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The effect of ionization and displacement damage on minority carrier lifetime☆

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ABSTRACT

Based on 1 MeV electrons and 40 MeV Si ion irradiations, the contribution of ionization and displacement damage to the decrease in the minority carrier lifetime of gate controlled lateral PNP (GLPNP) transistors is investigated by gate sweeping (GS) technique. Molecular hydrogen is employed to increase the ionization radiation sensitivity and help to understand the relationship between the minority carrier lifetime and ionization damage. Experimental results show that 1 MeV electrons mainly induce ionization damage to GLPNP transistors, 40 MeV Si ions primarily produce displacement defects in silicon bulk. For 40 MeV Si ions, with increasing the irradiation dose, the densities of interface trap and oxide charge are almost no change, the minority carrier lifetime obviously decreases. The decrease of the minority carrier lifetime is due to bulk traps induce by 40 MeV Si ions. For 1 MeV electrons, with increasing the irradiation dose, the densities of interface trap and oxide charge for the GLPNP with and without soaked in H_2 increase, and the minority carrier lifetime decreases. Compared with the GLPNP transistors without soaking in H_2, the density of the interface traps the irradiated GLPNP transistors by 1 MeV electrons and soaked in H_2 are larger and the minority carrier lifetime is lower. Therefore, both ionization and displacement damage can induce the decreases in the minority carrier lifetime including bulk minority carrier lifetime and surface minority carrier lifetime.

1. Introduction

Charged particles being abundant in space (like protons, electrons and heavy ions) can be injected in semiconductor devices, and the energy is deposited in the semiconductor via two modes of atomic collisions and electronic ionization, producing displacement and ionization damage, respectively [1]. Ionization radiation primarily affects the insulating layer and Si/SiO_2 interface of bipolar junction transistors (BJTs) [2]. Ionization damage causes net positive charges and interface traps in Si/SiO_2 interface, resulting in an increasing recombination current and the current gain degradation, basing on two interacting effects: (i) increasing surface recombination rate and (ii) spreading the emitter-base depletion region [3–5].

The incident charged particles produce vacancies and interstitials in the Si bulk, and induce displacement damage with different defect levels in the gap. These displacement defects strongly affect the performance of BJTs. Especially, vacancy-related defects, e.g., vacancy-oxygen (VO) pairs, vacancy-phosphorus (VP) pairs and divacancy centers (V_2), are fundamental electrically active defects generated in n-type silicon by ion irradiation [6,7]. Bulk defect complexes induced by displacement damage are effective recombination and trapping centers, leading to a decrease in minority carrier lifetime, and results in the degradation of current gain [7].

The gate-controlled lateral PNP bipolar transistor (GLPNP) is a combination of BJT and MOSFET devices. Based on the gate structure in the BJT, the gate sweeping (GS) technique can be used to separate positive oxide charge, interface traps and minority carrier lifetime [8,9]. Here, the decreases in minority carrier lifetime induced by ionizing damage are neglected and are mainly attributed to the displacement damage. However, our works show that the minority carrier lifetime τ extracted from GS technique is attributed to both the bulk and interfacial recombination centers, corresponding to bulk minority carrier lifetime and interface minority carrier lifetime, respectively. Based on GLPNP structure, researchers have extensively investigated the radiation effects of GLPNP transistors produced by protons, gamma rays and X-rays, respectively [8–14]. In general, protons can cause both ionization damage and displacement damage on GLPNP transistors, while gamma rays and X-rays induce mainly ionization damage. It is worth noting that heavy ions can cause primarily displacement damage in the Si bulk [7,15]. However, few references are available on the

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degradation of GLPNP transistors irradiated by heavy ions so far. As it is well known that electrons mainly induce the ionization damage in the oxide layer and at Si/SiO_2 interface [16,17]. Therefore, employing electrons and heavy ions, the minority carrier lifetime of GLPNP transistors induced by ionization damage and displacement damage can be researched well.

In this investigation, 1 MeV electrons and 40 MeV Si ions are chosen to reveal the contribution ionization damage and displacement damage to the minority carrier lifetime of GLPNP transistors, respectively. The GS technique is used to separate the radiation-induced defects. Moreover, hydrogen plays a significant role in determining the ionization radiation response of bipolar devices and changing the density of oxide charged traps and interface traps [10,18], which is used to change the sensitive of ionization damage. Based on these measurements, the evaluations of ionization and displacement defects in GLPNP transistors are shown clearly, which helps to understand the nature of the defects in lateral PNP bipolar transistors.

2. Experimental details

GLPNP transistors in this work were designed and manufactured in National Laboratory of Analog ICs, China. In order to minimize uncertainties caused by device construction and doping differences, a large number of transistors are obtained from single diffusion lot. Cross section of the GLPNP transistor is shown in Fig. 1. The thickness of gate oxide located in base region is 1.0 μm in GLPNP transistors. The passivation of all the samples is only silicon oxide layer, and no other passivation in order to the hydrogen penetration.

Molecular hydrogen (H_2) soaking process is utilized to show radiation sensitivity of GLPNP transistors. The package lids are removed, so that the chips can be exposed directly to H_2 atmosphere. GLPNP transistors were placed in an evacuated glass tube with the H_2 pressure of 1×10^5 Pa, and were soaked in the H_2 atmosphere for 168 h. The soaked GLPNP transistors were immediately exposed to electrons and Si ions after H_2 process.

GLPNP transistors with and without H_2 soaking were irradiated by 1 MeV electrons and 40 MeV Si ions. 1 MeV electron irradiation was performed at Technical Physics Institute of Heilongjiang Academy of Science, while 40 MeV Si ions were performed at State Key Laboratory of Nuclear Physics and Technology in China. Irradiation experiments were carried out in the evacuated chamber with a specially designed Faraday cup which is used to measure the beam current. Based on the beam current measurements, the flux and fluence were determined during the irradiation experiments.

GLPNP transistors were grounded during electron and Si ion exposures. Following each irradiation step, gate sweep (GS) and Gummel curves were in-situ measured immediately using KEITHLEY 4200-SCS semiconductor parameter measurement system. Measurement time for each step was less than 2 min. For the GS measurement, the base current was measured with the sweeping gate voltage (30 V to −150 V), and the step is 1 V. During the gate voltage sweep, collector, base, and substrate regions were grounded, and the emitter voltage is fixed at 0.5 V. Gummel characteristics were measured for the GLPNP transistors in a common-emitter configuration. Emitter voltage was swept from 0 to −1.2 V, and collector, base and gate was grounded.

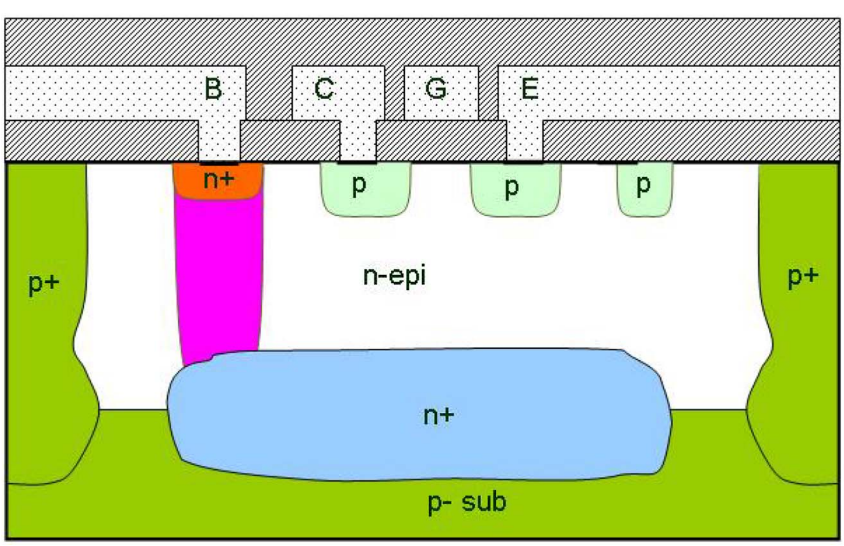

Fig. 1. Representative cross-sections of the GLPNP transistor.

3. Results and discussion

3.1. Calculation results of radiation absorbed dose

Ionization and displacement dose induced by 1 MeV electrons and 40 MeV Si ions were calculated by the Geant4 code [19]. The ionization absorbed dose D_i and displacement absorbed dose D_d produced by monoenergetic irradiation are calculated using the following equations:

$$D_i(t) = 1.6 \times 10^{-8} \times LET(t) \times \Phi \quad (1)$$

$$D_d(t) = 1.6 \times 10^{-8} \times NIEL(t) \times \Phi \quad (2)$$

where, $D_i(t)$ and $D_d(t)$ are the ionization absorbed dose and displacement absorbed dose as a function of depth in chip, the unit is rad; t is the chip depth, the unit is μm; 1.6×10^{-8} is the unit conversion parameter, the unit is rad·g/MeV; Φ is incident particles fluence, the unit is e/cm^2 for electrons and ion/cm^2 for heavy ions; $LET(t)$ and $NIEL(t)$ are separately the ionization and displacement energy loss caused by 1 MeV electrons and 40 MeV Si ions as a function of depth in chip, and calculated by Geant4 and SRIM, the unit is MeV·cm^2/g.

Ionization and displacement absorbed dose per unit fluence of electron and Si ion are plotted, as a function of the chip depth of GLPNP transistor in Fig. 2. It is obvious that both of 1 MeV electrons and 40 MeV Si ions can travel through the oxide layer and the Si bulk. As mentioned in reference [20], the ratio of $D_d/(D_d + D_i)$ can be used to show the displacement ability for incident particles. If the ratio is larger, the displacement damage induced by this particle is severer. From Fig. 2, it can be obtained that ionization and displacement absorbed dose per unit fluence of 1 MeV electron and 40 MeV Si ion in the base oxide and the base region of the GLPNP transistors is listed in Table 1. It can be calculated from Table 1 that the average ratio of $D_d/(D_d + D_i)$ for the 1 MeV electrons and 40 MeV Si ions is 2.09×10^{-5} and 1.22×10^{-3}, respectively. It is indicated that 40 MeV Si ions cause