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Investigation of bias dependence on enhanced low dose rate sensitivity in SiGe HBTs for space application

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ABSTRACT

NPN silicon–germanium (SiGe) heterojunction bipolar transistors (HBTs) were exposed to ^{60}Co gamma source at different dose rates under two bias conditions. Excess base currents and normalized current gains are used to quantify performance degradation. Experiment results demonstrate that the lower the dose rate, the more the irradiation damage, and some enhanced low dose rate sensitivity (ELDRS) exists in SiGe HBTs. The ELDRS effect is found to depend highly on the bias condition during exposure, and the transistors with forward active mode exhibit a more serious ELDRS effect compared to the floating case. The performance degradation at different dose rates and bias conditions is compared and discussed, and furthermore the underlying physical mechanisms are analyzed and investigated in detail.

1. Introduction

Extreme environments represent some harsh surrounding falling outside the domain of conventional circuit specifications, including cryogenic temperature (e.g., 77 K), very high temperature (e.g., 300 °C) and radiation environment (e.g., space) [1]. Usually, these extreme environments are unfriendly to electronic devices and could cause a serious reliability problem. For example, due to the high ionizing radiation damage, the conventional MOSFET will quickly fail [2]. Therefore, devices should be “harden” to its intended environments. Silicon–germanium (SiGe) heterojunction bipolar junctions (HBTs), due to the existence of energy band engineering in base region, have a wide temperature range capability and multi-Mrad total ionizing dose (TID) tolerance [3,4], and recently have attracted great attention in extreme environment electronics applications, especially in radiation-rich space exploration [5–9]. One potential application of SiGe HBTs in extreme environment is NASA's vision for Moon exploration [3]. The temperature range on the Moon surface is considerably wide, about from −180 °C to 120 °C; furthermore, high total dose and heavy ion radiation exist around the Moon. These extreme environments preclude the use of conventional devices for circuit design, and “warm boxes” are often needed to protect conventional devices from cryogenic temperature and irradiation, which will increase system volume and weight. However, bandgap-engineered SiGe HBTs could offer great potential to these extreme environment applications with little or no process modification.

According to the MIL-STD 883 Method 1019.7 [10], multi-Mrad TID tolerance for SiGe HBTs is generally obtained at a high dose rate of 50–300 rad(Si)/s. However, the dose rate in real space radiation environment is extremely low (typically about 0.0001–0.1 rad(Si)/s) and therefore the total dose accumulation is a relatively slow process, which may cause the known enhanced low dose rate sensitivity (ELDRS) effect [9,11,12]. Due to the existence of ELDRS effect in SiGe HBTs, performance degradation in real space mission cannot be estimated accurately by means of accelerated ground-based testing. Besides, SiGe HBTs often experience a wide variety of operating bias conditions in practical circuits. For example, in current-mode logic or emitter logic families, the transistors operate only under forward active mode. For some RF application, the transistors are biased at saturation mode. However, for certain BiCMOS logic families, the emitter–base (EB) junction can experience reverse-biased mode [13,14]. Thus, it is necessary to investigate the underlying mechanisms of ELDRS effect and rigorous hardness assurance requires a deeper look at the bias dependence on the ELDRS effect. Therefore, it would seem prudent to conduct some experiments for SiGe HBTs irradiated at different dose rates with various bias configurations.

In this work, we present a comprehensive investigation of irradiation response of NPN SiGe HBTs at different dose rates and bias conditions. Measurement results indicate that the performance degradation is indeed dose rate dependent and show an ELDRS effect for the two bias conditions. Compared to the floating configuration, the forward active mode suffers more serious ELDRS

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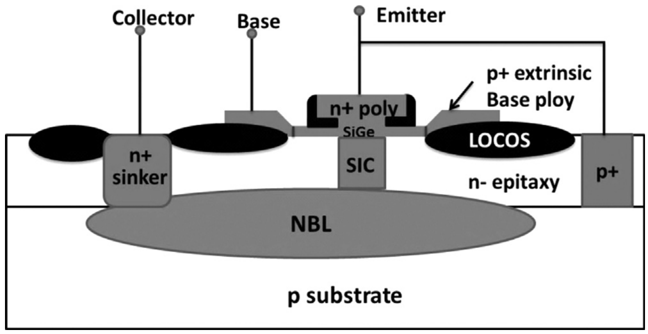

Fig. 1. Schematic cross-sectional view of SiGe HBT under investigation.

effect. The considerably different degradation behaviors at high and low dose rates are discussed, and furthermore, the underlying physics mechanisms are analyzed and investigated in detail.

2. Experiments

The devices under test (DUTs) are vertical NPN SiGe HBTs encapsulated in standard SOT-23 plastic packaging, which is designed and fabricated by Institute of Microelectronics, Tsinghua University. A schematic cross-sectional view is shown in Fig. 1. The main process is as follows: after n^+ buried layer (NBL) formation on p-type substrate, the lightly doped n^- collector epitaxy is completed. An n^+ collector sinker is then formed, followed by local oxidation of silicon (LOCOS) for device isolation, in situ boron doped graded SiGe base epitaxy, selectively implanted collector (SIC) and heavily doped n^+ polysilicon emitter contact. An inter-digital layout is adopted for chip design with each emitter finger of $0.4 \times 20\ \mu m^2$. Emitter and substrate are connected together via metal interconnection.

The examples were irradiated with ^{60}Co gamma source at both high dose rate (50 rad(Si)/s) and low dose rate (0.1 rad(Si)/s) at room temperature. A Pb/Al box was adopted to decrease the flux of secondary gamma ray and ensure a monochromatic gamma ray spectrum. The accumulated doses are 50 krad(Si), 100 krad(Si), 170 krad(Si), 300 krad(Si) and 500 krad(Si). Two different bias conditions were applied during exposure: (i) all terminals floating and (ii) forward active mode (V_{CE}=2 V, I_C=5 mA). The transistors were removed from the irradiation chamber at specified intervals and characterized with a Kensity 4200 Semiconductor Parameter Analyzer at room temperature. The irradiation resumed after the characterization until the required accumulated dose was reached.

3. Results and discussion

The forward Gummel characteristics of SiGe HBTs irradiated at high dose rate and low dose rate for the forward active mode are shown in Fig. 2. 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). The ionizing damage in SiGe HBTs, caused by gamma irradiation, can induce the creation of positive oxide-trapped charges in the spacer oxide over EB junction and interface states at SiO_2/Si interface [5,7]. The positive oxide-trapped charges deplete p-type base region, leading to an increased surface recombination current. The interface states act as effective recombination centers and increase the surface recombination velocity. As a result, the excess base current appears at a given V_{BE} since there is more recombination in the

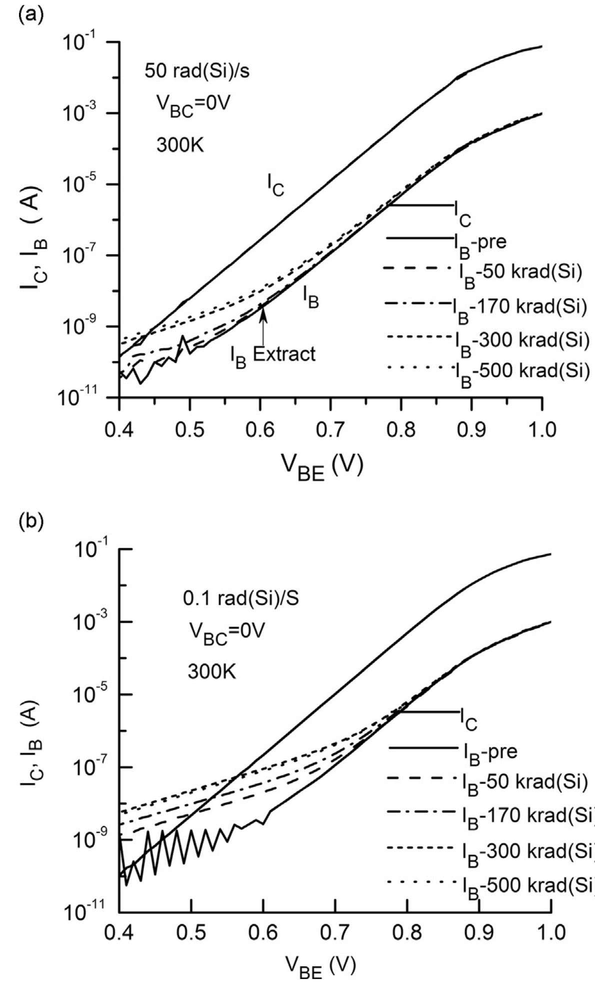

Fig. 2. Forward Gummel characteristics for the forward biased SiGe HBT irradiated at (a) high dose rate and (b) low dose rate.

transistors after irradiation, as shown in Fig. 2. The base current ideality factor in medium voltage bias regime (V_{BE}=0.6–0.8 V) is found to increase from about 1.06 to 1.37 after high dose rate irradiation when accumulated dose goes up to 500 krad(Si), and it also rises from 1.07 to 1.87 after low dose rate irradiation. This suggests that the non-ideal recombination current dominates the base current, and radiation-induced oxide trapped charges and interface states are indeed responsible for the excess base recombination current [5]. Besides, it is noted that I_B at a dose of 500 krad(Si) for low dose rate irradiation is slightly lower than that at the dose of 300 krad(Si), as shown in Fig. 2(b), which may be due to the annealing of the oxide trapped charges [12].

The carriers injected to base region flow slowly along the base surface, and the lower the V_{BE}, the longer the movement time, and thus the larger the carrier recombination probability. As a result, very large surface recombination current appears at low V_{BE}, i.e., the ionization damages have a large influence on base current degradation at low V_{BE}. In order to quantitatively compare the influence of dose rates on performance degradation, two electrical parameters, excess base current ($\Delta I_B = I_{B,post} - I_{B,pre}$) and normalized current gain ($\beta_{nor} = \beta_{post}/\beta_{pre}$), 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. The data extraction point is selected at V_{BE}=0.6 V to avoid high injection effects where large carrier densities severely diminish the G/R effects of radiation-induced traps. Fig. 3 depicts ΔI_B and β_{nor} at V_{BE} of 0.6 V as a function of gamma dose after high and low dose rate