Impact of doped boron concentration in emitter on high- and low-dose-rate damage in lateral PNP transistors*

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Abstract: The characteristics of radiation damage under a high or low dose rate in lateral PNP transistors with a heavily or lightly doped emitter is investigated. Experimental results show that as the total dose increases, the base current of transistors would increase and the current gain decreases. Furthermore, more degradation has been found in lightly-doped PNP transistors, and an abnormal effect is observed in heavily doped transistors. The role of radiation defects, especially the double effects of oxide trapped charge, is discussed in heavily or lightly doped transistors. Finally, through comparison between the high- and low-dose-rate response of the collector current in heavily doped lateral PNP transistors, the abnormal effect can be attributed to the annealing of the oxide trapped charge. The response of the collector current, in heavily doped PNP transistors under high- and low-dose-rate irradiation is described in detail.

Key words: doping concentration; lateral PNP transistors; radiation damage; dose rates
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1. Introduction

Bipolar junction transistors (BJTs) are the essential and key devices in the electronic systems working in nuclear reactors, accelerators, detectors and the satellites in space environments. Operating at these environments, the BJTs would be exposed to kinds of energetic particles and rays, which could induce the current gain degradation in BJTs. This will bring reliability problems to electronic systems in radiation environments. Thus, it is of great importance to study the dependence of radiation damage on processing factors. The study would be helpful to improve the reliability of electronic systems in radiation environments. Moreover, it can also obtain the experimental evidence to radiation hardening of bipolar devices and integrated circuits.

Lateral PNP transistors (LPNPs) are mostly used in modern bipolar integrated circuits. Compared to substrate and vertical structures, lateral structure is more sensitive to radiation[1], and it shows more damage in low-dose-rate environments, which are called enhanced low-dose-rate sensitivity (ELDRS). Therefore, the improvement of radiation tolerance of LPNPs is of great importance to the radiation hardness of bipolar integrated circuits or even an electronic system. In order to improve the radiation tolerance of LPNPs, it should be clear that the influence factors of radiation damage, and the underlying mechanisms to which they affect radiation damage. It has been found in previous studies that the radiation damage of LPNPs was influenced by many factors such as dose rate, geometry structure, biased conditions and temperature[1−4]. However, there were few reports on the damage characteristics of LPNPs with different doping concentrations in emitters that could easily be controlled by the processing technology. Although the influence of doping concentration in the emitter on radiation damage has been studied[5], the radiation characteristics and underlying mechanisms were not sufficiently discussed, especially for the low-dose-rate damage. The purpose of this work is to study the high- and low-dose-rate damage characteristics of LPNPs with heavily or lightly doped boron in emitters, and the influence mechanisms of doping concentration. We compared high- and low-dose-rate damage under the case of the same doping concentration, as well as the damage differences from heavily and lightly doped emitters. Through these comparisons, the underlying damage mechanisms were discussed in detail.

2. Experimental details

The samples used in our experiments were lateral PNP transistors, whose cross section is shown in Fig. 1. The area of emitters is 10×10 μm^2, and these emitters were heavily or lightly boron doped respectively during the processing technology.

The samples were irradiated at ^{60}Co-γ rays under high (0.5 Gy(Si)/s) and low (1.3×10^{-4} Gy(Si)/s) dose rates, respec-

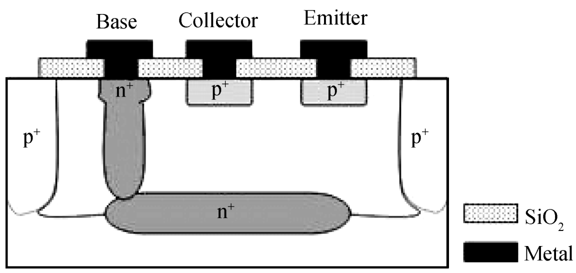

Fig. 1. Schematic cross section of lateral PNP transistors.

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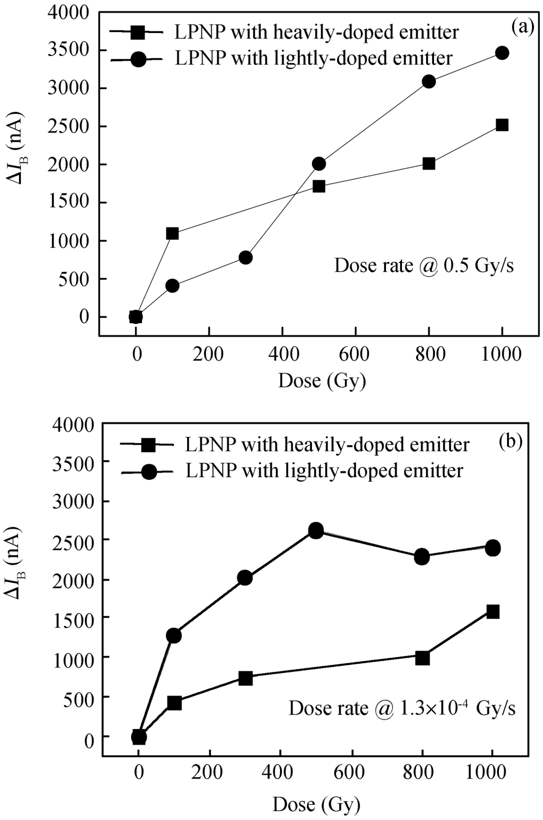

Fig. 2. Excess base current under (a) high- and (b) low-dose-rate irradiation for LPNP transistor with heavily or lightly doped emitters.

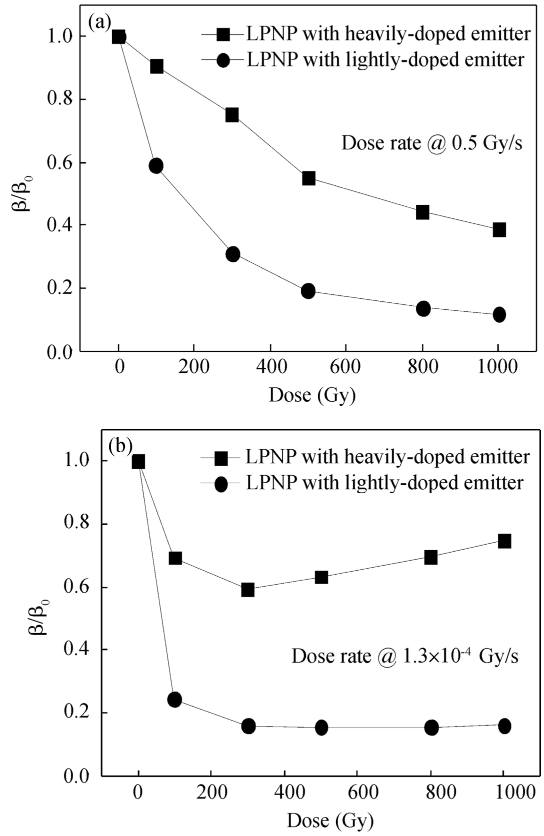

Fig. 3. Normalized current gain of heavily or lightly doped LNPN transistor under (a) high- and (b) low-dose-rate irradiation.

tively. These dose rates were calibrated before irradiation, so as to assure the correctness of accumulated dose during irradiation. Furthermore, the samples were placed in a lead/aluminum (Pb/Al) shielding box to avoid the scattered photons. During irradiation and annealing, the base–emitter junction was reversely biased, i.e., the base at +2 V and emitter and collector terminals grounded. The base, collector currents and current gain (I_B, I_C and $\beta = I_C/I_B$) versus emitter–base voltage (V_{EB}) were measured before and after irradiation with a semiconductor parametric analyzer, Hp4142, of pA accuracy. During the test, the base–collector voltage was kept at zero ($V_{BC} = 0$ V), and emitter at ground.

3. Results and discussion

The excess base current (EBC, $\Delta I_B = I_{Bpost\text{-}irrad.} - I_{B0}$) of heavily or lightly doped emitters versus total dose under high- and low-dose-rate irradiation is shown in Figs. 2(a) and 2(b). The base current was obtained at an emitter–base voltage of 0.608 V. It can be seen from Fig. 2(a) that the EBC increases in both heavily and lightly doped LPNP transistors after irradiation. Furthermore, the EBC of the lightly doped LPNP could gradually exceed that of the heavily doped LPNP. However, in the low-dose-rate case, the behavior of EBC is different in heavily and lightly doped LPNP, as shown in Fig. 2(b). The EBC of heavily doped LPNP always increases, while the EBC of lightly doped LPNP decreases after reaching 500 Gy(Si), showing the recovery of base current. Obviously, it can also be seen from Fig. 2(b) that EBC of lightly doped LPNP is much greater than that of heavily doped LPNP and this shows that lightly doped LPNP is more sensitive to total dose under low-dose-rate irradiation, comparing with heavily doped LPNP.

Through the comparison of radiation damage under high- (Fig. 2(a)) and low-dose-rate (Fig. 2(b)) irradiation, we find that the EBC induced by high-dose-rate irradiation is greater than that induced by low-dose-rate irradiation in heavily doped LPNP. However, unlike the heavily doped case, damage in lightly doped LPNP is also divided into two stages under high- and low-dose-rate irradiation. Before 500 Gy(Si), the EBC at low dose rate is greater that at high-dose-rate case. While, after that dose point, the high- and low-dose-rate response are different. A recovery of the EBC is found at low-dose-rate irradiation. However, under high-dose-rate irradiation, the EBC still increases, and exceed the EBC induced by low dose rate.

Figures 3(a) and 3(b) show the normalized current gain ($\beta = \beta_{postirrad.}/\beta_0$) versus accumulated dose under high and low dose rates, respectively. It can be found that there is more degradation in lightly doped LPNP for both high- and low-dose-rate irradiation, as shown in Figs. 3(a) and 3(b). For high-dose-rate irradiation, normalized current gain would degrade with the increase of accumulated dose. However, it has some differences for the low-dose-rate case. After the dose accumulating up to 300 Gy(Si), the normalized gain current has a slight increase for heavily doped LPNP. Meanwhile, the normalized gain has already degraded at least 80% at 100 Gy(Si) in lightly doped LPNP. This indicates that lightly doped LPNP are very sensitive to the low dose rate. Therefore, it can be concluded from the gain degradation that the lightly doped LPNP is more sensitive to radiation. Furthermore, an abnormal phenomenon

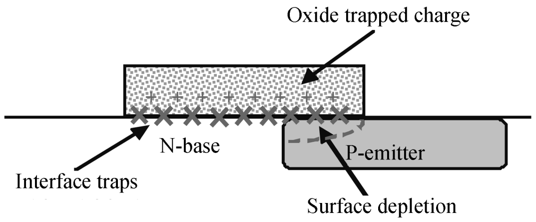

Fig. 4. Positive oxide trapped charge and interface traps near the Si–SiO_2 interface, and the expansion of depletion layer.

in heavily doped LPNP has been observed: although the base current gradually increases with the accumulated dose, the normalized gain slightly increases after 300 Gy(Si). This will be discussed below.

It has been known that ionizing radiation would produce a great amount of electron–hole pairs in the screen oxide layer, which overlies on the base–emitter junction. These electrons and holes could separate under the electric field in the oxide. Due to the much greater drift velocity of electrons[6, 7], the electrons could drift out of the oxide in about 10^{-12} s, and there would be a large amount of holes in the oxide, because of their slow transporting. Most of these holes can be trapped by the oxide traps to form positive oxide trapped charge. Meanwhile, during the holes' low transporting to the Si–SiO_2 interface, they can react with hydrogen passivated silicon bonds, Si–H, to release hydrogen ions near the interface. The holes or hydrogen ions would be trapped by interface traps, creating the interface trapped charge[8]. Radiation-induced oxide trapped charge and interface traps are schematically shown in Fig. 4. These two types of defects have different influences on the characteristics of transistors. As for LPNP transistors, positive oxide trapped charge would induce an accumulation layer in n-type base surface, which can decrease the surface recombination velocity and consequently makes the base current deduced[3, 9]. This is because the maximum recombination velocity occurs when the concentration of electron and hole are comparable. Meanwhile, positive oxide trapped charge can make the lightly doped p-type emitter depleted, expanding the surface depletion into emitter and increasing the effective width of depletion layer ($W_{\rm eff}$). This is similar to the impact of positive oxide trapped charge on the neutral base in NPN transistors[2, 10]. Because of the increase of $W_{\rm eff}$, the recombination of the carriers in emitter surface would be enhanced, leading to the increase of the base current. Thus, positive oxide trapped charge has double effects[3, 9]. On the one hand, it can induce the n-type base surface accumulated, decreasing the base current. On the other hand, it would also expand the depletion layer into the emitter surface, and increase the base current. The increase or decrease of recombination velocity in base surface is determined by the competition between these two effects.

The interface traps induced by irradiation could increase the recombination velocity in the base surface[2, 7, 9]. Recombination velocity depends on the density of interface traps, $D_{\rm it}$, and can be expressed as follows[11]:

$$S_{\rm r} = 0.5 v_{\rm th} \sqrt{\sigma_{\rm n}\sigma_{\rm p}} \pi k T D_{\rm it}, \quad (1)$$

where $S_{\rm r}$ is the surface recombination velocity, $v_{\rm th}$ is the thermal speed, k is the Boltzmann constant, T is the temperature in Kelvin, and $\sigma_{\rm n}$, $\sigma_{\rm p}$ are the cross sections of electrons and holes, respectively. In general, the EBC would be proportional to the surface recombination velocity[2].

$$\Delta I_{\rm B} = q S_{\rm r} A_{\rm s} \Delta n_{\rm s}, \quad (2)$$

where q is the elementary charge, $A_{\rm s}$ is the effective surface recombination area, and $\Delta n_{\rm s}$ is the nonequilibrium carrier concentration, depending on the injected current density and radiation-induced oxide trapped charge.

Knowing the effects of the oxide trapped charge and interface traps, we can analyze the behavior of excess base current in heavily or lightly doped LPNP at high- and low-dose-rate irradiation. Through the monotone increase of EBC, it can be concluded that the accumulation in base surface caused by the positive oxide trapped charge is not obvious. The interface traps and depletion-layer extension induced by the oxide trapped charge is the major reason for the EBC increase. Furthermore, compared with the heavily doped emitter, the lightly doped emitter is much easier to deplete, and the width and depth of the depletion layer would be larger. This could enhance the recombination of surface carriers. Therefore, with the increase of accumulated dose, the EBC of the lightly doped LPNP is gradually greater than that of the heavily doped LPNP. This suggests that lightly doped LPNP is more sensitive to ionizing radiation, and this can also be seen from more degradation in the lightly doped LPNP from Fig. 3. However, the decrease of EBC in the lightly doped LPNP is observed above 500 Gy(Si) at low-dose-rate irradiation in Fig. 2(b). This may be attributed to the annealing of radiation-induced positive oxide trapped charge. Studies have shown that the oxide trapped charge could easily anneal at room temperature, while the interface traps anneal above 100 °C[12–15]. Compared to the high-dose-rate irradiation, the irradiation time is very long at low dose rate. Oxide trapped charge would obviously anneal in so long a time at room temperature. However, the interface traps could not anneal at room temperature[16, 17]. The annealing of the oxide trapped charge would make the width of surface depletion layer deduced in lightly doped emitter, which decreases the surface recombination velocity. Consequently, it would make the excess base current decrease in lightly doped LPNP, as shown in Fig. 2(b).

Furthermore, for the same doping concentration in emitter, the response of the LPNP transistor is also different at high and low dose rates. This difference depends on the relative amount of oxide trapped charge and interface traps produced at high and low dose rates. It has been found that there are more oxide trapped charge and interface traps under low-dose-rate irradiation[8, 17]. For the heavily doped LPNP transistors, although it is hard to deplete the emitter surface, it can make the surface of natural base accumulated, which decreases the surface recombination. Due to more oxide trapped charge induced by low-dose-rate irradiation, it can lead to much less surface combination than the high-dose-rate case, which could not be compensated by more interface traps. Therefore, the EBC at low dose rate is less than that by high dose rate. However, for the lightly doped LPNP transistors, positive oxide trapped charge could easily make the lightly doped emitter surface deplete. The increase of surface combination velocity is dominant. Meanwhile, the EBC is proportional to the density of interface traps

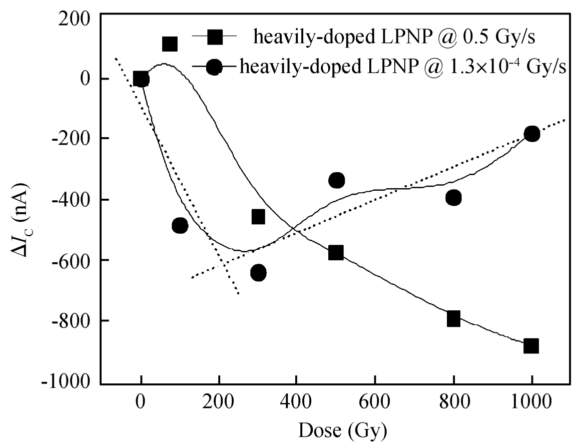

Fig. 5. Collector current of LPNP with heavily doped emitter versus total dose under high- and low-dose-rate irradiation.

according to Eqs. (1) and (2). Both of these factors can increase the EBC. Due to more oxide trapped charge and interface traps, the EBC at low dose rate would be greater than that at high dose rate before 500 Gy(Si). However, after 500 Gy(Si), the room-temperature annealing of oxide trapped charge is remarkable in long-term irradiation time, and as a results of that, the EBC would be less than that at the high dose rate.

As for the recovery of normalized gain observed in heavily doped LPNP as shown in Fig. 3(b), this may result from the change in collector current. Figure 5 shows the high- and low-dose-rate response of excess collector current ($\Delta I_C = I_{\text{Cpost-irrad.}} - I_{C0}$) in heavily doped LPNP. It can be seen from this figure that the response of the collector current is consistent with that of normalized gain under low-dose-rate irradiation. According to the theory of bipolar junction transistor, when the base–collector voltage is zero, i.e., $V_{CB} = 0$ V, the collector current can be expressed as follows[18]:

$$I_C = Aq\frac{D_B p_B}{L_B}\frac{1}{sh(W_{\text{eff}}/L_B)}[\exp(qV_{EB}/kT) - 1],$$

where A is the cross-section area of bipolar junction transistor, D_B is the diffusion coefficient of minority carriers (holes) in base, p_B is the concentration of minority carriers in base, L_B is the drift length of minority carriers, and V_{EB} is emitter–base voltage.

At a low dose level, the accumulation layer can be induced by positive oxide trapped charge in base surface, which can increase the concentration of major carriers (electrons) in base, so the concentration of minority carriers (p_B) in the base surface would be deduced. This could lead to the linearly decline of collector current before 200 Gy(Si), as shown in Fig. 5 by dot line. Meanwhile, the expansion of the effective width of the depletion layer can be neglected, due to the heavily doped emitter. It needs a long time to reach a higher dose level at a low dose rate. The oxide trapped charge would anneal during this irradiation time, which increases the concentration of minority carriers. Consequently, the collector current increases linearly with a high dose level. This “rebound” has also been reported in Ref. [5]. In order to confirm the reason of the increase of collector current mentioned above, Figure 5 also shows the high-dose-rate response of excess collector current in heavily doped LPNP. It can be obtained that the excess collector current decreases with the accumulated dose at a high dose rate, except the point at 100 Gy(Si). This “strange” point may originate from the interaction between radiation-induced defects and the intrinsic defects, for example the remaining implanted boron ions during the processing procedure. After the interaction, the potential of the emitter surface would be increased, which can relatively increase the concentration of holes in the emitter surface. Consequently, the emitter-junction efficiency will increase, causing the increase of the collector current at about 100 Gy(Si). However, with the continuous buildup of oxide trapped charge, the minority carriers gradually decrease in base, indicating the drop of collector current. Also, the annealing of oxide trapped charge can be omitted in so short a time. Therefore, the high-dose-rate response of the collector current of heavily doped LPNP has confirmed the cause of the increase of collector current at low-dose-rate irradiation, as mentioned above.

4. Conclusions

The high- and low-dose-rate damage in LPNP transistors with heavily and lightly doped emitters have been studied in detail in this paper. After irradiation, the excess base current and current gain in LPNP transistors would severely degrade. This degradation results from radiation-induced oxide trapped charge and interface traps. The interface traps would increase the surface recombination velocity, and the excess base current is proportional to the surface recombination velocity. Furthermore, the oxide trapped charge has double effects and the lightly doped LPNP is more sensitive to ionizing radiation. These are the comprehensive results of the positive oxide trapped charge and interface traps. Heavily doping in emitters could improve the radiation tolerance of lateral PNP transistors.

Under low-dose-rate irradiation, the observed abnormal effect of gain degradation in heavily doped LPNP is consistent with the change in collector current. The behavior of the collector current is attributed to the annealing of oxide trapped charge. Therefore, the collector current should be taken into consideration in the gain degradation of LPNP with heavily doped emitter.

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