Radiation Resistance of Fluorine-Implanted PNP Using Gated-Controlled Lateral PNP Transistor Structure

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The radiation damage responses of fluorinated and non-fluorinated lateral PNP transistors are studied with specially designed gated-controlled lateral PNP transistors that allow for the extraction of the oxide trapped charge (N_{ot}) and interface trap (N_{it}) densities. All the samples are exposed in the Co-60γ ray with the dose rate of 0.5 Gy(Si)/s. After the irradiation, the buildup of N_{ot} and N_{it} of the samples with total dose is investigated by the gate sweep test technique. The results show that the radiation resistance of fluorinated lateral PNP transistors is significantly enhanced compared with the non-fluorinated ones.

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Bipolar junction transistors (BJTs) continue to play an important role in the spaceflight electric system, particularly in the mixed-signal parts due to their excellent linear characteristic, high-current drivability, high frequency and low noise. The problems of ionizing-radiation-induced gain degradation in bipolar transistors and the radiation hardness of bipolar devices have remained acute.[1,2] By several years of study, the mechanism of ionizing-radiation-induced gain degradation in PNP bipolar junction transistors has been obtained, which is the increase in surface recombination velocity due to traps induced by ionizing radiation resulting in an increase in excess base current.[3–5]

It has been reported that since the 1990s by introducing minute amounts of fluorine into MOS gate oxide, the increase of oxide charges and interface states can be restrained effectually, thereby resulting in fewer shifts of the threshold voltage and less increase of N channel leakage current.[6,7] The radiation hardness of fluorine-implantation is not dependent on the type of devices and irradiation gate bias. Based on these research results, the gated-controlled lateral PNP (GCLPNP) transistors, a kind of specific devices which are widely used to measure the radiation-induced defect quantitatively,[8–12] have been used in this study to investigate the radiation resistance of the fluorine-implanted lateral PNP (LPNP) transistors.

The devices studied in this work are GCLPNP transistors made in domestic technology, which are divided into two groups according to their fabrication process: fluorine-implanted ones and normal ones. These GCLPNP transistors are a kind of specific devices which have an independent gate terminal patterned above the active base region of the lateral PNP transistors.[9] By applying appropriate biases to the gate, surface carrier concentrations within the device can be adjusted, thereby altering surface carrier recombination and the base current response. The existence of this independent gate terminal does not affect the device's electric characteristic and radiation response when the device works as a normal PNP transistor, and this conclusion has been demonstrated in previous studies.[8–12] The radiation-induced defect can be measured quantitatively with the suitable testing measurement such as the gate sweep technique used in this study.

The two sets of GCLPNP transistors were irradiated in the Co-60 γ-ray source at the Xinjiang Technical Institute of Physics & Chemistry of Chinese Academy of Sciences. These devices were exposed at a dose rate of 0.5 Gy(Si)/s to the total dose of 400 Gy(Si) with all of their pins grounded during the radiation. A remote test was carried out on these GCLPNP transistors after 100, 200, 300, and 400 Gy(Si) of total dose exposure with an HP4200 parameter analyzer. The change of the current–voltage characteristics versus total dose were obtained with the gate sweep techniques which can be used to separate the radiation that induced the oxide charge and interface state quantitatively. It has been proved that the positive oxide trapped charge can cause the horizontal shift in the base current curve, and the interface trapped charge can increase the base current amplitude.[5] Thus ac-

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quiring the base current amplitude from the I_b versus V_g curve, the interface trap density N_{it} can be estimated by

$$\Delta N_{it} = \frac{2\Delta I_B}{q\sigma v_{th} S_{peak} n_i \exp\left(\frac{V_{EB}}{2V_T}\right)}, \quad (1)$$

where q is the quantity of electric charge, ΔI_B is the increase of the base current amplitude, σ is the capture cross section of carriers, v_{th} is the velocity of carrier, S_{peak} is the area of base region when the base current reaches the peak, n_i is the base carrier concentration, V_T is the voltage equivalent, and V_{EB} is the emitter-to-base voltage.[10,12]

The oxide trap density N_{ot} can be estimated by

$$\Delta N_{ot} = \frac{C_{ox}}{q}\Delta V_{mg}, \quad (2)$$

where ΔV_{mg} is the offset of middle band voltage, C_{ox} is the oxide capacitor per unit area, and $C_{ox} = \varepsilon_{ox}/t_{ox}$, with ε_{ox} being the dielectric constant of SiO_2 and t_{ox} being the thickness of base oxide.

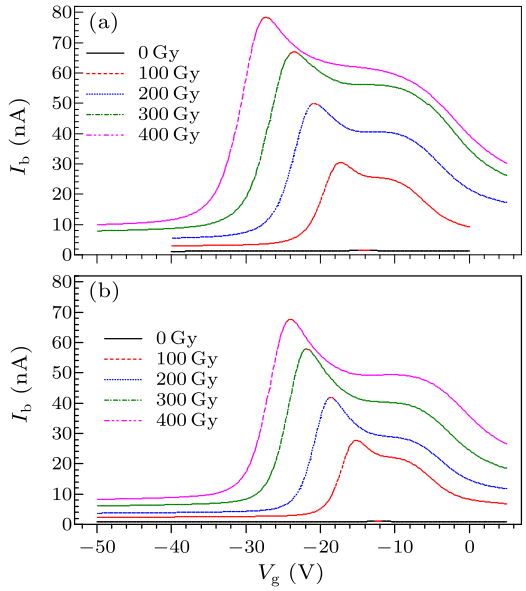

Fig. 1. Curves of base current versus gate voltage of (a) normal GCLPNP transistors and (b) fluorine-implanted LPNP transistor at different total dose levels.

Figure 1 show the curves of base current versus gate voltage at various total dose. The curves of the normal GCLPNP transistor are illustrated in Fig. 1(a), which shows that the base current amplitude increased and the gate voltage that corresponded became more negative with exposure to ionizing radiation. Figure 1(b) illustrates the curves of the fluorine-implanted LPNP transistor, which shows that the base current amplitude and its corresponding gate voltage have the same change trend with Fig. 1(a). However, the changes shown in Fig. 1(a) are greater compared with Fig. 1(b).

The oxide trapped charge density N_{ot} and the interface trapped charge density N_{it} of the two kinds of GCLPNP transistors are calculated from Fig. 1 with Eqs. (1) and (2). The results have been shown in Fig. 2, which indicate that the fluorine-implanting can improve the radiation resistance significantly. Though the oxide trapped charges and the interface trapped charges of the two kinds of GCLPNP transistors increase obviously with increasing exposure to ionizing irradiation as shown in Fig. 2, the increases of both N_{ot} and N_{it} of the fluorine implanting GCLPNP transistors are inhibited significantly.

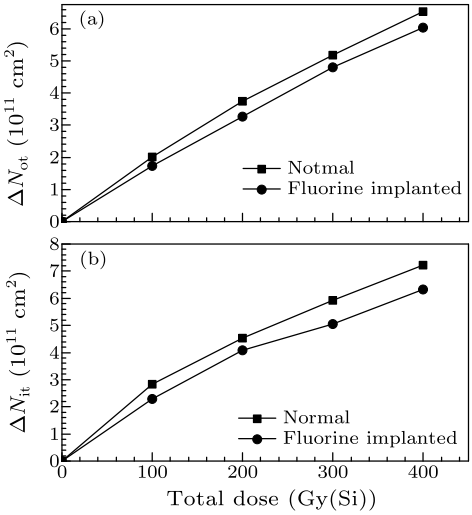

Fig. 2. The changes of N_{ot} and N_{it} of GCLPNP transistors with increasing the exposure to ionizing irradiation. (a) The oxide trapped charge density N_{ot}. (b) The interface trapped charge density N_{it}.

The differences of the expansion coefficient and lattice parameter between Si and SiO_2 result in an interfacial transition zone with strain gradient in thermally grown SiO_2. The level of the strain caused by Si–O bonds is directly related to quantity of the trap charges induced by ionizing radiation. The following action happens at the Si/SiO_2 interface after the fluorine implanting into SiO_2,

$$F+ \equiv Si - O - Si \equiv \rightarrow \equiv Si - F + O - Si.$$

The relaxation of Si/SiO_2 interface stress is due to the replacement of Si–O strain bonds by Si–F bonds and non-bridging oxygen bonds. The replacement of Si–H weak bonds in SiO_2 and the interface of Si/SiO_2 by Si–F bonds which have the higher bond energy are the mechanism of ionizing radiation hardening. The higher stability of Si–F makes the increase of the density of N_{ot} and N_{it} inhibited obviously, especially for N_{it}.[13–15] The main reaction is

$$\equiv Si - H + F \rightarrow \equiv Si - F + H.$$

In summary, the efficiency of the radiation hardening method of fluorine implanting into the SiO_2

layer in LPNP has been investigated by monitoring the numbers of defects induced by ionizing radiation using the special structure of GCLPNP. The results show that the fluorine implanting can inhibit the increase of the oxide trapped charges and interface trapped charge induced by ionizing radiation significantly.

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