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Technical Notes

Bias influence on ionizing radiation effects for 3CG130 PNP bipolar junction transistors

Chaoming Liu, Xingji Li *, Hongbin Geng, Dezhuang Yang, Shiyu He

School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China

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A B S T R A C T

In order to evaluate the influence of bias conditions on ionizing radiation effects for PNP bipolar junction transistors (BJTs), the 110 keV electrons' irradiations were performed and different electrical parameters were measured in-situ for 3CG130 PNP BJTs with different bias conditions during the exposure. Based on the experimental results, it is clear that the bias condition affects the ionization damage level on PNP BJTs, which is caused by 110 keV electrons' irradiations. The PNP transistors under reverse/forward bias of emitter–base junction exhibit greater/lower degradation than those under zero bias at a given irradiation fluence.

1. Introduction

Bipolar junction transistors (BJTs) are being extensively used in spacecraft due to their current drive capability, linearity and so on. Numerous studies have demonstrated that the sensitivity of a bipolar circuit to radiation damage is primarily determined by gain degradation in critical bipolar junction transistors within the circuit [1–3]. Therefore, it is valuable to research the radiation response of bipolar junction transistors to find better design strategies before employing them for specific applications. In space systems, electronic components are susceptible to radiation environment composed of cosmic rays, protons, electrons and other particles [4–8]. The bias condition during the irradiation or the employment is an important factor for bipolar devices [9–12].

BJTs are sensitive to both ionizing and displacement effects induced by charged particles [13–16]. However, the protons, neutrons, heavy ions and high energy electrons can cause both the ionizing and displacement damage to the BJTs. Even the γ-ray could produce displacement damage to semiconductor devices, as mentioned in Refs. [17,18]. Therefore, these particles are not convenient to explore the ionizing radiation damage mechanism of the devices. The low energy electrons and X-rays' irradiations are suitable to research the ionization radiation sensitivity of the device [19]. The work performed in this paper focuses on the influence of various bias conditions during 110 keV electrons' irradiation. Reverse, zero and forward emitter–base junction biases, that is, the most frequently encountered conditions of the device operation, are investigated in the paper. The results of this study provide valuable information to spacecraft projects and device designers, and also extend the body of information about ionizing radiation effects to additional devices.

2. Experimental details

The 3CG130 bipolar junction transistors were used as samples in this study. These are high radio frequency and low power Si PNP transistors. The thickness is about 700 nm, 1 μm, 4 μm and 12 μm for the insulating silicon dioxide (SiO_2), the emitter (p^+), the base (n^+) and the epitaxial layer (p^-) of the PNP BJTs, respectively. Uncertainties in measured parameters were less than 10 percent. In addition, the samples were mounted inside a package with removable upper lid for irradiation.

The irradiation test facility used in this investigation is an accelerator at Harbin Institute of Technology, China. The irradiation tests of lower energy electrons were performed in a vacuum chamber. The chamber is equipped with a specially designed Faraday cup, which is used to measure beam current. The beam area was defined and held constantly. To ensure the test accuracy, beam uniformity was monitored during irradiation. Based on these measurements, the fluences of incident electrons were determined, uncertainties of which are less than 5 percent. Based on the operation of the device, the following cases were performed:

(1) *No bias case*: $V_{EB}=V_{BC}=0$ V, all terminals grounded;
(2) *Forward bias case*: $V_{EB}=0.7$ V, $V_{BC}=0$ V;
(3) *Reverse bias case*: $V_{EB}=-4$ V, $V_{BC}=0$ V.

* Corresponding author. Tel.: +86 451 86414445; fax: +86 451 86415168.
E-mail addresses: lxj0218@hit.edu.cn, liuch23@foxmail.com (X. Li).

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All samples were under the same radiation conditions. Different electrical parameters of the PNP BJTs were measured in-situ using a KEITHLEY 4200-SCS semiconductor characterization system. The turn-around time between irradiation and device measurements is approximately less than 10 s. The irradiation and measurements were performed at room temperature. After irradiation, the PNP transistors irradiated by 110 keV electrons were annealed at room temperature (300 K). During the annealing, measurements are performed and all the pins of devices are open between the measurements. When the annealing time is less than 2 h, we measure the device every 10 min, and after 2 h, we measure it every 24 h.

3. Experimental results

3.1. Gummel characteristics

Gummel characteristics were measured for the PNP transistors before and after irradiation in a common-emitter configuration, applying a sweep in V_E from 0 to 1.2 V and keeping $V_B=V_C=V_{CB}=0$ V. Fig. 1 shows the variations of collector current (I_C) and base current (I_B) with emitter–base voltage (V_{EB}) for the PNP 3CG130 transistors irradiated by 110 keV electrons with different fluences in zero bias cases, respectively. According to Fig. 1, the collector current (I_C) remains approximately constant, while the base current (I_B) increases significantly with the increasing fluence. Consequently, the current gain β, defined as the ratio of collector current to base current, is reduced, and the gain degradation is mostly affected by the behavior of the base current under a given fluence. The results of the devices in forward and reverse bias cases have a similar trend as those in Fig. 1. Moreover, based on the results above, while in all the considered bias conditions, a significant change in the base current can be detected at a given V_{EB} ($V_{EB}=0.65$ V), as shown in Fig. 2. It is clear that the change of base current is the largest in reverse bias case, a little smaller when all the terminals are grounded, the smallest in forward bias case.

3.2. The degradation of current gain

In space, the radiation-induced gain degradation is a concern aspect for characterizations of the BJTs, and is the primary cause for parametric shifts and functional failures. The change in current gain ($\Delta\beta$) is defined as the transistor current gain after irradiation (β) minus the value before irradiation ($\beta_{\text{pre-rad}}$), that is $\Delta\beta=\beta-\beta_{\text{pre-rad}}$. Similarly, the change in the reciprocal of the gain variation ($\Delta(1/\beta)$) is defined as the value after irradiation minus the initial one, that is $\Delta(1/\beta)=1/\beta-1/\beta_{\text{pre-rad}}$. Fig. 3 shows the change of current gain ($\Delta\beta$) versus fluence and annealing time for the 3CG130 transistors under various bias conditions irradiated by 110 keV electrons, which could be extracted from the results at $V_{EB}=0.65$ V. The trend is consistent with the behavior of the base current. The slope of the current gain degradation is smaller at low fluences; it is then followed by a steeper region and finally by saturation at large fluences. From the results in Fig. 3, it is obvious that the degradation of current gain in the case of reverse biased emitter–base junction is greater than in the case of forward bias, and the degradation in the case of zero bias is in the middle. Based on the annealing effects results in Fig. 3, the current gain of the PNP transistor recovers gradually with time during annealing. The ionization damage caused by 110 keV electrons could recover partly at room temperature (300 K). The recover extents for devices irradiated at forward and reverse bias cases are

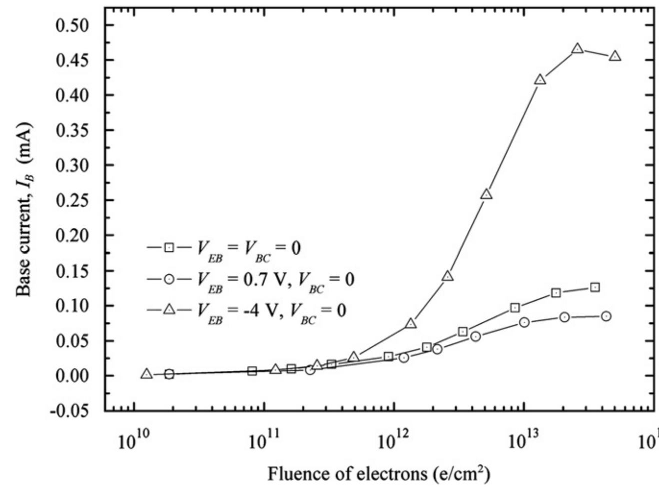

Fig. 2. The change of base current (I_B) as a function of fluence for the 3CG130 PNP bipolar transistor irradiated by 110 keV electrons in various bias conditions ($V_{EB}=0.65$ V).

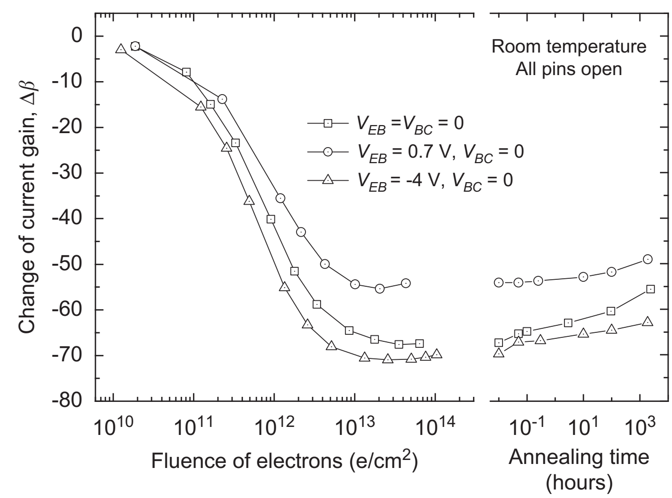

Fig. 3. The change of current gain as a function of fluence and annealing time for the 3CG130 PNP bipolar transistor irradiated by 110 keV electrons in various bias conditions ($V_{EB}=0.65$ V).

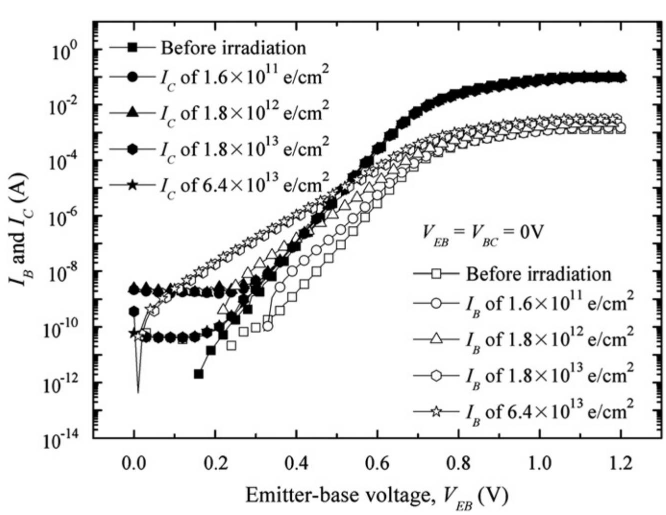

Fig. 1. Variations of collector current (I_C) and base current (I_B) with emitter–base voltage (V_{EB}) for the 3CG130 PNP bipolar transistor irradiated by 110 keV electrons with different fluences ($V_{EB}=V_{BC}=0$ V).