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Research Paper

# IMPACT OF DOPED BORON CONCENTRATION IN EMITTER ON HIGH- AND LOW-DOSE-RATE DAMAGE IN LATERAL PNP TRANSISTORS

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**ABSTRACT-**

Research has delved into the impact of radiation damage on lateral PNP transistors with varying levels of emitter doping under both high and low dose rates. Experimental findings indicate that with increasing total dose, transistor base current rises while current gain declines. Moreover, lighter-doped PNP transistors exhibit more pronounced degradation, with heavily doped transistors displaying an abnormal effect. The influence of radiation defects, particularly the dual effects of oxide trapped charge, is examined in both lightly and heavily doped transistors. Notably, the abnormal effect observed in heavily doped transistors can be attributed to the annealing of oxide trapped charge, elucidated through a comparison of high- and low-dose-rate responses in collector current. This sheds light on the detailed response of collector current in heavily doped PNP transistors under varying irradiation conditions.

**KEY WORDS-** doping concentration; lateral PNP transistors; radiation damage; dose rates.

## INTRODUCTION: CRAFTSMANSHIP AND ARTISAN TRADITIONS IN MEDIEVAL INDIA

Bipolar junction transistors (BJTs) play a pivotal role in electronic systems utilized within challenging environments such as nuclear reactors, accelerators, detectors, and satellites in space. Operating in these environments exposes BJTs to various energetic particles and radiation, potentially leading to degradation in current gain and reliability issues for electronic systems. Therefore, investigating the dependence of radiation damage on processing factors is crucial for enhancing the reliability of electronic systems in radiation environments and establishing experimental evidence for the radiation hardening of bipolar devices and integrated circuits.

Lateral PNP transistors (LPNPs) are predominantly employed in modern bipolar integrated circuits, with lateral structures being more susceptible to radiation compared to substrate and vertical structures, exhibiting enhanced low-dose-rate sensitivity (ELDRS). Hence, enhancing the radiation tolerance of LPNPs is paramount for the radiation hardness of bipolar integrated circuits and electronic systems overall. To achieve this, it is imperative to understand the influencing factors of radiation damage and the underlying mechanisms by which they affect it.

While previous studies have explored various factors affecting radiation damage in LPNPs, including dose rate, geometry structure, biased conditions, and temperature, few reports have specifically addressed the damage characteristics of LPNPs with different doping concentrations in emitters, a factor easily controlled by processing technology. Although some studies have examined the influence of emitter doping concentration on radiation damage, discussions regarding radiation characteristics and underlying mechanisms, especially concerning low-dose-rate damage, remain limited.

This study aims to investigate the damage characteristics of LPNPs with heavily or lightly doped boron in emitters under high- and low-dose-rate conditions and analyze the influence mechanisms of doping concentration. By comparing high- and low-dose-rate damage for LPNPs with the same doping concentration, as well as differences in damage between heavily and lightly doped emitters, detailed discussions on underlying damage mechanisms are facilitated.

**Experimental details**

In our experiments, we utilized lateral PNP transistors, as illustrated in Figure 1.1. The emitter area of these transistors measures 10 ×10 $\mu m^2$, with the emitters being either heavily or lightly boron-doped during the processing phase. The samples underwent irradiation using $^{60}$Co- rays at both high (0.5 Gy(Si)/s) and low (1.3× $10^{-4}$ Gy(Si)/s) dose rates.

**Figure 1.1 Schematic cross section of lateral PNP transistors**

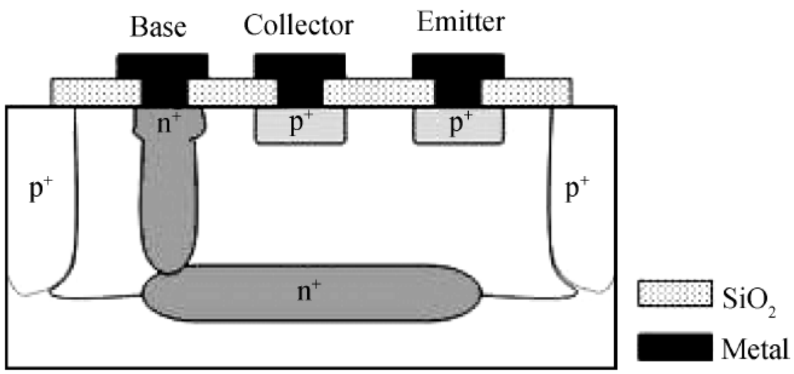
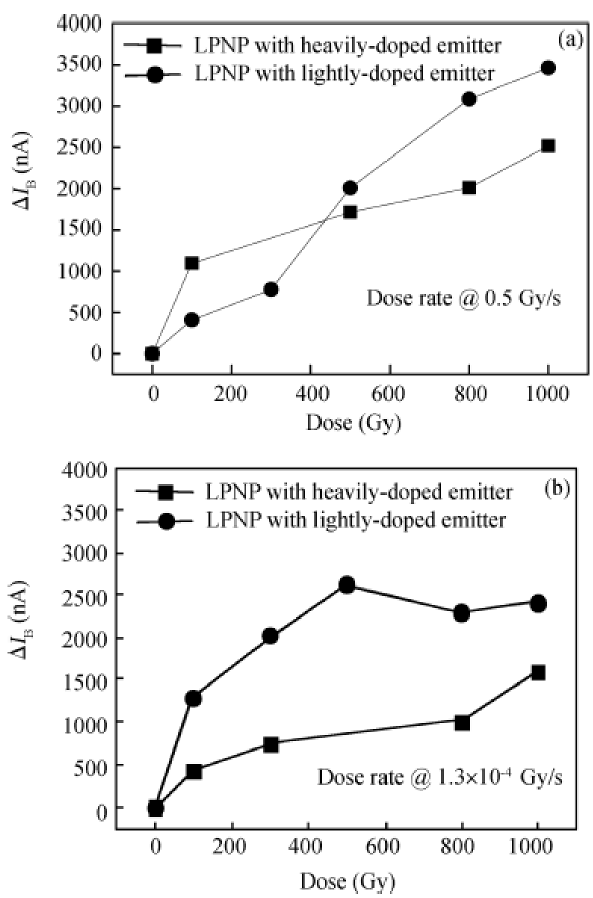



**Figure 1.2 Excess base current under (a) high- and (b) low-dose-rate irradiation for LPNP transistor with heavily or lightly doped emitters.**

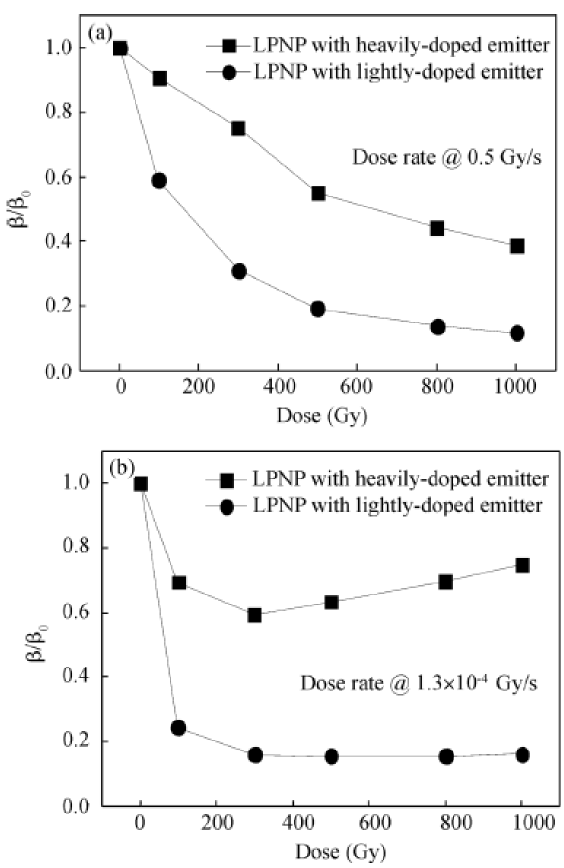



Prior to irradiation, these dose rates underwent calibration to ensure the accuracy of the accumulated dose. Additionally, to mitigate the effects of scattered photons, the samples were enclosed in a shielding box made of lead and aluminum (Pb/Al). Throughout both irradiation and annealing processes, the base–emitter junction was reverse biased, with the base at +2 V and the emitter and collector terminals grounded. Measurements of base and collector currents, as well as current gain ($I_B$,$I_C$ and $\beta = I_C/I_B$), were conducted before and after irradiation using a semiconductor parametric analyzer, specifically an Hp4142, with a precision of pA. Throughout the testing phase, the base–collector voltage remained at zero ($V_{BC}$ D 0 V), while the emitter was grounded.

**RESULTS AND DISCUSSION**

Figures 1.2 (a) and 2(b) depict the excess base current (EBC,$\Delta I_B = I_{Bpost\text{-}irrad} - I_{BO}$) of both heavily and lightly doped emitters against the total dose under high- and low-dose-rate irradiation. The base current measurements were conducted at an emitter–base voltage of 0.608 V. In Figure 1.2(a), it is evident that the EBC increases in both heavily and lightly doped LPNP transistors following irradiation. Additionally, the EBC of the lightly doped LPNP gradually surpasses that of the heavily doped LPNP. However, under low-dose-rate conditions, as depicted in figure 2(b), the behavior of EBC differs between heavily and lightly doped LPNPs. While the EBC of heavily doped LPNPs consistently rises, that of lightly doped LPNPs decreases after reaching 500 Gy(Si), indicating base current recovery. Notably, figure 1.2(b) also highlights that the EBC of lightly doped LPNPs significantly exceeds that of heavily doped LPNPs, underscoring the heightened sensitivity of lightly doped LPNPs to total dose under low-dose-rate irradiation compared to heavily doped LPNPs.

**Figure 1.3 Normalized current gain of heavily or lightly doped LNPN transistor under (a) high- and (b) low-dose-rate irradiation.**

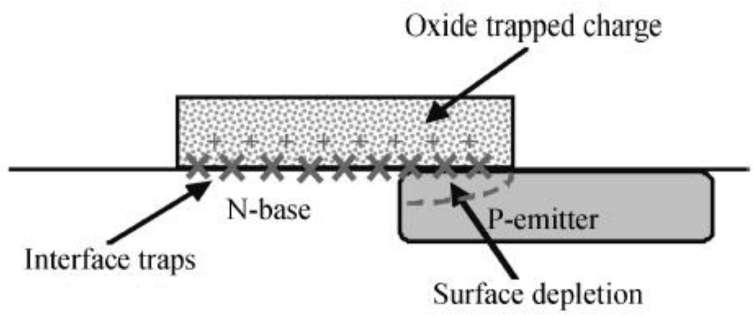


Upon comparing the effects of high- (Figure 1.2(a)) and low-dose-rate (Figure 1.2(b)) irradiation, we observe that in heavily doped LPNPs, the excess base current (EBC) induced by high-dose-rate irradiation surpasses that induced by low-dose-rate irradiation. However, for lightly doped LPNPs, radiation damage manifests in two stages under both high- and low-dose-rate conditions. Before reaching 500 Gy(Si), the EBC under low dose rate exceeds that under high-dose-rate conditions. Subsequently, beyond this dose point, the response to high- and low-dose-rate irradiation diverges, with a recovery of the EBC observed under low-dose-rate irradiation while it continues to increase under high-dose-rate conditions.

Figures 1.3(a) and 3(b) illustrate the normalized current gain ($\beta = \beta_{\text{postirrad}}./\beta_0$) versus accumulated dose under high and low dose rates, respectively. It is evident from both figures that there is more pronounced degradation in lightly doped LPNPs under both high- and low-dose-rate irradiation. Under high-dose-rate irradiation, the normalized current gain degrades as the accumulated dose increases. However, there are differences in the response under low-dose-rate conditions. After accumulating a dose of up to 300 Gy(Si), there is a slight increase in normalized gain current for heavily doped LPNPs. Conversely, in lightly doped LPNPs, normalized gain has already degraded by at least 80% at 100 Gy(Si), indicating their high sensitivity to low dose rate.

Therefore, based on the observed gain degradation, it can be concluded that lightly doped LPNPs are more sensitive to radiation. Additionally, an abnormal phenomenon is noted in heavily doped LPNPs: despite the gradual increase in base current with accumulated dose, the normalized gain slightly increases after 300 Gy(Si), a point which warrants further discussion.

**Figure 1.4 Positive oxide trapped charge and interface traps near the Si–SiO2 interface, and the expansion of depletion layer**




Ionizing radiation generates a significant number of electron-hole pairs within the screen oxide layer, situated above the base–emitter junction. These pairs, subjected to the electric field within the oxide, undergo separation. Owing to the considerably higher drift velocity of electrons, they swiftly exit the oxide layer within approximately $10^{-12}$ seconds, leaving behind a surplus of holes due to their slower transport. Most of these holes become trapped by oxide traps, forming positive oxide trapped charge. Simultaneously, as holes traverse toward the Si–$SiO_2$ interface, they can interact with hydrogen passivated silicon bonds (Si–H), liberating hydrogen ions in the vicinity of the interface. These holes or hydrogen ions, in turn, get ensnared by interface traps, thereby generating interface trapped charge. The schematic representation of radiation-induced oxide trapped charge and interface traps is depicted in Figure 1.4. These two types of defects exert distinct influences on transistor characteristics. Specifically, in the context of LPNP transistors, positive oxide trapped charge induces an accumulation layer on the n-type base surface. This layer diminishes surface recombination velocity, consequently reducing base current.

The maximum recombination velocity occurs when the concentration of electrons and holes are comparable. Positive oxide trapped charge has a similar impact on LPNP transistors as it does on neutral bases in NPN transistors. This charge can cause the lightly doped p-type emitter to become depleted, extending the surface depletion into the emitter and increasing the effective width of the depletion layer ($W_{eff}$). Consequently, carrier recombination at the emitter surface is enhanced, leading to an increase in base current. Thus, positive oxide trapped charge exhibits dual effects: it induces accumulation at the n-type base surface, decreasing base current, while simultaneously expanding the depletion layer into the emitter surface, thereby increasing base current. The net effect on recombination velocity at the base surface is determined by the interplay between these two effects.

Irradiation-induced interface traps can also impact recombination velocity at the base surface. This recombination velocity is contingent upon the density of interface traps, $D_{it}$, and can be mathematically expressed.

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

In general, the excess base current (EBC) tends to be proportional to the surface recombination velocity ($S_r$), which is influenced by various factors including thermal speed ($v_{th}$), the Boltzmann constant (k), temperature (T) in Kelvin, and the cross sections of electrons ($\sigma_n$) and holes ($\sigma_p$).

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

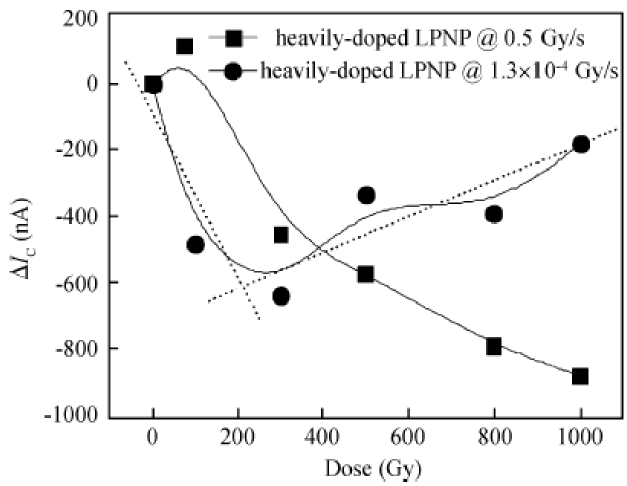
Where q is the elementary charge, as is the effective surface recombination area and �ns is the no equilibrium carrier concentration, dependent on the injected current density and radiation-induced oxide trapped charge. Understanding the effects of oxide trapped charge and interface traps allows us to analyze the behavior of excess base current in heavily or lightly doped LPNPs under high- and low-dose-rate irradiation. The monotonic increase in EBC suggests that accumulation on the base surface due to positive oxide trapped charge is not significant. Instead, the major contributors to the increase in EBC are the interface traps and the extension of the depletion layer induced by the oxide trapped charge. Additionally, compared to heavily doped emitters, lightly doped emitters are more prone to depletion, resulting in larger widths and depths of the depletion layer. This, in turn, enhances surface carrier recombination, leading to gradually greater EBC in lightly doped LPNPs with increasing accumulated dose compared to heavily doped LPNPs.

This heightened sensitivity of lightly doped LPNPs to ionizing radiation is also reflected in the greater degradation observed in figure 1.3. However, a decrease in EBC in lightly doped LPNPs is noted above 500 Gy(Si) at low-dose-rate irradiation in figure 1.2(b). This phenomenon can be attributed to the annealing of radiation-induced positive oxide trapped charge. Research indicates that oxide trapped charge can readily anneal at room temperature, while interface traps anneal at temperatures above 100°C. Compared to high-dose-rate irradiation, the extended irradiation duration at low dose rate allows ample time for oxide trapped charge to anneal at room temperature. However, interface traps do not undergo annealing at room temperature. Consequently, the annealing of oxide trapped charge reduces the width of the surface depletion layer in lightly doped emitters, thereby decreasing surface recombination velocity. This, in turn, leads to a decrease in excess base current in lightly doped LPNPs, as illustrated in Figure 1.2(b).

Moreover, the response of LPNP transistors with the same doping concentration in the emitter varies at high and low dose rates. This discrepancy hinges on the relative quantities of oxide trapped charge and interface traps generated at these rates. Studies have indicated a higher prevalence of both oxide trapped charge and interface traps under low-dose-rate irradiation. For heavily doped LPNP transistors, despite the difficulty in depleting the emitter surface, accumulation occurs on the surface of the natural base, reducing surface recombination. The greater abundance of oxide trapped charge induced by low-dose-rate irradiation results in significantly lower surface recombination compared to the high-dose-rate scenario, a phenomenon not compensated for by the increase in interface traps. Consequently, the excess base current at low dose rate is lower than that at high dose rate.

Conversely, in lightly doped LPNP transistors, positive oxide trapped charge readily induces depletion on the lightly doped emitter surface, leading to a predominant increase in surface recombination velocity. Meanwhile, the density of interface traps, as per Eqs. (1) and (2), is directly proportional to the excess base current.

**Figure 1.5 Collector current of LPNP with heavily doped emitter versus total dose under high- and low-dose-rate irradiation.**




Both oxides trapped charge and interface traps contribute to an increase in the excess base current (EBC). The greater prevalence of these factors under low-dose-rate irradiation results in a higher EBC compared to high-dose-rate irradiation before reaching 500 Gy(Si). However, beyond this point, the remarkable room temperature annealing of oxide trapped charge during long-term irradiation leads to a decrease in EBC compared to high dose rate.

The observed recovery of normalized gain in heavily doped LPNPs, as depicted in Figure 1.3(b), may stem from changes in the collector current. Figure 1.5 illustrates the high- and low-dose-rate responses of excess collector current ($\Delta I_C = I_{Cpost\text{-}irrad.} - IC_0$) in heavily doped LPNPs. It is evident from this figure that the response of the collector current aligns with that of the normalized gain under low-dose-rate irradiation.

According to the theory of bipolar junction transistors, when the base–collector voltage is zero (i.e., $V_{CB}$ D 0 V), the collector current can be expressed as follows.

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

At lower dose levels, the accumulation layer can be triggered by positive oxide-trapped charge on the base surface, thereby boosting the concentration of majority carriers (electrons) within the base region. Consequently, the presence of these majority carriers reduces the concentration of minority carriers ($p_B$) in the base surface. This phenomenon contributes to the observed linear decline in collector current, illustrated by the dotted line in Figure 5, before reaching a dose of 200 Gy(Si). Additionally, due to the heavily doped emitter, the expansion of the effective width of the depletion layer can be disregarded. However, reaching higher dose levels at a low dose rate requires a considerable amount of time. During this irradiation period, the oxide-trapped charge tends to anneal, leading to an increase in the concentration of minority carriers.

As a result, the collector current experiences a linear increase at higher dose levels, a phenomenon also documented. To validate the underlying cause behind this surge in collector current, Figure 1.5 displays the high-dose-rate response of excess collector current in heavily doped LPNP. It reveals that the excess collector current declines with the accumulated dose at a high rate, except for the anomaly observed at 100 Gy(Si). This anomaly might stem from the interplay between radiation-induced defects and intrinsic defects, such as residual implanted boron ions from the processing procedure. This interaction potentially elevates the potential of the emitter surface, thereby relatively augmenting the concentration of holes in the emitter surface. Consequently, the efficiency of the emitter-junction rises, leading to an upsurge in collector current around 100 Gy(Si). However, as oxide-trapped charge continues to accumulate, the minority carriers gradually diminish in the base, signaling a decline in collector current. Additionally, the short duration of irradiation makes it unlikely for significant annealing of oxide-trapped charge to occur. Hence, the high-dose-rate response of the collector current in heavily doped LPNP confirms the cause of the collector current increase observed during low-dose-rate irradiation, as discussed earlier.

**CONCLUSIONS**

This paper delves into a detailed examination of high- and low-dose-rate damage in LPNP transistors, comparing those with heavily and lightly doped emitters. Following irradiation, both excess base current and current gain in LPNP transistors experience significant deterioration. This degradation is primarily attributed to radiation-induced oxide trapped charge and interface traps. The presence of interface traps escalates surface recombination velocity, directly impacting excess base current, which is proportional to this velocity. Moreover, oxide trapped charge exhibits dual effects, with lightly doped LPNP transistors proving more susceptible to ionizing radiation.

These findings represent a comprehensive analysis of the impact of positive oxide trapped charge and interface traps. Notably, heavily doping emitters can enhance the radiation tolerance of lateral PNP transistors.

During low-dose-rate irradiation, the observed anomalous degradation in gain within heavily doped LPNP aligns with the trends in collector current. This behavior in collector current is attributed to the annealing process of oxide trapped charge. Consequently, when assessing gain degradation in LPNP with heavily doped emitters, careful consideration of collector current dynamics becomes imperative.

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