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Yabin Sun

Research on the Radiation Effects and Compact Model of SiGe HBT

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Supervisor's Foreword

With the rapid development of wireless communications and continuous progress of information technology, the characteristics of high frequency, low power, low noise, multi-functional, and low cost have become a hot pursuit of the communications industry. As a success of band gap engineering in semiconductor devices, silicon-germanium (SiGe) heterojunction bipolar transistor (HBT) technology possesses desirable performance far superior to their Si-only homojunction cousins and better compatibility with CMOS process than classical III-V HBTs. Similar to any other new technology, SiGe HBT is also aggressively exploring device performance and scaling limits. As a vertical rather than lateral (like CMOS) transport devices, the length scale of SiGe HBTs is determined by the ability to control layer thicknesses rather than lateral lithography. SiGe HBTs with f_T and f_{max} more than 300 GHz and circuits with operation frequency in excess of 100 GHz have been successfully demonstrated. An accurate physically oriented model and parameter-extraction technique for SiGe HBTs are very important for evaluating the fabrication process, optimizing the device structure, and helping in circuit design.

The future global competition, especially the military confrontation, will shift from traditional sea, land, and air into outer space. The space radiation environments are generally “unfriendly” to electronic systems operating in space exploration platforms, causing a serious reliability pressure and challenge. The electronics must be “hardened” for its intended operation environment, through hardening-by-process and “hardening-by-design.” Thus, process complexity, layout area, and design cost are bound to rise. Due to the unique band gap-engineered features, SiGe HBTs enable excellent tolerance to total ionizing dose (TID), displacement damage (DD), and single-event effects (SEE) with little or no process modification and are expected to offer significant potential and be used across a wide variety of environmentally invariant electronics platform.

It is vital to investigate the device model and related radiation effects in SiGe HBT, to accurately evaluate the radiation response and establish a compact device model. With the continuous development and research in the past few decades, there are still some problems to be solved about the radiation effect and compact model of SiGe HBTs. Such as the enhanced low-dose-rate sensitivity

(ELDRS), which is closely related to the device structure, layout, and manufacturing process. Whether ELDRS exists and the physical mechanism needs to be further demonstrated. A simple method to collect the real-time information of SEE, as well as the way to quickly detect the device sensitive area of SEE remains to be further studied. Besides, the non-uniform radiation damages exist within the transistor structure after being exposed to space environment, the whole transistor network may have an obvious distributed effect, and the current compact model may not meet the requirement of space radiation application. Establishing a compact model and the corresponding parameter-extraction method suitable for space radiation environment have an important significance.

Many achievements to radiation effects and compact model for SiGe HBT technology can be found in this text, and the chapters in this volume represent examples of author's tremendous effort. This text makes the future of SiGe technology in extreme environment electronics applications significantly brighter. I hope you find this text illuminating as to the path that maturation followed.

Beijing, China
July 2017

Prof. Jun Xu

Abstract

With the rapid development of space exploration, more and more electronic systems will operate in a variety of radiation environments. Due to the radiation effects, the electronic devices operated in the radiation environments will suffer certain degree of damage or destroy. Silicon-germanium heterojunction bipolar transistors (SiGe HBTs) have been widely used in the field of wireless communication and RF microwave because of the advantages of high gain, high linearity, low noise, and low cost. Recently, owing to the built-in multi-Mrad total ionizing dose tolerance, SiGe HBTs have offered great promise in the space applications. However, due to the diversities of space environments, device process, and structure, there are still many critical issues to be solved when SiGe HBTs apply in the radiation environments. This work focuses on the irradiation effects and compact model of SiGe HBTs, mainly including research on performance degradation, mechanism analysis, model building, and parameter extraction.

First of all, SiGe HBTs are validated to be radiation hard as fabricated without intentional hardening by ^{60}Co radiation. The devices under test exhibit a significant enhanced low-dose-rate sensitivity (ELDRS). The varied bias dependence of ionization damage under different dose rates is also found. The transistors with all terminals floating suffer the worst degradation when irradiated at high-dose rate, while the case of forward-biased mode shows the largest degradation when irradiated at low-dose rate. Then the swift heavy ions are used to detect the radiation-induced displacement damage in SiGe HBTs. The displacement damages induced by heavy ions are found to be related to the non-ionizing energy loss (NIEL). Moreover, the larger the NIEL is, the more the displacement damages will be created, and the more serious degradation will occur. In addition to the current gain degradation, the parasitic resistance, Early voltage, neutral base recombination, and other important electrical parameters all appear serious degradation when the transistors are exposed to heavy ion radiation, which demonstrates that the displacement damage has become a major issue of SiGe HBTs in the radiation environments. Finally, combining the pulse laser and high bandwidth digital oscilloscope, the real-time transient characteristics of collector voltage are successfully detected. The impact of laser energy, load resistance, and bias condition

on single-event transient (SET) is also discussed, and the results point out that the power supply voltage should be lowered and the collector load resistance should be decreased in order to reduce the single-event transient sensitivity.

In respect of compact model, the whole transistor network is divided into three parts according to the base region distribution in the actual transistor structure: intrinsic transistor, link base region, and extrinsic base-collector junction region. A small-signal equivalent circuit model, which takes into accounts of the distribution effects, is obtained by solving the transmission line equations. To extract all the parameters in the proposed model, a novel extraction technique based on the rational function fitting over the range of whole frequency is developed. After the rational function fitting to related admittance parameters, a number of coefficients are accurately obtained and then all the model parameters are directly extracted without any special test structures or numerical optimization. The proposed model and extraction technique are validated on SiGe HBTs exposed to 10MeV Cl ion irradiation as well as a wide temperature ranging from -55 to 200°C . An excellent agreement is obtained between the measured and simulated S parameters.

The results in this work are of great importance to understand the physical mechanism of radiation effects, provide theoretical guidance to optimize the device structure, and seek radiation-hardened design technique.

Keywords SiGe HBT • Radiation effects • Heavy ion radiation • Compact model • Parameter extraction

Preface

As a successful fruit of semiconductor band gap engineering, silicon-germanium (SiGe) heterojunction bipolar transistor (HBT) has already made considerable progress in wireless communication applications, especially in the past decade. Due to the special device structure and band gap engineering in base region, SiGe HBT technology has been demonstrated with multi-Mrad total dose tolerance and can be used as a strong candidate in space electronics. This book mainly relates to radiation effects and device model of bipolar transistor, and it is intended for a number of different audiences and venues. My purposes are as follows:

1. To introduce some new research achievement about the radiation effects of SiGe HBTs, including the total dose effect and single-event effects
2. To provide some new research results about the device model and parameter-extraction method for heterojunction bipolar transistor

This book starts with a brief introduction of research status about the radiation effects and compact model of SiGe HBTs. Then various aspects of radiation effect are covered; the corresponding performance degradations and physics mechanisms for each radiation effect are discussed in detailed. Finally, the equivalent circuit model parameter-extraction techniques are introduced and applied to the transistor exposed to extreme environments. The presentation of this book assumes that the reader has some modest background in semiconductor physics and semiconductor devices.

This book can be intended to provide a hands-on reference for researchers and engineers working on various aspects of SiGe HBT technology, including radiation effects, radiation hardening, device model and simulation, and parameter extraction. This book should also be useful as a hands-on research resource for graduate students in electrical engineering and computer science who require knowledge about the advanced SiGe HBT technologies. The references listed at the end of each chapter are elaborate and useful for readers using this book. I hope my efforts please you!

Shanghai, China

Dr. Yabin Sun

Declaration

I solemnly declare that this dissertation is my independent research result under the guidance of my supervisor, Jun Xu, in Tsinghua University. As far as I know, the research results in this dissertation do not contain any content that is copyrighted by others, unless the cited text has been specified. Other individuals and collectives who have contributed to the research involved in this paper have been identified in a clear manner.

Published Academic Articles

1. **Yabin Sun**, Jun Fu, Ji Yang, Jun Xu, Yudong Wang et.al, An improved small-signal model for SiGe HBT under off-state, derived from distributed network and corresponding model parameter extraction, *IEEE Transactions on Microwave Theory and Techniques*, 63(10), 2015,1131–1141
2. **Yabin Sun**, Jun Fu, Ji Yang, Jun Xu, Yudong Wang et.al, Novel analytical parameters extraction for SiGe HBTs based on the rational function fitting, *Superlattices and Microstructure*, 80, 2015, 11–19
3. **Yabin Sun**, Jun Fu, Ji Yang, Jun Xu, Yudong Wang et.al, Extraction of temperature dependences of small-signal model parameters in SiGe HBT HICUM model, *Chin. Phys. B*, 25(4), 2016 048501
4. **Yabin Sun**, Jun Fu, Yudong Wang, Wei Zhou, Xiaojin Li, and Yanling Shi, Novel Method to Determine Base Resistance in SiGe HBT from Small-Signal S-Parameters, *Microwave and Optical Technology Letters*, 59(3), 2017, 555–560
5. **Yabin Sun**, Jun Fu, Yudong Wang, Wei Zhou, Zhihong Liu, Xiaojin Li, Yanling Shi, Experimental study of bias dependence of pulsed laser-induced single-event transient in SiGe HBT, *Microelectronics Reliability*, 65, 2016, 41–46

6. **Yabin Sun**^{*}, Jun Fu, Yudong Wang, Wei Zhou, Xiaojin Li, Yanling Shi, In-suit investigation of DC characteristics degradation in SiGe HBT included by halogen lamp irradiation, *Superlattices and Microstructures*, 98, 2016, 62–69
7. **Yabin Sun**, Jun Fu, Yudong Wang, Wei Zhou, Wei Zhang, Zhihong Liu, Direct analytical parameter extraction for SiGe HBTs Ttopology small-signal equivalent circuit, *Superlattices and Microstructures*, 94, 2016, 223–230
8. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang, et.al. Bias dependence of ionizing radiation damage in SiGe HBTs at different dose dates. *Physica B*, 2014, 434: 95–100
9. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang, et.al. Degradation differences in the forward and reverse current gain of 25MeV Si ion irradiated SiGe HBTs. *Physica B*, 2014, 449:186–192
10. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al. Impact of bias conditions on performance degradation in SiGe HBTs irradiated by 10MeV Br ion, *Microelectronics Reliability*, 2014, 54(12): 2728–2734
11. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al, Investigation of bias dependence on enhanced low dose rate sensitivity in SiGe HBTs for space application, *Nuclear Instruments and Methods in Physics Research A*, 2014, 738: 82–86
12. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al, Irradiation Effects of 25MeV Silicon Ions on SiGe Heterojunction Bipolar Transistors. *Nuclear Instruments and Methods in Physics Research B*, vol. 312, pp. 77–83, 2013
13. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al, A Single-event transient induced by pulsed laser in silicon–germanium heterojunction bipolar transistor, *Chin. Phys. B*, 2013, 22(5): 056103
14. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al, Comparison of total dose effects on SiGe HBT induced by different swift heavy ions irradiation for space application, *Chin. Phys. B*, 2014, 23(11): 116104
15. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al. The total-dose-effects of gamma and proton irradiations on high-voltage silicon–germanium heterojunction bipolar transistors, *Radiation Effects & Defects in Solids*, 2013, 168 (4): 253–263
16. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al, the study on ionization damage of silicon-germanium heterojunction bipolar transistors at various dose rates, *Acta Phys. Sin.* vol. 62, no. 19, pp. 196104, 2013
17. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al. The Reliability of SiGe HBT under Swift Heavy Ion Irradiation, 2013 IEEE International Conference on Electron Devices and Solid-State Circuits (EDSSC), Hongkong, China, June 2013
18. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al, Novel method to determine base resistance in SiGe HBT HICUM based on rational function fitting, 2014 IEEE 12th International Conference on Solid-States and Integrated Circuit Technology, Guilin, China, October 2014

19. **Yabin Sun**, Jun Fu, Jun Xu, Yudong Wang et.al. A Comparison of 10MeV Chlorine and 20MeV Bromine Ion Irradiation Effects on SiGe HBTs for Space Application. 2013 IEEE International Semiconductor Device Research Symposium (ISDRS), Maryland, USA, December 2013
20. Ji Yang, Jun Fu, **Yabin Sun**, Yudong Wang et.al, Novel extraction of emitter resistance of SiGe HBTs from forward-Gummel measurements, 2014 IEEE International Conference on Electron Devices and Solid-State Circuits (EDSSC), Chengdu, China, June 2014

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Contents

1	Introduction	1
1.1	Background	2
1.1.1	Space Radiation Environment and Radiation Effect	2
1.1.2	Development and Application of SiGe HBT Technology	5
1.2	Radiation Effect and Compact Model of SiGe HBT	7
1.2.1	Radiation Effect of SiGe HBT	7
1.2.2	Compact Model of SiGe HBT	12
1.3	Research Work in This Dissertation	14
	References	16
2	Ionization Damage Effect in SiGe HBT	25
2.1	Interaction Mechanism Between Gamma Rays and Materials	25
2.2	Experiment	26
2.3	Results and Discussion	28
2.3.1	SiGe HBT1 with Emitter and Substrate Connecting Together	28
2.3.2	Ionization Damage in SiGe HBTs with Backside Collector Electrode	34
2.3.3	Degradation Mechanism in Gamma Ray Irradiated SiGe HBTs	38
2.4	Ionization Damage in SiGe HBT at Different Dose Rate	42
2.4.1	Results of Ionization Damage at Different Dose Rate	43
2.4.2	Mechanism of Enhanced Low-Dose-Rate Sensitivity	45
2.5	Bias Dependence of Ionization Damage in SiGe HBT	48
2.5.1	Irradiation Under High-Dose Rate	49
2.5.2	Irradiation Under High-Dose Rate	51
2.6	Conclusion	54
	References	55

3	Displacement Effects in SiGe HBT	57
3.1	Interaction Mechanism Between Swift Heavy Ion and Materials	57
3.2	Experiment	58
3.3	Irradiation Effects of 25 MeV Silicon Ions	60
3.3.1	Sige HBT1 with Emitter and Substrate Connecting Together	60
3.3.2	Performance Degradation of SiGe HBT2	63
3.3.3	Physical Mechanism Analysis for Heavy Ion Radiation	67
3.4	Degradation Difference for Forward and Reverse Current Gain	73
3.4.1	Experimental Result	73
3.4.2	Mechanism Analysis and Discussion	77
3.5	Comparison of Different Heavy Ion Radiation	80
3.5.1	Experimental Samples and Methods	80
3.5.2	Experimental Results Analysis and Discussion	81
3.6	Effect of Bias Conditions	88
3.7	Conclusion	90
	References	91
4	Single Event Transients in SiGe HBT	93
4.1	Mechanism of Single Event Effects	93
4.2	Experiment	94
4.3	Results and Discussion	96
4.3.1	Effects of Laser Energy	96
4.3.2	Effects of Load Resistance	100
4.3.3	Effects of Bias Condition	102
4.4	Simulation of Single Event Transient in SiGe HBT	107
4.4.1	Electric Potential and Electric Field	109
4.4.2	Location Sensitivity Analysis of Single Event Transient	112
4.5	Conclusion	115
	References	115
5	Small-Signal Equivalent Circuit for SiGe HBT Based on Distributed Network	117
5.1	Significance of SiGe HBT Distributed Equivalent Circuit	117
5.2	Establishment of Small-Signal Model	118
5.2.1	Link Base Region (Region I)	119
5.2.2	Intrinsic Transistor (Region II)	123
5.2.3	Extrinsic Base Region (Region III)	127
5.2.4	Equivalent Circuit for the Whole Transistor	128
5.3	Approximation and Simplification of Proposed Model	128

5.4	Conclusion	131
	References.	132
6	Parameter Extraction of SiGe HBTs	133
6.1	Small-Signal Model Parameter Extraction.	134
6.1.1	Parameter Extraction Under Off-State	134
6.1.2	Parameter Extraction Under Forward-Active Mode.	142
6.2	Parameter Extraction Under Irradiation Environment	149
6.3	Temperature Characteristics of Model Parameter	153
6.3.1	Parameter Extraction Under High and Low Temperature	155
6.3.2	Temperature Dependence Model	157
6.4	Summary	162
	References.	162
7	Summary	165
7.1	Main Work and Research Results.	165
7.2	Innovations.	167
7.3	Suggestions for Further Work.	168

About the Author



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Abbreviations

AC	Alternating current
BC	Base-collector
BE	Base-emitter
BiCMOS	Bipolar and complementary metal oxide semiconductor
BJT	Bipolar junction transistor
CCE	Charge collection efficiency
CS	Collector-substrate
DC	Direct current
DD	Displacement damage
DLTS	Deep-level transient spectroscopy
DUT	Devices under test
EHP	Electron-hole pairs
ELDRS	Enhanced low-dose-rate sensitivity
ESD	Electrostatic discharge
GICCR	Generalized integral charge control relation
HBT	Heterojunction bipolar transistors
HICUM	High Current model
IBICC	Ion beam-induced charge collector
IC	Integrated circuit
LET	Linear energy transfer
LOCOS	Local oxidation of silicon
MEXTRAM	Most exquisite transistor model
MOSFET	Metal oxide semiconductor field-effect transistor
NBL	n ⁺ buried layer
NBR	Neutral base recombination
NIEL	Non-ionizing energy loss
PKA	Primary knock-on atoms
RF	Radio frequency
SEE	Single-event effect
SEL	Single particle latch

SET	Single-event transient
SEU	Single-event upset
SGP	SPICE Gummel–Poon
SIC	Selectively implanted collector
SiGe	Silicon-germanium
SOLT	Short-open-load-thru
SRIM	Stopping and range of ions in matter
TCAD	Technology computer aided design
TID	Total ionization damage
VBIC	Vertical bipolar intercompany
VNA	Vector network analyzer

Chapter 1

Introduction

With the continuous development of space technology, recently an increasing number of electronic systems will work in the varied radiation environments. Space radiation effects, induced by various kinds of charged particles, can destroy the aerospace materials, electronic devices, and circuit system, so that the entire spacecraft cannot work properly. The early satellites launch by USA and Soviet Union suffer several malfunctions due to the irradiation effect, which greatly reduces the reliability or working lifetime of spacecrafts [1, 2]. Space radiation effects have become a huge obstacle to the continuous development of human spaceflight technology. Due to the excellent current driving ability, high gain, high linearity, and low noise, silicon-germanium (SiGe) heterojunction bipolar transistors (HBT) have a wide potential in the application of RF microwave circuit, wireless communications, and automotive radar. Besides, because of the inherent multi-Mrad total dose tolerance, recently SiGe HBT has attracted great attention in the extreme electronics. The research on the radiation effects of SiGe HBTs can provide theoretical guidance to radiation hardening. An accurate physically oriented model and parameter-extraction technique for SiGe HBTs are very important to evaluate the fabrication process, optimize the device structure, and help in circuit design. However, due to the existence of irradiation effects, the routine physics model and parameter extraction may not apply for the transistors in radiation environment. Therefore, it is of great academic significance to study the device model and parameter-extraction technique under irradiation environment.

This chapter is divided into three sections. The background, including the space radiation environment and the current development and application of SiGe HBT technology, is introduced in the first section. The second section summarizes the current research progress of radiation effect and compact model of SiGe HBTs. The third section points out the problems/shortcomings of that radiation effect and device model of SiGe HBTs, and finally, the main research content and thesis frame are proposed.

1.1 Background

1.1.1 Space Radiation Environment and Radiation Effect

With the rapid development of space exploration, the space radiation environment has received great attentions. The space particles can directly perturb the normal operation of electronic systems. The space radiation environment is divided into three types: geomagnetic capture zone, solar cosmic ray, and galactic cosmic ray, as shown in Fig. 1.1 [3–5]. Each radiation particle has a corresponding energy and density.

- (1) Geomagnetic Capture Zone
- The geomagnetic capture zone, also known as the Van Allen radiation zone, is a gathering area of a large number of high-energy charged particles around the earth. It is composed of two parts: the inner radiation belt closer to the ground and the outer radiation belt farther from the ground. The inner radiation belt is within a zone of 1.5 earth’s radius from the center of the earth, mainly consisting of protons of tens to hundreds of MeV and electrons below MeV [4]. In the absence of external magnetic field and solar wind, the intensity and spatial distribution of the particles in the inner radiation belt are relatively stable. In July 1962, the USA exploded a hydrogen bomb in this layer, and the high-energy electrons continued in the next few years [6]. The outer radiation belt is mainly distributed in the space region with the height of 3–4 earth’s radius, and the energy of the particles is smaller than that in the inner belt, mainly consisting of electrons above 1 MeV and a few low-energy protons and heavy ions. It is worth noting that the charged particles are distributed throughout the earth’s space, and there is actually no obvious dividing line, but the density of particles in the inner radiation belt is larger and the intensity is relatively stable, compared to those in the outer radiation belt. The damage to

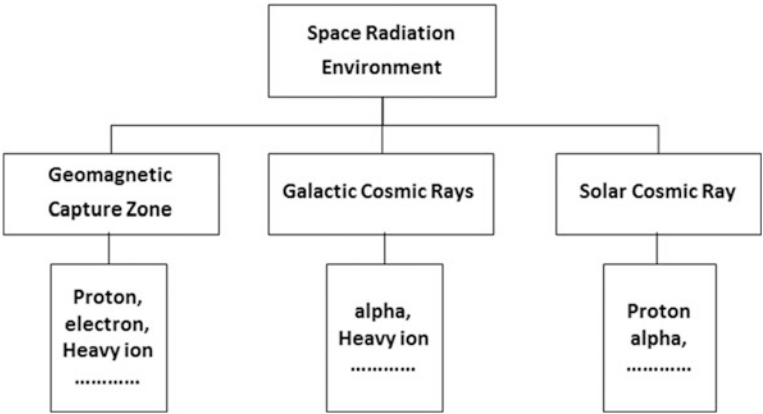


Fig. 1.1 Distribution of space radiation environment

the astronauts and satellite systems in the inner radiation belt is mainly due to the high-energy protons and that in the outer radiation belt is from the high-energy electrons. At the beginning of 1992, the scientists from USA and Russian found that there was a third radiation belt in the middle of the Van Allen band, which was mainly composed of oxygen ions [6].

(2) Solar Cosmic Rays

Solar cosmic rays are the high-energy particle streams emitted by the solar activity (typical energy of 10 MeV to 10 GeV). The principal components are protons and small amounts of electrons and heavy ions. The solar cosmic rays can be classified into solar wind and solar flare. The solar wind usually occurs in the corona (the outermost layer of the sun). It is created by the high-speed charged particles, which break away from the sun's gravitational attraction. The average density of solar wind is about $1\text{--}30$ particles/cm³, and the components are similar to those of sun, such as 95% proton, 4% alpha particles, and a small amount of heavy ions (such as carbon, nitrogen, silicon, and iron). Besides, amounts of electrons exist to keep the whole solar wind electrically neutral [5]. The solar wind will disturb the geomagnetic field and create a kind of magnetic storms, resulting in the radio communication interruption.

The solar flare is a phenomenon of sudden increased local radiation in the sun's ball. It is the most violent solar activity and often appears in the sun's active area (such as near the sunspots). The frequency of solar flare is uncertain, once a few days, or even does not appear within a few weeks. The duration of solar flare is usually short, a few minutes to several tens of minutes, but it can release a huge amount of energy. When the solar flare occurs, the radio waves, ultraviolet rays, and X-rays rapidly increase, affecting the ionosphere of earth atmosphere and destroying the electromagnetic communication [4, 5].

(3) Galactic Cosmic Rays

The galactic cosmic rays are the high-energy charged particles from the Milky Way beyond the solar system, consisting of 87% protons, 12% alpha particles, and 1% heavy ions. It generally has a low fluence (about $2\text{--}4/\text{cm}^2/\text{s}$), high energy (about $40\text{--}10^{13}$ MeV), and great penetration ability [5]. The intensity is affected by solar activity, for example, the intensity of low-energy particles is opposite to the solar activity cycle, when the solar activity is frequent, the intensity of galaxy cosmic ray is low, and vice versa. The particles in the space environment can produce a variety of radiation effects, resulting in a serious threat to the electronic systems.

The space radiation effects can be divided into ionization effect and displacement effect, as shown in Fig. 1.2 [1]. The ionization effect is induced by the collision between the particles and the atoms extranuclear electrons, and the electron-hole pairs are generated. The ionization effect can not only produce the long-term ionization damage effects, but also induce the transient single-event effects. The ionization damage effects will degrade some characteristic parameters of the circuit system. The current gain of bipolar transistor decreases [7–9], and in MOSFET, the threshold voltage drifts,

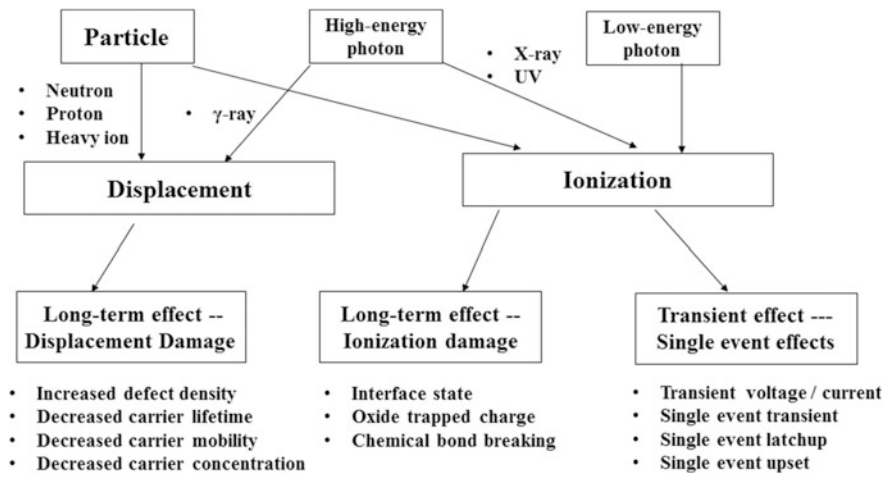
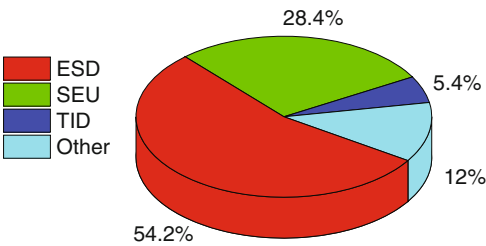


Fig. 1.2 Classification of space particle and radiation effect

transconductance drops, and the leakage current increases [10]. The displacement effect is caused by the collision between the particles and the nucleus of material, and the vacancy-gap atom pairs are produced, as a result, the long-term displacement damage effects are created. Many electrical parameters of the semiconductor material, such as minority carrier lifetime, carrier mobility, and effective doping concentration, all suffer some certain degree due to the existence of displacement damages. Compared to the transient single-event effect, the ionization damage effect and the displacement damage effect are a kind of permanent irreversible damage, which is the result of the long-term accumulation of space radiation and only can be manifested at a certain radiation dose. Therefore, the ionization damage effect and the displacement damage effect are also referred as total dose effects.

Figure 1.3 shows the statistical distribution of the failure of electronic systems in the space radiation environment [3]. In addition to the failure induced by ESD, the total dose effects and single-event effects are the two important sources for the systems' failure. In the thesis, we will discuss these two kinds of space radiation effects.

Fig. 1.3 Distribution of electrical system fault in space environment

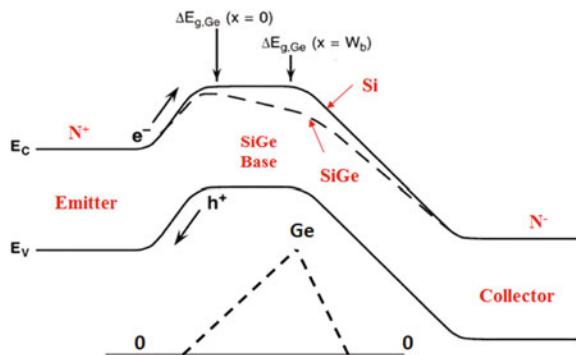


1.1.2 Development and Application of SiGe HBT Technology

Since IBM developed the first SiGe HBT in the 1980s, SiGe HBT has made great progress in material preparation, process integration, and device structure and circuit design. In order to meet the needs of different applications, the transistor structure is constantly changing, such as single polycrystalline non-self-aligned structure [11], double polycrystalline self-aligned structure [12], self-aligned shallow trough isolation table structure [13], selectivity epitaxial emitter window structure [14], and epitaxial base transistor structure [15]. In the future, it will be toward the direction of the smaller size and higher integration. Compared to the conventional Si BJT, the additional Ge composition in the base region changes the base band gap of SiGe HBTs [7], as shown in Fig. 1.4. Due to the close electron affinity of Si and Ge (4.00 and 4.05 eV, respectively), the band difference between Si and Ge mainly appears at the valence band, which suppresses the reverse injection from base to emitter region and then greatly improves the injection efficiency of the electrons from emitter to base region. As a result, SiGe HBTs show a significant increase in current gain at a given V_{BE} . Therefore, it is possible to increase the base doping concentration and reduce the emitter doping concentration under the premise of higher current gain. Thus, the base resistance, maximum oscillation frequency, noise figure, base-width modulation effect, and emitter band gap narrowing effect are greatly improved. Besides, the graded Ge component introduces an accelerating field in the base region, further increasing the device cutoff frequency. Finally, the band gap difference around the interface of BE junction and BC junction can effectively increase Early voltage and slow the base-width modulation effect.

The performances of SiGe HBTs largely depend on the vertical structure, size, doping, and Ge components. Being different from MOSFETs with the lithography gate length as the technical node, the cutoff frequency f_T and maximum oscillation frequency f_{max} are generally adopted as the technical node of SiGe HBTs. Over the past decades, f_T and f_{max} of SiGe HBT have rapidly grown from the tens of GHz in

Fig. 1.4 The band gap diagram for SiGe HBTs



the late 1990s to the current hundreds of GHz [16]. More importantly, as for the same f_T or $f_{\max}$, SiGe HBTs often have 2–3 generations advantages over the CMOS technology. For example, f_T of nFET in 65 nm or even 45 nm process only achieves that of SiGe HBTs in 0.13 μm process [16]. One should bear in mind that the breakdown voltage will decrease as the operating frequency increases. However, due to the existence of non-quasi-static effect in SiGe HBTs, the drop of breakdown voltage becomes very slow when the operating frequency comes into the hundreds of GHz [16]. Recently, SiGe HBTs with $f_T > 500$ GHz and $BV_{\text{CEO}} > 1.5$ V have been developed in 90 nm or 65 nm process technology [16–19].

Table 1.1 shows the comparison of some important electrical parameters of SiGe HBT and MOSFET in RF or analog circuit design [16]. It can be seen that most electrical parameters of SiGe HBT are ahead of those of MOSFET, and the advantage is becoming more evident as the technology node shrinks.

Due to the excellent performance, recently SiGe HBTs have shown great potential in the application of mobile cellular networks, 2.4–60 GHz wireless LAN, power amplifiers, radar, wireless base stations, and automotive electronics. In order to maximize the advantages of SiGe HBT and CMOS technology, SiGe BiCMOS technology (SiGe HBT + Si CMOS) is introduced, which is based on the mature CMOS technology and SiGe HBT process modules are embedded. SiGe BiCMOS technology is suitable for the analog–digital mixed circuit design, where SiGe HBTs are used for analog, RF, microwave, and ultra-high-speed digital circuit design, and CMOS technology is used for the high-integration circuit, memory, and basic analog unit design. In recent years, SiGe HBTs are found with an inherent multi-Mrad total dose tolerance to space radiation and are considered to be one of the most promising candidates in extreme environments [20–23]. For example, due to the existence of larger space radiation and severe temperature fluctuation, the electronic system on the lunar surface requires a kind of large and heavy “warm box,” which increases the system cost and weight. On the contrary, SiGe HBT

Table 1.1 The trend of electrical parameters of SiGe HBT and MOSFET with the technology node decreasing

Parameters	SiGe HBT		CMOS	
	Basic performance	Size scaling	Basic performance	Size scaling
Cutoff frequency f_T	+	+	+	+
Noise figure $NF_{\min}$	+	+	+	+
$1/f$ noise	+	0	0	--
Transconductance	+	+	–	+
Match	+	0	–	--
Linearity	+	0	+	--
Voltage swing	0	0	–	--
Breakdown voltage	+	0	–	--

Excellent: ++, Good: +, General: 0, Bad: –, Worse: --

technology can be directly used in the space radiation environment. From the comparison of the remote control unit in the lunar system based on conventional CMOS process and SiGe HBT technology [24], it can be seen that the volume, weight, power consumption, and operating temperature are greatly improved when SiGe HBT technology is adopted.

Due to the inherent multi-Mrad total dose tolerance, SiGe HBTs have been recently considered to be one of the most promising candidates in extreme environments. However, due to the complexity of radiation effects and the close correlation with the manufacturing process, it is necessary to explore the mechanism of radiation effect, device model, and parameter extraction of SiGe HBTs in the space environment. In the following two sections, we will introduce the current state of radiation effects and compact models of SiGe HBT, point out the existing problems, and then lead to the research content and structure of this doctoral dissertation.

1.2 Radiation Effect and Compact Model of SiGe HBT

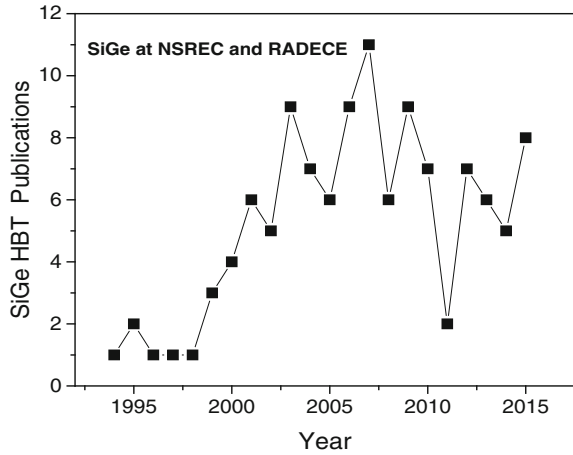
1.2.1 Radiation Effect of SiGe HBT

Space radiation is a serious threat to the electronic systems. Radiation effects can lead to the device or circuit failure, such as Si MOSFET exposed to long-term ionization exposure [7, 10]. Therefore, the electronic systems must be hardened to the specified space environment, which can be achieved through the following two ways, radiation hardening by process and radiation hardening by design. Thus, it inevitably increases the cost of design and manufacturing. Consequently, it is natural to adopt the inherent hardened devices to operate in the space radiation environment. Due to the multi-Mrad total dose tolerance, SiGe HBTs have been recently considered one of the most promising candidates in extreme environments.

Since the first discovery of radiation damage in SiGe HBTs [25], numerous studies have been carried out and significant progress has been made. Figure 1.5 shows the variation of articles about the radiation effects of SiGe HBTs in the two important conferences, Nuclear and Space Radiation Effects Conference (NSREC) and Radiations Effects on Components and Systems (RADECS), from 1994 to 2015. Several related papers about the radiation effects in SiGe HBTs will be appeared every year. So far nearly 100 articles have been published in the two top conferences about the radiation effects, and its trend is increased in the future, which indicates that research about SiGe HBTs has become a hot spot in the field of radiation effects.

The radiation effects in SiGe HBT are mainly focused on the total dose effects [26–44] and single-event effects [45–62], involving the degradation of device and circuit [26, 27, 31–35, 63], physical mechanism of radiation effects [64–67], and radiation hardening techniques [45–47, 55–58]. In the following part, we will discuss the progress of the total dose effect and single-event effects of SiGe HBTs.

Fig. 1.5 The number of articles about SiGe HBTs in NSREC and RADECS from 1994 to 2015

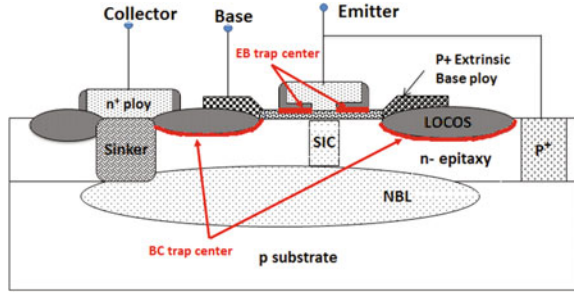


A. Total Dose Effects

Ohyama first reported the radiation damages in SiGe HBTs in 1994, and the effects of Ge component and doping concentration have been investigated in detail [25]. In 1995, J.D. Cressler reported the total dose effects of IBM's first-generation SiGe HBT for the first time [41]. In the following 20 years, numerous studies have been carried out about the total dose effects in SiGe HBTs, including different radiation sources [63, 68, 69], radiation temperatures [28–30], dose rate [42, 70], and so on. The results show that SiGe HBT has inherent multi-Mrad total dose tolerance with no intentional hardening [71–74]. Figure 1.6 shows the two sensitive regions to radiation damages in SiGe HBTs, the spacer oxide around EB junction and LOCOS (or STI in certain technology). The radiation hardness of SiGe HBTs is irrelevant to the Ge component in the base region, which mainly originates from the special epitaxial base structure [7]. As shown in Fig. 1.6, the spacer oxide around EB junction is very narrow (about 10 nm) and surrounded by heavily doped extrinsic base region; as a result, the radiation damages are effectively shielded. The base region is very thin and heavily doped, dramatically reducing the displacement damage effects. These special structures result in a multi-Mrad total dose tolerance of SiGe HBT.

The total dose effects of SiGe HBTs are seriously affected by the space environment, radiation source, dose rate, and ambient temperature. Several common radiation sources, including gamma rays [73, 75], X-rays [43, 76], neutrons [77, 78], and protons [31–35, 79–81], are widely used. The dose rate ranges from high-dose rates (150–300 rad/s) to low-dose rate (0.001–0.1 rad/s) [42, 63, 68, 70] and the ambient temperature from 300 °C to 77 K [28–30, 82, 83]. The devices under test cover from the IBM's first-generation to fourth-generation SiGe HBT [40, 54, 69], including NPN HBT and PNP HBT [26, 60, 84]. Almost all of electrical parameters are studied, such as base current and current gain [63, 68, 69],

Fig. 1.6 Cross-section of SiGe HBT, where the spacer oxide around EB junction and LOCOS edge are the sensitive region to radiation damage



transconductance [35], Early voltage [11], temperature dependence [28, 29, 82], bias dependence [44, 77, 85], parasitic resistance [44, 77, 85], S parameter [35, 81, 86], neutral base recombination [35], breakdown voltage [35, 87, 88], impedance matching [86], noise [26, 89], linearity [33], and self-heating effect [33]. Figure 1.7a shows the typical variation of base current I_B and normalized current gain under low V_{BE} region in modern SiGe HBTs exposed to different irradiation sources. The degradations are found to be closely related to the type of radiation source.

The inherent multi-Mrad total dose tolerance of SiGe HBTs is generally obtained under the dose rate of 50–300 rad/s according to US military standard MIL-STD883 [90]. However, the dose rate in the actual space environment is extremely low (about 10^{-4} – 10^{-2} rad/s), and under this low-dose rate range, the radiation damages in some silicon bipolar junction transistors are ten times as high as those under high-dose rate range, i.e., there exists enhanced low-dose-rate sensitivity (ELDRS) [91, 92]. Consequently, the ground accelerated radiation experiment may overestimate the total dose tolerance of some electronic devices operated at low-dose rate environment. At present, few reports document ELDRS in SiGe HBT, and there still lacks a unified understanding about the existence of ELDRS and corresponding physical mechanism in SiGe HBTs. The total dose

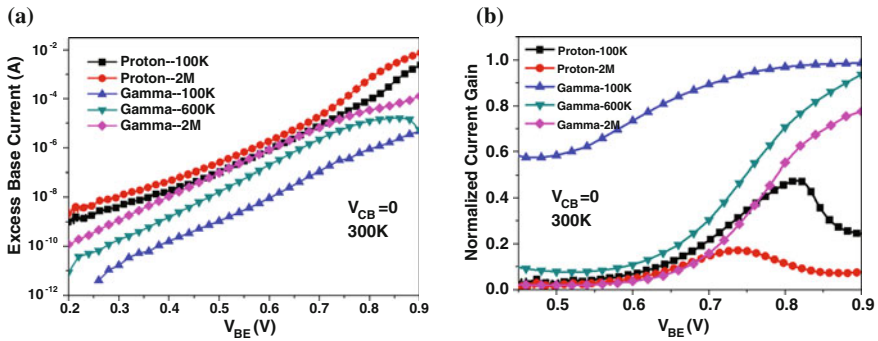


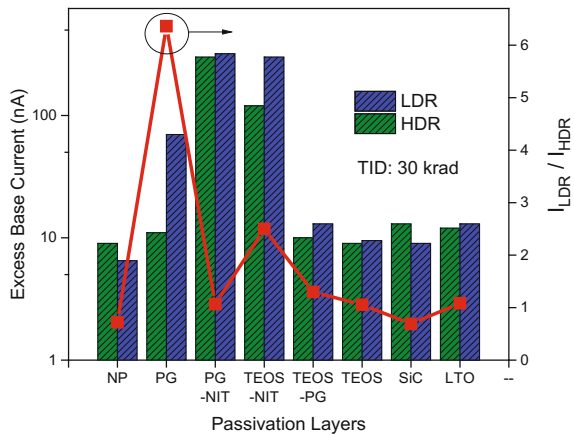
Fig. 1.7 Comparison of **a** excess base current and **b** normalized current gain as a function of V_{BE} for both gamma and proton irradiations

effects of IBM's fourth-generation SiGe HBTs were reported under different dose rates, and no significant ELDRS appeared [91, 92]. However, some experiment data under 0.01 rad/s are still larger than those under 50 rad/s, i.e., it is possible that ELDRS effect exists. Up to now, there is no uniform conclusion about ELDRS in SiGe HBTs.

Space radiation effects, especially the ELDRS effects, are closely related to the fabrication process, such as the passivation layer used in subsequent process [93–95], the thermal stress [96], and the hydrogen content [97, 98] introduced in the encapsulation process. The greater the amount of hydrogen content, the more severe the radiation damage in the bipolar device [98]. Figure 1.8 shows the effects of different passivation layers. Compared the transistors without the passivation layer, a large amount of radiation damages appear in the examples with the passivation layer of borophosphosilicate glass (PG) and nitride deposited by CVD process, and a significant ELDRS exists in the transistors using PG as the passivation layer [93]. The physical mechanism about the effect of passivation layer on ELDRS in bipolar devices has not been clarified, and it may be related to the hydrogen and stress in the passivation layer [93]. Therefore, as for the anti-radiation characteristics of SiGe HBTs, the actual manufacturing process should be considered and it still needs to carry out some radiation test.

Over the past few decades, neutrons have been used as a traditional radiation source to detect displacement damage [27, 77, 78]. Abundant radiation residue exists in the transistors after neutron radiation. The measurements are carried out after a long-time replacement and unnecessary annealing effects are introduced. Furthermore, in recent years, most of the world's neutron reactors have been closed, therefore, there is an urgent need to seek another kind of radiation source to detect the displacement damage. The US Navy Laboratory has conducted the radiation experiments on Si BJT with swift heavy ions for the first time in 2006, and a strict Messenger-Spratt equation is found between the reciprocal of current gain and ion fluence [99], which is similar to the case of neutron radiation. Then the researches

Fig. 1.8 Excess base current of bipolar transistors under passivation conditions



about the total dose effect of swift heavy ions receive widespread attention [100, 101], but there is still a lack of in-depth study of the radiation effects of swift heavy ions in SiGe HBTs.

B. Single-Event Effects

Compared to the total dose effect, single-event effect is a serious problem for the microelectronic devices in the space radiation environment, single-event upset (SEU), single-event transient (SET), and single-particle latch (SEL). As for SiGe HBTs, due to the self-isolation of heavily doped sub-collector region, SEE is mainly SET and SEU, and no obvious SEL exists [7]. Since the first report about SEU sensitivity of SiGe HBT 32-bit shift register in 2000 [102], a great deal of studies have been carried out on SiGe HBTs and related circuit.

(1) Experiment and simulation. Since the discovery of SEE in SiGe HBT, a great deal of researches have been studied combining the experimental measurements and TCAD simulations [49–51, 53, 103, 104]. When the heavy ions pass through the sensitive region of PN junction, a number of electron–hole pairs (EHPs) are generated along the incident path. Part of EHPs is separated under the built-in or applied electric field and then is collected by device terminal, resulting in a transient current pulse. When the collected charge is larger than the critical one required for the circuit turning, SEU appears. Figure 1.9 gives the TCAD-simulated transient current in SiGe HBTs induced by heavy ion radiation. One can see that SEE in SiGe HBT mainly originates from the reverse-biased collector-substrate (CS) junction. The transient current contains two parts. The first one is the fast and large drift current, generally a picosecond-scale process. The second one is the long and diffusion current, and the collected charge in this period is relatively more than that over the first one. Recently, some new SEE phenomena, such as multiple upset and charge sharing, appear as the feature size of the IC chip decreases.

The heavy ion microbeam and broad beam are two typical radiation sources for the single-event effect measurement [61, 105, 106]. The cross-section curve is used to characterize SEE sensitivity of SiGe HBT integrated circuit [107–110]. As for the single SiGe HBT, the collected charges measured in the ion beam-induced charge collector (IBICC) or time-resolved IBICC are adopted to evaluate the SEE

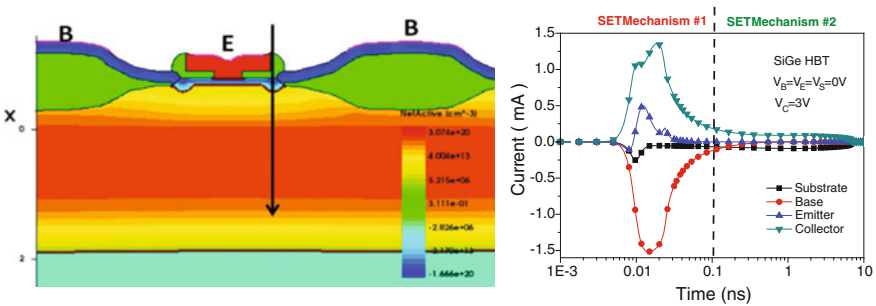


Fig. 1.9 Simulation of transient current in SiGe HBT induced by heavy ion radiation

sensitivity [47, 48, 111, 112]. The above cross-section curve and collected charge can be used to reflect the SEE sensitivity. However, both lack the detailed characteristics of transient voltage and current.

Compared to the heavy ion irradiation, the pulsed laser microbeam has high resolution, low noise, and high incident depth. Furthermore, combining with the high-bandwidth real-time digital oscilloscope, the detailed time information of transient voltage and transient current during the single-event effect can be obtained. Therefore, pulsed laser microbeam attracts great attention recently and is also used to characterize SEE sensitivity [59, 62, 113]. Jonathan et al. measured the single-event transients of SiGe HBT with pulsed laser microbeam for the first time in 2008 [59]. The captured transient currents are about nanoseconds, which is enough to cause the bit flip in the Gbit/s high-speed circuit.

(2) Radiation hardening. Since the first report of the single-event effects in SiGe HBT shift register in 2000 [114], various radiation hardening techniques have been proposed. First, it can be achieved by changing the transistor structure and layout, such as using SOI substrates [60, 115], P^+ blocking buried layers or reducing p-type substrate thickness [60, 115], N^+ guard rings [116, 117] shared dummy collector [46], junction isolation [58], and inverse-mode Cascode technique [55–57]. As for the circuit level, the radiation hardening method includes three-mode redundancy [118], double interleaving (DI), and gated element feedback (GFC) [102, 119]. However, now a single hardening method cannot meet the needs of today's space applications. In order to find the appropriate hardening technology, it is necessary to combine the manufacturing process, device layout, circuit, and system and take into account the performance, power consumption, area, and other constraints.

1.2.2 Compact Model of SiGe HBT

With the rapid development of manufacturing process, device, and circuit design technology, the compact model for bipolar transistor has also continuously improved, such as SGP [120], VBIC [121], HICUM [122], and MEXTRAM [123]. SGP is the first compact model for bipolar transistor with relatively simple equivalent circuit and can accurately describe the DC characteristics under low injection conditions, but lack physical description for higher order effects, such as quasi-saturation effect and high-frequency effect [120]. VBIC is an advanced bipolar model based on SGP by improving quasi-saturation effect and Early effect, but no significant improvement in transit time, therefore, there are still shortcomings in high-frequency effects [121]. In order to solve the shortcomings of SGP and VBIC in high-frequency characteristics, two kinds of high-level compact model, MEXTRAM and HICUM, are proposed for bipolar transistor. MEXTRAM is based on actual device structure and improves the extrinsic transistor, epitaxial layer resistance, high-current effects, neutral base recombination, and Early effect in the gradient band gap of base region [123]. HICUM adopts the generalized integral charge control relation (GICCR), which is

dedicated to describe the large current effect, quasi-saturation effect, Early effect, current crowding, and high-frequency characteristic. However, it is generally hard to extract all the model parameter due to the complex circuit equations and the couple between AC and DC parameters [123].

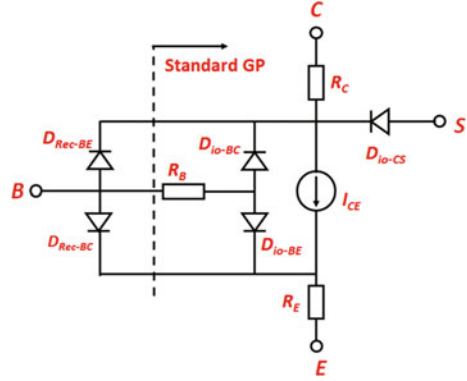
Each above compact model has different strengths and is separately adopted in different applications. Though SGP and VBIC are relatively simple, they are also used in the case of low precision circuit design. When need accurately model high-current, high-frequency, and noise characteristics, MEXTRAM and HICUM are strong candidates. It is due to the accurate ability to model the high-current effects and high-frequency characteristics, MEXTRAM and HICUM models were established as standard model for bipolar transistor in 2004.

It is the key and foundation for circuit simulation to establish a physics-based transistor model and determine all the model parameters. Fast and accurate parameter extraction is essential for process evaluation, device performance optimization, and circuit design. For bipolar transistors (such as SiGe HBT), there exist two types of parameter-extraction methods:

- (1) Numerical optimization method [124–128]: Combining the numerical optimization with device simulation, the optimal solutions are aimed to match the simulated and measured value in the global scope. This method is relatively simple but the efficiency is low. The final optimization results are often dependent on the selected initial value and may not have a clear physical meaning. Therefore, it cannot accurately reflect the physical characteristics of the device and is not conducive to the establishment of scalable model.
- (2) Analytical or semi-analytical direct extraction method [129–137]: In order to overcome the drawbacks of the above numerical optimization methods, many analytical or semi-analytical direct extraction techniques have been proposed over the past years. All the elements are determined by an analytical equation derived under certain assumptions and approximations, such as the frequency dependence of the model parameters, assuming that the higher order frequency terms are much smaller than the lower order ones. However, an error will be introduced depending on the validity of the assumptions. Furthermore, these assumptions are not always held for different process technologies and device geometries. Therefore, an accurate extraction technique over the whole range of frequencies is necessary to model device performance.

With the rapid development of space exploration technology, more and more applications require the electronic devices to work in high radiation environments, such as high-energy physical detectors (the total radiation dose can be up to tens of Mrad). Thus, it is necessary to carry out the field tests, which is bound to increase the time and cost of circuit design. If the radiation effects are included during the circuit design, the design time and cost will be greatly reduced. Based on the conventional SGP model, Montagner introduced two additional diodes to describe the degradation of the forward and reverse base currents due to the radiation effect, as shown in Fig. 1.10 [138]. The base current degradation under low injection level

Fig. 1.10 Compact model of radiation-induced excess IB in bipolar transistor



is accurately modeled, but a significant deviation appears for the large injection level. In order to correct the deviation under high bias conditions, two additional parameters, I_{RK} and N_{RK} , are required, but which will result in a deviation under the middle bias conditions. The additional electrical parameters make the parameters extraction more difficult. Then M. Ullán introduced some empirical parameters on the basis of Montagner's model to improve the estimation of the base current degradation under full bias voltage region [139, 140].

It should be noted that SGP model cannot accurately describe the behavior of modern SiGe HBTs, therefore, the above radiation model based on SGP has severe shortness. Besides to the ionization damages, much displacement damages exist when the transistors are exposed to the neutron and heavy ion radiation. As a consequence, the parasitic resistance and parasitic capacitance degrade while are not included in radiation model. Few studies document the parameter extraction for the irradiated transistors, and further research is now needed.

1.3 Research Work in This Dissertation

Space radiation effects can cause the device and circuit system failure. It is important to study the radiation effects and damage mechanisms, especially how to accurately evaluate the radiation response and establish a compact device model. With the continuous development and improvement of SiGe HBT technology in the past few decades, the radiation effect and compact model face many problems and shortcomings, including:

- (1) Total dose effect, especially ELDRS, is closely related to the device structure, layout, and manufacturing process. The present results about SiGe HBTs of IBM, Jazz, and other companies need to be further demonstrated. The impacts of the manufacturing process and layout structure on the radiation effect are worthy of further study.

- (2) Displacement damage effect: Neutrons are used as the traditional radiation source to characterize the displacement damage. However, the neutron reactors are now available and less, and it is necessary to find another radiation sources instead of neutrons to detect displacement damages. Similar to the neutrons, heavy ions can produce the displacement damage within the device, but few researches document the displacement damages of swift heavy ions in SiGe HBTs.
- (3) Single-event effect: At present, the studies of single-event effects in SiGe HBTs mainly focus on TCAD simulation and heavy ion radiation experiment. The collected charge of each terminal is used to characterize the SEE sensitivity, but the real-time information of some electrical parameters (such as transient voltage and current) is lost. Besides, how to quickly find the device sensitive area of SEE remains to be further studied.
- (4) Compact model and parameter-extraction technique: Precise model and parameter extraction are important for SiGe HBT process evaluation, device structure optimization, and circuit design. First, due to the non-uniform distribution of radiation damage within the transistor structure, the whole transistor network may have an obvious distributed effect, and the current compact model may not meet the requirement of space radiation application. Besides, some problems also exist in the present parameter extraction, such as the numerical optimization, semi-analytical method, and analytic method. Therefore, establishing a compact model and the corresponding parameter-extraction method suitable for space radiation environment has an important significance.

As for above problems in SiGe HBT radiation effects and compact model, an in-depth research was carried out in this dissertation. First, the ionizing damage effect, displacement damage effect, and single-particle effect in SiGe HBT were studied by using ^{60}Co gamma ray, heavy ion, and pulsed laser microbeam. The radiation damage and degradation mechanism were analyzed. Second, a novel small-signal equivalent circuit considering the distributed effect is established for SiGe HBTs, and an extraction method based on the nonlinear rational function fitting is proposed. Finally, the feasibility of the extraction method is verified in SiGe HBTs exposed to 10 MeV Cl ion radiation and variable temperature environment from -55 to $200\text{ }^{\circ}\text{C}$.

Figure 1.11 shows the framework of this dissertation. According to the logical hierarchical relationship, this dissertation is divided into seven chapters. The first and the seventh chapters are separately the Introduction and Conclusion part. In the second chapter, the ionization damage effects induced by ^{60}Co radiation are studied. Chapter 3 studies the displacement damage effects in SiGe HBTs exposed to swift heavy ions. Chapter 4 discusses the single-event effect induced by pulsed laser microbeam. A novel device model of SiGe HBT considering the distributed effect is proposed in Chap. 5. Chapter 6 focuses on the parameter extraction, including the conventional conditions and the space radiation environment.

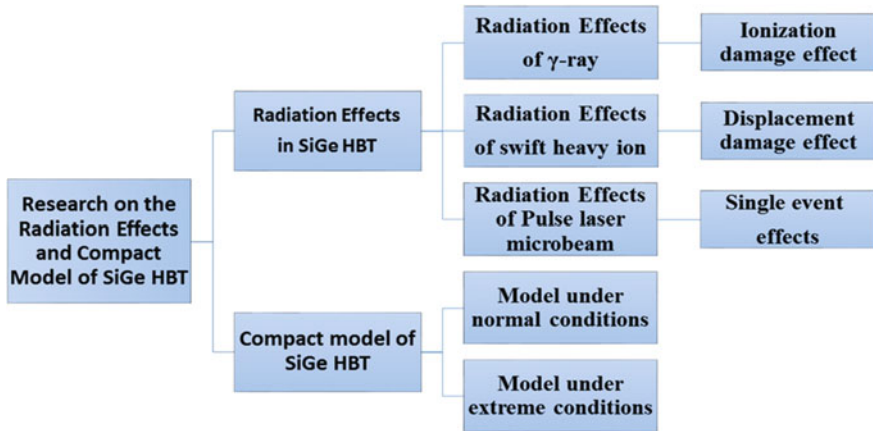


Fig. 1.11 The framework and main content of this dissertation

References

1. Z.C. Shen, D.K. Yan, Present status and prospects of space radiation environmental engineering. *Spacecraft Environ. Eng.* **03**, 229–240 (2014)
2. Z.L. Liu, *Radiation Effects in Advanced Semiconductor Materials and Devices*. (National Defence Industry Press, 2008)
3. J. Mazur, The radiation environment outside and inside a spacecraft. *Proc. 2002 (NSREC Short Course 2002)*
4. E.G. Stassinopoulos, J.P. Raymond, The space radiation environment for electronics. *Proc. IEEE* **76**(11), 1423–1442 (1988)
5. J.R. Schwank, M.R. Shaneyfelt, P.E. Dodd, Radiation hardness assurance testing of microelectronic devices and integrated circuits: radiation environments, physical mechanisms, and foundations for hardness assurance. *IEEE Trans. Nucl. Sci.* **60**(3), 2074–2100 (2013)
6. <http://zh.wikipedia.org/wiki/magnetosphere>
7. J.D. Cressler, Radiation effects in SiGe technology. *IEEE Trans. Nucl. Sci.* **60**(3), 1992–2014 (2013)
8. Z.E. Fleetwood, E.W. Kenyon, N.E. Lourenco, S. Jain, E.X. Zhang, T.D. England, J.D. Cressler, R.D. Schrimpfand, D.M. Fleetwood, Advanced SiGe BiCMOS technology for multi-Mrad electronic systems. *IEEE Trans. Device Mater. Reliab.* **14**(3), 844–848 (2014)
9. J.S. Rice, M. Ullan, G. Brooijmans, J.D. Cressler, D. Damiani, S. Diez, T. Gadfort, A.A. et al, Performance of the SiGe HBT 8HP and 8WL technologies after high dose/fluence radiation exposure, in *IEEE Nuclear Science Symposium (NSS) Conference Record*, (Dresden, Germany, 2008), pp. 2206–2210
10. H.J. Barnaby, Total-ionizing-dose effects in modern CMOS technologies. **53**(6), 3103–3121 (2006)
11. D. Knoll, B. Heinemann, H.J. Osten, B. Ehwald, B. Tillack, P. Schley, R. Barth, M. Matthes, S.P. Kwang, K. Youngand W. Winkler, Si/SiGe: C heterojunction bipolar transistors in an epi-free well, single-polysilicon technology, in *International Electron Devices Meeting (IEDM)*. (San Francisco, CA, USA, 1998), pp. 703–706
12. E. Ganin, T.C. Chen, J.M.C. Stork, B.S. Meyerson, J.D. Cressler, G. Scilla, J. Warnock, D. L. Harame, G.L. Pattonand, T.H. Ning, Epitaxial-base double-poly self-aligned bipolar

- transistors, in *International Electron Devices Meeting (IEDM)*. (San Francisco, CA, USA, 1990), pp. 603–606
13. R. Schulz, M. Jost, D.L. Hareme, G.J. Scilla, B.S. Meyersonand, G.B. Bronner, A fully self-aligned epitaxial-base transistor, in *1989 Symposium on VLSI Technology*, (1989), pp. 89–90
 14. J.N. Burghartz, B.J. Ginsberg, J.H. Comfort, G.L. Patton, B.S. Meyerson, J.Y.C.ô. Sun, S.R. Mader, C.L. Stanisand, G.J. Scilla, Self-aligned SiGe-base heterojunction bipolar transistor by selective epitaxy emitter window (SEEW) technology. *IEEE Electron Device Lett.* **11**(7), 288–290 (1990)
 15. J.H. Comfort, G.L. Patton, J.D. Cressler, W. Leeand E.F. CrabbC, Profile leverage in a self-aligned epitaxial si or sige base bipolar technology, in *IEEE International Electron Devices Meeting (IEDM)* (1990). pp. 21–24
 16. P. Chevalier, Advanced BiCMOS technologies for GHz integrated circuits, in *Short course of the 2011 IEEE Bipolar/BiCMOS Circuits and Technol. Meeting*. (2011)
 17. B. Heinemann, R. Barth, D. Bolze, J. Drews, G.G. Fischer, A. Fox, O. Fursenko, T. Grabolla et.al, SiGe HBT technology with ft of 300 GHz/500 GHz and 2.0 ps CML gate delay, in *IEEE International Electron Devices Meeting (IEDM)*. (San Francisco, CA, 2010)
 18. P. Chevalier, T.F. Meister, B. Heinemann, S. Van Huylenbroeck, W. Liebl, A. Fox, A. Sibaja-Hernandezand A. Chantre, Towards THz SiGe HBTs, in *IEEE Bipolar/BiCMOS Circuits and Technology Meeting (BCTM)*. (IEEE: Atlanta, GA. 2011), pp. 57–65
 19. J.J. Pekarik, J. Adkisson, P. Gray, Q. Liu, R. Camillo-Castillo, M. Khater, V. Jain, B. Zetterlund et.al, A 90 nm SiGe BiCMOS technology for mm-wave and high-performance analog applications, in *Bipolar/BiCMOS Circuits and Technology Meeting (BCTM) IEEE*. (Coronado, CA, 2014)
 20. S. Diez, M. Lozano, G. Pellegrini, I. Mandic, D. Knoll, B. Heinemannand, M. Ullan, IHP SiGe: C BiCMOS technologies as a suitable backup solution for the ATLAS upgrade front-end electronics. *IEEE Trans. Nucl. Sci.* **56**(4), 2449–2456 (2009)
 21. M. Ullán, J. Rice, G. Brooijmans, J.D. Cressler, D. Damiani, S. Diez, T. Gadfort, A.A. Grillo et al., Evaluation of silicon-germanium (SiGe) bipolar technologies for use in an upgraded atlas detector. *Nucl. Instrum. Methods Phys. Res., Sect. A* **604**(3), 668–674 (2009)
 22. A.S. Cardoso, P.S. Chakraborty, N.E. Lourenco, P. Song, T.D. England, E.W. Kenyon, N. Karaulacand, J.D. Cressler, Total ionizing dose response of triple-well FET-based wideband, high-isolation RF switches in a 130 nm SiGe BiCMOS technology. *IEEE Trans. Nucl. Sci.* **60**(4), 2567–2573 (2013)
 23. N.E. Lourenco, R.L. Schmid, K.A. Moen, S.D. Phillips, T.D. England, J.D. Cressler et.al, Total dose and transient response of SiGe HBTs from a new 4th-generation, 90 nm SiGe BiCMOS technology, in *IEEE Radiation Effects Data Workshop (REDW)*. (IEEE: Tucson, AZ, 2012), pp. 1–5
 24. T.D. England, B. Blalock, A. Mantooth, M. Barlow, F. Dai et al., A new approach to designing electronic systems for operation in extreme environments: part II—the SiGe remote electronics unit. *IEEE Aerosp. Electron. Syst. Mag.* **27**(7), 29–41 (2012)
 25. H. Ohyama, J.V. Llemont, Y. Takamiand, K. Hayama, Germanium content dependence of radiation damage in strained Si1-xGex epitaxial devices. *IEEE Trans. Nucl. Sci.* **41**(6), 2437–2442 (1994)
 26. E. Zhao, A.K. Sutton, B.M. Haugerudand, J.D. Cressler, The effects of radiation on 1/f noise in complementary (npn + pnp) SiGe HBTs. *IEEE Trans. Nucl. Sci.* **52**(6), 3243–3249 (2004)
 27. K. Petrosyants, E. Vologdin, D. Smirnov, R. Torgovnikov, M. Kozhukhov, Si BJT and SiGe HBT performance modeling after neutron radiation exposure, in *9th East-West Design and Test Symposium (EWDTS)* (IEEE, 2011), pp. 267–270
 28. G. Qin, N. Jiang, J. Ma, Z. Ma, P. Maand M. Racanelli, Dc characteristics of proton radiated SiGe power HBTs at cryogenic temperature, in *IEEE International Conference of Electron Devices and Solid-State Circuits* (2011), pp. 1–2

29. G. Xueyang, M. Desheng, C. Zhenqi, D. Fa, J.D. Cressler, J.A. Yaeger, M.M. Mojaradi, A. Mantooth, B.J. Blalock and R.W. Berger. High speed channel resistive sensor interface with RHBD in 0.5 μm SiGe BiCMOS for UWT from -180C to 120C, in *IEEE Bipolar/BiCMOS Circuits and Technology Meeting (BCTM)*. 2011. Atlanta, GA
30. L. Najafizadeh, C. Zhu, R. Krithivasan, J.D. Cressler, Y. Cui, G. Niu, S. Chen, C. Ulaganathan, B.J. Blalock, SiGe BiCMOS precision voltage references for extreme temperature range electronics, in *IEEE Bipolar/BiCMOS Circuits and Technology Meeting* (IEEE, 2006), pp. 1–4
31. A.P.G. Prakash, J.D. Cressler, The effect of 63 MeV hydrogen ion irradiation on 65 GHz UHV/CVD SiGe HBT BiCMOS technology. *Radiat. Eff. Defects Solids* **166**(8–9), 703–709 (2011)
32. N. Jiang, N. Cho, Z. Ma, Effects of proton irradiation on SiGe HBTs implemented with isolation guard rings. *Semicond. Sci. Technol.* **25**, 125007 (2010)
33. N. Jiang, Z. Ma, P. Maand, M. Racanelli, Proton radiation tolerance of SiGe power HBTs. *Semicond. Sci. Technol.* **22**(1), S46–S49 (2007)
34. L. Najafizadeh, M. Bellini, A.P.G. Prakash, G.A. Espinel, J.D. Cressler, P.W. Marshall and, C.J. Marshall, Proton tolerance of SiGe precision voltage references for extreme temperature range electronics. *IEEE Trans. Nucl. Sci.* **53**(6), 3210–3216 (2006)
35. A.K. Sutton, B.M. Haugerud, L. Yuan, L.K. Wei-Min, J.D. Cressler, P.W. Marshall, R.A. Reed, R. Jae-Sung, G. Freeman and, D. Ahlgren, Proton tolerance of fourth-generation 350 GHz UHV/CVD SiGe HBTs. *IEEE Trans. Nucl. Sci.* **51**(6), 3736–3742 (2004)
36. K.C. Praveen, N. Pushpa, P.S. Naik, J.D. Cressler, A. Tripathi and A.P. Gnana Prakash, Application of a Pelletron accelerator to study total dose radiation effects on 50 GHz SiGe HBTs. *Nucl. Instrum. Methods Phys. Res. Sect. B* **273**, 43–46 (2012)
37. A.P.G. Prakash, N. Pushpa, K.C. Praveen, P.S. Naik and D. Revannasiddaiah, Evaluation of Pelletron accelerator facility to study radiation effects on semiconductor devices, in *AIP Conference Proceedings* (2012), pp. 489–490
38. K.C. Praveen, N. Pushpa, A. Tripathi, D. Revannasiddaiah, J.D. Cressler and, A.P. Gnana Prakash, 50 MeV Li^{3+} ion irradiation effects on advanced 200 GHz SiGe HBTs. *Radiat. Eff. Defects Solids* **166**(8–9), 710–717 (2011)
39. F. Inanlou, N.E. Lourenco, Z.E. Fleetwood, I. Song, D.C. Howard, A. Cardoso, S. Zeinolabedinzadeh, E. Zhang, C.X. Zhang, P. Paki-Amouzou, J.D. Cressler, Impact of total ionizing dose on a 4th generation, 90 nm SiGe HBT Gaussian pulse generator. *IEEE Trans. Nucl. Sci.* **61**(6), 3050–3054 (2014)
40. J. Metcalfe, D.E. Dorfan, A.A. Grillo, A. Jones, F. Martinez-McKinney, P. Mekhedjian et al., Evaluation of the radiation tolerance of several generations of SiGe heterojunction bipolar transistors under radiation exposure. *Nucl. Instrum. Methods Phys. Res., Sect. A* **579** (2), 833–838 (2007)
41. J.A. Babcock, J.D. Cressler, L.S. Vempati, S.D. Clark, R.C. Jaeger, D.L. Hareme, Ionizing radiation tolerance of high-performance SiGe HBT's grown by UHV/CVD. *IEEE Trans. Nucl. Sci.* **42**(6), 1558–1566 (1995)
42. Z.E. Fleetwood, A.S. Cardoso, I. Song, E. Wilcox, N.E. Lourenco, S.D. Phillips, R. Arora, P. Paki-Amouzou, J.D. Cressler, Evaluation of enhanced low dose rate sensitivity in fourth-generation SiGe HBTs. *IEEE Trans. Nucl. Sci.* **61**(6), 2915–2922 (2014)
43. L. Najafizadeh, A.K. Sutton, R.M. Diestelhorst, M. Bellini, B. Jun, J.D. Cressler, P.W. Marshall, C.J. Marshall, A comparison of the effects of X-ray and proton irradiation on the performance of SiGe precision voltage references. *IEEE Trans. Nucl. Sci.* **54**(6), 2238–2244 (2007)
44. M. Bellini, B. Jun, T. Chen, J.D. Cressler, P.W. Marshall, D. Chen, R.D. Schrimpf, D.M. Fleetwood and J. Cai, X-ray irradiation and bias effects in fully-depleted and partially-depleted SiGeHBTs fabricated on CMOs-compatible SOI *IEEE Trans. Nucl. Sci.* **53**(61), 3182–3186, 2006

45. N. Guofu, Y. Hua, M. Varadharajaperumal, S. Yun, J.D. Cressler, R. Krithivasan, P.W. Marshalland, R. Reed, Simulation of a new back junction approach for reducing charge collection in 200 GHz SiGe HBTs. *IEEE Trans. Nucl. Sci.* **52**(6), 2153–2157 (2005)
46. M. Varadharajaperumal, G. Niu, X. Wei, T. Zhang, J.D. Cressler, R.A. Reed, P.W. Marshall, 3-D simulation of SEU hardening of SiGe HBTs using shared dummy collector. *IEEE Trans. Nucl. Sci.* **54**(6), 2330–2337 (2007)
47. G. Vizkelethy, S.D. Phillips, L. Najafizadeh J.D. Cressler, Nuclear microbeam studies of silicon–germanium heterojunction bipolar transistors (HBTs). *Nuc. Instrum. Methods Phys. Res. Sect. B* **268**(11–12), 2092–2098 (2010)
48. T. Zhang, X. Wei, G. Niu, J.D. Cressler, P.W. Marshall, R.A. Reed, A mechanism versus SEU impact analysis of collector charge collection in SiGe HBT current mode logic. *IEEE Trans. Nucl. Sci.* **56**(6), 3071–3077 (2009)
49. Jung, N.E. Lourenco, I. Song, M.A. Oakley, T.D. England, R. Arora, A.S. Cardoso, N.J.H. Roche et al., An investigation of single-event transients in C-SiGe HBT on SOI current mirror circuits. *IEEE Trans. Nucl. Sci.* **61**(6), 3193–3200 (2014)
50. N.E. Lourenco, S.D. Phillips, T.D. England, A.S. Cardoso, Z.E. Fleetwood, K.A. Moen, D. McMorro et al., An investigation of single-event effects and potential SEU mitigation strategies in fourth-generation, 90 nm SiGe BiCMOS. *IEEE Trans. Nucl. Sci.* **60**(6), 4175–4183 (2013)
51. K.A. Moen, S.D. Phillips, E.W. Kenyon, J.D. Cressler, Establishing best-practice modeling approaches for understanding single-event transients in Gb/s SiGe digital logic. *IEEE Trans. Nucl. Sci.* **59**(4), 958–964 (2012)
52. S.D. Phillips, K.A. Moen, N.E. Lourenco, J.D. Cressler, Single-event response of the SiGe HBT operating in inverse-mode. *IEEE Trans. Nucl. Sci.* **59**(6), 2682–2690 (2012)
53. D.L. Hansen, P.W. Marshall, R. Lopez-Aguado, K. Jobe, M.A. Carts, C.J. Marshall, P. Chu, S.F. Meyer, A study of the SEU performance of InP and SiGe shift registers. *IEEE Trans. Nucl. Sci.* **52**(4), 1140–1147 (2005)
54. R. Krithivasan, P.W. Marshall, M. Nayeem, A.K. Sutton, W. Kuo, B.M. Haugerud et al., Application of RHBD techniques to SEU hardening of third-generation SiGe HBT logic circuits. *IEEE Trans. Nucl. Sci.* **53**(6), 3400–3407 (2006)
55. I. Song, S. Jung, N.E. Lourenco, U.S. Raghunathan, Z.E. Fleetwood et al., Design of radiation-hardened RF low-noise amplifiers using inverse-mode SiGe HBTs. *IEEE Trans. Nucl. Sci.* **61**(6), 3218–3225 (2014)
56. T. Thrivikraman, E. Wilcox, S.D. Phillips, J.D. Cressler, C. Marshall, G. Vizkelethy, P. Dodd, P. Marshall, Design of digital circuits using inverse-mode cascode SiGe HBTs for single event upset mitigation. *IEEE Trans. Nucl. Sci.* (2010)
57. S.D. Phillips, T. Thrivikraman, A. Appaswamy, A.K. Sutton, J.D. Cressler, G. Vizkelethy, P. Dodd, R.A. Reed, A novel device architecture for SEU mitigation: the inverse-mode cascode SiGe HBT. *IEEE Trans. Nucl. Sci.* **56**(6), 3393–3401 (2009)
58. R.M. Diestelhorst, S.D. Phillips, A. Appaswamy, A.K. Sutton, J.D. Cressler et al., Junction isolation single event radiation hardening of a 200 GHz SiGe: C HBT technology without deep trench isolation. *IEEE Trans. Nucl. Sci.* **56**(6), 3402–3407 (2009)
59. J.A. Pellish, R.A. Reed, D. McMorro, J.S. Melinger, P. Jenkins, A.K. Sutton et al., Laser-induced current transients in silicon-germanium HBTs. *IEEE Trans. Nucl. Sci.* **55**(6), 2936–2942 (2008)
60. E.P. Wilcox, S.D. Phillips, P. Cheng, T. Thrivikraman, A. Madan, J.D. Cressler et al., Single event transient hardness of a new complementary (npn + pnp) SiGe HBT technology on thick-film SOI. *IEEE Trans. Nucl. Sci.* (2010)
61. P. Chu, D.L. Hansen, B.L. Doyle, K. Jobe, R. Lopez-Aguado, M. Shoga, D.S. Walsh, Ion-microbeam probe of high-speed shift registers for SEE analysis-part I: SiGe. *IEEE Trans. Nucl. Sci.* **53**(3), 1574–1582 (2006)
62. W. Chen, N. Varanasi, V. Pouget, H.J. Barnaby, B. Vermeire, P.C. Adell, T. Copani, P. Fouillat, Impact of VCO topology on SET induced frequency response. *IEEE Trans. Nucl. Sci.* **54**(6), 2500–2505 (2007)

63. A.K. Sutton, B.M. Haugerud, A.P.G. Prakash, B. Jun, J.D. Cressler, C.J. Marshall, P.W. Marshall, R. Ladbury, F. Guarin, A.J. Joseph, A comparison of gamma and proton radiation effects in 200 GHz SiGe HBTs. *IEEE Trans. Nucl. Sci.* **52**(6), 2358–2365 (2005)
64. A.K. Sutton, A.P.G. Prakash, J.D. Cressler, J. Metcalfe, J. Rice, A.A. Grillo et al, Source dependence and technology scaling effects on the radiation tolerance of SiGe HBTs at extreme dose and fluence levels, in *9th European Conference on Radiation and Its Effects on Components and Systems(RADECS)*. (Deauville, 2007)
65. M. Varadharajaperumal, N. Guofu, J.D. Cressler, R.A. Reedand, P.W. Marshall, Three-dimensional simulation of heavy-ion induced charge collection in SiGe HBTs on SOI. *IEEE Trans. Nucl. Sci.* **51**(6), 3298–3303 (2004)
66. M. Turowski, J.A. Pellish, K.A. Moen, A. Raman, J.D. Cressler, R.A. Reed, G. Niu, Reconciling 3-D mixed-mode simulations and measured single-event transients in SiGe HBTs. *IEEE Trans. Nucl. Sci.* **57**(6), 3342–3348 (2010)
67. X. Wei, T. Zhang, G. Niu, M. Varadharajaperumal, J.D. Cresslerand, P.W. Marshall, 3-D mixed-mode simulation of single event transients in SiGe HBT emitter followers and resultant hardening guidelines. *IEEE Trans. Nucl. Sci.* **55**(6), 3360–3366 (2008)
68. A.K. Sutton, A.P. Gnana Prakash, B. Jun, E. Zhao, M. Bellini, J. Pellish et al., An Investigation of dose rate and source dependent effects in 200 GHz SiGe HBTs. *IEEE Trans. Nucl. Sci.* **53**(6), 3166–3174 (2006)
69. B.M. Haugerud, M.M. Pratapgarhwal, J.P. Comeau, A.K. Sutton, A.P.G. Prakash, J.D. Cressler et al., Proton and gamma radiation effects in a new first-generation SiGe HBT technology. *Solid-State Electron.* **50**(2), 181–190 (2006)
70. M. Ullán, M. Wilder, H. Spieler, E. Spencer, S. Rescia, F.M. Newcomer, F. Martinez-McKinney et al., Enhanced low dose rate sensitivity (ELDRS) tests on advanced SiGe bipolar transistors for very high total dose applications. *Nucl. Instrum. Methods Phys. Res., Sect. A* **724**, 41–46 (2013)
71. P. Leroux, M. Van Uffelen, F. Berghmans, A. Giraud, Design and assessment of a high gamma-dose tolerant VCSEL driver with discrete SiGe HBTs. *IEEE Trans. Nucl. Sci.* **53**(4), 2033–2039 (2006)
72. P. Leroux, W. De Cock, M. Van Uffelen, M. Steyaert. Design, assessment and modeling of an integrated 0.4 μm SiGe Bipolar VCSEL driver under γ -radiation, in *European Conference on Radiation and Its Effects on Components and Systems (RADECS)*. (Jyvaskyla, 2008)
73. M. Ullan, S. Diez, F. Campabadal, M. Lozano, G. Pellegrini, D. Knoll, B. Heinemann, Gamma radiation effects on different varieties of SiGe: C HBT technologies. *IEEE Trans. Nucl. Sci.* **54**(4), 989–993 (2007)
74. J.P. Comeau, A.K. Sutton, B.M. Haugerud, J.D. Cressler, L.K. Wei-Min, P.W. Marshall, R. A. Reed, A. Karroy, R. Van Art, Proton tolerance of advanced SiGe HBTs fabricated on different substrate materials. *IEEE Trans. Nucl. Sci.* **51**(6), 3743–3747 (2004)
75. S. Put, M. Qureshi, E. Simoen, S. Van Huylbroeck, R. Venegas, C. Claeys, M. Van Uffelen, P. Leroux, F. Berghmans. Proton and gamma radiation of 0.13 μm 200 GHz NPN SiGe:C HBTs featuring an airgap deep trench isolation, in *9th European Conference On Radiation And Its Effects On Components And Systems*. (Deauville, 2007)
76. R.M. Diestelhorst, S. Finn, B. Jun, A.K. Sutton, P. Cheng, P.W. Marshall, J.D. Cressler et al., The effects of X-ray and proton irradiation on a 200 GHz/90 GHz complementary (npn + pnp) SiGe: C HBT technology. *IEEE Trans. Nucl. Sci.* **54**(6), 2190–2195 (2007)
77. M. Ullán, S. Díez, M. Lozano, G. Pellegrini, D. Knolland, B. Heinemann, Combined effect of bias and annealing in gamma and neutron radiation assurance tests of SiGe bipolar transistors for HEP applications. *Solid-State Electron.* **56**(1), 179–184 (2011)
78. S. Liu, D. Lin, X. Guo, N. Liu, X. Jiang, G. Zhu, D. Li, Z. Wang, B. Tang, W. Chen, W. Zhang, H. Zhou, B. Shao, J. Li, Degradation of SiGe HBT with reactor pulse neutron and gamma rays irradiation. *Nucl. Instrum. Methods Phys. Res. Sect. A* **569**(3), 810–814 (2006)

79. J. Metcalfe, D.E. Dorfan, A.A. Grillo, A. Jones, D. Lucia, F. Martinez-McKinney, M. Mendoza et al., Evaluation of the radiation tolerance of SiGe heterojunction bipolar transistors under 24-GeV proton exposure. *IEEE Trans. Nucl. Sci.* **53**(6), 3889–3893 (2006)
80. S. Diez, M. Lozano, G. Pellegrini, F. Campabadal, I. Diez, D. Knoll, B. Heinemann, M. Ullan, Proton radiation damage on SiGe: C HBTs and additivity of ionization and displacement effects. *IEEE Trans. Nucl. Sci.* **56**(4), 1931–1936 (2009)
81. W.M.L. Kuo, L. Yuan, B.A. Floyd, B.M. Haugerud, A.K. Sutton, R. Krithivasan et al., Proton radiation response of monolithic Millimeter-wave transceiver building blocks implemented in 200 GHz SiGe technology. *IEEE Trans. Nucl. Sci.* **51**(6), 3781–3787 (2004)
82. G. Qin, Y. Yan, N. Jiang, J. Ma, P. Ma, M. Racanelliand, Z. Ma, RF characteristics of proton radiated large-area SiGe HBTs at extreme temperatures. *Microelectron. Reliab.* **52**(11), 2568–2571 (2012)
83. A.K. Sutton, K. Moen, J.D. Cressler, M.A. Carts, P.W. Marshall, J.A. Pellish, V. Ramachandran, R.A. Reed, M.L. Alles, G. Niu, Proton-induced SEU in SiGe digital logic at cryogenic temperatures. *Solid-State Electronics* **52**(10), 1652–1659 (2008)
84. N.E. Lourenco, Z.E. Fleetwood, S. Jung, A.S. Cardoso, P.S. Chakraborty, T.D. England et al., On the transient response of a complementary (nnp + pnp) SiGe HBT BiCMOS technology. *IEEE Trans. Nucl. Sci.* **61**(6), 3146–3153 (2014)
85. S. Zhang, J.D. Cressler, G. Niu, C.J. Marshall, P.W. Marshall, H.S. Kim, R.A. Reed, M. J. Palmer, A.J. Joseph, D.L. Hareme, The effects of operating bias conditions on the proton tolerance of SiGe HBTs. *Solid-State Electron.* **47**(10), 1729–1734 (2003)
86. J. Andrews, M. Morton, L. Jongsoo, J. Papapolymerou, J.D. Cressler et al., The effects of proton irradiation on the performance of mm-wave transmission lines implemented in SiGe technology. *IEEE Trans. Nucl. Sci.* **51**(6), 3807–3810 (2004)
87. C.M. Grens, B.M. Haugerud, A.K. Sutton, C. Tianbing, J.D. Cressler, P.W. Marshall, C. J. Marshall, A.J. Joseph, D.L. Hareme, The effects of proton irradiation on the operating voltage constraints of SiGe HBTs. *IEEE Trans. Nucl. Sci.* **52**(6), 2403–2407 (2005)
88. C. Tianbing, A.K. Sutton, M. Bellini, B.M. Haugerud, J.P. Comeau, L. Qingqing, J.D. Cressler, C. Jin, T.H. Ning, P.W. Marshall, C.J. Marshall, Proton radiation effects in vertical SiGe HBTs fabricated on CMOS-compatible SOI. *IEEE Trans. Nucl. Sci.* **52**(6), 2353–2357 (2005)
89. Z. Jin, G. Niu, J.D. Cressler, C.J. Marshall, P.W. Marshalland, HSôR Kim, 1/f noise in proton-irradiated SiGe HBTs. *IEEE Trans. Nucl. Sci.* **48**(6), 2244–2249 (2001)
90. MIL-STD-883G, Ionizing radiation (Total Dose) test procedure, Method 1019.7. (2006)
91. G. Banerjee, G. Niu, J.D. Cressler, S.D. Clark, M.J. Palmer, D.C. Ahlgren, Anomalous dose rate effects in gamma irradiated SiGe heterojunction bipolar transistors. *IEEE Trans. Nucl. Sci.* **46**(61), 1620–1626 (1999)
92. H.P. Hjalmarson, R.L. Pease, C.E. Hembree, R.M. Van Ginhovenand P.A. Schultz, Dose-rate dependence of radiation induced interface trap density in silicon bipolar transistors. *Nucl. Instrum. Methods Phys. Res. B*, **250** (269–273) (2006)
93. J.E. Seiler, J.E. Seiler, D.G. Platteter, D.G. Platteter, G.W. Dunham, G.W.ô.P. Dunham, M. C. Maher, M.R. Shaneyfelt, Effect of passivation on the enhanced low dose rate sensitivity of National LM124 operational amplifiers, in *IEEE Radiation Effects Data Workshop*. (IEEE, 2004), pp. 42–46
94. M.R. Shaneyfelt, R.L. Pease, J.R. Schwank, M.C. Maher, G.L. Hash, D.M. Fleetwood et al., Impact of passivation layers on enhanced low-dose-rate sensitivity and pre-irradiation elevated-temperature stress effects in bipolar linear ICs. *IEEE Trans. Nucl. Sci.* **49**(6), 3171–3179 (2002)
95. M.R. Shaneyfelt, R.L. Pease, M.C. Maher, J.R. Schwank, S. Gupta, P.E. Dodd, L.C. Riewe, Passivation layers for reduced total dose effects and eldrs in linear bipolar devices. *IEEE Trans. Nucl. Sci.* **50**(6), 1784–1790 (2003)
96. M.R. Shaneyfelt, J.R. Schwank, S.C. Witzak, D.M. Fleetwood, R.L. Pease, PSôR Winokur, Thermal-stress effects and enhanced low dose rate sensitivity in linear bipolar ICs. *IEEE Trans. Nucl. Sci.* **47**(6), 2539–2545 (2000)

97. R.L. Pease, D.G. Platteter, G.W. Dunham, J.E. Seiler, P.C. Adell, H.J. Barnaby, J. Chen. The effects of hydrogen in hermetically sealed packages on the total dose and dose rate response of bipolar linear circuits. *IEEE Trans. Nucl. Sci.* **54**(6), 2168–2173 (2007)
98. R.L. Pease, P.C. Adell, B.G. Rax, X.J. Chen, H.J. Barnaby, K.E. Holbert, H.P. Hjalmarson, The effects of hydrogen on the enhanced low dose rate sensitivity (ELDRS) of bipolar linear circuits. *IEEE Trans. Nucl. Sci.* **55**(6), 3169–3173 (2008)
99. E. Bielejec, G. Vizkelethy, N.R. Kolb, D.B. King, B.L. Doyle, Damage equivalence of heavy ions in silicon bipolar junction transistors. *IEEE Trans. Nucl. Sci.* **53**(6), 3681–3686 (2006)
100. K.C. Praveen, N. Pushpa, H.B. Shiva, J.D. Cressler, A. Tripathi, A.P.G. Prakash, A comparison of 75 MeV boron and 50 MeV lithium ion irradiation effects on 200 GHz SiGe HBTs, in *AIP Conference Proceedings*. (2013), pp. 1030–1031
101. K.C. Praveen, N. Pushpa, A. Tripathi, D. Revannasiddaiah, P.S. Naik, J.D. Cressler, A.P.G. Prakash, A comparison of 100 MeV oxygen ion and C0–60 gamma irradiation effect on 200 GHz SiGe HBTs, in *16th International Workshop on Physics of Semiconductor Devices*, 8549(85490 J) (2012)
102. P.W. Marshall, M.A. Carts, A. Campbell, D. McMorro, S. Buchner, R. R.B. Stewart, B. Gilbert, R.A. Reed, Single event effects in circuit-hardened SiGe HBT logic at gigabit per second data rates. *IEEE Trans. Nucl. Sci.* **47**(6), 2669–2674 (2000)
103. T.S. Mukherjee, A.K. Sutton, K.T. Kornegay, R. Krithivasan, J.D. Cressler, G. Niu, P.W. Marshall, A novel circuit-level SEU hardening technique for high-speed SiGe HBT logic circuits. *IEEE Trans. Nucl. Sci.* **54**(6), 2086–2091 (2007)
104. A.S. Cardoso, P.S. Chakraborty, N. Karaulac, D.M. Fleischhauer, N.E. Lourenco et al., Single-event transient and total dose response of precision voltage reference circuits designed in a 90-nm SiGe BiCMOS technology. *IEEE Trans. Nucl. Sci.* **61**(6), 3210–3217 (2014)
105. J.A. Pellish, R.A. Reed, D. McMorro, G. Vizkelethy, V.F. Cavois, J. Baggio et al., Heavy ion microbeam- and broadbeam-induced transients in SiGe HBTs. *IEEE Trans. Nucl. Sci.* **56**(6), 3078–3084 (2009)
106. R.A. Reed, P.W. Marshall, J.C. Pickel, M.A. Carts, B. Fodness et al., Heavy-ion broad-beam and microprobe studies of single-event upsets in 0.20 μm SiGe heterojunction bipolar transistors and circuits. *IEEE Trans. Nucl. Sci.* **50**(6), 2184–2190 (2003)
107. D.E. Fulkerson, A physics-based engineering methodology for calculating soft error rates of bulk CMOS and SiGe heterojunction bipolar transistor integrated circuits. *IEEE Trans. Nucl. Sci.* **57**(1), 348–357 (2010)
108. J.A. Pellish, R.A. Reed, A.K. Sutton, R.A. Weller, M.A. Carts, P.W. Marshall et al., A generalized SiGe HBT single-event effects model for on-orbit event rate calculations. *IEEE Trans. Nucl. Sci.* **54**(6), 2322–2329 (2007)
109. R.A. Reed, P.W. Marshall, H. Ainspan, C.J. Marshall, H.S. Kim, J.D. Cressler, N. Guofu, K. A. LaBel, Single event upset test results on a prescaler fabricated in IBM’s 5HP silicon germanium heterojunction bipolar transistors BiCMOS technology, in *IEEE Radiation Effects Data Workshop*. (2001) pp. 172–176
110. P. Marshall, M. Carts, S. Currie, R. Reed, B. Randall, K. Fritz, K. Kennedy et al., Autonomous bit error rate testing at multi-gbit/s rates implemented in a 5AM SiGe circuit for radiation effects self test (CREST). *IEEE Trans. Nucl. Sci.* **52**(6), 2446–2454 (2005)
111. R.A. Reed, G. Vizkelethy, J.A. Pellish, B. Sierawski, K.M. Warren, M. Porter et al., Applications of heavy ion microprobe for single event effects analysis. *Nucl. Instrum. Methods Phys. Res. Sect. B* **261**(1–2), 443–446 (2007)
112. E.J. Montes, R.A. Reed, J.A. Pellish, M.L. Alles, R.D. Schrimpf et al., Single event upset mechanisms for low-energy-deposition events in SiGe HBTs. *IEEE Trans. Nucl. Sci.* **55**(3), 1581–1586 (2008)
113. A.K. Sutton, R. Krithivasan, P.W. Marshall, M.A. Carts, C. Seidleck, R. Ladbury, J.D. Cressler et al., SEU error signature analysis of Gbit/s SiGe logic circuits using a pulsed laser microprobe. *IEEE Trans. Nucl. Sci.* **53**(6), 3277–3284 (2006)

114. P.W. Marshall, M.A. Carts, A. Campbell, D. McMorow, S. Buchner, R. Stewart, B. Gilbert, R.A. Reed, Single event effects in circuit-hardened SiGe HBT logic at gigabit per second data rates. *IEEE Trans. Nucl. Sci.* **47**(6), 2669–2674 (2000)
115. M. Bellini, S.D. Phillips, R.M. Diestelhorst, P. Cheng, J.D. Cressler et al., Novel total dose and heavy-ion charge collection phenomena in a new SiGe HBT on thin-film SOI technology. *IEEE Trans. Nucl. Sci.* **55**(6), 3197–3201 (2008)
116. S.D. Phillips, K.A. Moen, L. Najafizadeh, R.M. Diestelhorst, A.K. Sutton, J.D. Cressler, G. Vizkelethy, P.E. Dodd, P.W. Marshall, A comprehensive understanding of the efficacy of N-Ring SEE hardening methodologies in SiGe HBTs. *IEEE Trans. Nucl. Sci.* (2010)
117. A.K. Sutton, M. Bellini, J.D. Cressler, J.A. Pellish, R.A. Reed, P.W. Marshall, G. Niu, G. Vizkelethy, M. Turowski, A. Raman, An evaluation of transistor-layout RHBD techniques for SEE mitigation in SiGe HBTs. *IEEE Trans. Nucl. Sci.* **6**(54), 2044–2052 (2007)
118. E.P. Wilcox, S.D. Phillips, J.D. Cressler, P.W. Marshall, M.A. Carts, J.A. Pellish et al., Non-TMR SEU-hardening techniques for SiGe HBT shift registers and clock buffers. *IEEE Trans. Nucl. Sci.* **57**(4), 2119–2123 (2010)
119. R. Krithivasan, G. Niu, J.D. Cressler, S.M. Currie, K.E. Fritz, R.A. Reed, P.W. Marshall, P. A. Riggs, B.A. Randall, B. Gilbert, An SEU hardening approach for high-speed SiGe HBT digital logic. *IEEE Trans. Nucl. Sci.* **50**(6), 2126–2134 (2003)
120. B.R. Chawla, Circuit representation of the integral charge-control model of bipolar transistors. *IEEE J. Solid-State Circuits* **6**(4), 262–264 (1971)
121. C. McAndrew, J. Seitchik, D. Bowers, M. Dunn, M. Foisy, I. Getreu, M. McSwain, S. Moinian, J. Parker, P. van Wijnen, L. Wagner, VBIC95: An improved vertical, IC bipolar transistor model, in *IEEE Bipolar/BiCMOS Circuits and Technology Meeting*. (Minneapolis, MN, 1995), pp. 170–177
122. M. Schröter, A. Chakravorty, *Compact hierarchical modeling of bipolar transistors with HICUM* (World Scientific, Singapore, 2010)
123. R. Van Der Toorn, J. C. J. Paasschens, W.J. Kloosterman, in *The Mextram Bipolar Transistor Model level 504.11.0* (Delft University of Technology, 2012)
124. M. Kim, D. Yoon, S. Cha, J. Jin, S. Lim, K. Choi, A global optimization of bipolar model parameters using simulated diffusion, in *IEEE International Conference on Microelectronic Test Structures*. (1994), pp. 1–6
125. S. Lee, S.W. Kang, A parameter extraction method using cutoff measurement for a large-scale HSPICE model of HBTs. *IEEE Trans. Electron Devices* **41**(1), 112–114 (1994)
126. J.M.M. Rios, L.M. Lunardi, S. Chandrasekhar, Y. Miyamoto, A self-consistent method for complete small-signal parameter extraction of InP-based heterojunction bipolar transistors. *IEEE Trans. Microw. Theory Tech.* **45**(1), 39–45 (1997)
127. H.C. Tseng, Efficient optimization of InGaAs and SiGe RF HBTs with a mixed-mode genetic-algorithm technique. *Solid-State Electron.* **50**(5), 853–857 (2006)
128. S. Lee, G. A. New circuit model for RF probe pads and interconnections for the extraction of HBT equivalent circuits. *IEEE Electron Device Lett.* **13**(10), 521–523 (1991)
129. D. Berger, N. Gambetta, D. Celi, C. Dufaza, Extraction of the base-collector capacitance splitting along the base resistance using HF measurements, in *IEEE Bipolar/BiCMOS Circuits and Technology Meeting* (2000), pp. 180–183
130. S. Bousnina, P. Mandeville, A.B. Kouki, R. Surridge, F.M. Ghannouchi, Direct parameter-extraction method for HBT small-signal model. *IEEE Trans. Microw. Theory Tech.* **50**(2), 529–536 (2002)
131. H.Y. Chen, K.M. Chen, G.W. Huangand, C.Y. Chang, Small-Signal modeling of SiGe HBTs using direct parameter-extraction method. *IEEE Trans. Electron Devices* **53**(9), 2287–2295 (2006)
132. K. Lee, K. Choi, S.H. Kook, D.H. Cho, K.W. Parkand, B. Kim, Direct parameter extraction of SiGe HBTs for the VBIC bipolar compact model. *IEEE Trans. Electron Devices* **52**(3), 375–384 (2005)

133. A. Oudir, M. Mahdouani, R. Bourguiga, Direct extraction method of HBT equivalent-circuit elements relying exclusively on S-parameters measured at normal bias conditions. *IEEE Trans. Microw. Theory Tech.* **59**(8), 1973–1982 (2011)
134. A. Oudir, M. Mahdouani, R. Bourguiga, F. Pardoand, J.L. Pelouard, An analytic procedure for extraction of metallic collector-up InP/InGaAsP/InGaAs HBT small signal equivalent circuit parameters. *Solid-State Electron.* **52**(11), 1742–1750 (2008)
135. H.C. Tseng, J.H. Chou, A pure analytic method for direct extraction of collector-up HBT's small-signal parameters. *IEEE Trans. Electron Devices* **51**(12), 1972–1977 (2004)
136. T. Yang, J.M. Tsai, C. Ho, R. Hu, SiGe HBT's small-signal Pi modeling. *IEEE Trans. Microw. Theory Tech.* **55**(7), 1417–1424 (2007)
137. J. Fu, Small-signal model parameter extraction for microwave SiGe HBTs based on Y- and Z-parameter characterization. *Chin. J. Semicond.* **8**, 71–77 (2009)
138. X. Montagner, P. Fouillat, R. Briand, R.D. Schrimpf, A. Touboul, KFôC Galloway, Implementation of total dose effects in the bipolar junction transistor Gummel-Poon model. *IEEE Trans. Nucl. Sci.* **44**(6), 1922–1929 (1997)
139. M. Ullan, M. Ullan, J.P. Alegre, S. Diez, G. Pellegrini, F.ô.L.M. Campabadal, Excess base current model for gamma-irradiated SiGe bipolar transistors, in *IEEE International Conference on Microelectronic Test Structures* (IEEE, 2007), pp. 162–164
140. M. Van Uffelen, S. Geboers, P. Leroux, F. Berghmans, SPICE modelling of a discrete COTS SiGe HBT for digital applications up to MGy dose levels. *IEEE Trans. Nucl. Sci.* **53**(4), 1945–1949 (2006)

Chapter 2

Ionization Damage Effect in SiGe HBT

In space environment, many charged particles, such as protons, electrons, and gamma rays, can cause ionization damages and performance degradation, resulting in serious threats to the reliability of the space electronic system. Due to the special device structure, SiGe HBT has shown an inherent multi-Mrad total dose tolerance and gained significant attention as a candidate for extreme environmental electronic applications. However, due to the complexity of fabrication process and the diversity of device structure, the ionization damage effects are complicated. It is necessary to carry out some radiation experiments to study its ionization damage effect in SiGe HBT with different process and device structure. In this chapter, we will first introduce the interaction mechanism between gamma rays and materials and then discuss the ionization damage effects of SiGe HBTs for two kinds of layout structure under different dose rates and bias conditions.

2.1 Interaction Mechanism Between Gamma Rays and Materials

Gamma ray is a kind of an electromagnetic wave with a wavelength less than 0.2 Å. Due to the shorter wavelength, gamma ray generally has a higher energy and a stronger penetrating power. According to the different incident energy, the interaction between gamma ray and material can be divided into the following three kinds: photocurrent effect, Compton scattering effect, and electron–hole pair effect, as shown in Fig. 2.1 [1]. When the incident energy is low, some electron in material will be excited and the photocurrent is created. When gamma ray with high energy strikes at the material surface, the electrons in valence band absorb enough energy to excite to the conduction band, creating a free electron–hole pair. For the gamma ray with middle energy, the Compton scattering effect dominates, where the photon energy is not completely absorbed and lower energy secondary electrons (known as

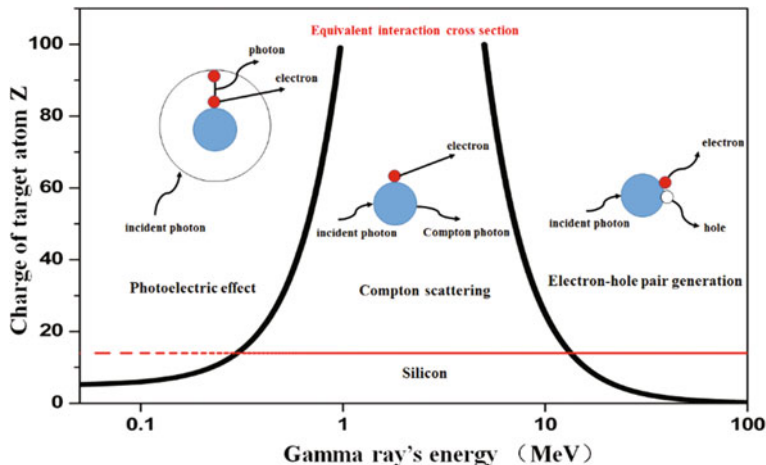


Fig. 2.1 Diagram of interaction between gamma rays with different energies and material, the solid line represents the case of silicon

Compton electrons) are produced. If the second electron energy is still high enough, it can even excite another electron. In general, the generation of electron-hole pairs becomes very important if the photon energy exceeds 1.02 MeV. ^{60}Co radiation source undergoes two decays, producing ^{60}Ni and two kinds of gamma ray flux with energy of 1.17 and 1.33 MeV (average of 1.25 MeV). The gamma ray with this energy can produce a large number of electron-hole pairs with Compton effect.

2.2 Experiment

The devices under test (DUT) are two kinds of SiGe HBT designed and fabricated by the Institute of Microelectronics, Tsinghua University. The first one is a microwave low-noise SiGe HBT, named SiGe HBT1, and the schematic cross-sectional view is shown in Fig. 2.2. The main process is as follows: After the formation of n^+ buried layer (NBL) on the p-type substrate, the lightly phosphorus-doped ($7\text{--}15\text{ cm}^{-3}$) n^- collector epitaxy is completed. An n^+ collector sinker is then formed, followed by local oxidation of silicon (LOCOS) for device isolation, in situ 120 nm boron-doped graded SiGe base epitaxy, selectively implanted collector (SIC), and heavily doped n^+ polysilicon emitter contact. An interdigital layout (4E5B2C) is adopted for chip design with each emitter finger of $0.4 \times 20\text{ }\mu\text{m}^2$. The typical BV_{CEO} is 4.5 V, BV_{CBO} is 9 V, and current gain β_F is 100. Emitter and substrate are connected together via metal interconnection.

A schematic cross-sectional view of second DUT, named SiGe HBT2, is shown in Fig. 2.3. The device architecture features low resistivity n^+ substrate, lightly doped n^- collector epitaxy layer, in situ boron-doped SiGe intrinsic base epitaxy

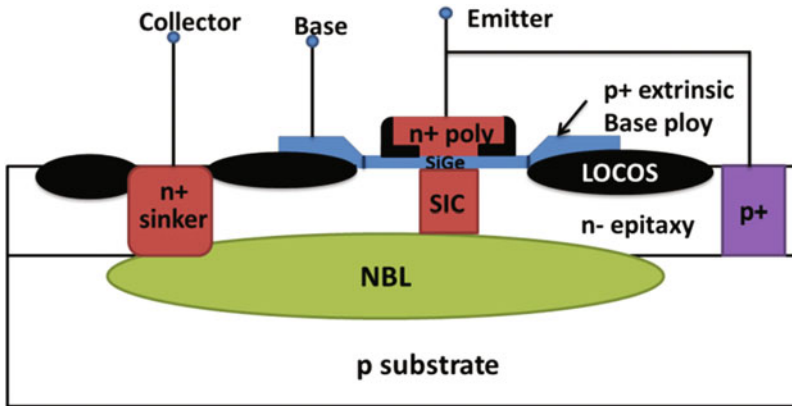


Fig. 2.2 Cross-sectional view of SiGe HBT1 with emitter and substrate connected together

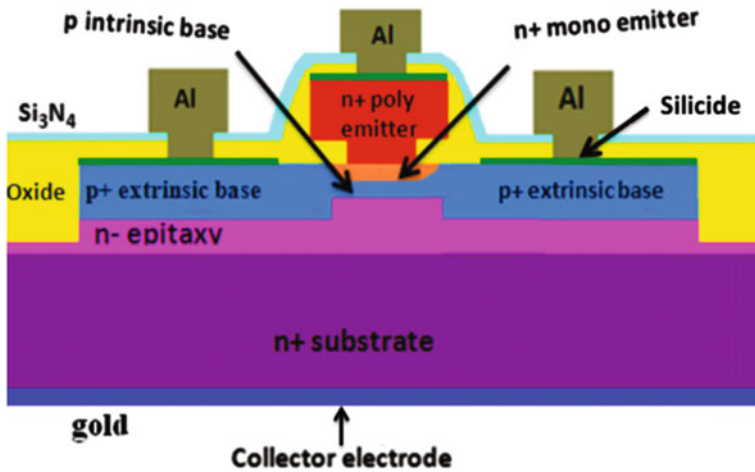


Fig. 2.3 Cross-sectional view of SiGe HBT2 with the collector electrode elicited from the backside of the substrate

region, heavily doped n^+ polysilicon emitter, extrinsic p^+ extrinsic base region formed through heavy dose implant self-aligned to the emitter-poly, and self-aligned titanium silicide formed based on the emitter-base sidewall spacer oxide. There is no SIC in the fabrication process. The collector electrode is elicited from the backside of the substrate through gold evaporation. The layout of the SiGe HBT consists of 15 emitter fingers, with the dimension of $0.6 \times 20 \mu\text{m}^2$ for each finger. The device is encapsulated in a standard SOT-23 plastic package. Owing to the thick n^- collector epitaxy layer, the SiGe HBT is a high-voltage transistor with $f_T = 7 \text{ GHz}$, $\beta_F = 200$, $BV_{CBO} > 20 \text{ V}$, and $BV_{CEO} > 12 \text{ V}$.

The examples were irradiated with ^{60}Co gamma source at room temperature. A Pb/Al box was used to decrease the flux of secondary gamma ray and ensure a monochromatic gamma ray spectrum. Two dose rates of 50 rad (Si)/s and 0.1 rad (Si)/s were adopted to investigate the effects of dose rate on ionization damage. For convenience, the unit of rad(Si)/s here is simplified as rad/s throughout this dissertation. The transistors were removed from the irradiation chamber at specified intervals and then characterized with an Agilent B1500 Semiconductor Parameter Analyzer at room temperature. The irradiation resumed after the characterization until the required accumulated dose was reached.

2.3 Results and Discussion

The DC performance degradation, including forward Gummel, reverse Gummel, leakage current, output characteristic, parasitic resistance, and neutral base recombination, are first discussed under high-dose-rate irradiation (50 rad/s). During the exposure, all the device terminals are floating.

2.3.1 SiGe HBT1 with Emitter and Substrate Connecting Together

The forward Gummel characteristics of SiGe HBT1 under different irradiation dose are shown in Fig. 2.4. The base currents (I_B) all increase monotonically with accumulated total dose, especially in low emitter–base voltage (V_{BE}) region, while collector current (I_C) remains unchanged during the whole irradiation; thereby, a remarkable drop appears in the current gain β ($\beta = I_C/I_B$). The peak value of β is

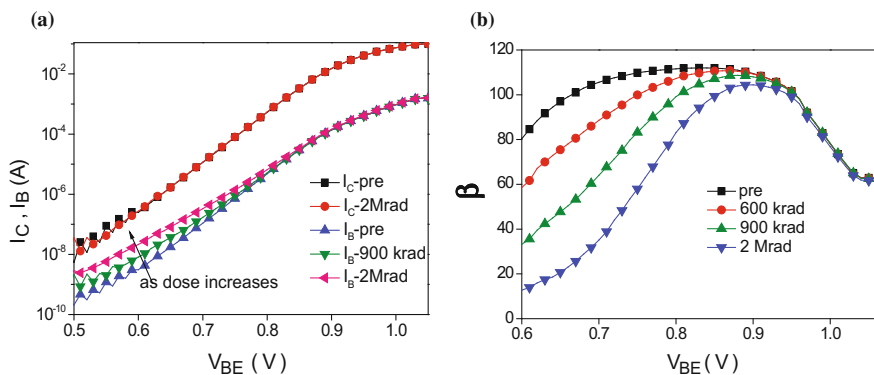


Fig. 2.4 **a** Forward Gummel characteristics and **b** current gain β of SiGe HBT1 before and after gamma irradiation with different dose levels

still higher than 100 and decreases only 7.2% after 2 Mrad dose irradiation, which demonstrates an inherent multi-Mrad total ionizing dose (TID) tolerance.

For a PN junction, we have

$$I = I_S \left(e^{\frac{V}{nV_T}} - 1 \right) \quad (2.1)$$

where I_S is the inverse-saturation current, V_T is thermal voltage and is about 25.6 mV at room temperature, and n is ideality factor. When the PN junction is forward biased, there exists $V \gg n \cdot V_T$, and n is given as

$$n \approx \frac{1}{V_T} \cdot \left(\frac{d \ln(I)}{dV} \right)^{-1} \quad (2.2)$$

Generally, n has a value between 1 and 2. If n is close to 1, the diffusion current dominates I_B , while a value of 2 means the recombination current dominates. At a given temperature, the larger n means a greater ration of non-ideal recombination current to total current. Figure 2.5 shows the ideality factor of base current and collector current for SiGe HBT1 before and after irradiation. Ideality factor n_{IC} remains constant of 1 during the whole irradiation. However, the ideality factor n_{IB} is found to increase from 1.02 to 1.38 as irradiation dose increases at medium V_{BE} region ($V_{BE} = 0.7\text{--}0.75$ V), which suggests that there exists an abundant of recombination current and I_B is mainly dominated by the recombination current.

In order to quantitatively analyze the performance degradation after gamma ray irradiation, electrical parameter $\Delta(1/\beta)$, defined as $1/\beta_{\text{post}} - 1/\beta_{\text{pre}}$, is calculated at $V_{BE} = 0.6$ and 0.7 V, where β_{pre} and β_{post} are separately current gain before and after irradiation. The variation of $\Delta(1/\beta)$ is depicted in Fig. 2.6. A nonlinear trend between $\Delta(1/\beta)$ and irradiation dose is expected, and a saturation value appears at high-dose level.

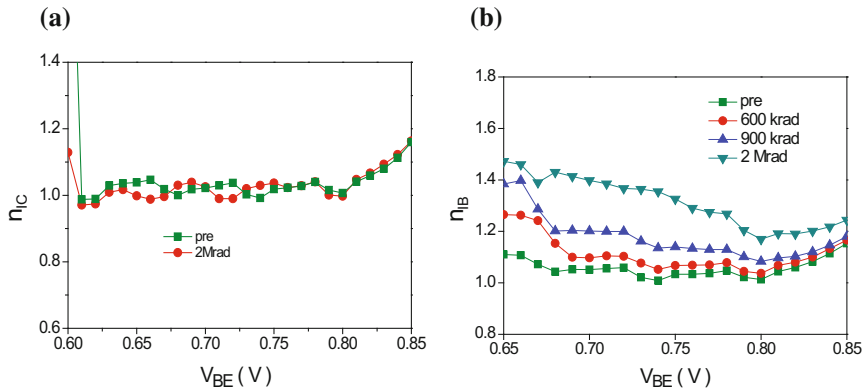
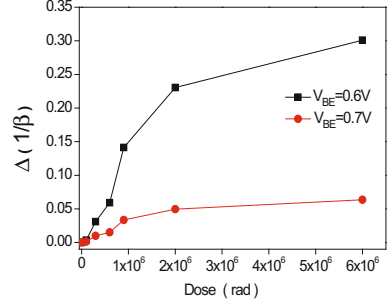


Fig. 2.5 Variation of current ideality factor before and after ^{60}Co irradiation for **a** base current and **b** collector current

Fig. 2.6 Variation of $\Delta(1/\beta)$ for SiGe HBT1 under two base voltages V_{BE}



Similar to the previous studies [2–4], a distinct increase in the low-injection base current of inverse-mode Gummel characteristics appears when the transistors are exposed to gamma irradiation, as shown in Fig. 2.7a. It is the result of radiation-induced generation–recombination (G/R) traps near LOCOS oxide interface regions. However, unlike current reports, for SiGe HBT1 there exists an unexpected increase in I_E under low V_{BC} region, as depicted in Fig. 2.7b. The relevant discussion will be presented in the following section.

The leakage current of BC and BE junctions was also investigated, and it is shown in Fig. 2.8. The reverse leakage currents for both the junctions almost keep unchanged with total dose increasing. Besides, the reverse leakage current of BC junction is nearly invariable with V_{BC} increasing; however, the reverse leakage current of BE junction is not saturated and greatly increases with reverse bias voltage increasing. The reverse leakage current for BC and BE junction is composed of reverse minority diffusion current (I_{DR}) and generation current in the space charge region (I_G). The I_{DR} for the BE junction (N^+P) is given by Meng et al. [5]

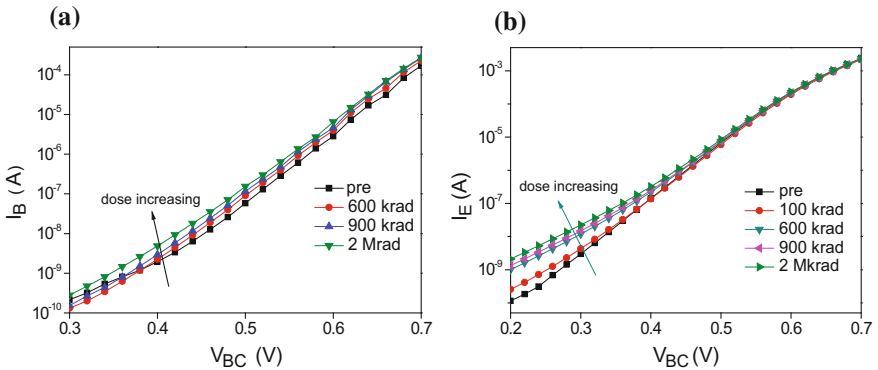
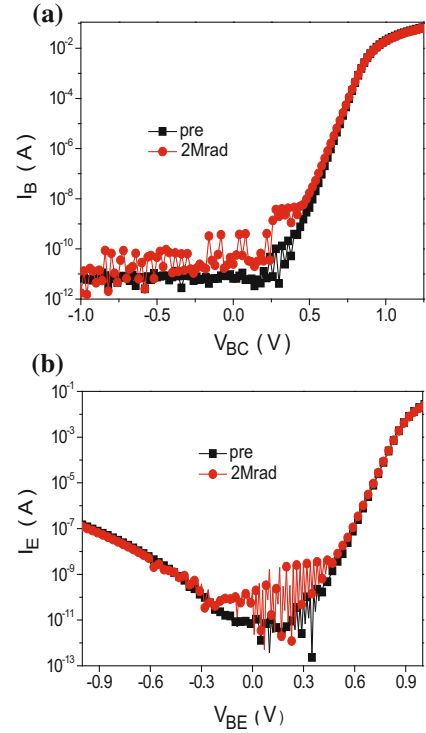


Fig. 2.7 Variation of reverse Gummel plot before and after ^{60}Co irradiation: **a** base current I_B and **b** emitter current I_E

Fig. 2.8 Variation of leakage current for **a** BC junction and **b** BE junction



$$I_{DR} \approx qA \frac{D_n n_i^2}{L_n N_B} \quad (2.3)$$

where A stands for the area of BE junction, and D_n , n_i , L_n , and N_B represent the electron diffusion coefficient, the intrinsic carrier density, the electron diffusion length, and the doping concentration in base region, respectively. The I_{DR} is saturated and independent of the reverse bias voltage of BE junction. The I_G is given by Meng et al. [5]

$$I_G \approx qA \frac{n_i^2 W_{BE}}{2\tau} \quad (2.4)$$

where τ is minority carrier lifetime in the BE junction depletion region. W_{BE} is the width of BE junction depletion region and increases with the reverse bias voltage

increasing, and therefore, I_G is not saturated and increases with the reverse bias voltage V_{BE} increasing.

The ratio of I_{DR} to I_G is given by

$$\frac{I_{DR}}{I_G} \Big|_{BE} = \frac{2L_n}{N_B W_{BE}} \quad (2.5)$$

Similarly, for the case of BC junction (P^+N), the ratio of I_{DR} to I_G is as follows:

$$\frac{I_{DR}}{I_G} \Big|_{BC} = \frac{2L_p}{N_C W_{BC}}. \quad (2.6)$$

where L_p and N_C represent the hole diffusion length and the doping concentration in collector region, respectively. W_{BC} stands for the width of BC junction depletion region. Compared to the BC junction, a greater proportion of generation current (I_G) appears in the total leakage current of BE junction due to the heavy base doping N_B , and I_G might dominate the reverse leakage current. Therefore, the reverse leakage current for BE junction is not saturated and greatly increases with the reverse bias voltage increasing, and the reverse leakage current for BC junction slightly increases with the reverse bias voltage increasing, as shown in Fig. 2.8.

The variation of parasitic emitter resistance R_E , base resistance R_B , and collector resistance R_C before and after irradiation is depicted in Fig. 2.9. Considering the measurement error, those parasitic resistances remain unchanged during the whole irradiation process, which demonstrates that no significant displacement damage appears and the effective doping concentration of each region does not change significantly.

The output characteristic of the SiGe HBT1 at different I_B is shown in Fig. 2.10. It is found that the collector current (I_C) declines with the ion fluence increasing, which is a result of the degradation in current gain, as shown in the Fig. 2.4b. For the low I_B level (such as 100 μA), the curve slope at high V_{CE} region remains nearly unchanged after 2 Mrad dose irradiation, i.e., there is no significant base-width

Fig. 2.9 Variation of series resistance in SiGe HBT1 before and after ^{60}Co irradiation

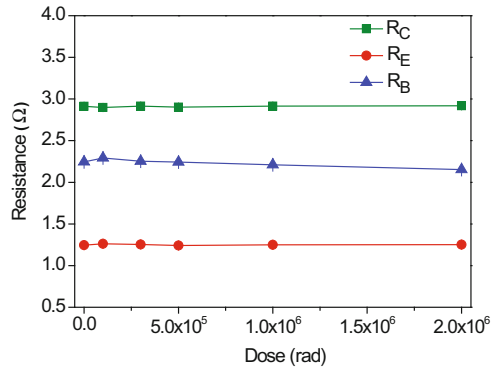
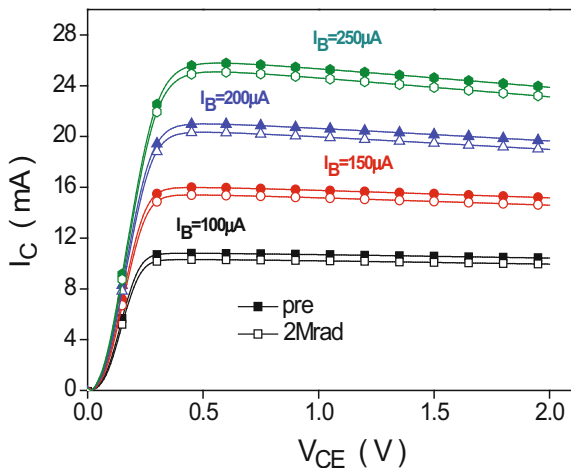


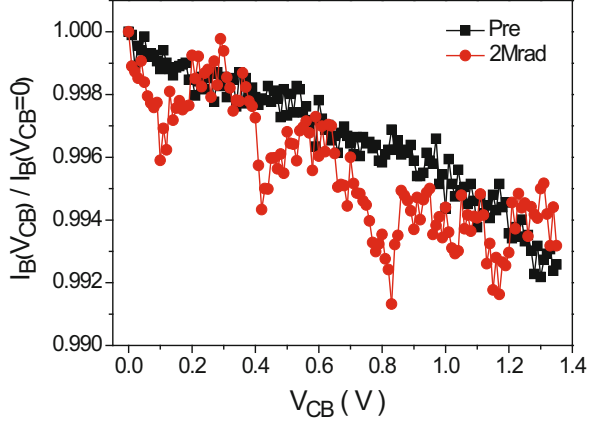
Fig. 2.10 Variation of output characteristics at fixed base current



modulation in the transistor and Early voltage (V_A) remains nearly unchanged, as shown in Fig. 2.10. Besides, negative differential resistance characteristics occur at high I_B level (such as $250 \mu\text{A}$) region before the gamma irradiation, which is due to the self-heating effect. The self-heating effect can induce a decreased current gain β with the internal temperature increasing.

Four significant components generally contribute to I_B of the conventional SiGe HBT under arbitrary forward-active bias: the recombination current in the BE depletion region and the interface between the extrinsic base and the BE spacer oxide, the neutral base recombination (NBR) current, the impact ionization current in the BC depletion region, and the hole current injected into the emitter. The impact ionization only occurs in the high V_{CB} region. NBR includes the recombination of injected electrons with holes via intermediate trap levels in neutral base region. It is proportional to total charge Q_B injected from emitter to base and is inversely proportional to the lifetime of minority carrier τ in neutral base [6]. Therefore, any method that changes Q_B and τ can vary NBR in the transistor. Q_B is proportional to the width of neutral base region W_B , which is changed by the voltage V_{BC} across base-collector junction. Thus, a conventional way to characterize NBR is to observe the rate of normalized base current decreasing with varied V_{CB} at fixed V_{BE} [3, 4]. Figure 2.11 depicts the normalized base current $I_B(V_{CB})/I_B(V_{CB} = 0)$ as a function of V_{CB} at $V_{BE} = 0.65 \text{ V}$. The negative slope at low V_{CB} ($V_{CB} < 3 \text{ V}$) is indicative of NBR in the transistors, which means there is no distinct increased NBR in transistor after 2 Mrad dose radiation.

Fig. 2.11 Variation of I_B (V_{CB}/I_B ($V_{CB} = 0$) as function of V_{CB} under $V_{BE} = 0.65$ V



2.3.2 Ionization Damage in SiGe HBTs with Backside Collector Electrode

As for the SiGe HBT2 with backside collector electrode, forward Gummel characteristics before and after irradiation are depicted in Fig. 2.12. Similar to the case of SiGe HBT1, I_B increases while I_C keeps unchanged with accumulated total dose increasing, resulting in a decline in current gain β . The peak value of β is still higher than 100 after 2 Mrad dose irradiation, which can meet the requirements of most applications, and an inherent multi-Mrad TID tolerance is demonstrated.

The variation of current ideal factor n_{IB} and n_{IC} for SiGe HBT2 is shown in Fig. 2.13. Before irradiation, n_{IB} and n_{IC} are about 1, which means that the diffusion current dominates and there is no significant recombination current. During the whole irradiation, n_{IC} remains nearly unchanged; however, n_{IB} sharply increases to

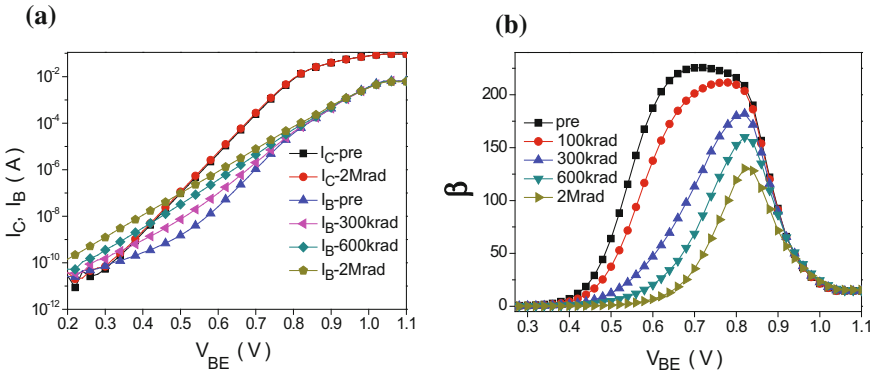


Fig. 2.12 Variation of **a** forward Gummel and **b** current gain before and after ^{60}Co radiation

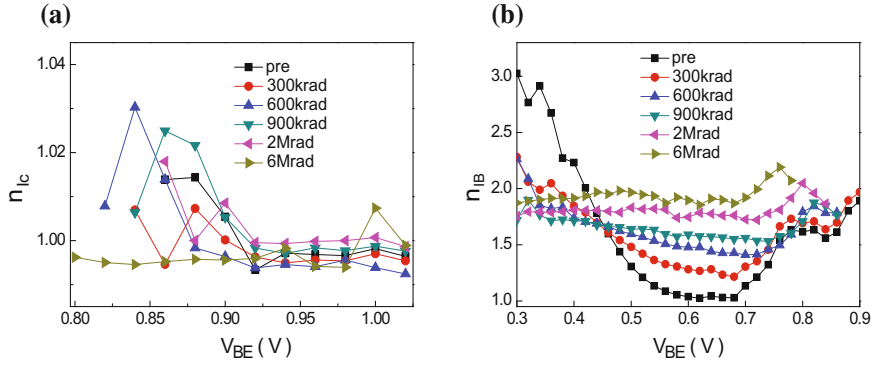


Fig. 2.13 Variation of **a** collector current ideal factor n_{IC} and **b** base current ideal factor n_{IB} before and after ^{60}Co radiation

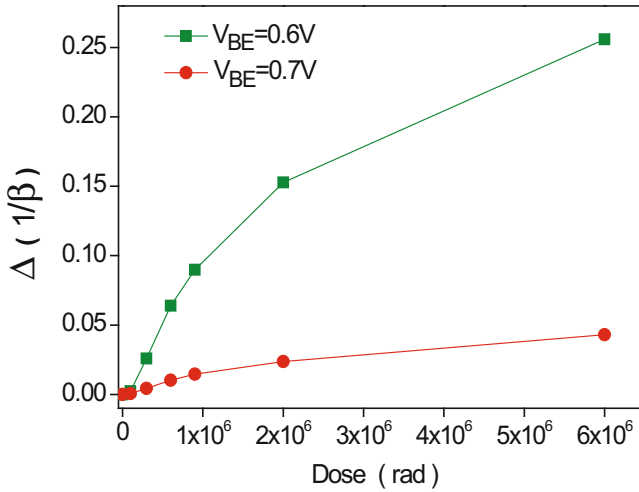


Fig. 2.14 Variation of $\Delta(1/\beta)$ for SiGe HBT2 under two different V_{BE}

2 after 2 Mrad total dose irradiation, implying that much recombination current appears in base current.

Figure 2.14 depicts the variation of $\Delta(1/\beta)$ for SiGe HBT2 before and after gamma irradiation. Similar to the case of SiGe HBT1, $\Delta(1/\beta)$ here increases nonlinearly until saturation is reached.

Figure 2.15 shows the reverse Gummel curve of SiGe HBT2 before and after ^{60}Co irradiation. It can be seen that the irradiation has less influence on the reverse Gummel characteristic of SiGe HBT2, and I_B and I_E hardly change with the total dose of 2 Mrad, which has not been reported previously. This may be due to the special device structure and will be discussed and analyzed in the following section.

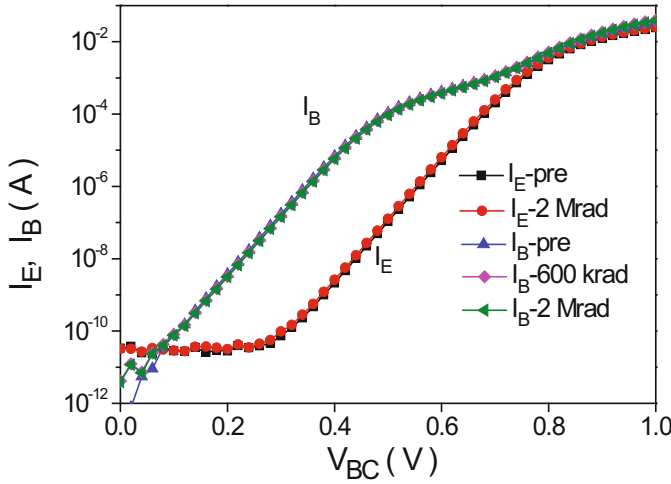


Fig. 2.15 Variation of reverse Gummel characteristics of SiGe HBT2

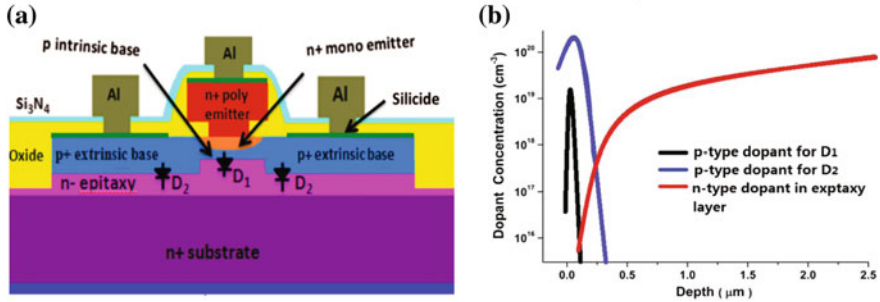


Fig. 2.16 **a** Schematic cross-sectional view of SiGe HBT2. D_1 and D_2 represent intrinsic and extrinsic BC junctions. **b** Schematic doping profile for the extrinsic D_2 and intrinsic D_1

It is found that an interesting “double shoulder” appears in base current, as shown in Fig. 2.15. The special shape of I_B curve can be interpreted in the following way. As for the device architecture shown in Fig. 2.16a, the whole BC junction may be considered as intrinsic base diode D_1 and extrinsic base diode D_2 in parallel. The schematic doping distribution for D_1 and D_2 diodes is shown in Fig. 2.16b. Because of the heavy dose extrinsic base implant, the p-type concentration for the extrinsic D_2 diode is much larger than that for the intrinsic D_1 diode. Because of the inevitable upward diffusion of n-type impurities from the n+ substrate during the device manufacturing process, the p-type doping profile will intersect with the n-type doping profile at a much larger concentration for D_2 than for D_1 . The forward current of D_1 is larger in the low-injection region, but affected by the high-injection effect earlier due to the lighter n-type doping concentration.

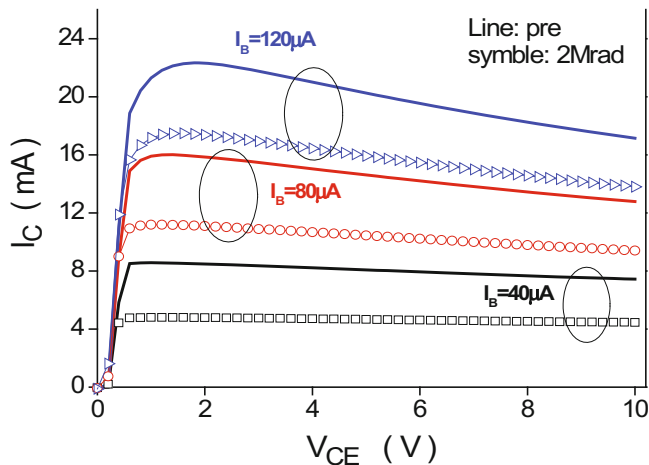


Fig. 2.17 Variation of output characteristics of SiGe HBT2 before and after irradiation

On the contrary, the higher n-type doping level of D_2 gives a smaller forward current under low bias conditions, while the high-injection effect is delayed to a higher critical current value. Therefore, a “double shoulder” I_B appears as a superposition of the two diode current curves in the semi-logarithmic scale reverse Gummel plot [7], as shown in Fig. 2.15.

Figure 2.17 shows the variation of the output characteristic of SiGe HBT2 before and after irradiation at fixed base current. Because of self-heating effect, I_C will decrease as V_{CE} increases when transistors are biased at high base current level (such as 120 μA). Due to the degradation of current gain, the collector current I_C of the irradiated transistor decreases with the total dose increasing. Besides, when base current was relatively low (40 μA), the slope of IV curves keep nearly unchanged, i.e., the gamma irradiation has less influence on V_A .

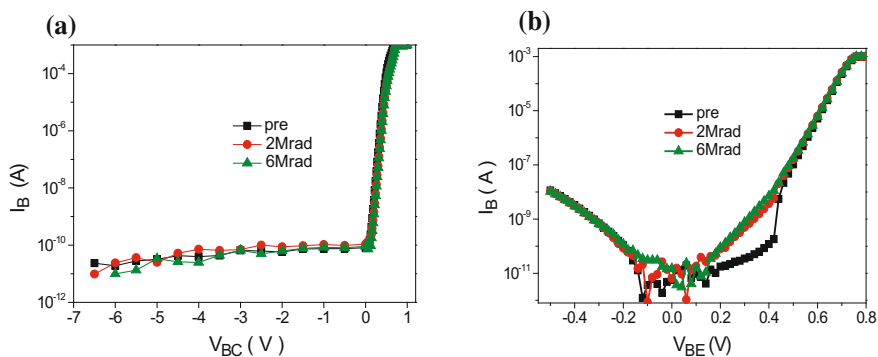


Fig. 2.18 Variation of **a** BC junction leakage current and **b** BE junction leakage current of SiGe HBT2 before and after ^{60}Co radiation

Figure 2.18 shows the variation of leakage current of SiGe HBT2 before and after irradiation. Similar to SiGe HBT1, the leakage current of BC junction is nearly invariable with V_{BC} increasing, while the reverse leakage current of BE junction is not saturated. Besides, when the transistors are exposed to irradiation, the leakage current keeps nearly unchanged.

2.3.3 Degradation Mechanism in Gamma Ray Irradiated SiGe HBTs

Experiment results show that base current and current gain will suffer degradation when the transistors are exposed to ^{60}Co irradiation. Large quantity of EHPs will be generated in the oxide as ionizing radiation passes through the SiO_2 film. Some fraction of the EHPs will recombine within a very short time, and the remains will transport within the oxide. The electrons, being much more mobile than holes, are swept out of the oxide rapidly. While the hole will slowly travel to the SiO_2/Si interface and a fraction will be trapped in deep energy-level sites in SiO_2 region, creating the positive oxide-trapped charges [6]. Besides, the radiation-induced holes will release proton (H^+) as they transport through the oxide, and the released protons transport toward the interface where they react with the passivated Si-H bond to form the interface traps [8, 9]. In bipolar transistor, the above irradiation damages generally appear in the spacer oxide near EB junction and the LOCOS edge near BC junction [10, 11], as shown in Fig. 2.19.

When the transistors are biased under forward-active mode, as depicted in forward Gummel measurement, base current is mainly composed of three parts: hole current I_{B1} injected from base to emitter region, recombination current I_{B2} near the interface and space charge region, and the neutral base recombination current I_{B3} . For modern SiGe HBT, I_{B1} plays a major role in the base current before radiation. It

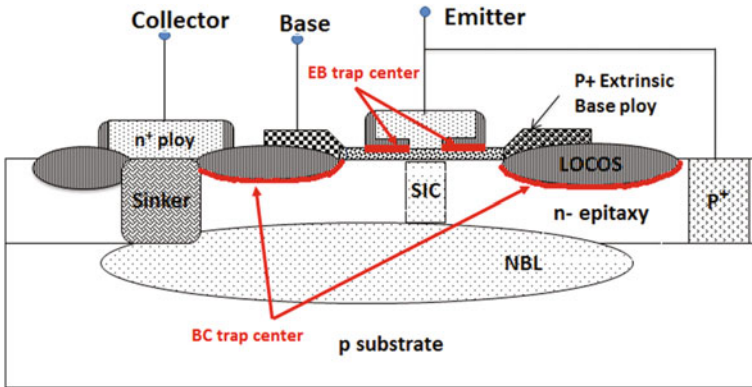


Fig. 2.19 Sensitive region of bipolar transistor for ^{60}Co radiation distribution

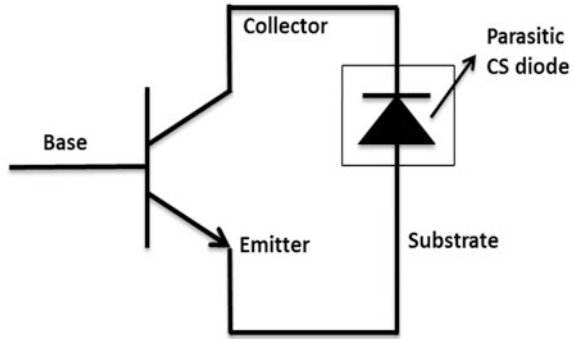
is the increment in I_{B2} that leads to the base degradation after γ -ray irradiation. The irradiation-induced trapped charges and interface states at SiO_2/Si interface near EB junction act as recombination centers, resulting in the significant increase in base current [12–14], as shown in Figs. 2.4 and 2.12. As for NPN bipolar transistor, the positive oxide trap charge in the SiO_2 produces a downward positive electric field; as a result, the depletion layer of EB junction extends toward the low-doped p-type base region and increases the depletion layer area. Besides, the surface electric field reduces hole concentration near p-type base surface and then decreases the concentration difference between the hole and electron near the base surface. Based on the Shockley–Read–Hall (SRH) recombination theory, a lower carrier concentration difference will result in a larger base region recombination current.

For a given radiation damage, base current degradation at a low V_{BE} region is more severe than at high V_{BE} region. It means that the radiation damage at low V_{BE} region is significantly pronounced. Ignoring the neutral base recombination current, the base current includes two parts: the hole reverse-injection current from base to emitter and the surface recombination current. At high V_{BE} region, the base current is dominated by hole reverse-injection current and the ideality factor is 1. At low V_{BE} region, the surface recombination current dominates and the ideality factor is 2. The ionization damages in the spacer oxide near EB junction increase the base surface recombination current and have less influence on the hole reverse-injection current. Therefore, in the semi-logarithmic coordinate system, the surface recombination current is more obvious under the low V_{BE} region and increases with irradiation dose increasing, while it is hidden by the hole reverse-injection current at high V_{BE} region [15]. It should be noted that the carrier concentration injected from emitter to base depends on the bias conditions, base doping concentration, the Ge composition in base, and so on. Under a given V_{BE} voltage, the increase in surface recombination current only increases the base current and emitter current, while the collector current cannot be reduced. However, if the electrons injected into the base region are recombined in the neutral base region and cannot reach the collector region, the collector current will decrease.

The sub-linear variation of $\Delta (1/\beta)$ with radiation dose in Figs. 2.6 and 2.14 is the result of interaction between the oxide trap charge and the interfacial state [15]. The generation of interface states is related to the radiation dose and time, and only after high enough dose, the interfacial states can be created. However, the formation time for the oxide-trapped charge is relatively short, usually earlier than the interface states. The electric field induced by the oxide trap charge will prevent the subsequent formation of interface states. However, once the interface states are formed, the generated electric field will hinder the further increase in the oxide trap charge. It is due to the mutual inhibition between interface states and oxide-trapped charges that the degradation of current gain gradually decreases with the radiation dose increasing, in a form of sub-linear trend.

Similar to the case of spacer oxide near EB junction in forward-active mode, ionization irradiation damages also appear around LOCOS edge near BC junction during the gamma ray irradiation, resulting in a base current degradation in the

Fig. 2.20 Equivalent circuit of the SiGe HBT1 with parasitic CS diode



reverse-active mode [2–4, 16, 17]. However, due to the special device structure, the base current degradation here shows a different degradation result.

As for SiGe HBT1, unlike the previous studies, an unexpected increase in emitter current appears after irradiation. The emitter and substrate are connected together in this case, and the equivalent circuit of the SiGe HBT is shown in Fig. 2.20. The parasitic collector-substrate (CS) diode contributes to the observed non-ideal excess emitter current. During the reverse Gummel test, the collector terminal is connected to the ground and the substrate (emitter) is connected to the high potential. Under this case, the parasitic CS diode becomes forward biased and two current components contributed to the forward current of this CS diode: One is hole injection current from substrate to n-epitaxy and NBL layer (collector), and the other is electron injection current from n-epitaxy and NBL layer to substrate. The forward CS diode current contributes to the excess emitter current [2–4, 16, 17]. The forward current of this CS diode may exceed the intrinsic emitter current and dominate the emitter current in the reverse Gummel plots. The increased emitter current ideality factor at low voltage bias regime ($V_{BC} = 0.4$ V) demonstrates that non-ideal recombination current appears after irradiation, and much ionization damages are created in the spacer charge of CS junction. Therefore, the recombination current in CS junction is increased due to the irradiation-induced G/R centers. However, for the forward Gummel test, the emitter (substrate) terminal is connected to the ground and the collector is connected to the high potential. Hence, the parasitic CS diode is reversed biased. Compared to the collector current of intrinsic SiGe HBT in the forward-active mode, the reverse leakage current of CS diode is negligible. As a result, the effect of parasitic CS diode cannot be observed in the forward-model Gummel plot.

As shown in Fig. 2.15, the reverse Gummel characteristics for SiGe HBT2 are not influenced by gamma irradiation, which is due to the special device structure [18]. Figure 2.21 shows the distribution of forward base current and reverse base current in SiGe HBT2. The forward base current flows in parallel with the BE junction, but the reverse base current flows across the BC junction down to the backside collector contact through the collector region. That is to say, the forward base current flow is confined to the thickness of base region, while the reverse base

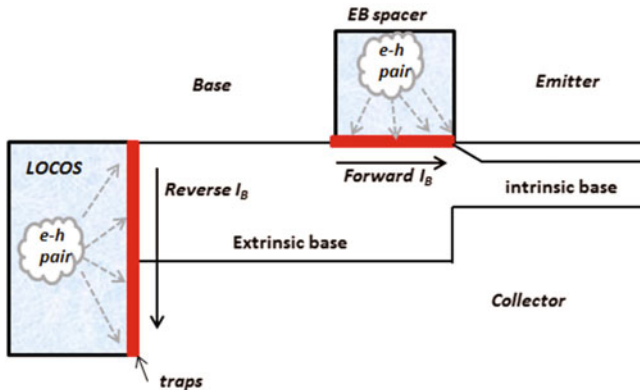


Fig. 2.21 Paths of forward and reverse base current in SiGe HBT2. The forward I_B flows along the base surface and in parallel with BE junction, whereas the reverse I_B flows across BC junction down to the backward collector contact

current flow is distributed over the width of base region. Since the base width is generally much larger than the base thickness, as a result, in contrast to much more chance for carrier recombination happening at the EB spacer oxide/Si interface in the forward mode, a much smaller fraction of the base current flow in the reverse mode will pass through the isolation oxide/Si interface. Therefore, no detectable excess recombination current is found to contribute to the I_B curve in the reverse Gummel plot.

From Fig. 2.22, one can clearly distinguish the degradation of base current measured in forward mode at $V_{BE} = 0.6$ V and reverse mode at $V_{BC} = 0.6$ V. The post-irradiation I_B in two modes exhibits an obvious increase as a function of the equivalent gamma dose. Due to the larger LOCOS area around collector epitaxy

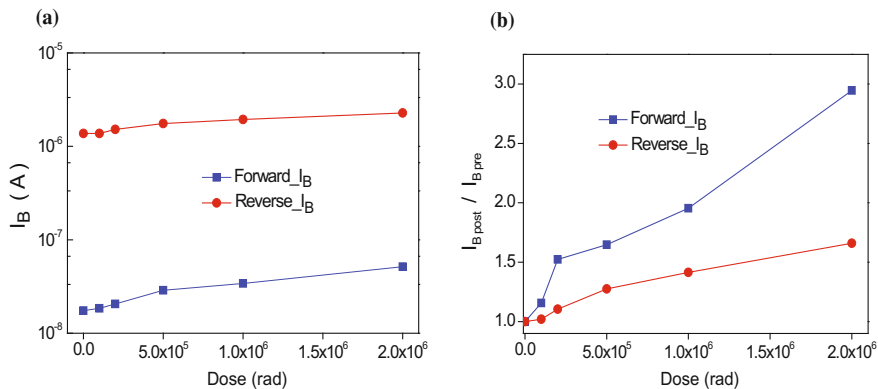


Fig. 2.22 Variation of **a** base current and **b** normalized base current of SiGe HBT1

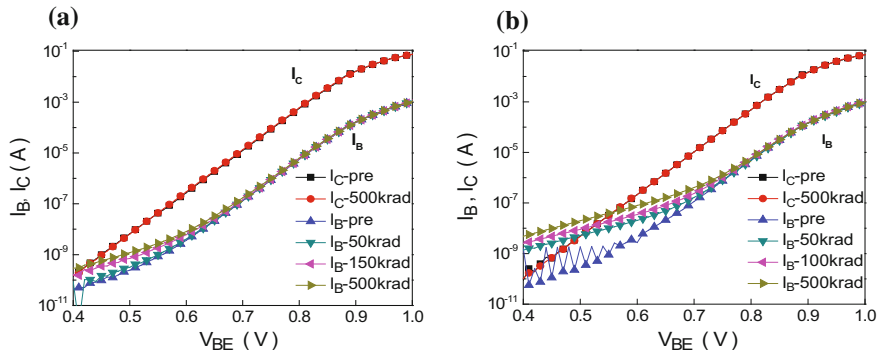


Fig. 2.23 Forward Gummel characteristics of SiGe HBT irradiated by two dose rates: **a** 50 rad/s; **b** 0.1 rad/s

layer, the base current in reverse mode is larger than that in forward mode, as shown in Fig. 2.22a. The normalized base current, defined as $I_{B\text{post}}/I_{B\text{pre}}$, is depicted in Fig. 2.22b. Compared to the base current in reverse mode, the base current in forward mode is found to be more sensitive to gamma irradiation, which might be due to the following two factors. The first one is the different components of EB spacer oxide and LOCOS oxide. Generally, the EB spacer oxide is the oxide/nitride through the deposition process, whereas the LOCOS oxide is silicon dioxide (SiO_2) through the thermal oxidation process. Compared to the former, the quality of LOCOS oxide might be relatively well and is immune to gamma irradiation. The second one is the different current directions. The base current in reverse mode flows across the BC junction and is distributed over the width of base region, while that in forward mode flows in parallel with BE junction and is confined to the thickness of base region. As a consequence, there is much more chance for carrier recombination around EB spacer oxide, and a much smaller fraction of base current will pass through the LOCOS interface in the reverse mode. Therefore, the base current in forward mode is more sensitive to gamma irradiation.

2.4 Ionization Damage in SiGe HBT at Different Dose Rate

In general, the irradiation dose rate in real space environments is very low (about 10^{-4} – 10^{-2} rad/s). Under such low-dose rate, some bipolar devices (e.g., Si BJT) exhibit significant enhanced low-dose-rate sensitivity (ELDRS) [19, 20]. However, less data are available about the ELDRS effect in SiGe HBT, and the unified understanding of the physical mechanism is not achieved [21, 22]. Besides, ELDRS effect in bipolar devices is closely related to the device structure, manufacturing process, etc. Therefore, it is necessary to carry out a series of radiation experiments

on SiGe HBT. In this study, SiGe HBT1 was irradiated at high-dose rate (50 rad/s) and low-dose rate (0.1 rad/s). The accumulated doses are 50, 100, 170, 300, and 500 krad, respectively. During the whole irradiation process, the transistor is biased at forward-active mode with $V_{CE} = 2$ V, $I_C = 5$ mA. For high-dose-rate irradiated samples, room temperature annealing was performed at the same bias conditions when the total dose reached 500 krad. The annealing time equals the low-dose-rate irradiation time.

2.4.1 Results of Ionization Damage at Different Dose Rate

The forward Gummel characteristics for high-dose-rate and low-dose-rate irradiation are shown in Fig. 2.23. The base currents all increase monotonically with accumulated total dose, especially in low V_{BE} region, while collector current remains unchanged during the whole irradiation; thereby, a remarkable drop appears in the current gain.

In order to quantitatively compare the influence of dose rates on performance degradation, two electrical parameters, excess base current ΔI_B ($\Delta I_B = I_{B,post} - I_{B,pre}$) and normalized current gain β_{nor} ($\beta_{nor} = \beta_{post}/\beta_{pre}$), are calculated at $V_{BE} = 0.6$ V, where $I_{B,pre}$, β_{pre} , $I_{B,post}$, and β_{post} are base currents and current gains before and after irradiation, respectively. Figure 2.24 depicts ΔI_B at V_{BE} of 0.6 and 0.7 V after high- and low-dose-rate irradiation, and the room temperature annealing for high-dose-rate irradiation is also performed. It is indicated that a larger ΔI_B appears under low-dose-rate irradiation, demonstrating a more ionizing damage at low-dose-rate irradiation. During the subsequent room temperature annealing, the base current for high-dose-rate irradiation first decreased in the initial 25 h and then increased, and its final stable value is still lower than that for low-dose-rate irradiation.

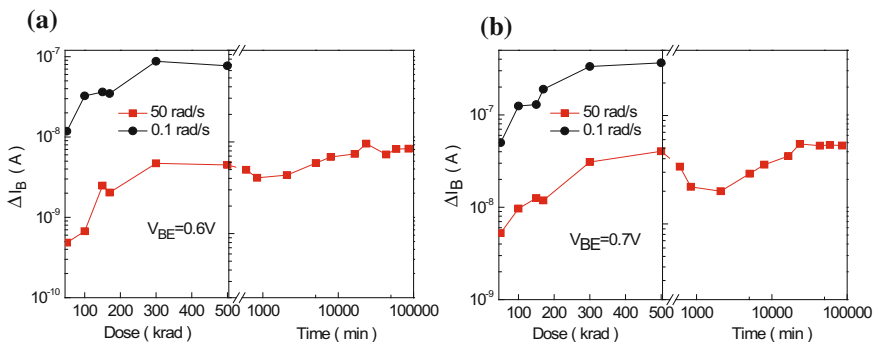


Fig. 2.24 Variation of excess base current ΔI_B after high- and low-dose-rate irradiation at **a** $V_{BE} = 0.6$ V; **b** $V_{BE} = 0.7$ V

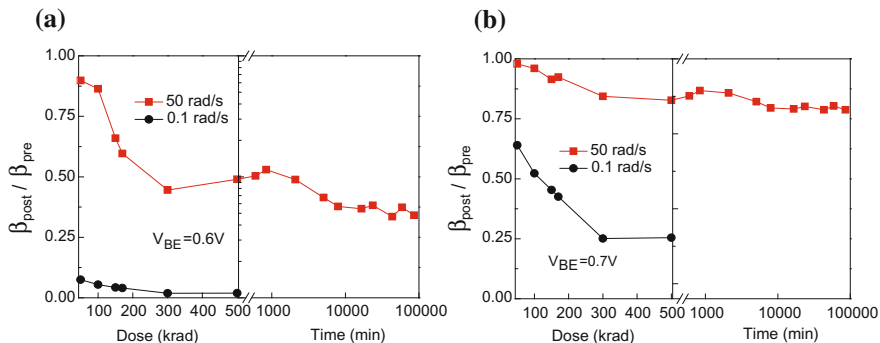


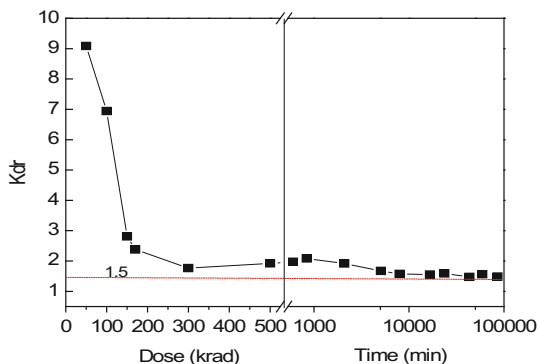
Fig. 2.25 Variation of normalized current gain β_{nor} after high- and low-dose-rate irradiation at **a** $V_{\text{BE}} = 0.6 \text{ V}$; **b** $V_{\text{BE}} = 0.7 \text{ V}$

Consistent with the excess base current, β_{nor} declines with the accumulation dose increasing and the current gains at low-dose-rate irradiation are smaller than those at high-dose-rate irradiation, as shown in Fig. 2.25. The base current for high-dose-rate irradiation first increases in the initial 25 h and then decreases in subsequent room temperature annealing process; however, it cannot rebound to the level of low-dose-rate irradiation even after a long-term annealing, which indicates that the radiation damage at low-dose rate cannot be estimated by high-dose-rate irradiation followed by a room temperature annealing, i.e., a “true” dose rate effect exists in SiGe HBTs.

In order to characterize the effect of dose rate on current gain degradation, an over-enhanced factor (K_{dr}) is introduced and defined as

$$K_{\text{dr}} = (\beta_{\text{pre}} - \beta_{\text{post}})_{\text{low}} / (\beta_{\text{pre}} - \beta_{\text{post}})_{\text{high}} \quad (2.7)$$

Fig. 2.26 Variation of ratio K_{dr} under $V_{\text{BE}} = 0.6 \text{ V}$ as a function of radiation dose and annealing time



where the subscripts “high” and “low” denote the high- and low-dose-rate radiation, respectively. According to MIL-STD-883G [23], if the ratio K_{dr} exceeds 1.5 for any of the most sensitive parameters, then the part is considered to be ELDRS susceptible, and the larger the K_{dr} , the stronger the ELDRS effect. Figure 2.26 shows the over-enhanced factor K_{dr} under $V_{BE} = 0.6$ V as a function of gamma dose and annealing time. It can be seen that K_{dr} is still greater than 1.5 after room temperature annealing, which means that SiGe HBT has a real ELDRS effect rather than a time-cumulative effect of radiation damage.

2.4.2 Mechanism of Enhanced Low-Dose-Rate Sensitivity

In bipolar transistor manufacturing process, some defects containing H atoms, such as the non-bridging oxygen defect S_{OH} , are inevitably introduced in SiO_2 layer [24]. These defects have a great influence on the ionization damages in SiGe HBT under low-dose-rate radiation. Assuming that the radiation dose rate is g , then the generation rate of electron-hole pairs in the per unit volume of SiO_2 is γg , where γ is a constant (for SiO_2 , $\gamma = 8.1 \times 10^{12} \text{ cm}^{-3} \text{ rad}^{-1}$) [25]. The electrons drift out of the oxide layer quickly, but the holes only slowly move toward the SiO_2/Si interface. When a part of hole moves to the vicinity of the non-bridging oxygen defect S_{OH} in SiO_2 layer, they can release the neutral H atom, as shown in the following equation [24]



where p is the generated hole. Assuming that the concentration of S_{OH} in SiO_2 layer is large enough, then the release rate of the neutral H atom is $x\gamma g$, where x is the percentage of holes involved in the reaction (2.8). Due to the lower activation energy, H atom can capture another H atom, forming a H_2 molecule



The reaction rate constant of (2.9) is assumed as k_{HH} . Then, under the steady conditions, H atom concentration C_H satisfies [24]

$$x\gamma g - k_{HH}C_H^2 - r_H C_H = 0 \quad (2.10)$$

where the first term is the release rate of the neutral H atom, the second term is the consumption in (2.9), and the third term is the lost part captured by the other trap. Then, we can obtain

$$C_H = r_H \left(\sqrt{1 + \frac{4x\gamma g k_{HH}}{r_H^2}} - 1 \right) / 2k_{HH} \quad (2.11)$$

Part of neutral H atom can capture hole and releases protons



Assuming that the ratio of H atoms in the reaction (2.12) is α , then the proton concentration C_{H^+} satisfies $C_{\text{H}^+} = \alpha C_{\text{H}}$. Once the protons arrive at SiO_2/Si interface, they will combine the interface dangling bond Si-H and create the interface state [26], as shown in the following equation:



Si-H dangling bond is generally formed in the device passivation process. P_{b}^+ is the interface state. The forward reaction rate constant of (2.13) is assumed as k_{f} , and then, the concentration of P_{b}^+ can be written as [24]

$$\frac{dC_{\text{P}_{\text{b}}^+}}{dt} = k_{\text{f}} C_{\text{Si-H}} C_{\text{H}^+} \quad (2.14)$$

where $C_{\text{P}_{\text{b}}^+}$, $C_{\text{Si-H}}$ and C_{H^+} are separately the concentration of interface state P_{b}^+ , Si-H dangling bond, and proton H^+ . Assuming that the concentration of Si-H dangling bond at SiO_2/Si interface is sufficiently large, then we will arrive at

$$C_{\text{P}_{\text{b}}^+}(t) = \frac{\alpha r_{\text{H}} C_{\text{Si-H}} k_{\text{f}}}{2k_{\text{HH}}} \left(\sqrt{1 + \frac{4x\gamma g k_{\text{HH}}}{r_{\text{H}}^2}} - 1 \right) t \quad (2.15)$$

where $C_{\text{P}_{\text{b}}^+}(t)$ is the concentration of P_{b}^+ at any time t . When the dose rate is high enough ($\frac{4x\gamma g k_{\text{HH}}}{r_{\text{H}}^2} \gg 1$ generally exists), (2.15) can be simplified as

$$C_{\text{P}_{\text{b}}^+}(D) = \alpha k_{\text{f}} C_{\text{Si-H}} D \sqrt{\frac{x\gamma}{g k_{\text{HH}}}} \quad (2.16)$$

where $D = gt$ is the accumulated total dose level, $C_{\text{P}_{\text{b}}^+}(D)$ is the concentration of P_{b}^+ at any dose level D . It can be seen that $C_{\text{P}_{\text{b}}^+}(D)$ increases with the radiation dose rate decreasing, and the lower the dose rate, the higher the $C_{\text{P}_{\text{b}}^+}(D)$ under the same total dose level. When the dose rate decreases to the level that satisfies $\frac{4x\gamma g k_{\text{HH}}}{r_{\text{H}}^2} \ll 1$, then Eq. (2.15) can be reduced to

$$C_{\text{P}_{\text{b}}^+}(D) = \alpha k_{\text{f}} C_{\text{Si-H}} x\gamma D / r_{\text{H}} \quad (2.17)$$

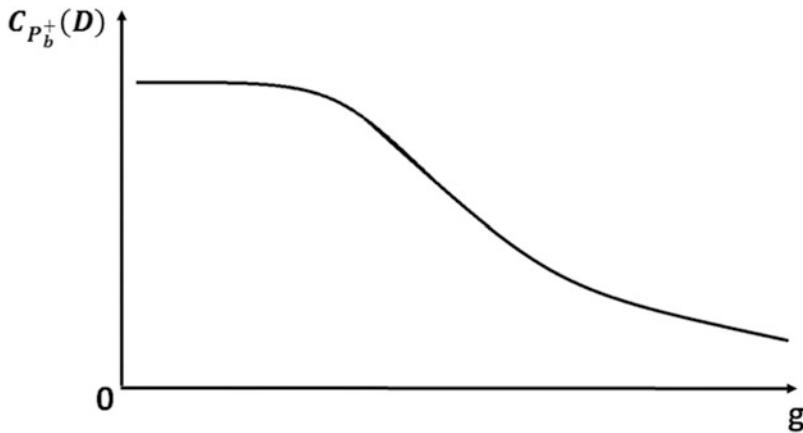


Fig. 2.27 Variation of interface states concentration as a function of dose rate

It can be seen that the concentration of interface state P_b^+ is a constant value and independent of the radiation dose rate. As the dose rate decreases gradually from high level to low level, the interface state concentration increases, and the radiation damages and performance degradation increase. When the dose rate reduces to a certain extent, the concentration of interface states reaches a constant value, as shown in Fig. 2.27 [27]. The above analysis is a good explanation of ELDRS effect in SiGe HBTs.

As for the physical mechanism, during the high-dose-rate irradiation, a large number of H atoms are produced with high generation rate. Most of the H atoms combined with each other to form H_2 molecules in a short time. Only a few H atoms can move to the SiO_2/Si interface creating the interface states. The generated H_2 molecules, with a lower diffusion barrier in SiO_2 film [24], can quickly spread to the SiO_2/Si interface and re-passivate the Si–H dangling bond, decreasing the concentration of interface states. However, in the case of low-dose-rate radiation, it is difficult for H atoms to interact with other H atoms to form H_2 molecules due to the low radiation generation rate. On the contrary, most of the H atoms will capture holes to release H^+ and then create the interface states at the SiO_2/Si interface, leading to serious radiation damage and performance degradation.

As shown in Fig. 2.24, the excess base current ΔI_B under high-dose-rate radiation first decreases and then increases in the subsequent annealing process. It may be due to the different annealing properties of oxide trap charge and interface state. Because of the low activation energy, the oxide trap charge can release the captured hole at room temperature, but the interface state only anneals at above 100 °C due to the high binding energy [15]. Besides, the generation of interface state is related to the total dose and radiation time. Compared to the oxide trap charge, the interface state can only be formed at a certain high total dose level and a relatively long

radiation time. The radiation-induced holes and H^+ transport to the SiO_2/Si interface in the subsequent annealing process and react with the $Si-H$ bond to produce more interface states. This epigenetic effect of interface state and the annealing effect of oxide trap charge together determine the base current annealing characteristics as shown in Fig. 2.23. The decrease in ΔI_B during the initial annealing period may be caused by the annealing of oxide trap charge, and the subsequent formation of more interfacial states results in the increase in ΔI_B .

2.5 Bias Dependence of Ionization Damage in SiGe HBT

In practical applications, SiGe HBTs usually operate at different bias conditions. In current mirror and emitter follower, SiGe HBTs usually work in forward-active mode, and in certain RF circuit, the transistors are biased in saturation mode, while in some BiCMOS logic circuit, SiGe HBTs often operate in the cutoff state. In order to evaluate the total ionizing dose effect of SiGe HBT in practical circuit, it is necessary to study the ionization damage effect in SiGe HBT under different bias conditions. In this section, SiGe HBT1 is irradiated at high-dose rate of 50 rad/s and low-dose rate of 0.1 rad/s, separately. Three different bias conditions are selected: (1) all terminals are floating, (2) saturation mode ($V_{CE} = 0.4$ V, $I_C = 5$ mA), (3) forward-active mode ($V_{CE} = 2$ V, $I_C = 5$ mA), radiation dose rates of 50 and 0.1 rad/s. The effects of bias conditions on the ionization damage of SiGe HBT at high- and low-dose-rate radiation are presented.

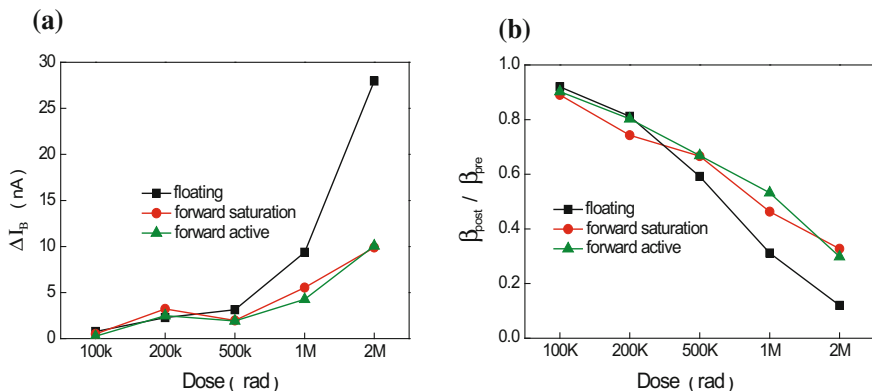


Fig. 2.28 Excess base current **a** and normalized current gain **b** for high-dose-rate irradiation as a function of accumulated doses at V_{BE} of 0.6 V for the three bias conditions

2.5.1 Irradiation Under High-Dose Rate

Figure 2.28 shows the excess base current ΔI_B and normalized current gain β_{nor} as a function of accumulated doses for the three bias conditions at V_{BE} of 0.6 V. The dose rate is 50 rad/s. It can be seen that the degradation is closely related to the bias conditions. For the accumulated doses below 200 krad, ΔI_B and β_{nor} for the three bias conditions are similar. However, with the doses increasing from 500 krad to 2 Mrad, the difference between the three bias conditions begins to appear and increases monotonously as the total doses go up. Compared to the forward-saturation and forward-active configurations, the case with all terminals floating shows a largest degradation in base current and current gain, especially at the dose of 2 Mrad. Therefore, the floating case can be considered as the worse bias condition from the radiation assurance viewpoint during the high-dose-rate irradiation

Normally, the spacer oxide layer around the emitter-base (EB) junction is well known to play an important role in the performance degradation of modern SiGe HBTs under gamma irradiation. In order to better investigate the effect of electrical field on gamma irradiation, a 2D simulation of electrical field was performed using TCAD Sentaurus. The 2D device structure of the SiGe HBT was first constructed using Sentaurus process simulation and then used to the Sentaurus device simulation. The physics models used in the device simulation are doping-dependent SRH recombination, Auger recombination, velocity saturation, phillips unified mobility model, and band gap narrowing, respectively. The fixed charges in the EB spacer oxide layer were set to $1\text{--}15\text{ cm}^{-3}$. The simulated bias conditions are same as these during the irradiation process. Part of simulation structure including the EB spacer oxide layer is shown in Fig. 2.29a, and the electrical field distribution along the cutline A (as shown in Fig. 2.29a) is depicted in Fig. 2.29b. Note that this electrical field directs from the SiO_2 to Si region as shown in Fig. 2.29b. Compared to the forward-active and forward-saturation mode where EB junction is forward

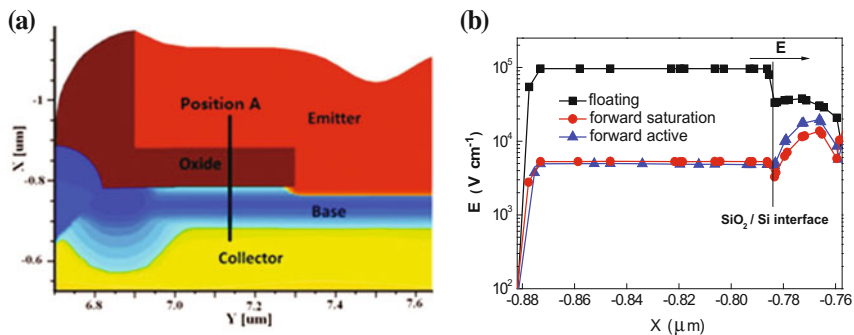


Fig. 2.29 **a** Simulation structure of extrinsic SiGe HBT including EB spacer oxide layer; **b** the electric field distribution near the SiO_2/Si interface for two different bias conditions

biased, for the floating case a larger electrical field exists in the oxide and the silicon underneath the SiO_2/Si interface.

The electrical field distribution can be explained in terms of fringing field approach. The fringing electric field in spacer oxide originates from the built-in potential of EB junction for the floating case, and it decreases under forward-active and forward-saturation mode due to the forward bias of BE junction. The bias voltage of BC junction has little influence on the BE junction, and therefore, the electrical field distribution under forward-active mode is similar to that under forward-saturation mode.

As discussed above, some fraction of the generated electron-hole pairs in SiO_2 film will recombine within a very short time and the remains will transport within the oxide. The concentration of the remaining hole strongly depends on the electric field in the oxide and increases with the electric field increasing. The bias dependence of the ionizing radiation at high-dose rate can be explained by the trapping and transport of the created holes in EB spacer oxide. As the electric field in the oxide increases, hole fractional yield will rise up and more holes and protons become available for acceleration toward the interface in the existing fields, creating more positive oxide-trapped charges and interface states in the EB oxide layer. In other words, the bias condition causing a larger electrical field distribution in the oxide layer might result in enhanced degradation, when more radiation-induced holes and protons are available to transport to SiO_2/Si interface and produce the irradiation damage. Based on the above 2D electric field simulations in Fig. 2.29b, the forward-active and forward-saturation case weakens the electric field in the EB spacer oxide, resulting in a less degradation compared to the floating case.

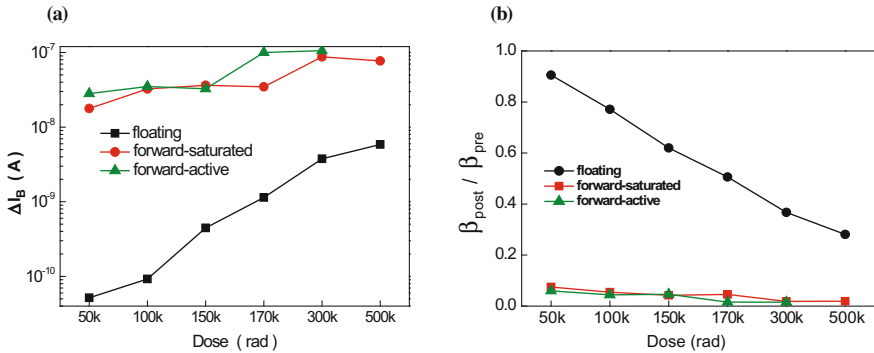


Fig. 2.30 Excess base current **a** and normalized current gain **b** for low-dose-rate irradiation as a function of accumulated dose at V_{BE} of 0.6 V for the three bias conditions

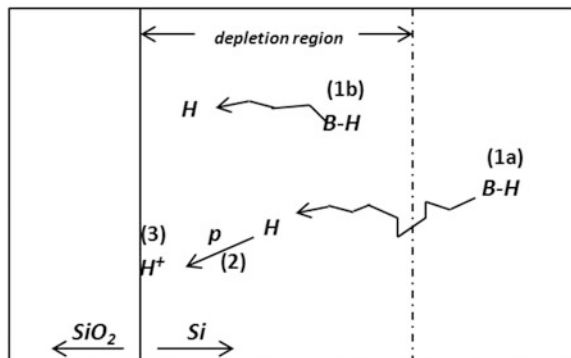
2.5.2 Irradiation Under High-Dose Rate

The bias influences on performance degradation at low-dose-rate irradiation (0.1 rad/s) were also investigated. The excess base currents and normalized current gains at V_{BE} of 0.6 V for low-dose-rate irradiation are shown in Fig. 2.30. There is no significant difference in the performance degradation between the forward-active and forward-saturation mode. Compared to the floating case, however, the forward-active and forward-saturation cases suffer more degradation in base current and current gain at the low-dose-rate irradiation, which contrasts with the degradation at the high-dose-rate irradiation, where larger irradiation damage appears in floating case. Even at the low dose of 50 krad, there exists a large difference in current gain degradation between the both bias conditions, while the difference only begins to appear for the doses larger than 500 krad during the high-dose-rate irradiation. The large degradation gap between the floating and forward-active mode at low-dose-rate irradiation may be due to the enhanced low-dose-rate sensitivity (ELDRS) effect.

Based on the above results, it is indicated that the bias dependence on irradiation damage at low-dose-rate irradiation varies greatly from that at high-dose-rate irradiation. As discussed above, the trapping and transport of the created holes and H^+ in EB spacer oxide layer are responsible for the bias dependence at high-dose-rate irradiation. However, it cannot well explain the bias dependence at low-dose-rate irradiation. These results suggest that other mechanisms in addition to hole and H^+ transport within the SiO_2 can lead to radiation-induced interface-trap formation and the different bias dependence from the high-dose-rate irradiation.

Previous study demonstrated that neutral hydrogen H atoms could be released easily from dopants in bulk Si, especially near SiO_2/Si interfacial area as shown in Fig. 2.31 [20]. The typical hydrogen precursors in Si are identified as hydrogen-dopant complexes. The most stable configuration in the boron-doped silicon corresponds to H resting in the bridge bond between dopant boron (B) atom and a neighboring Si atom [24]. The extrinsic base region is formed through heavy dose implant self-aligned to the emitter-poly for the SiGe HBT under test, and there

Fig. 2.31 Interface states formation origin from the extrinsic base region: (1a)–(1b) release of H from B–H complexes, (2) release of H^+ due to the capture of holes, and (3) formation of interface states [20]



might be many B–H complexes in the extrinsic base region. The binding energy of B–H bond is about 0.61 eV, and the B–H complex can capture a minority carrier (where it is electron) and release H when minority carriers are introduced in the extrinsic base region under the EB spacer oxide



where e denotes an electron. The released H is a highly mobile species in silicon due to very small diffusion barrier of about 0.1–0.2 eV. If H captures another hole, as happening during irradiation, it will release a proton H^+ . The released H^+ moves to the SiO_2/Si interface and react with the interfacial passivated Si–H bond to create the interface states.

For the high-dose-rate irradiation, the duration is relatively short and the electrical field hampers the transport of hole and proton in extrinsic base to the SiO_2/Si interface. Therefore, there is not enough time for the hole and proton in extrinsic base to reach the interface. The bias dependences at high-dose rate are only determined by the transport of hole and H^+ in SiO_2 region. As discussed above, the floating mode with a large electrical field distribution in the SiO_2 region is expected to cause a serious degradation in SiGe HBT. However, the irradiation time is very long during the low-dose-rate irradiation. Most of the hole and proton in extrinsic base can transport to the SiO_2/Si interface and create the interface states. Besides, the concentration of hole and proton in extrinsic base is much larger than that in the SiO_2 region [25]. Therefore, the formation of interface states in low-dose-rate irradiation might be determined by the transport of the hole and H^+ in extrinsic base. As shown in Fig. 2.29b, the electrical field hampers the transport of hole in extrinsic base to the SiO_2/Si interface. The lower the electrical field in extrinsic base, the more the holes and H^+ transporting to SiO_2/Si interface. Compared to the case with all terminals floating, the forward-active configuration may suffer more radiation damage due to the smaller electrical field in extrinsic base, and only the trapping and transport of holes and H^+ in EB spacer oxide are responsible for the bias dependence at high-dose-rate irradiation, which is reasonable due to the short time at high-dose-rate irradiation. However, during the low-dose-rate irradiation, the contribution of holes and proton in extrinsic base should be included, especially when there are abundant B–H complexes in the extrinsic base region, since the hole and proton in the extrinsic base may reach the SiO_2/Si interface during such a long irradiation time, which is not paid attention to in pervious researches. Of course, the underlying detail of physical mechanisms needs to be further justified and explored.

According to MIL-STD-883G, if the ratio K_{dr} exceeds 1.5 for any of the most sensitive parameters, then the part is considered to be ELDRS susceptible, and the larger the K_{dr} , the stronger the ELDRS effect. Figure 2.32 shows the over-enhanced factor K_{dr} for the two bias configurations as a function of gamma dose. As shown in Fig. 2.32, the over-enhanced factor K_{dr} for forward-active mode is significantly larger than that for the floating case, especially at the doses below 170 krad(Si). The transistors under forward-active mode exhibit a significant ELDRS effect; however, no distinct ELDRS effect appears in the transistors with all terminals floating.

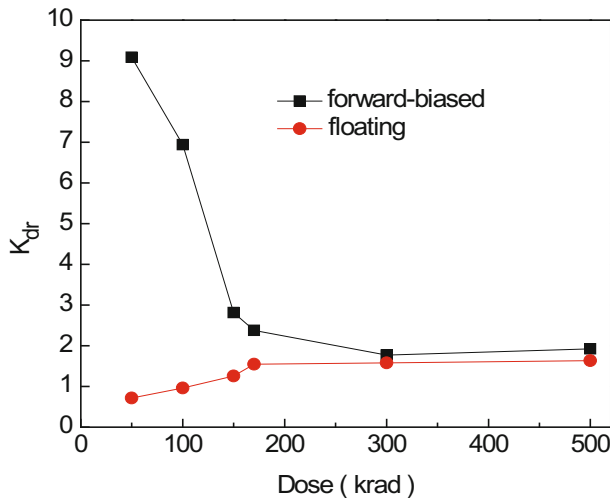


Fig. 2.32 Over-enhanced factor K_{dr} for the two bias conditions

Besides, it is found that the enhanced factor K_{dr} decreases, i.e., the ELDRS effect declines with the accumulated dose increasing for the SiGe HBTs under forward-active mode. For example, the enhanced factor K_{dr} is about 11.23 for an accumulated dose of 50 krad(Si), while it is only about 1.78 when the accumulated dose reaches 500 krad(Si).

As the positive oxide-trapped charges and interface traps build up in the oxide layer, two crucial time parameters exist. One is the characteristic time (τ_g) required to build up the space field in the oxide, and the other is the characteristic time (τ_h) required for holes and H^+ transport across the oxide. Carefully observing the result in Fig. 2.32, we find that the forward-active mode has a more serious ELDRS effect than that of the floating case, which can be explained from the viewpoint of τ_h decreasing in the floating case. Compared to the forward-active mode, SiGe HBTs with terminals floating have a larger fringe field across the BE spacer oxide; furthermore, the larger fringe field could accelerate the holes transport to Si/SiO₂ interface and reduce the characteristic time τ_h . For the high-dose-rate irradiation, a decreased τ_h will reduce the density of holes trapped in oxide bulk and then weaken the space electric field; as a result, the impediment of space electric field to the holes transport declines and more irradiation damages appear at the Si/SiO₂ interface. However, during the low-dose-rate irradiation, due to the small value of τ_h , the further decrease in τ_h has almost no influence on the buildup of space electric field in oxide bulk, and the irradiation damage remains nearly unchanged. Therefore, a larger fringe field will reduce the gap of irradiation damage between high-dose-rate and low-dose-rate irradiation, i.e., alleviating the ELDRS effect. The fringe field in floating SiGe HBTs is relatively larger than that in the forward-active mode; therefore, the transistors with all terminals floating will experience a smaller

ELDRS effect compared to those biased in forward-active mode [28], as shown in Fig. 2.32.

ELDRS effect in the forward-active mode weakens monotonously with the accumulated total dose increasing, and it saturates for total dose larger than 300 krad(Si), which might be attributed to the increased impediment of space field to the transport of hole and H^+ to the interface in the low-dose-rate irradiation. The space field EQ gradually increases with the accumulated total dose increasing during the low-dose-rate irradiation. The increased space field EQ hinders the further transport of holes and H^+ to the interface and slows the accumulation of interface traps. Besides, the increased space field EQ weakens the total electric field within the oxide layer and then decreases the hole fractional yield, which will also slow the accumulation of interface traps near the Si/SiO₂ interface. Therefore, with increasing accumulated dose, the degradation of base current is mitigated in the low-dose-rate irradiation, thereby resulting in a decreased ELDRS effect as shown in Fig. 2.32.

2.6 Conclusion

In this chapter, we mainly study the ionization damage effects in SiGe HBTs and analyze the corresponding physical mechanism. The results show that SiGe HBT naturally has multi-Mrad total ionizing dose (TID) tolerance, due to the special device structure. The performance degradation closely depends on the device structure. For SiGe HBTs with emitter and substrate connected together, an unexpected increase in emitter current appears in the reverse Gummel characteristic. For the transistors with collector elicited from the backside of the substrate through gold evaporation, the reverse Gummel characteristic is almost kept unchanged. Therefore, in order to improve the device's anti-radiation performance, the emitter and substrate should not be shorted.

Then, we study the effects of radiation dose rate on ionization damages from the point of the actual space radiation environment and find ELDRS effect. Besides, the effects of bias conditions are also compared. The floating configuration shows an enhanced degradation in the high-dose-rate irradiation, while the forward-active mode suffered more irradiation damage in the low-dose-rate irradiation. ELDRS effect is also bias dependent, and the transistors under forward-active mode exhibit a more severe ELDRS effect than those with all terminals floating. Therefore, the influence of dose rate and bias condition on ionization damages should be considered when evaluating the transistor anti-radiation capability.

References

1. J.R. Schwank, M.R. Shaneyfelt, P.E. Dodd, Radiation hardness assurance testing of microelectronic devices and integrated circuits: radiation environments, physical mechanisms, and foundations for hardness assurance. *IEEE Trans. Nucl. Sci.* **60**(3), 2074–2100 (2013)
2. L. Najafizadeh, M. Bellini, A.P.G. Prakash, G.A. Espinel, J.D. Cressler, P.W. Marshalland, C. J. Marshall, Proton tolerance of SiGe precision voltage references for extreme temperature range electronics. *IEEE Trans. Nucl. Sci.* **53**(6), 3210–3216 (2006)
3. A.P.G. Prakash, J.D. Cressler, The effect of 63 MeV hydrogen ion irradiation on 65 GHz UHV/CVD SiGe HBT BiCMOS technology. *Radiat. Eff. Defects Solids* **166**(8–9), 703–709 (2011)
4. A.K. Sutton, B.M. Haugerud, L. Yuan, L.K. Wei-Min, J.D. Cressler, P.W. Marshall, R.A. Reed, R. Jae-Sung, G. Freemanand, D. Ahlgren, Proton tolerance of fourth-generation 350 GHz UHV/CVD SiGe HBTs. *IEEE Trans. Nucl. Sci.* **51**(6), 3736–3742 (2004)
5. Q.J. Meng, H.B. Liu, Q.H. Meng, *Physics of Semiconductor Devices*. (Science Press, 2005), p. 108
6. J.M. Roldan, W.E. Ansley, J.D. Cressler, S.D. Clarkand, D. Nguyen-Ngoc, Neutron radiation tolerance of advanced UHV/CVD SiGe HBT BiCMOS technology. *IEEE Trans. Nucl. Sci.* **44** (61), 1965–1973 (1997)
7. Y. Sun, J. Fu, J. Xu, Y. Wang, J. Yang, W. Zhou, The total-dose-effects of gamma and proton irradiations on high-voltage silicon—germanium heterojunction bipolar transistors. *Radiat. Eff. Defects Solids* **168**(4), 253–263 (2013)
8. Z. Wang, Y. Ma, J. Liu, Y. Xue, B. He, Z. Yao, S. Huang, M. Liu, J. Sheng, Degradation and annealing studies on gamma rays irradiated COTS PPD CISs at different dose rates. *Nucl. Instrum. Methods Phys. Res. Sect. A*, **820**, 89–94 (2016)
9. C. Wang, W. Chen, Y. Liu, X. Jin, S. Yangand C. Qi, The effects of gamma irradiation on neutron displacement sensitivity of lateral PNP bipolar transistors. *Nucl. Instrum. Methods Phys. Res. Sect. A*, **831**, 328–333 (2016)
10. A.K. Sutton, B.M. Haugerud, A.P.G. Prakash, B. Jun, J.D. Cressler, C.J. Marshall, P.W. Marshall, R. Ladbury, F. Guarinand, A.J. Joseph, A comparison of gamma and proton radiation effects in 200 GHz SiGe HBTs. *IEEE Trans. Nucl. Sci.* **52**(6), 2358–2365 (2005)
11. A.K. Sutton, A.P. Gnana Prakash, B. Jun, E. Zhao, M. Bellini, J. Pellish, R.M. Diestelhorst et al., An investigation of dose rate and source dependent effects in 200 GHz SiGe HBTs. *IEEE Trans. Nucl. Sci.* **53**(6), 3166–3174 (2006)
12. P. Leroux, W. De Cock, M. Van Uffelen, M. Steyaert, Design, assessment and modeling of an integrated 0.4 μm SiGe Bipolar VCSEL driver under γ -radiation, in *European Conference on Radiation and Its Effects on Components and Systems (RADECS)*. (Jyvaskyla, 2008)
13. P. Leroux, M. Van Uffelen, F. Berghmansand, A. Giraud, Design and assessment of a High Gamma-Dose Tolerant VCSEL Driver With Discrete SiGe HBTs. *IEEE Trans. Nucl. Sci.* **53** (4), 2033–2039 (2006)
14. M. Ullan, S. Diez, F. Campabadal, M. Lozano, G. Pellegrini, D. Knolland, B. Heinemann, Gamma radiation effects on different varieties of SiGe: C HBT technologies. *IEEE Trans. Nucl. Sci.* **54**(4), 989–993 (2007)
15. Y. Sun, J. Fu, J. Xu, Y. Wang, W. Zhou, W. Zhang, J. Cui, G. Li, Z. Liu, Study on ionization damage of silicon-germanium heterojunction bipolar transistors at various dose rates. *Acta Physica Sinica* **62**(19610419), (2013)
16. N. Jiang, N. Cho, Z. Ma, Effects of proton irradiation on SiGe HBTs implemented with isolation guard rings. *Semicond. Sci. Technol.* **25**, 125007 (2010)
17. N. Jiang, Z. Ma, P. Maand, M. Racanelli, Proton radiation tolerance of SiGe power HBTs. *Semicond. Sci. Technol.* **22**(1), S46–S49 (2007)
18. Y. Sun, J. Fu, J. Xu, Y. Wang, J. Yang, The total-dose-effects of gamma and proton irradiations on high-voltage silicon—germanium heterojunction bipolar transistors

19. H.P. Hjalmarson, R.L. Pease, C.E. Hembree, R.M. Van Ginhoven, P.A. Schultz, Dose-rate dependence of radiation induced interface trap density in silicon bipolar transistors. *Nucl. Instrum. Meth. Phys. Res. B*, **250**, 269–273 (2006)
20. M. Ullán, M. Wilder, H. Spieler, E. Spencer, S. Rescia, F.M. Newcomer, F. Martinez-McKinney, W. Kononenko, A.A. Grillo and S. Diez, Enhanced Low Dose Rate Sensitivity (ELDRS) tests on advanced SiGe bipolar transistors for very high total dose applications. *Nucl. Instrum. Meth. Phys. Res. Sect. A*, **724**, 41–46 (2013)
21. G. Banerjee, G. Niu, J.D. Cressler, S.D. Clark, M.J. Palmer and D.C. Ahlgren, Anomalous dose rate effects in gamma irradiated SiGe heterojunction bipolar transistors. *IEEE Trans. Nucl. Sci.* **46**(6), 1620–1626 (1999)
22. Z.E. Fleetwood, A.S. Cardoso, I. Song, E. Wilcox, N.E. Lourenco, S.D. Phillips, R. Arora, P. Paki-Amouzou and J.D. Cressler, Evaluation of enhanced low dose rate sensitivity in fourth-generation SiGe HBTs. *IEEE Trans. Nucl. Sci.* **61**(6), 2915–2922 (2014)
23. MIL-STD-883G, Ionizing radiation (Total Dose) test procedure, Method 1019.7. 2006
24. L. Tsetseris, R.D. Schrimpf, D.M. Fleetwood, R.L. Pease and S.T. Pantelides, Common origin for enhanced low-dose-rate sensitivity and bias temperature instability under negative bias. *IEEE Trans. Nucl. Sci.* **52**(6), 2265–2271 (2005)
25. J.M. Benedetto, H.E. Boesch, The relationship between ^{60}Co and 10-keV X-Ray damage in MOS devices. *IEEE Trans. Nucl. Sci.* **33**(6), 1317–1323 (1986)
26. H.P. Hjalmarson, R.L. Pease, S.C. Witczak, M.R. Shaneyfelt, J.R. Schwank, A.H. Edwards, C.E. Hembree and T.R. Mattsson, Mechanisms for radiation dose-rate sensitivity of bipolar transistors. *IEEE Trans. Nucl. Sci.* **50**(6), 1901–1909 (2003)
27. Y. Sun, J. Fu, J. Xu, Y. Wang, W. Zhou, W. Zhang, J. Cui, G. Li, Z. Liu, Bias dependence of ionizing radiation damage in SiGe HBTs at different dose rates. *Phys. B. Condens. Matter*, **434**, 95–100 (2014)
28. Y. Sun, J. Fu, J. Xu, Y. Wang, W. Zhou, W. Zhang, J. Cui, G. Li, Z. Liu, Investigation of bias dependence on enhanced low dose rate sensitivity in SiGe HBTs for space application. *Nucl. Instr. Meth. Phys. Res. Sect. A*, **738**, 82–86 (2014)

Chapter 3

Displacement Effects in SiGe HBT

The displacement damage induced by neutrons and high-energy heavy ions in space environment is another major source of device and circuit failure, which has become an important issue in the study of radiation effects. In the past few years, as the traditional radiation source, neutrons have been always used to characterize the displacement damage effects in devices and circuit systems [1, 2]. However, the available neutron reactors are getting less and less, and there is a large radiation residue in the neutron-radiated samples. Therefore, there is an urgent need to find other sources instead of neutrons to assess the displacement damages. Similar to the neutron, the swift heavy ions also create a collision cascade in transistor structure, and there is a trend to employ the swift heavy ions to characterize the displacement damage effect. However, there are few data available for heavy ion irradiation on SiGe HBTs up to now.

In this chapter, we mainly study the effect of heavy ion radiation on the DC characteristics of SiGe HBTs, including the performance degradation and the potential physical mechanism. The interaction between heavy ions and materials is briefly introduced in the first section. The second section presents the experimental details, including the device under test, the adopted heavy ions, and electrical parameters to be tested. In the following four sections, the irradiation effects of swift heavy ions on the displacements damages are discussed in detail. In the last section, the conclusion is drawn.

3.1 Interaction Mechanism Between Swift Heavy Ion and Materials

Due to the large mass and charge, the interaction between the high-energy heavy ions and material shows different properties with neutrons or electrons. When the transistors were exposed to the swift heavy ions, the ions deposit high energy

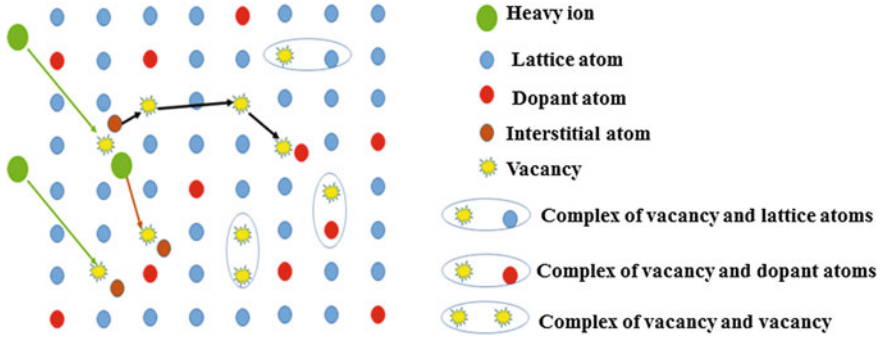


Fig. 3.1 Interaction diagram between high-energy heavy ion and material

through electronic energy loss and nuclear energy loss, which will produce ionization damage and displacement of atoms along their path during irradiation process [3]. The electronic energy loss is generally realized by inelastic interaction of the ions with the target electrons, producing large number of electron–hole pairs and ionization damage along their path. The nuclear energy loss is mainly due to elastic scattering by the target nuclei. When the energy of incident ions is high enough to displace the lattice atoms, then the primary knock-on atoms (PKA) are created. Simultaneously, the PKAs can displace other atoms, creating secondary knock-on atoms, etc., thus a cascade of atomic collision is created in the material. The formation of atomic collision leads to the distribution of vacancies, interstitial atoms, and other types of lattice disorder, as shown in Fig. 3.1.

The displacement damages induced by heavy ion irradiation affect most of the physical parameters of semiconductor materials, such as resistivity [4], carrier mobility, and minority carrier lifetime [5]. The displacement damages can introduce some additional energy levels within the band gap of semiconductor materials. Taking n-type semiconductors as an example, the generated acceptor deep levels will compensate for the free electrons in the donor energy level, thereby reducing the effective concentration of the majority carrier, i.e., the “carrier removal” effect occurs [6]. Besides, the generated point defects can act as carrier scattering centers, enhancing the carrier coulomb scattering and reducing the carrier mobility. The heavy ions can also create many kinds of defects and their complexes that are effective recombination and trapping centers in the transistors structure, leading to a decrease in the minority carrier lifetime.

3.2 Experiment

The devices under test are the two kinds of SiGe HBT fabricated in Institute of Microelectronics, Tsinghua University, as discussed in Sect. 2.2. The swift heavy ion irradiation is carried out in EN tandem electrostatic accelerator, and the tested

Table 3.1 Energy loss and range of four ions in the transistor structure

Ion	LET in MeV · cm ² /mg		NIEL in MeV · cm ² /mg		Range in μm	
	Si	SiO ₂	Si	SiO ₂	Si	SiO ₂
25 MeV Si	14.10	15.66	0.0274	0.0282	9.51	8.80
10 MeV Cl	14.4	16.5	0.101	0.105	4.49	4.44
20 MeV Br	20.9	23.7	0.423	0.433	6.49	6.41
10 MeV Br	15.2	15.8	0.713	0.733	4.21	4.31

samples are separately exposed to 25 MeV Si, 10 MeV Cl, 10 MeV Br, and 20 MeV Br at room temperature. The ion beam was scanned over the devices with an area of 10 cm × 2 cm by a magnetic scanner to obtain a uniform fluence on the transistors. The absorbed dose equivalent for each ion is set as 300, 600 krad, 1, 3, 6, and 10 Mrad, separately. The formula for converting the ion fluence Φ to absorbed dose (in rad) for different ions is stated as follows [3]:

$$D_i(\text{rad}) = \Phi(\text{cm}^{-2}) \times K \times \text{LET}(\text{MeV} \cdot \text{cm}^2/\text{mg}) \quad (3.1)$$

$$D_d(\text{rad}) = \Phi(\text{cm}^{-2}) \times K \times \text{NIEL}(\text{MeV} \cdot \text{cm}^2/\text{mg}) \quad (3.2)$$

where D_i and D_d are the ionizing dose and the displacement dose, respectively. The equivalent total absorbed dose is the sum of D_i and D_d . The conversion factor K is about 1.6018×10^{-5} with a unit of rad · mg/MeV [7]. LET and NIEL are separately the ionizing and non-ionizing energy loss in the device structure, which can be simulated by SRIM program and are shown in Table 3.1. The calculated absorbed dose at specified ion fluence is depicted in Table 3.2. The samples were measured at room temperature before and after irradiation with the Keithley 4200 semiconductor parameter analyzer. The post-irradiated samples were characterized after irradiation immediately at a specified fluence, and the every measurement time between two adjacent exposures is about 1 h.

Table 3.2 Fluence of four kind of swift heavy ions

Absorbed dose	Fluence (cm ⁻²)			
	25 MeV Si	10 MeV Cl	20 MeV Br	10 MeV Br
300 krad	9.1e8	1.3e9	9.1e8	1.23e9
600 krad	1.8e9	2.6e9	1.8e9	2.47e9
1 Mrad	3e9	4.34e9	3e9	4.11e9
3 Mrad	1.34e10	1.3e10	9e9	1.23e10
6 Mrad	2.68e10	2.6e10	1.8e10	2.47e10

3.3 Irradiation Effects of 25 MeV Silicon Ions

3.3.1 *Sige HBT1 with Emitter and Substrate Connecting Together*

The forward-Gummel characteristics and common-emitter current gain β before and after the 25 MeV Si ion irradiation is shown Fig. 3.2. As the 25 MeV Si ion fluence increases, base current I_B increases monotonically with the accumulated ion fluence, while collector current I_C remains unchanged during the whole irradiation process. Thereby a remarkable drop in β can be found with the fluence increasing, but the current gain is even above 60 after $4.46 \times 10^{10} \text{ cm}^{-2}$ (absorbed dose is 10 Mrad) Si ion irradiation, as shown in Fig. 3.2.

The self-annealing effects on I_B and β were also investigated after $4.46 \times 10^{10} \text{ cm}^{-2}$ Si ion irradiation at room temperature, and it is shown in Fig. 3.3 for $V_{BE} = 0.6 \text{ V}$. Considering the measurement data error, it is indicated

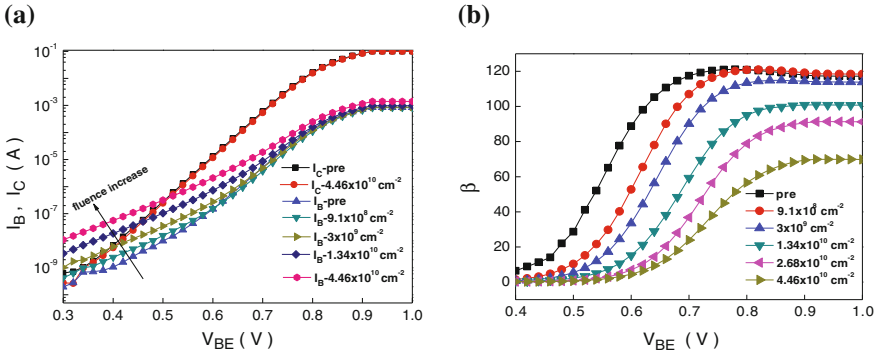
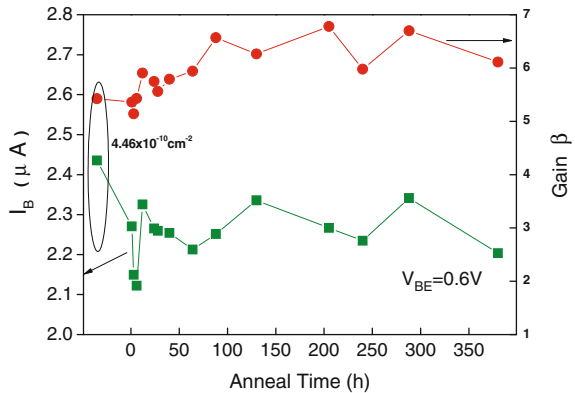


Fig. 3.2 Variation of **a** forward Gummel and **b** current gain β of SiGe HBT1 before and after 25 MeV Si ion irradiation

Fig. 3.3 Variation of base current I_B and current gain β with annealing time at room temperature



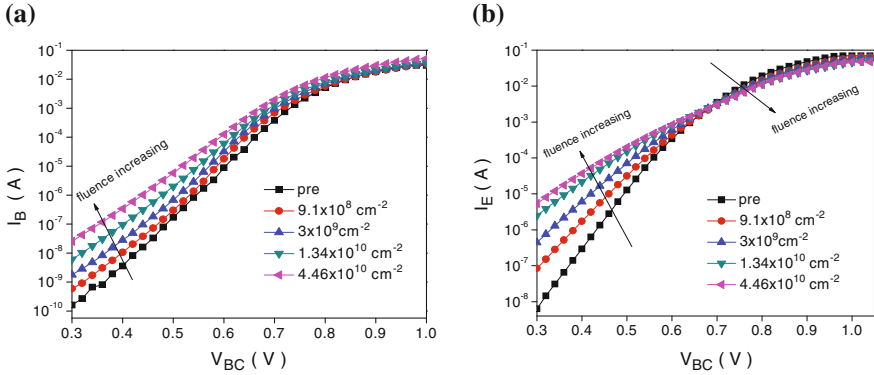


Fig. 3.4 Reverse-Gummel plots for SiGe HBT irradiated by 25 MeV Si^{4+} ion

that I_B and β hardly vary during the 388 h annealing process at room temperature. Therefore, the self-annealing at room temperature has less influence on the SiGe HBTs irradiated by 25 MeV Si ion.

The reverse-Gummel plots of the SiGe HBT are depicted in Fig. 3.4. Similar to the forward-Gummel characteristics, the base current I_B increases with the ion fluence increasing, and it may be a result of ionization damage at the BC junction around the LOCOS field oxide and/or bulk displacement damage in collector region. Unlike the previous studies, an unexpected degradation appears in emitter current I_E . In the low bias region ($V_{BC} < 0.6$ V), I_E increases, but in the high bias region, I_E decreases with the ion fluence increasing, as shown in Fig. 3.4b. The increased I_E at low V_{BC} region has been reported in the case of ^{60}Co irradiation and the parasitic collector-substrate (CS) diode contributes. The decreased I_E at high V_{BC} region is a result of increased collector resistance R_C . The increased R_C reduces the effective internal bias voltage across BC junction, resulting in a decrease in I_E at high bias voltage [7].

The impacts of 25 MeV Si^{4+} ion irradiation on the leakage current of BC and BE junctions are shown in Fig. 3.5, respectively. The reverse leakage currents for both the junctions increase with the ion fluence increasing. The extracted base resistance R_B , emitter resistance R_E , and collector resistance R_C before and after irradiation are shown in Fig. 3.6. The increased R_C confirms the degradation of I_E under the high V_{BC} region in the reverse-Gummel characteristics, as shown in Fig. 3.4.

The output characteristic of the SiGe HBT1 at a fixed $I_B = 0.25$ mA is shown in Fig. 3.7. It is found that the collector current I_C declines with the ion fluence increasing. For example, I_C drops about from 30 to 14 mA after 4.46×10^{10} ions/cm² ion irradiation. The decrease in I_C is mainly due to the current gain degradation. Besides, the increased collector resistance, as shown in Fig. 3.6, also contributes to the decreased collector current with the ion fluence increasing.

Figure 3.8 depicts the normalized base current as a function of V_{CB} at $V_{BE} = 0.6$ V for the irradiated SiGe HBT. The negative slope at low V_{CB}

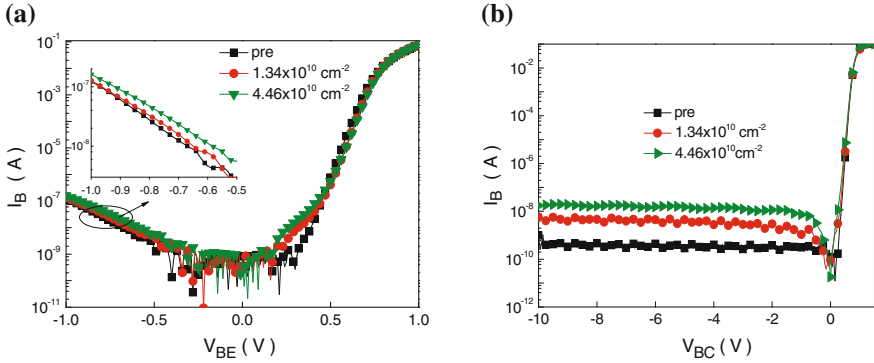
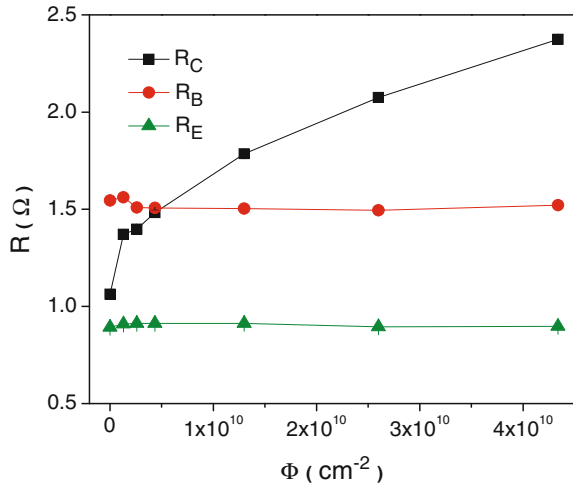


Fig. 3.5 Variation of **a** BE junction leakage current and **b** BC junction leakage current after 25 MeV Si ion irradiation

Fig. 3.6 Extracted parasitic resistance before and after 25 MeV Si ion irradiation



($V_{CB} < 3 \text{ V}$) is indicative of neutral base recombination (NBR) in the transistors. It can be seen that the NBR component descends at first and then increases with the ion fluence increasing, as shown in Fig. 3.8. The increased NBR is a result of the increased carrier recombination in the neutral base region due to the displacement damage. The rapid decrease in I_B at large V_{CB} ($V_{CB} > 3 \text{ V}$) is due to the impact of ionization. As shown in Fig. 3.8, the slope at high V_{CB} region declines monotonically with the accumulated ion fluence, which demonstrates that the impact ionization weakens after heavy ion irradiation. This lattice disorder induced by the 25 MeV Si^{4+} ion in the BC depletion region prevents the collision between the electron and lattice atom and thereby reduces the impact ionization [7, 8].

The breakdown characteristics of BC junction is also investigated, and Fig. 3.9 shows the reverse leakage current I_{CBO} as a function of V_{CB} . Due to the

Fig. 3.7 Output characteristic of SiGe HBT at $I_B = 0.25$ mA before and after 25 MeV Si^{4+} ion irradiation

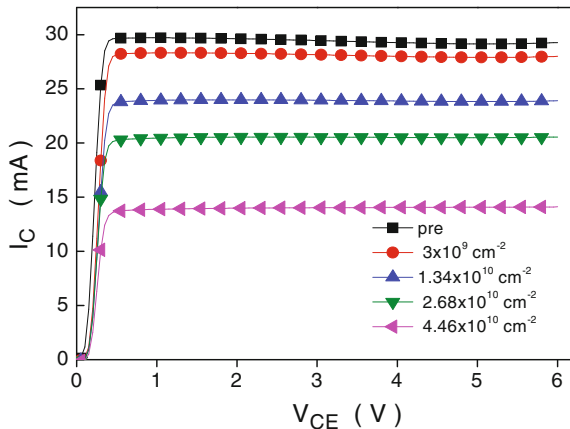
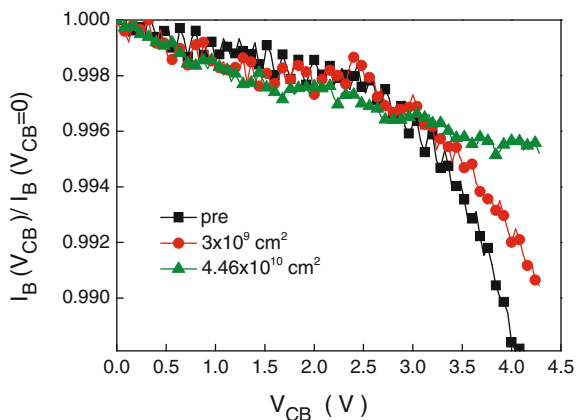


Fig. 3.8 Neutral base recombination for 25 MeV Si^{4+} ion irradiated SiGe HBT at $V_{BE} = 0.6$ V



irradiation-induced generation current in the BC depletion region, I_{CBO} increases before the breakdown occurs. The applied voltage is assumed as the breakdown voltage when I_{CBO} increases to $100 \mu\text{A}$. Figure 3.9 also demonstrates that the breakdown voltage (BV_{CBO}) increases from 28.1 to 29.6 V after $4.46 \times 10^{10} \text{ cm}^{-2}$ Si ion irradiation, providing additional evidence for the decrease impact ionization as shown in Fig. 3.8 [7, 8].

3.3.2 Performance Degradation of SiGe HBT2

Figure 3.10 shows the forward-Gummel characteristics and common-emitter current gain β of SiGe HBT2 before and after 25 MeV Si ion irradiation. Similar to SiGe HBT1, with ion fluence increasing, I_B monotonically increases but I_C remains

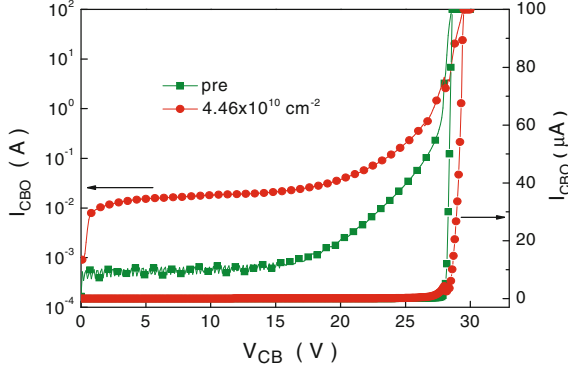


Fig. 3.9 Variation of the reverse-biased BC junction current I_{CBO} after 25 MeV Si^{4+} ion irradiation

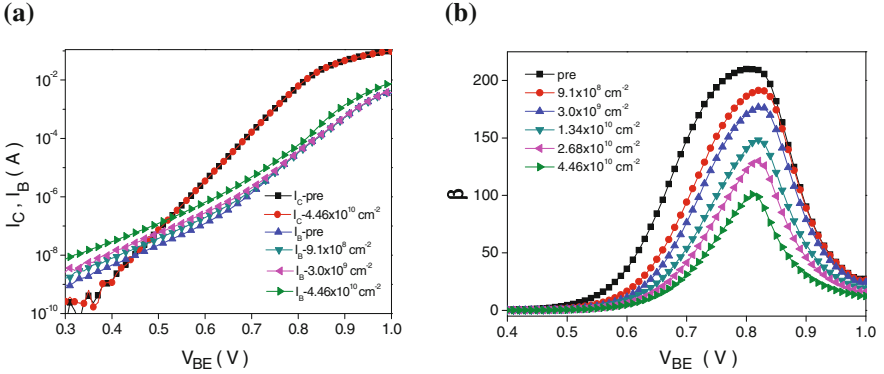


Fig. 3.10 Variation of **a** forward Gummel and **b** current gain in SiGe HBT2 after 25 MeV Si irradiation

constant, which directly leads to a large degradation in current gain β , as shown in Fig. 3.10b. Besides the ionization damage in the spacer oxide near EB junction, the displacement damages also contribute to above base current degradation. The deep-level defects are introduced and act as carrier recombination centers, accelerating the recombination of electrons and holes in neutral base region.

Figure 3.11 shows the change of I_B and β in subsequent room temperature annealing process after the $4.46 \times 10^{10} \text{ cm}^{-2}$ Si ion irradiation, where V_{BE} is fixed at 0.6 V. It can be found that both show a small recovery after 360 h room temperature annealing. The base current is slightly reduced, from 0.48 to 0.42 μA . Correspondingly, the current gain β gradually increases from 5.0 to 9.7. It is indicated that the annealing effects of radiation damages introduced by the heavy ion radiation are relatively weak at room temperature.

Fig. 3.11 Variation of base current I_B and current gain β with room temperature annealing time

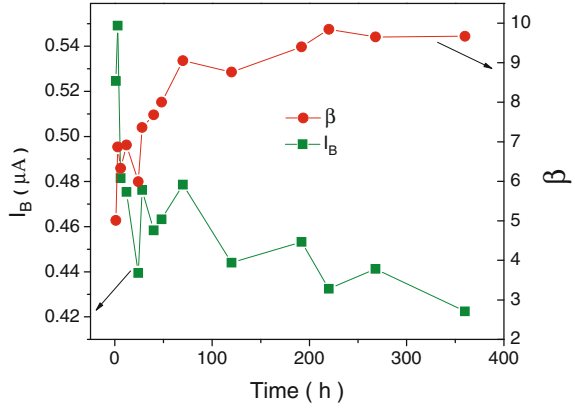


Figure 3.12 shows the variation of the emitter current I_E and the base current I_B in the reverse-Gummel characteristics of SiGe HBT2 before and after ion irradiation. It was found that I_B increases with the radiation fluence increasing over the whole bias range. As mentioned above, the degradation of I_B mainly comes from the surface recombination caused by ionization damages, the neutral base recombination induced by the displacement damages, and the increased hole injected current from base region to collector region. Unlike the case in SiGe HBT1, I_E in SiGe HBT2 decreases only in the high V_{BC} range, which is the result of increased collector resistance.

The reverse leakage current of BE junction and BC junction, shown in Fig. 3.13, increase with ion fluence increasing. Figure 3.14 shows the variation of the parasitic resistance before and after radiation. Similar to the case in SiGe HBT1, considering the measurement and extraction errors, the base resistance R_B and the emitter resistance R_E are almost unaffected by radiation, while the collector resistance R_C increases with ion fluence increasing. Compared to the base and emitter region, the doping concentration in collector region is relatively lower (about 2–3 orders of magnitude), and a serious carrier removal effect exists, resulting in the decreased collector resistance.

The output characteristics of SiGe HBT2 at fixed base current of 20 μA before and after 25 MeV Si irradiation are shown in Fig. 3.15. Similar to the case of SiGe HBT1, due to the degradation of current gain, collector current I_C decreases monotonically as the ion fluence increases. The curve slope of I_C verse V_{CE} under high bias voltage does not significantly change, and there is no significant base-width modulation effect (Early effect) after irradiation.

Figure 3.16 shows the normalized base current $I_B(V_{CB})/I_B(V_{CB} = 0 V)$ as a function of V_{CB} in 25 MeV Si ion irradiated SiGe HBT2, where V_{BE} is fixed at

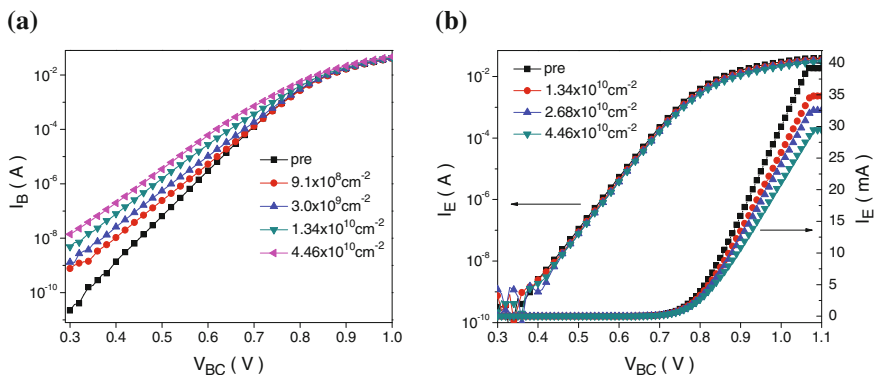


Fig. 3.12 Variation of **a** I_B and **b** I_E in reverse-Gummel characteristics of SiGe HBT2

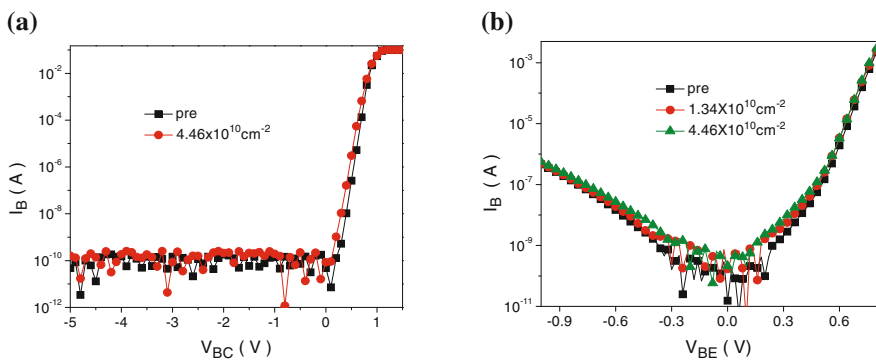


Fig. 3.13 Variation of leakage current for 25 MeV Si irradiated SiGe HBT2 **a** BC junction, **b** BE junction

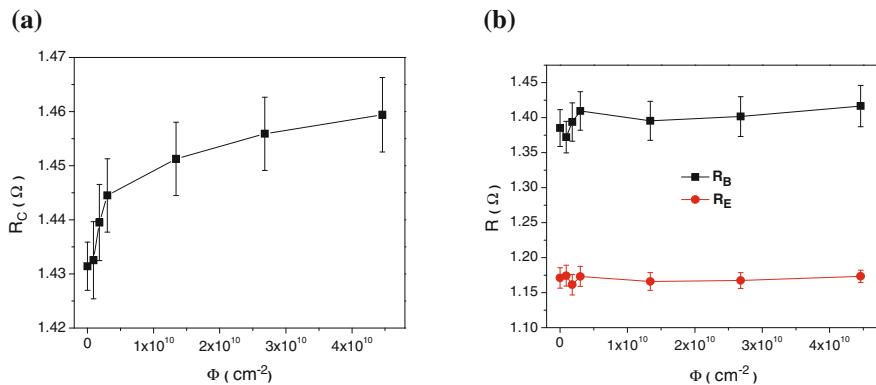


Fig. 3.14 Variation of parasitic resistance for 25 MeV Si irradiated SiGe HBT2 **a** R_C ; **b** R_E and R_B

Fig. 3.15 Output characteristics of 25 MeV Si irradiated SiGe HBT2 at fixed $I_B = 20 \mu\text{A}$

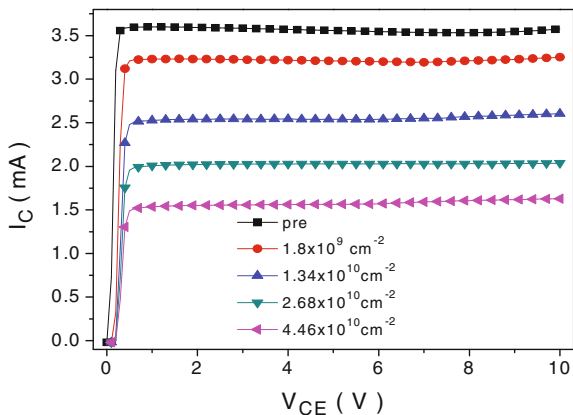
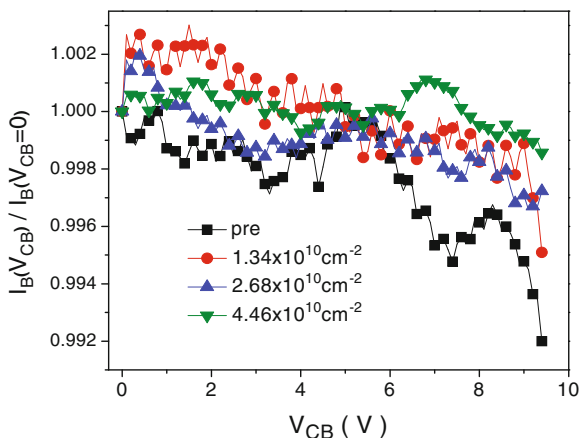


Fig. 3.16 Normalized base current in SiGe HBT2 before and after heavy ion irradiation



0.6 V. It can be seen that the slope of the curve under low V_{CB} does not change obviously after radiation. In other words, 25 MeV Si ion radiation does not introduce significant neutral recombination in the transistor.

3.3.3 Physical Mechanism Analysis for Heavy Ion Radiation

The above two sections show that heavy ion radiation (here 25 MeV Si ion as an example) can degrade the base current, common-emitter current gain, parasitic resistance, junction leakage current, and output characteristics of bipolar transistor. Due to the inherent characteristics, the interaction between the high-energy heavy ions and materials exhibits many different properties, compared to gamma ray and

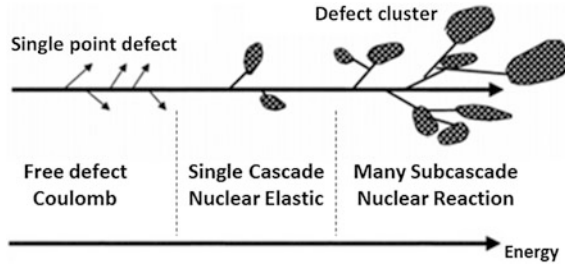


Fig. 3.17 Interaction between heavy ions and materials

neutron [3, 9–14]. As described in Chap. 2, when Gamma ray with low energy is incident into the material, the ionization damages (including the interface states and oxide trap charges) are created through the Compton scattering, and the energy loss is only ionization energy loss. When the neutron is incident on the materials, it collides with the nucleus of the material. The lattice atoms get sufficient energy and deviate from their original position, resulting in the displacement damages. The energy loss is only nuclear energy loss. When the high-energy charged heavy ion is incident on the material; it can create the ionization damage through ionization energy loss and displacement damage through nuclear energy loss along the ion path. As shown in Fig. 3.17 [15], the interaction between heavy ions and materials can be divided into three categories according to the energy of incident ions. (1) When the incident energy is low, similar to gamma ray, the interaction is mainly Coulombic. The generated electron–hole pairs in the oxide layer are separated by the applied electric field, and the oxide trap charges and the interface states are finally formed in the oxide layer and SiO_2/Si interface. (2) When the energy is further increased, in addition to the above ionization damage, the heavy ions can transfer part of energy to the adjacent lattice atoms and deviate them from the original position. Due to the lower energy, the displaced atom cannot continue to collide other atoms and then stop at a certain location of the material, creating a single displacement damage, such as Frank defects and so on. (3) When the incident ion energy is high enough, the displaced atom obtain sufficient energy to continue to collide with other lattice atoms. Thus, the collision will continue until the energy of the displaced atom is less than the threshold, and ultimately a large number cascade of displacement damages exist.

Due to the smaller elastic scattering cross section, the nuclear energy loss is usually much smaller (about three orders of magnitude) than the ionization energy loss when charged heavy ions are incident on the material. In the first part of ion incidence path, the ionization energy loss dominates the energy loss, while the nuclear energy loss dominates as the ion incidence path increases. For bipolar transistors, the performance degradation under heavy ion radiation is the result of ionization damage and displacement damage. The ionization damages (oxide trap

charges and interface states) alter the surface potential of Si/SiO₂ interface and then increase the surface recombination rate, leading to an increased base current, BE and BC junction leakage. The displacement damages can introduce some deep energy levels within the transistor, resulting in a reduced effective doping concentration, carrier mobility, and minority carrier lifetime [14, 16–18].

The deep energy levels can trap the majority of carriers and cause a “carrier removal effect,” which closely depends on doping concentration. The lower the doping concentration, the more obvious the carrier removal effect and the greater the increased parasitic resistance [5]. Compared to the emitter and base region, the doping concentration in collector region is relatively lower (about 2–3 orders of magnitude); therefore, the collector resistance significantly increases while the emitter resistance and base resistance are hardly effected by heavy ion radiation.

The minority carrier lifetime degradation has an important role on bipolar transistors. We focus on the degradation of base current and current gain after heavy ion radiation. For bipolar transistors, the reciprocal of the common-emitter current gain at low bias is written as [19]:

$$\frac{1}{\beta} = \frac{N_a x_B D_{pE}}{N_{dE} L_{pE} D_{nB}} + \frac{x_B^2}{2 D_{nB} \tau_{nB}} + \frac{s A_s x_B}{D_{nB} A_E} e^{\left(\frac{1}{\eta}-1\right) \frac{V_{BE}}{V_T}} \quad (3.3)$$

where the first term is related to the emitter injection efficiency, the second term is related to the neutral base recombination, and the third term is related to the surface recombination. x_B is the base width. L_{pE} is the hole diffusion length in emitter region. D_{nB} and D_{pE} are separately the diffusion coefficients of electrons and holes. A_E is the emitter area. A_s is the effective surface recombination area. s is the surface recombination velocity. τ_{nB} is the electron lifetime in base region. The role of each term is different under different radiation environment. Generally, the first term dominates the current gain before irradiation, and it is hardly effected by radiation. The second and third terms are separately related to displacement damages and ionization damages, and are greatly effected by the radiation effects. As a result, the variation of the current gain reciprocal before and after irradiation can be expressed as

$$\Delta\left(\frac{1}{\beta}\right) = \Delta\left(\frac{1}{\beta}\right)_i + \Delta\left(\frac{1}{\beta}\right)_d \quad (3.4)$$

where the subscripts ‘i’ and ‘d’ represent the contribution of ionization damages and displacement damages, respectively. From the research about ionization damage effects in the second chapter, if the current gain degradation is dominated by ionization damage, i.e., $\Delta(1/\beta) = \Delta(1/\beta)_i$, $\Delta(1/\beta)$ will sub-linearly increase until a saturation value is reached at high dose level, due to the inhibition between the oxide trap charges and interface states, as shown in Figs. 2.6 and 2.14.

The defects introduced by the heavy ion radiation can act as the carrier recombination center and reduce the carrier lifetime. The degradation of the carrier lifetime satisfies the following relationship [2, 5]

$$\frac{1}{\tau_{\text{post}}} - \frac{1}{\tau_{\text{pre}}} = K_{\tau} \Phi \quad (3.5)$$

where τ_{pre} and τ_{post} are separately the carrier lifetime before and after radiation. Φ is the incident ion fluence. K_{τ} is the carrier lifetime damage constant and strongly depends on the lifetime test conditions, such as temperature, Fermi energy level, and injection level. If the displacement damages dominate the current gain degradation, the first term and the third term in formula (3.3) are negligible. Submitting formula (3.5) into formula (3.3), the variation of current gain reciprocal is simplified as

$$\Delta \frac{1}{\beta} = \left(\Delta \frac{1}{\beta} \right)_D = \frac{x_B^2}{2D_{nB}} K_{\tau} \Phi \quad (3.6)$$

Unlike the case of ionization damages, $\Delta(1/\beta)$ increases linearly with ion fluence increasing when the displacement damages dominate the performance degradation.

Note that the Eq. (3.3) only applies to the low injection level. As for the high injection level, there still exists a linear relationship similar to Eq. (3.6) and is expressed as [19]

$$\frac{1}{\beta} = \frac{N_a x_B D_{pE}}{N_{dE} x_E D_{nB}} \left(1 + \frac{I_E x_B}{2q D_{nB} A N_a} \right) + \frac{x_B^2}{4D_{nB} \tau_{nB}} \quad (3.7)$$

Compared to the second term in (3.7), the first item is less effected by radiation and the corresponding current gain reciprocal is reduced to

$$\Delta \frac{1}{\beta} = \left(\Delta \frac{1}{\beta} \right)_D = \frac{x_B^2}{4D_{nB}} K_{\tau} \Phi \quad (3.8)$$

Similar to the case of low bias condition, $\Delta(1/\beta)$ varies linearly with the ion fluence increasing at high injection level. Therefore, as long as the current gain degradation of bipolar transistor is dominated by the displacement damages, a strict linear relationship between $\Delta(1/\beta)$ and Φ will always exist over the whole bias voltage.

Figure 3.18 separately shows the variation of $\Delta(1/\beta)$ for the two investigated SiGe HBTs before and after 25 MeV Si ion radiation at $V_{BE} = 0.6$ V. $\Delta(1/\beta)$ increases sub-linearly at low ion fluence, indicating that the current gain degradation is dominated by ionization damages. With the ion fluence increasing, the sub-linearity gradually changes linearity and the current gain degradation is dominated by the displacement damages [20].

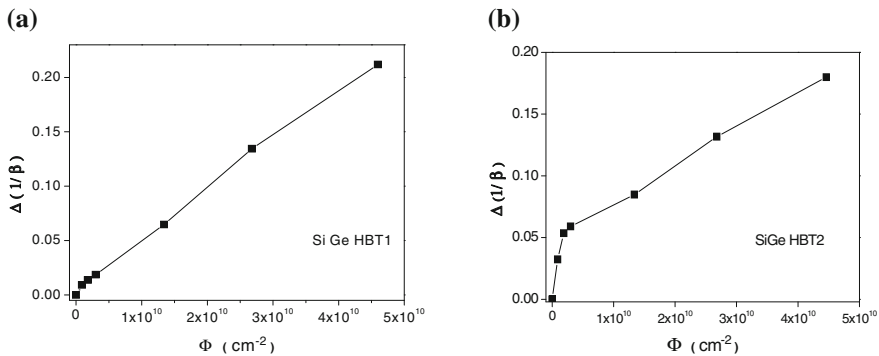


Fig. 3.18 Variation of $\Delta(1/\beta)$ after 25 MeV Si ion irradiation at $V_{BE} = 0.6$ V. **a** SiGe HBT1, **b** SiGe HBT2

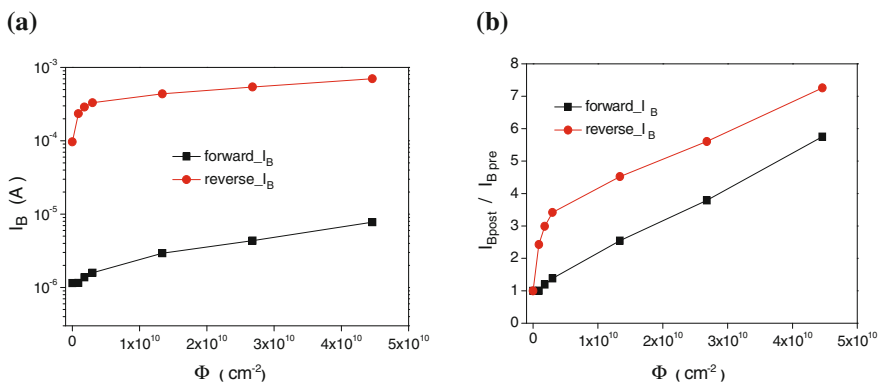


Fig. 3.19 Comparison of **a** base current I_B and **b** normalized base current $I_{B,post}/I_{B,pre}$ in forward- and inverse-mode for SiGe HBT1 at $V_{BE}/V_{BC} = 0.6$ V during 25 MeV Si ion irradiation

Based on above analysis, two factors contribute to gain degradation for SiGe HBTs under heavy ion irradiation: the ionization damage near the oxide layer of BE junction and BC junction, and the displacement damages in the body region. Figures 3.19 and 3.20 show the comparison of forward/reverse I_B and the ratio of $I_{B,post}/I_{B,pre}$ extracted at $V_{BE} = 0.6$ V or $V_{BC} = 0.6$ V for the two SiGe HBTs exposed to 25 MeV Si ion irradiation. Similar to the case of gamma rays irradiation, at the same dose level, I_B in reverse-Gummel mode is larger than that in forward-Gummel mode. However, the normalized $I_{B,post}/I_{B,pre}$ in reverse-Gummel mode is higher than that in forward-Gummel mode, i.e., the reversed I_B is more sensitive to heavy ion irradiation, which is contrary to the case of gamma ray

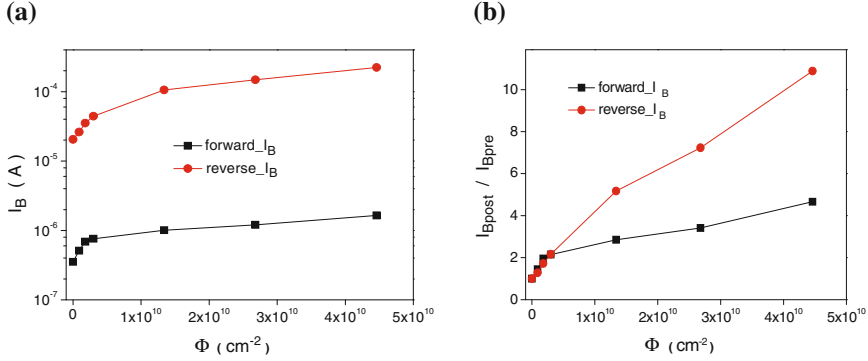


Fig. 3.20 Comparison of **a** base current I_B and **b** normalized base current $I_{B\text{post}}/I_{B\text{pre}}$ in forward- and inverse-mode for SiGe HBT2 at $V_{BE}/V_{BC} = 0.6$ V during 25 MeV Si ion irradiation

irradiation. There must exist another different degradation mechanism. During the heavy ion irradiation, the base current degradation mainly originates from the displacement damages. In the forward-Gummel measurement, the neutral base recombination in bulk base region contributes to the increased I_B . As for the case of reverse-Gummel measurement, besides to the neutral base recombination, hole current injected from base to collector region also contributes to I_B degradation. Due to the impurity removal effect, the effective collector doping concentration will dramatically decrease after heavy ion irradiation; hence, more hole will be injected into collector region and increases the base current. As a result, the normalized $I_{B, \text{post}}/I_{B, \text{pre}}$ in reverse Gummel is larger than that in forward Gummel after 25 MeV Si ion irradiation.

The variation of base current and current gain in Figs. 3.3 and 3.11 shows that there is no significant annealing effect at room temperature after heavy ion radiation. Due to the high binding energy, the interface states and displacement damages generally anneal only above 100 °C [15]. Figure 3.21 shows the variation of base current and current gain of SiGe HBT2 after 25 MeV Si ion radiation at ion fluence of $4.46 \times 10^{10} \text{ cm}^{-2}$ during the high-temperature annealing process. The annealing temperature increases from 50 to 300 °C, and the annealing time for each temperature is 1 h. It can be seen that when the annealing temperature is higher than 100 °C, the radiation damages gradually begin to anneal, and the higher the temperature, the more obvious the annealing. When the annealing temperature rises to 300 °C, the base current gradually decreases from 0.594 to 0.128 μA . It indicates that heavy ion radiation damages exist a significant annealing effect at high temperature (>100 °C).

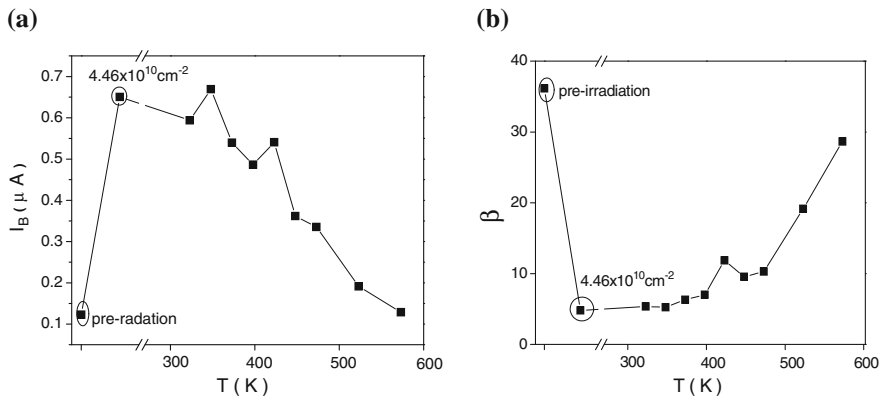


Fig. 3.21 Variation of **a** base current and **b** current gain for SiGe HBT2 during the high-temperature annealing process

3.4 Degradation Difference for Forward and Reverse Current Gain

As mentioned above, the degradations in base current and current gain after swift heavy ion irradiation are the results of ionization damage and displacement damage. To investigate the interaction of ionization damage and displacement damage during irradiation, the degradation in forward current gain and reverse current gain is compared. The device under test here is SiGe HBT2.

3.4.1 Experimental Result

The forward current gain β_F is defined as I_C/I_B , where I_C and I_B are separately the base current and collector current in forward-Gummel measurement. Due to the existence of ionization damage around EB junction and displacement damage in bulk region, β_F will decrease when exposed to heavy ion irradiation. Figure 3.22 shows the variation of $\Delta(1/\beta_F)$ under different V_{BE} as a function ion fluence Φ after 25 MeV Si irradiation. It is indicated that $\Delta(1/\beta_F)$ highly depends on bias voltage V_{BE} , and three categories exist:

- (i) In the low V_{BE} region (such as $V_{BE} = 0.4 \text{ V}$), as shown in Fig. 3.22a, $\Delta(1/\beta_F)$ varies sub-linearly with the ion fluence and tends to saturate at high fluence, which is a typical result of ionization damage.
- (ii) In the medium V_{BE} region (e.g., $V_{BE} = 0.6\text{--}0.8 \text{ V}$), $\Delta(1/\beta_F)$ varies nonlinearly at low fluence and then linearly at high ion fluence, as shown in Fig. 3.22b, c.

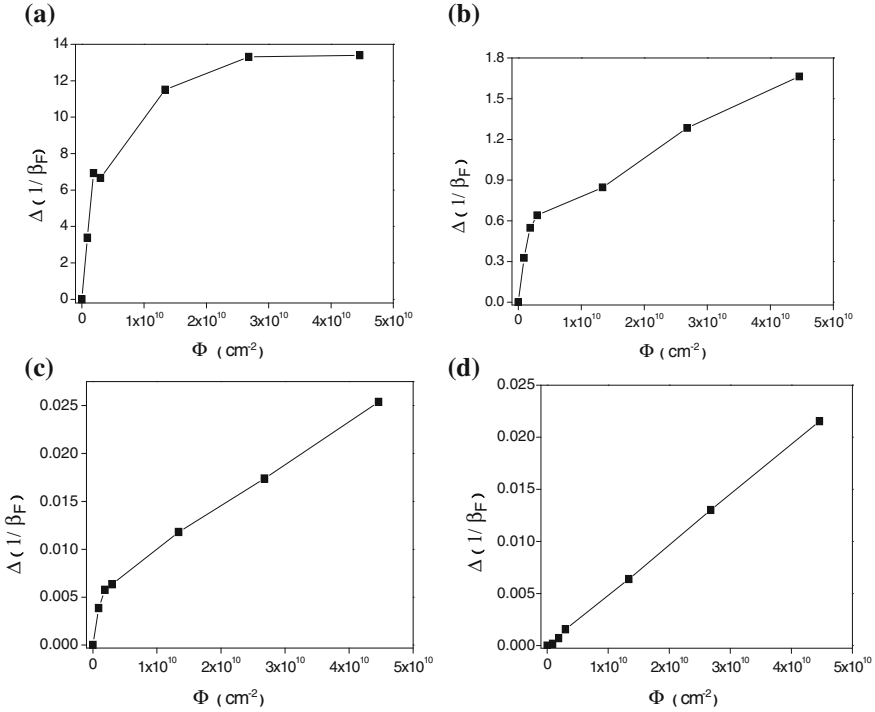


Fig. 3.22 Variation in $\Delta(1/\beta_F)$ as a function of ion fluence for different V_{BE} : **a** $V_{BE} = 0.4$ V; **b** $V_{BE} = 0.5$ V; **c** $V_{BE} = 0.7$ V; **d** $V_{BE} = 0.9$ V

- (iii) In the high V_{BE} region (e.g. $V_{BE} = 0.9$ V), as depicted in Fig. 3.22d, $\Delta(1/\beta_F)$ varies linearly throughout all the influence. It is a typical result of displacement damage.

When the displacement damage dominates current gain degradation, a crucial parameter, displacement damage factor K_F , is introduced and defined as the linear regression slope of $\Delta(1/\beta_F)$ versus influence Φ . The calculated K_F under different bias voltage V_{BE} is depicted in Fig. 3.23. It is indicated that K_F highly depends on V_{BE} . A significant decrease in damage factor K_F is observed with V_{BE} increasing until some critical value. Once V_{BE} is larger than the critical value, 0.8 V in this case, the damage factor K_F begins to rebound with V_{BE} increasing, as shown in Fig. 3.23a. Besides, the reverse extension of the linear region of the curves in Fig. 3.23a generally does not pass through the ordinate origin unless V_{BE} is large enough ($V_{BE} = 0.9$ V in the present study), which is not similar to the case of neutron irradiation where the curve always passes through the ordinate origin for arbitrary V_{BE} . The intercept for heavy ion irradiation, defined as S_L , can quantitatively characterize the contribution of ionization damages to current gain. As shown in Fig. 3.23b, S_L is found to decrease with V_{BE} increasing, which proves that

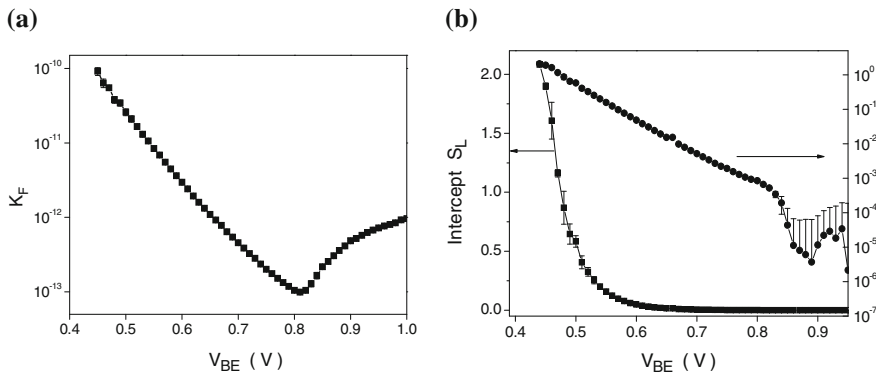
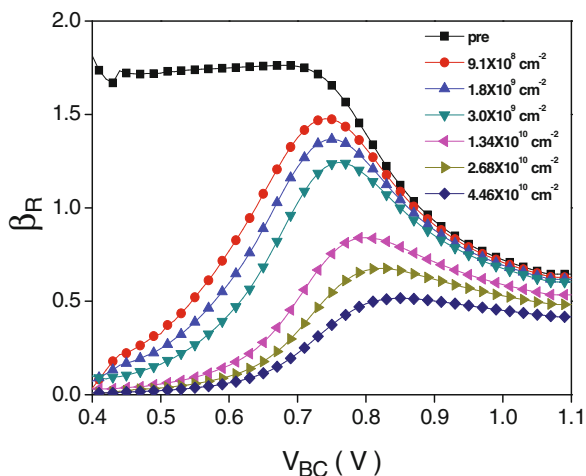


Fig. 3.23 Variations of **a** displacement damage K_F , **b** intercept K_L a function of V_{BE} for 25 MeV Si ion irradiated SiGe HBTs

Fig. 3.24 Reverse current gain β_R for 25 MeV Si^{4+} ion irradiated SiGe HBT



ionization damages have less influence on current gain degradation at high V_{BE} region.

The reverse current gain is defined as $\beta_R = I_E/I_B$, where I_E and I_B are separately emitter current and base current in reverse-Gummel measurement. Because of the ionization damage near BC junction and displacement damage in bulk region, β_R also declines as the ion fluence goes up, as shown in Fig. 3.24.

Figure 3.25 shows the variation of $\Delta(1/\beta_R)$ after heavy ion irradiation as a function of ion fluence Φ under different V_{BC} . In contrast to $\Delta(1/\beta_F)$ shown in Fig. 3.22, $\Delta(1/\beta_R)$ approximately varies linearly throughout all the ion influence for arbitrary V_{BC} from 0.4 to 0.9 V. The damage factor (K_R) for reverse current gain, determined by the linear regression slope of $\Delta(1/\beta_R)$ versus ion fluence, is shown in Fig. 3.26. It is proved that the degradation in β_R is dominated by

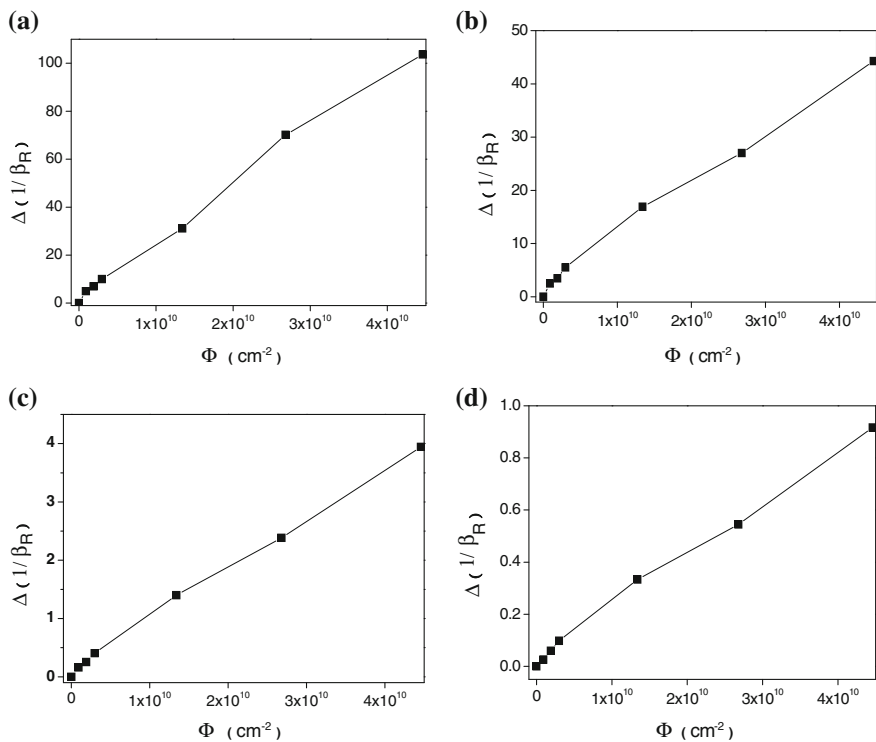
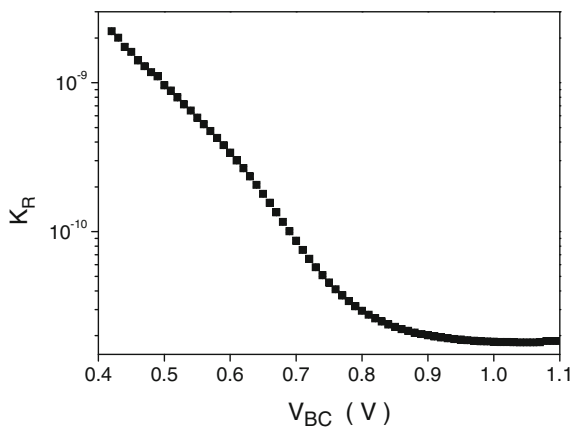


Fig. 3.25 Change in $\Delta(1/\beta_F)$ as a function of ion fluence for different V_{BC} : **a** $V_{BC} = 0.4$ V, **b** $V_{BC} = 0.6$ V, **c** $V_{BC} = 0.8$ V, **d** $V_{BC} = 0.9$ V

Fig. 3.26 Variations in displacement damage K_R as a function V_{BC}



displacement damage in bulk region over the whole ion influence. Besides, it is observed that K_R decreases with the base-collector voltage (V_{BC}) increasing until it reaches saturation, and there is no similar rebound phenomenon with V_{BC} increasing.

3.4.2 Mechanism Analysis and Discussion

Based on the above analysis, the degradation in forward gain β_F is apparently different from that in reverse gain β_R . The degradation of reverse gain β_R at arbitrarily given V_{BC} is dominated by displacement damage in bulk region, while it is relatively complicated for the case of forward gain β_F . In low V_{BE} region, the ionization damage near BE junction determines the β_F degradation. As V_{BE} increases, the influence of ionization damage gradually decreases while the contribution of displacement damages increases. When V_{BE} is high enough, the degradation in β_F is now mainly determined by displacement damages, and the influence of ionization damage is ignored [20].

The different degradation mechanisms between forward and reverse current gain are due to the special device structure under test. During 25 MeV Si ion irradiation, ionization damages (G/R trapping centers) are generated at the SiO_2/Si interfaces near the BC and BE junction (depicted in red in Fig. 3.27). Besides, various types of deep defects and their complexes (i.e., displacement damage) appear in the bulk region. The base current in the forward mode flows in parallel with BE junction, while the base current in the reverse mode flows across the BC junction and down

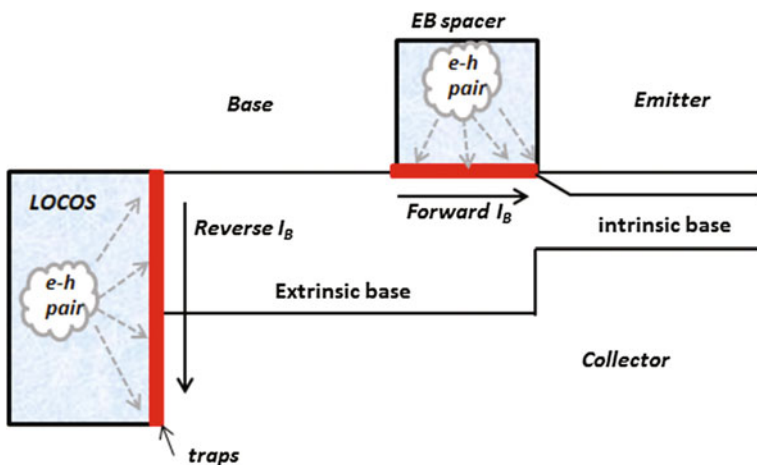


Fig. 3.27 Paths of forward- and reverse base current in SiGe HBT. The forward I_B flows along the base surface and in parallel with BE junction, whereas the reverse I_B flows across BC junction down to the backward collector contact

to the backside collector contact through the collector region, as shown in Fig. 3.27. Namely, the base current flow in the forward mode is confined to the thickness of base region, while the base current in the reverse mode is distributed over the width of base region. Due to the thinner base region, in the forward mode, there is much more chance for carrier recombination at the spacer oxide/Si interface near BE junction. In other words, the interface traps have certain contribution to forward base current degradation, especially in the low fluence region. On the contrary, since the base width is generally much larger than the base thickness, a much smaller fraction of base current will pass through the isolation oxide/Si interface in the reverse mode. As a result, no detectable interface recombination current is found to contribute to I_B degradation in the reverse mode, which is, in fact, mainly dominated by the bulk damages in the transistors. Therefore, we expect the reciprocal of reverse current gain to be dominated by displacement damage and show linear behavior throughout the whole fluence region, while the reciprocal of forward current gain is nonlinear at low fluence and then become linear at high fluence when the ionization effect saturates [20].

The bias dependence of forward gain degradation (shown in Fig. 3.22) can be interpreted in the following way. It is known that the lower the bias voltage V_{BE} , the larger proportion of base surface recombination current in the total I_B . When the V_{BE} is very low (e.g., 0.4 V), the surface recombination accounts for a large percentage in the whole base current. As a result, the ionization damages around BE junction dominate IB degradation and the reciprocal of forward gain shows a nonlinear behavior. Conversely, the proportion of surface recombination current is very low when V_{BE} is relatively high (e.g., 0.9 V); hence, the gain degradation is mainly controlled by the displacement damage in the bulk region and the reciprocal of forward gain varies linearly throughout the whole fluence region. However, for the medium V_{BE} region, the ionization damages and displacement damages contribute to the forward gain degradation simultaneously. At low fluence, the ionization damages dominate the change in the reciprocal of current gain, leading to a nonlinear behavior at low fluence. However, at high fluence, the displacement damages make the main contribution to current gain degradation, resulting in the linear response that obeys the Messenger–Spratt equation [99].

The deep-level transient spectroscopy (DLTS) studies have revealed that swift heavy ions can create different type defects in the forbidden band gap of semiconductor materials and in turn reduce the carrier lifetime. The lifetime damage coefficient K_τ is given as [5]

$$K_\tau = \frac{\partial(1/\tau)}{\partial\Phi} \approx \frac{1/\tau(\Phi) - 1/\tau(0)}{\Phi} \quad (3.9)$$

where $\tau(0)$ and $\tau(\Phi)$ are the minority carrier lifetime before and after irradiation, respectively. K_τ is related to the test conditions and is greatly influenced by temperature, Fermi level E_F , and injection level. When displacement damages dominate the current gain degradation, damage factor K for current gain is proportional to carrier lifetime damage coefficient K_τ , as shown in Eqs. (3.6) and (3.8). Therefore,

the varied trends of K_F 与 K_R come from the diversity of carrier lifetime damage factor K_τ under different injection levels.

According to the energy level distribution, some of the irradiation-induced defects are deep-level defects, and the others are shallow-level defects near the conduction band E_C or valence band E_V . Generally, under low injection condition, only the deep-level defects act as effective recombination center and accelerate the carrier recombination, while the shallow-level defects have less influence on carrier recombination [19]. Assuming that the deep-level defects are independent, the effective carrier recombination lifetime is given by

$$\frac{1}{\tau_{\text{eff}}} = \sum_{i=1}^m \frac{1}{\tau_i} \quad (3.10)$$

where m is the number of trap level. Each item in the right side of Eq. (3.10) corresponds to the carrier lifetime contributed by i non-interacting deep-level traps ($i = 1, 2, \dots, n$). According to the Shockley-Read-Hall (SRH) recombination theory, the carrier lifetime for a single deep recombination center is given by [19]

$$\tau_{\text{ss}} = \tau_{0n} \frac{p_0 + p_1 + \delta_n}{p_0 + n_0 + \delta_n} + \tau_{0p} \frac{n_0 + n_1 + \delta_n}{n_0 + p_0 + \delta_n} \quad (3.11)$$

where $n_1 = n_i \exp\left(\frac{E_i - E_i}{kT}\right)$, $p_1 = n_i \exp\left(\frac{E_i - E_i}{kT}\right)$. n_0 , p_0 , δ_n , τ_{0n} , and τ_{0p} are the equilibrium electron concentration, equilibrium hole concentration, excess carrier concentration, equilibrium electron lifetime, and equilibrium hole lifetime, respectively.

The variations in damage factor K_F as a function of bias voltage V_{BE} , as shown in Fig. 3.23, are discussed. As shown in Fig. 3.28, taking a deep-level acceptor defect E_1 and a shallow-level acceptor defect E_2 in p-type base for example, n_1 and p_1 are much smaller than p_0 because the trap level is above the Fermi level E_F . According to the Eq. (3.11), with the injection level (i.e., V_{BE} or δ_n) increasing, the carrier life τ_{ss} will increase gradually until the asymptotic value of $\tau_{0n} + \tau_{0p}$ is reached. But in fact, with V_{BE} increasing, the high injection effect might occur, namely the injected electron concentration (from emitter to base) may approach or even larger than the hole concentration in base region. As a result, hole quasi-Fermi level moves toward the valence band gradually and might even lower some shallow acceptor defect levels. These shallow acceptor defects are then equipped with the desired charge state and become an effective recombination center. The higher the V_{BE} , the lower the hole quasi-Fermi level, the more shallow-level defects will act the effect recombination center and contribute the degradation of minority carrier lifetime [19]. Now the carrier lifetime is not solely determined by the deep-level defects as described in Eq. (3.11), but also determined by the shallow level defects. Due to the combined effects of deep-level and shallow-level defects, the effective carrier lifetime will decrease with the injection level increasing when the high injection effect occurs, as shown in Fig. 3.29. The variation of lifetime damage

Fig. 3.28 Variation of Fermi energy level E_{fp} as a function of injection level, where E_1 and E_2 are separately the radiation-induced deep energy level and shallow energy level

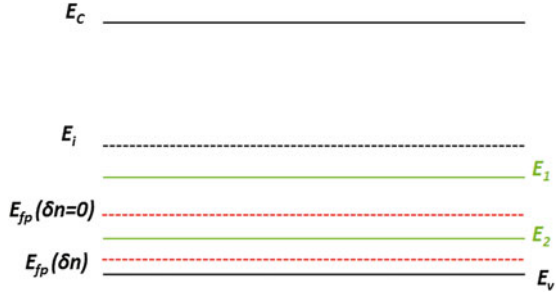
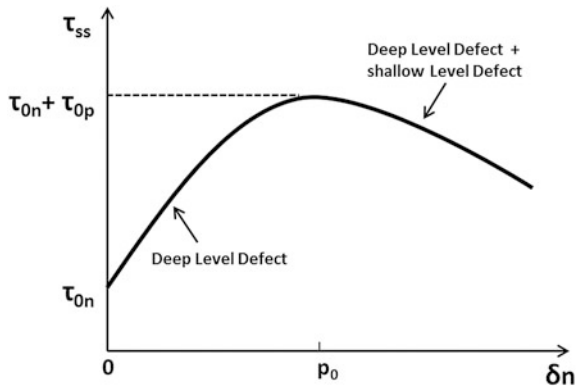


Fig. 3.29 Schematic diagram for the variation of carrier effective recombination lifetime as a function of injection level in the forward-active mode



coefficient K_t with bias voltage V_{BE} is precisely the opposite of that for minority carrier lifetime τ . Therefore, damage factor K_F first decreases and then increases with injection level (V_{BE} or δ_n) increasing, as expected in Fig. 3.23.

3.5 Comparison of Different Heavy Ion Radiation

3.5.1 Experimental Samples and Methods

The performance degradation varies greatly when SiGe HBTs are exposed to different irradiation environments. The degradation under different heavy ions, including different ion species, energy and fluence, is discussed in this section. The device under test is SiGe HBT1, and the adopted heavy ions are separately 25 MeV Si, 10 MeV Cl, 20 MeV Br, and 10 MeV Br. The range, fluence, and LET for every heavy ion are depicted in Tables 3.1 and 3.2. The irradiation was carried out at room temperature, and the terminals of transistors are all floating. The samples were measured with an Agilent B1500 semiconductor parameter analyzer at room temperature before and after irradiation. For each fluence level, the electric measurements are completed with 1 h, and then the transistor was re-irradiated until the next fluence level arrives.

3.5.2 Experimental Results Analysis and Discussion

Figure 3.30 depicts the forward-Gummel plots of SiGe HBT1 before and after heavy ion irradiations. It is indicated that the degradations vary greatly under different heavy ion irradiation. The base current all increases monotonically throughout the entire V_{BE} range. As reported above, it is simultaneously the result of ionization damages and displacement damages in the transistors. However, two distinct trends exist in I_C after four kinds of heavy ion irradiations. For 25 MeV Si and 10 MeV Cl ion irradiation, I_C is held nearly constant over the whole irradiation process. For 20 MeV Br and 10 MeV Br ion irradiation, an unexpected degradation in I_C appear with the fluence increasing, that is an increase at the low V_{BE} region and but a decrease at the high V_{BE} region, as shown in Fig. 3.30c, d.

The parasitic CS junction contributes to the observed non-ideal I_C at the low V_{BE} region. Compared to 25 MeV Si and 10 MeV Cl ion, Br ion with larger NIEL can create much more displacement damages around the CS junction. During the forward-Gummel test, the CS diode is reverse biased. It is the generation current in the space charge region of the reversed CS junction that leads to I_C increasing at the low V_{BE} region. Two possible factors contribute to I_C degradation at the high V_{BE}

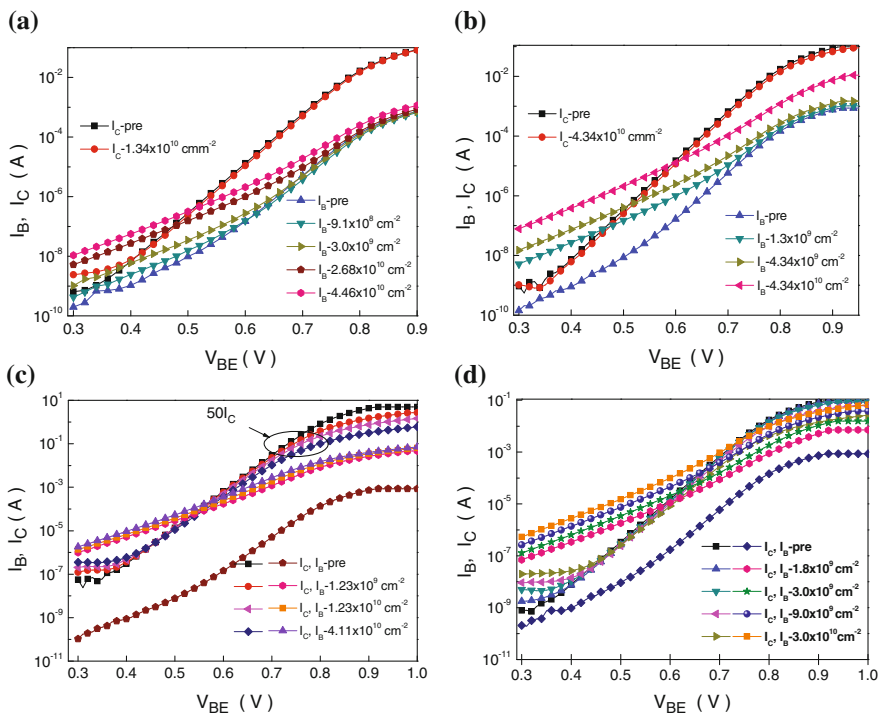


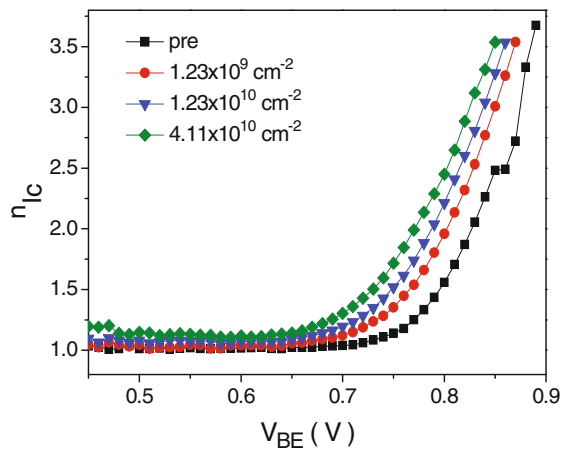
Fig. 3.30 Variation of forward Gummel of SiGe HBT1 before and after four kinds of heavy ion irradiation: **a** 25 MeV Si; **b** 10 MeV Cl; **c** 10 MeV Br; **d** 20 MeV Br

region. One is the increased emitter series resistance R_E , and the other is the high injection effect. When the transistor is exposed to 10 MeV Br ion irradiation, R_E increases from 0.77 to 1.25 Ω , which directly cause a decrease of inter V_{BE} and thus a drop of I_C . As for the bipolar transistor, many high injection effects, such as Kirk effect, strongly depends on the doping concentration in collector region. The high injection effect occurs in advance in the transistor with a lower concentration collector region. Because of the carrier removing effect, the effective collector doping concentration decreases after heavy ion irradiation. As a result, the high injection effects occur in advance and I_C decreases. The appearance of high injection effects can be verified from the variation of ideal factor n_{IC} . The high injection effects slow the rate of I_C increasing. Once the high injection effect occurs, the ideal factor n_{IC} will increase. As shown in Fig. 3.31, When V_{BE} is lower than 0.65 V, n_{IC} is above 1 before irradiation, indicating that there are no obvious high injection effects. However, n_{IC} suddenly increases at a certain critical V_{BE} , and this critical value decreases monotonically with ion fluence increasing. It indicates that the high injection effects occur in advance due to the decreased collector doping concentration, resulting a decreased I_C at high V_{BE} region.

In order to quantitatively compare the performance degradation in SiGe HBTs irradiated by different heavy ions, Fig. 3.32 compares the base current I_B and common-emitter current gain β at fixed V_{BE} of 0.6 V as a function of ion fluence. A significant degradations in I_B and β are found with ion fluence increasing, and 25 MeV Si ion induces the smallest degradation, while 10 MeV Br ion creates the largest degradation at arbitrary ion fluence.

After four kinds of heavy ion irradiation, the variation of current gain reciprocal $\Delta(1/\beta)$ at fixed V_{BE} of 0.6 V is shown in Fig. 3.33. Four curves all show a nonlinear behavior at low fluence, while change linearly over a high fluence region, following the Messenger–Spratt equation [99]. The damage factor for 25-MeV Si

Fig. 3.31 Variation of collector current ideal factor n_{IC} under different 10 MeV Br ion fluence



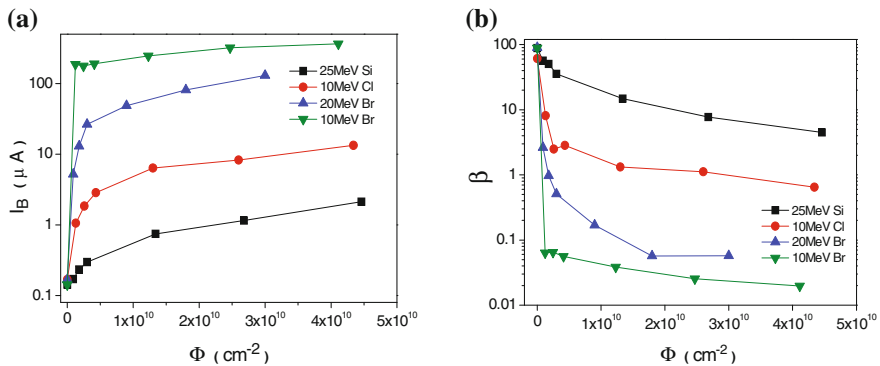
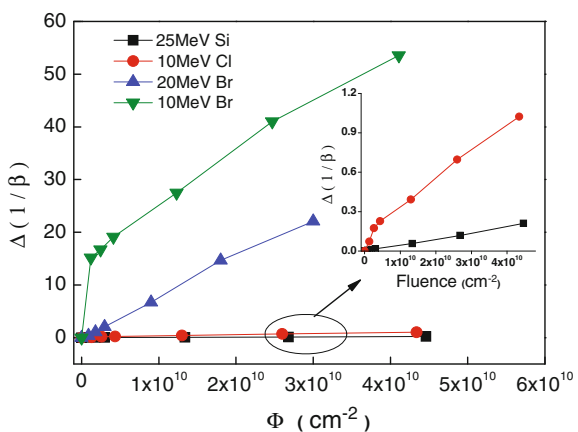


Fig. 3.32 Comparison of **a** base current I_B , **b** current gain β at fixed $V_{BE} = 0.6$ V for four kinds of heavy ion irradiations

Fig. 3.33 Variation of $\Delta(1/\beta)$ with ion fluence after four kinds of heavy ion irradiation at a fixed V_{BE} of 0.6 V. The inserted plot shows the zoom-in variation for 25-MeV Si and 10-MeV Cl ion irradiation



ion is the smallest one, while that for 10-MeV Br ion is the largest one (Fig. 3.34). The heavy ions with larger NIEL impart more energy to the target material and create much more displacement damages in the semiconductor material. The larger the ion nuclear energy loss is, the more the displacement damages created in the transistors are, and then the more serious the performance degradation in SiGe HBTs is. Compared to the 10-MeV Cl and 25-MeV Si ions, the 20-MeV Br and 10-MeV Br ions have a larger nuclear energy loss that then can create much more displacement damages in the transistor structure, leading to a serious performance degradation of SiGe HBTs. The larger displacement damages may make the occurrence of high injection effects earlier and then decrease the collector current at the high V_{BE} region.

Fig. 3.34 Extracted displacement damage factors K for different heavy ions

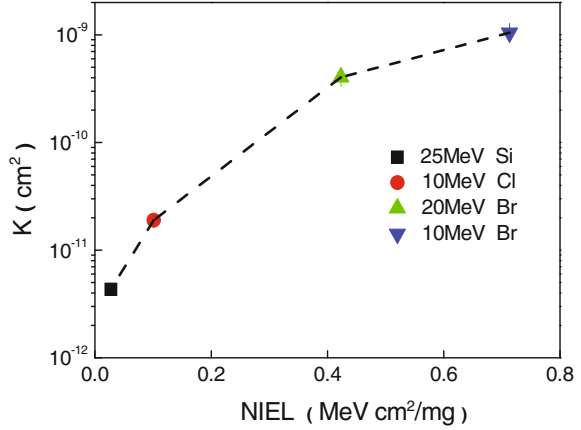


Figure 3.8 depicts the normalized base current as a function of V_{CB} at fixed $V_{BE} = 0.65$ V after four kinds of heavy ion irradiations. The negative slope at low V_{CB} ($V_{CB} < 3$ V) means the existence of NBR, and a larger slope represents a serious NBR in the transistors. For the transistors irradiated by 25-MeV Si and 10-MeV Cl ions, the NBR increases monotonously with ion fluence increasing, as shown in Fig. 3.35a, b. However, for 20-MeV Br and 10-MeV Br ions irradiated SiGe HBTs, the NBR increases at first and then descends with further ion fluence increasing. For example, for the ion fluence lower than $1.8 \times 10^{10} \text{ cm}^{-2}$, the NBR in SiGe HBTs irradiated by the 20-MeV Br ion increases with ion fluence increasing. When ion fluence increases to $3 \times 10^{10} \text{ cm}^{-2}$, the NBR appears to slow down compared to that at a fluence of $1.8 \times 10^{10} \text{ cm}^{-2}$, as shown in Fig. 3.35c. Displacement damages involve some deep-level defects in the neutral base region, which can act as the effective recombination center. As a result, the minority carrier lifetime decreases and then NBR will increase, as certified by the monotonously increased slope of $I_B(V_{CB})/I_B(V_{CB} = 0 \text{ V})$ versus V_{CB} at the low V_{CB} region in Fig. 3.35a, b. Similar to the case of 25-MeV Si and 10-MeV Cl ion irradiation, when the Br ion fluence is low, NBR also increases with the ion fluence increasing due to the decrease of the carrier lifetime. For the NBR decrease at high fluence in SiGe HBTs irradiated by 20-MeV and 10-MeV Br ions, a plausible hypothesis might be given below. Supposing that more than enough displacement damages are created in the transistors after a higher fluence Br ion irradiation, there may exist some damages near the emitter/base interface, which could decrease the electron injection efficiency from the emitter to the base region. Thus, the magnitude of excess minority carrier density drops with further ion fluence increasing at fixed V_{BE} , leading to a decreasing NBR component for higher fluence Br ion irradiation. Therefore, the decline in NBR for high fluence Br ion irradiated SiGe HBTs may be explained in this way. Of course, the potential physical mechanisms need to be further justified and explored.

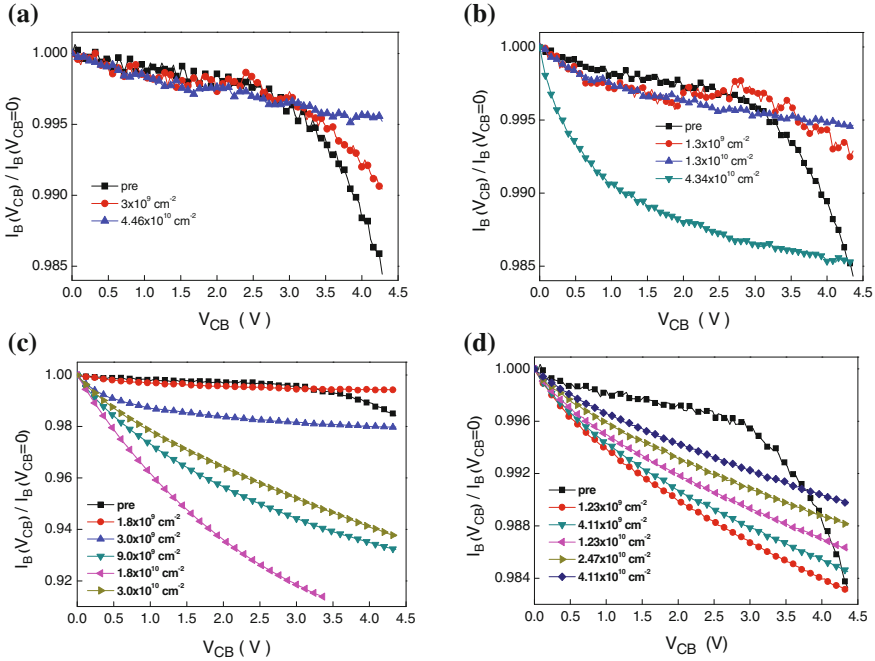


Fig. 3.35 Normalized I_B as a function of V_{CB} in SiGe HBT at fixed V_{BE} of 0.65 V after **a** 25-MeV Si, **b** 10-MeV Cl, **c** 20-MeV Br, and **d** 10-MeV Br ion irradiation

For the fresh device, the rapid decline in normalized I_B at the large V_{CB} region ($V_{CB} > 3$ V) is a result of the impact ionization in the transistor. After heavy ion irradiation, the slopes at this region decrease compared to those of the fresh devices, as shown in Fig. 3.35, which means that the impact ionization weakens. The decline in impact ionization might be due to the lattice disorder in the BC depletion region created by heavy ion irradiation. The existence of lattice disorder may prevent the collision between the electron and lattice atom and thereby weaken the impact ionization.

The output characteristics at fixed V_{BE} of 0.6 V after four kinds of heavy ion irradiation are shown in Fig. 3.36. I_C decline monotonously with ion fluence increasing. Two factors contribute to I_C decreasing after heavy ion irradiation: One is the degradation in the current gain and the other is the increased collector series resistance R_C . The DLTS studies have shown that swift heavy ions can create a variety of point defects such as interstitials, vacancies, and divacancies in the collector region, then the effective dopant density and carrier mobility will degrade, and thereby R_C increases after heavy ion irradiation, leading to a decreased collector current I_C .

Besides, as shown in Fig. 3.35, a significant base-width modulation appears in the transistors irradiated by Br ion, compared with the nearly ideal output characteristics of the fresh device, which is almost independent of V_{CE} . A direct

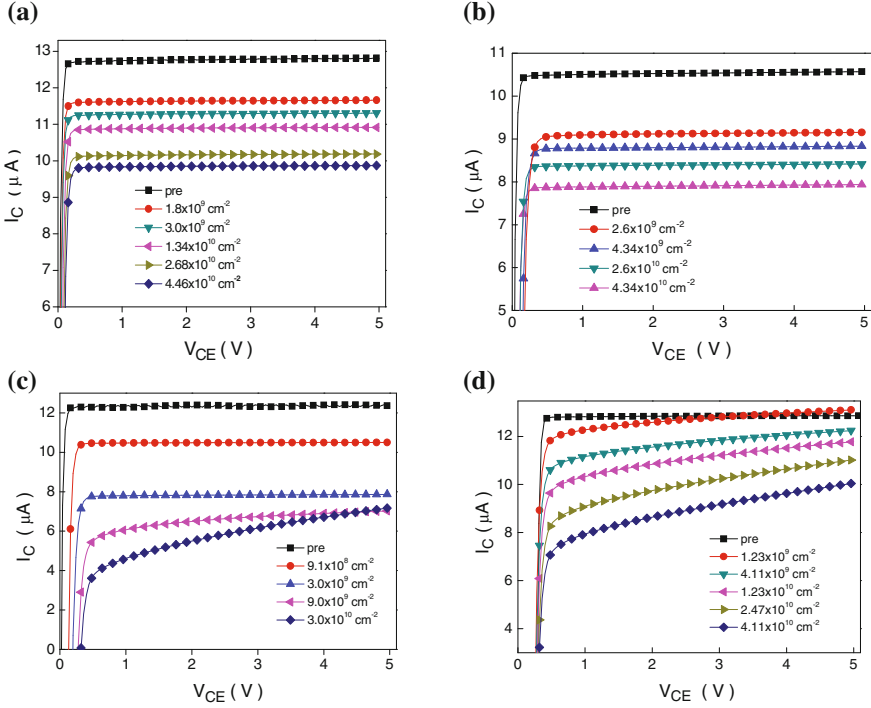


Fig. 3.36 Output characteristics for SiGe HBTs irradiated by **a** 25-MeV Si, **b** 10-MeV Cl, **c** 20-MeV Br, and **d** 10-MeV Br ion irradiation at fixed $V_{BE} = 0.6$ V

consequence is the decline in Early voltage V_A . The variations of V_A after four kinds of heavy ion irradiations are depicted in Fig. 3.37 as a function of ion fluence. Considering the calculation error, V_A remains nearly unchanged after 25-MeV Si and 10-MeV Cl ion irradiation, i.e., there is no significant base-width modulation in the transistor. For the case of 20-MeV Br and 10-MeV Br ion irradiation, however, V_A declines dramatically with ion fluence increasing. V_A degradation may be a result of the decreased concentration of the ionized impurities in the base region due to the impurities passivation induced by the displacement damage. The displacement damage in the base region can result in dopant deactivation and then the effective base dopant density N_B will decrease, thereby causing a reduced V_A . Due to the larger nuclear energy loss, 20 MeV and 10 MeV Br ions are capable of creating more displacement damages in the neutral base region, and the effective base dopant density N_B declines and thereby V_A decreases after irradiation. However, 25-MeV Si and 10-MeV Cl ions create relatively less displacement damages, and no significant degradation in V_A appears.

Figures 3.38 and 3.39 show the variation of junction leakage current, parasitic resistance after four kinds of heavy ion radiation, respectively. It can be seen that the parasitic resistance and leakage current of BE junction and BC junction all

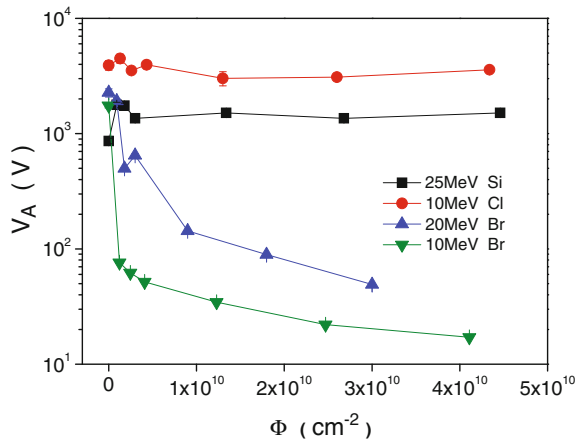


Fig. 3.37 Variation of Early voltage after four kinds of heavy ion irradiation

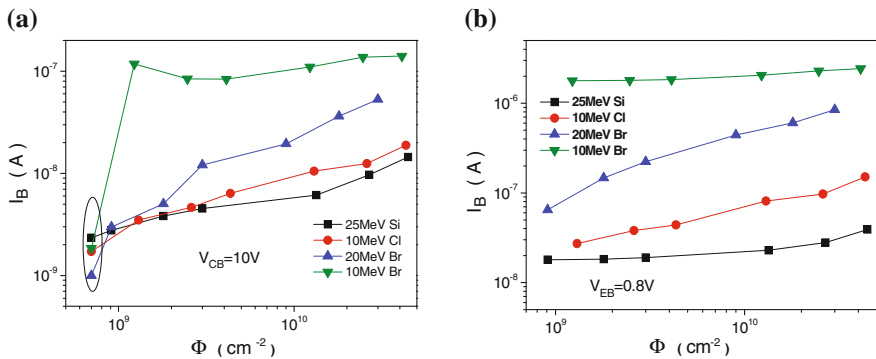


Fig. 3.38 Variation of junction leakage current for different heavy ion irradiation: **a** BC junction, **b** BE junction

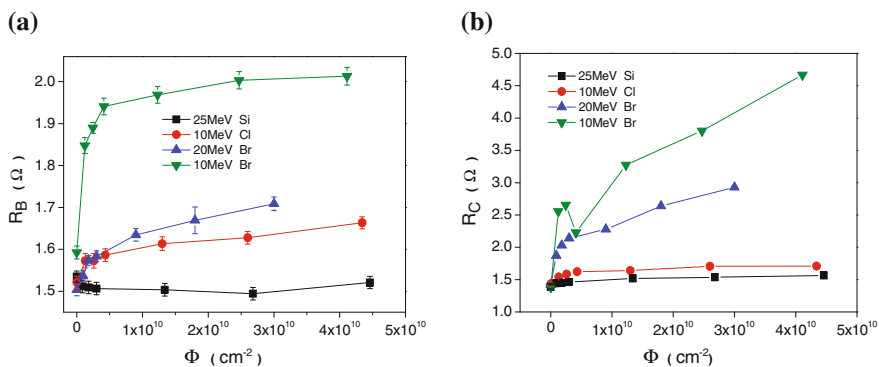


Fig. 3.39 Variation of parasitic resistance for different heavy ion irradiation

increases after heavy ion irradiation. Consistent with the above results, the performance degradation induced by different heavy ion varies, and 10 MeV Br ions lead to the most serious degradation, while 25 MeV Si ions cause a minimum one.

3.6 Effect of Bias Conditions

In order to compare the performance degradation under different bias conditions, three bias conditions were applied during 10 MeV Br ion irradiation: (I) all terminals floating. (II) Forward V_{BE} mode ($V_{BE} = 0.7$ V, $V_{BC} = 0$ V). (III) Reverse V_{BE} mode ($V_{BE} = -0.7$ V, $V_{BC} = 0$ V). The DUT in this section is SiGe HBT1, and the underlying physical mechanisms are analyzed and investigated in detail.

Two electrical parameters, excess base current ($\Delta I_B = I_{B\text{post}} - I_{B\text{pre}}$) and current gain reciprocal ($\Delta(1/\beta) = 1/\beta_{\text{post}} - 1/\beta_{\text{pre}}$), are first calculated and compared as shown in Fig. 3.40, where V_{BE} is fixed at 0.6 V. It can be seen that the performance degradation after 10 MeV Br ion irradiation is indeed bias dependent. The forward-biased EB junction mode shows the smallest degradation at the same irradiation level, and the reverse-biased EB junction condition suffers the largest degradation. Besides, the variation of $\Delta(1/\beta)$ under three bias conditions all shows an obvious linear behavior at high NIEL dose region, which is a result of displacement damages. The extracted displacement damage factor K , i.e., the linear regression slope of $\Delta(1/\beta)$ versus ion fluence, is depicted in Fig. 3.41 as a function of V_{BE} . It is found that K for three bias conditions all decrease with V_{BE} increasing. Under arbitrary given V_{BE} , K is the smallest for the forward-biased EB junction condition, and the case of reversed-biased EB junction shows a maximum K .

The variations of leakage current of BE junction, base resistance (R_B), Early voltage (V_A), and neutral base recombination (NBR) at three bias conditions are separately shown in Figs. 3.42 and 3.43. It is found that the leakage current, R_B , V_A , and NBR all degrade after Br ion irradiation. Furthermore, the case with reversed

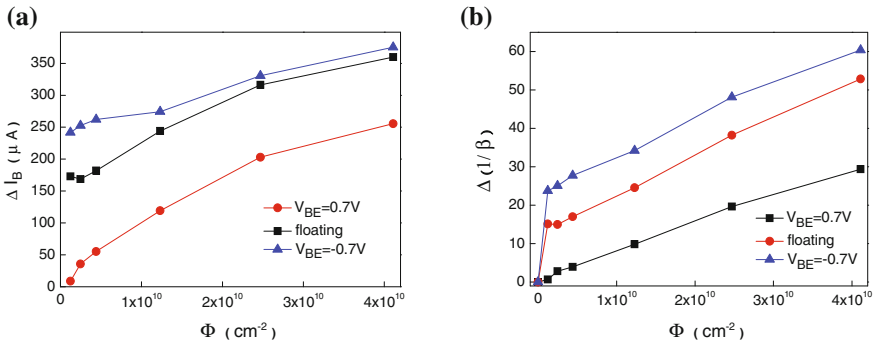


Fig. 3.40 Variation of **a** excess base current ΔI_B and **b** current gain reciprocal $\Delta(1/\beta)$ under $V_{BE} = 0.6$ V induced by 10 MeV Br ion for different bias conditions

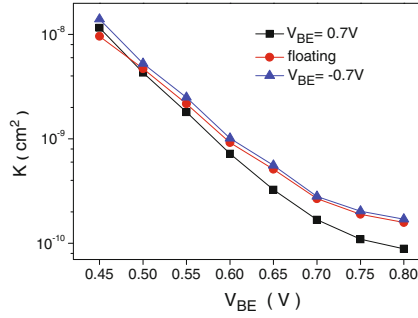


Fig. 3.41 Variation of current gain damage factor K as a function of V_{BE} for different bias conditions

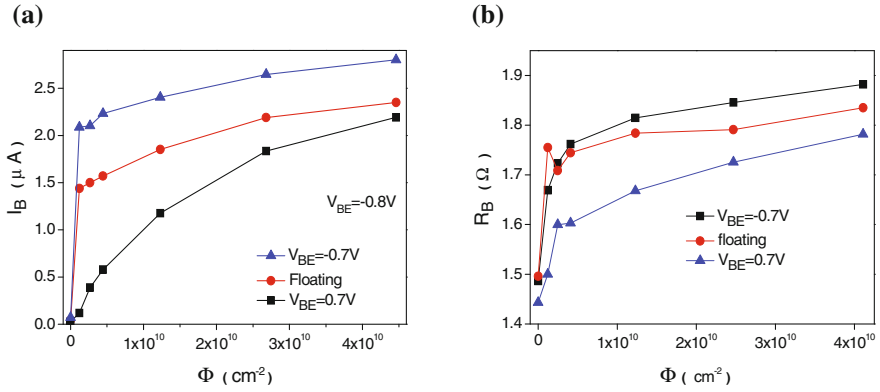


Fig. 3.42 Variation of **a** BE junction leakage current and **b** base resistance R_B under three bias conditions

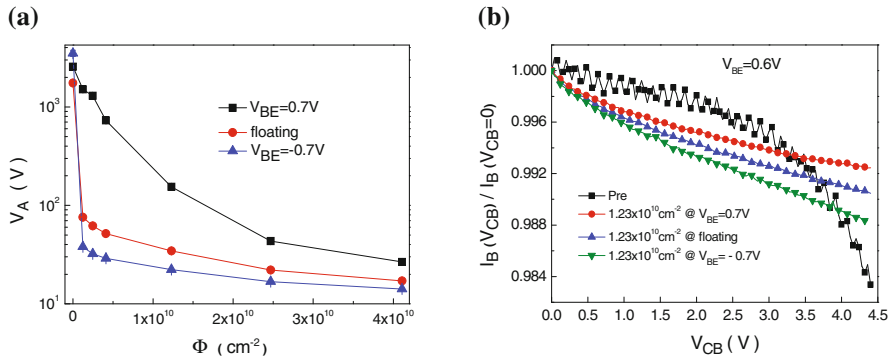


Fig. 3.43 Variation of **a** early voltage and **b** normalized base current $I_B(V_{CB})/I_B(V_{CB} = 0 \text{ V})$ for three different bias conditions

V_{BE} mode shows an enhanced degradation, while the forward V_{BE} mode suffers the smallest degradation. Therefore, the BE junction reverse-biased mode is considered as the worst bias condition from the radiation assurance viewpoint during the heavy ion irradiation.

Two factors contribute to the above bias dependence of performance degradation induced by 10 MeV Br ion irradiation. The first one is the diversity of ionization damages at different bias conditions. As reported, a mount of free electrons and holes are induced in the spacer oxide after irradiation. The electrons are rapidly swept out of the oxide, while the holes move toward the interface and then are trapped in the oxide or the oxide/Si interface, resulting in the oxide positive charges and the interface charges. The local electric field in the spacer oxide plays an important role in the degradation. The larger the local electric fields, the rapider the holes move toward to SiO_2/Si interface, the more the holes arrive to the interface and therefore the more the ionization damages will be created. The fringing electric field in the spacer oxide decreases under forward V_{BE} mode while increases under reverse V_{BE} mode, therefore, from the point of ionization damages, the forward V_{BE} causes the smallest degradation, and the reverse V_{BE} leads to the largest degradation.

Another factor is the injection annealing of displacement damage in the transistor [15]. Injection annealing is a process of enhanced defect reordering via the presence of free charge carriers. As mentioned above, heavy ion irradiation creates various types of point defects and their complex in the transistors. The vacancy is the most common defect in silicon, and it is quite mobile at room temperature. Due to the electron injection, the charge state of vacancy in base region will change from neutral to negative, as a result, the vacancy mobility increases and then enhances the process of defect reordering, reducing the concentration of displacement damage in the transistors. The more the injected carriers into base region or BE junction space charge region, the stronger the injection annealing of displacement damage, and the less the performance degradation. Compared to the case of all terminals floating, the more electron injection appears at forward V_{BE} mode, while less electron injection even reverse extraction occurs at reverse V_{BE} mode. As a result, the injection annealing effect of displacement damage will be enhanced and then less performance degradation exists at forward V_{BE} mode, while a weaker injection annealing effect and then larger performance degradation appear when the BE junction is reversed biased.

3.7 Conclusion

The effects of heavy ion radiation on the DC characteristics of SiGe HBT are studied in this chapter. Due to the existence of ionization damages and displacement damages, base current shows a significant degradation, and the current gain reciprocal under high fluence range varies linearly with the ion fluence increasing. Besides the base current and current gain, the junction leakage current, parasitic

resistance, early voltage, and neutral base recombination are also significantly degraded. It indicates that compared to the ionization damages, the displacement damages cannot be ignored and have become another major factor to the performance degradation of bipolar transistor. The larger the nuclear energy loss NIEL, the more the damage, and the more serious the degradation.

The interactions between the displacement damage and ionization damage induced by heavy ion radiation are complicated and greatly influenced by device structure, ion fluence, and bias condition. For SiGe HBT with three terminals, the displacement damages dominate the degradation of reverse current gain over the whole ion fluence and bias range. However, the current gain degradation in forward-active mode is more complicated. The ionization damages near EB junction side wall dominate at low V_{BE} region, while the displacement damages dominate at high V_{BE} region; and in the middle V_{BE} region, current gain degradation is a result of interactions among displacement damage and ionization damage. The bias effects are also found during heavy ion radiation. The transistors with BE junction forward-biased shows a smaller degradation, while the case with BE junction reverse-biased suffered more irradiation damage.

References

1. M. Ullán, S. Díez, M. Lozano, G. Pellegrini, D. Knolland, B. Heinemann, Combined effect of bias and annealing in gamma and neutron radiation assurance tests of SiGe bipolar transistors for HEP applications. *Solid-State Electron.* **56**(1), 179–184 (2011)
2. S. Liu, D. Lin, X. Guo, N. Liu, X. Jiang, G. Zhu, D. Li, Z. Wang, B. Tang, W. Chen, W. Zhang, H. Zhou, B. Shao and J. Li, Degradation of SiGe HBT with reactor pulse neutron and gamma rays irradiation. *Nucl. Instrum. Methods Phys. Res. Sect. A* **569**(3), 810–814 (2006)
3. N. Pushpa, K.C. Praveen, A.P. Gnana Prakash, P.S. Naik, J.D. Cressler, S.K. Gupta and D. Revannasiddaiah, Reliability studies on NPN RF power transistors under swift heavy ion irradiation. *Nucl. Instrum. Methods Phys. Res. Sect. B* **273**, 36–39 (2012)
4. S. Díez, M. Lozano, G. Pellegrini, F. Campabadal, I. Díez, D. Knoll, B. Heinemann and, M. Ullán, Proton radiation damage on SiGe: C HBTs and additivity of ionization and displacement effects. *IEEE Trans. Nucl. Sci.* **56**(4), 1931–1936 (2009)
5. Z.L. Liu, *Radiation Effects in Advanced Semiconductor Materials and Devices* (National Defence Industry Press, 2008)
6. J.D. Cressler, M.C. Hamilton, G.S. Mullinax, Y. Li, G. Niu, C.J. Marshall and, P.W. Marshall, The effects of proton irradiation on the lateral and vertical scaling of UHV/CVD SiGe HBT BiCMOS technology. *IEEE Trans. Nucl. Sci.* **47**(6), 2515–2520 (2000)
7. Y. Sun, J. Fu, J. Xu, Y. Wang, W. Zhou, W. Zhang, J. Cui, G. Li, Z. Liu, Irradiation effects of 25 MeV silicon ions on SiGe heterojunction bipolar transistors. *Nucl. Instrum. Methods Phys. Res. Sect. B* **312**, 77–83 (2013)
8. Y. Sun, J. Fu, J. Xu, Y. Wang, W. Zhou, W. Zhang, J. Cui, G. Li, Z. Liu, Y. Yu, Y. Ma, G. Feng, J. Han, Comparison of total dose effects on SiGe heterojunction bipolar transistors induced by different swift heavy ion irradiation. *Chin. Phys. B* **23**(11), 116104 (2014)
9. K.C. Praveen, N. Pushpa, A. Tripathi, D. Revannasiddaiah, J.D. Cressler and, A. P. Gnana Prakash, 50 MeV Li³⁺ ion irradiation effects on advanced 200 GHz SiGe HBTs. *Radiat. Eff. Defects Solids* **166**(8–9), 710–717 (2011)

10. K.C. Praveen, N. Pushpa, A. Tripathi, D. Revannasiddaiah, P.S. Naik, J.D. Cressler and A.P. G. Prakash, A comparison of 100 MeV oxygen ion and C^{0-60} gamma irradiation effect on 200 GHz SiGe HBTs (HF 12), in *Proceedings of the SPIE—The International Society for Optical Engineering*, 8549, 2011, pp. 85490
11. K.C. Praveen, N. Pushpa, H.B. Shiva, J.D. Cressler, A. Tripathi, A.P.G. Prakash, A comparison of 75 MeV boron and 50 MeV lithium ion irradiation effects on 200 GHz SiGe HBTs, in *AIP Conference Proceedings*, vol. 1512, 2013, pp. 1030–1031
12. E. Bielejec, G. Vizkelethy, N.R. Kolb, D.B. King and B.L. Doyle, Damage equivalence of heavy ions in silicon bipolar junction transistors. *IEEE Trans. Nucl. Sci.* **53**(6), 3681–3686 (2006)
13. A.P.G. Prakash, N. Pushpa, K.C. Praveen, P.S. Naik and D. Revannasiddaiah, Evaluation of pelletron accelerator facility to study radiation effects on semiconductor devices, in *AIP Conference Proceedings*, vol. 1447, 2012, pp. 489–90
14. K.C. Praveen, N. Pushpa, P.S. Naik, J.D. Cressler, A. Tripathi, A.P. Gnana Prakash, Application of a Pelletron accelerator to study total dose radiation effects on 50 GHz SiGe HBTs. *Nucl. Instrum. Methods Phys. Res. Sect. B* **273**, 43–46 (2012)
15. J.R. Srour, C.J. Marshall, P.W. Marshall, Review of displacement damage effects in silicon devices. *IEEE Trans. Nucl. Sci.* **50**(3), 653–670 (2003)
16. A.P.G. Prakash, N. Pushpa, K.C. Praveen, P.S. Naik, D. Revannasiddaiah, Evaluation of Pelletron accelerator facility to study radiation effects on semiconductor devices, in *AIP Conference Proceedings*, 2012, pp. 489–490
17. K.C. Praveen, N. Pushpa, H.B. Shiva, J.D. Cressler, A. Tripathi, A.P.G. Prakash, A comparison of 75 MeV Boron and 50 MeV Lithium ion irradiation effects on 200 GHz SiGe HBTs, in *AIP Conference Proceedings*, 2013, pp. 1030–1031
18. K.C. Praveen, N. Pushpa, A. Tripathi, D. Revannasiddaiah, P.S. Naik, J.D. Cressler, A.P.G. Prakash, A comparison of 100 MeV oxygen Ion and C^{0-60} gamma irradiation effect on 200 GHz SiGe HBTs, in *16th International Workshop on Physics of Semiconductor Devices*, vol. 8549, (85490 J), 2012
19. Q.J. Meng, H.B. Liu, Q.H. Meng, *Physics of Semiconductor Devices*, vol. 108 (Science Press, 2005)
20. Y. Sun, J. Fu, J. Xu, Y. Wang, W. Zhou, W. Zhang, J. Cui, G. Li, Z. Liu, Degradation differences in the forward and reverse current gain of 25 MeV Si ion irradiated SiGe HBT. *Phys. B-Condens. Matter* **449**, 186–192 (2014)

Chapter 4

Single Event Transients in SiGe HBT

When the high-energy charged particles strike the transistors or circuits, an amount of high-density electron hole pairs are generated, and then single event effects are produced when the electron hole pairs are collected by device terminals. Single event effects, including single event upset [1], single event latchup [2], single event transient [3] and single event burnout [4], are an important source of devices and circuit failure. Due to the existence of collector-substrate (CS) junction, the single event effects are more serious compared to the ionization damage and displacement damage effects. The detection of single event effect is mainly achieved by heavy ion beam and micro-beam irradiation [5, 6]. Recently, a novel technique using pulsed laser has been adopted, due to its low cost, high resolution, large incident depth and simple apparatus. Combined with high-precision real-time digital oscilloscope, the technique with pulsed laser not only can detect the collected port charge, but also the real-time information about the transient voltage or current.

In this chapter, the physics mechanism of single event effect in SiGe HBT induced by pulsed laser microbeam is studied. This chapter is divided into five sections. The first section briefly introduces the interaction between laser and material. The second section is experimental device and experimental condition. Third section gives the experimental results of single particle effect, and the effects of laser energy, load resistance and bias conditions are investigated. In the fourth section, the physics mechanism of single event effect is analyzed by Senturus simulation. Finally, the conclusion is summarized.

4.1 Mechanism of Single Event Effects

Number of high-density electron-hole pairs will be generated when the particles are incident on the device surface. The separation of electron and hole under built-in electric field leads to a kind of voltage or current pulse at the circuit port [7]. Two processes are included here. The first one is the energy deposition and generation of

electron-hole pair, and the second one is the energy transfer and charge collection process. Pulsed laser and heavy ion beam both can produce single event effect, and the physical mechanism of charge collection is similar, but there exists a fundamental difference in the energy deposition and generation of electron-hole pair. The electron-hole pair generated by swift heavy ions are mainly due to the ionization effects [8]. The high-energy heavy ion collides with the nuclei of the target atoms. Some of the energy is transferred to the extranuclear electron, and then become free electrons and create electron-hole pairs. The electron-hole pairs induced by pulsed laser is due to photoionization [9]. The pulsed laser generates photons with energy above Si band gap such that they are absorbed and then numbers of EHPs are produced. The electron-hole pairs produced by heavy ions have a larger density at the center, and decreases gradually along the radial direction. The track width of low energy ion is about 0.1–0.5 μm , while is about 3 μm for high energy (about GeV) heavy ions, and the charge concentration at the center can reach 10^{23} cm^{-3} [10]. The pulsed laser spot with size of 1–2 μm is now available. The spatial distribution of generated electron-hole pairs is broader than that induced by low energy ion, and is comparable to that of high-energy heavy ions [11].

Due to the high-density electron-hole pairs along the ion or laser track, the built-in electric field of PN junction will be distorted, and a “funnel region” is formed [12]. The carriers in the space charge region and “funnel region” are first separated by the electric field, and the carriers within certain depth region below the “funnel region” are then collected by corresponding terminal. Compared to the heavy ion beam, the carrier density at the center is relatively lower, since the carriers produced by pulsed laser are spatially distributed. If the density of generated carrier is lower than the doping concentration of semiconductor sensitive region (especially for highly doped devices), no significant “funnel effect”, i.e., no significant single event effect exist.

4.2 Experiment

Laser microbeam irradiation was performed at the Center for Space Science and Applications, Chinese Academy of Sciences. The optical setup is shown in Fig. 4.1. The DUT is SiGe HBT1 as discussed in Chap. 2 and was fixed on a xyz stage, which controls the position and focus of the incident pulsed laser microbeam. The DUT is irradiated by the laser microbeam with pulse width of 25 ns, repetition rate of 1 kHz, and wavelength of 1064 nm. A combination of waveplate and polarizer varies the energy of pulsed laser. A 50 $\times$ microscope is applied to focus the laser beam on the front side of the DUT, producing a laser pulse spot with diameter of about 2.0 μm . A 2.5-GHz Tektronix oscilloscope with 1 M Ω impedance is used to detect and record the SET.

The DUT, connected in a common-emitter configuration, as shown in Fig. 4.2, is irradiated with emitter grounded. The transient collector voltage pulse is directly detected by the oscilloscope. The effects of laser energy, collector voltage V_{CC} , base

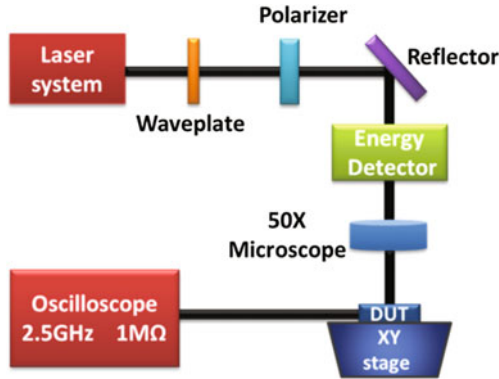


Fig. 4.1 Experimental setup for the pulsed laser SET measurement

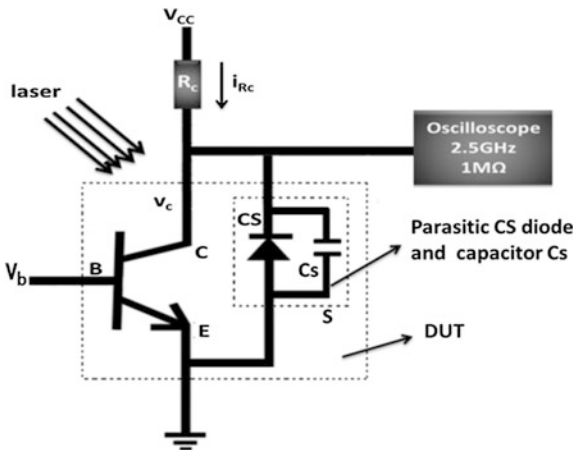


Fig. 4.2 The waveform, amplitude, and width of the SET pulse as well as collected charge are used to characterize the SET response

voltage V_b and load resistance R_c on single event transient (here is transient collector voltage pulse) are investigated in detail. The waveform, amplitude, and width of the SET pulse as well as collected charge are used to characterize the SET response.

4.3 Results and Discussion

The pulsed laser generates photons with energy above Si band gap such that they are absorbed and then numbers of EHPs are produced. Most of EHPs in the neutral regions recombine rapidly, and only those in the space charge region or within an effective diffusion length will be separated and then collected by the built-in or applied electric field, as a result, a single event effect is produced. Compared to collector-base (CB) junction, the collector-substrate (CS) junction has a large area. The SET in SiGe HBTs originates from the reverse-biased CS junction and is related with the laser incident position. As depicted in Fig. 4.3, when pulsed laser strikes into the six choose positions, the most serious SET appear at position 2, and the weakest one is around position 5 and 6. Therefore, In order to study the influence of laser energy, load resistance and bias condition on SET in detail, the incident position is fixed at position 2.

4.3.1 Effects of Laser Energy

The SiGe HBT loaded with R_c of 10 k Ω is irradiated by the pulsed laser with energy ranging from 2.05 to 22.4 nJ. The collector voltage V_{CC} is fixed at 2 V and the base terminal is ground. The transient voltage captured at collector terminal (v_c) and transient collector current calculated by $i_{Rc} = (V_{CC} - v_c)/R_c$, are separately shown in Fig. 4.4. The varying laser energy is found not to change the waveform of transient pulse, but a significant increase in the v_c drop and the peak i_c at the very beginning of the SET is observed with increasing laser energy until some critical value. Once the energy is larger than the critical value, 9.3 nJ in this case, both the starting v_c and the peak i_c begin to saturate, leading to a saturated starting v_c of about -0.8 V and a saturated peak i_c around 0.27 mA, as shown in Fig. 4.4.

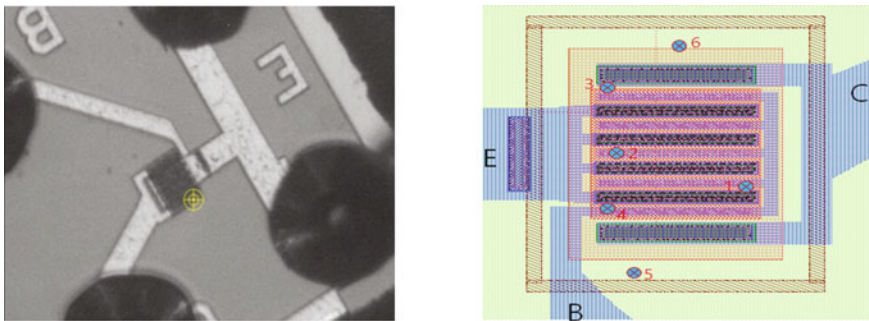


Fig. 4.3 The device under test and the pulsed laser incident position diagram

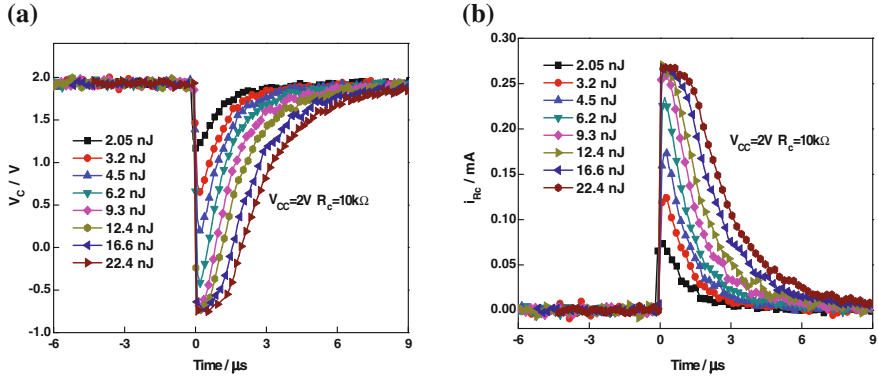


Fig. 4.4 **a** Transient collector voltage v_c and **b** transient collector current through R_c for different laser energies

The initial electron collection by V_{CC} will cause a transient upward-step current pulse and a transient downward-step voltage pulse, which is generally a picosecond-scale process [12] and the details are not captured here. Only the voltage and current recovering process are detected in this study. As the base bias is set as zero, the DUT operates at the off state over most of the period except when v_c is much lower than zero, and the EHPs are mainly discharged via R_c and collector-substrate capacitor (C_s). As long as CS junction is reverse biased or weakly forward biased and carrier recombination is neglected, C_s can be approximated to be roughly constant, so v_c will follow an ideal exponential law during the duration of discharging [13]

$$v_c(t) = V_{CC} - [V_{CC} - v_c(0)]e^{-t/\tau} \quad (4.1)$$

where $v_c(0)$ is the value of $v_c(t)$ at the beginning of discharge, and t is the time constant for the ideal exponential charge. Rearranging Eq. (4.1) yields

$$\ln[V_{CC} - v_c(t)] = \ln[V_{CC} - v_c(0)] - \frac{t}{\tau} \quad (4.2)$$

indicating that $\ln(V_{CC} - v_c)$ will vary linearly with discharging time, and τ can be determined by the linear regression slope of $1/\tau$. The above exponential expression (4.2) is verified by the straight-line part of the curves shown in Fig. 4.5, where linear dependence of $\ln(V_{CC} - v_c)$ on discharging time is clearly observed for different energies.

The charge collected by V_{CC} , i.e., Q_c , and τ for different laser energies are shown in Fig. 4.6. The charge Q_c , calculated as a time integral of i_{R_c} , increases monotonically with increasing laser energy, and τ is roughly constant for lower laser energies (<6.2 nJ), and then increases rapidly as the energy gets higher than 9.3 nJ.

The above results showed that SET in SiGe HBT can approximately be considered as a process of a laser-induced transient step charge followed by an ideal

Fig. 4.5 Dependence of $\ln(V_{CC} - v_c)$ on discharge time for different laser energies

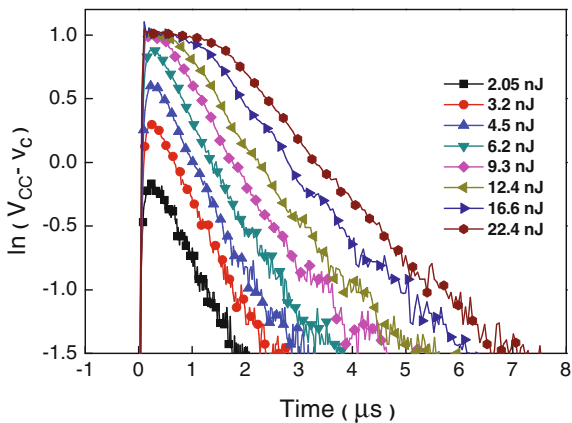
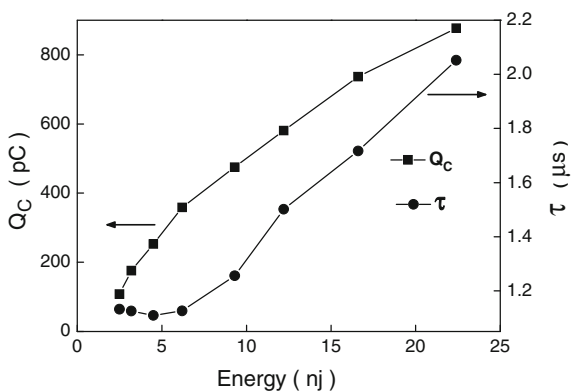


Fig. 4.6 Charge collected by V_{CC} and time constant τ as functions of laser energy



exponential discharge characterized by Eqs. (4.1) and (4.2) [13]. When the laser energy is low (<9.3 nJ), the laser-induced carrier density and i_c are so small that the voltage drop across R_c is not large enough to significantly forward bias either CS or BC junction. Under this condition, the electrons and holes generated in the space charge region of CS junction are separated and only collected by V_{CC} and ground through R_c and C_s , respectively, as shown in Fig. 4.7a. As long as the laser energy is set below the critical value of 9.3 nJ, the higher the energy is, the larger the initial peak i_c is, and thus the larger the starting drop in v_c is. When the laser energy is large enough to make the starting v_c drop to about 0.8 V, both CS and BC junctions will be strongly forward biased, driving the SiGe HBT into reversely active operation. Under these bias conditions, the electron collection via R_c by V_{CC} , on one hand, is shunted by the reverse-operated SiGe HBT to emitter and base, on the other hand, is compensated by the electron injection to substrate through the forward biased CS diode. Note that substrate, emitter, and base are all grounded here. Therefore, as the laser energy increases (over 9.3 nJ in this work), as shown in Fig. 4.7b, as a result of a dynamic equilibrium among electron generation by the

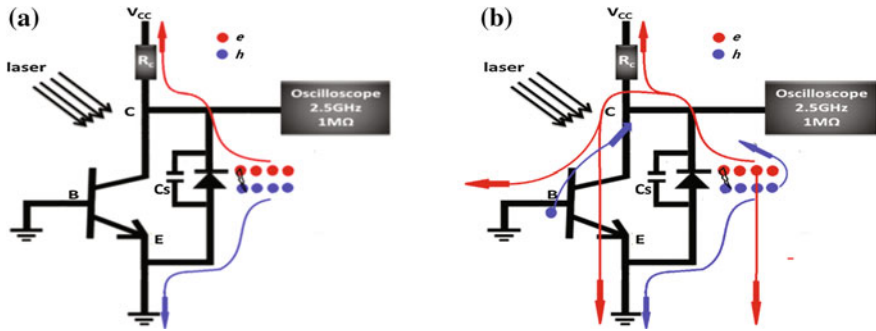


Fig. 4.7 The path of charge collection for different laser energies **a** lower than 9.3 nJ; **b** higher than 9.3 nJ

pulsed laser, electron collection by V_{CC} and ground, and electron recombination with holes, the initial peak i_c becomes saturated, and thus the starting v_c is clamped at about 0.8 V.

Further inspection of Figs. 4.4 and 4.5 indicates that for the laser energies higher than 9.3 nJ, a stage of multi-path electron discharge (besides V_{CC} via R_C , the electrons are also collected by ground through the reverse-operated SiGe HBT and the forward biased CS diode) is inserted between the transient step charge and the single-path ideal exponential discharge (to V_{CC} via R_C only). During the multi-path discharge stage, v_c will increase slowly until the BC and CS junctions recover to be weakly forward biased and even reverse biased, beginning the ideal exponential discharge stage.

As the laser energy goes up, the i_c pulse amplitude increases for the energies lower than 9.3 nJ, and the width increases despite of the saturated plateau for the energies higher than 9.3 nJ, as can be seen in Fig. 4.4b. Therefore, the time integral charge Q_c increases monotonically with the laser energy, as shown in Fig. 4.6. As for the discharge time constant, τ is approximately equal to the product of R_C and C_s in this case, so it keeps nearly unchanged for the laser energy lower than 9.3 nJ due to the negligible change of C_s with reverse CS bias voltage. However, once the laser energy is larger than 9.3 nJ, the CS junction is initially driven to be strongly forward biased, initiating the multi-path discharge. Then, the CS junction turns gradually back to be weakly forward biased and even reverse biased, switching to an ideal exponential discharge with a time constant τ . If $\tau \approx R_C C_s$ still holds, it is found that the C_s will increase monotonically with laser energy. The reason for this is that a plausible hypothesis might be given below. Suppose some minority traps could be produced by the laser irradiation, and then during the multi-path discharge stage some minority carriers are injected due to the forward biased CS junction and might be captured by the traps. After entering the ideal discharge phase, the captured carriers might be released as CS junction returns from forward bias toward reverse bias. The trapping and releasing of the part of minority carriers with varying CS junction bias voltage would result in an additional trapping capacitor, which, in

parallel with the CS junction capacitor, would increase C_s . Moreover, the higher the laser energy is, the more traps may be created, and the higher trapping capacitance would contribute to C_s . Therefore, the increase in time constant τ with increasing energy larger than 9.3 nJ may be explained this way.

4.3.2 Effects of Load Resistance

Transient pulses for different R_c from 200 Ω to 100 k Ω are captured at laser energy of 11.4 nJ, V_{CC} of 2 V and V_b of 0 V. The changes of v_c and i_c with time for different R_c is shown in Fig. 4.8a, b, respectively. The results clearly show that the SET pulse highly depends on the load resistance R_c . Similar to the case of the laser energy effect as shown in Fig. 4.4a, the initial v_c drop rises from 0.75 V for 200 Ω to 2 V for 1 k Ω with R_c increasing, then the starting v_c becomes saturated and clamped at about 0.8 V when the CS and BC junctions become strongly forward biased for R_c over 5.1 k Ω . Transient current i_c , however, shows a rapid decrease with increasing R_c in spite of increasing voltage drop across R_c , as shown in Fig. 4.8b. Similar to the laser energy effect, the near-ideal singlepath exponential discharge phase, where $\ln(V_{CC} - v_c)$ decreases approximately linearly with discharge time at a slope of $1/\tau$, also exists for different R_c , and an additional multipath discharge stage is also present before the near-ideal discharge for R_c larger than 5.1 k Ω , as shown in Fig. 4.9.

By calculating the linear regression slope of $\ln(V_{CC} - v_c)$ versus time in the near-ideal discharge stage in Fig. 4.9 and integrating i_{R_c} over time in Fig. 4.8b, respectively, both τ and Q_c as functions of R_c are plotted in Fig. 4.10. Regarding the time constant, τ is found to increase with increasing R_c , verifying the relation of with the linear-fitting slope of τ versus R_c giving the approximate value of the

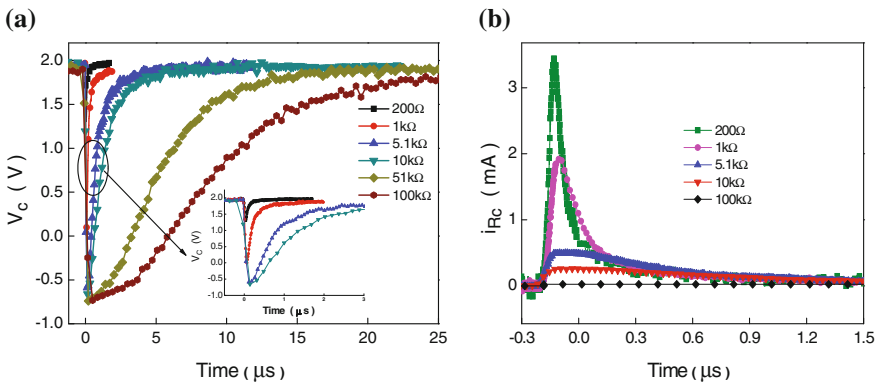


Fig. 4.8 **a** Transient collector voltage v_c and **b** transient collector current i_c for different R_c

Fig. 4.9 Dependence of $\ln(V_{CC} - v_c)$ on discharge time for different R_c

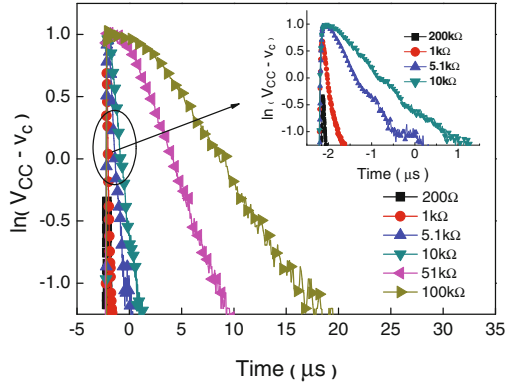
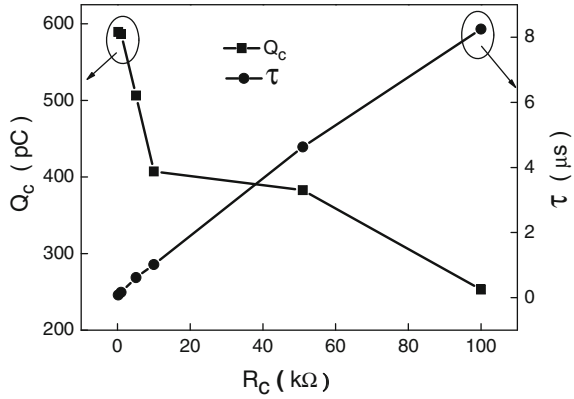


Fig. 4.10 Charge (Q_c) collected by V_{CC} and time constant τ as functions of R_c



reverse biased C_s . As to the charge collected by V_{CC} , Q_c is shown to hardly change in the range from $R_c = 200 \Omega$ to $1 \text{ k}\Omega$, and then decrease as R_c further increases.

In order to explain the Q_c variation with R_c , different discharge modes for the varying R_c should be considered. When R_c is so small ($R_c = 200 \Omega$ and $1 \text{ k}\Omega$ here) that neither CS junction nor BC junction can be reverse-biased, and thus the laser-induced electrons can only be collected by V_{CC} through the near-ideal discharge process. As long as recombination can be neglected due to the weak forward bias or reverse bias for all pn junctions concerned, the amount of the laser-induced carriers available for the discharge should be a constant, so Q_c is approximately equal for $R_c = 200 \Omega$ and $1 \text{ k}\Omega$. As can be seen from Fig. 4.8b, when R_c increases from 200Ω to $1 \text{ k}\Omega$, the width of i_c pulse is actually widened though the pulse amplitude is lowered remarkably, leading to almost the same time integration of i_c , i.e., Q_c . As a large R_c ranging from 5.1 to $100 \text{ k}\Omega$ is used, the additional multipath discharge stage will precede the near-ideal discharge process. It is the multi-path discharge that makes a difference in the observed Q_c decrease with increasing R_c from 5.1 to $100 \text{ k}\Omega$. On the one hand, during the multi-path discharge stage, there

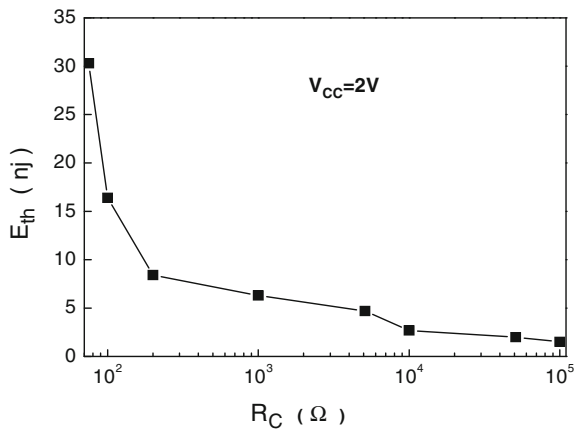
exist three competitive electron discharge paths, i.e., the electron collection via R_c by V_{CC} , the electron shunting by the reverse operated SiGe HBT to ground, and the electron injection to ground through the strongly forward biased CS junction. The first path with larger R_c would obviously present higher impedance compared with the other two paths, thus less electrons would pass through R_c and are collected by V_{CC} eventually. On the other hand, a larger R_c leads to longer discharging time and more electrons, which would have been collected by V_{CC} and tend to annihilate via recombination with holes because of the strong forward bias of the CS junction in the course of the multi-path discharge. For a logic inverter with load resistor R_c shown in Fig. 4.2, based on the above analysis, it is interesting to observe that a larger R_c with a less charge collection results in a longer (worse) duration of the collector voltage upset.

The pulse laser energy threshold of SET is defined as the minimum laser energy value at which the pulse amplitude is reduced below $0.5 V_{CC}$. Figure 4.11 shows the variation of energy threshold for different collector load resistances R_c . It can be found that the energy threshold of SET decreases monotonically with the load resistance increasing, which means the larger load resistance has a more severe SET effect. As a consequence, a larger R_c in the inverters depicted in Fig. 4.2 have less charge collection, but result in a worse (longer duration) SET.

4.3.3 Effects of Bias Condition

The influence of bias conditions on SET in SiGe HBT is also investigated. Figure 4.12 shows the variation of collector transient voltage v_c and transient current i_{R_c} under different V_{CC} , where the laser energy is fixed at 9.1 nJ, R_c is 10 k Ω and V_B is 0 V. For visual comparison, the transient voltage at $V_{CC} = 0$ and 1 V are separately shifted upward by 2 and 1 V, to the initial SET level of $V_{CC} = 2$ V. One

Fig. 4.11 Variation of laser energy threshold for Single event transient in SiGe HBT under different R_c



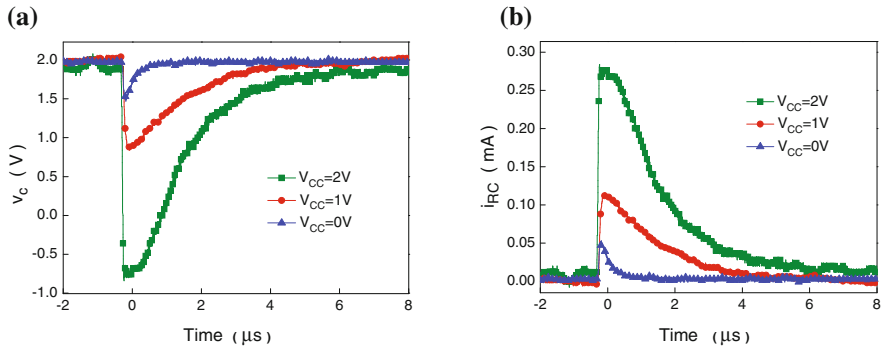


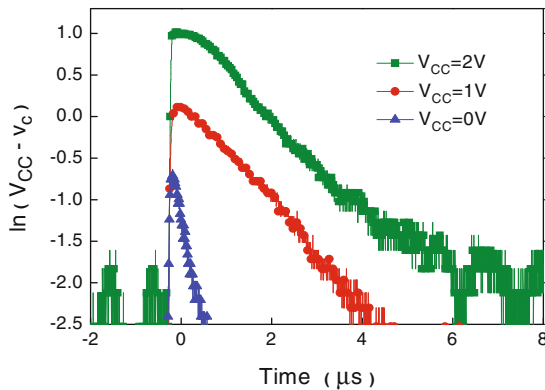
Fig. 4.12 Variation of **a** collector transient voltage v_c , and **b** collector transient voltage i_c for different V_{CC}

can see that SET pulse amplitude decreases (from 2.8, 1.12 to 0.5 V) as V_{CC} decreases, i.e., a higher V_{CC} will result in a more severe SET.

Similar to the effect of laser energy and load resistance, a strict linear trend is predicted between $\ln[V_{CC} - v_c(t)]$ and discharge time under different V_{CC} , as shown in Fig. 4.13, which demonstrates the proposed ideal exponential discharge model in Eq. (4.1). The discharge time constant τ can be determined from the slope of $-1/\tau$, in the plot of $\ln[V_{CC} - v_c(t)]$ versus time. The larger slope for $V_{CC} = 0$ V means smaller discharge time τ , compared to two other bias voltage $V_{CC} = 2$ and 1 V.

As shown in Figs. 4.12 and 4.13, a larger V_{CC} corresponds to a larger collector-collected charge Q_C and discharge time constant τ . Therefore, in SiGe HBT logic inverter as shown in Fig. 4.2, larger V_{CC} is considered as the worse bias condition from the single event transient viewpoint, which is mainly due to the various discharge path under different V_{CC} . When $V_{CC} = 1$ V and $V_{CC} = 2$ V, CS junction is reversed-biased in most discharge time. The deposited charges are separately collected by the applied V_{CC} and ground through load resistance R_C and

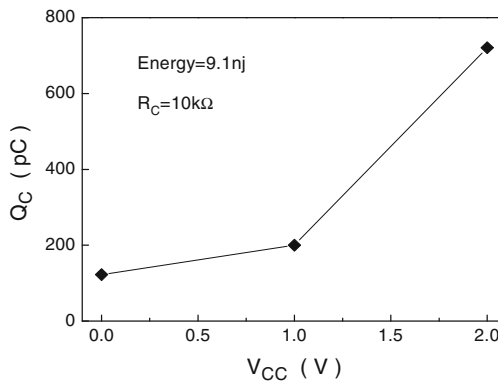
Fig. 4.13 The variation of $\ln(V_{CC} - v_c)$ as a function of time for different V_{CC}



parasitic capacitance C_{cs} , and thus the discharge time constant is approximately the product of R_C and C_{cs} . However, as for the case of $V_{CC} = 0$ V, v_c is below zero during the whole discharge stage, as a consequence, BC junction and CS junction are weakly forward-biased, i.e. the SiGe HBT is driven into reversed-active operation. Thus the deposited charges will no longer just be collected by V_{CC} and ground through R_C and C_{cs} . Because of the forward-biased BC junction, a portion of electrons, which should have been collected by V_{CC} , are injected into the reverse-biased SiGe HBT and then collected by base and emitter [13]. Simultaneously, a number of electrons are injected into substrate (ground) and collected through the forward-biased CS junction. Accordingly, additional discharge path exists for the deposited hole: collected by substrate (ground) through capacitance C_{cs} under built-in electric field, injected from substrate to collector region (compensating the electron there) and injected from base to collector region through the reversed-operated SiGe HBT. It is the existence of additional discharge path that leads to a lower time constant and collected charge Q_C for $V_{CC} = 0$ V, compared to $V_{CC} = 1$ and 2 V [14].

The variation of collected charge Q_C for different collector voltages V_{CC} is shown in Fig. 4.14. It can be seen that Q_C increases monotonically with increasing V_{CC} , which is mainly due to the increased space charge region width of CS junction with V_{CC} increasing. As mentioned above, only the electron within a diffusion length near space charge region can be effectively collected, and those away from the space charge region will quickly recombined. As a consequence, the collected charge Q_C increases as the width of the CS junction space charge region increases. Another factor contributes to the lower Q_C for $V_{CC} = 0$ V. Because of the high concentration of generated carriers, Auger recombination might appear before the carriers are completely collected. Then the charge collection efficiency (CCE), defined as the ratio of the actual collected-charge to the ideal total deposited-charge, increases with the applied reversed voltage V_{CC} increasing [14]. As a consequence, a smaller Q_C is expected for $V_{CC} = 0$ V due to a decreased CCE, compared to other bias condition of $V_{CC} = 2$ and $V_{CC} = 1$ V.

Fig. 4.14 The collected charge Q_C under different V_{CC}



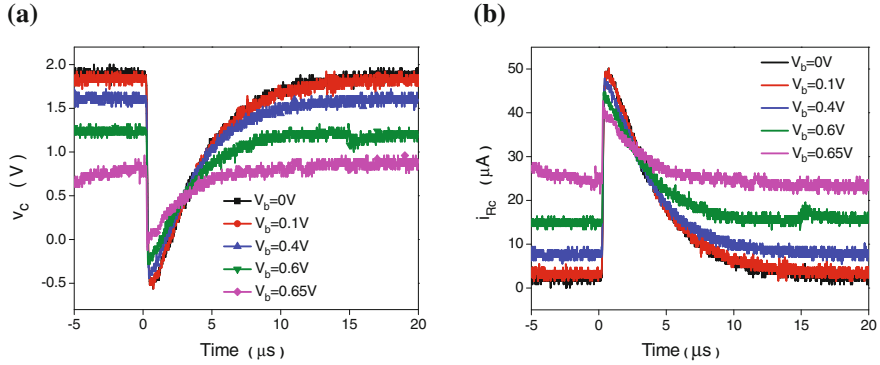


Fig. 4.15 Variation of **a** collector transient voltage v_c , and **b** collector transient voltage i_c for different V_B

To examine the effects of base voltage V_B on SET response, Fig. 4.15 shows the variation of collector transient voltage v_c and transient current i_c under different V_B as a function of time. The laser energy is fixed at 4.7 nJ and the collector terminal is connected to $V_{CC} = 2$ V through a load resistance R_C of 51 k Ω . It is clearly indicated that the magnitude of initial v_c drop decreases with V_B increasing. All of the lowest v_c under different V_B is below zero, and the absolute value decreases monotonically as V_B increases. As a result, the collector transient current i_c shows a rapid decrease with V_B increasing.

Since the transistor is biased at on-state ($V_B = 0.1$ – 0.65 V, $V_{CC} = 2$ V), a steady-state current i_{Cq} exists before the pulsed laser irradiation, as shown in Fig. 4.15b. Thus the collector current i_c , calculated as $(V_{CC} - v_c)/R_C$, is no longer a valid indicator of photon-generated carriers. The additional photocurrent i_L (defined as $i_c - i_{Cq}$) generated by pulsed laser is a significant physical quantity to characterize SET in SiGe HBT. The comparison of photocurrent i_L at different V_B is shown in Fig. 4.16, from which a significant increase in i_L is found with V_B decreasing, from 15.6 μA for $V_B = 0.65$ V to 46.4 μA for $V_B = 0.1$ V. Furthermore, the ratio of i_L to i_{Cq} decreases as V_B increases, which means that SET has less influence on the steady-state current when a larger V_B is applied. Thus, a lower V_B can be considered as worse bias conditions from SET assurance viewpoint.

Considering the existence of steady-state current i_{Cq} , the ideal exponential discharge law for transient v_c , as expressed in Eq. (4.3), will be modified as [14]

$$\ln[V_{CC} - i_{Cq}R_C - v_c(t)] = \ln[V_{CC} - i_{Cq}R_C - v_c(0)] - \frac{t}{\tau} \quad (4.3)$$

Similar to the case under different V_{CC} , the expected linear dependence between $\ln[V_{CC} - i_{Cq}R_C - v_c(t)]$ and discharge time t has also been found under different V_B , as shown in Fig. 4.17, with a slope of $-1/\tau$, which demonstrates that the collector transient voltage v_c satisfies the exponential discharge law under different applied V_B .

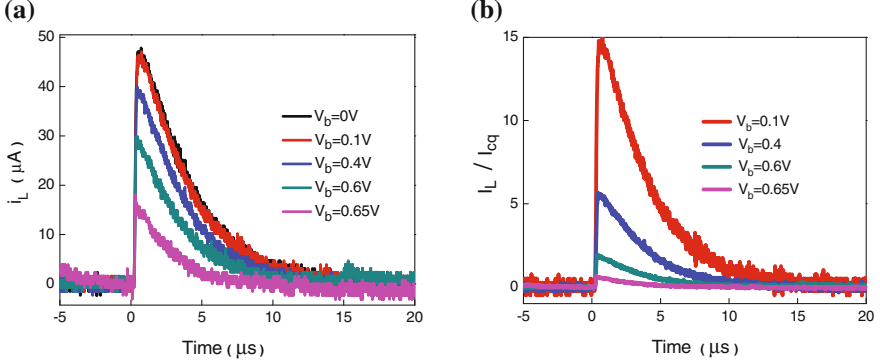


Fig. 4.16 **a** Transient photocurrent i_L and **b** the ratio of i_L to i_{Cq} for different V_B

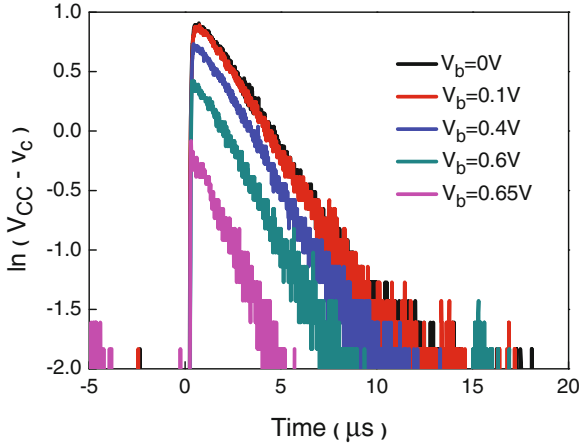


Fig. 4.17 The variation of $\ln(V_{CC} - i_{Cq} R_C - v_c)$ versus time t for different V_B

The discharge time constant τ and collector-collected charge Q_C under different V_B are depicted in Fig. 4.18. Here Q_C is obtained from the integration of photocurrent i_L rather than terminal current i_c with respect to time. It can be seen that Q_C and τ decrease monotonically as V_B increases. As for the decreased Q_C and time constant τ under high V_B , the different charge collection paths contribute. As discussed above, when SiGe HBT is based at reversed-active mode, some fraction of deposited electrons exit through the reversed-operated SiGe HBT and are collected by the base and emitter, instead of the collector. Figure 4.19 shows the variation of the forward bias voltage across BC junction, $V_B - v_c(t)$, as a function of discharge time. A positive V_{BC} during the initial discharge stage certifies a reversed-operated SiGe HBT, and the duration time for $V_{BC} > 0$ increases with V_B increasing. Therefore, more electrons will injected into base and collected by base and emitter for a larger V_B , and naturally the collector-collected charge decreases

Fig. 4.18 Collector-collected charge Q_C and discharge time constant τ for different V_B

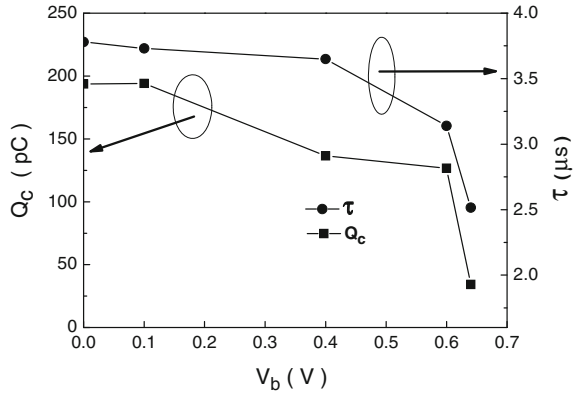
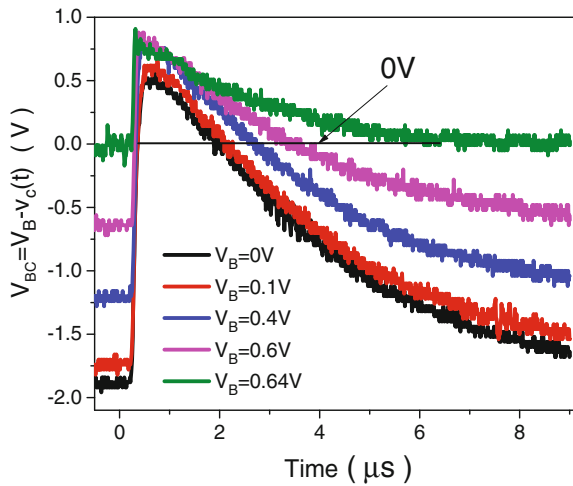


Fig. 4.19 The variation of bias voltage across BC junction for different V_B



with V_B increasing. Regarding the discharge time constant, τ equals the product of junction capacitance C_{cs} and the equivalent resistance along the discharge path. When SiGe HBT is biased at reversed-active mode, the equivalent resistance here is approximately R_C in parallel with BC junction diffusion resistance r_{bc} , and the latter sharply decreases with V_B increasing. Therefore, the discharge time constant τ declines with V_B increasing, as shown in Fig. 4.18.

4.4 Simulation of Single Event Transient in SiGe HBT

Due to the discharge delay induced by load resistor R_C , the above SET only captures the subsequent microsecond discharge process and lacks a detailed description of the instantaneous charging process. In fact, the SET in SiGe HBT is

usually a picosecond process. In order to study the microscopic mechanism of SET in SiGe HBT, TCAD simulation of heavy ion radiation are carried out. Before the heavy ion simulation, the equivalent relationship between the pulsed laser beam and the heavy ion beam should be estimated, that is, the equivalent LET of the pulsed laser microbeam should be calculated.

Assuming that the laser microbeam, injected into the surface of semiconductor material, satisfies the linear absorption law, the laser intensity I at different depths x is written as [15]

$$I = I_0 \exp(-\alpha x) \quad (4.4)$$

where I_0 is laser intensity at material surface $x = 0$, α is the absorption coefficient in material. Assuming that each photon only produces one electron-hole pair (i.e., single-photon absorption), the equivalent LET of the pulsed laser is expressed as [16]

$$\text{LET}(x) = \text{LET}(0) \exp(-\alpha x) \quad (4.5)$$

where $\text{LET}(0) = (\lambda \alpha E_{\text{ion}} / hc \rho) E_0$, E_{ion} is the energy required to produce an electron-hole pair, E_0 is the laser energy at material surface $x = 0$, ρ is the material density, λ is the laser wavelength, h is Planck's constant and c is the light speed. The equivalent LET gradually decreases with the incident depth increasing. In this work the adopted laser wavelength λ is 1.06 μm , which is weakly absorbed in Si. The penetration depth is usually much greater than the thickness of the device sensitive region. There exists $\alpha x \ll 1$ and the equivalent LET can be simplified as

$$\text{LET} = \lambda \alpha E_{\text{ion}} E_0 / hc \rho \quad (4.6)$$

Considering the weak absorbing conditions, similar to the case of high energy heavy ion, the equivalent LET of pulsed laser can be regarded as constant. The equivalent LET for arbitrary energy can be calculated by the Eq. (4.6), but in fact, when the laser energy is high enough, in addition to linear absorption, the nonlinear absorption should also be considered. As a consequence, the calculated equivalent LET from Eq. (4.6) is usually higher than that of the swift heavy ion. In this paper, we do not go into detail how to calculate the equivalent LET of pulsed laser, but use Senturus to simulate the transient effect and potential physical mechanism of a single LET ion in SiGe HBT.

Figure 4.20 shows the schematic diagram of the SiGe HBT. Assuming that the incident heavy ions penetrate the whole structure of the transistor, and the LET of incident heavy ion is 10 $\text{meV cm}^2/\text{mg}$. The generation rate of electron-hole pairs is assumed to be Gaussian distribution in space and time. The 1/e characteristic radius in space is 0.2 μm , 1/e characteristic time is 2 ps and Gaussian peak is 2 ps. The physical models used in device simulation are doping-dependent SRH recombination, Auger recombination, velocity saturation, Phillips unified mobility model and band gap narrowing model. During the entire simulation, the collector voltage is kept at 3 V and the other electrodes are grounded.

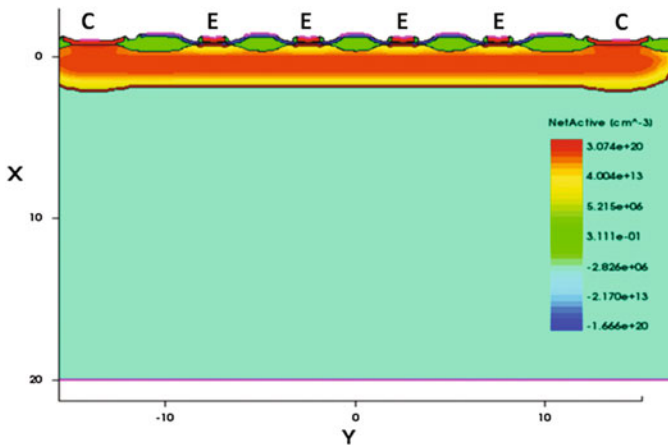


Fig. 4.20 The cross-sectional of the device to be simulated

4.4.1 Electric Potential and Electric Field

Figure 4.21 shows the variation of potential distribution when the heavy ion strikes at the center of left emitter ($Y = -7.5 \mu\text{m}$). When the heavy ions pass through the device structure, a large number of electron-hole pairs are generated along the ion-incident path. The internal potential of PN junction is distorted, and the equipotential lines are shifted to the substrate, creating a funnel-like potential distribution, as shown in Fig. 4.21d. The electron and hole in the funnel drifts towards opposite directions under the built-in electric field or applied electric field, and then collected by different terminal ports. Due to the strong electric field in the funnel region, the collected charge is much more than that deposited in the depletion layer. Besides, the duration of funnel effect is usually short and is about picosecond. When the funnel effect disappears, the carriers will be further collected through the subsequent diffusion under the action of concentration gradient. The diffusion process lasts nanosecond or even microsecond. As shown in Fig. 4.21, the funnel effect begins to appear at 8 ps and is most severe at 50 ps. At 100 ps, the potential weakens. At 8 ns the funnel effect disappears and the potential recovers to the initial state. The corresponding electric field distribution is shown in Fig. 4.22. It can be found that the electric field along the ion incident path collapses within the initial 50–80 ps.

Due to the funnel effect and the subsequent diffusion mechanism, the electron-hole pairs induced by heavy ion radiation are separated by the built-in electric field or the applied electric field, and then are finally collected by the terminal of SiGe HBT. The collected charge and transient current are two critical quantities in the SET process. In the following section, we will analyze the position sensitivity of SET in SiGe HBT through analyzing these two physical quantities.

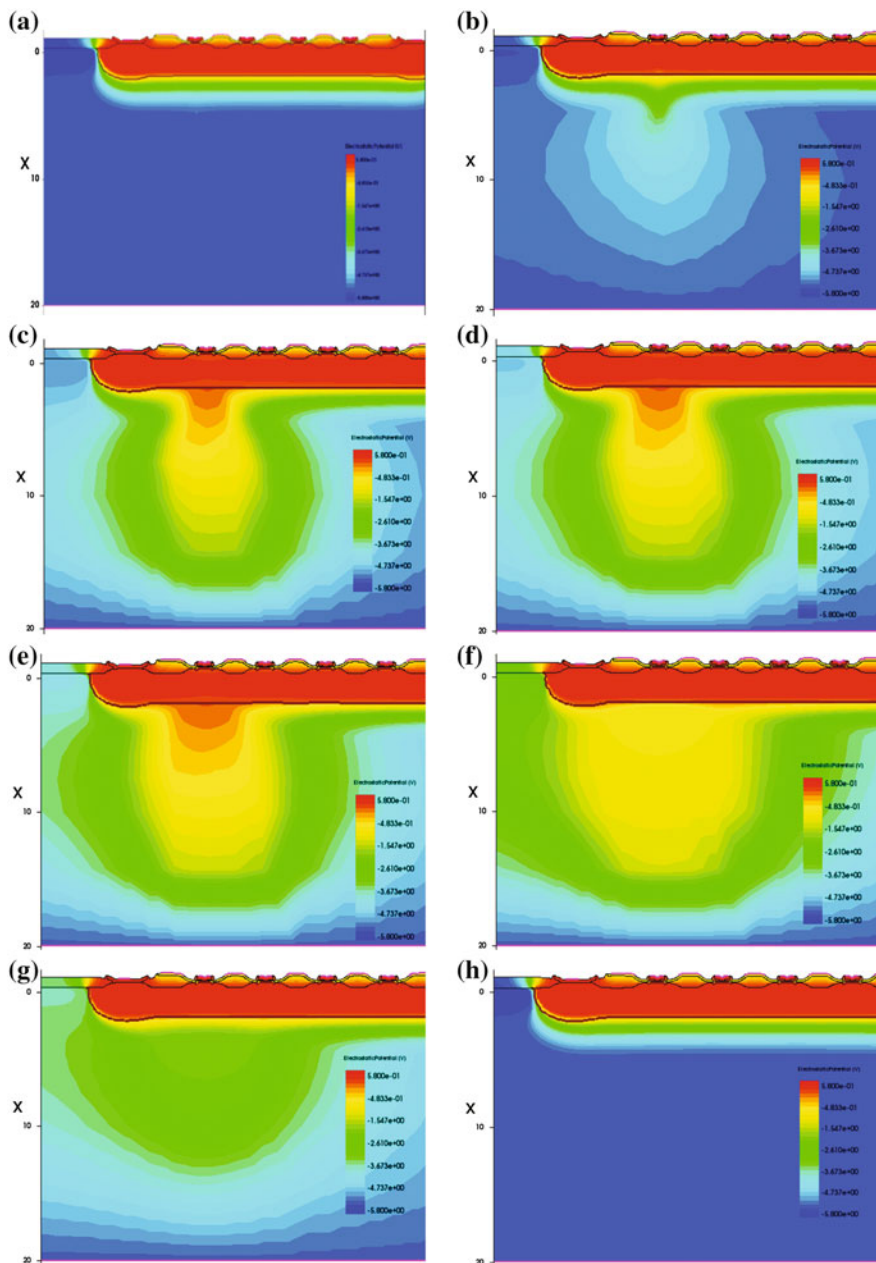


Fig. 4.21 Potential distribution at different time when heavy ions are incident on the left emitter ($Y = -7.5 \mu\text{m}$): **a** 5 ps; **b** 8 ps; **c** 30 ps; **d** 50 ps; **e** 100 ps; **f** 1 ns; **g** 5 ns; **h** 8 ns

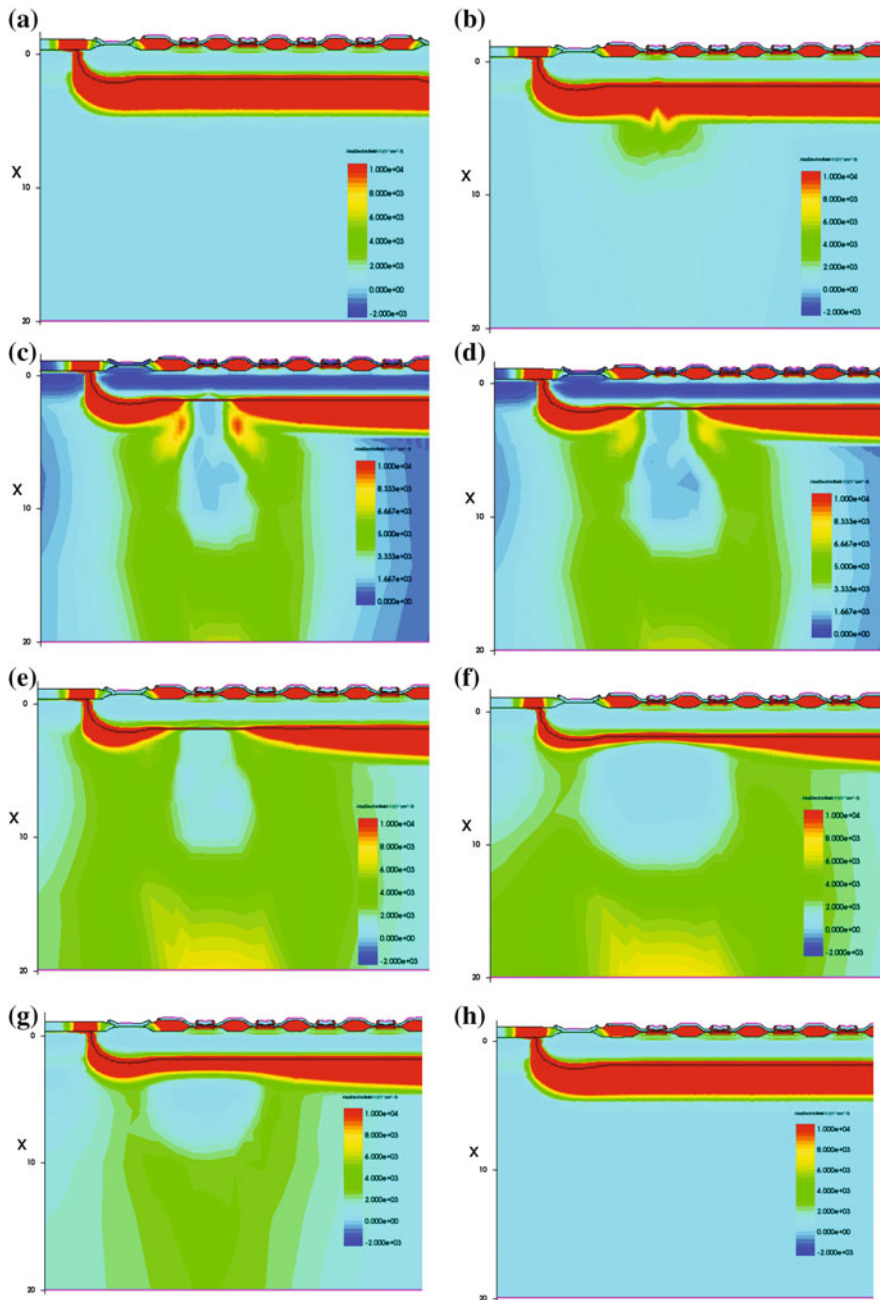


Fig. 4.22 Electric field distribution at different time when heavy ions are incident on the left emitter ($Y = -7.5 \mu\text{m}$): **a** 5 ps; **b** 8 ps; **c** 30 ps; **d** 50 ps; **e** 100 ps; **f** 1 ns; **g** 5 ns; **h** 8 ns

4.4.2 Location Sensitivity Analysis of Single Event Transient

SET in SiGe HBT is closely related to the strike position, and the sensitive region for SET can be obtained through analyzing the port charge and current at different positions. According to the actual device structure, four typical positions are selected:

- (1) The leftmost collector at $Y = -14 \mu\text{m}$, the heavy ion only pass through CS junction, as shown in Fig. 4.23a;
- (2) The center of left emitter at $Y = -7.5 \mu\text{m}$, the heavy ion pass through BE junction, BC junction and CS junction;
- (3) The extrinsic base near the leftmost emitter at $Y = -7 \mu\text{m}$, the heavy ion pass through BC junction and CS junction, as shown in Fig. 4.23b;
- (4) LOCOS at $Y = -5 \mu\text{m}$, the heavy ion only pass through CS junction, as shown in Fig. 4.23c.

Figures 4.24, 4.25, 4.26 and 4.27 separately shows the variation of collected charge and transient current with time for the four different positions. It can be seen that the collector current and emitter current are mainly electron current, and the base current and the substrate current are mainly hole current. When the incident ions only pass through CS junction (such as position 1 and position 4), the base and emitter current are relatively small. The collector current and the substrate current consist of two parts, one is the short but large current pulse induced by funnel effect, and another is long but small current pulse due to the subsequent diffusion process. The duration of the funnel effect is very short, and the collected charge by the collector and substrate are mainly from the subsequent diffusion process. For the position (2), the heavy ion will pass through the BE junction, BC junction and CS junction in turn, thus, a large transient drift current pulse and a gentle diffusion current pulse appear at each electrode port, as shown in Fig. 4.25. For the position (3), the heavy ion will pass through BC and CS junction, at this time, a large drift current pulse appears at the collector and base electrode.

Table 4.1 shows the distribution of collected charge at each terminal for different incident locations. According to Figs. 4.24, 4.25, 4.26 and 4.27, the collected charges at base and emitter terminal are three to five orders of magnitude lower than those of collector and substrate terminal, and the collected charges at position

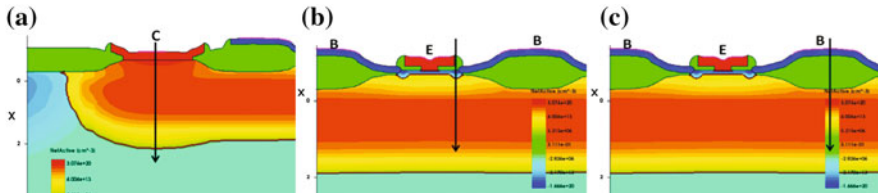


Fig. 4.23 Ion path at three different incident positions: **a** $Y = -14 \mu\text{m}$, **b** $Y = -7 \mu\text{m}$, **c** $Y = -5 \mu\text{m}$

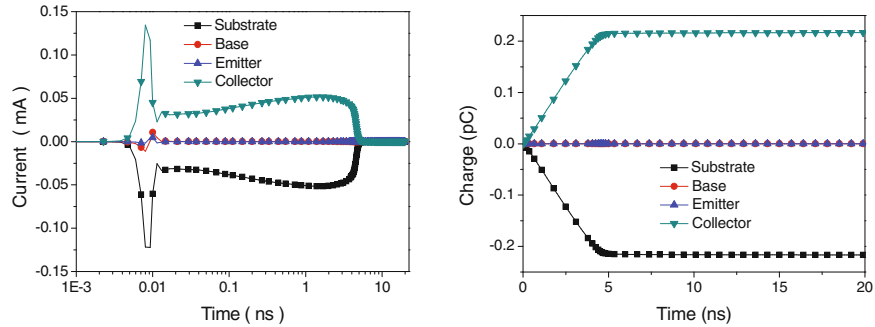


Fig. 4.24 Current and the collected charge at each terminal when the incident position is $Y = -14 \mu\text{m}$

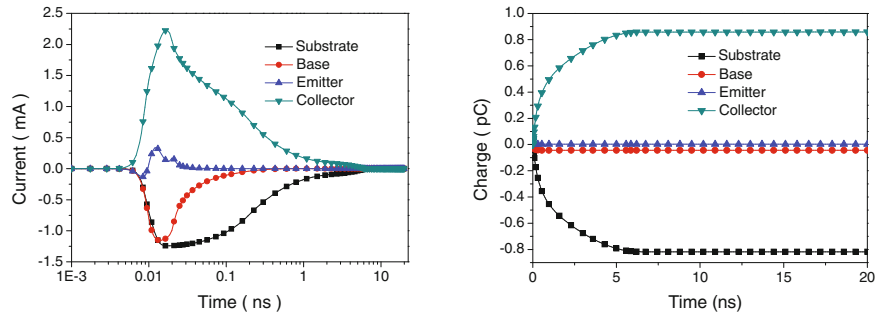


Fig. 4.25 Current and the collected charge at each terminal when the incident position is $Y = -7.5 \mu\text{m}$

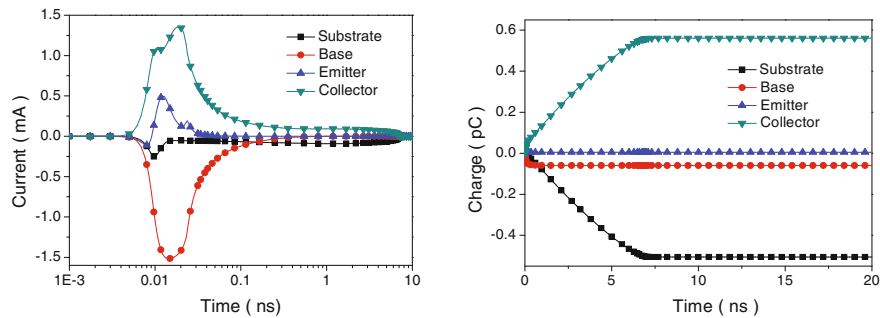


Fig. 4.26 Current and the collected charge at each terminal when the incident position is $Y = -7 \mu\text{m}$

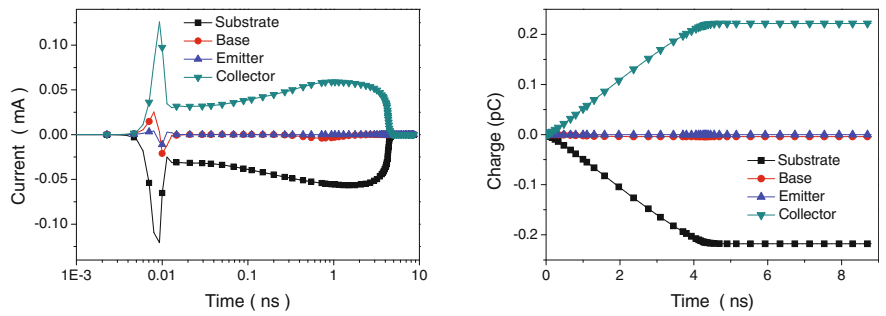


Fig. 4.27 Current and the collected charge at each terminal when the incident position is $Y = -5 \mu\text{m}$

Table 4.1 Collected charges at each terminal for different incident locations

Location/ μm	Collected charge/C			
	Emitter	Base	Collector	Substrate
$Y = -14$	$1.13892\text{E-}18$	$1.86107\text{E-}18$	$2.16642\text{E-}13$	$-2.16645\text{E-}13$
$Y = -7.5$	$2.93754\text{E-}15$	$-4.38772\text{E-}14$	$8.58253\text{E-}13$	$-8.17548\text{E-}13$
$Y = -7$	$4.64864\text{E-}15$	$-5.96257\text{E-}14$	$5.6054\text{E-}13$	$-5.05568\text{E-}13$
$Y = -5$	$-2.52065\text{E-}18$	$-3.96042\text{E-}15$	$2.21732\text{E-}13$	$-2.17769\text{E-}13$

(2) and (3) are one to three orders of magnitude higher than those at position (1) and (4). It indicates that the intrinsic transistor region within LOCOS is the sensitive region for the base and emitter charge collection. The collected charges at collector is nearly identical to that at substrate for each incident position, which demonstrates the collected charges are mainly from the reverse biased CS junction. When heavy ion passes through the depletion layer of CS junction, the generated high-density electron-hole pair distort the electric field, and the equipotential line extends to the substrate direction to form the “funnel potential”. The carriers in the funnel region are separated and then collected by collector and substrate. Part of carriers outside the funnel region can diffuse to the depletion layer under the concentration gradient, and then collected by collector and substrate. Therefore, the reverse biased CS junction is the sensitive region for charge collection at collector and the substrate terminal. Besides, the collector/charge collected charges at position (2) and (3) are significantly larger than that at position (1) and (4). For position (1), the heavy ions pass through the heavily doped sinker region, and most of the carriers within this region have been recombined before collection, leading to a reduced charge collection at collector/substrate terminal. As for the position (4), there exists a decreased collector volume and effective funnel volume, leading to a reduced charge collection. From the point of view of charge collection, the collected charges at emitter and base terminal are negligible, and the generated carriers are mainly collected by collector and substrate.

4.5 Conclusion

The single event transient induced by pulse laser in SiGe HBT is investigated in this chapter. The effects of laser energy, load resistance and bias condition are discussed detailedly, and the physical mechanisms are analyzed with TCAD Senturus. A near-ideal exponential model is proposed for the first time to describe the discharge of laser-induced electrons via collector resistance to collector supply when both BC and CS junctions are reverse biased or weakly forward biased. An additional multi-path discharge plays an important role once the BC and CS junctions get strongly forward biased due to a strong transient step charge by the laser pulse. From the point of view of anti-radiation, a reduced supply voltage VCC and smaller load resistance R_C should be adopted. The simulated results shows that single event transients in SiGe HBT are actually composed of a short and large drift current pulse, and a subsequent long and fulcrum diffusion current pulse. By comparing the transient current and collected charge at different positions, the intrinsic transistor region within LOCOS is found as the sensitive region for base and emitter charge collection.

References

1. F. Darracq, H. Lapuyade, N. Buard, F. Mounsi, B. Foucher, P. Fouillat, M. Calvetand, R. Dufayel, Backside SEU laser testing for commercial off-the-shelf SRAMs. *IEEE Trans. Nucl. Sci.* **49**(6), 2977–2983 (2002)
2. P.W. Marshall, M.A. Carts, A. Campbell, D. McMorow, S. Buchner, R. Stewart, B. Randall, B. Gilbertand, R.A. Reed, Single event effects in circuit-hardened SiGe HBT logic at Gigabit per second data rates. *IEEE Trans. Nucl. Sci.* **47**(63), 2669–2674 (2000)
3. J.A. Pellish, R.A. Reed, D. McMorow, J.S. Melinger, P. Jenkins, A.K. Sutton et al., Laser-induced current transients in silicon-germanium HBTs. *IEEE Trans. Nucl. Sci.* **55**(6), 2936–2942 (2008)
4. R.A. Reed, R.A. Weller, R.D. Schrimpf, M.H. Mendenhall, K.M. Warrenand, L.W. Massengill, Implications of nuclear reactions for single event effects test methods and analysis. *IEEE Trans. Nucl. Sci.* **53**(6), 3356–3362 (2006)
5. R.A. Reed, P.W. Marshall, J.C. Pickel, M.A. Carts, B. Fodness, G.F. Niu et al., Heavy-ion broad-beam and microprobe studies of single-event upsets in 0.20- μ m SiGe heterojunction bipolar transistors and circuits. *IEEE Trans. Nucl. Sci.* **50**(61), 2184–2190 (2003)
6. P. Chu, D.L. Hansen, B.L. Doyle, K. Jobe, R. Lopez-Aguado, M. Shogaand, D.S. Walsh, Ion-microbeam probe of high-speed shift registers for SEE Analysis-part I: SiGe. *IEEE Trans. Nucl. Sci.* **53**(3), 1574–1582 (2006)
7. J.D. Cressler, Radiation Effects in SiGe Technology. *IEEE Trans. Nucl. Sci.* **60**(3), 1992–2014 (2013)
8. N.E. Lourenco, R.L. Schmid, K.A. Moen, S.D. Phillips, T.D. England, J.D. Cressler et al., Total Dose and Transient Response of SiGe HBTs from a New 4th-Generation, 90 nm SiGe BiCMOS Technology. 2012, IEEE. pp. 1–5
9. D. McMorow, W.T. Lotshaw, J.S. Melinger, S. Buchnerand, R.L. Pease, Subbandgap laser-induced single event effects: carrier generation via two-photon absorption. *IEEE Trans. Nucl. Sci.* **49**(6), 3002–3008 (2002)
10. A. Yariv, *Quantum Electmnics* (Wiley, New York, 1975)

11. J.S. Melinger, S. Buchner, D. McMorrow, W.J. Stapor, T.R. Weatherford, A.B. Campbelland, H. Eisen, Critical evaluation of the pulsed laser method for single event effects testing and fundamental studies. *IEEE Trans. Nucl. Sci.* **41**(6), 2574–2584 (1994)
12. G.F. Niu, J.D. Cressler, M. Shoga, K. Jobe, P. Chuand, D.L. Harame, Simulation of SEE-induced charge collection in UHV/CVD SiGeHBTs. *IEEE Trans. Nucl. Sci.* **47**(63), 2682–2689 (2000)
13. Y. Sun, J. Fu, J. Xu, Y. Wang, W. Zhou, W. Zhang, J. Cui, G. Li, Z. Liu, Y. Yu, Y. Ma, G. Fengand J. Han, A single-event transient induced by a pulsed laser in a silicon—germanium heterojunction bipolar transistor. *Chinese Phys. B*, **22**(5), 056103 (2013)
14. Y. Sun, J. Fu, Y. Wang, W. Zhou, Z. Liu, X. Liand, Y. Shi, Experimental study of bias dependence of pulsed laser-induced single-event transient in SiGe HBT. *Microelectron. Reliab.* **65**, 41–46 (2016)
15. A.H. Johnston, Charge generation and collection in p-n junctions excited with pulsed infrared lasers. *IEEE Trans. Nucl. Sci.* **40**(6), 1694–1702 (1993)
16. J.G. Hang, J.W. Han, Calculation of equivalent LET of pulsed laser simulating single particle effect. *Sci. China (Series G: Physics, Mechanics & Astronomy)*, (06), 601–609 (2004)

Chapter 5

Small-Signal Equivalent Circuit for SiGe HBT Based on Distributed Network

Since the late 1980s, SiGe HBTs have gained great attention in wireless communication and RF microwave applications due to the advantages of high gain, high linearity, and low noise. An accurate physically oriented model and parameter-extraction technique for SiGe HBTs are vital to evaluate fabrication process, optimize device structure, and help circuit design. The conventional compact models, such as SGP [1], VBIC [2], HICUM [3], and MEXTRAM [4], are often used to characterize SiGe HBT performance. However, the transistor is a complicated distributed network consisting of a series of resistor, capacitor, inductor, and diode. The above four compact models lack a detailed description of these distributed effects. As SiGe HBTs continue to expand into the space radiation environment, especially the heavy ion radiation-rich space exploration, the distributed effects are more significant because of the non-uniform displacement. As a result, the model's parameters greatly vary with different regions and cannot be characterized by compact models.

This chapter is arranged as follows. The necessity of a distributed model for SiGe HBT under radiation environment is first discussed in Sect. 5.1. In Sect. 5.2, an improved distributed small-signal model is proposed, based on the transmission line equations solved in intrinsic transistor, link base, and extrinsic base region. In Sect. 5.3, the obtained distributed model is reasonably simplified in the perspective of parameter extraction. Finally, the conclusions are summarized in Sect. 5.4.

5.1 Significance of SiGe HBT Distributed Equivalent Circuit

An accurate physically oriented circuit model for SiGe HBTs are very important to evaluate fabrication process, optimize device structure, and help circuit design. When modeling the equivalent circuit, the transistor microstructure, and the carrier

distribution/transport should be considered, since only such model and parameter have a clear physical meaning. Firstly, the circuit model cannot be too simple; otherwise, it cannot accurately describe the transistor's electrical behavior. However, the circuit model cannot be too complicated; otherwise, it is difficult to accurately extract the model's parameters. To extract all element parameters, it is generally required to simplify the transistor topology under certain approximations and assumptions. Lumped circuit models are conventionally used to describe the transistor equivalent circuit, such as HICUM and MEXTRAM. However, being not always as simple as described in lumped models, the actual transistor is extremely complicated, which is generally a huge distributed network made of basic elements, such as resistance, capacitance, and diode [5].

At present, the mainstream HICUM, MEXTRAM and other models can accurately describe the parasitic transistors, large current effect, and self-heating effect [6, 7], but lack the consideration of distributed effects in the whole transistor region. When the transistors are exposed to the radiation environment, a mount of ionization damage and displacement damage non-uniformly distribute over the whole transistor region [8, 9]. Therefore, the electrical parameters such as effective doping concentration, parasitic resistance and capacitance, vary with locations. In other words, a significant distributed effect exists in the transistor exposed to space irradiation environment. The compact model for conventional conditions is not suitable for the above-mentioned distributed effects.

It is of great significance to investigate the circuit model based on distributed effects from the actual device structure. Due to the complexity of the circuit form, the model parameter extraction is more difficult, so certain approximations and simplifications should be considered. A completed transistor model typically includes a small-signal model and a large-signal model. The small-signal model is a linear approximation of the large-signal model near particular bias point, and can accurately describe the electrical characteristics. Furthermore, compared to the large-signal model, the parameter extraction for the small-signal model is relatively simple, and the bias dependence of model parameters has a reasonable correspondence with the large-signal model, providing a basis and premise for large-signal model parameter extraction. Therefore, in this paper, we mainly discuss small-signal equivalent circuit model and the corresponding parameter-extraction method for SiGe HBTs.

5.2 Establishment of Small-Signal Model

In this section, a self-aligned SiGe HBT with a CBEC layout is investigated, as shown in Fig. 5.1. Considering its structure symmetry, only half of the schematic cross section, i.e., (1/2)E1B1C layout is shown. It is divided into three parts according to the base position, which are: (I) link base region under the spacer oxide; (II) intrinsic transistor region; and (III) extrinsic base-collector (BC) junction

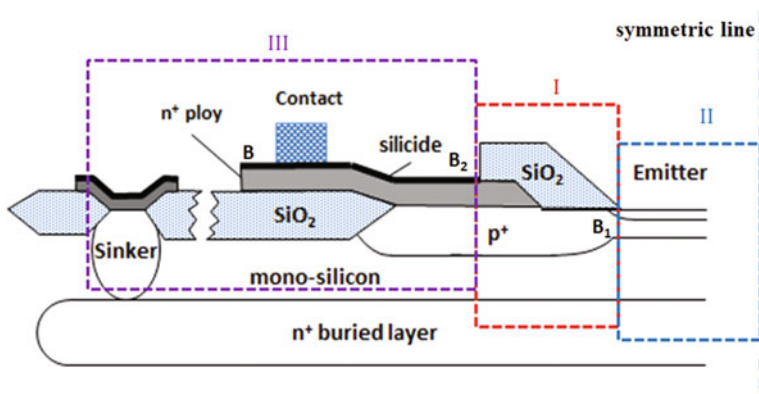


Fig. 5.1 Schematic cross section of a self-aligned bipolar transistor with CBEBC layout (only half of the structure is shown due to the symmetry). Three parts are included according to the position of the base region

containing metal silicide. The distributed network for each region is first built under reasonable approximation, and then the equivalent circuit is obtained by solving transmission line equations.

5.2.1 Link Base Region (Region I)

The equivalent circuit for the link base (region I) is first obtained. As shown in Fig. 5.2, only the BC junction is included in the link base region. Due to the existence of the emitter–base (EB) sidewall spacer, the extrinsic base ion implantation cannot reach this region, and therefore the link base resistance R_{BL} is not ignored. It is assumed that all the electrical parameters are distributed uniformly along the length direction, and their values do not depend on the position z . The

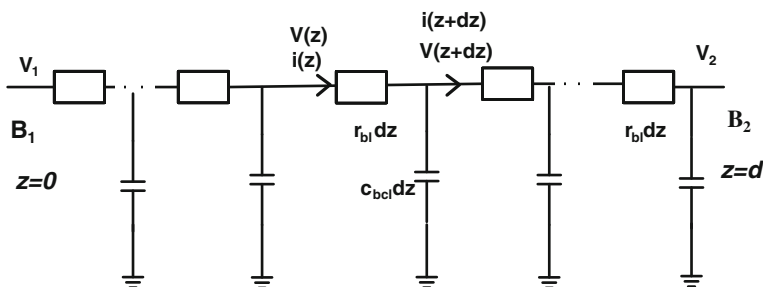


Fig. 5.2 Distributed network for the link region under the spacer oxide (only half of structure is shown due to the symmetry)

total length of the link base is assumed as $2d$. The distributed network for the region is shown in Fig. 5.2, where r_{bl} and c_{bcl} represent the series resistance and shunt capacitance of link base region, respectively.

As shown in Fig. 5.2, the current and voltage at arbitrary position from its beginning are assumed as $i(z)$ and $v(z)$. According to Kirchhoff's law, the telegrapher equations are given by

$$\begin{cases} \frac{d^2 v(z)}{dz^2} - \gamma^2 v(z) = 0 \\ \frac{d^2 i(z)}{dz^2} - \gamma^2 i(z) = 0 \end{cases} \quad (5.1)$$

where $\gamma = \sqrt{j\omega C_{bcl} r_{bl}}$ is the complex propagation constant. Combining the boundary conditions $v(0) = V_1$ and $v(d) = V_2$, the general solutions of (5.1) for $i(z)$ and $v(z)$ of the traveling wave in the transmission line can be written as

$$v(z) = \frac{V_1 e^{dr} - V_2}{e^{dr} - e^{-dr}} e^{-\gamma z} + \frac{V_2 - V_1 e^{-dr}}{e^{dr} - e^{-dr}} e^{\gamma z} \quad (5.2)$$

$$i(z) = \frac{\gamma}{r_{bx}} \left(\frac{V_1 e^{dr} - V_2}{e^{dr} - e^{-dr}} e^{-\gamma z} - \frac{V_2 - V_1 e^{-dr}}{e^{dr} - e^{-dr}} e^{\gamma z} \right) \quad (5.3)$$

Consequently, considering the structure symmetry, the admittance parameters for the whole link base region of the SiGe HBT with a CBEC layout are given as

$$Y_{11} = Y_{22} = \left. \frac{2i(0)}{V_1} \right|_{V_2=0} = \frac{2\gamma e^{dr} + e^{-dr}}{r_{bl} e^{dr} - e^{-dr}} \quad (5.4)$$

$$Y_{21} = Y_{12} = -\frac{2\gamma}{r_{bl}} \frac{2}{e^{dr} - e^{-dr}} \quad (5.5)$$

then

$$-Y_{12} = \frac{2\gamma}{r_{bx}} \frac{2}{e^{dr} - e^{-dr}} \quad (5.6)$$

$$Y_{11} + Y_{12} = Y_{22} + Y_{12} = \frac{2\gamma e^{dr} + e^{-dr} - 2}{r_{bl} e^{dr} - e^{-dr}} \quad (5.7)$$

According to Taylor-series expansion, $e^{\pm\gamma d}$ can be calculated as follows

$$e^{\pm\gamma d} = 1 \pm \gamma d + \frac{(\pm\gamma d)^2}{2!} + \frac{(\pm\gamma d)^3}{3!} + \dots + \frac{(\pm\gamma d)^n}{n!} + \dots \quad (5.8)$$

Considering the different levels of approximation in (5.8), different equivalent circuits will be obtained.

- (i) If γd is set as the highest degree term, i.e., $e^{\pm\gamma d} \approx 1 \pm \gamma d$, then (5.6) and (5.7) can be simplified as

$$Y_{12} = -\frac{2}{dr_{bl}} = -\frac{4}{R_{BL}} \quad (5.9)$$

$$Y_{11} + Y_{12} = Y_{22} + Y_{12} = 0 \quad (5.10)$$

where $R_{BL} = 2dr_{bl}$ is the total link base resistance. Using the characteristics of the well-known π network shown in Fig. 5.3a, the distributed network of the link base region can be equivalent to a simple resistance network, as shown in Fig. 5.3b.

- (ii) When the highest order term in (5.8) is set as $(\gamma d)^2$, we can derive

$$Y_{12} = -\frac{4}{R_{BL}} \quad (5.11)$$

$$Y_{11} + Y_{12} = Y_{11} + Y_{22} = j\omega C_{BCL}/2 \quad (5.12)$$

where $C_{BCL} = 2dc_{bcl}$ presents the total link BC junction capacitance under the spacer oxide. As a consequence, the distributed network for the link base region can be equivalent to the following form, as shown in Fig. 5.4.

- (iii) When the highest order terms in (5.8) is set as $(\gamma d)^3$, we can arrive at the following expressions

$$Y_{12} = -\frac{4\gamma d}{R_{BL}} \frac{1}{\gamma d + \frac{(\gamma d)^3}{3!}} \approx -\frac{4}{R_{BL}} \quad (5.13)$$

Fig. 5.3 **a** Typical characteristics of well-known network. **b** Equivalent circuit for the link base region when the highest degree term is set as rd

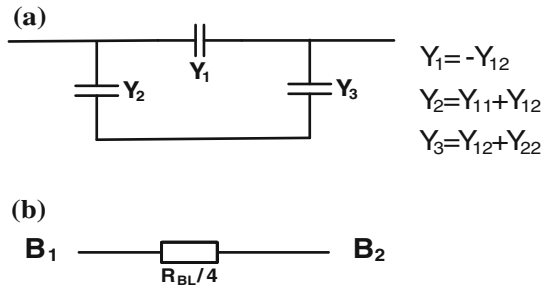


Fig. 5.4 Equivalent circuit for distributed network of link base region when the highest degree term is set to $(\gamma d)^2$

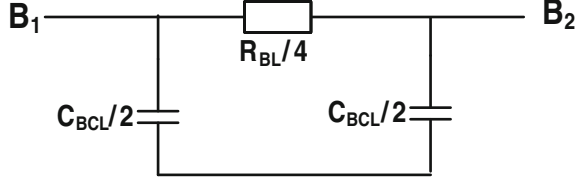
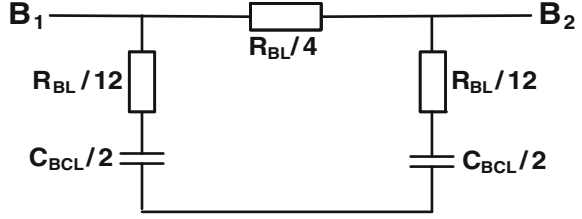


Fig. 5.5 Equivalent circuit for distributed network of link base region when the highest degree term is set to three times $(\gamma d)^3$



$$Y_{11} + Y_{12} = Y_{12} + Y_{22} = \frac{4\gamma d}{R_{BL}} \frac{\frac{(\gamma d)^2}{2}}{\left(\gamma d + \frac{(\gamma d)^3}{3!}\right)} = \frac{1}{\frac{R_{BL}}{12} + \frac{1}{\frac{j\omega C_{BCL}}{2}}} \quad (5.14)$$

According to (5.13) and (5.14), the equivalent circuit for the distributed network of region *I* can be reduced to the form as shown in Fig. 5.5.

- (iv) For the case of highest order terms larger than 3, it is demonstrated that the obtained equivalent circuit is the same as the case of third order, as shown in Fig. 5.5. For example, when the highest order term is set as $(\gamma d)^n$ ($n > 3$), (5.6) and (5.7) can be reduced as

$$Y_{12} = -\frac{4\gamma d}{R_{BX}} \frac{1}{\left(\gamma d + \frac{(\gamma d)^3}{3!}\right) + \sum_{i=0}^{+\infty} \frac{(\gamma d)^{(5+2i)}}{(5+2i)!}} \quad (5.15)$$

$$Y_{11} + Y_{12} = \frac{4d\gamma}{R_{BX}} \frac{\frac{(\gamma d)^2}{2} + \sum_{i=0}^{+\infty} \frac{(\gamma d)^{(4+2i)}}{(4+2i)!}}{\left(\gamma d + \frac{(\gamma d)^3}{3!}\right) + \sum_{i=0}^{+\infty} \frac{(\gamma d)^{(5+2i)}}{(5+2i)!}} \quad (5.16)$$

Under the assumption $|\gamma d| \ll 1$, $(\gamma d)^{(5+2i)}$ in the denominator is much smaller than $(\gamma d)^3$, and $(\gamma d)^{(4+2i)}$ in the numerator is also much smaller than $(\gamma d)^2$. Thus, (5.15) and (5.16) are then simplified to (5.13) and (5.14), respectively. Therefore, the equivalent circuit is the same with the case in which the highest order term is chosen as 3, shown in Fig. 5.5.

5.2.2 Intrinsic Transistor (Region II)

Next, the equivalent circuit for the intrinsic transistor region will be discussed. All the parameters are also assumed to be distributed uniformly along the intrinsic base region. The total length of this intrinsic base is assumed as $2l$. Figure 5.6 shows the distributed network for the intrinsic transistor, where r_{bi} , c_{tc} , and c_{te} are intrinsic base resistance, intrinsic BC junction capacitance, and intrinsic BE junction capacitance per unit length, respectively.

First, the admittance parameters Y_{11} and Y_{21} ($Y_{12} = Y_{21}$) of the two-port network shown in Fig. 5.6 are solved. The emitter terminal is connected to ground ($V_2 = 0$ V) and voltage V_1 is applied to base terminal B_1 . The equivalent distributed network is then simplified to the case of region I as shown in Fig. 5.2. However, the capacitance here represents the total of BE junction capacitance c_{te} and BC junction capacitance c_{tc} per unit length, and the resistance is the intrinsic base resistance r_{bi} per unit length. Using the transmission line equation and the boundary condition of $v(0) = V_1$ and $i(l) = 0$, the admittance Y_{11} for SiGe HBTs with CBEBC layout is given as

$$Y_{11} = \frac{2i(0)}{V_1} = \frac{2\beta}{r_{bi}} \left(\frac{e^{\beta l} - e^{-\beta l}}{e^{\beta l} + e^{-\beta l}} \right) \quad (5.17)$$

where $\beta = \sqrt{j\omega(c_{te} + c_{tc})r_{bi}}$. Here we define three parameters $i(0)$, $i_{C_{TE}}$, and $i_{C_{TC}}$ as the total current flowing into base terminal B_1 , the capacitance C_{TE} , and the capacitance C_{TC} , respectively, where $C_{TC} = c_{tc} * 2l$ and $C_{TE} = c_{te} * 2l$. According to Kirchhoff's law, we can obtain

$$-i(0) = i_{C_{TE}} + i_{C_{TC}} \quad (5.18)$$

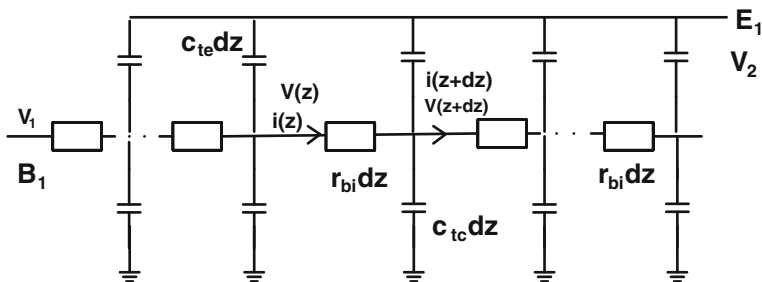


Fig. 5.6 Distributed network for the intrinsic transistor (region II shown in Fig. 5.1) under the cutoff state

Then the current $i_{C_{TE}}$ is given by

$$i_{C_{TE}} = -i(0) \frac{C_{TE}}{C_{TC} + C_{TE}} \quad (5.19)$$

By combining (5.17) and (5.19), we obtain the following equations

$$Y_{12} = Y_{21} = \frac{2i_{C_{TE}}}{V_1} = -\frac{2\beta e^{\beta l} - e^{-\beta l}}{r_{bi} e^{\beta l} + e^{-\beta l}} \frac{C_{TE}}{C_{TE} + C_{TC}} \quad (5.20)$$

$$Y_{11} + Y_{12} = \frac{2\beta e^{\beta l} - e^{-\beta l}}{r_{bi} e^{\beta l} + e^{-\beta l}} \frac{C_{TC}}{C_{TC} + C_{TE}} \quad (5.21)$$

Next, the admittance Y_{22} will be solved. Now the emitter terminal is applied to voltage V_2 , and base terminal B_1 is connected to ground. The current $i(z)$ and voltage $v(z)$ at arbitrary position z satisfies

$$\begin{cases} \frac{dv(z)}{dz} = -i(z)r_{bi} \\ \frac{di(z)}{dz} = -j\omega(c_{te} + c_{tc})v(z) + j\omega c_{te} V_2 \end{cases} \quad (5.22)$$

With the bound condition $v(0) = 0$ V and $i(d) = 0$ A, the voltage $v(z)$ and current $i(z)$ along the intrinsic base region at position z are obtained

$$v(z) = V_0^+ e^{-\beta z} + V_0^- e^{\beta z} + \frac{c_{te} V_2}{c_{te} + c_{tc}} \quad (5.23)$$

$$i(z) = \frac{\beta}{r_{bi}} (V_0^+ e^{-\beta z} - V_0^- e^{\beta z}) \quad (5.24)$$

where V_0^- and V_0^+ are given as

$$V_0^- = -\frac{C_{TE}}{C_{TC} + C_{TE}} \frac{1}{e^{2\beta l} + 1} V_2 \quad (5.25)$$

$$V_0^+ = -\frac{C_{TE}}{C_{TC} + C_{TE}} \frac{e^{2\beta l}}{e^{2\beta l} + 1} V_2 \quad (5.26)$$

The admittance Y_{22} is expressed as

$$Y_{22} = \frac{2 \int_0^l j\omega c_{te} (V_2 - v(z)) dz}{V_2} \quad (5.27)$$

Combining (5.23) and (5.27), the admittance Y_{22} can be rewritten as

$$Y_{22} = j\omega C_{TE} \frac{C_{TE}}{C_{TC} + C_{TE}} \left(\frac{C_{TC}}{C_{TE}} + \frac{1}{\beta l} \frac{e^{\beta l} - e^{-\beta l}}{e^{\beta l} + e^{-\beta l}} \right) \quad (5.28)$$

Then $Y_{12} + Y_{22}$ is given by

$$Y_{12} + Y_{22} = \frac{C_{TE}}{C_{TC} + C_{TE}} \left[\frac{e^{\beta l} - e^{-\beta l}}{e^{\beta l} + e^{-\beta l}} \left(j\omega C_{TE} - \frac{2\beta}{r_{bi}} \right) + j\omega C_{TC} \right] \quad (5.29)$$

- (i) Similarly, according to Taylor series expansion, if βl is set as the highest degree term (i.e., $e^{\beta l} \approx 1 + \beta l$), then (5.20), (5.21) and (5.29) are, respectively, simplified to

$$-Y_{12} \approx j\omega C_{TE} \quad (5.30)$$

$$Y_{11} + Y_{12} \approx j\omega C_{TC} \quad (5.31)$$

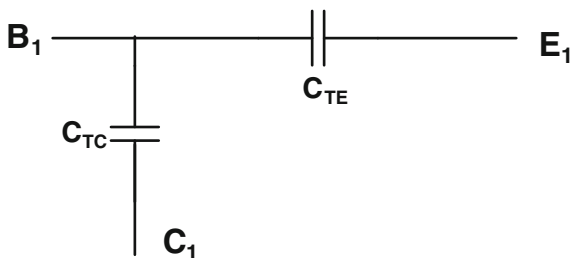
$$Y_{12} + Y_{22} \approx 0 \quad (5.32)$$

Hence, we can reach the equivalent circuit for the intrinsic transistors, as shown in Fig. 5.7. It is deserved to note that the resistance R_{BI} does not appear. Even in a simple single pole description of the internal base, the RC product will be visible. Therefore, the approximation of $e^{\beta l} \approx 1 + \beta l$ here is not reasonable, and a higher order approximation should be used.

- (ii) When the highest degree terms in (5.20), (5.21), and (5.29) are chosen as second order ($e^{\beta l} \approx 1 + \beta l + \frac{(\beta l)^2}{2!}$), we can derive

$$Y_{12} \approx - \frac{1}{\frac{C_{TC} + C_{TE}}{C_{TE}} * \frac{R_{BI}}{8} + \frac{1}{j\omega C_{TE}}} \quad (5.33)$$

Fig. 5.7 Equivalent circuit for the intrinsic transistor distributed network when the highest degree term is set to one time βl



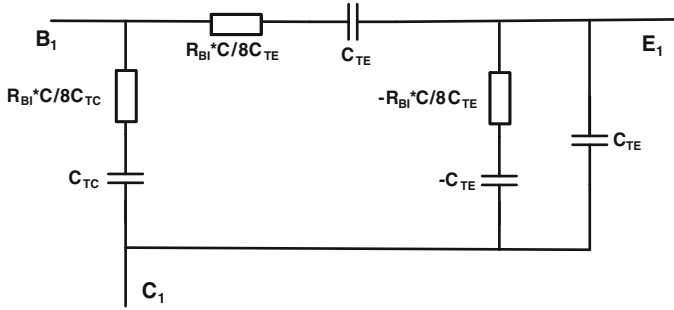


Fig. 5.8 Equivalent circuit for distributed network of intrinsic transistor when the highest degree term is set to two times $(\beta l)^2/2$

$$Y_{11} + Y_{12} \approx \frac{1}{\frac{C_{TC} + C_{TE}}{C_{TC}} * \frac{R_{BI}}{8} + \frac{1}{j\omega C_{TC}}} \quad (5.34)$$

$$Y_{12} + Y_{22} = \frac{1}{-\frac{R_{BI}}{8} * \frac{C_{TC} + C_{TE}}{C_{TE}} - \frac{1}{j\omega C_{TE}}} + j\omega C_{TE} \quad (5.35)$$

where $R_{BI} = 2lr_{bi}$ is the total intrinsic base resistance. Then the distributed network of intrinsic transistor can be approximated with the following form, as shown in Fig. 5.8, where $C = C_{TE} + C_{TC}$.

(iii) When the highest degree terms in Taylor series expansion are chosen as third order $(\beta l)^3$, then (5.20), (5.21), and (5.29) can be approximately rewritten as

$$Y_{12} \approx -\frac{1}{\frac{1}{j\omega C_{TE}} + \frac{C_{TC} + C_{TE}}{C_{TE}} * \frac{R_{BI}}{12}} \quad (5.36)$$

$$Y_{11} + Y_{12} \approx \frac{1}{\frac{1}{j\omega C_{TC}} + \frac{C_{TC} + C_{TE}}{C_{TC}} * \frac{R_{BI}}{12}} \quad (5.37)$$

$$Y_{12} + Y_{22} \approx -\frac{1}{\frac{1}{j\omega C_{TE}} + \frac{C_{TC} + C_{TE}}{C_{TE}} * \frac{R_{BI}}{12}} + j\omega C_{TE} \quad (5.38)$$

Therefore, the distributed network of intrinsic transistor can be equivalent to the following circuit, as depicted in Fig. 5.9.

Undoubtedly, the more accurate the approximation of $e^{\beta l}$, the more general the equivalent circuit will be. Therefore, compared with the case of $e^{\beta l} \approx 1 + \beta l + (\beta l)^2/2$, the equivalent circuit for the approximation of $e^{\beta l} \approx 1 + \beta l + (\beta l)^2/2 + (\beta l)^3/6$ is more precise. Besides, the factor 1/12 here is consistent with the result of the dc-current crowding effect. Of course, one can also

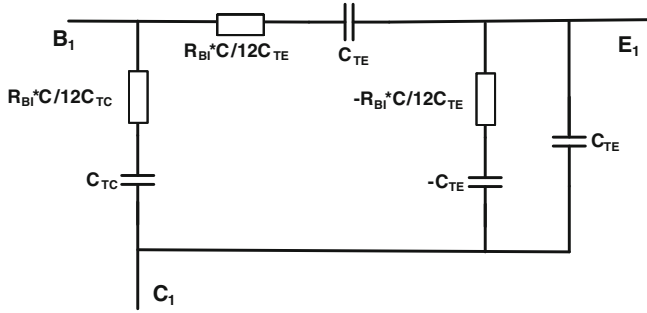


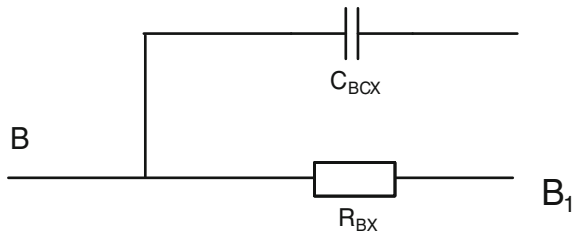
Fig. 5.9 Equivalent circuit for distributed network of intrinsic transistor when the highest degree term is set to three times $(\beta l)^3$

calculate higher order corrections, and try to find a more general fitting circuit to physical transistor network; however, the equivalent circuit may be far more complicated and we avoid doing this. Similarly, when the chosen highest degree term is larger than three times, (5.20), (5.21), and (5.29) will be reduced to the case of order 3 under the assumption $|\beta l| \ll 1$. Therefore, the result in Fig. 5.9 is adopted as the final equivalent circuit for the intrinsic transistor.

5.2.3 Extrinsic Base Region (Region III)

For the extrinsic BC junction (region III) as shown in Fig. 5.1, the extrinsic base resistance R_{BX} is generally very small due to the existence of metal silicides and heavily doped polysilicon [10]. For simplicity, it can be equivalent to a lumped RC network, as shown in Fig. 5.10, where C_{BCX} represents the extrinsic base-collector capacitance.

Fig. 5.10 Equivalent circuit for extrinsic base region, where a simple resistance and capacitance parallel network is used



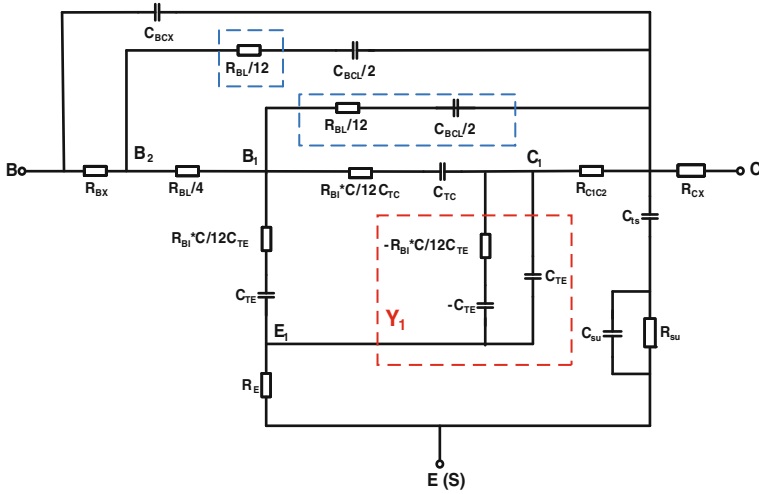


Fig. 5.11 Small-signal equivalent circuit for SiGe HBT under common emitter configuration, where the substrate network adopts a parallel RC block connected in series with C_{ts}

5.2.4 Equivalent Circuit for the Whole Transistor

After the equivalent circuits for link base, intrinsic transistor and extrinsic base region are determined, the small-signal equivalent circuit for SiGe HBTs with CBEBC layout under common emitter configuration can be obtained, as shown in Fig. 5.11. R_{CX} and R_{C1C2} represent the constant part and the bias-dependent part of collector resistance. The emitter resistance R_E and collector resistances R_{CX} , R_{C1C2} are all treated as lumped elements and connected to the distributed model common nodes of the emitter and collector, respectively. The substrate network adopts a conventional parallel RC block (substrate resistance R_{SU} and bulk capacitance C_{SU}) connected in series with collector-substrate depletion capacitance C_{ts} .

5.3 Approximation and Simplification of Proposed Model

As shown in Fig. 5.11, there are as many as 13 unknown elements to be extracted in the proposed small-signal equivalent circuit. It is necessary to simplify the equivalent circuit in order to extract the model parameters accurately. The networks circled by the solid line are first dealt with and the admittance Y_1 is given by

$$Y_1 = j\omega C_{TE} + \frac{1}{-\frac{1}{j\omega C_{TE}} \left(1 + j\omega C_{TE} R_{BI} \frac{C_{TE} + C_{TC}}{12C_{TE}} \right)} \approx 0 \big|_{\omega C_{TE} R_{BI} \ll 1} \quad (5.39)$$

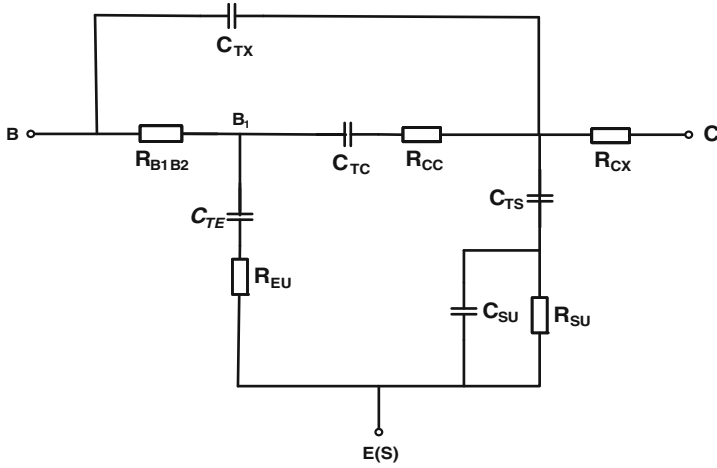


Fig. 5.12 Simplified small-signal equivalent circuit for the proposed SiGe HBTs model under common emitter configuration, after the admittance Y_1 , resistance R_{BX} , $R_{BL}/12$ and capacitance $C_{BCL}/2$ are ignored

under the assumption $|\omega C_{TE} R_{BI}| \ll 1$. This means that it can be considered open when the above assumption is adopted. As mentioned above, due to the heavily doped extrinsic base and silicides, R_{BX} can be ignored. Besides, for the sake of parameter extraction, the networks circled by the dashed line (resistance $R_{BL}/12$ and resistance $R_{BL}/12$ in series with $C_{BCL}/2$), are also ignored. As a result, the circuit can be reduced to the following form as shown in Fig. 5.12, where

$$R_{B1B2} = R_{BL}/4 \quad (5.40)$$

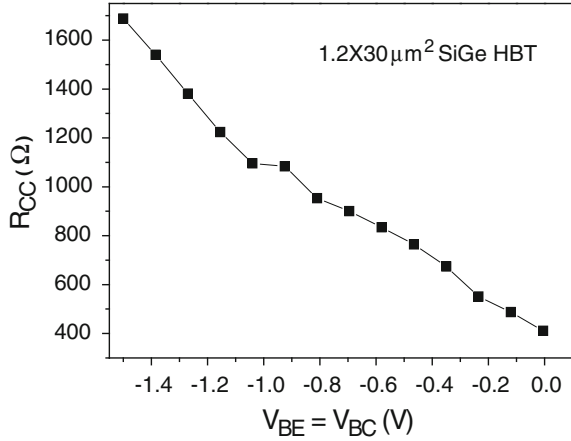
$$R_{EU} = R_E + \frac{R_{BI}}{12} \frac{C_{TE} + C_{TC}}{C_{TE}} \quad (5.41)$$

$$R_{CC} = R_{C1C2} + \frac{R_{BI}}{12} \frac{C_{TE} + C_{TC}}{C_{TC}} \quad (5.42)$$

$$C_{TX} = C_{BCX} + C_{BCL}/2 \quad (5.43)$$

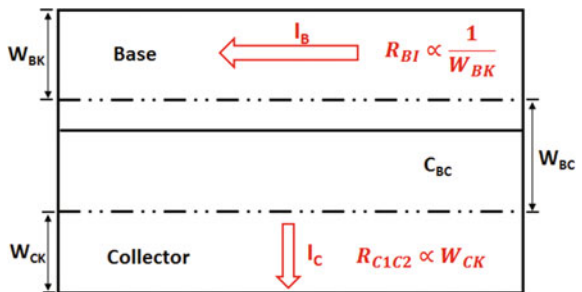
It is noted that the simplified small-signal model, as depicted in Fig. 5.12, has similar topology structure with the previous reported MEXTRAM model. However, the physical meanings of the model elements, especially R_{B1B2} , R_{CU} , and R_{EU} , are obviously different. In the conventional MEXTRAM, R_{B1B2} , R_{EU} , and R_{CU} are separately intrinsic base resistance, emitter resistance, and bias-dependent collector resistance. But in our proposed model, R_{B1B2} is a quarter of the link base resistance, and the real intrinsic base resistance has been pushed into the node B_1 and is added to the emitter and collector resistances. R_{EU} and R_{CU} here are the equivalent emitter and collector resistances, and the details are shown in (5.41) and (5.42).

Fig. 5.13 Bias dependence of collector resistance R_{CC} for $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT under $V_E = V_C = V_S = 0 \text{ V}$, $V_B = -1.5$ to 0 V



As shown in reference [11] the bias-dependent collector resistance R_{CC} increases with the reverse-biased voltage V_B increasing, as shown in Fig. 5.13, which is not explained in conventional MEXTRAM. According to the cross-sectional view of BC junction as depicted in Fig. 5.14, the base-collector depletion width W_{BC} decreases with V_{BC} increasing due to a decreased reverse bias voltage across the junction. According to the cross-sectional view of BC junction as depicted in Fig. 5.14, the base-collector depletion width W_{BC} decreases with V_{BC} increasing, due to a decreased reverse bias voltage across the junction. Therefore, the width of the neutral collector region W_{CK} increases, leading to the increase of collector resistance R_{C1C2} , which obviously does not match the results in Fig. 5.13. However, in our proposed model, R_{CU} is an equivalent collector resistance and contains some part of intrinsic base resistance R_{BI} . The width of neutral base region W_{BK} also increases with increasing V_{BC} , leading to a reduction in R_{BI} . Besides, the ratio $(C_{BEI} + C_{BCI})/C_{BCI}$ is very large due to a larger C_{BEI} compared to C_{BCI} . As a result, it might be the decreased R_{BI} that causes the decline in R_{CU} with increasing V_{BC} [12].

Fig. 5.14 Simplified schematic cross-section for BC junction of SiGe HBT



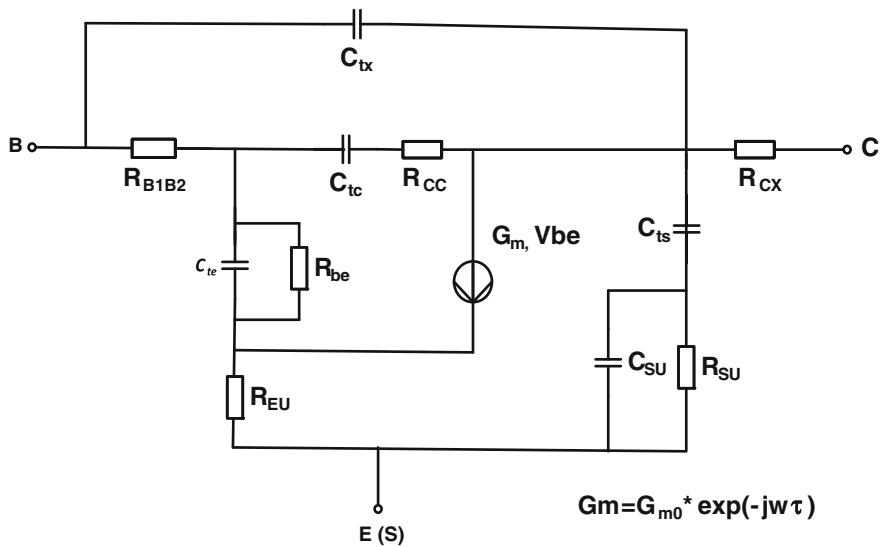


Fig. 5.15 Small-signal equivalent-circuit model for SiGe HBTs in the forward-active region

The small-signal equivalent-circuit model in the forward-active mode can be directly obtained from the equivalent circuit under off state, by adding a dynamic diffusion resistance of BE junction (R_{be}) and a voltage-controlled current source, as shown in Fig. 5.15. G_m is expressed as

$$G_m = G_{m0} * \exp(-j\omega\tau) \quad (5.44)$$

where G_{m0} and τ are separately the intrinsic transconductance at low frequencies and the base transit time.

5.4 Conclusion

In this chapter, an improved high-frequency, small-signal model for SiGe HBTs has been presented. The proposed model takes into account the distribution characteristics of the intrinsic transistor, link base region under spacer, and extrinsic base-collector junction. The equivalent circuit for each region is separately derived using the transmission line equation with reasonable approximations. The proposed model can theoretically explain the anomalous bias dependence of the epitaxial layer resistance R_{CC} in the traditional MEXTRAM model.

References

1. B.R. Chawla, Circuit representation of the integral charge-control model of bipolar transistors. *IEEE J. Solid-State Circuits* **6**(4), 262–264 (1971)
2. C. McAndrew, J. Seitchik, D. Bowers, M. Dunn, M. Foisy, I. Getreu, M. McSwain, S. Moinian, J. Parker, P. van Wijnenand, L. Wagner, VBIC95: an improved vertical, IC bipolar transistor model, in *IEEE Bipolar/BiCMOS Circuits and Technology Meeting, Minneapolis, MN* (1995), pp. 170–177
3. M. Schröter, A. Chakravorty, *Compact Hierarchical Modeling of Bipolar Transistors with HiCUM* (World Scientific, Singapore, 2010)
4. R. Van Der Toorn, J.C.J. Paasschens, W.J. Kloosterman, *The Mextram Bipolar Transistor Model level 504.11.0* (Delft University of Technology, Delft, 2012)
5. J.D. Cressler, *Measurement and Modeling of Silicon Heterostructure Devices* (CRC Press, Boca Raton, FL, 2008)
6. H.S. Rhee, S. Lee, B.R. Kim, DC and AC current crowding effects model analysis in bipolar junction transistors using a new extraction method. *Solid State Electron.* **38**(1), 31–35 (1995)
7. M. Schröter, A. Chakravorty, *Compact Hierarchical Bipolar Transistor Modeling With HiCUM* (World Scientific, Singapore, 2010)
8. S. Diez, M. Lozano, G. Pellegrini, F. Campabadal, I. Diez, D. Knoll, B. Heinemannand, M. Ullan, Proton radiation damage on SiGe: C HBTs and additivity of ionization and displacement effects. *IEEE Trans. Nucl. Sci.* **56**(4), 1931–1936 (2009)
9. Y. Sun, J. Fu, J. Xu, Y. Wang, W. Zhou, W. Zhang, J. Cui, G. Liand, Z. Liu, Irradiation effects of 25 MeV silicon ions on SiGe heterojunction bipolar transistors. *Nucl. Instrum. Methods Phys. Res. Sect. B* **312**, 77–83 (2013)
10. E. Ojefors, J. Grzyb, Z. Yan, B. Heinemann, B. Tillackand, U.R. Pfeiffer, A 820 GHz SiGe chipset for terahertz active imaging applications, in *IEEE International Solid- State Circuits Conference. San Francisco, CA, USA* (2011)
11. J. Yang, *Research on Mextram Model and Parameter Extraction for SiGe HBTs* (Institute of Microelectronics, Tsinghua University, Beijing, China, 2014)
12. Y. Sun, J. Fu, J. Yang, J. Xu, Y. Wang, J. Cui, W. Zhouand, Z. Wei, An improved small-signal model for SiGe HBT under off-state, derived from distributed network and corresponding model parameter extraction. *IEEE Trans. Microw. Theory Techn.* **63**(10), 3131–3141 (2015)

Chapter 6

Parameter Extraction of SiGe HBTs

There are two kinds of parameter extraction methods for SiGe HBT small-signal equivalent circuit, i.e., numerical optimization [1–3] and analytical extraction [4–6]. The extracted results using the numerical optimization strongly depends on the initial value and the selection of simulation tool. Direct analytical extraction method is generally based on the frequency response. Certain reasonable assumptions and approximations are adopted to simplify the circuit equation to obtain the corresponding model parameters [7, 8]. The barrier capacitances of BE junction, BC junction and CS junction are extracted with the low-frequency approximation under off-state [4]. The ratio of the intrinsic and extrinsic BC junction barrier capacitor is directly obtained by $\text{Re}(Y_{12})$ under the forward active mode [9]. Model parameters related with voltage-controlled current source (such as intrinsic transconductance G_{mo} , phase delay τ) are determined by ABCD parameters under common-collector orientation [10]. These studies have laid a good foundation for the SiGe HBT parameter extraction, providing a reference for new methods exploration, but there are still some shortcomings. First, the approximations are based on the frequency dependence of model parameters, assuming the higher order terms are generally much smaller than the lower ones. However, an error will be introduced depending on the validity of the assumptions. Furthermore, these assumptions are not always held for different process technologies and device geometries. Secondly, all model parameters are not simultaneously obtained at certain bias condition. The conversion of model parameters under different bias states are only achieved when the corresponding bias dependence is available, however, the bias dependence is often unknown in advance. In addition, some special test structures are needed when extracting certain model parameters, such as test layout with two independent base contact for determining base resistance in Tetrode method [11]. Therefore, an accurate extraction technique over the whole range of frequencies is necessary to model device performance.

This chapter presents a direct analytic parameter extraction for SiGe HBT small signal equivalent circuit, based on nonlinear rational function fitting. This chapter is arranged as follows. The feasibility of parameter extraction under the conventional

conditions, inducing off-state and forward-active mode, is first presented in Sect. 6.1. In Sect. 6.2, we mainly discuss the parameter extraction in space radiation environment, taking 10 MeV Cl ions as an example. In Sect. 6.3, parameter extractions under high and low temperature environment (-55 to -200 °C) are discussed.

6.1 Small-Signal Model Parameter Extraction

6.1.1 Parameter Extraction Under Off-State

The feasibility of proposed parameter extraction method in non-irradiated environment is first validated in this chapter. The small-signal model parameter extraction under off-state is the precondition of the whole circuit parameters extraction. In order to obtain the model parameters in Fig. 5.13, the constant collector resistance R_{CX} is first extracted through conventional flyback method and then removed from the small-signal equivalent circuit. After removing R_{CX} , the admittance matrix $[Y_k]$ are given by

$$Y_{11} = \frac{\frac{j\omega C_{TE}}{1+j\omega R_{EU}C_{TE}} + \frac{j\omega C_{TC}}{1+j\omega R_{CC}C_{TC}}}{1 + \frac{j\omega R_{B1B2}C_{TE}}{1+j\omega R_{EU}C_{TE}} + \frac{j\omega R_{B1B2}C_{TC}}{1+j\omega R_{CC}C_{TC}}} + j\omega C_{TX} \quad (6.1)$$

$$Y_{12} = Y_{21} = -\frac{\frac{j\omega C_{TC}}{1+j\omega R_{CC}C_{TC}}}{1 + \frac{j\omega R_{B1B2}C_{TE}}{1+j\omega R_{EU}C_{TE}} + \frac{j\omega R_{B1B2}C_{TC}}{1+j\omega R_{CC}C_{TC}}} - j\omega C_{TX} \quad (6.2)$$

$$Y_{22} = \frac{\frac{j\omega C_{TC}}{1+j\omega R_{CC}C_{TC}} - \frac{\omega^2 R_{B1B2}C_{TE}C_{TC}}{(1+j\omega R_{EU}C_{TE})(1+j\omega R_{CC}C_{TC})}}{1 + \frac{j\omega R_{B1B2}C_{TE}}{1+j\omega R_{EU}C_{TE}} + \frac{j\omega R_{B1B2}C_{TC}}{1+j\omega R_{CC}C_{TC}}} + \frac{\omega^2 \frac{R_{SU}}{1+j\omega R_{SU}C_{SUB}} C_{IS}^2 + j\omega C_{IS}}{1 + \frac{(\omega R_{SU}C_{IS})^2}{1+j\omega R_{SU}C_{SUB}}} + j\omega C_{TX} \quad (6.3)$$

Combining (6.1)–(6.3), we can obtain

$$\text{Im}(Y_{11} + Y_{12}) = \frac{N_{11}\omega^3 + N_{10}\omega}{M_{12}\omega^4 + M_{11}\omega^2 + 1} \quad (6.4)$$

$$\text{Re}(Y_{11} + Y_{12}) = \frac{N_{21}\omega^4 + N_{20}\omega^2}{M_{12}\omega^4 + M_{11}\omega^2 + 1} \quad (6.5)$$

$$\text{Im}(-Y_{12}) = \frac{N_{32}\omega^5 + N_{31}\omega^3 + N_{30}\omega}{M_{12}\omega^4 + M_{11}\omega^2 + 1} \quad (6.6)$$

$$\operatorname{Re}(-Y_{12}) = \frac{N_{41}\omega^4 + N_{40}\omega^2}{M_{12}\omega^4 + M_{11}\omega^2 + 1} \quad (6.7)$$

$$\operatorname{Im}(Y_{12} + Y_{22}) = \frac{N_{53}\omega^7 + N_{52}\omega^5 + N_{51}\omega^3 + N_{50}\omega}{M_{23}\omega^6 + M_{22}\omega^4 + M_{21}\omega^2 + 1} \quad (6.8)$$

$$\operatorname{Re}(Y_{12} + Y_{22}) = \frac{N_{63}\omega^8 + N_{62}\omega^6 + N_{61}\omega^4 + N_{60}\omega^2}{M_{23}\omega^6 + M_{22}\omega^4 + M_{21}\omega^2 + 1} \quad (6.9)$$

where

$$N_{10} = C_{\text{TE}} \quad (6.10)$$

$$N_{20} = C_{\text{TE}}(R_{\text{EU}}C_{\text{TE}} + R_{\text{B1B2}}C_{\text{TE}} + R_{\text{B1B2}}C_{\text{TC}}) \quad (6.11)$$

$$N_{30} = C_{\text{TC}} + C_{\text{TX}} \quad (6.12)$$

$$N_{40} = C_{\text{TC}}(R_{\text{B1B2}}C_{\text{TE}} + R_{\text{B1B2}}C_{\text{TC}} + R_{\text{CC}}C_{\text{TC}}) \quad (6.13)$$

$$N_{50} = C_{\text{TS}} \quad (6.14)$$

$$N_{60} = R_{\text{SU}}C_{\text{IS}} - R_{\text{B1B2}}C_{\text{TE}}C_{\text{TC}} \quad (6.15)$$

Other high-order terms' coefficients N_{ij} and M_{ij} in (6.4)–(6.9) are all function of C_{TX} , C_{TC} , C_{TE} , C_{TS} , R_{CU} , R_{B1B2} and R_{SU} , and the details are not shown here.

The constants N_{i0} ($i = 1-6$) can be determined from the non-linear rational function fitting to (6.4)–(6.9) respectively [12], considered as a function of ω . The typical fitting results for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT biased at $V_{\text{BE}} = V_{\text{CE}} = 0 \text{ V}$ are shown in Fig. 6.1, from which an excellent agreement between the measured and fitted data over the whole frequency range (from 100 MHz to 20.89 GHz) are observed. Table 6.1 depicts the fitted constant terms N_{i0} ($i = 1-6$) and the corresponding confidence intervals. As shown in Table 6.1, the confidence intervals for the extracted N_{i0} ($i = 1-6$) are narrow and hence the calculation error is small.

In order to extract all the model parameters, R_{B1B2} and C_{TC} should be determined first. Combinng (6.5) and (6.7), at low frequency range R_{B1B2} is given as [10]

$$\begin{aligned} \frac{\operatorname{Re}(Y_{11} + Y_{12})}{\operatorname{Re}(Y_{11})} * \operatorname{Re}\left(\frac{1}{Y_{11} + Y_{12}}\right) &\approx \frac{[(C_{\text{TC}} + C_{\text{TE}})R_{\text{B1B2}} + C_{\text{TE}}R_{\text{EU}}]^2}{(C_{\text{TC}} + C_{\text{TE}})^2 R_{\text{B1B2}} + C_{\text{TC}}R_{\text{CU}} + C_{\text{TE}}^2 R_{\text{EU}}} \\ &\approx R_{\text{B1B2}} \end{aligned} \quad (6.16)$$

The typical result for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT under $V_{\text{BE}} = V_{\text{CE}} = 0 \text{ V}$ is depicted in Fig. 6.2. The extracted R_{B1B2} is almost independent of frequency, and

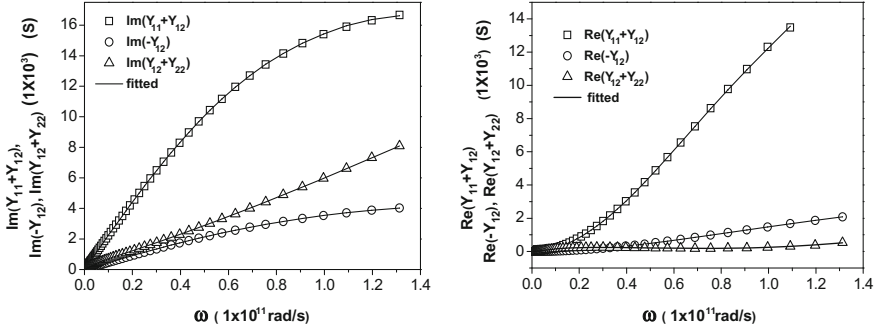
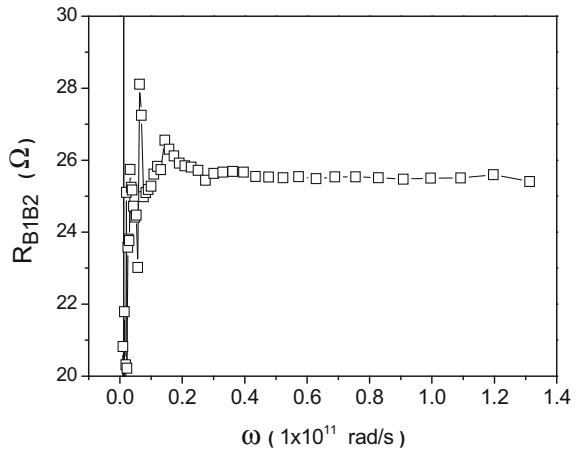


Fig. 6.1 Measured (symbol) and fitted (line) data of (6.4)–(6.9) versus ω for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT biased at $V_{\text{BE}} = V_{\text{CE}} = 0 \text{ V}$

Table 6.1 The calculated N_{i0} ($i = 1-6$) and confidence intervals (CIs) based on rational function fitting for $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT biased at $V_{\text{BE}} = V_{\text{CE}} = 0 \text{ V}$

Variable	Value	Confidence intervals (CIs)
$N_{10}(1\text{e-}13)$	2.253	(2.251, 2.255)
$N_{20}(1\text{e-}24)$	1.513	(1.497, 1.528)
$N_{30}(1\text{e-}13)$	0.4602	(0.4602, 0.4603)
$N_{40}(1\text{e-}24)$	0.2155	(0.2136, 0.2173)
$N_{50}(1\text{e-}13)$	0.8523	(0.8483, 0.8562)
$N_{60}(1\text{e-}24)$	3.482	(3.354, 3.61)

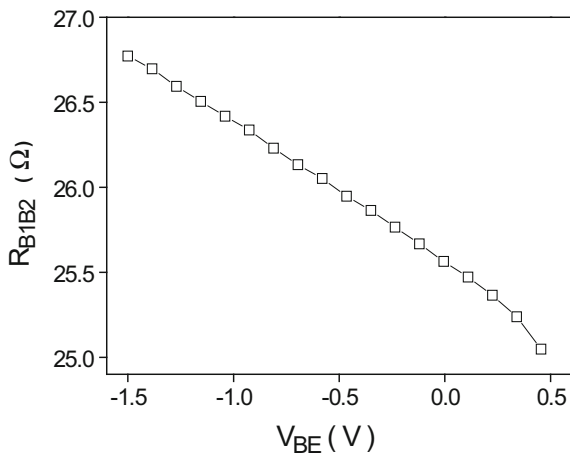
Fig. 6.2 Frequency dependence of extracted R_{BIB2} for $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT under $V_{\text{BE}} = V_{\text{CE}} = 0 \text{ V}$



monotonically decreases with V_{BE} increasing, as shown respensted in Fig. 6.3, which a result of an increment of the neutral base region width.

Assuming that $R_{\text{BIB2}} \gg R_{\text{EU}}$, $C_{\text{TE}} \gg C_{\text{TC}}$ at low frequency range, then $\text{Re}(Y_{11})$ can be simplified as [10]

Fig. 6.3 Bias dependence of extracted R_{B1B2} for $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT



$$\text{Re}(Y_{11}) \approx \frac{\omega^2 R_{B1B2} (C_{TE} + C_{TC})^2}{1 + \omega^2 R_{B1B2}^2 (C_{TE} + C_{TC})^2} \quad (6.17)$$

For a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT under $V_{BE} = V_{CE} = 0$ V, the typical fitting result of Eq. (6.17) is depicted in Fig. 6.4, and the fitted coefficient of $\beta = R_{B1B2} (C_{TE} + C_{TC})^2$ is $1.53 \times 10^{-24} \Omega\text{F}^2$. The intrinsic capacitance C_{TC} and C_{TX} can be determined as

$$C_{TC} = (\beta / R_{B1B2})^{0.5} - C_{TE} \quad (6.18)$$

$$C_{TX} = N_{30} - C_{TC} \quad (6.19)$$

Fig. 6.4 $\text{Re}(Y_{11})$ versus ω for the $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT biased at $V_{BE} = V_{CE} = 0$ V

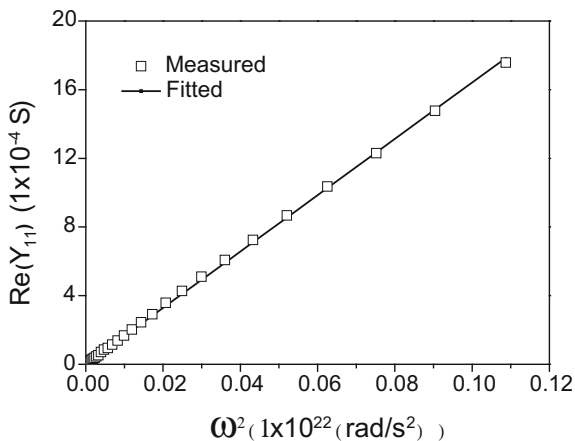
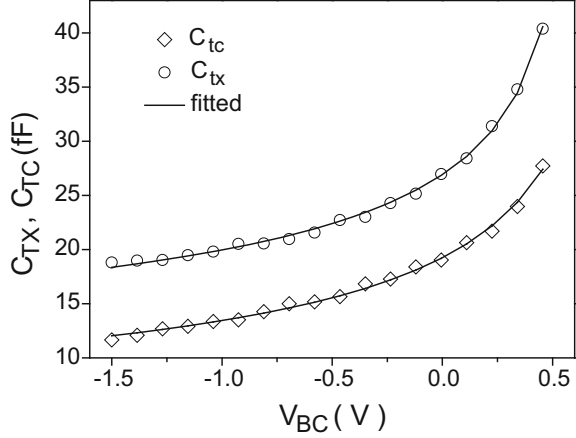


Fig. 6.5 Bias dependence of extracted C_{TX} , C_{TC} as function of V_{BC} for the $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT



Then the intrinsic BC capacitance C_{TC} can be extracted as 19.05 fF. The bias dependences of extracted C_{TC} and C_{TX} are depicted in Fig. 6.5. The solid line is the empirical fitting by the equation $C_{XX} = C_{XX,0}(1 - V_{BC}/V_{XXi})^{-z_{XX}}$, where XX represents ‘TX’ or ‘TC’. The fitted values are 19.25 fF, 26.92 fF, 0.84 V, 0.62 V, 0.46 and 0.31 for $C_{TC,0}$, $C_{TX,0}$, V_{TCi} , V_{TXi} , Z_{TC} and Z_{TX} , respectively.

Combining (6.11), (6.13) and (6.15), we can extract the equivalent emitter resistance R_{EU} , collector resistance R_{CU} and substrate resistance R_{SU} through the following equation

$$R_{EU} = \frac{N_{20}}{C_{TE}^2} - \frac{R_{B1B2}(C_{TE} + C_{TC})}{C_{TE}} \quad (6.20)$$

$$R_{CC} = \frac{N_{40}}{C_{TC}^2} - \frac{R_{B1B2}(C_{TE} + C_{TC})}{C_{TC}} \quad (6.21)$$

$$R_{SU} = \frac{N_{60} + R_{B1B2}C_{TE}C_{TC}}{C_{TS}^2} \quad (6.22)$$

We find $R_{EU} = 2.08 \Omega$, $R_{CU} = 273.46 \Omega$ and $R_{su} = 494.46 \Omega$ for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT at $V_{BE} = V_{CE} = 0$ V. Figures 6.6 and 6.7 shows the bias dependence of extracted R_{EU} , R_{CU} and R_{SU} as function of V_{BE} or V_{SC} , respectively. Emitter resistance is found invariable with increasing V_{BE} . The substrate resistance R_{SU} is found to increase and collector resistance R_{CU} decreases with increasing V_{SC} (or V_{BC}), as shown in Fig. 6.7b. According to the space charge region broadening effect, the substrate resistance R_{SU} is expected to increase with increasing V_{SC} ($V_{BC} = V_{SC}$). But the variation of collector resistance R_{CU} is not well explained in the conventional compact model [13, 14]. According to the cross-sectional view of BC junction, the base-collector depletion width W_{BC} decreases with increasing V_{BC} , due to a decreased reverse bias voltage across the junction. Therefore, the width of the neutral collector

Fig. 6.6 Bias dependence of extracted R_{EU} versus V_{BE} for $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT

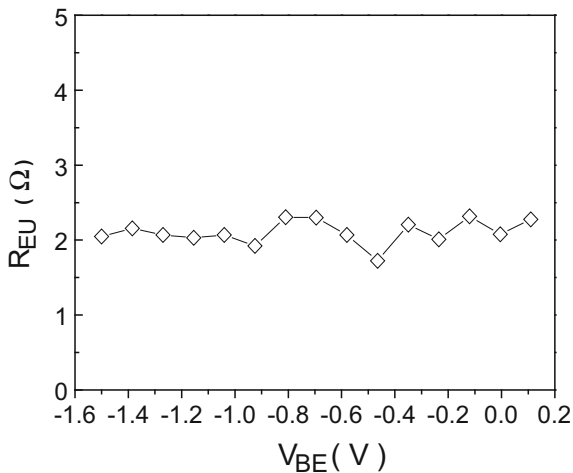
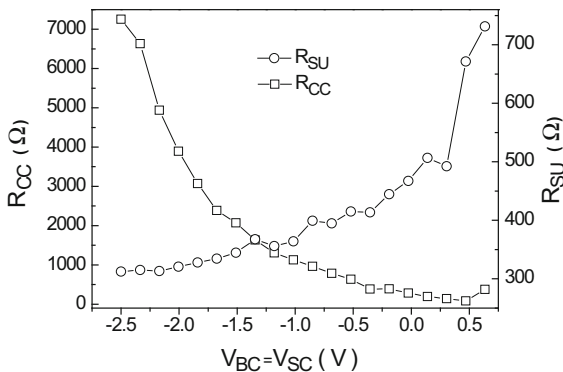


Fig. 6.7 Bias dependence of R_{CC} and R_{SU} versus V_{BE} for $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT



region W_{CK} increases, leading to the increase of collector resistance R_{C1C2} , which obviously does not match the results in Fig. 6.7b. However, in our proposed model, R_{CU} is an equivalent collector resistance and contains some part of intrinsic base resistance R_{BI} . The width of neutral base region W_{BK} also increases with increasing V_{BC} , leading to a reduction of R_{BI} . Besides, the ratio $(C_{BEI} + C_{BCI})/C_{BCI}$ is very large due to a larger C_{BEI} compared to C_{BCI} . As a result, it might be the decreased R_{BI} that causes the decline in R_{CU} with increasing V_{BC} .

The only remaining parameter in the small-signal equivalent circuit is the substrate bulk capacitance C_{sub} . Combining (6.8) and (6.9), we arrive at the following equation

$$X = \frac{N_{72}\omega^8 + N_{71}\omega^6 + N_{70}\omega^4}{M_{23}\omega^6 + M_{22}\omega^4 + M_{21}\omega^2 + 1} \quad (6.23)$$

where

$$N_{70} = a * C_{SU}^2 + b * C_{SU} + c \quad (6.24)$$

$$a = C_{TS}^3 R_{SU}^3 \quad (6.25)$$

$$b = C_{TC} C_{TE} C_{TS}^2 R_{B1B2} R_{SU}^3 + C_{TS}^4 R_{SU}^3 \quad (6.26)$$

$$\begin{aligned} c = & -C_{TC}^3 C_{TE} R_{B1B2} (R_{B1B2} + R_{C1C2}) (C_{TE} R_{B1B2} + C_{TS} (R_{B1B2} + R_{C1C2})) \\ & - C_{TC} C_{TE}^3 C_{TS} R_{B1B2} (R_{B1B2} + R_E)^2 + C_{TC} C_{TE}^2 C_{TS}^2 R_{B1B}^2 (R_{B1B2} + R_E) R_{SU} \\ & + C_{TC} C_{TE} C_{TS}^2 R_{B1B2} R_{SU}^2 - C_{TC}^2 C_{TE} R_{B1B2} (C_{TE}^2 R_{B1B2} (R_{B1B2} + R_E)) \\ & + C_{TE} C_{TS} [2R_{B1B2}^2 + R_{C1C2} R_E + R_{B1B2} (R_{C1C2} + R_E)] \\ & - C_{TS}^2 (R_{B1B2} + R_{C1C2}) R_{SU} \end{aligned} \quad (6.27)$$

Then C_{sub} can be directly obtained as

$$C_{SU} = \frac{-b + \sqrt{b^2 - 4a(c - N_{70})}}{2 * a} \quad (6.28)$$

Figure 6.8 depicts the plot of X as a function of ω^2 for $1 \times 1.2 \times 30 \mu m^2$ SiGe HBT biased at $V_{BE} = V_{CE} = 0$ V, from which an excellent agreement is obtained between the measured and fitted data, and the coefficient N_{70} is fitted as $2.746 \times 10^{-57} F^5 \Omega^3$. Then the bulk capacitance C_{sub} is given as 140.6 fF according to (6.28). Figure 6.9 shows the bias dependence of extracted C_{sub} versus V_{CS} . A slightly increase in C_{sub} is found with increasing V_{CS} , which is a result of the decreased neutral substrate region and which is consistent with previous report in [10].

By far all the model parameters in the small-signal equivalent circuit have been extracted. Noting that the model parameter extraction here is performed at the same

Fig. 6.8 X versus ω^2 for $1 \times 1.2 \times 30 \mu m^2$ SiGe HBTs at $V_{BE} = V_{CE} = 0$ V

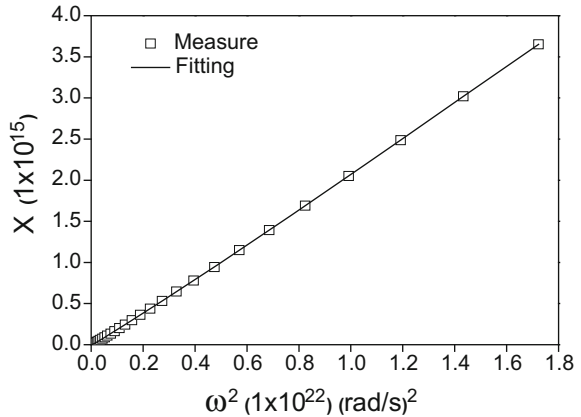


Fig. 6.9 Bias dependence of C_{sub} for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT

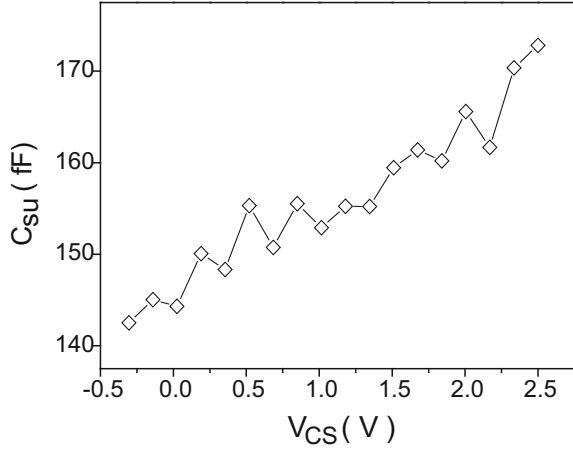


Table 6.2 Extracted model parameter for $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT under $V_{\text{BE}} = V_{\text{CE}} = 0 \text{ V}$

Vara.	Resistance (Ω)					Capactiance (fF)				
Para.	R_{B1B2}	R_{E}	R_{cc}	R_{su}	R_{CX}	C_{te}	C_{tx}	C_{te}	C_{TS}	C_{su}
Value	25.56	2.08	273.5	494.5	5.44	19.05	26.97	225.3	85.25	140.6

bias point. Table 6.2 shows the extracted values for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT at $V_{\text{BE}} = V_{\text{CE}} = 0 \text{ V}$, and the comparison of measured and simulated S -parameter is depicted in Fig. 6.10. The simulated S -parameters match well with the measured one over the whole frequency range, which proves the feasibility of proposed parameter extraction technique under cut-off mode.

The error of this method mainly comes from the estimation of C_{TC} in Eq. (6.16) and R_{B1B2} in Eq. (6.17). Without any approximation, $\text{Re}\left(\frac{1}{y_{11} + y_{12}}\right) \cdot \text{Re}(y_{11} + y_{12}) / \text{Re}(y_{11})$ is 26.04Ω , while it is 25.56Ω based on the approximation in (6.16), and the error is only 1.843%. $\text{Re}(Y_{11})$ is approximated when extracting C_{TC} as depicted in (6.17). Figure 6.11 presents the comparison of measured, calculated and fitted $\text{Re}(Y_{11})$ using Eq. (6.17). It can be seen that the calculated value agrees well with the measured one, and the fitted value is close to the calculated data. In other word, the approximation in (6.16) and (6.17) are reasonable.

To extend the extraction technique to the transistors in the whole device operation range and with different device sizing, a series of other SiGe HBTs are also investigated. Figure 6.12 depicts the comparison of measured and simulated S -parameters for four different cases. Good agreement is also found, thus validating the accuracy of our proposed model parameters extraction method.

The bias dependences of model parameters are shown in Figs. 6.13, 6.14 and 6.15, where the capacitances satisfy the basic C - V expression and the resistance satisfies the bias voltage relationship. Figures 6.16 and 6.17 show the geometric dimension dependencies of capacitance C_{TC0} , C_{TX0} , C_{TE0} , C_{TS0} , and resistance R_{B0} ,

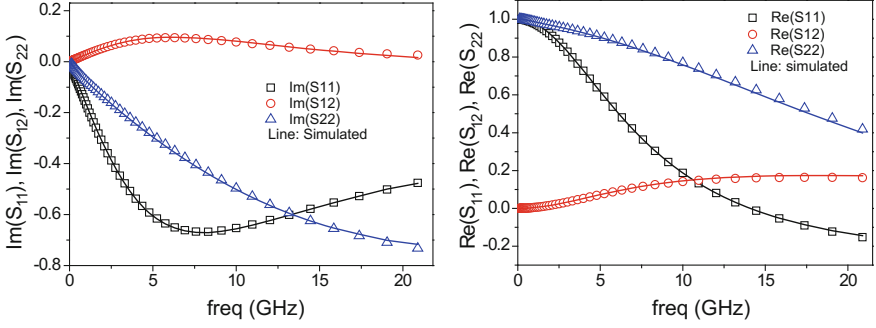
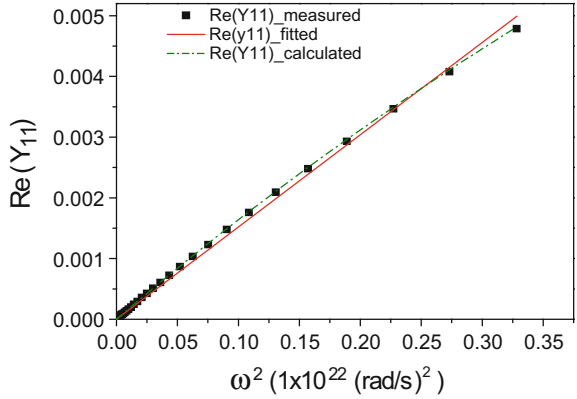


Fig. 6.10 Comparison of measured (*symbol*) and simulated (*line*) S -parameter for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT at $V_{\text{BE}} = V_{\text{CE}} = 0 \text{ V}$

Fig. 6.11 Comparison of measured, calculated and fitted $\text{Re}(Y_{11})$ for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT under zero-biased condition



R_{E0} , and R_{CC0} under zero-bias condition, respectively. It can be seen that the base resistances R_{B0} is proportional to $1/L$. the capacitance elements varies linearly with the mieter length L , and the emitter resistance R_{E0} and the collector resistance R_{CC0} increase monotonically with mieter length L .

6.1.2 Parameter Extraction Under Forward-Active Mode

The substrate-network usually operates at reversed-biased state, thus, the corresponding parameters (C_{ts} , C_{SU} and R_{SU}) can be extracted exactly from the cutoff operation mode and then de-embedded from the obtained S -parameter. Besides, R_{BX} can be reasonably ignored since it mainly arises from salicided extrinsic base region whose sheet resistance are normally negligibly small. After de-embedding the pad parasitics, substrate network parameters and collector resistance R_{CX} , we arrive at the following Y -parameters for the de-embedded equivalent-circuit

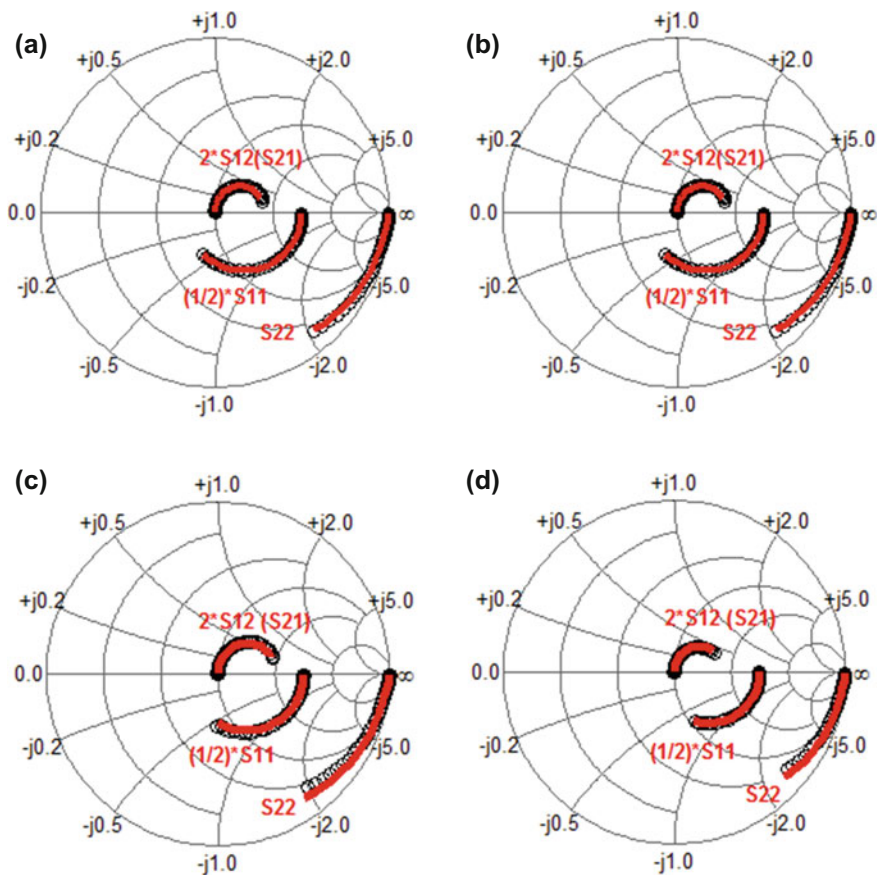


Fig. 6.12 The comparison of measured (symbol) and simulated (line) S -parameter for **a** $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT@ $V_{BE} = V_{BC} = -1 \text{ V}$; **b** $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT@ $V_{CB} = V_{CS} = -1 \text{ V}$; **c** $1 \times 0.9 \times 30 \mu\text{m}^2$ SiGe HBT@ $V_{BE} = V_{BC} = -1 \text{ V}$; **d** $1 \times 1.2 \times 15 \mu\text{m}^2$ SiGe HBT@ $V_{BE} = V_{BC} = -1 \text{ V}$

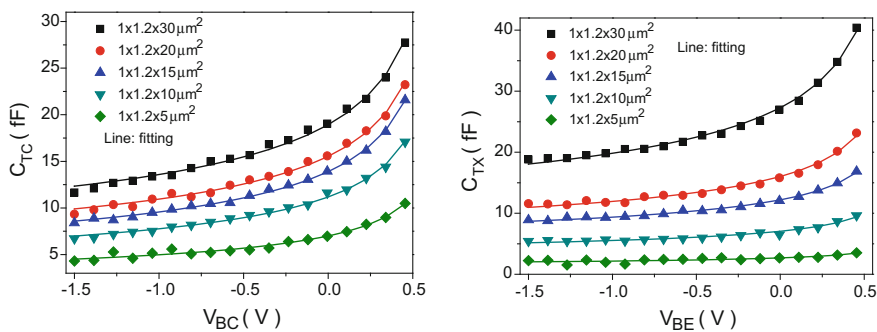


Figure 6.13 Bias dependence of C_{TC} and C_{TX} for SiGe HBT with several emitter sizes

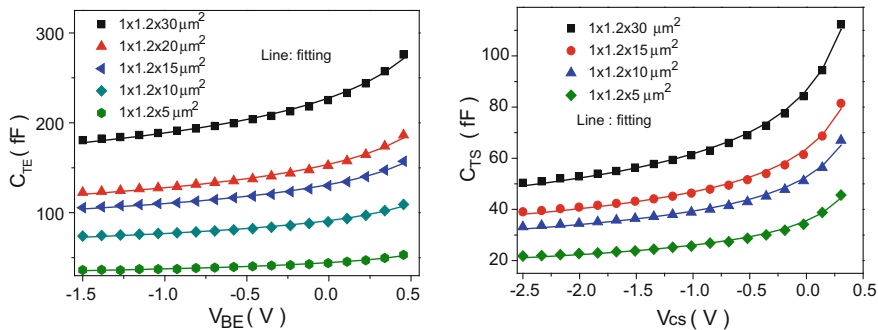


Fig. 6.14 Bias dependence of C_{TE} and C_{TS} for SiGe HBT with several emitter sizes

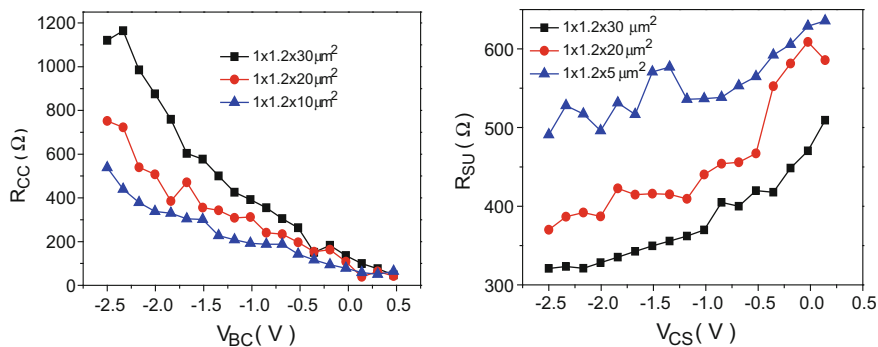


Fig. 6.15 Bias dependence of R_{CC} and R_{SU} for SiGe HBT with several emitter sizes

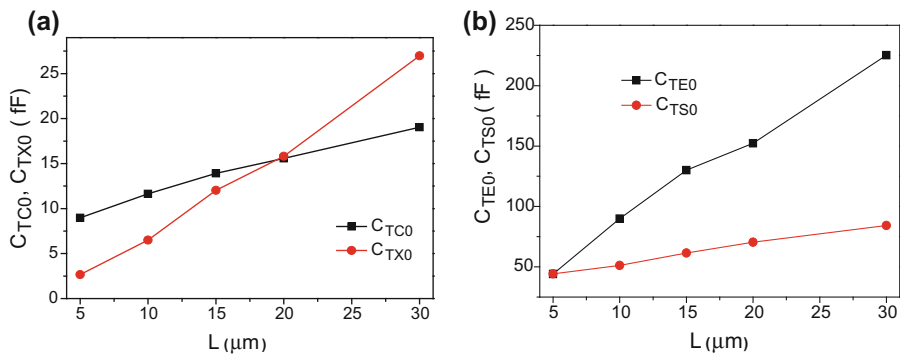


Fig. 6.16 Geometric dependence of **a** C_{TC0} , C_{TX0} , and **b** C_{TE0} , C_{TS0} under zero-biased condition

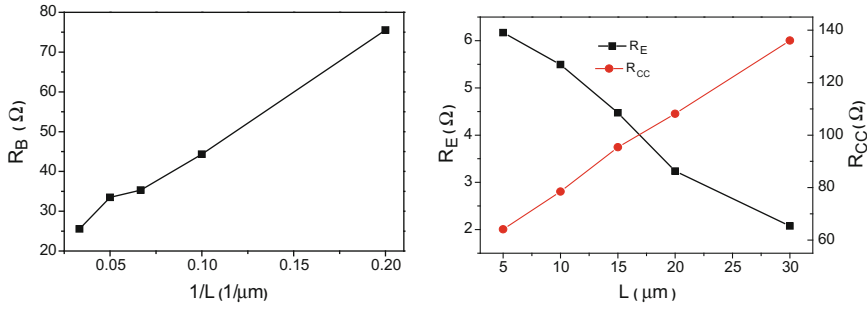


Fig. 6.17 Geometric dependence of R_B , R_E and R_{CC} under zero-biased condition

$$Y_{11} = j\omega C_{tx} + \frac{Y_A(Y_B + G_m R_{EU} Y_B + Y_C + R_{EU} Y_B Y_C)}{Y_A + G_m R_{EU} Y_A + Y_B + G_m R_{EU} Y_B + Y_C + R_{EU} Y_A Y_C + R_{EU} Y_B Y_C} \quad (6.29)$$

$$Y_{21} = -j\omega C_{tx} - \frac{Y_A(Y_B + G_m(-1 + R_{EU} Y_B) + R_{EU} Y_B Y_C)}{Y_A + G_m R_{EU} Y_A + Y_B + G_m R_{EU} Y_B + Y_C + R_{EU} Y_A Y_C + R_{EU} Y_B Y_C} \quad (6.30)$$

$$Y_{12} = -j\omega C_{tx} + \frac{Y_A Y_B(1 + G_m R_{EU} + R_{EU} Y_C)}{Y_A + G_m R_{EU} Y_A + Y_B + G_m R_{EU} Y_B + Y_C + R_{EU} Y_A Y_C + R_{EU} Y_B Y_C} \quad (6.31)$$

$$Y_{22} = j\omega C_{tx} + \frac{Y_B(G_m + Y_A + G_m R_{EU} Y_A + Y_C + R_{EU} Y_A Y_C)}{Y_A + G_m R_{EU} Y_A + Y_B + G_m R_{EU} Y_B + Y_C + R_{EU} Y_A Y_C + R_{EU} Y_B Y_C} \quad (6.32)$$

where

$$Y_A = 1/R_{B1B2} \quad (6.33)$$

$$Y_B = j\omega C_{tc} / (j\omega R_{CC} C_{tc} + 1) \quad (6.34)$$

$$Y_C = j\omega C_{te} + 1/R_{be} \quad (6.35)$$

Combining (6.29)–(6.32), the real part and imaginary part of related admittance parameter are derived respectively as a non-linear rational function of angular frequency ω as follows:

$$\text{Im}\left(\frac{1}{Y_{11} + Y_{12}}\right) = \frac{N_{10}\omega + N_{11}\omega^3}{1 + (C_{tc}^2 R_{be}^2 + C_{tc}^2 R_{cc}^2)\omega^2 + C_{tc}^2 C_{te}^2 R_{be}^2 R_{cc}^2 \omega^4} \quad (6.36)$$

$$\operatorname{Re}\left(\frac{1}{Y_{11} + Y_{12}}\right) = \frac{N_{20} + N_{21}\omega^2 + N_{22}\omega^4}{1 + (C_{\text{te}}^2 R_{\text{be}}^2 + C_{\text{tc}}^2 R_{\text{cc}}^2)\omega^2 + C_{\text{tc}}^2 C_{\text{te}}^2 R_{\text{be}}^2 R_{\text{cc}}^2 \omega^4} \quad (6.37)$$

$$\operatorname{Im}(Y_{22} + Y_{12}) = \frac{N_{30}\omega + N_{31}\omega^3}{1 + M_{11}\omega^2 + M_{12}\omega^4} \quad (6.38)$$

$$\operatorname{Re}\left(\frac{Y_{22} + Y_{12}}{Y_{21} - Y_{12}}\right) = \frac{N_{120}\omega^2 + N_{121}\omega^4}{1 + (C_{\text{tc}}^2 R_{\text{cc}}^2 + s^2)\omega^2 + C_{\text{tc}}^2 R_{\text{cc}}^2 s^2 \omega^4} \quad (6.39)$$

$$\operatorname{Im}(-Y_{12}) = \frac{N_{50}\omega + N_{51}\omega^3 + N_{52}\omega^5}{1 + M_{11}\omega^2 + M_{12}\omega^4} \quad (6.40)$$

$$\operatorname{Re}(-Y_{12}) = \frac{N_{60}\omega^2 + N_{61}\omega^4}{1 + M_{11}\omega^2 + M_{12}\omega^4} \quad (6.41)$$

$$\operatorname{Im}\left(\frac{Y_{11} + Y_{12}}{Y_{21} - Y_{12}}\right) = \frac{N_{90}\omega}{1 + \tau^2 \omega^2} \quad (6.42)$$

$$\operatorname{Re}(Y_{21} - Y_{12}) = \frac{N_{80} + N_{81}\omega^2 + N_{82}\omega^4}{1 + M_{11}\omega^2 + M_{12}\omega^4} \quad (6.43)$$

where all the coefficients N_{ij} and M_{ij} are functions of the circuit elements in Fig. 5.16 and some useful coefficients are expressed as below:

$$N_{10} = C_{\text{tc}} R_{\text{B}}(N_{20} - R_{\text{B}}) - R_{\text{be}}(C_{\text{tc}} R_{\text{be}}(1 + G_{\text{mo}} R_{\text{EU}}) + G_{\text{mo}} R_{\text{EU}} s) \quad (6.44)$$

$$N_{20} = R_{\text{B}} + R_{\text{be}} + R_{\text{EU}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}} \quad (6.45)$$

$$N_{30} = \frac{C_{\text{tc}} R_{\text{B}}(1 + G_{\text{mo}} R_{\text{be}})}{(R_{\text{B}} + R_{\text{be}} + R_{\text{EU}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}})} \quad (6.46)$$

$$N_{120} = \frac{C_{\text{tc}} R_{\text{B}}}{G_{\text{mo}} R_{\text{be}}} (C_{\text{tc}} R_{\text{cc}}(1 + G_{\text{mo}} R_{\text{be}}) - C_{\text{tc}} R_{\text{be}} - \tau) \quad (6.47)$$

$$N_{50} = \frac{(C_{\text{tc}}(R_{\text{be}} + R_{\text{EU}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}}) + C_{\text{tx}}(R_{\text{B}} + R_{\text{be}} + R_{\text{EU}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}}))}{(R_{\text{B}} + R_{\text{be}} + R_{\text{EU}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}})} \quad (6.48)$$

$$\begin{aligned} N_{60} = & \frac{C_{\text{tc}}^2 (R_{\text{be}} + R_{\text{EU}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}})}{(R_{\text{B}} + R_{\text{be}} + R_{\text{EU}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}})^2} * [R_{\text{B}} R_{\text{be}} (C_{\text{tc}} (R_{\text{be}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}}) + G_{\text{mo}} R_{\text{EU}} s) \\ & + (R_{\text{cc}} + R_{\text{B}})(R_{\text{be}} + R_{\text{EU}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}}) + R_{\text{B}} R_{\text{cc}}] \end{aligned} \quad (6.49)$$

$$N_{80} = \frac{G_{\text{mo}} R_{\text{be}}}{(R_{\text{B}} + R_{\text{be}} + R_{\text{EU}} + G_{\text{mo}} R_{\text{be}} R_{\text{EU}})} \quad (6.50)$$

$$N_{90} = (C_{\text{te}} R_{\text{be}} + \tau) / G_{\text{mo}} R_{\text{be}} \quad (6.51)$$

Other high-order terms coefficients N_{ij} and M_{ij} in formula (6.36)–(6.43) are all function of circuit elements in Fig. 5.16, and the detail are not shown here. The emitter resistance R_{E} can be extracted from a standard flyback measurement and considered as a known quantity. Solving the equation group consisting of (6.44)–(6.51), the circuit parameters can be obtained as

$$G_{\text{mo}} = A/B \quad (6.52)$$

$$A = -(N_{20} N_{80} (N_{10} N_{30} (1 + N_{20} N_{80}) + N_{20} (N_{60} + N_{120} N_{80} + N_{20}^2 N_{60} N_{80}^2 + N_{20} (N_{30}^2 + 2N_{60} N_{80} + N_{120} N_{80}^2 + N_{30} N_{80} N_{90}))))$$

$$B = ((1 + N_{20} N_{80}) (N_{10} N_{30} (R_{\text{EU}} + N_{20} (N_{80} R_{\text{EU}} - 1)) + N_{20} ((N_{60} + N_{120} N_{80}) R_{\text{EU}} + N_{20}^2 N_{60} N_{80} (N_{80} R_{\text{EU}} - 1) + N_{20} ((N_{30}^2 + N_{120} N_{80}^2 + N_{30} N_{80} N_{90}) R_{\text{EU}} + N_{60} (2N_{80} R_{\text{EU}} - 1)))))$$

$$R_{\text{be}} = \frac{N_{20} N_{80}}{G_{\text{mo}}} \quad (6.53)$$

$$R_{\text{B1B2}} = N_{20} - \frac{N_{20} N_{80}}{G_{\text{mo}}} - R_{\text{EU}} - N_{20} N_{80} R_{\text{EU}} \quad (6.54)$$

$$C_{\text{TC}} = - \frac{G_{\text{mo}} N_{20} N_{30}}{(1 + N_{20} N_{80}) (N_{20} N_{80} + G_{\text{mo}} (R_{\text{EU}} + N_{20} (N_{80} R_{\text{EU}} - 1)))} \quad (6.55)$$

$$R_{\text{CC}} = - \frac{N_{80} (N_{120} + N_{120} N_{20} N_{80} + N_{20} N_{30} N_{90}) (N_{20} N_{80} + G_{\text{mo}} (R_{\text{EU}} + N_{20} (-1 + N_{80} R_{\text{EU}})))}{G_{\text{mo}} N_{20} N_{30}^2} \quad (6.56)$$

$$C_{\text{TE}} = - \frac{G_{\text{mo}} (-N_{20}^2 N_{30} N_{80} + G_{\text{mo}} (1 + N_{20} N_{80}) (N_{10} + N_{20} (-N_{30} + N_{20} N_{80}^2 N_{90}) R_{\text{EU}}))}{N_{20}^2 N_{80}^2 (1 + N_{20} N_{80})} \quad (6.57)$$

$$C_{\text{TX}} = \frac{N_{20} N_{80} (N_{30} + N_{50} + N_{20} N_{50} N_{80}) + G_{\text{mo}} (1 + N_{20} N_{80}) ((N_{30} + N_{50}) R_{\text{EU}} + N_{20} N_{50} (N_{80} R_{\text{EU}} - 1))}{(1 + N_{20} N_{80}) (N_{20} N_{80} + G_{\text{mo}} (R_{\text{EU}} + N_{20} (N_{80} R_{\text{EU}} - 1)))} \quad (6.58)$$

$$\tau = \frac{N_{20}^2 N_{80} (-N_{30} + N_{80} (1 + N_{20} N_{80}) N_{90}) + G_{mo} (1 + N_{20} N_{80}) (N_{10} + N_{20} (N_{20} N_{80}^2 N_{90} - N_{30}) R_{EU})}{N_{20} N_{80} (1 + N_{20} N_{80})} \quad (6.59)$$

By far, the problem of extracting each element in the equivalent-circuit as shown in Fig. 5.16 is theoretically solved. In order to validate and assess the accuracy of the proposed direct parameters extraction method, an emitter area of $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT was first investigated. S -parameters were measured in the common-emitter configuration with on-wafer RF probes system and a vector network analyzer (VNA) over the frequency range 100 MHz–20.89 GHz. The calibration was first performed on a ceramic calibration substrate using a short-open-load-thru (SOLT) calibration method. Then the measured S -parameters were de-embedded with a standard ‘open’ and ‘short’ structure to remove the pad parasitics. The extrinsic collector resistance R_{CX} , emitter resistance R_E , substrate-network parameters R_{SU} , C_{TS} and C_{SU} are extracted as 5.44 Ω , 2.5 Ω , 300 Ω , 48.8 fF and 180 fF, respectively.

The typical rational function fitting results of the formulas (6.36)–(6.43) for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT under $V_{BE} = 0.875$ V and $V_{CE} = 3$ V are shown in Fig. 6.18, where the fitting curves (solid lines) are compared with the corresponding measured data (symbols). An excellent agreement is obtained over the whole frequency range from 100 MHz to 20.89 GHz. Table 6.3 depicts the fitted

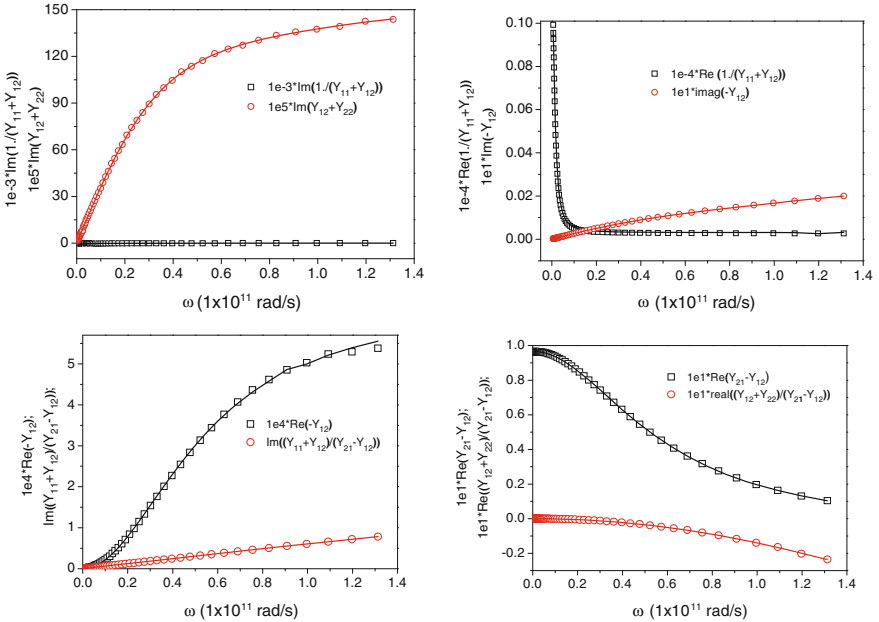


Fig. 6.18 Comparison between the measured (*symbols*) and fitted results (*solid lines*) of formulas (6.36)–(6.43) for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT biased at $V_{CE} = 3$ V, $V_{BE} = 0.875$ V

Table 6.3 The fitted constants N_{i0} and the confidence interval based on rational functions fitting for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT under $V_{\text{CE}} = 3 \text{ V}$, $V_{\text{BE}} = 0.875 \text{ V}$

Parameter N_{i0}	Value	Confidence interval
$N_{10}(1\text{e}-7)$	-6.5971	(-6.608, -6.586)
$N_{20}(1\text{e}3)$	1.1383	(1.137, 1.145)
$N_{30}(1\text{e}-14)$	3.1603	(3.159, 3.161)
$N_{50}(1\text{e}-14)$	2.665	(2.661, 2.669)
$N_{60}(1\text{e}-25)$	2.1042	(2.104, 2.1045)
N_{80}	0.09603	(0.9601, 0.9605)
$N_{90}(1\text{e}-12)$	5.4514	(5.451, 5.452)
$N_{120}(1\text{e}-25)$	-6.6755	(-6.689, -6.662)

constant terms N_{i0} and the corresponding confidence intervals. It is found that the coefficients N_{i0} are obtained accurately through the rational functions fitting, and the confidence intervals are narrow and hence the calculate error is quite small.

After the constants N_{i0} are exactly determined, all the circuit elements in the equivalent-circuit model can be extracted according to the formulas (6.52)–(6.59). For the $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT biased at $V_{\text{CE}} = 3 \text{ V}$ and $V_{\text{BE}} = 0.875 \text{ V}$, Table 6.4 gives the values of the obtained small-signal model parameters for the extracted bias-dependent and bias-independent circuit elements. Figure 6.19 presents the comparison between the measured and simulated S -parameters (from equivalent circuit set up in the ADS) for $V_{\text{CE}} = 3 \text{ V}$ and $V_{\text{BE}} = 0.875 \text{ V}$ over the frequency range of 100 MHz–20.89 GHz. Good agreements were obtained over the whole frequency range.

To extend the extraction technique to the transistors in the whole device operation range and with different device sizing, a series of other SiGe HBTs are also investigated. The results demonstrate that the proposed method is available for extracting the model parameters of SiGe HBTs. For example, the comparisons of simulated and measured S -parameters for (I) $1 \times 1.2 \times 15 \mu\text{m}^2$ SiGe HBT under $V_{\text{BE}} = 0.875 \text{ V}$ and $V_{\text{CE}} = 3 \text{ V}$; (II) $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT under $V_{\text{BE}} = 0.875 \text{ V}$ and $V_{\text{CE}} = 1 \text{ V}$ are depicted in Figs. 6.20 and 6.21, respectively. Good agreement is also found, thus validating the accuracy of our proposed model parameters extraction method. Therefore, we believe that the proposed parameter extraction technique are of great accuracy to evaluate the process technology and optimize the transistor design.

6.2 Parameter Extraction Under Irradiation Environment

With the development of space electronics, it is of great significance to extract the model parameters of SiGe HBT in radiation environment. In order to validate and assess the accuracy of the proposed model and extracted method in the radiation environment, $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT exposed to 10 MeV Cl ion is adopted, and the ion fluence is $1.8 \times 10^{10} \text{ cm}^{-2}$ and $9 \times 10^9 \text{ cm}^{-2}$. The terminals are all floating during the irradiation.

Figure 6.22 shows comparison of the fitted and measured admittance parameters under $V_{\text{B}} = -1 \text{ V}$, $V_{\text{E}} = V_{\text{S}} = V_{\text{C}} = 0 \text{ V}$. Good agreement exists over the whole

Table 6.4 The extracted values for circuit elements for a $1 \times 1.2 \times 30 \text{ }\mu\text{m}^2$ SiGe HBT under $V_{CE} = 3 \text{ V}$, $V_{BE} = 0.875 \text{ V}$

Variable	Capacitance (fF)			Resistance (Ω)						Controlled source			
	C_{TX}	C_{TC}	C_{TE}	C_{TS}	C_{SU}	R_{EU}	R_{BIB2}	R_{SU}	R_{be}	R_{CX}	R_{CC}	τ (ps)	G_{m0} (mS)
Para.	14.67	12.27	711.6	48.8	180	2.5	26.59	300	836	5.44	275.1	1.108	130.7
Value													

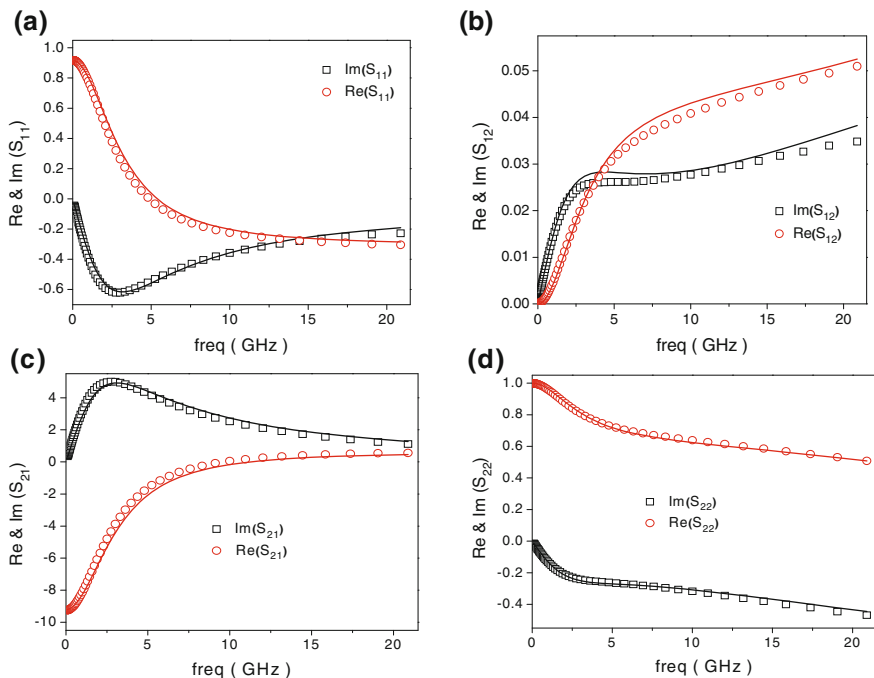


Fig. 6.19 Comparison of the measured (*symbols*) and simulated S -parameter (*solid lines*) for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT biased at $V_{\text{CE}} = 3 \text{ V}$, $V_{\text{BE}} = 0.875 \text{ V}$: **a** S_{11} , **b** S_{12} , **c** S_{21} , **d** S_{22}

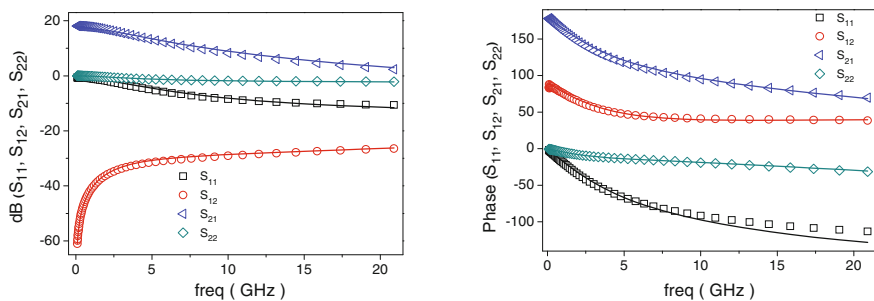


Fig. 6.20 Comparison of the measured (*symbols*) and simulated S -parameter (*solid lines*) for a $1 \times 1.2 \times 15 \mu\text{m}^2$ SiGe HBT biased at $V_{\text{CE}} = 3 \text{ V}$, $V_{\text{BE}} = 0.875 \text{ V}$

frequency range from 100 MHz to 20.89 GHz, and the obtained lowest terms' coefficient has narrow confidence interval, as depicted in Table 6.5. Then the model parameters under cut-off mode can be extracted with the method in Sect. 6.1. The comparison of measured and simulated S -parameter in ADS is shown in Fig. 6.23, and the simulated value matches well with the measured one.

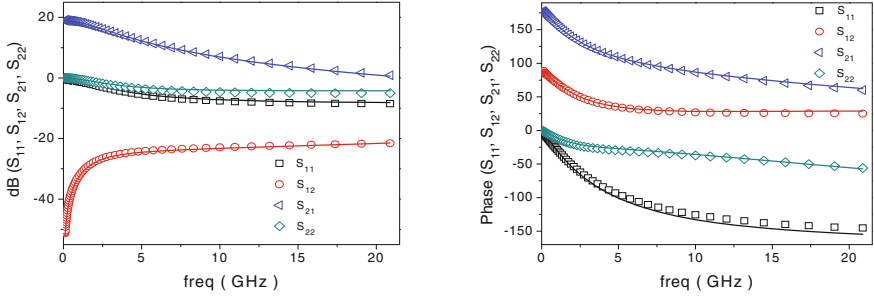


Fig. 6.21 Comparison of the measured (*symbols*) and simulated S -parameter (*solid lines*) for a $1 \times 1.2 \times 30 \mu\text{m}^2$ SiGe HBT biased at $V_{\text{CE}} = 1 \text{ V}$, $V_{\text{BE}} = 0.875 \text{ V}$

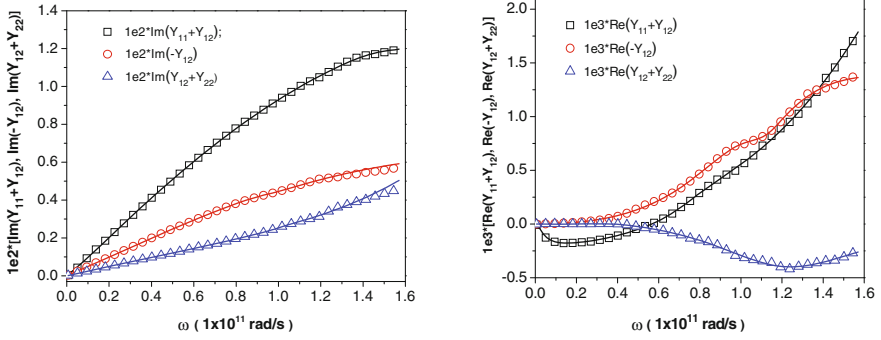


Fig. 6.22 Comparison of the fitting (*line*) and measured (*symbol*) admittance parameters before irradiation under $V_{\text{B}} = -1 \text{ V}$, $V_{\text{E}} = V_{\text{C}} = V_{\text{S}} = 0 \text{ V}$ $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT

Table 6.5 The fitted lowest terms' coefficient for $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT before irradiation, biased at $V_{\text{B}} = -1 \text{ V}$, $V_{\text{E}} = V_{\text{C}} = V_{\text{S}} = 0 \text{ V}$

Variable	Value	Confidence intervals
$N_{10}(1\text{e}-13)$	0.9147	(0.8901, 0.9394)
$N_{20}(1\text{e}-23)$	-1.0706	(-1.23, -0.9114)
$N_{30}(1\text{e}-13)$	0.4902	(0.4884, 0.4919)
$N_{40}(1\text{e}-25)$	0.386	(0.3692, 0.4027)
$N_{50}(1\text{e}-13)$	0.2468	(0.2458, 0.2479)
$N_{60}(1\text{e}-26)$	0.12244	(0.1121, 0.1427)

As for the transistor exposed to $9.0 \times 10^9 \text{ cm}^{-2}$ and $1.8 \times 10^9 \text{ cm}^{-2}$ 10 MeV Cl ion irradiation, the fitting results of admittance parameters is shown in Figs. 6.24 and 6.26. Similar to non-irradiated case, the obtained coefficients N_{i0} have narrow confidence interval (separately in Tables 6.6 and 6.7). The parameter extraction method based in nonlinear rational function fitting is also applicable to the

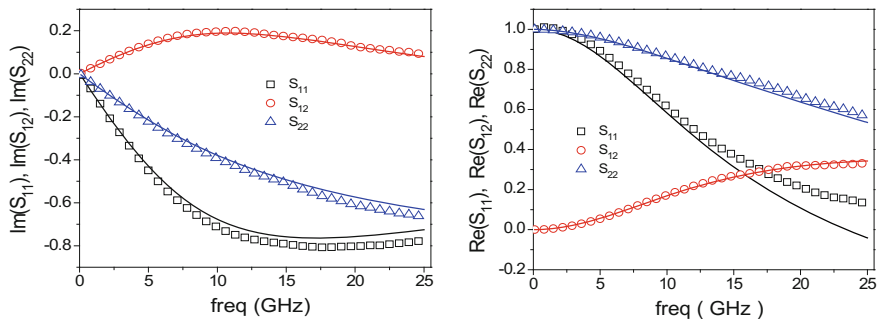


Fig. 6.23 Comparison of the measured (*symbol*) and simulated (*line*) S -parameters under for $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT biased at $V_B = -1$ V, $V_E = V_C = V_S = 0$ V before irradiation

irradiated transistor. The simulated S -parameters also agree well with the measured data, as shown in Figs. 6.25 and 6.27, respectively.

For the $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT under $V_B = -1$ V, $V_C = V_S = V_E = 0$ V, from the above extracted result, it is found that the resistance elements (R_{EU} , R_{B1B2} , R_{CX}) increase while the capacitance elements decreases with ion fluence increasing. It is mainly due to the existence of displacement damages induced by heavy ion radiation, which can cause the carrier removal effect and then the effective doping concentration decreased. As a result, the width of PN junction increase at the same reverse applied voltage, leading to a decrease of the parasitic capacitance.

6.3 Temperature Characteristics of Model Parameter

Since the existence of bandgap-engineering in base region, the narrowed-bandgap induced by the Ge profile retards the classical problems associated with cooling conventional transistors, such as base freezeout, carrier diffusivity and mobility degradation. Therefore, nearly all the transistor metrics improve with temperature decreasing, which enables SiGe HBT to operate well in a low temperature range. Obviously, on the other hand, SiGe HBTs also suffer some degradations in AC and DC characteristics as temperature increases. However, it is lucky to find that the speed of such a degradation is not very fast. For example, even at 300C IBM the 2nd generation SiGe HBT also possesses a current gain of above 100 and f_T above 75 GHz [15, 16]. It demonstrates a potential of SiGe HBT operating over a wide range of temperature. Therefore, it is vital to investigate the physics of SiGe HBT model parameters over a wide temperature, and important to build the temperature dependences of model parameters with good fidelity.

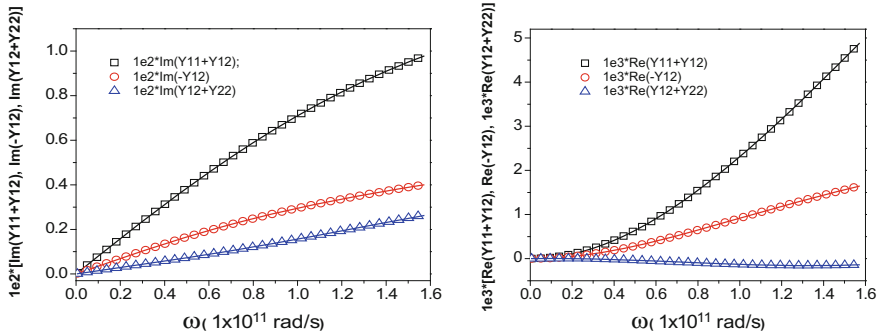


Fig. 6.24 Comparison of the fitting (*line*) and measured (*symbol*) admittance parameters under $V_B = -1$ V, $V_E = V_C = V_S = 0$ V after 9.0×10^9 cm $^{-2}$ 10 MeV Cl ion irradiation

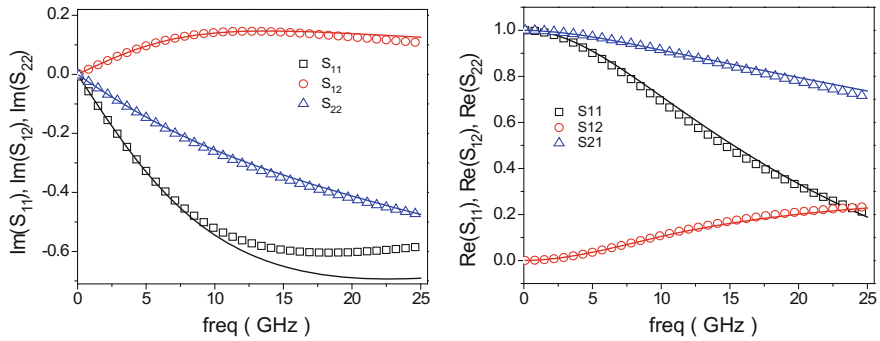


Fig. 6.25 Comparison of measured (*symbol*) and simulated (*line*) S -parameters under for $1 \times 0.2 \times 20$ μm^2 SiGe HBT basied at $V_B = -1$ V, $V_E = V_C = V_S = 0$ V after 9.0×10^9 cm $^{-2}$ 10 MeV Cl irradiation

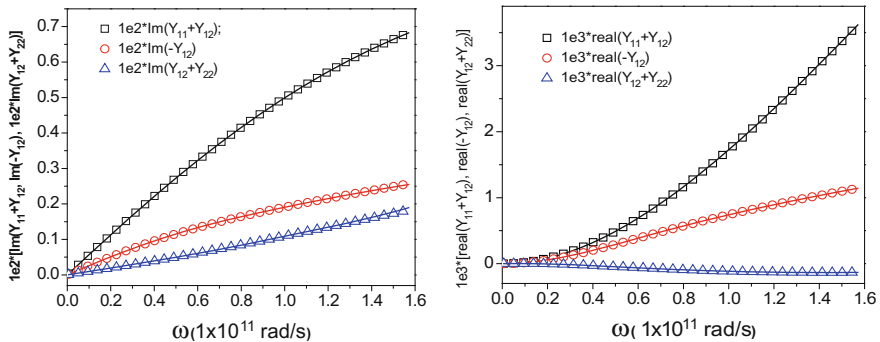


Fig. 6.26 Comparison of the fitting (*line*) and measured (*symbol*) admittance parameters under $V_B = -1$ V, $V_E = V_C = V_S = 0$ V after 1.8×10^{10} cm $^{-2}$ 10 MeV Cl ion irradiation

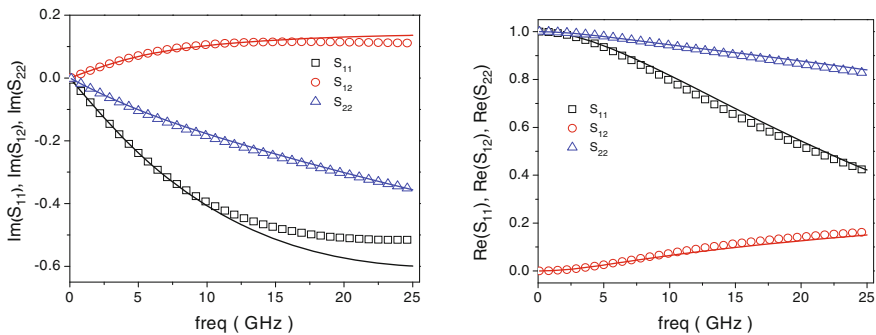


Fig. 6.27 Comparison of measured (*symbol*) and simulated (*line*) S -parameters under for $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT biased at $V_B = -1$ V, $V_E = V_C = V_S = 0$ V after $1.8 \times 10^{10} \text{ cm}^{-2}$ 10 MeV Cl irradiation

Table 6.6 The fitted lowest terms' coefficient for $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT after $9.0 \times 10^9 \text{ cm}^{-2}$ 10 MeV Cl ion irradiation, biased at $V_B = -1$ V, $V_E = V_C = V_S = 0$ V

Variable	Value	Confidence intervals
$N_{10}(1\text{e}-13)$	0.7937	(2.624, 2.788)
$N_{20}(1\text{e}-25)$	2.706	(-1.961, -1.5)
$N_{30}(1\text{e}-13)$	0.3487	(0.3483, 0.3495)
$N_{40}(1\text{e}-25)$	1.255	(1.249, 1.260)
$N_{50}(1\text{e}-13)$	0.1535	(0.1523, 0.1542)
$N_{60}(1\text{e}-25)$	0.7023	(0.6277, 0.7769)

Table 6.7 The fitted lowest terms' coefficient for $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT after $1.8 \times 10^{10} \text{ cm}^{-2}$ 10 MeV Cl ion irradiation, biased at $V_B = -1$ V, $V_E = V_C = V_S = 0$ V

Variable	Value	Confidence intervals
$N_{10}(1\text{e}-13)$	0.5673	(0.5669, 0.5675)
$N_{20}(1\text{e}-25)$	2.0913	(2.065, 2.096)
$N_{30}(1\text{e}-13)$	0.2599	(0.2591, 0.2605)
$N_{40}(1\text{e}-25)$	1.5065	(1.461, 1.552)
$N_{50}(1\text{e}-13)$	0.1008	(0.09169, 0.1053)
$N_{60}(1\text{e}-25)$	0.4084	(0.3649, 0.4539)

6.3.1 Parameter Extraction Under High and Low Temperature

In order to establish the scaling model in wide temperature range, the model parameter at each temperature first should be extracted. Since the temperature characteristic are independent of geometric dimensions, $1 \times 0.2 \times 20 \mu\text{m}^2$

SiGe HBT is adopted here. The temperatures are set as -55 , -25 , 25 , 100 and 200 °C. The model parameters at each temperature are separately determined based on the proposed extraction method. The extracted results at room temperature (25 °C) has been depicted in above section, and here we only present the related results at -55 and 200 °C.

Figure 6.28 shows the the comparison between the measured and fitted Y -parameters at -55 °C, for a $1 \times 0.2 \times 20$ μm^2 SiGe HBT biased at $V_B = -1$ V, $V_E = V_C = V_S = 0$ V. An excellent agreement is obtained at -55 °C over the whole frequency range from 100 MHz to 20.89 GHz. The fitted coefficients N_{i0} ($i = 1-6$) has narrow confidence interval, as depicted in Table 6.8. Therefore the obtained N_{i0} based on the nonlinear rational function fitting here are credibly accurate enough.

With the rational function fitting result, the model parameters are extracted based on the above proposed thchnique, and then are put into ADS simulator. The comparision of measured and simulated S -parameters is shown in Fig. 6.29. A good agreememnt is found over the whole frequency range. Therefore, the proposed extraction technique is valid for SiGe HBT opeating at the low temperature of -55 °C.

Figure 6.30 shows the the comparison between the measured and fitted Y -parameters at 200 °C, for a $1 \times 0.2 \times 20$ μm^2 SiGe HBT biased at $V_B = -1$ V, $V_E = V_C = V_S = 0$ V. An excellent agreement is also obtained at 200 °C over the whole frequency range. The fitted coefficients N_{i0} ($i = 1-6$) also has narrow confidence interval, as depicted in Table 6.9. The simulated S -parameters also match well with the measured one, as shown in Fig. 6.31. Therefore, the proposed extraction technique is also valid for SiGe HBT opeating at the high temperature of 200 °C.

The extracted results at other temperature can also verify the feasibility of this method. Therefore, the proposed method here based on the nonlinear rational function fitting is applicable in the range of -55 to 200 °C. The related model parameters at each temperature can be extracted through the proposed mothod here, which lays the foundation for the following temperature scaling.

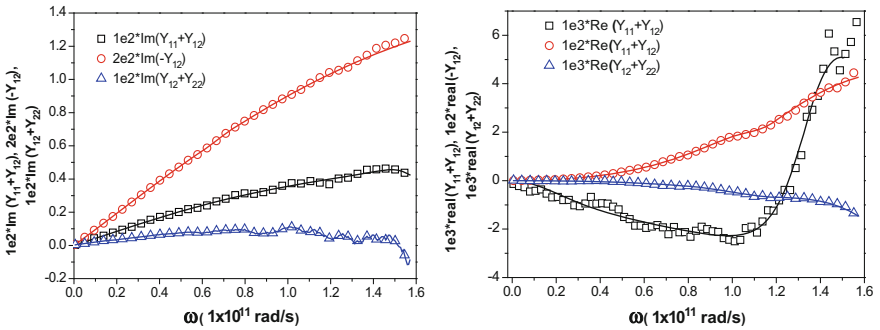


Fig. 6.28 Measured (*symbol*) and rational function fitted (*line*) realted Y -parameter for a $1 \times 0.2 \times 20$ μm^2 SiGe HBT inder $V_B = -1$ V, $V_E = V_C = V_S = 0$ at -55 °C

Table 6.8 Calculated P_{i0} ($i = 1-7$) based on rational function fitting for $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT under $V_B = -1$ V, $V_E = V_C = V_S = 0$ V at -5°C

Variable	Value	Confidence intervals
$N_{10}(1\text{e}-13)$	0.3986	(0.3759, 0.4112)
$N_{20}(1\text{e}-24)$	-1.73	(-1.961, -1.5)
$N_{30}(5\text{e}-14)$	0.9747	(0.9724, 0.9769)
$N_{40}(1\text{e}-24)$	0.05753	(0.05548, 0.05957)
$N_{50}(1\text{e}-13)$	0.1719	(0.1676, 0.1762)
$N_{60}(1\text{e}-25)$	-0.2608	(-0.285, -0.2366)

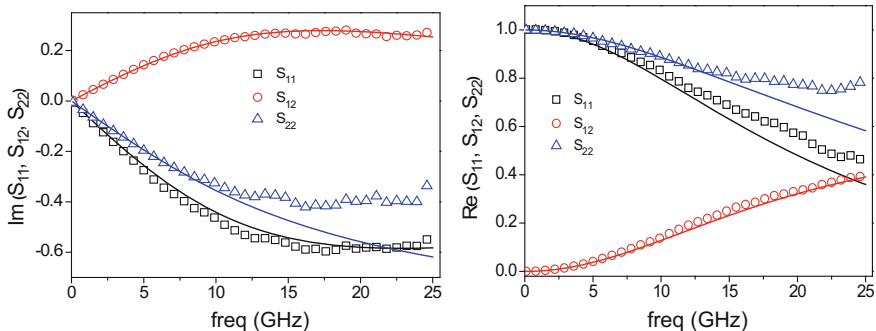


Fig. 6.29 The Comparison of measured (symbol) and simulated (line) S -parameters for a $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT under $V_B = -1$ V, $V_E = V_C = V_S = 0$ at -55°C

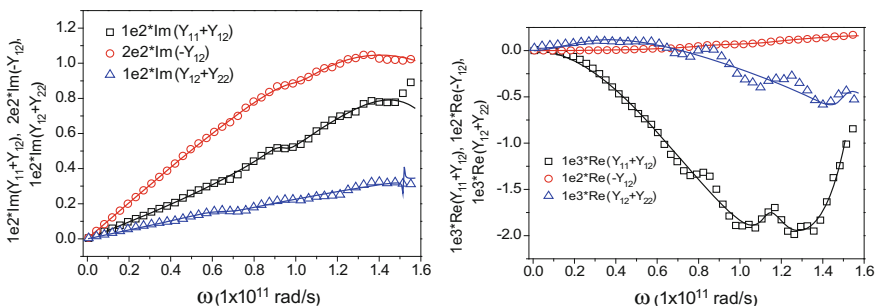


Fig. 6.30 Measured (symbol) and rational function fitted (line) realted Y -parameter for a $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT under $V_B = -1$ V, $V_E = V_C = V_S = 0$ at 200°C

6.3.2 Temperature Dependence Model

Tens of parameters related with the temperature characteristics exist in SiGe HBT compact model. In this section, the temperature dependences of model parameters related to the small-signal equivalent circuit are presented. As we know, the temperature dependence of the resistance is mainly induced by the carrier mobility. Due

Table 6.9 Calculated P_{i0} ($i = 1-7$) based on rational function fitting for $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT under $V_B = -1$ V, $V_E = V_C = V_S = 0$ V at 200°C

Variable	Value	Confidence intervals
$N_{10}(1\text{e}-13)$	0.4764	(0.4722, 0.4805)
$N_{20}(1\text{e}-24)$	-2.851	(-2.934, -2.769)
$N_{30}(5\text{e}-14)$	1.029	(1.024, 1.034)
$N_{40}(1\text{e}-24)$	0.03623	(0.03447, 0.038)
$N_{50}(1\text{e}-13)$	0.2524	(0.2458, 0.2591)
$N_{60}(1\text{e}-25)$	3.017	(2.767, 3.268)

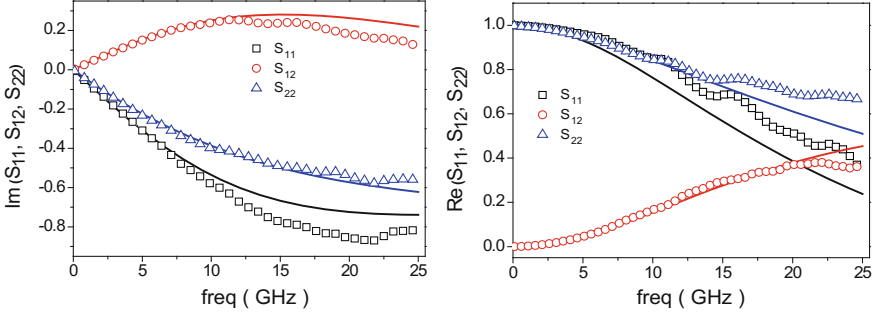


Fig. 6.31 Comparison of measured (*symbol*) and simulated (*line*) S -parameters for a $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT under $V_B = -1$ V, $V_E = V_C = V_S = 0$ at 200°C

to lattice vibration scattering and ionization impurity scattering, carrier mobility is usually determined by materials, doping and temperature. When the doping concentration is low, the carrier mobility, dominated by the lattice vibration scattering, generally decreases with the temperature increasing. When the doping concentration is high, the carrier mobility, dominated by ionization impurity scattering, increases with the temperature increasing. The experimental results show that the temperature dependence of carrier mobility in Si and Ge materials is satisfied by [17]

$$\mu \propto (T/T_0)^{-A} \quad (6.60)$$

In the bipolar transistors, the intrinsic base resistance $r_{\text{Bi}0}(T)$ at arbitrary temperature T can be expressed as [18]

$$r_{\text{Bi}0}(T) = r_{\text{Bi}0}(T_0) \left(\frac{T}{T_0} \right)^{\zeta_{\text{rBi}}} \quad (6.61)$$

where $r_{\text{Bi}0}(T_0)$ is the zero bias intrinsic base resistance at reference temperature T_0 , ζ_{rBi} is a function of base doping concentration. Similarly, the external collector resistance R_{CX} and the emitter resistance R_{E} also satisfy this relationship, and the model parameters ζ_{rCX} and ζ_{rE} are functions of the dopant concentration of respective regions.

The temperature dependence of capacitance contains the built-in potential V_D , gradient coefficient z and zero bias capacitance C_{j0} . In SiGe HBT HICUM model, the gradient coefficient z is assumed to be constant. In order to obtain the temperature dependence of the built-in potential V_D , an auxiliary voltage $V_{Dj}(T_0)$ at the reference temperature T_0 is introduced [18]

$$V_{Dj}(T_0) = 2V_{T0} \ln \left[\exp \left(\frac{V_D(T_0)}{2V_{T0}} \right) - \exp \left(-\frac{V_D(T_0)}{2V_{T0}} \right) \right] \quad (6.62)$$

where $V_{T0} = k_B T_0 / q$ is thermo voltage at the reference temperature T_0 . Through the temperature dependence of band voltage V_{geff} , the auxiliary voltage $V_{Dj}(T)$ at arbitrary temperature T is [18]

$$V_{Dj}(T) = V_{Dj}(T_0) \frac{T}{T_0} - m_g V_T \ln \left(\frac{T}{T_0} \right) - V_{\text{geff}}(0) \left(\frac{T}{T_0} - 1 \right) \quad (6.63)$$

where m_g is a constant to characterize the temperature dependence of the intrinsic carrier density. $V_{\text{geff}}(0)$ is the finite bandgap at $T = 0$ K. Since V_D is related to the relevant junction region, V_{geff} should be averaged as

$$V_{\text{geff}} \rightarrow V_{g(x,y)\text{eff}} = \frac{V_{\text{gxeff}} + V_{\text{gyeff}}}{2} \quad (6.64)$$

where $(x, y) = (B, E), (B, C), (C, S)$. Finally, the built-in voltage $V_D(T)$ can be calculated as [18]

$$V_D(T) = V_{Dj}(T) + 2V_T \ln \left(\frac{1}{2} \left[1 + \sqrt{1 + 4 \exp \left(-\frac{V_{Dj}(T)}{V_T} \right)} \right] \right) \quad (6.65)$$

Generally, the depletion junction C_{j0} at zero bias is expressed as $C_{j0} \propto V_D^{-z}$, therefore, the temperature dependence of C_{j0} can be directly obtained from the previously determined V_D , and expressed as

$$C_{j0}(T) = C_{j0}(T_0) \left(\frac{V_D(T_0)}{V_D(T)} \right)^z \quad (6.66)$$

The temperature dependence of above model parameters is established as follows [18]: According to Eq. (6.61), The temperature coefficient ζ_{rBi} , ζ_{rE} and ζ_{rCx} are first extracted from intrinsic base resistance R_{Bi0} , emitter resistance R_E and collector resistance R_{Cx} at the reference temperature $T_0 = 298$ K, respectively. Then the C - V characteristics at given reference temperature T_0 is fitted directly, then the built-in voltage $V_D(0)$, zero-biased capacitance $C_{j0}(0)$ and grading coefficient $z(0)$ will be obtained simultaneously if high accuracy exists. Otherwise, set $V_D(0)$ as the default value, and extract the C_{j0} and z_d from the C - V curve fitting. Finally, the values of V_D and C_{j0} at different temperatures can be determined from the corresponding

C - V curve fitting under the assumption of $Z_d(T) = Z_d(T_0)$. Thus, the temperature dependences of $V_D(T)$ and $C_{j0}(T)$ are obtained.

In HICUM the temperature dependence of model parameters is assumed to be irrelevant to device size, therefore, the extraction of temperature dependence for a single transistor geometry can also be applied to other-sized devices. According to Eqs. (6.60)–(6.66), the obtained relative temperature coefficients for a $1 \times 0.2 \times 20 \mu\text{m}^2$ SiGe HBT are as followong: $m_g = 3$, $Z_{dei} = 0.1763$, $V_{gEeff} = 1.099 \text{ V}$, $Z_{dci} = 0.2755$, $V_{gCEff} = 0.943 \text{ V}$, $Z_{dsi} = 0.071$, $V_{gSEff} = 0.962 \text{ V}$, $\zeta_{rBi} = 0.136$, $\zeta_{rEi} = -1.427$, $\zeta_{rCi} = 0.8135$. The variations of built-in voltage V_D and zero-biased depletion capacitances C_{j0} for BE junction, BC junction, and CS junction, with temperature are shown in Figs. 6.32, 6.33, 6.34 and 6.35, respectively. Excellent agreement is obtained between the extracted and fitted model parameters at most temperature points

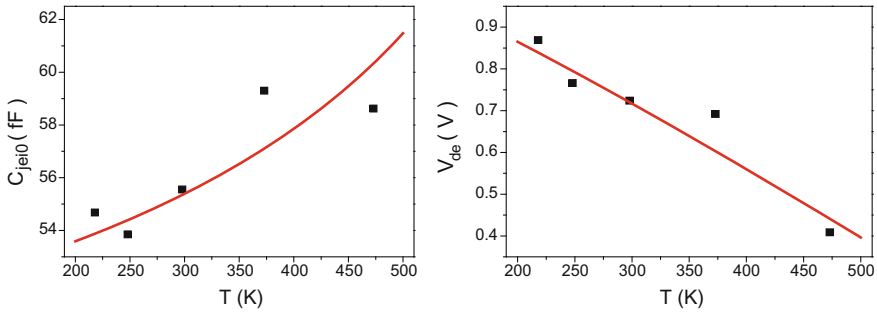


Fig. 6.32 Temperature dependences of zero-bias capacitance and built-in voltage for BE junction: extracted value (*dot*) and modeled value (*line*)

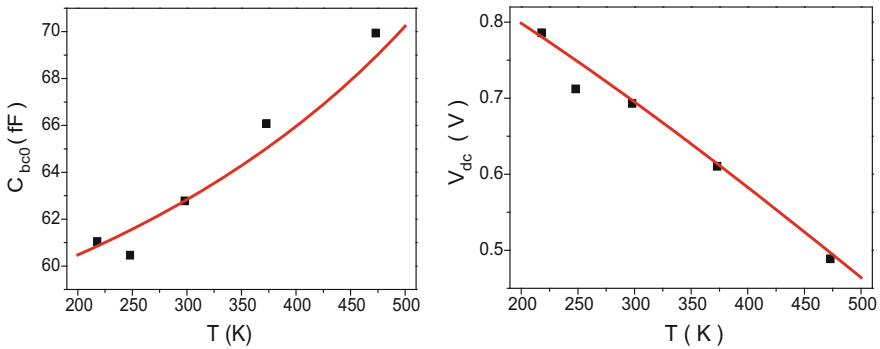


Fig. 6.33 Temperature dependences of zero-bias capacitance and built-in voltage for BC junction: extracted value (*dot*) and modeled value (*line*)

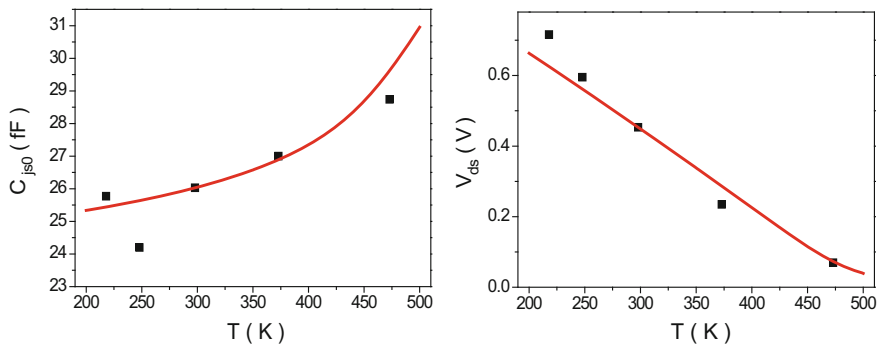


Fig. 6.34 Temperature dependences of zero-bias capacitance and built-in voltage for CS junction: extracted value (*dot*) and modeled value (*line*)

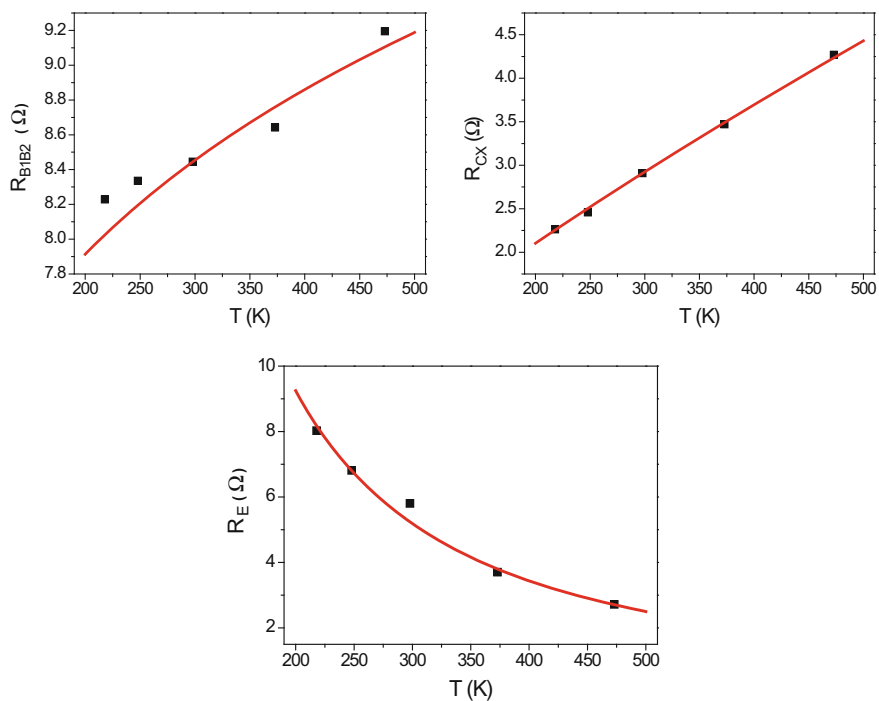


Fig. 6.35 Temperature dependences of series resistances: extracted value (*dot*) and modeled value (*line*)

Because of the low doping concentration, the carrier mobilities in base, collector and substrate region are mainly dominated by the lattice vibration scattering, which shows a temperature dependence of $T^{3/2}$ and increases with temperature increasing.

Therefore, the carrier mobility in these regions decreases and the corresponding series resistances increase as temperature increases. While in the emitter region, it is the ionized impurity scattering that dominates the carrier mobility due to the higher doping concentration (generally at a level of 10^{20} cm^{-3}). The ionized impurity scattering shows a temperature dependence of $T^{3/2}$ and hence decreases with temperature increasing; as a result, the carrier mobility in the emitter region increases and then the emitter resistance R_E decreases [19].

6.4 Summary

In this chapter, we introduce a novel parameter extraction method based on the nonlinear rational function fitting. The model parameters for SiGe HBT small-signal equivalent circuit under cut-off state and forward-active mode are described. The proposed method is also successfully applied to the case of swift heavy ion irradiation and wide temperature range of -55 to 200°C , and the temperature dependences of small-signal model parameter are established.

References

1. X. Zheng, G. Zhang, K. Chen, A parameter extraction method based on particle swarm optimization, in *International Semiconductor Device Research Symposium (ISDRS)* (College Park, MD, 2011)
2. A.D. Sadovnikov, D.J. Roulston, D. Celi, Extraction of SPICE BJT model parameters in BIPOLE3 using optimization methods. *IEEE Trans. Comput. Aided Des. Integr. Circuits Syst.* **15**(11), 1332–1339 (1996)
3. X. Cao, J. McMacken, K. Stiles, P. Layman, J.J. Liou, A. Sun, S. Moinian, Parameter extraction and optimization for new industry standard VBIC model, in *2th International Conference on Advanced Semiconductor Devices and Microsystems* (1998)
4. A. Oudir, M. Mahdouani, R. Bourguiga, Direct extraction method of HBT equivalent-circuit elements relying exclusively on S-parameters measured at normal bias conditions. *IEEE Trans. Microw. Theory Tech.* **59**(8), 1973–1982 (2011)
5. T.K. Johansen, R. Leblanc, J. Poulainand, V. Delmouly, Direct extraction of InP/GaAsSb/InP DHBT equivalent-circuit elements from S-parameters measured at cut-off and normal bias conditions. *IEEE Trans. Microw. Theory Tech.* **64**(1), 115–124 (2016)
6. A. Ouslimani, J. Gaubert, H. Hafdallah, A. Birafane, P. Pouviland, H. Leier, Direct extraction of linear HBT-model parameters using nine analytical expression blocks. *IEEE Trans. Microw. Theory Tech.* **50**(1), 218–221 (2002)
7. H. Taher, Direct extraction technique of π -topology small-signal equivalent circuit model for Si/SiGe heterojunction bipolar transistor. *Microw. Opt. Tech. Lett.* **54**(3) (2012)
8. H. Taher, R. Farrell, D. Schreursand, B. Nauwelaers, Extraction of small-signal model parameters of Si/SiGe heterojunction bipolar transistor sing least squares support vector machines. *Electron. Lett.* **51**(22), 1821–1823 (2015)
9. D. Berger, N. Gambetta, D. Celiand, C. Dufaza, Extraction of the base-collector capacitance splitting along the base resistance using HF measurements, in *IEEE Bipolar/BiCMOS Circuits and Technology Meeting* (2000), pp. 180–183

10. H.Y. Chen, K.M. Chen, G.W. Huangand, C.Y. Chang, Small-signal modeling of SiGe HBTs using direct parameter-extraction method. *IEEE Trans. Electron Devices* **53**(9), 2287–2295 (2006)
11. J. Ang, Research on Mextram model and parameter extraction for SiGe HBTs (Institute of Microelectronics, Tsinghua University, Beijing, China, 2014)
12. Y. Sun, J. Fu, J. Yang, J. Xu, Y. Wang, J. Cuiand, W. Zhou, An improved small-signal model for SiGe HBT under OFF-State, derived from distributed network and corresponding model parameter extraction. *IEEE Trans. Microw. Theory Techn.* **63**(10), 3131–3141 (2015)
13. J. Paasschens, W. Kloosterman, The Mextram bipolar transistor model-level 504. Nat. Lab unclassified report. 2001 (koninklijke Philips Electron., Delft, The Netherlands, NL-UN 2000811, 2001)
14. M. Schröter, A. Chakravorty, Compact Hierarchical Bipolar Transistor Modeling with HiCUM (World Sci., Singapore, 2010)
15. T. Chen, W.M.L. Kuo, E. Zhao, Q. Liang, Z. Jin, J.D. Cresslerand, A.J. Joseph, On the High-Temperature (to 300C) Characteristics of SiGe HBTs. *IEEE Trans. Electron Devices* **51** (11), 1825–1832 (2004)
16. D.B. Thomas, J.D. Cressler, L. Najafizadehand, R.W. Johnson, Performance and reliability of SiGe devices and circuits for high-temperature applications, in *Proceeding of IMAPS International Conference on High-Temperature Electronics Network* (2009), pp. 49–56
17. Q.J. Meng, H.B. Liu, Q.H. Meng, *Physics of Semiconductor Devices*, vol. 108 (Science Press, Beijing, 2005)
18. M. Schröter, A. Chakravorty, *Compact hierarchical modeling of bipolar transistors with HICUM* (World Scientific, Singapore, 2010)
19. Y. Sun, J. Fu, Y. Wang, W. Zhou, W. Zhangand, Z. Liu, Extraction of temperature dependences of small-signal model parameters in SiGe HBT HICUM model. *Chin. Phys. B* **25**, 0485014 (2016)

Chapter 7

Summary

7.1 Main Work and Research Results

With the continuous extension of space exploration, space environment is closely bound up with microelectronics technology. Various radiation effects in the space environment cause the electronic system to fail. Because of the strong anti-radiation ability, SiGe HBT has shown great potential in space radiation environment. However, due to the variability of space environment and the diversity of SiGe HBT process and device structure, there are still many key problems to be studied when the SiGe HBT is applied to the space radiation environment.

This dissertation mainly investigate the radiation effect and device model for SiGe HBTs. Firstly, the ionization damage effects, displacement damage effects and single event effect in SiGe HBT are separately studied using ^{60}Co gamma ray, swift heavy ion and pulsed laser, and the potential physical mechanism is discussed. Then, a novel equivalent circuit considering distributed effects is established, and a direct analytical parameter extraction method is proposed based on nonlinear rational function fitting. Finally, the proposed model and parameter extraction method are successfully applied to SiGe HBTs exposed to heavy ion radiation and high/low temperature environment. Some meaningful results are obtained, which can help to understand the physical mechanism of radiation effects, providing guidance for the device design and radiation hardening in radiation environment. The main results are summarized as follows:

1. The inherent multi-Mrad total ionizing dose (TID) tolerance of SiGe HBTs is verified, and the different ionization damage effects are found for different device structures. For three-terminal SiGe HBT with collector electrode directly eliciting from the backside of the substrate through gold evaporation, the reverse Gummel characteristic is almost unaffected by radiation, due to the smaller proportion of base current flowing through LOCOS edge. For SiGe HBT with emitter and substrate connected, an unexpected increase in emitter current exists,

besides to the base current degradation. Therefore, from the point of view of anti-radiation, it should avoid the emitter and the substrate shorting.

2. The effects of bias conditions on the ionizing damage under high and low dose rate irradiation were investigated. The experiment results indicated that the floating configuration shown an enhanced degradation in the high dose rate irradiation, while the forward active mode suffered more irradiation damage in the low dose rate irradiation. The varied bias dependences for both the dose rates irradiation might be attributed to the different origins of holes and released protons. During the high dose rate irradiation, the hole and proton in the spacer oxide around the EB junction are found to contribute to the formation of irradiation damages, and more serious performance degradation exists in the floating configuration. On the contrary, the ionizing damages at low dose rate irradiation might originate from the hole and proton in the extrinsic base region and the forward active mode shows an enhanced degradation due to the smaller electricfield in extrinsic base compared to the case with all terminals floating.
3. A new method to detect displacement damages using swift heavy ions instead of neutrons is proposed. The displacement damages induced by heavy ions are related with the non-ionization energy loss (NIEL). The larger the NIEL, the more the displacement damage, and the more serious the performance degradation. Besides the current gain degradation, other DC parameters, such as parasitic resistance, leakage current, Early voltage and neutral base recombination, show significant degradation. It indicates that displacement damage has become another major factor to performance degradation of SiGe HBT.
4. Results show that the interaction between displacement damages and ionization damages induced by heavy ion radiation is complicated, and influenced by of device structure, ion fluence and bias condition. For three-terminal SiGe HBT with collector electrode directly eliciting from the backside of the substrate through gold evaporation, the change in $\Delta(1/\beta_F)$ shows three distinct tendencies with influence Φ : sub-linearly under low V_{BE} , sub-linearly at low fluence and then linearly at high fluence under medium V_{BE} , and varies linearly throughout all ion fluence under high V_{BE} . On the reverse gain reciprocal $\Delta(1/\beta_R)$, only the displacement damages contribute to β_R degradation, and $\Delta(1/\beta_R)$ varies linearly throughout all the ion fluence under arbitrary V_{BC} . The underlying physical mechanisms were analyzed and investigated in detail.
5. The transient characteristics of SET in SiGe HBTs were successfully detected through pulsed laser microbeam combining with high-bandwidth real-time digital oscilloscope. The effects of laser energy, load resistance and bias states were analyzed. For a logic inverter with load resistor R_c , the larger V_{CC} is, the more serious the SET is, and larger R_c with a less charge collection results in a longer (worse) duration of the collector voltage upset. A near-ideal exponential model is proposed for the first time to describe the discharge of laser-induced electrons via collector resistance to collector supply when both BC and CS junctions are reverse biased or weakly forward biased. An additional multi-path

discharge is found to play an important role in the SET once the BC and CS junctions get strongly forward biased due to a strong transient step charge by the laser pulse.

6. An improved high-frequency small-signal model for SiGe HBTs is presented based on distributed effects. The proposed model takes into account the distribution characteristics of the intrinsic transistor, link base region under spacer, and extrinsic base–collector junction. The equivalent circuit for each region is separately derived using the transmission line equation with reasonable approximations. Being different from previous models, the intrinsic base resistance in the proposed model is pushed inside the internal base node and added to the components of collector and emitter resistance, which can fundamentally, explained the anomalous variation between bias-dependent collector resistance and base bias voltage in conventional compact model.
7. A novel direct analytical parameter extraction method based on nonlinear rational function fitting is proposed for SiGe HBT small signal equivalent circuit. After fitting to related admittance parameters, a number of coefficients are accurately obtained and then all the model parameters are directly extracted without any special test structure or numerical optimization. An excellent agreement is obtained between the measured and simulated S-parameters.
8. The small-signal model and parameter extraction method are successfully applied to SiGe HBT exposed to swift heavy ion irradiation and -55 to 200 °C wide temperature environment. The temperature-scaling model of extracted parameters was established.

7.2 Innovations

1. Different bias dependence of ionization damages at high and low dose rate radiation were found in SiGe HBTs. During the high dose rate irradiation, the hole and proton in the spacer oxide around the EB junction are found to contribute to the formation of irradiation damages, and more serious performance degradation exists in the floating configuration. On the contrary, the ionizing damages at low dose rate irradiation might originate from the hole and proton in the extrinsic base region and the forward active mode shows an enhanced degradation.
2. A method to detect the displacement damages in SiGe HBT using swift heavy ion is proposed. The displacement damages in transistors are found to be related with non-ionization energy loss (NIEL). The larger the NIEL, the more the displacement damage, and the more serious the performance degradation.
3. The real-time information of single event transient (SET) in SiGe HBT was successfully detected using pulsed laser, and the influence of laser energy, load resistance and bias states on SET was analysed in detail. An exponential discharge model was established for SET.

4. A new small-signal equivalent circuit for SiGe HBT is presented considering distributed effect. A direct analytical parameter extraction method is proposed based on nonlinear rational function fitting, and the extraction method is successfully applied to SiGe HBTs exposed to heavy ion and high/low temperature environments with -55 to 200 °C.

7.3 Suggestions for Further Work

For the subsequent research, the author suggests that:

1. This dissertation presents the DC characteristics degradation of SiGe HBTs in radiation environment. However, the degradation of AC parameters, such as capacitance, S -parameter and noise, are less involved. Further work should be carried out about AC characteristics degradation to fully evaluate the anti-radiation ability.
2. Degradations induced by heavy ion irradiation are depicted, and the potential physical mechanisms are analyzed in this dissertation, but lack the quantitative comparison to the conventional neutron radiation. This aspect should be paid attention in future.
3. As for the single event effect (SET), only the SET on device level is discussed. Subsequent work can be performed from circuit level (such as the simple logic circuit) to investigate the degradation of SiGe HBT circuit induced by the device-level SET. SET and the sensitive region of SiGe HBT circuit should also be considered.
4. This dissertation presents the parameters extraction of SiGe HBT small-signal model under radiation environment, and high/low temperature. In the follow-up work, the variation of model parameters with ion type, energy and fluence should be established, to obtain a universal SiGe HBT compact model considering the radiation effect.