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Radiation defects studies on silicon bipolar junction transistor irradiated by Br ions and electrons

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ABSTRACT

Bipolar junction transistors are sensitive to both ionization and displacement damage due to charged particles from space radiation. Passivating oxides and the SiO_2/Si interface are more sensitive to ionization damage whereas displacement damage may strongly influence the bulk properties of a device. Fast electrons with energies below a few MeV introduces exclusively target ionization while heavy ions at moderate energies (lower than 2 MeV/amu) results in displacement damage due to individual Frenkel-pairs generation. Although both kinds of radiation are basically independent an effective correlation was seen in the electronic characteristics of transistors. We report on the effects on current gain and current–voltage characteristics of bipolar junction transistors due to successive irradiation with 20 MeV Br ions and 110 keV electrons.

1. Introduction

Bipolar junction transistors (BJTs) are essential components in electrical circuits and system in spacecrafts, but are known to be susceptible to space environment radiation [1–5]. Deep level defects were caused by displacement damage in active regions decrease the current gain by increasing the base-emitter current and lowers carrier lifetime [1]. Ionization damage due to electronic stopping of charged particles or electron scattering affects the characteristics of BJTs by increasing the densities of semiconductor oxide (interface) traps and net oxide charge as well [2].

In the last decade, some reports on a correlation between these two modes of defect generation were published after subsequent ion and electron irradiation. So far the underlying physical mechanism are not clearly understood, but some first indications are: (i) low energy electrons may stimulate an simultaneous reduction of vacancy related defects similar to the annealing effect of electron currents in PN junctions; (ii) passing ions in dielectric surface near regions of a device may alter the charge state and eventually change defect structures [6].

This investigation compares individual radiation effects of 20 MeV Br ions and 110 keV electrons with combined ones on the forward current gain of NPN BJTs. The experimental procedure for the sequential irradiations of Br ions and electrons irradiations are performed. The combined exposures will produce both the displacement effect in Si bulk (due to the 20 MeV Br ions) and the ionization in the oxide layer (due to the 110 keV electrons).

2. Experimental details

Commercial BJTs (3DG112 from Shijiazhuang Tianlin Shiwuer Electronics Co., Ltd.) in the NPN configuration were used in our study. All samples of one type are from a single diffusion lot to exclude any influence from varying shallow doping. Doping levels of NPN transistor are about $1.0 \times 10^{20}\,cm^{-3}$, $1.0 \times 10^{18}\,cm^{-3}$, $7.0 \times 10^{14}\,cm^{-3}$ for the emitter (n+), the base (p+) and the epitaxial layer (n−), respectively. The thickness is about 600 nm, 1.0 μm, 1.3 μm and 12 μm for the insulating silicon dioxide (SiO_2), the emitter (n+), the base (p+) and the epitaxial layer (n−) in NPN transistor, respectively.

Ion irradiation with 20 MeV Br + ions was performed at the EN tandem accelerator in the State Key Laboratory of Nuclear Physics and Technology, Peking University, China, whereas the 110 keV electron irradiation was carried out at Harbin Institute of Technology, China. Transistors were de-capped before exposure and all terminals are grounded during irradiation at room temperature. The electrical characteristics were determined at room temperature within less than 1 min after stop of radiation exposure.

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3. Results and discussion

3.1. Current gain degradation induced by individual irradiations

Current gain (often h_{FE} or β) is one of the most important electrical parameters for application of bipolar junction transistors and turns out to be sensitive to radiation. Here the current gain of the NPN transistors is recorded before and after irradiation at a fixed base-emitter bias (V_{BE}) of 0.65 V. Furthermore, a change in the reciprocal of current gain ($\Delta(1/\beta)$) is defined as the difference of the reciprocal current gain after irradiation and its value before exposure.

Irradiation with both electrons and Br ions under our conditions do only marginally affect the collector current (see Figs. 1 and 2). In contrast, the emitter current shows a substantial dependence for ions and electrons as well. In case of collision damage due to nuclear stopping the variation of base current is significant for all fluence while for electrons a threshold fluence of about 10^{11} electrons/cm^2 was found. In Fig.1, the transition of the dominating current transport mechanism from diffusion currents (dotted line, slope 1 kT) to recombination currents (dashed line, slope 2 kT) with increasing fluence can be seen clearly. For a fluence above 5×10^8 cm^{-2}, the defect density becomes as high as the doping density in the emitter (10^{14} cm^{-3}) and the rectifying feature of base-emitter disappears and the series resistance starts to decrease. In case of electron irradiation occurs with increasing exposure a continuous transition from diffusion limited current transport ($n = 1$) towards the recombination limit ($n = 2$). It is remarkable, that for both the ion- and electron-irradiation no (or very marginal) degradation of the emitter collector current was found. The consequences to the current gain are discussed in Section 3.2.

Fig. 3 shows that the change in reciprocal of the current gain as a function of 20 MeV Br ions fluence for 3DG112 transistors. As shown in Fig. 3, it is shown that $(1/\beta)$ of NPN transistor increases linearly with the increasing fluence. As reviewed in references [7], the change in the reciprocal of the current gain is dominated by the displacement effects, leading to a linear behavior that follows the Messenger–Spratt equation [3]. Fig. 4 shows that the change in reciprocal of the current gain as a function of 110 keV electrons fluence for 3DG112 transistors. As shown in Fig. 4, it is shown that $(1/\beta)$ of NPN transistor increases non-linearly with the increasing fluence. The change in the reciprocal of the current

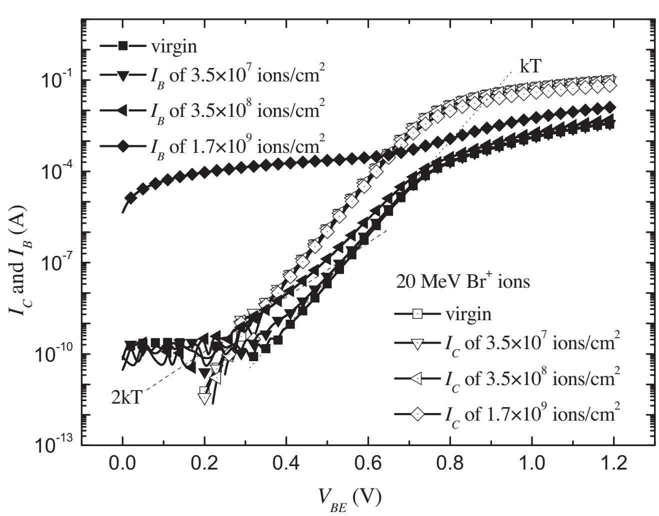

Fig. 1. Base current (I_B) and collector current (I_C) with base-emitter voltage (V_{BE}) for various fluences in NPN BJT irradiated by 20 MeV Br ions.

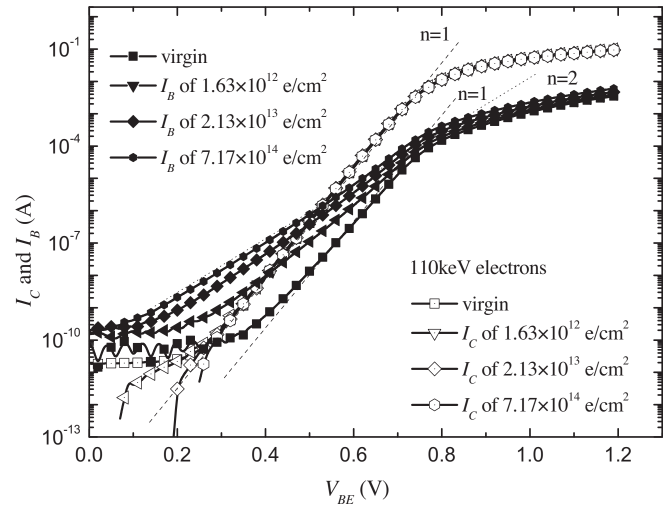

Fig. 2. Base current (I_B) and collector current (I_C) with base-emitter voltage (V_{BE}) for various fluences in NPN BJT irradiated by 110 keV electrons.

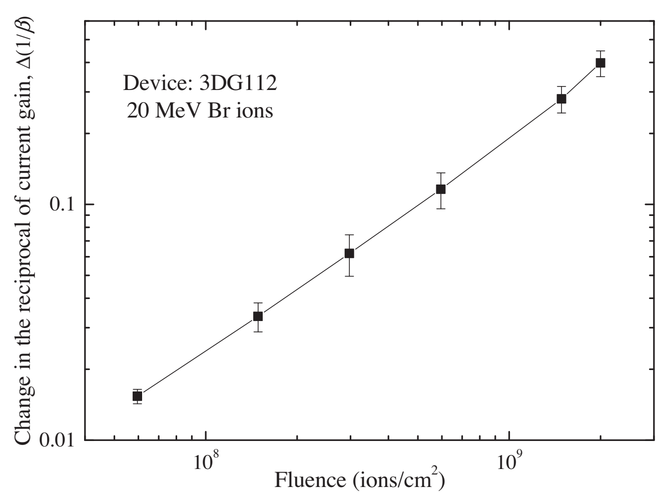

Fig. 3. Change in reciprocal of current gain as a function of the 20 MeV Br ions fluence for NPN transistors.

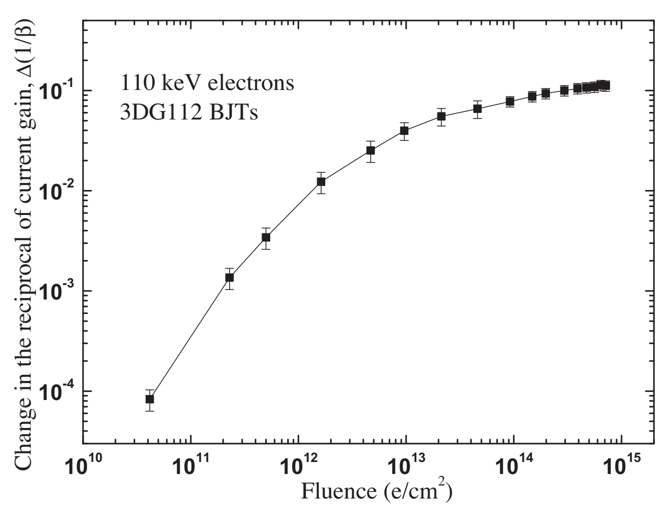

Fig. 4. Change in reciprocal of current gain as a function of the 110 keV electrons fluence for NPN transistors.

gain is dominated by the ionizing effects during the electrons irradiations, leading to a non-linear behavior at low fluence [7]. This result can further prove that displacement damage is the principal radiation damage in NPN BJTs irradiated by 20 MeV Br ions, and the ionization damage is the main damage in NPN BJTs irradiated by 110 keV electrons.

3.2. Current gain degradation of BJTs under sequential irradiations

In order to study the impact of an electron post-irradiation on the characteristics of 20 MeV Br ions pre-damaged transistors (20 MeV Br ions, 2.0×10^9 ions/cm^2) an electron irradiation at 110 keV with different exposures were applied.

Fig. 5 shows the current gain with the fluence of 110 keV electrons for the 3DG112 NPN transistor after 20 MeV Br ions irradiation. The current gain recovers with the fluence of the electrons below 3.0×10^{12} e/cm^2, and decreases linearly with the logarithm of the electrons fluence above 3.0×10^{12} e/cm^2. When the fluence of electrons is higher than 2.0×10^{14} e/cm^2, the current gain degradation induced by 110 keV electrons tends to be saturated. Fig. 6 is the $(1/\beta)$ vs. fluence of 110 keV electrons for the 3DG112 NPN transistors after 20 MeV Br ions irradiation. The similar result is shown in Fig. 6. It indicated that electron irradiation can recover a part of displacement damage at lower fluence of electrons (below 3.0×10^{12} e/cm^2), and produce more radiation damage with the increasing fluence. When the fluence of electrons is higher than 2.0×10^{14} e/cm^2, the radiation damage induced by electrons tends to be saturated. Based on this phenomenon, it can be believed that the main radiation damage induced by electrons is ionization damage above 3.0×10^{12} e/cm^2.

As mentioned above, the 20 MeV Br ions mainly produce the displacement damage, and the 110 keV electrons mainly produce the ionization damage in the BJTs. The displacement damage induced vacancies and interstitial atoms in the Si bulk. The ionization damage could cause interface traps in the Si/SiO$_2$ interface and net positive charges in the oxide layer. After 20 MeV Br ions irradiation, there are a large amount of vacancies and interstitial atoms in the Si bulk. When the electrons irradiation begins, the electrons inject the Si bulk as the new free charge carriers. These injected free carriers can make the displacement defects (vacancies and interstitial atoms) reorder. Therefore, electron irradiation can recover a part of displacement damage at lower fluence of electrons (below 3.0×10^{12} e/cm^2). When the electron fluence is higher than 3.0×10^{12} e/cm^2, the ionization damage induced by 110 keV electrons accumulate gradually, and went beyond the recovery of the displacement damage, leading to the current gain degradation of the BJT continue.

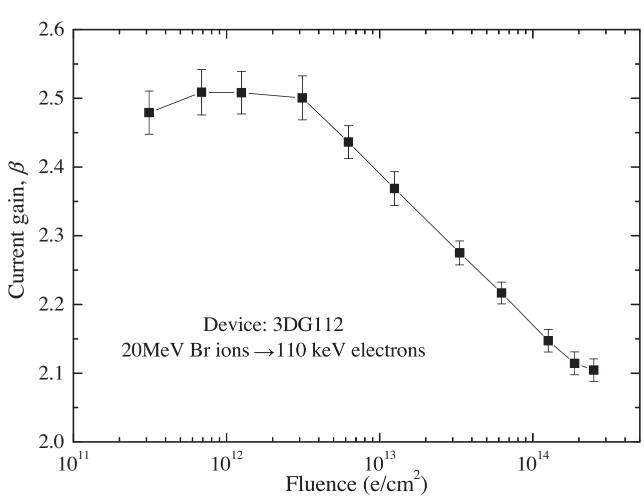

Fig. 5. Current gain vs. fluence of 110 keV electrons for the 3DG112 NPN transistor after 20 MeV Br ions irradiation.

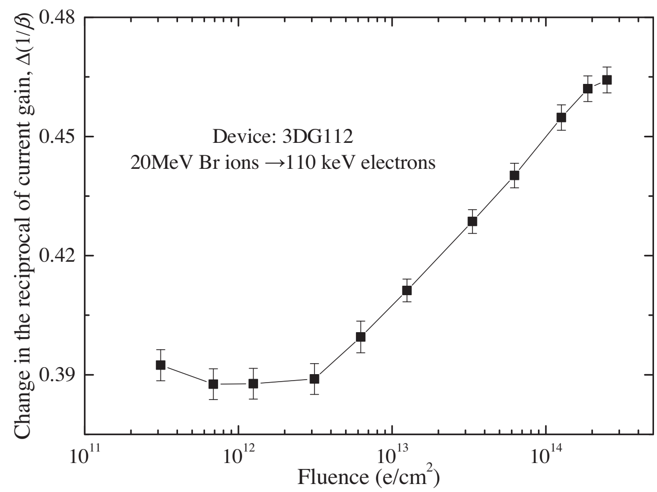

Fig. 6. Change in the reciprocal of current gain vs. fluence of 110 keV electrons for the 3DG112 NPN transistors after 20 MeV Br ions irradiation.

4. Conclusions

Exposures of 20 MeV Br ions and 110 keV electrons were carried out to study the combined radiation effects on NPN 3DG112 bipolar junction transistors. The result of sequential irradiation shows that electron irradiation can recover a part of displacement damage at lower fluence of electrons (below 3.0×10^{12} e/cm^2), and produce more radiation damage with the increasing fluence. When the fluence of electrons is higher than 2.0×10^{14} e/cm^2, the radiation damage induced by electrons tends to be saturated. This phenomenon further proves the 110 keV electrons can produce both the enhancement and mitigation contribution to degradation of current gain induced by displacement damage in the combined exposure.

Acknowledgments

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