Effects of orientation of substrate on the enhanced low-dose-rate sensitivity (ELDRS) in NPN transistors

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Abstract: The radiation effects and annealing characteristics of two types of domestic NPN bipolar junction transistors, fabricated with different orientations, were investigated under different dose-rate irradiation. The experimental results show that both types of the NPN transistors exhibit remarkable Enhanced Low-Dose-Rate Sensitivity (ELDRS). After irradiation at high or low dose rate, the excess base current of NPN transistors obviously increased, and the current gain would degrade rapidly. Moreover, the decrease of collector current was also observed. The NPN transistor with ⟨111⟩ orientation was more sensitive to ionizing radiation than that with ⟨100⟩ orientation. The underlying mechanisms of various experimental phenomena are discussed in detail in this paper.

Key words: NPN bipolar junction transistors, ^{60}Co-γ irradiation, ELDRS, orientation of substrate

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1 Introduction

Since Enlow et al. reported the Enhanced Low Dose Rate Sensitivity (ELDRS) of several bipolar devices for the first time in 1991 [1], there have been many reports about ELDRS in the world. Most of these studies relate to the ELDRS and damage mechanisms in different types of bipolar devices and circuits, and explore various laboratory evaluation methods for ELDRS [2–10]. However, there have been few studies on the effects of specific parameters in processing technology on the ELDRS. Previous research found that the formation of ELDRS strongly depends on the manufacture technology of devices. In order to understand the impact factors of low-dose-rate response, and at the same time to be helpful to develop radiation hardness of bipolar devices, two types of NPN bipolar junction transistors were specially fabricated by using the same processing technology but with different substrate orientations. These NPN transistors were irradiated under different dose rates. Then, the radiation effects and annealing characteristics, as well as the underlying mechanisms are discussed in detail in this paper.

2 Experimental samples and methods

The samples used in the experiments were two types of domestic NPN transistors with the same junction depth and screening oxide height but with two orientations of the substrate. The NPN transistors with ⟨111⟩ orientation were noted as A technology, and the other NPN transistors with ⟨100⟩ were noted as B technology. Irradiation experiments were conducted in strong and weak ^{60}Co-γ radiation sources with a high dose rates (HDR, 50 rad(Si)/s) and a low dose rate (LDR, 0.013 rad(Si)/s) which is the smallest dose rate specified in Military-Standard (MIL-STD) and the low dose rate in space, respectively. Before irradiation, the dose rates were calibrated using a Thermal Luminance Dosimeter (TLD). During the irradiation and annealing procedures, the NPN transistors were reversely biased, i.e. the emitter-base voltage was −2 V. After irradiation at high dose rate, the NPN transistors were annealed at room temperature, and the annealing time was the same as the time needed in low-dose-rate irradiation.

To assure the correctness of experimental data,

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each biased board was supplied a TLD to detect the real dose rate. Furthermore, the samples were placed in a Pb/Al shielding box made according to MIL-STD 883 test method, to avoid the scattering photons and enhanced dose effect.

Before and after irradiation, the parameters of the NPN transistors were measured by a semiconductor parametric analyzer, Hp4142. These parameters include base current (I_B), collector current (I_C) and current gain ($\beta = I_C/I_B$), etc. Measuring all of these parameters was completed within 20 m after the irradiation and annealing procedures.

3 Results

3.1 The radiation effects of the A and B type transistors irradiation at high- and low-dose-rate

Experimental studies of the radiation effects and annealing behavior of the two types of domestic NPN transistors show that the NPN transistors are very sensitive to ionizing radiation and their electrical parameters have different degradation at various does rate. Fig. 1(a) and 1(b) show the excess base current (EBC, $\Delta I_B = I_{\text{Birrad.}} - I_{\text{Bbefore}}$) of the A type transistors as functions of the accumulated dose and annealing time at the high- and low-dose-rates. From Fig. 1(a) one can find that the EBC increases with the accumulated dose. However, the amplitude of the EBC is different after the high- and low-dose-rate irradiation. When the accumulated radiation was at 1000 Gy(Si) at high dose rate, the EBC is about 100 nA. But the EBC is more than 1400 nA when it was irradiated with the low-dose-rate radiation, which is almost 14 times larger than that irradiated at the high-dose-rate. The annealing characteristics as illustrated in Fig. 1(b) show that the EBC firstly increases and then decreases after long-term annealing at room temperature. Although the EBC is more than that after the high-dose-rate irradiation, it is much less than that induced by the low dose rate irradiation. Therefore, the A type NPN transistors exhibit obvious ELDRS, as seen from the response of EBC.

Figures. 2(a) and 2(b) show the EBCs of the B type transistors as functions of the accumulated dose and annealing time. As shown in Fig. 2(a), the EBCs are quite different with the high- and low-dose-rate irradiation. The EBC firstly decreases and then increases for the high dose rate irradiation. After reaching 1000 Gy (Si), the base current is only several nAs larger than the initial value. As for the low-dose-rate irradiation, the EBC almost stays constant before 800 Gy (Si), whereas it has a sharp increase to about 800 nA after 1000 Gy (Si). Fig. 2(b) shows that the EBC firstly increases and then decreases after long-term annealing at room temperature. Although the

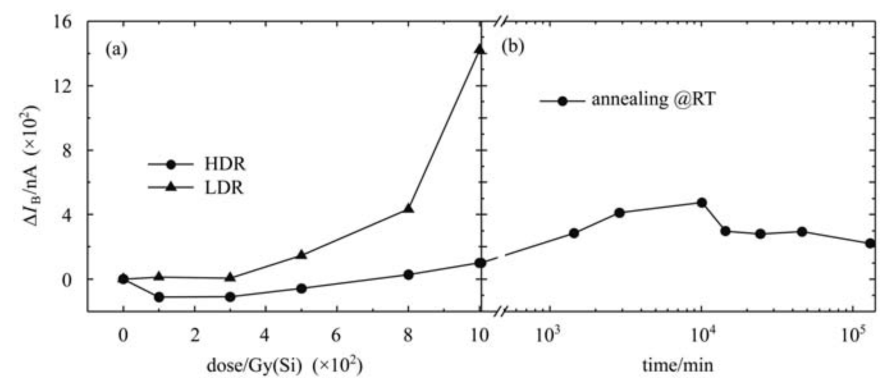

Fig. 1. The radiation response (a) and annealing behavior (b) of excess base current of the A type transistors.

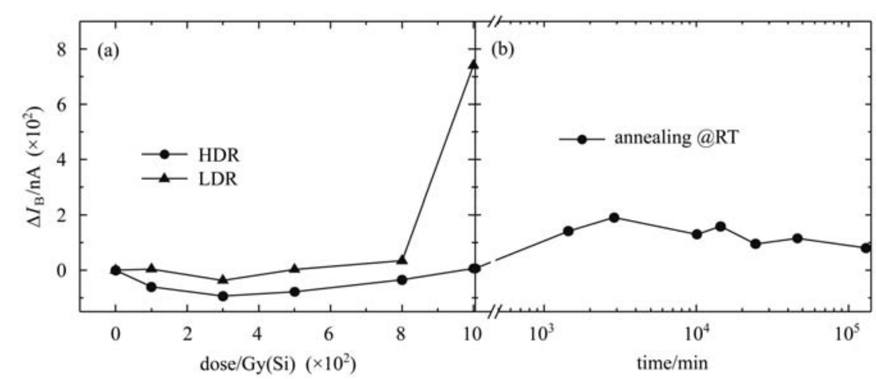

Fig. 2. The radiation response (a) and annealing behavior (b) of excess base current of the B type transistors.

EBC is more than that after the high-dose-rate irradiation, it is also less than that induced by low dose rate. Therefore, the B type NPN transistors also exhibit obvious ELDRS, as seen from the response of EBC.

3.2 Relationship between orientation and radiation damage

Radiation response and annealing behavior of the normalized current gain ($\beta=\beta_{\text{irrad.}}/\beta_{\text{before}}$) of the A and B type transistors are shown in Fig. 3. It can be seen from Fig. 3 that the current gain of the A type transistor has more degradation after the high- or low-dose-rate irradiation. This indicates that transistors with $\langle 111\rangle$ orientation are more sensitive to ionizing radiation.

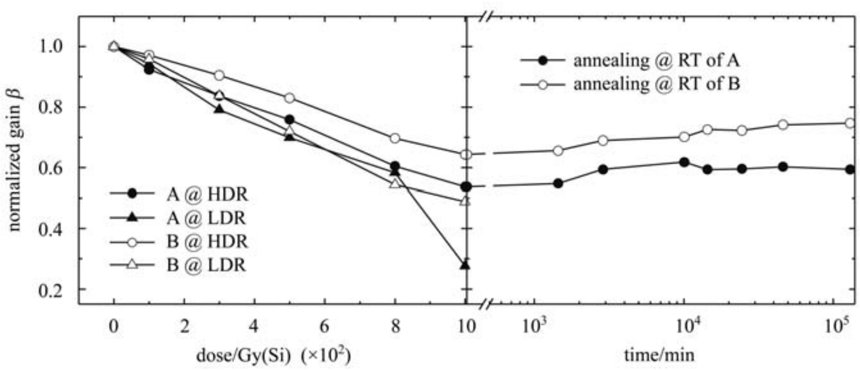

Fig. 3. Radiation response and annealing behavior of normalized current gain of the A and B type transistors.

4 Discussion

The radiation response and annealing behavior have shown that the two types of NPN transistors are different not only in radiation response but also in radiation damage induced by the high- and low-dose-rates, exhibiting ELDRS. This is mainly caused by different damage mechanisms induced by high- and low-dose-rates radiation.

It has been found that there are two major factors which can cause the current gain degradation in ionizing radiation environment. First, the formation of interface traps at the Si/SiO_2 interface which covers the emitter-base junction results in increased of the surface recombination velocity. Second, the net positive charge accumulated in the oxide above the emitter-base junction causes the field induced depletion layer to expand into the p-type base. Due to the maximum combination velocity occurring in depletion layer, the spread of surface depletion can further increase the base current [2, 3]. The combination current at base surface (I_{bsr}) can be written as follows [3]:

$$I_{\text{bsr}} \propto N_{\text{it}} \exp(\alpha N_{\text{ot}}^2),$$

where N_{it} is the radiation induced interface trap density, N_{ot} is the oxide trapped positive charge, $\alpha = 1/2q\varepsilon\varepsilon_0 N_{\text{a}}$ is related to electron charge (q), absolute and relative dielectric permittivity (ε, ε_0) and doping level (N_{a}) in the substrate. It can be seen from the equation that the increase of combination velocity of the base surface is proportional to the radiation induced interface states and the oxide trapped positive charge. And, the effect of oxide trapped positive charge is dominant, which can be concluded from the exponential increase of excess base current, in the form of exp (αN_{ot}^2).

The degradation of current gain as shown in Fig. 3 shows that both types of the NPN transistors have much more degradation at low-dose-rate than that at high-dose-rate, despite their different orientations of substrate. This could be explained by a space-charge model. In a space-charge model, the slow transporting holes would be trapped to create a great deal of trapped positive charge in the screening oxide during the high-dose-rate irradiation. These trapped charge would form a space field, which can impede radiation induced holes or H^+ to migrate to the Si/SiO_2 interface. Consequently, after a long time, only few of them can reach Si/SiO_2 interface, where they react with passivated dangling bonds to form interface states. However, the electric field in oxide could be weaker, due to the less oxide trapped positive charge in case of the low-dose-rate irradiation. Furthermore, radiation induced holes or H^+ have enough time to migrate to the Si/SiO_2 interface and react to produce interface states. Therefore, there will be more interface states induced by low dose rate, compared with the high-dose-rate case. These interface states act as the recombination centers, increase base current, and degrade the current gain. Thus, more interface states caused by the low-dose-rate irradiation result in the rise of enhanced low-dose-rate sensitivity [2, 5].

More degradation of current gain is observed in the A type of NPN transistors than in the B type, as shown in Fig. 3. This is due to more effective bonds per unit area. It has been found that the density of interface traps in ⟨111⟩ orientation would be ten times more than that in ⟨100⟩ orientation, which relates to the effective bonds per unit area [6]. Due to more effective bonds of silicon, the trivalent dangling bonds will be more at the interface in ⟨111⟩ orientation than in ⟨100⟩ orientation, when growing the silicon dioxide on silicon substrate. These dangling bonds are very active, easy to bond with H or OH to decrease the interface traps, and improve the electrical properties of devices. But ionizing radiation can break these bonds, and thus increase the interface traps and degrade the devices. Due to more dangling bonds in ⟨111⟩ orientation, the radiation induced interface states would be greater than ⟨100⟩ orientation. As a result, the A type transistors are more sensitive to ionizing radiation.

From Figs. 1(b) and 2(b), one can also find that the EBC of the A and B types samples first increase and then decrease during the annealing procedure after high-dose-rate irradiation. This phenomenon may be mainly attributed to the different annealing characteristics of the radiation-induced oxide trapped charge and interface state. Some researchers have found that the radiation-induced oxide trapped charge could easily anneal at room temperature, and the formation and annealing of the interface state have strong dependence on radiation time and temperature. Generally speaking, due to the accelerated migration of the radiation-induced holes and H^+ at elevated temperatures, the interface state would have a gradual increase. However, the interface state could not have effective annealing at temperatures less than 100 ℃. When temperature is greater than 175 ℃, a great deal of interface states would anneal [2, 4]. There are two kinds of reasons for the first increase and then decrease of EBC in Figs. 1(b) and 2(b). One reason is that the annealing of oxide trapped charge caused in the high-dose-rate irradiation could weak the space electric field. Consequently, it makes more interface states form, and increases the EBC. The other reason is that a great amount of oxide trapped charge anneals when the annealing time is long enough. This can decrease the surface recombination which is induced by the accumulation of oxide trapped charge. Meanwhile, the generation rate of interface states would be reduced at room temperature. Finally, the damage originating from the oxide trapped charge and interface state may accordingly decrease due to these two reasons.

Comparing the results as shown in Figs. 1–3, it can be found that the change of the EBC in Figs. 1 and 2 is less obvious than that induced in the low dose rate. However, the degradation current gain of both types of NPN transistors is very significant at the high dose rate. This is caused by the change of collector current during the radiation procedure.

Figure 4 (a), (b) shows the excess collector current versus the accumulated dose and annealing time. Under high-dose-rate irradiation, the collector current of both types of transistors decrease at the beginning, and A type of transistors are more obvious than B type. After 300 Gy (Si), the degradation curves become flat, and even slightly recover after 800 Gy (Si). For the low-dose-rate irradiation, the trend of collector current of the A type transistors is the same as those observed at high dose rate, only more significant in amplitude. Nevertheless, the collector current of the B type transistors is always decreasing before 800 Gy (Si), and afterwards has a sharp increase. Finally, it almost reaches the initial value at low dose rate. This obviously contradicts the traditional one which considers that the collector current stays constant during the radiation. Figs. 3 and 4 show that the small differences of current gain induced by the high and low dose rate irradiations are mainly affected by two factors. One is the decrease of the collector current at the high dose rate, and the other one is the increase of the collector current after 800 Gy (Si) at the low dose rate can compensate the current gain degradation. As a result, the mutual function of these two factors reduces the differences in current gain degradation induced by the high and low dose rate irradiations.

As for the reason of the decrease of collector current, it also can be attributed to two factors. One is the recombination of the injected carriers in the neutral base, and the other one is the reduction of the injection efficiency of the emitter. This reduction results from the establishment of the injection area created by the oxide trapped positive charge, which can increase the height of the surface potential and reduce the injected carriers in this area [7]. This can also be verified by the results as shown in Fig. 4. By careful analysis, it can be found in Fig. 4 that the collector current always decreases during the high-dose-rate irradiation, but it rapidly recovers at room-temperature annealing. And this phenomenon represents the characteristics of oxide trapped charge: quick growth in high-dose-rate irradiation and easy to anneal even at room temperature. The behavior of collector current at the low dose rate firstly decreases and then increases, is also closely related to the production and annealing of oxide trapped charge. All these results have confirmed that the decrease of collector current mainly results from the buildup of positive charge in the oxide layer. A great amount of oxide trapped positive charge is the real reason for the rapid degradation of electrical properties of these two types of NPN transistors, showing many defects produced during the semiconductor processing technology. Thus, the easy production of oxide trapped positive charge is the first problem that should be taken into consideration in order to improve the radiation hardness at low dose rate for these two types of NPN transistors.

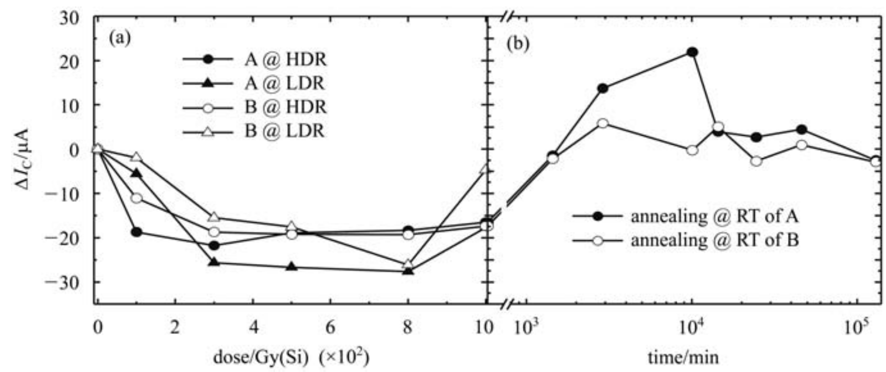

Fig. 4. Radiation response (a) and annealing behavior (b) of collector current of the A and B type transistors.

5 Conclusions

The following conclusions can be drawn by the above analysis:

(1) Both types of the domestic NPN transistors are sensitive to the irradiation at high and low dose rate. All measured parameters show remarkable changes at a total dose of 1000 Gy(Si), such as the obvious increase in excess base current, degradation in current gain and gradual decrease in collector current. The radiation damage is more obvious at low does rate.

(2) Due to more dangling bonds in ⟨111⟩ orientation, the NPN transistors with ⟨111⟩ orientation are more sensitive than those with ⟨100⟩ orientation. The passivated dangling bonds can crack when exposed to ionizing radiation. More dangling bonds would induce more interface traps. Therefore, these radiation induced defects can further make the parameters degrade.

(3) Because of the weaker electric field at low dose rate caused by positive oxide trapped charge, the NPN transistors could have more degradation under low-dose-rate irradiation. The weaker electric field can make more radiation induced holes and protons get to the Si/SiO_2 interface, where they can react to form interface trapped charge. Therefore, the EBC would be greater in the low dose rate case than that in the high dose rate case.

(4) The obvious decrease of collector current results from the reduction of injection efficiency of the emitter. Radiation-induced oxide trapped positive charge can create an injection area in the emitter to decrease the injection efficiency of carriers. Consequently, this causes the gradual decrease of collector current.

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