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Estimation of enhanced low dose rate sensitivity mechanisms using temperature switching irradiation on gate-controlled lateral PNP transistor*

Xiao-Long Li(李小龙)[1,2,3], Wu Lu(陆妩)[1,2,†], Xin Wang(王信)[1,2], Xin Yu(于新)[1,2], Qi Guo(郭旗)[1,2], Jing Sun(孙静)[1,2], Mo-Han Liu(刘默寒)[1,2,3], Shuai Yao(姚帅)[1,2,3], Xin-Yu Wei(魏昕宇)[1,2], and Cheng-Fa He(何承发)[1,2]

[1] *Key Laboratory of Functional Materials and Devices for Special Environments, Xinjiang Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Urumqi* 830011, *China*

[2] *Xinjiang Key Laboratory of Electronic Information Material and Device, Urumqi* 830011, *China*

[3] *University of Chinese Academy of Sciences, Beijing* 100049, *China*

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The mechanisms occurring when the switched temperature technique is applied, as an accelerated enhanced low dose rate sensitivity (ELDRS) test technique, are investigated in terms of a specially designed gate-controlled lateral PNP transistor (GLPNP) that used to extract the interface traps (Nit) and oxide trapped charges (Not). Electrical characteristics in GLPNP transistors induced by ^{60}Co gamma irradiation are measured *in situ* as a function of total dose, showing that generation of Nit in the oxide is the primary cause of base current variations for the GLPNP. Based on the analysis of the variations of Nit and Not, with switching the temperature, the properties of accelerated protons release and suppressed protons loss play critical roles in determining the increased Nit formation leading to the base current degradation with dose accumulation. Simultaneously the hydrogen cracking mechanisms responsible for additional protons release are related to the neutralization of Not extending enhanced Nit buildup. In this study the switched temperature irradiation has been employed to conservatively estimate the ELDRS of GLPNP, which provides us with a new insight into the test technique for ELDRS.

Keywords: ionizing radiation damage, enhanced low dose rate sensitivity (ELDRS), switched temperature irradiation, gate-controlled lateral PNP transistor (GLPNP)

PACS: 61.80.–x, 61.80.Ed, 85.30.Pq **DOI:** 10.1088/1674-1056/27/3/036102

1. Introduction

The enhanced low dose rate sensitivity (ELDRS) was first reported in 1991[1] on bipolar transistors (BJTs) and integrated circuits (ICs) that showed enhanced radiation-induced degradation when exposed to low dose rate (LDR), particularly at lateral and substrate PNP transistors.[2] Since then, various experimental research and theoretical models have been examined to explain ELDRS,[3–7] and it is most widely accepted that both interface traps (Nit) and oxide trapped charges (Not) would contribute to degrade the performance of devices. The physical mechanisms in BJTs responsible for base current degradation are related to the changes in surface recombination caused by the buildup of Nit and spreading of depletion layer or electrons injection into the emitter induced by the formation of Not. The two-stage hydrogen model incorporates hydrogen release mechanisms as well as the Nit formation due to hydrogen depassivation of Si–H bonds near the interface as proposed by McLean *et al.*[8] After exposure to ionizing radiation, excess hydrogen released in devices would be trapped in the oxide with affecting the densities of Not.[9] Additionally, hydrogen molecules cracking at oxide trapped charges, releasing hydrogen to enhance Nit buildup, are included in the theoretical calculation.[7] Simultaneously the annealing of Nit is controlled by the passivation of interfacial defects by hydrogen molecules.[5] This has made it difficult to identify the process in terms of Nit and Not formation, since the distribution of Nit and Not varies with the irradiation conditions, such as dose rate, bias, and irradiation temperature.

On the other hand, due to the presence of ELDRS, the testing at a high dose rate is not feasible, since the experiments with high dose rate do not provide the upper bound of the LDR response of devices. However, testing with LDR is an extremely time-consuming and expensive task. For example, it will take about 4 months to accumulate 100 krad(Si) when performing at typical LDR (0.01 rad(Si)/s) experiment. So, several accelerated test techniques have been attempted to evaluate ELDRS, such as (i) elevated temperature irradiation (ETI),[3,10] (ii) irradiation with molecular hydrogen,[6,11] (iii) the switched dose rate technique,[12,13] and (iv) the switched temperature irradiation.[14–16] Among them, switched temperature technique, proposed by Lu *et al.*[14] as a promising and

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†Corresponding author. E-mail: luwu@ms.xjb.ac.cn

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applicable accelerated ELDRS test method, has been demonstrated on a series of bipolar devices by experimental verification. Unfortunately, there was no further exploration on how the Nit and Not affect the devices damage during temperature irradiation and the mechanisms behind this technique. Therefore, understanding the mechanism at play when the switched temperature irradiation applied is important and necessary to develop and popularize this accelerated total dose hardness assurance test intended for space missions.

In this work, special structures, gated lateral PNP transistors (GLPNP), have been designed to investigate the total dose induced changes in Not and Nit under different irradiation conditions. The physical mechanisms behind the switched temperature irradiation have been established on the basis of the characterization of Nit and Not. Additionally, the experimental results have emphasized the importance of the radiation-induced species mutual transformation in understating the ionizing radiation effects.

2. Experiment details

The gate-controlled lateral PNP transistors tested in this work were fabricated by the State Key Laboratory of Analog Integrated Circuit, China. Those devices have an independent gate electrode which covers the active base region of the PNP transistor, controlling the potential of the interface independently. The cross section and technical parameters of the GLPNP are illustrated in Fig. 1 and Table 1, respectively.

Table 1. The parameters of the GLPNP.

Parameter	Description
oxide thickness	320 nm
doping concentration of base	1×10^{17} cm^{-3}
doping concentration of emitter	1×10^{19} cm^{-3}
doping concentration of collector	1×10^{19} cm^{-3}

The experiments were carried out on the gamma source in the Xinjiang Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. All of the transistors examined in this work were exposed to the total dose of 100 krad(Si) with all pins shorted during the irradiation. The dose rate used for elevated temperature was 5.8 rad(Si)/s and the low dose rate was 0.01 rad(Si)/s. After irradiation, besides Gummel curve measurement, the gate sweep (GS) characteristics and sub-threshold sweep (SS) characteristics were tested using a KEITHLEY 4200SCS parameter analyzer. In the Gummel curve measurement, base–emitter voltage was swept from 0 to -1 V, fixing the gate floated and $V_{BC} = 0$ V. In the GS test, the gate voltage was swept from -40 V to 10 V at $V_{BE} = 0.5$ V. In the SS test, the gate voltage was swept from -50 V to -10 V at $V_{BE} = 0.5$ V.

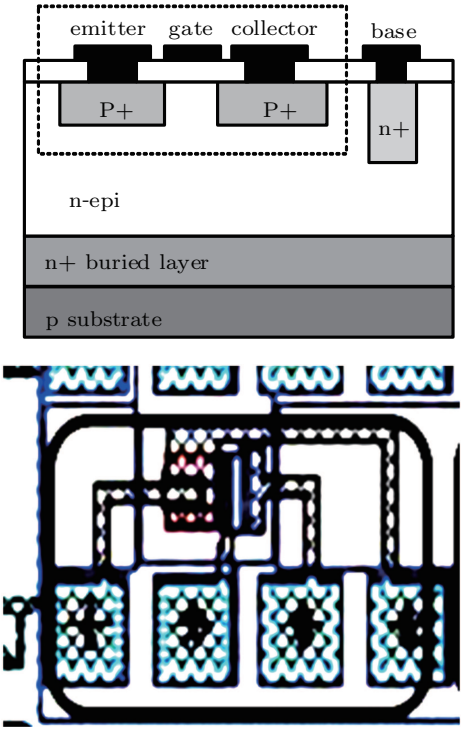


Fig. 1. The cross section and layout of the GLPNP.

The elevated temperature irradiations, consisting of fixed temperature irradiation and switched temperature irradiation, were performed in a special heating system with a precision of ±2 °C. As for fixed temperature irradiation, the devices were irradiated at a constant temperature ranging from 120 °C to 80 °C over the range of dose accumulated. According to previous works,[14–16] for switched temperature irradiation the test procedure was that the samples were first exposed to 20 krad(Si) at 120 °C, then to 80 krad(Si) at 100 °C, and finally to the total dose of 100 krad(Si) at 80 °C, as shown in Fig. 2.

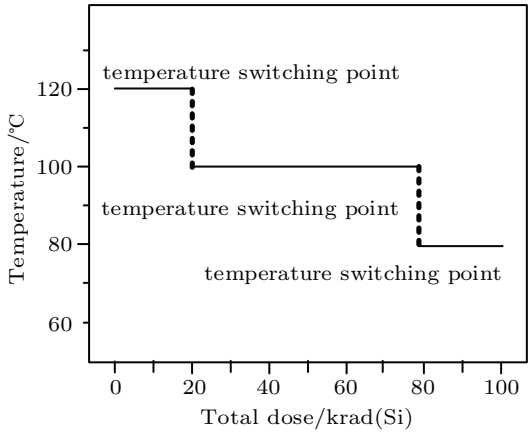


Fig. 2. Schematic illustration of temperature switching irradiation.

3. Experimental results

3.1. Gummel curve measurement

As for most bipolar devices, excess base current (ΔI_b),[15] $\Delta I_b = I_{b-postrad} - I_{b-prerad}$, is identified as the most sensitive parameter to irradiation, where $I_{b-postrad}$ and $I_{b-prerad}$ present the base current after and before irradiation, respectively. Figure 3 shows the increase in base current tested at $V_{BE} = 0.7$ V and gate floated, versus the total dose accumulation under various irradiation conditions. It is clearly seen that the excess base current ΔI_b submitted to various configurations (i.e., fixed temperature of 120, 100, and 80 °C) is directly proportional to the dose examined before 80 krad(Si). Moreover, at a given dose, the excess base current ΔI_b substantially increases with the increasing irradiation temperature, whereas the fading property of the 120 °C curve is observed at the total dose of 100 krad(Si). More interestingly, after the switch of temperature the greater degradation is obtained when compared to the fixed temperature configurations, similarity with the LDR response.

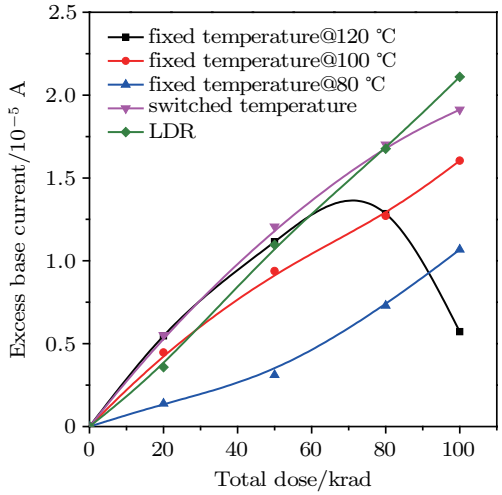


Fig. 3. (color online) The excess base current (ΔI_b) versus total dose for the GLPNP during various temperature irradiations (Gummel plots at $V_{BE} = 0.7$ V).

3.2. Gate sweep and sub-threshold sweep characteristics

Figures 4–8 show the base current (I_b) versus gate voltage (V_g) curves for GLPNP as a gated transistor and collector current (I_c) versus gate voltage (V_g) curves for GLPNP as a MOSFET. It is clearly demonstrated that for GS curves the base current of GLPNP reaches a maximum (a peak of base current) with the gate voltage swept from −40 V to 10 V. Also, the vertical shifts in GS curves which are typical causes of Nit variation are similar to those observed in Figs. 4–8 as the function of total dose. In addition, in a comparison of the results shown in SS curves, the horizontal shifts corresponding to the Not variation occur and the sub-threshold slope decreases with the total dose accumulation. Specifically, one of the most obvious features of the results shown in Fig. 4(a) is that while an unexpected decrease in base current takes place at 120 °C after being exposed to 100 krad(Si), the magnitude of peak base current increases monotonously along with increasing the dose when submitted to 100 °C, 80 °C, switched temperature, and LDR configurations. Further, under 100 °C exposures there is a significant base current peak broadening to occur in GS characteristics, dependent on the Nit density.

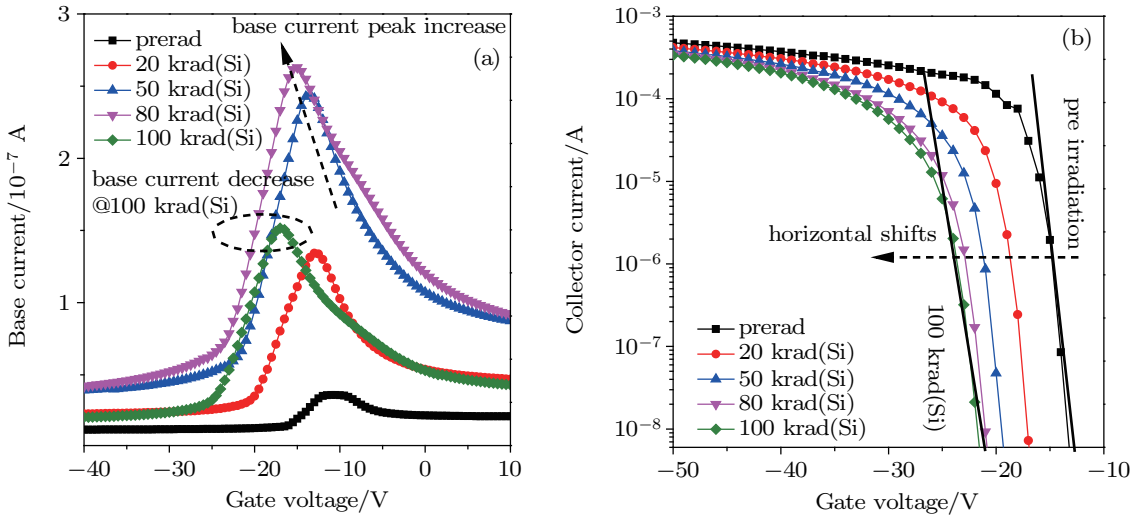


Fig. 4. (color online) The current versus gate voltage of the GLPNP with the fixed temperature at 120 °C. (a) Base current (I_b) versus gate voltage (V_g) and (b) collector current (I_c) versus gate voltage (V_g).

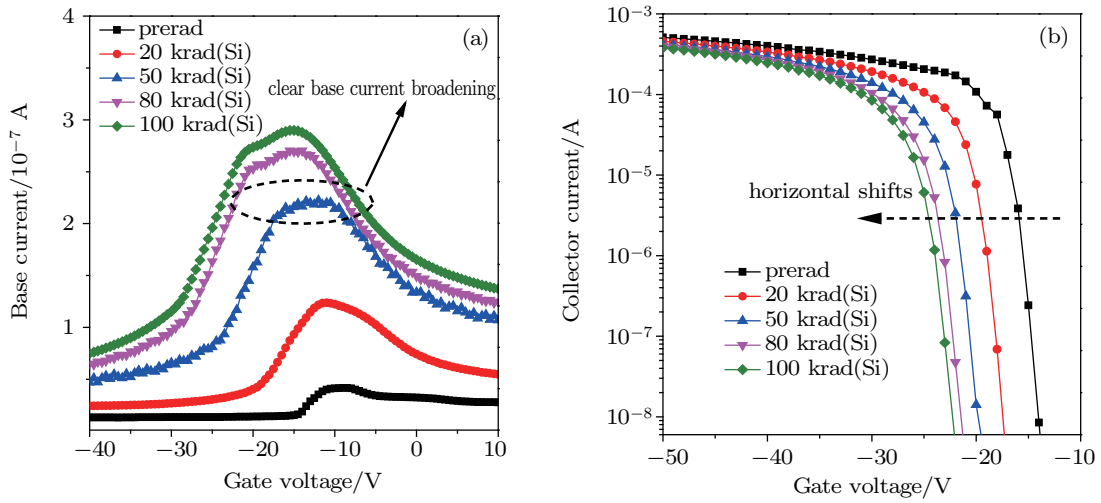


Fig. 5. (color online) The current versus gate voltage of the GLPNP with the fixed temperature at 100 °C. (a) Base current (I_b) versus gate voltage (V_g) and (b) collector current (I_c) versus gate voltage (V_g).

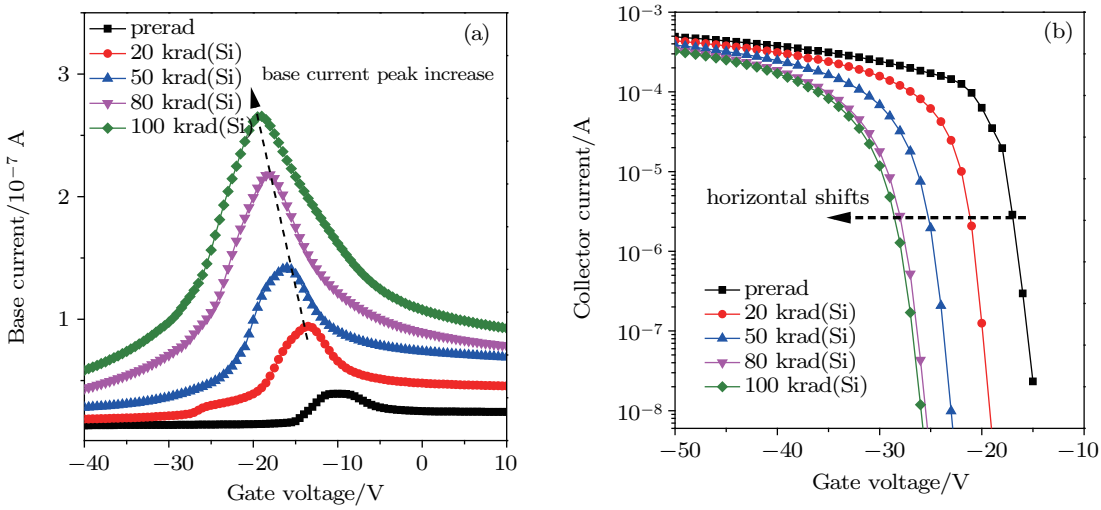


Fig. 6. (color online) The current versus gate voltage of the GLPNP with the fixed temperature at 80 °C. (a) Base current (I_b) versus gate voltage (V_g) and (b) collector current (I_c) versus gate voltage (V_g).

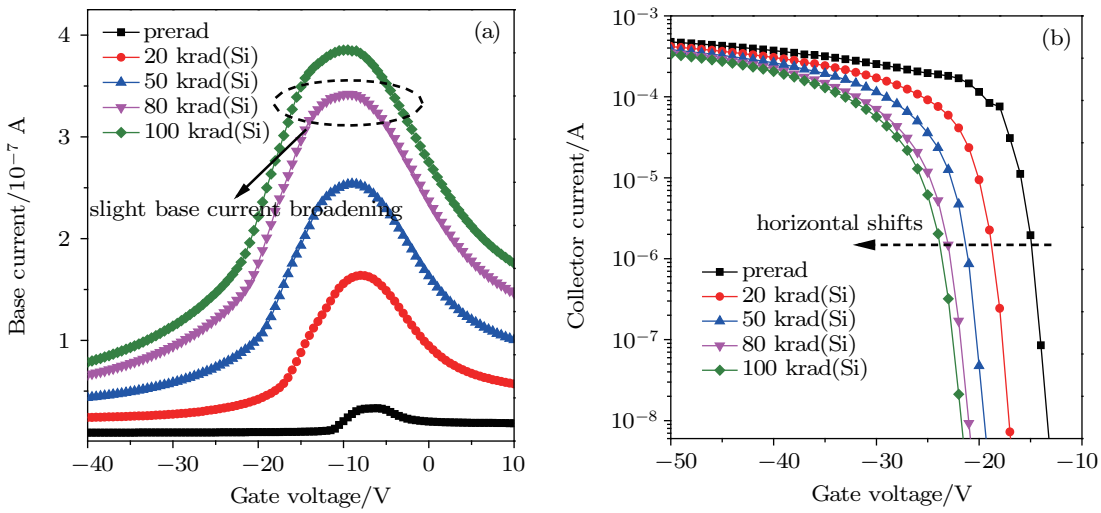


Fig. 7. (color online) The current versus gate voltage of the GLPNP with the switched temperature from 120 to 80 °C. (a) Base current (I_b) versus gate voltage (V_g) and (b) collector current (I_c) versus gate voltage (V_g).

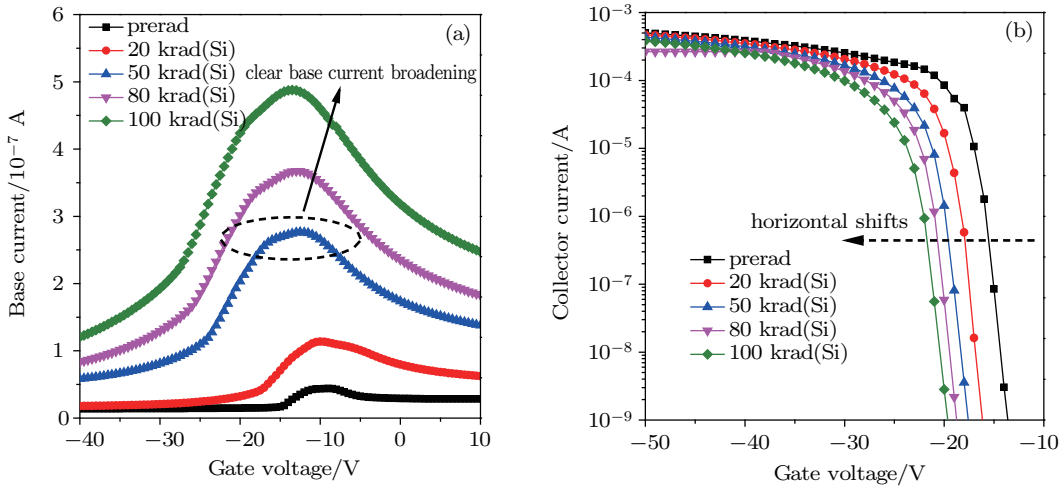


Fig. 8. (color online) The current versus gate voltage of the GLPNP with low dose rate. (a) Base current (I_b) versus gate voltage (V_g) and (b) collector current (I_c) versus gate voltage (V_g).

3.3. The distribution of oxide-traps and interface-traps

It is known that,[17] after exposure to ionizing radiation, Not and Nit have impacts on the surface potential and recombination velocity, resulting in the changes in the base current for bipolar transistors. With the knowledge of the literature and our previous work,[18–21] the Not and Nit could be extracted by applying GS and SS separation technique. Unlike the existence of the clear base current peak as shown in Fig. 9(a), the missing clear base current peak in Fig. 9(b) arising from peak broadening has an obvious influence on the accurate extraction of mid-gap V_{mg} relative to the estimation of Not, yet Nit still is calculated from the shift of peak base current in the GS test. Furthermore, the SS technique by operating the GLPNP as a MOSFET can precisely deal with the V_{mg} extraction. In this work, in conjunction with the SS technique, the GS test is performed to extract the radiation-induced Nit and Not distribution. As an example, in the case of 100 °C the mid-gap V_{mg} (shown in Table 2) extracted from SS characteristics is mapped onto the GS curve to accurately identify the base current,[21] as illustrated schematically in Fig. 9(b).

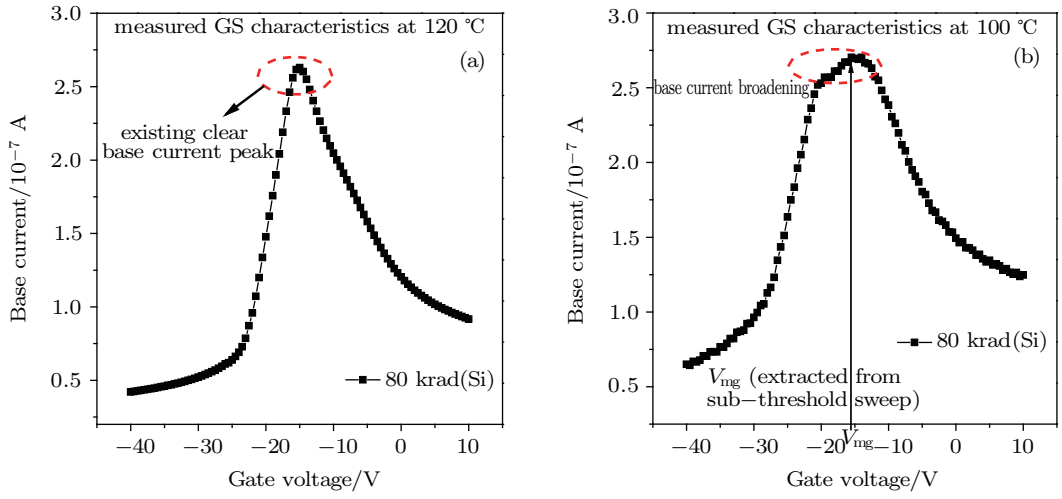


Fig. 9. (color online) The base current (I_b) versus gate voltage (V_g). (a) Existence of clear base current peak and (b) conjunction of sub-threshold sweep extracted V_{mg} with gate sweep.

Table 2. The extraction of V_{mg} and base current peak at 100 °C.

	20 krad(Si)	50 krad(Si)	80 krad(Si)	100 krad(Si)
V_{mg} (SS)	11.5 V	14.1 V	15.7 V	16.3 V
Base current (GS)	1.23×10^{-7} A	2.16×10^{-7} A	2.65×10^{-7} A	2.81×10^{-7} A

The radiation-induced Nit and Not are extracted from GS and SS results in Fig. 10, showing that the trapped charges response varies obviously in the range of temperatures from 25 to 120 °C. In Fig. 10(a) the trends observed in distribution of Nit show the acceleration in interface traps buildup with increasing temperature at a dose less than 80 kard(Si), whereas in the case of 120 °C irradiation an obvious recovery is observed at a dose of 100 krad(Si), similarity with the base current behavior. In addition, a similar trend to the LDR response has been observed as the ones suffered from switched temperature irradiation.

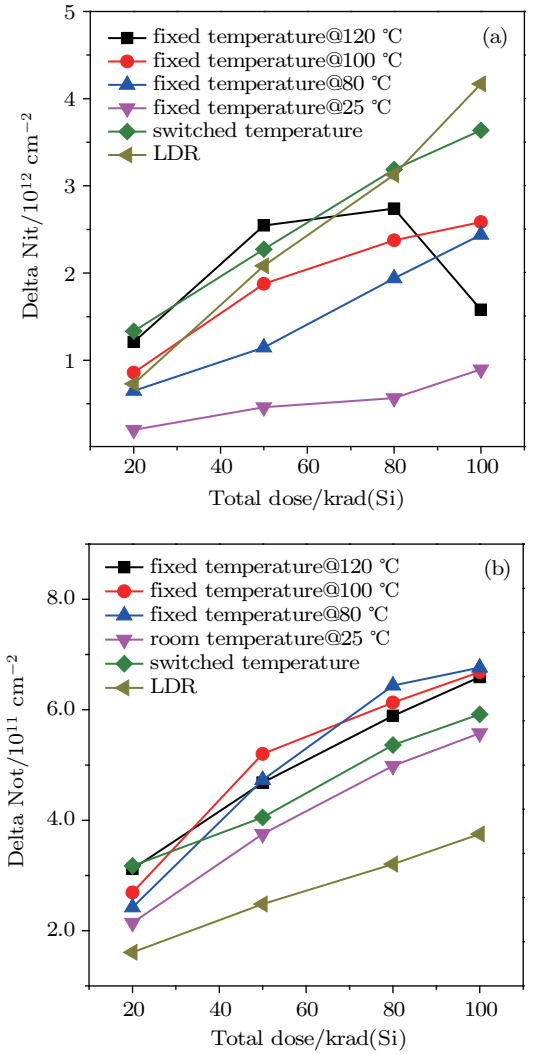


Fig. 10. (color online) Nit and Not versus total dose for the GLPNP during various temperature irradiations.

Different from Nit, the changes in Not in Fig. 10(b) monotonically increase with the dose accumulation at both fixed and switched temperature. Additionally, the interesting feature of the results at switched temperature is that the amount of Not is more competitive at the first dose examined compared to fixed temperature irradiation, whereas this superiority is replaced by the parts irradiated at 80 °C. Meanwhile, by comparison of results observed at two different dose rates during room temperature irradiation, the GLPNP at LDR has a smallest Not shift of 3.75×10^{11} cm^{-2} after 100 krad(Si).

For all the GLPNP testing, the experimental results of Figs. 3 and 10, where the overall curves in Fig. 3 follow the variations of Nit in Fig. 10(a), indicate that excess base current occurs in the GLPNP primarily as the result of the Nit buildup.

4. Discussion

4.1. The influence of interface traps during different irradiation conditions

Based on the experimental results of Fig. 10, it is suggested that an enhanced buildup of Nit would be produced by either fixed or switched temperature irradiations. By comparison of this temperature dependence on Nit at the same dose rate, the increased distribution of Nit, which is determined by the protons concentration near the interface[7,22] because of $\text{Nit} \propto \int([\text{H}^+][\text{SiH}])\,\text{d}t$, arises from the accelerated protons release and transport mechanisms in

$$\text{VH} + \text{h}^+ \xrightarrow{k_1} \text{V} + \text{H}^+, \tag{1}$$

$$k_n = L_\text{c} D \exp\left(\frac{-E_\text{b}}{k_\text{B} T}\right), \tag{2}$$

which is strongly temperature-dependent. Here VH represents the hydrogenated oxygen vacancy, V represents the oxygen vacancy, H^+ represents a proton, k_n represents the reaction rate coefficient, D is diffusivity of species, L_c is the capture length, E_b is the reaction barrier, k_B is the Boltzmann constant, and T is the temperature.

For fixed temperature in Fig. 10(a), it is shown that in the case of 120 and 100 °C the rate of Nit formation tends to slow down after being exposed to 50 krad(Si). This behavior can be illustrated schematically in Fig. 11(a), in which fixed temperature irradiations cause the loss of proton and hinder the transport of the proton to the Si/SiO_2 interface. According to Refs. [23] and [24], protons can be trapped in hydrogenated oxygen vacancies (V_δH) to form molecular hydrogen in

$$\text{V}_\delta\text{H} + \text{H}^+ \xrightarrow{k_2} \text{V}_\delta^+ + \text{H}_2. \tag{3}$$

This hydrogen dimerization process has an obvious influence on the protons concentration (i.e., the proton concentrations $[\text{H}^+]$ loss in Eq. (3), $[\text{H}^+] \propto \int(k_1[\text{VH}][\text{h}^+] - k_2[\text{VH}][\text{H}^+])\,\text{d}t < \int(k_1[\text{VH}[\text{h}^+])\,\text{d}t)$, resulting in the Nit tending to saturation or even recovery with the dose accumulation. More importantly, proton loss in hydrogen dimerization will be enhanced when the temperature increases due to the reaction coefficient strongly dependent of temperature, as given in Table 3. Additionally due to the existence of the converted H_2, the annealing of Nit (as described by process (5) in Fig. 11(a)) will occur at medium temperature instead of 175 °C considered as the appreciable temperature to anneal interface traps,[25,26] which

can account for the recovery of Nit under 120 °C configuration after 80 krad(Si).

Table 3. The diffusivity and reaction rate coefficient for hydrogen dimerization.

Temperature	Diffusivity D/cm^{2}s^{-1}	Reaction rate coefficient k_2/cm^{3}s^{-1}
300 K	3.03×10^{-12}	1.61×10^{-31}
350 K	2.50×10^{-10}	6.26×10^{-28}
370 K	1.04×10^{-9}	9.13×10^{-27}
400 K	6.77×10^{-9}	3.07×10^{-25}

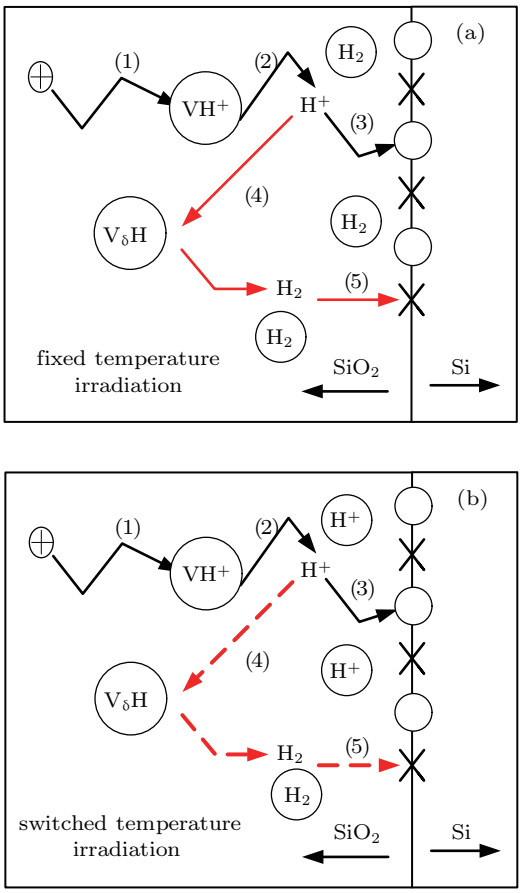


Fig. 11. Core of proton interactions near the interface. (1) and (2) Proton release from hydrogen-containing defects, (3) depassivation of Si–H bonds (interface traps formation), (4) hydrogen dimerization reaction (formation of H_2), and (5) annealing of interface traps. VH represents a hydrogen-containing defect, × represents an interface trap, O represents a Si–H bond, red arrow represents enhanced reaction, and red dashed-line arrows represents a relatively suppressive reaction. (a) Conditions at fixed temperature and (b) conditions at switched temperature.

In addition, the obvious differences with respect to the variation of Nit observed at switched temperature and fixed temperature suggest that decreased temperature can extend the liberation of proton with the dose accumulation. In order to understand this additional proton release, two factors would be considered. On one hand, owing to the hydrogen dimerization strongly dependent on temperature near the interface, the decrease in temperature will contribute to weakening the reaction rate and dropping of the more protons loss in Eq. (3), as illustrated in Fig. 11(b). On the other hand, the accumulated hydrogen molecules, which are generated from hydrogen dimerization, would be cracked at positively oxide traps to extend additional protons instead of annealing of Nit at low temperature, as discussed in the following section.

4.2. The influence of oxide traps during different irradiation conditions

When comparing the room temperature irradiation (at dose rate of 5.8 rad(Si)/s and 0.01 rad(Si)/s) in Fig. 10(b), there is an obvious difference on spatial distribution of Not (composed of E'_δ centers associated with V_δ oxygen vacancy and E'_γ centers related with V_γ oxygen vacancy). This phenomenon is related to the dose rate and annealing mechanism. Firstly, since the electron–hole generation rate is affected by the dose rate, the concentration of holes generated at a high dose rate may be much more than that at LDR, leading to the Not generation in

$$V_\delta + h^+ \longrightarrow V_\delta^+, \tag{4}$$

$$V_\gamma + h^+ \longrightarrow V_\gamma^+, \tag{5}$$

dependent on the dose rate. More importantly, the room temperature annealing mechanism, which is log-linearly dependent on time, may contribute to the Not loss when irradiating to a total dose of 100 krad(Si) requires 4 months at LDR. Further, owing to the variation of probability of radiation-induced holes recombining with the electrons,[27] Not densities are experimentally high at elevated temperature. For bipolar devices during the irradiation, it has demonstrated that the more holes are available to escape from the initial recombination when the temperature increases, which is responsible for the increased hole trap filling (Not) at first dose accumulation.

On the other hand, as described in Section 3.3, those experimental data of Not at fixed temperature indicate that the probability of hole trap filling is much larger at low temperature (80 °C) with dose accumulation. After being exposed to 100 krad(Si), the greatest increase in Not at 80 °C arises from the relatively decreased thermal emission of trapped holes compared to 120 and 100 °C, if one considers the thermal emission of hole trapped in defects from band-gap to valence band during the temperature irradiation.[25,26] Note that, since this emission rate is on the order of $\exp(-E_t/kT)$, where E_t is the trap energy, the Not locating at E'_δ centers are neutralized at a temperature below that case of E'_γ centers,[3] resulting in a suppressed neutralization at E'_γ centers as shown in Fig. 12. However, in the case of switched temperature irradiation, the shifts of Not increase rapidly at first 20 krad(Si) and then become less competitive when the temperature decreases, opposite from the above-mentioned temperature response. This interesting phenomenon is attributed to the different mechanisms affecting the changes in Not concentrations. The first explanation of the greater amount of Not at first 20 krad(Si)

to occur is mainly due to increased holes trapped in defects in Eqs. (4) and (5), resulting in them being more competitive compared to fixed 100 and 80 °C. The second mechanism, which is responsible for there being less changes in Not during the subsequent decreased temperature irradiation, is that the Not (V_γ puckered configuration) could be neutralized by hydrogen molecules in

$$V_\gamma^+ + H_2 \xrightarrow{k_3} V_\gamma H + H^+, \tag{6}$$

leaving a proton release, as illustrated in Fig. 12. This additional liberation of proton is consistent with the experimental data that an enhanced Nit occurs when the switched temperature is applied. Therefore, we found that the formation of Not performed in various temperature configurations suggest that oxide traps would capture holes, as well as involvement in Nit formation.

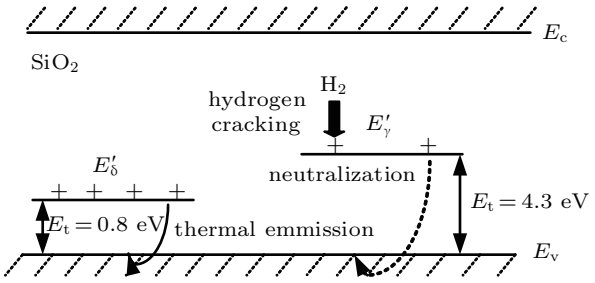


Fig. 12. Thermal emission of holes trapped in E' centers and neutralization of oxide trapped charges.

4.3. The mechanisms of temperature switching irradiation test

The analysis of the variations of Nit and Not suggests that the primary mechanisms for temperature switching irradiation as an ELDRS test technique are the accelerated liberation of protons and formation of Nit, which are key mechanisms in ELDRS.[22] Firstly, bipolar devices demonstrate sensitivity to temperature irradiation,[27] and a higher temperature (above 100 °C) accelerates the protons release to form Nit, resulting in enhanced degradation at a low dose level. Further, the increased Not also acts as an agent for Nit buildup, by the hydrogen cracking mechanism to release additional protons. Secondly, the temperature was switched from higher to moderate (100 °C) for the purpose of suppressing the hydrogen dimerization reaction at the medium dose level. This is because the decreased temperature can effectively suppress the hydrogen dimerization but proton release does not.[24] Thirdly, noting that the annealing effect will affect the device degradation, the further reduction in irradiation temperature (below 100 °C) is applied, restraining the annealing of Nit at high dose level because the barrier for this reaction is high, which is about 1.3 eV.[5] Therefore, for switched temperature irradiation the Nit and Not at the first higher temperature bring some positive influences on the evolution of Nit at subsequent low temperatures compared to fixed temperature irradiation.

5. Conclusion

In this work, the gated-controlled lateral PNP transistor has been performed to characterize the distribution of Not and Nit under low dose rate and elevated temperature irradiation. The results from the experiments are shown as follows. (i) The increase in base current of GLPNP is a result of Nit and Not changes, and Nit plays a more dominant role. (ii) Besides acceleration in protons release and diffusivity, elevated temperature also affects the occurrence of hydrogen dimerization, resulting in an unexpected loss in interface traps corresponding to the excess base current recovery. (iii) The additional changes in Nit are obtained for the parts exposed to switched temperature, since the reduction in temperature will suppress the hydrogen dimerization associated with protons loss. (iv) The oxide defects are not only dominant hole traps but also act as agent for interface formation. More importantly, Not would be neutralized by hydrogen molecules, inducing the increase of Nit because of the additional protons released in Eq. (6).

The results of this work have revealed why such switched temperature irradiation could enable estimation of LDR response for the bipolar transistor sensitive to ELDRS. This is because of accelerated liberation of protons and suppressive protons loss at switched temperature responsible for increased Nit. Meanwhile, converted hydrogen molecules cracking mechanisms at the Not site result in additional proton release, extending the enhanced degradation. Hence, it is applicable to evaluate the risk of failure of bipolar devices at low dose rate, and extensive research considering optimal conditions (dose rate, temperature, and dose level) is necessary for further investigation.

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