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# 3-D simulation study of single event effects of SiGe heterojunction bipolar transistor in extreme environment

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ABSTRACT

A 3-D simulation of single event effects (SEEs) for domestic Silicon–Germanium heterojunction bipolar transistor (SiGe HBT) in extreme environment is performed with TCAD simulation tools. The influences of environment temperature and linear energy transfer (LET) on SEE are investigated. The combined effects of temperature and LET are also discussed. The results show some interesting phenomena by analyzing collected charges and transient current. The collected charges increase as temperature rises, but the current peaks decline with temperature increasing at base, collector and substrate. However, the peak of emitter transient current rises up and then declines. As LET rises, the collected charges go up linearly, and the transient current peaks also increase but their growth trends are slow. Mobility, carrier ionization and recombination of various regions at different conditions are the main causes of these differences. Current transient is very severe at low temperature. But charge collection is sensitive to high temperature and high LET. Transient pulse caused by diffusion mechanism may have a serious effect on SEEs.


## 1. Introduction

Silicon–Germanium heterojunction bipolar transistors (SiGe HBTs) have been widely applied in high-speed digital, RF and microwave circuits because of their excellent transistor performance and integratability with CMOS [1]. In addition, SiGe HBT is a strong contender for space applications in extreme environment on account of superior temperature characteristics [2,3]. It can be used from very low to high temperature owing to the bandgap engineering in silicon. Consequently, SiGe HBTs have a possibility to replace bulk-Si components in deep space exploration, which can remove the huge warm box so as to reduce launch costs and extend the function of remote control of satellite [4,5]. Moreover, SiGe HBTs have been demonstrated outstanding hardness to both total ionizing dose (TID) radiation and displacement damage due to their device structure features [6–8]. However, relevant research results have shown that SiGe HBTs could be sensitive to the single event effects (SEEs). When ions strike the device, each terminal would collect a great number of charges. Terminal current would be a large pulse due to charge collection. These serious phenomena may cause "0", "1" upset in digital circuits of SiGe HBTs, and related circuits may burn in worse cases [9].

Electronic systems, which work in space environments, must accept the challenges of extreme temperature and various particle bombardments. Thus, it is important to explore the effects of extreme environment on SEEs in SiGe HBTs. The Georgia Institute of Technology and Auburn University obtained the charge collection mechanism of SEE in SiGe HBTs both by heavy ion micro-beam experiment and computer simulation [10,16,19]. In 2010, the group of Prof. Niu reported charge collection and single event upset (SEU) in SiGe HBT logic circuit at cryogenic temperatures by TCAD. The results showed that the collected charges of SiGe HBTs are few and the LET threshold of logic circuit improves at low temperature [10]. However, SEEs of SiGe HBTs in a wider temperature range are rarely reported. And the combined influence of temperature and LET is not considered. The heavy ion testing is expensive and it is difficult to achieve extreme temperatures. A validated computational modeling provides an effective method to investigate the SEE damage mechanism for SiGe HBTs in extreme environment.

Thus, we built a 3-D simulation model for SEE in domestic SiGe HBTs by TCAD. First, we construct a reasonable device structure model based on the actual device and the test data of electrical parameters. Then, a series of simulations of SEE at different temperatures and different LETs are carried out. Through analyzing the transient current and charge collected at different terminals, the impacts of extreme environment on SEE of the SiGe HBT are investigated. Finally, the combined influences of temperature and

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LET are discussed. The results show that the SEEs of SiGe HBTs in extreme environment are complicated.

## 2. 3D simulation of device structure

This paper selects the SiGe HBT manufactured by Tsinghua University. The size of the device is 30 μm × 30 μm × 21.35 μm. Its basic structure is similar to the bulk silicon vertical NPN bipolar transistor (Si BJT). But the base region is constituted by gradient SiGe in the SiGe HBT. The content of Ge gradually changes from 0% at Emitter/Base (E/B) junction and Base/Collector (B/C) junction to 20% in the intrinsic base that forms grading heterojunctions, and maintains 20% in the base. Fig. 1 shows the energy band structure of this SiGe HBT. The doping concentration of base is about $1 \times 10^{19}\ cm^{-3}$, and the thickness of base is 0.08 μm. The thin low-resistivity base effectively improves the frequency and current gain [11,12]. An epitaxial base region of p-type polysilicon is grown above the shallow trench isolation (STI) which is located inside the collector. The area of C/S junction is about 18 μm × 20 μm. The collector contact is lead out by a heavily doped $n^+$ buried layer. A ring wall of heavily doped boron leads out substrate contact near the edge of the device. The doping concentrations of emitter and collector are $1.5 \times 10^{20}\ cm^{-3}$ and $6 \times 10^{15}\ cm^{-3}$ respectively. According to the process and layout information of the device, a 3-D model of the SiGe HBT is built using TCAD tools which include Sentaurus Structure Editor and Sentaurus Device. Fig. 2 shows the 2-D cross section which is the result of a cut of the simulated 3-D structure at the central point of z coordinate axis. The internal structure of the device and the distribution of impurities can be observed better by the 2-D cross section.

Both high values of current gain and early voltage are the most outstanding electrical properties in SiGe HBTs. Thus, the Gummel curve and output characteristic curve obtained by simulation are compared with the curves achieved by device test so that the simulation model is close to the real device. A reasonable 3-D structural model of the SiGe HBT is constructed through adjusting doping profile near the pn junctions. The physical models in simulation include Phillips unified mobility, SRH recombination, Auger recombination, velocity saturation, and bandgap narrowing (BGN) [16-18]. The electrical performances of the device are measured by KEITHLEY 4200. Figs. 3 and 4 show the Gummel characteristic and output characteristic in simulation and test, respectively. The zigzag shapes of I–V characteristic at small voltage are formed by noise signals. The results of simulation and test are consistent. The simulated Gummel characteristics at 77 K, 300 K, and 473 K are given in Fig. 5. The changing trend of simulation is relatively similar to that reported in literature [3] and [19], so the temperature model could reflect the SEEs changes with temperature.

## 3. Single-event effect simulation

The TCAD simulation process, in which heavy ions strike semiconductor devices, is as follows. Firstly, the program calculates the carrier generation rate along the track of striking ions. Then, the calculator solves Poisson equation and carrier continuity equation according to the number of electron-hole pairs (e-h pairs) at the first step. Finally, the simulation gets the information of the internal potential changes, current transient and charge collection. The generation rate of carriers induced by heavy ions as

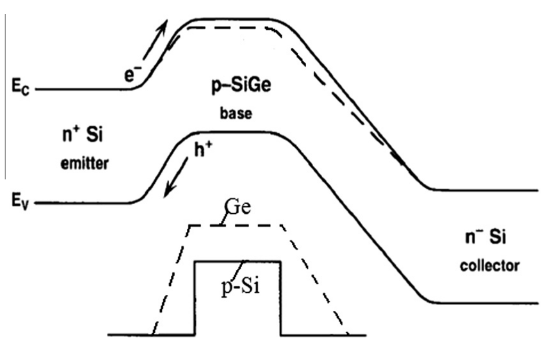


**Fig. 1.** The energy band diagram of the SiGe HBT.

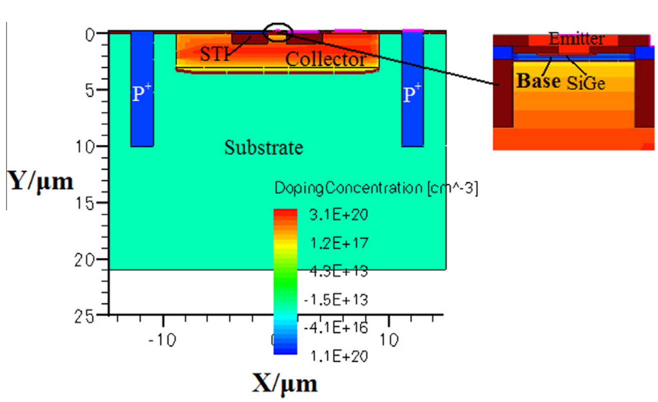


**Fig. 2.** 2-D cross section of SiGe HBT.

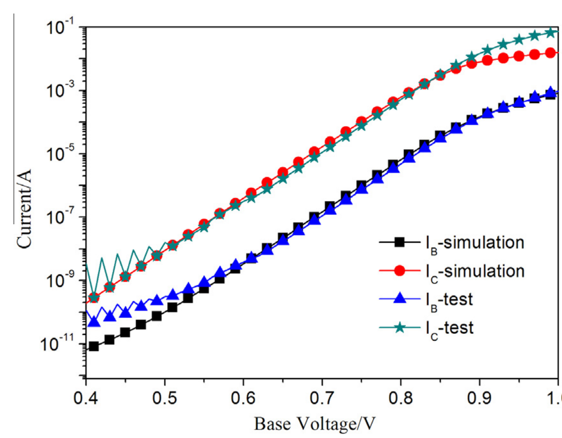


**Fig. 3.** Gummel characteristic in simulation and test.

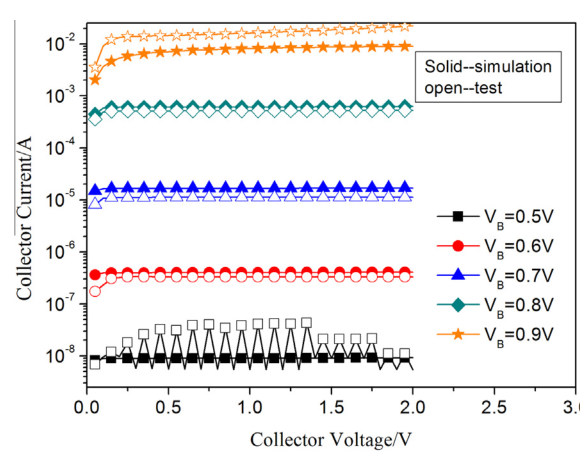


**Fig. 4.** Output characteristic in simulation and test.