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Electron-induced damage to NPN transistors under different fluxes

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Abstract Radiation damage of NPN transistors under different fluxes with electron energy of 1.5 MeV was investigated in this article. It has been shown that when NPN transistors were irradiated to a given fluence at different electron fluxes, the shift of base current was dependent on flux. With electron flux decreasing, the shift of base current becomes larger, while collector current almost keeps constant. Thus, more degradation of NPN transistors could be caused by low-electron-flux irradiation, similar to enhanced low-dose-rate sensitivity (ELDRS) of transistors under ^{60}Co γ-irradiation. Finally, the underlying mechanisms were discussed here.

Key words Electron flux, NPN transistor, Radiation damage
CLC numbers TN322$^+$.8, O47

1 Introduction

Satellites on the geo-synchronous orbit (GEO) are located in the Van Allen radiation belts. Particles trapped by outer belts are mainly energetic electrons, which may cause reliability problem to electronic systems of a satellite. Electron-induced damages to bipolar transistors may include parameters degradation of the transistors, such as base current increase and obvious degradation of the current gain[1, 2]. However, fewer reports are available on damages to bipolar transistors under different electron fluxes[1], which vary with time and location in the Van Allen belts. Therefore, such a study is needed to have an insight into the space radiation damage.

There have been extensive studies on the damage caused by ^{60}Co γ-rays at various dose rates. It was found that bipolar transistors would suffer more degradation at low dose rates than that at high dose rates[3,4]. This is called enhanced low-dose-rate sensitivity (ELDRS). In this work, we tried to understand what will happen to bipolar transistors under different electron fluxes, and the mechanisms. NPN transistors were irradiated by different fluxes of 1.5 MeV electron beams, and the electron-induced damages were studied.

2 Materials and method

The NPN transistors were domestic 3DG120, with iron package of about 0.3 mm thickness. Fig.1 shows a cross section of the NPN transistors. They were irradiated on a 2 MeV ELV-8 accelerator.

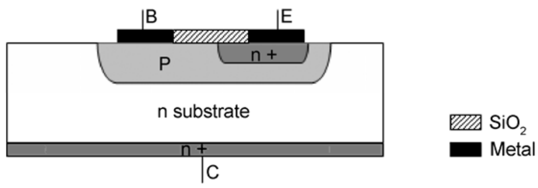

Fig.1 Schematic cross section of NPN transistor.

The NPN transistors were irradiated by 1.5 MeV E-beams to 1×10^{14} cm^{-2} at high (1×10^{12} cm$^{-2}\cdot$s^{-1}) or low (1×10^{10} cm$^{-2}\cdot$s^{-1}) flux. During the irradiation, the transistors were inversely biased, i.e. the emitter at +2 V and the collector and base terminals grounded. The base and collector currents (I_B and I_C) versus base-emitter voltage (V_{BE}) were measured before and

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after irradiation with a semiconductor parametric analyzer, HP4142, of pA current accuracy. The base-collector junction was scanned from –1V to +1V when the emitter was grounded, and the collector current (I_C) versus base-collector voltage (V_{BC}) curve was obtained. Furthermore, I_B, I_C and current gain ($\beta = I_C/I_B$) were compared with the data of ^{60}Co γ-ray irradiation under high (0.5 Gy·s^{-1}) and low (1.3×10^{-4} Gy·s^{-1}) dose rates. They were irradiated to 1000 Gy at the same biased condition as electron-irradiation case.

3 Results and discussion

The I_B and I_C vs. base-emitter voltage of γ-ray and electron irradiation are shown in Fig.2. The I_B and I_C have similar behaviors in these two sources. The I_B increased after irradiation, while I_C almost kept constant. Besides, I_B of low-flux or dose rate irradiation is greater than I_B of high-flux or dose rate irradiation, suggesting more degradation for current gain ($\beta = I_C/I_B$) at low flux or low dose rate.

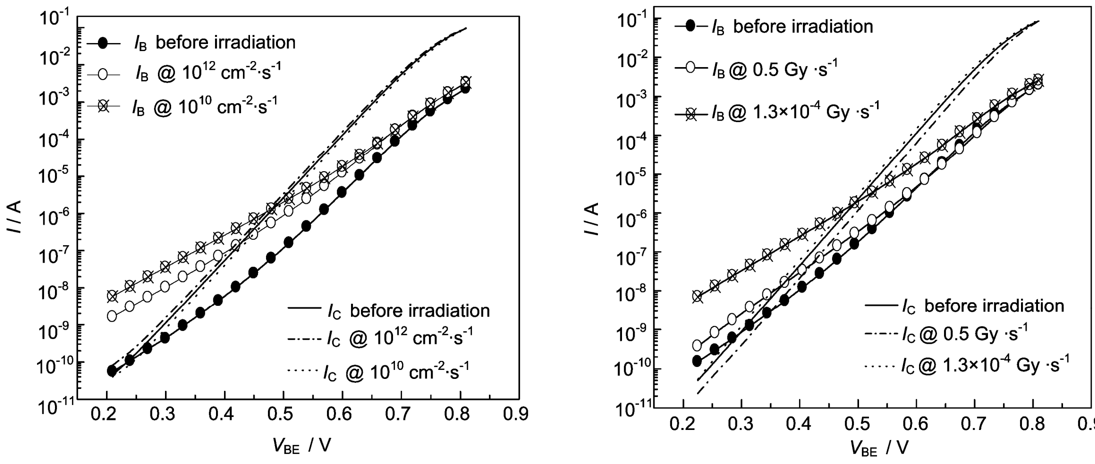

Fig. 2 I_B and I_C versus V_{BE} under high and low electron fluxes(a), or high and low γ-ray dose rates (b).

Current gain degradation of the NPN transistors (Fig.3) shows more degradation occurred in low-flux irradiation. Current gain under high flux has a decrease of about 65%, while a decrease of 85% is found at low flux at base-emitter voltage of 0.6 V.

By grounding the emitter, I_C-V_{BC} characteristic of base-collector junction was measured to study the bulk damage. Absolute collector current versus base-collector voltage is given in Fig.4. The I_C-V_{BC} curve includes forward and reverse base-collector voltage. It can be seen from Fig.4 that minimum collector current occurred at base-collector voltage of 0 V, and the current at high- and low-flux irradiation is almost the same in the forward voltage, while in the reverse-voltage stage, I_C of high-flux radiation is larger than that induced by low-flux radiation. This is inconsistent with Ref.[1], where deep level transient spectroscopy (DLTS) was conducted for base-collector junction. The DLTS showed that lattice defects (oxygen-vacancy complex and phosphorus-vacancy complex) induced by electron irradiation were found in the junction, and low flux induced defects were greater than that produced at high flux. However, the identical collector current shows that lattice defects at high and low flux irradiation have no differences in collector-, base- and emitter-region.

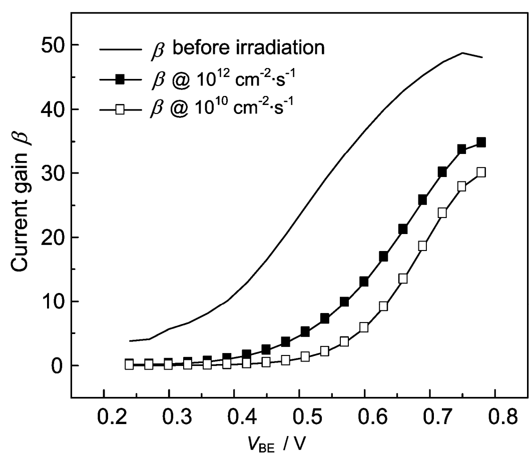

Fig.3 Current gain β versus base-emitter voltage at both high and low electron fluxes.

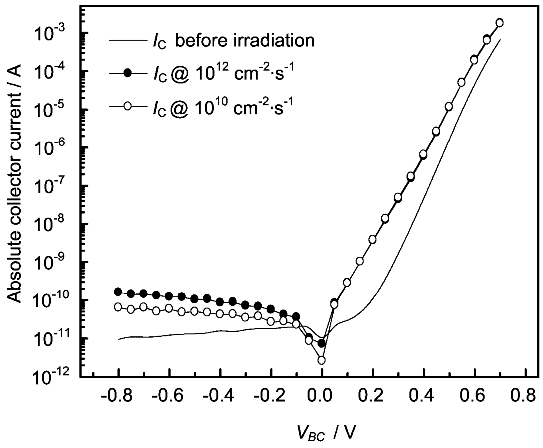

Fig. 4 $I-V$ characteristics of base-collector junction.

Although lattice defects are identical, the base current increased, and it increased more at lower flux, as shown in Fig.2(a). In ^{60}Co γ-ray irradiation, however, the increase of I_B results from ionizing radiation-induced defects in isolation oxide that overlies base-emitter junction[4,5]. The defects include oxide-trapped positive charge and interface traps near or at Si-SiO_2 interface. The positive oxide-trapped charge can make the base-emitter depletion region spread into base surface, increasing the base combination. Interface traps are directly proportional to surface recombination velocity[3].

Oxide-trapped charge and interface traps should be also created, due to the ionizing effect of E-beam[6]. At the same time, electron beam can make the p-base intrinsic. This can easily spread depletion region into base surface. Therefore, oxide trapped charge and interface traps are one origin of the excess base current

$$\triangle I_B = I_{B,\ postirrad.} - I_{B0}.$$

About 0.8 MeV of the 1.5 MeV E-beam lost in iron package as shown in Fig.5. The data was obtained by Monte Carlo simulation. Because of insulation of vacuum in transistors and exposure in air, temperature effect on the transistors was not significant during irradiation. Furthermore, more damage occurred at high flux than at high dose rate, which was shown in Fig.2. This may be caused by displacement damage or lattice defects induced by electrons. The defects would shorten carrier lifetime and act as recombination center to result in a high recombination probability of carrier in NPN transistors. This would cause a larger base current[4], represented by $I_{Blattice}$. Therefore, excess base current can be written as

$$\triangle I_B = I_{Blattice} + I_{Bot} + I_{Bit},$$

where $I_{Blattice}$, I_{Bot} and I_{Bit} are recombination current caused by lattice defects, oxide trapped charge and interface state, respectively.

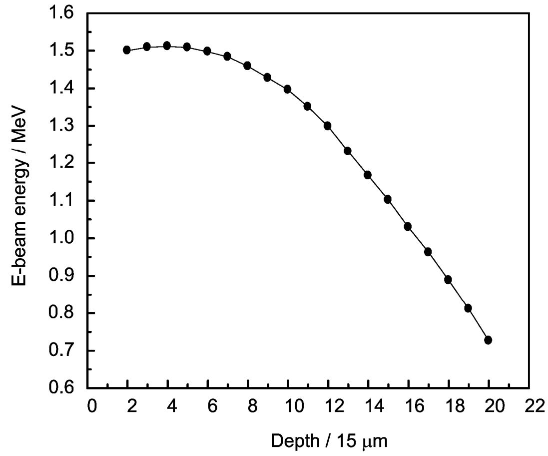

Fig.5 Energy loss of 1.5 MeV electron-beam in iron.

The difference in base current between high and low flux irradiation may result from oxide trapped charge and interface state. Space-charge model was successful to interpret enhanced low-dose-rate sensitivity for ^{60}Co γ-ray irradiation[7-9]. This model involves stronger electronic field formed at high dose rate than at low dose rate. The inner electronic field would slow the migration of holes to Si-SiO_2 interface, where they react with Si-H bond to form interface trapped charge. Thus, fewer interface trapped charges are created at high dose rate, inducing enhanced low-dose-rate sensitivity.

The bimolecular recombination mechanisms, however, may be dominant in electron irradiation. The mechanisms include electron-hole recombination, hydrogen recapture at hydrogen source sites, and hydrogen dimerization to form hydrogen molecules[5]. E-beam would produce electron-hole pairs in its tracks, and crack hydrogen-containing sources, releasing hydrogen (ionized hydrogen or neutral hydrogen). These electron-hole pairs could recombine by direct and indirect ways, and the released hydrogen can be recaptured by empty source sites. Sufficient hydrogen released at low flux is available for creating interface traps. However, at high-flux irradiation, a larger fraction of hydrogen is consumed by recapture and dimerization. Therefore, according to bimolecular recombination mechanism, irradiation at high electron flux is less effective in creating interface traps at

Si-SiO_2 interface. However, at low-flux irradiation, the probability of interface traps induced by generated holes and electrons would be greater. Moreover, the rate of electron-hole pair generation is much larger at high-flux irradiation, giving a greater combination probability[10]. Thus, positive oxide-trapped charge would be reduced in high flux. Consequently, more degradation was found in low electron flux irradiation, similar to the enhanced damage induced by low dose rate of ^{60}Co γ-rays.

4 Conclusion

Comparing damages at high and low fluxes, we can indicate that low-electron-flux irradiation would enhance the degradation of NPN transistors. Through analysis and discussion of experimental results, conclusions can be obtained as follows:

(1) The base current I_B of NPN transistors increases after electron irradiation, while collector current I_C approximately keeps constant.

(2) The current gain degraded at high and low fluxes for NPN transistors, and more degradation occurred at low electron flux.

(3) This current gain degradation origins from lattice defects, oxide trapped charge and interface state. The lattice defects (oxygen-vacancy complex and phosphorus-vacancy complex) act as recombination centers, and make the current baseline increase. Oxide trapped charge and interface state are also contribute to the increase of base current.

(4) Electron-induced damage is different between high and low fluxes irradiation. The difference can be interpreted by the bimolecular recombination model. According to this model, greater degradation of NPN transistors can be attributed to more interface strapped charge induced by low-flux irradiation.

References

1 Hayama K, Takakura K, Ohyama H, *et al*. Physica B-Condensed Matter, 2007, 401(402): 469-472.

2 HUANG Wentao, WANG Jilin, LIU Zhinong, *et al*. Nucl Tech (in Chinese), 2005, 28 (3): 213-216.

3 Kosier S L, Schrimpf R D, Nowlin R N, *et al*. IEEE Trans Nucl Sci, 1993, 40 (6): 1276-1285.

4 Wei A, Kosier S L, Schrimpf R D, *et al*. Applied Physics Letters, 1994, 65 (15):1918-1920.

5 Hjalmarson H P, Pease R L, Witczak S C, *et al*. IEEE Trans Nucl Sci, 2003, 50 (6): 1901-1909.

6 Ma T P. Applied Physics Letters, 1975, 27 (11): 615-617.

7 Fleetwood D M, Kosier S L, Nowlin R N, *et al*. IEEE Trans Nucl Sci, 1994, 41 (6): 1871-1883.

8 Graves R J, Cirba C R, Schrimpf R D, *et al*. IEEE Trans Nucl Sci, 1998, 45 (6): 2352-2360.

9 Rashkeev S N, Cirba C R, Fleetwood D M, *et al*. IEEE Trans Nucl Sci, 2002, 49 (6): 2650-2655.

10 Hjalmarson H P, Pease R L, Hembree C E, *et al*. Nucl Instrum Meth Phys Res 2006, B250: 269-273.