ELDRS and dose-rate dependence of vertical NPN transistor

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Abstract The enhanced low-dose-rate sensitivity (ELDRS) and dose-rate dependence of vertical NPN transistors are investigated in this article. The results show that the vertical NPN transistors exhibit more degradation at low dose rate, and that this degradation is attributed to the increase on base current. The oxide trapped positive charge near the SiO_2-Si interface and interface traps at the interface can contribute to the increase on base current and the two-stage hydrogen mechanism associated with space charge effect can well explain the experimental results.

Key words bipolar junction transistor, ELDRS effect, dose-rate dependence

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1 Introduction

Bipolar Junction Transistors (BJTs) may exhibit more current degradation when exposed to low dose rate (typically less than 0.1 rad(Si)/s) rather than high dose rate, and the degradation can not be accurately estimated after high-dose-rate irradiation followed by room-temperature annealing. This is the so-called “Enhanced Low-Dose-Rate Sensitivity (ELDRS)”. This effect was reported by Enlow and his co-workers in bipolar transistors in 1991[1]. Since this initial report, many kinds of linear integrated circuits, including operational amplifiers, comparators and voltage regulators, were found to show the ELDRS effect[2, 3]. Moreover, the dose rate in real space radiation environment is extremely low. The dose-rate range is about 10^{-4}—10^{-2} rad(Si)/s[4]. Therefore the main issue related to ionizing dose effects in bipolar technology is the ELDRS effect exhibited by these bipolar devices and circuits working in space electronic systems, and the existence of the ELDRS makes it difficult to evaluate the degradation for long-term space mission by means of accelerated ground tests. Thus, it is necessary to understand the underlying mechanisms of ELDRS effect and the information obtained from dose-rate dependence, and the ELDRS effect of discrete transistors could be helpful to make them clear.

In this paper, we report the ELDRS of NPN transistor and its dose-rate dependence, and then discuss the underlying mechanism for the ELDRS effect and dose-rate dependence using two-stage hydrogen model[5, 6] associated with the space-charge model[7, 8].

2 Experimental details

The input stage of integrated circuits manufactured with bipolar technology is usually the vertical NPN transistors. So, transistor used in the experiment was silicon vertical NPN bipolar transistor, 3DG120. The schematic structure of 3DG120 is illustrated in Fig. 1.

The radiation experiment was conducted in ^{60}Co gamma ray radiation source. The dose rate was calibrated by the thermo luminescence dosimeter to ensure the accuracy of dose rate. The accumulated total dose is 1×10^5 rad(Si) at five dose rates. The groups of dose rates included two high dose rates (50 rad (Si)/s, 10 rad (Si)/s) and three low dose rates (0.1 rad(Si)/s, 10 mrad(Si)/s and 5.5 mrad (Si)/s). These dose rates used in experiment were to investigate the dose-rate

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dependence of the performance degradation of NPN transistor. Before and after irradiation, the base and collector current (I_B and I_C) were measured at various base-emitter voltages (V_{BE}) at collector-base voltage (V_{CB}) of 0 V. During the irradiation and annealing, the testing time for each device was less than 1 minute. Transistors were negative biased, that is, the emitter connected to +2 V with base and collector terminals grounded. Test was performed in a parametric analyzer, HP4142B, which has a current precision of pA. The annealing time followed by the 50 rad(Si)/s irradiation is long enough for studying the time dependent effect.

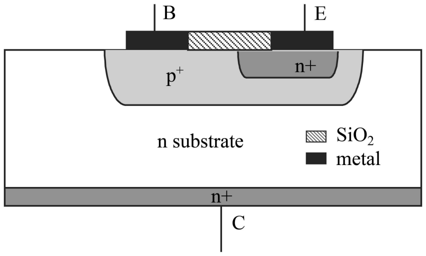

Fig. 1. Schematic cross section of vertical NPN transistor.

3 Results and discussion

The normalized current gain β/β_0 under five dose-rate irradiation, with base-emitter voltage of 0.4 V, is shown in Fig. 2. It can be seen from Fig. 2 that more degradation occurs at lower dose rate, and that with 5.5 mrad (Si)/s irradiating to 80 krad (Si), the degradation becomes saturated. This phenomenon can also be observed in Fig. 3.

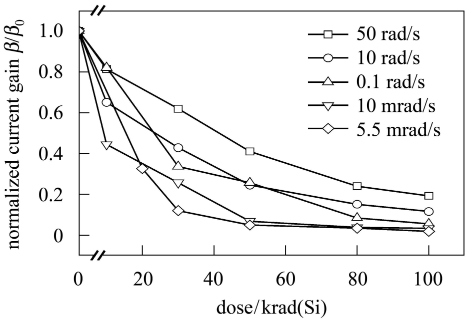

Fig. 2. Normalized current gain degradation at five dose-rate irradiation.

Figure 3(a, b) shows the excess base current ($\Delta I_B = I_{B\text{postrad.}} - I_{B0}$) at five dose rates is dependent of the absorbed dose (Fig. 3(a)) and the room-temperature annealing after irradiation at high dose rate of 50 rad(Si)/s (Fig. 3(b)). The excess base current is plotted at the base-emitter voltage of 0.4 V. The base current increases after irradiation, while the collector current keeps approximately constant during the irradiation. Therefore, the current gain ($\beta = I_C/I_B$) decreases after irradiation, and the main factor of this degradation is base current. At lower dose rate irradiation, the base current becomes larger. So, more degradation appears at lower dose rate. Also, the saturation of degradation in Fig. 2 can be explained by the saturation of base current, as shown in Fig. 3 at the total dose of 80 krad(Si). Long-term annealing at room temperature after 50 rad(Si)/s irradiation shows that the ionizing radiation induced damage almost holds the same as that before annealing. This indicates that the vertical NPN transistors truly exhibit enhanced damage at low dose rate.

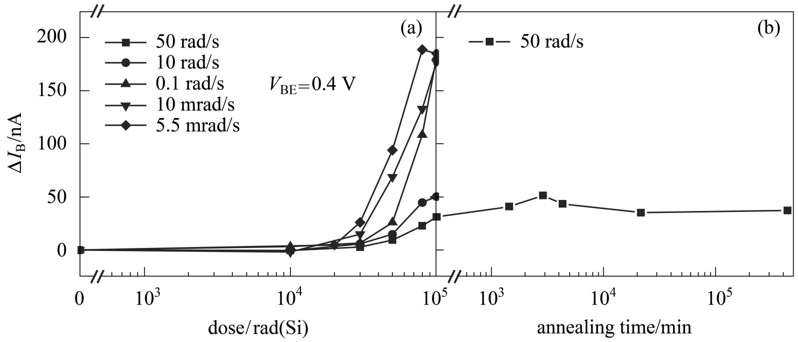

Fig. 3. Excess base current versus total dose (a) and room-temperature annealing time (b).

Recently, it is generally accepted that the primary cause of degradation mechanism of bipolar transistors is the SiO_2-Si interface state and the trapped positive charge in silicon dioxide which overlies the base-emitter junction. The interface state and positive oxide charge can make the surface recombination velocity increase and depletion in the P-base surface spread, respectively[8]. These two factors could result in the increase of base current of NPN transistors. The origin of oxide trapped charge and interface state is correlated with the radiation-induced defects near or at the SiO_2-Si interface. Due to the mobility differences of radiation-induced electrons and holes, the electrons can move across the oxide layer fast, while the holes could play a major role in creating the positive trapped charge and interface state. The trapped positive charges, known as E′ centers, are stable and formed by the reaction between the holes and the neutralized hole traps (T^0) in the silicon dioxide or near the SiO_2-Si interface on the SiO_2 side[7].

$$T^0 + h^+ = T^+ \ . \qquad (1)$$

The neutralized traps may originate from the strained silicon bonds such as oxygen vacancy. This procedure also involves the release of H^+ by the reaction of holes near the interface and hydrogen-containing Defects (DH), releasing H^+[5, 6].

$$DH + h^+ = D + H^+ \ . \qquad (2)$$

This is the first stage that actually involves two reactions. During this stage the stable positive oxide traps are created and a space field is formed in the silicon dioxide that further prevents the formation of interface straps. The interface straps are formed through the mechanism as follows

$$SiH + H^+ = (Si\cdot)^+ + H_2 \ , \qquad (3)$$

where H^+ comes from the former reaction. The Si-H bonds are thought to be abundant at the SiO_2-Si interface to make silicon dangling bonds “passive” during the processing technology. Here in the second stage, the interface traps directly created by the holes were neglected[5].

For the case of high-dose-rate irradiation, there will generate a mass of holes in the SiO_2 layer. These mobile holes could be heavily trapped near the interface, thereby creating a strong space field to prevent H^+ from reaching the interface to form the interface traps there. Furthermore, due to the comparatively short radiation time, there is not enough time for the holes to transport to the interface. However, at low-dose-rate irradiation, the generating rate of electron-hole is slow, with fewer holes trapped in the oxide. Thus, the space field will be sufficiently weak. And the long-term radiation will enable the released H^+ to have enough time to arrive at the interface, and react with Si-H to create interface traps. Therefore, in the low-dose-rate case, the interface traps are much more than those at high dose rate. This can explain the existence of enhanced damage at low dose rate.

What has been discussed above could also be described by Fig. 4. The dose-rate dependence of the vertical NPN transistor at various dose levels is illustrated in Fig. 4. It can be seen from this figure that the excess base current at lower dose rate is larger than that at higher dose rate. At low dose rate, the excess base current becomes larger at higher total dose, which shows the buildup of interface traps. While at high dose rate, this buildup is blocked because of the space charge formed by positive oxide trapped charge. The information given by dose-rate dependence is useful for understanding the mechanism of enhanced low-dose-rate sensitivity.

The saturation also appeared in dose-rate dependence at very low dose rate. It can be explained by the balance between the formation of interface traps and the trapped charge annealing after so long time radiation.

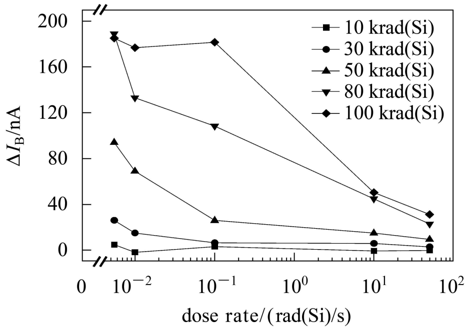

Fig. 4. Dose-rate dependence of NPN transistor at various total dose levels.

4 Conclusions

The vertical NPN transistors exhibit enhanced low-dose-rate sensitivity, which has appeared on most discrete devices and integrated circuits with bipolar technology processes. It is found that the gain degradation is attributed to the increase on base current, while the collector current keeps approximately constant. The degradation mechanism is related to the interface traps at SiO_2-Si interface and oxide trapped charge near the interface. It is found that the radiation-induced interface traps are closely related to the ELDRS effect. The two-stage hydrogen processes associated with space charge effect could well explain the phenomena observed in the experiments.

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