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Radiation effects on bipolar junction transistors and integrated circuits produced by different energy Br ions

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A B S T R A C T

The radiation responses of the NPN bipolar junction transistors (BJTs) and the TTL bipolar integrated circuits (ICs) have been examined using 20, 40 and 60 MeV Br ions. Key electric parameter was measured and compared after each energy irradiation. Experimental results demonstrate that the degradation in electric parameters caused by the Br ions shows a common feature for the NPN BJTs and TTL ICs, in which the degradation is strengthened with decreasing the Br ions energy. The ionizing dose (D_i) and displacement dose (D_d) as a function of the chip depth in the bipolar devices were calculated using the SRIM code, in order to analyze the radiation effects on the NPN BJTs and the Bipolar ICs. From the experiment and calculation results, it could be deduced that the Br ions mainly cause displacement damage to both the NPN BJTs and the TTL ICs, and the higher the ratio of $D_d/(D_d+D_i)$, the larger the degradation in electric parameters at a given total dose.

1. Introduction

The bipolar devices including NPN bipolar junction transistors (BJTs) and their integrated circuits (ICs) are being widely used in spacecraft, due to their current drive capability, linearity and excellent matching characteristics [1–4]. Under the exposition to energetic charged particles, the bipolar devices might be damaged, failing to give their functions. The radiation effects on the bipolar devices have been extensively investigated by using protons, neutrons, electrons and ^{60}Co gamma rays [5–11]. To date, a few references were available on the radiation effects of heavy ions on the bipolar devices. The radiation effects of heavy ions are important to understand the radiation damage mechanism of the devices. Refs. [3, 4] report on the radiation effects on NPN transistors induced by 60 MeV oxygen ions and 50 MeV lithium ions. Unfortunately, no investigations were concerned with radiation effects on bipolar ICs and consequences on their electrical parameter degradation with total (or displacement) dose. Such information is useful for the application of bipolar devices in engineering.

The insulators on the surface of the bipolar devices are susceptive to ionizing radiation effects, and the Si bulk is sensitive to displacement damage. Therefore, the bipolar devices could be degraded by both the ionization and displacement damage due to three basic processes: (1) inversion at the surface, which occurs because of charge trapping in the insulators, (2) changes in the surface recombination rate of minority carriers, and (3) bulk damage [8,9]. The incident particles with various energies may contribute to the ionization and displacement damage differently. It will be very useful to investigate the ionization and displacement damage in the bipolar devices produced by heavy ions with a different energy.

The objective of this study is to examine the radiation effects on the electrical behavior of the NPN BJTs and TTL ICs induced by different energy Br ions, in order to reveal the relationship of radiation damages between the NPN transistors and the bipolar ICs. The experimental data of NPN BJTs could be used to compare with the experimental results of the TTL ICs. Also, an attempt is made to explain the radiation-induced degradation of the electric characteristics, based on the dose distribution for both the ionizing and displacement radiation in the bipolar devices.

2. Experimental

The bipolar devices used in this investigation are the NPN BJTs 3DG112D and the TTL ICs 54LS86. The thickness is about 600 nm, 1, 1.3 and 12 μm for the insulating silicon dioxide (SiO_2), the emitter (n^+), the base (p^+) and the epitaxial layer (n^-) of the NPN BJTs, respectively. The thickness is approximately 1.5 and 1.5 μm for the insulators on the chip surface and the p-Si base region of TTL 54LS86 ICs, respectively. Uncertainties in measured parameters were less than 10%.

The irradiation tests were performed using the EN Tandem Accelerator in the State Key Laboratory of Nuclear Physics and

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Technology, Peking University, China. The irradiations were carried out in an evacuated chamber with a specially designed Faraday cup, which was used to measure the Br ions beam current. From these measurements, the flux and fluences were determined for the irradiation experiments. The total dose distribution in the bipolar devices is calculated with the use of SRIM Code.

The NPN BJTs and TTL ICs were unbiased during the irradiation, and processed under MIL-STD-883G specifications. Different electrical parameters of the bipolar devices were measured in-situ using a semiconductor parameter measurement system that consists of KEITHLEY 4200-SCS and AGILENT E4980A. The turn-around time between irradiation and device measurements was approximately within 5 s or less. The irradiation and measurements were performed at room temperature, and all the samples were decapped.

3. Results and discussion

3.1. Calculation of radiation absorbed dose

The incident charged particles with high energies deposit their energy in materials of the devices, producing the total dose composed of ionizing and displacement components. Commonly, the ionizing dose component is much higher than the latter. The ionizing absorbed dose D_i and displacement absorbed dose D_d induced by monoenergetic particles are calculated as follows:

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

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

where $D_i(t)$ and $D_d(t)$ are the ionizing and displacement dose as a function of depth in materials, in the unit of rad; t is the depth of the devices, μm; 1.6×10^{-8} is a unit conversion parameter, radg/MeV; Φ is the fluence of incident particles, ion/cm^2; $LET(t)$ and $NIEL(t)$ are the ionizing and displacement energy losses as a function of the chip depth in devices. The $LET(t)$ and $NIEL(t)$ given by the incident Br ions are calculated by the SRIM Code.

The ionizing dose and displacement dose per unit fluence of the different energy Br ions are plotted as a function of the chip depth in the NPN BJTs and TTL 54LS86, as shown in Figs. 1 and 2, respectively. It is obvious that under a given energy of Br ions,

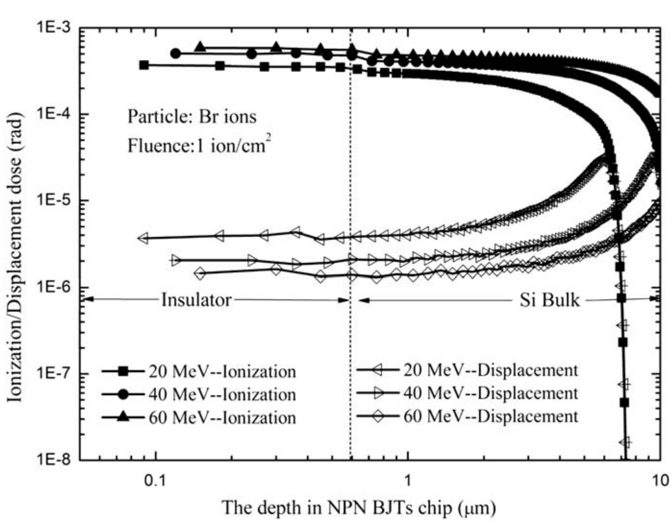

Fig. 1. The ionization and dispalcement dose per unit fluence as a function of the NPN BJTs chip depth induced by Br ions with various energies.

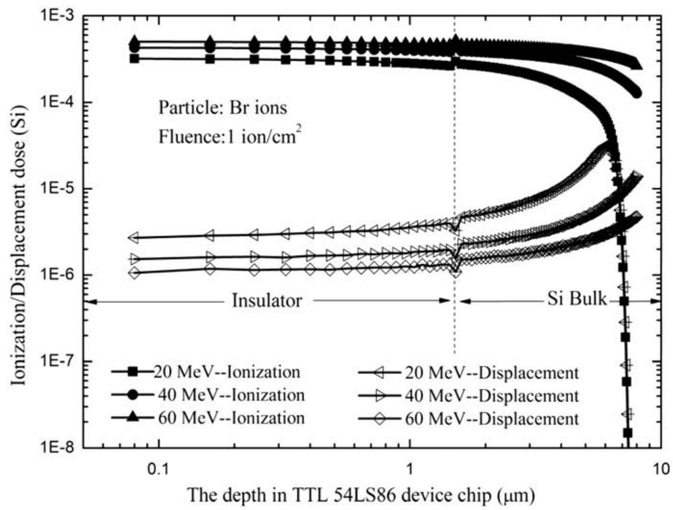

Fig. 2. The ionization and dispalcement dose per unit fluence as a function of the TTL devices chip depth induced by Br ions with various energies.

both changes in the ionization and displacement dose are similar as a function of the chip depth in the NPN BJTs and TTL ICs. The ionizing dose increases an increasing the energy of Br ions, while the lower energy Br ions induce larger displacement dose than the higher energy ones at a given chip depth. Based on Fig. 1, when the depth t equals 1.3 μm (beyond the base region in the NPN BJTs Si bulk), the ratio of the $D_d/(D_d+D_i)$ can be calculated as approximately 1.48E−2, 5.18E−3 and 3.01E−3 for the 20, 40 and 60 MeV Br ions, respectively. Based on Fig. 2, when the depth t equals 3.0 μm (beyond the base region in the TTL devices Si bulk), the ratio of the $D_d/(D_d+D_i)$ can be calculated as approximately 3.37E−2, 8.35E−3 and 4.28E-3 for the 20, 40 and 60 MeV Br ions, respectively. The above results show that the displacement damage given by one Br ion (or per unit fluence) should be higher on the TTL devices with respect to the NPN BJTs.

3.2. Degradation in electric parameters

3.2.1. Degradation of the NPN BJTs

The I_C–V_{CE} characteristic curves, which are plots of collector current (I_C) vs. collector–emitter voltage (V_{CE}), were measured at a constant emitter–base current (I_B). The current gain (h_{FE} or β) of the NPN BJTs is obtained for all of the samples using the same test setup before and after irradiation at a fixed collector current (I_C=1 mA). From these results, the change in current gain ($\Delta\beta$), the reciprocal of the gain ($\Delta(1/\beta)$) and the collector–emitter saturation voltage (ΔV_{CEsat}) can be given. The $\Delta\beta$, $\Delta(1/\beta)$ and ΔV_{CEsat} are defined as the transistor current gain, the reciprocal of the gain and the collector–emitter saturation voltage after irradiation subtracting their pristine values, respectively.

Fig. 3 shows the changes in current gain of the NPN BJTs as a function of total dose induced by different energy Br ions. It is shown that the current gain of the NPN BJTs is sharply degraded after the total dose larger than 200 Gy. The current gain decreases more rapidly with decreasing the energy of Br ions. The reciprocal of gain variation vs. Br ion fluence with various energies for the NPN BJTs is given in Fig. 4 in order to show the relationship between $1/\beta$ and ion fluence. It is obvious that the change in reciprocal of the current gain varies linearly with increasing the Br ion fluence. Fig. 5 shows the change in the collector–emitter saturation voltage as a function of total dose. The collector–