Modeling Single-Event Transients in SiGe HBT Low-Noise Amplifiers Incorporating a Look-Up Table Approach

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Full Text

Preamble

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Abstract

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Keywords: SiGe HBT, single-event transient, coupled injection, TCAD simulation, look-up table

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Introduction

Silicon-Germanium heterojunction bipolar transistor (SiGe HBT) technology is highly promising for space applications [1]. By employing a graded Germanium profile in the base region, SiGe HBTs exhibit superior DC and AC characteristics compared to conventional silicon bipolar transistors [2]. Furthermore, SiGe HBTs can be monolithically integrated with silicon complementary metal-oxide-semiconductor (CMOS) processes through SiGe BiCMOS technology, which reduces cost and enhances integrated circuit (IC) performance [3]. Most importantly, SiGe HBTs are capable of reliable operation under extreme temperatures ranging from -180°C to +200°C [4] and demonstrate strong tolerance to total ionizing dose (TID) effects up to multi-Mrad levels [5]. However, numerous experiments and simulations have shown that SiGe HBTs are vulnerable to single event effects (SEEs) [6-7].

With the continuous scaling of feature sizes in ICs and semiconductor devices in recent years, the risk of SEEs has become increasingly severe in aerospace applications. The impact of a striking single particle on a transistor induces excess charge carriers, which further affect the electrical system through single-event transient (SET) [8]. The SET has emerged as a major cause of IC failures, making accurate injection of SET perturbations into ICs a key step in radiation effect evaluation.

Currently, two primary methods are employed for SET injection: the independent current source method and the device/circuit mixed-mode simulation method. The independent current source approach includes the double-exponential current source method and the piecewise linear (PWL) current source method, which inject predefined or empirically measured current waveforms into the circuit netlist in SPICE simulators. However, this technique suffers from limited accuracy and is unsuitable for complex circuits due to its inability to account for circuit feedback and loading effects [9]. In contrast, the mixed-mode simulation method establishes self-consistent boundary conditions based on the dynamic response of the circuit. This method builds a computational model of the device and injects the simulated transient current into the circuit, thereby enabling coupled simulation of node voltage variations and SET propagation. In this manner, the node voltage variations within the circuit can be calculated, enabling the simulation of coupling effects. A key advantage of this approach is its capability to yield more accurate SET currents [10].

The study presented in this paper is divided into four stages. Initially, a low-noise amplifier (LNA) circuit is built using a germanium-silicon heterojunction transistor (SiGe HBT). Secondly, SET experiments of the LNA circuit are carried out on the ADS platform, utilizing a look-up table coupling injection method. Then, the results of the experiments are compared with the outcomes of mixed-mode simulation on the Sentaurus TCAD platform. Finally, coupled injection SET experiments are performed on circuits at the analog circuit level on the ADS platform to analytically investigate the generation and propagation mechanisms of single-event transient currents under the influence of multiple factors (different energies, angles of incidence, characteristic radius, etc.).

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2. Device Structure and TCAD Modeling

A. The Structure of SiGe HBT

The SiGe HBT modeled in this work uses the NPN vertical bipolar transistor process, which is characterized by the fact that the base region of the transistor is made of SiGe with a gradient of components, using wide-band Si for the emitter and collector and narrow-band SiGe as the base region [11]. Thus, two grading heterojunctions are formed at the emitter/base (E/B) junction and base/collector (B/C) junction. The simulated 2D structure device size of SiGe HBT is 2.4 m × 1.5 m.

The large substrate and collector regions are manufactured from silicon with light doping. The emitter region has a width of 0.12 m and a thickness of 0.225 m, with a heavy arsenic doping concentration of 5×10^{18} cm^{-3}. There is an epitaxial silicon layer with gradually doped germanium to form an intrinsic SiGe-base region. The base region has a width of 0.72 m and a thickness of 0.075 m, with a doping concentration of 1×10^{20} cm^{-3}. The heavy doping base region could be fabricated to reduce base resistance and improve the frequency characteristic of the device. The local oxidation of silicon is applied to the isolation process under the epitaxial base region. The thickness of the substrate is 0.6 m and its doping concentration is 1.5×10^{15} cm^{-3}. [Figure 1: see original paper] shows the two-dimensional structure model of the device constructed by the TCAD simulation tool.

B. The Process of Numerical Simulation Modeling

[Figure 2: see original paper] shows the schematic of a high-energy ion striking a semiconductor material. A significant number of electron-hole pairs are generated along the track of the incident ion. In the TCAD Sentaurus tool, the HeavyIon function is employed to define the energy, characteristic radius (R), and incident angle (ϕ) of the ion for subsequent numerical analysis. Here, ϕ denotes the angle between the ion track and the normal to the material plane, while R represents the characteristic radius of the incident ion.

Based on the particle incidence model of TCAD above, [Figure 3: see original paper] shows the two-dimensional model of the 0.12 m SiGe HBT under ion incidence. The ion strike is positioned at the center of the device, with a characteristic radius of 0.1 m and a duration of 0.1 ns. The ionization charge follows a Gaussian distribution in both space and time. The central region of the device corresponds to the active area of the vertically configured SiGe HBT, which is also the most sensitive to single-event transients (SETs) and yields the strongest transient response. The simulation incorporates multiple physical models, including Fermi-Dirac statistics, bandgap narrowing, concentration-dependent Shockley-Read-Hall (SRH) recombination, and Auger recombination.

Numerical simulations were performed on a SiGe HBT device with carrier transport equation. Figures 4 and 5 depict the temporal evolution of electron concentration and potential distribution following ion incidence in the SiGe HBT model. Under reverse bias conditions, the depletion layer of the SiGe HBT acts as a sensitive region for charge collection, primarily owing to the presence of a strong applied electric field. The ion track generates a high density of electron-hole pairs, which behave as a conductive pathway, enabling the electric field from the depletion layer to extend several micrometers beyond its original boundary along the ion track. The resulting junction electric field rapidly collects charges along the track, inducing a transient current. This process leads to a funnel-shaped distortion of the potential within the depletion region of the PN junction—a phenomenon known as the funneling effect [12].

The funneling effect considerably enhances the depth of charge collection, leading to a total collected charge that can exceed the charge originally deposited in the depletion layer by more than an order of magnitude [13]. As shown in [Figure 5: see original paper], a distinct funnel-shaped potential emerges at 10 ps after ion strike. Subsequently, as the funneling effect diminishes, excess carriers located away from the PN junction are gradually removed through diffusion. Both the potential distribution and electron concentration return to their pre-incidence states by 100 ps. This recovery process occurs significantly faster than diffusion alone. As one of the most prominent mechanisms in single-event effects, the funneling effect justifies the use of a simplified current source model to emulate SET injection in subsequent analog circuit experiments.

C. The Construction of the LNA Circuit

The mixed-mode tool of Sentaurus TCAD is used to construct the circuit model. [Figure 6: see original paper] presents the circuit topology of an RF low-noise amplifier (LNA) designed based on the 0.12 m SiGe process, with a center frequency operating in the X-band. To achieve higher gain, impedance matching networks are implemented at both input and output ports, resulting in a center frequency of 9.5 GHz. In the proposed LNA structure, emitter degeneration inductor L_3 introduces negative feedback, providing real impedance at the RF input port to compensate for capacitive reactance and enhance circuit stability. Inductor L_2 is utilized to match the imaginary part of the input impedance, while DC-blocking capacitor C_2 serves both isolation and matching purposes. Bias voltage is provided through the resistive voltage divider formed by R_1 and R_3. Collector load resistor R_2 adjusts the real component of the output impedance to improve matching. The collector inductor L_1 and output capacitor C_1 tune the LNA circuit to the center frequency. Transistors CE and CB are the 0.12 m SiGe HBTs, which are fabricated as described in the above work and are critical for ensuring stable circuit operation.

Upon completion of the circuit design, the performance of the LNA is simulated and evaluated using ADS software. [Figure 7: see original paper] shows the S-parameters of the designed LNA. It can be observed that both S_{11} and S_{22} remain below -40 dB at the center frequency of 9.5 GHz, while S_{12} is also below -40 dB, demonstrating excellent input/output matching and high isolation. Furthermore, the forward gain (S_{21}) exceeds 20 dB at the center frequency, indicating strong amplification capability. These results confirm that the LNA built in mixed-mode exhibits favorable RF performance. The key technical specifications of the proposed LNA are summarized in .

3. SET-Coupled Injection Based on 2D Look-Up Tables

The large number of charges generated by the ion strike is collected primarily at the collector terminal in the SiGe HBT of the LNA. This causes a dynamic variation in the collector voltage, which gradually decreases as the charge is collected [14]. In addition, as discussed in previous sections, the ion striking induces a funneling effect in the transistor. Based on the relationship between the collector voltage and the amount of charge collected from the ion strike, it can be inferred that the SET response of the transistor can be emulated by adjusting the bias voltage applied to the collector of the SiGe HBT in the LNA circuit. By aggregating the induced single-event transient current (ISET) data from SiGe HBT LNA circuits under different collector bias voltages (VC), a look-up table is constructed, with time (t) and collector bias voltage (VC) as independent variables and ISET as the dependent variable.

A. Construction of the Look-Up Table

The SET simulation in the LNA circuit is carried out using mixed-mode Sentaurus TCAD. The ion strike position is chosen at the center of transistor CB shown in [Figure 6: see original paper], and the device model is the 0.12 m SiGe HBT that was previously constructed. The physical model of simulation aligns with those established in prior studies. The single-event transient current response of the CB transistor was scanned, and the results are shown in [Figure 8: see original paper].

The parameters for the incident ions encompass a LET value of 80 $\mathrm{MeV \cdot cm^2/mg}$, a characteristic radius of 0.05 m, an incidence angle of 0°, an incidence time of 2 ps, and a characteristic delay time of 1 ps. The resulting data shown in [Figure 8: see original paper] are compiled into a two-dimensional (2-D) look-up table. In this table, the collector voltage (VC) of the CB transistor and time (t) serve as the independent variables, while the SET current (ISET) constitutes the dependent variable, as summarized in .

B. Coupling Injection via a 2-D Look-Up Table for SET Simulation

The incorporation of the 2-D look-up table is implemented by invoking a Verilog-AMS module within the ADS platform using the Verilog-AMS hardware description language (HDL). [Figure 10: see original paper] shows the corresponding schematic diagram of the import process. The specific procedure is as follows: The collector voltage VC of the CB transistor in the LNA circuit and the current simulation time t are acquired using the $table function. By calling the Verilog-A module, the dataset stored in the 2-D lookup table is accessed, and the corresponding transient current ISET is obtained through interpolation or extrapolation. The computed ISET is then injected into the circuit, after which the updated collector voltage VC and the current time t are sampled again [15]. This process is repeated iteratively, ultimately yielding the complete ISET waveform while accounting for circuit coupling effects.

The two-dimensional look-up table simulates the scenario when the CB transistor is subjected to ion impact. A current transient simulation is performed on the LNA circuit on the ADS platform, simulating that the CB device in the LNA circuit is subjected to ion incidence with a LET value of 80 MeV · cm^{2}/mg, an incidence radius of 0.05 m, and an incidence angle of 0°. The results of the simulation are shown in [Figure 11: see original paper].

The simulation results obtained using the 2-D look-up table-based coupling injection method in the LNA circuit were compared with those from mixed-mode TCAD simulation. As shown in [Figure 12: see original paper], the close agreement between the two sets of results demonstrates the viability and accuracy of the proposed 2D look-up table approach for coupling injection.

4. Results and Analysis of Coupled Injection SET Experiments

To investigate the key factors that influence SEEs in SiGe HBTs and their LNA circuits under extreme operating conditions, this study conducted mixed-mode simulations of SET in SiGe HBT LNAs using Sentaurus TCAD. The simulations varied ion strike parameters, including linear energy transfer (LET) values, incident angles, and characteristic radius. The resulting data were compiled to construct a 2-D look-up table using the methodology described previously. This table was then integrated into the LNA circuit model on the ADS platform through a coupling injection method, enabling SET simulation at the analog circuit level. This approach allows detailed analysis of the generation and transmission mechanisms of SET currents under varied energy, angle of incidence, and characteristic radius conditions in a realistic circuit environment.

A. Simulation Analysis of Coupled Injection SET with Different LET Values

In the SET experiments investigating the influence of ions with different LET values, the LET parameters were selected based on the energy spectrum of heavy ions in space and the available energy range of ground heavy ion accelerators. Specifically, ions with LET values of 10, 50, and 80 MeV · cm^{2}/mg were used to generate the SET datasets. The ion incidence angle was set to 0°, and the characteristic radius was fixed at 0.05 m. The resulting transient currents measured at the output port of the LNA circuit are shown in [Figure 13: see original paper].

[Figure 13: see original paper] shows the transient current waveforms at the output port of the LNA circuit obtained from coupled-injection SET simulations using datasets corresponding to different LET values. As shown in the figure, the amplitude of the output current exhibits a consistent increase with higher LET values of the incident ions, accompanied by an extension of the transient duration. This phenomenon can be attributed to the fact that LET corresponds to the energy deposited per unit path length by striking ions, resulting in enhanced charge generation and, consequently, more pronounced transient disturbances.

The ions incident in the Si material produce electron-hole pairs per unit length according to:

$$\frac{dN}{dP} = \frac{eV}{\text{pair}}$$

As the linear energy transfer (LET) value increases, more electron-hole pairs are generated per unit length within the device, leading to enhanced charge accumulation. According to the literature [16], mixed-mode circuit experiments using different ion species incident on silicon devices demonstrate this trend: oxygen ions (LET = 2.19 MeV · cm^{2}/mg) produced a collected charge of approximately 0.29 pC; neon ions (LET = 3.49 MeV · cm^{2}/mg) yielded about 0.38 pC; and argon ions (LET = 9.74 MeV · cm^{2}/mg) resulted in approximately 1 pC of collected charge. Extrapolation of these results suggests that when the LET value reaches 80 MeV · cm^{2}/mg, the accumulated charge is roughly 8–9 times greater than that generated by ions with an LET of 10 MeV · cm^{2}/mg. This increase in accumulated charge not only amplifies the SET current but also prolongs the tail duration of the transient currents.

The higher LET value enhances charge generation in the collector-base (CB) transistor region. The excess charge is then evacuated through the collector terminal, resulting in an overall increase in the amplitude of the transient current at the low-noise amplifier (LNA) output port induced by ion strike. This elevated current response may render downstream circuit devices more susceptible to damage.

B. Simulation Analysis of Coupled Injection SET for Different Incidence Angles

In SET experiments where the ion incidence angle is varied as an influencing factor, the ion angle range was selected as 0–30° considering the nm-scale feature size of the SiGe process used in this study. Experiments were conducted at incidence angles of 0°, 15°, and 30°, with the LET value of 10 MeV · cm^{2}/mg and a characteristic radius of 0.05 m. The resulting transient currents measured at the output port of the LNA circuit are summarized in [Figure 14: see original paper].

[Figure 14: see original paper] presents a comparison of the transient currents at the output port of the LNA circuit obtained from coupled-injection SET experiments under different ion incidence angles. In these experiments, the LET value of the striking ions remained constant. The substrate breakdown length is denoted as L (in m), and the collected charge is represented as Q (in pC) [17]:

$$Q = \text{LET} \times L$$

As indicated by Equation (4-3), when ions pass through the substrate, an extended ion range should be produced by a larger incidence angle. This increased trajectory within the device results in greater charge generation and improved charge collection efficiency. However, even when the incidence angle is raised to 45°, the collected charge only increases to approximately 1.5 times that of vertical incidence. Moreover, larger angles cause striking ions to be deflected away from the sensitive regions of the transistor, leading to incomplete charge collection. Consequently, the amplitude of the SET current does not change significantly, and no more pronounced current tailing is observed.

With increasing ion incidence angle, the charge collected by the collector-base (CB) transistor in the LNA circuit rises. The excess charge is evacuated through the collector port, causing the transient current at the LNA output induced by ion strike to increase in the initial phase and decrease in the later phase, resulting in only a minor overall variation in amplitude. Since LNAs and other RF front-end components process very weak signals received from the antenna, even slight signal disturbances can markedly affect downstream circuits [18]. Therefore, this effect warrants serious consideration in radiation-effect hardening strategies.

C. Simulation Analysis of Coupled Injection SET with Different Characteristic Radii

In SET experiments where the characteristic radius of ions is the influencing factor, the variation range was set to 0.05–0.1 m. This choice accounts for minor fluctuations in the characteristic radius that may occur under extreme conditions—even when using the same material and ion energy. The experimental data correspond to characteristic radii of 0.05 m and 0.1 m. Throughout these measurements, the ion LET value was held constant at 10 MeV · cm^{2}/mg, and the incidence angle was fixed at 0°. The resulting transient currents measured at the output port of the LNA circuit are summarized in [Figure 15: see original paper].

[Figure 15: see original paper] compares the transient currents at the output port of the LNA circuit obtained from coupled-injection SET experiments under different characteristic ion radii. A smaller characteristic radius implies a more concentrated charge deposition, which can facilitate more efficient charge collection by the collector. However, this increased localization of electron-hole pairs also enhances Auger recombination, thereby reducing the net collected charge [19]. The general expression for the Auger recombination rate in semiconductors is given by Equation (4-4):

$$R_{\text{Aug}} = r_{n\text{Aug}}(n^{2p}) + r_{p\text{Aug}}(p^{2n})$$

where $r_{n\text{Aug}}$ and $r_{p\text{Aug}}$ represent the Auger recombination coefficients for electrons and holes, respectively. From Equation (4-4), it can be inferred that a higher carrier concentration leads to a larger electron-hole pair product, which in turn increases the rate of Auger recombination. As shown in [Figure 15: see original paper], when the characteristic radius of the incident ion increases from 0.05 m to 0.1 m (on the micrometer scale), the amplitude of the transient current at the LNA output exhibits a slight increase in the initial phase, while the trailing-edge current magnitude of the ISET decreases. This behavior can be explained as follows: in the early stage of the transient, a smaller characteristic radius results in more localized charge deposition, leading to higher carrier concentrations that enhance Auger recombination and reduce charge collection efficiency. In the later stage, as charge is gradually collected, the Auger recombination effect diminishes. Consequently, at the tail of the SET current, the amplitude for ions with a smaller characteristic radius is further reduced.

5. Summary

In this work, a SiGe HBT structure is established using Sentaurus TCAD to explore and analyze mechanisms of single-event transients (SETs). Based on the developed SiGe HBT device model, a low-noise amplifier (LNA) circuit is constructed, and SET experiments are conducted using a two-dimensional (2-D) look-up table approach for coupled current injection. The results confirm the feasibility and accuracy of the 2-D look-up table-based injection method for simulating SETs. Furthermore, the variations in SET pulses with respect to ion linear energy transfer (LET) values, incidence angles, and characteristic radii are systematically investigated within the analog simulation environment. The obtained data are thoroughly analyzed and interpreted to draw theoretical conclusions. In subsequent work, the 2-D look-up table coupled injection method will be applied to more complex LNA circuits to further evaluate the impact of SETs on circuit performance.

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