Microelectronics Reliability 82 (2018) 130–135

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

# Synergistic effects of NPN transistors caused by combined proton irradiations with different energies☆

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ARTICLE INFO

*Keywords:*
Bipolar junction transistors
DLTS
Protons
Radiation effect
Ionization damage
Displacement damage

ABSTRACT

There are a large number of protons with different energies from the dozens of keV to hundreds of MeV in space environment, which simultaneously act on the bipolar junction transistors (BJTs), and induce different irradiation effect and damage defects. Moreover, interaction between displacement defects and ionization defects occurs. In the paper, the interaction mechanisms between oxide charge and displacement defects in 3DG112 NPN BJTs caused by the combined 70 keV and 170 keV protons with 5 MeV proton irradiation are studied. Experimental results show the degradation of current gain increases linearly with increasing the irradiation fluence of the 170 keV and 5 MeV protons, but increases nonlinearly for the 70 keV protons, implying that the 170 keV and 5 MeV protons mainly induce displacement damage on the NPN BJTs, while the 70 keV protons cause ionization damage. It can be seen from the Geant4 calculation that 70 keV and 170 keV protons cause almost the same ionization damage on the 3DG112 transistors, while have significant difference in displacement damage ability, which is favorable to analyze the effect of displacement damage in oxide layer of NPN BJTs induced by 170 keV and 70 keV protons on ionization damage caused by the subsequent 5 MeV protons. DLTS analyses show that 5 MeV protons produce mainly displacement defect centers in based-collector junction of 3DG112 transistors, and 170 keV and 70 keV protons only induce almost the same number of the oxide trapped charges. While the combined irradiation can produce the more oxide trapped charges, except displacement defects, showing that displacement damage in oxide layer caused by 170 keV and 70 keV protons can increase the oxide trapped charges during the subsequent 5 MeV exposures. Moreover, the more displacement defects in oxide layer will induce more oxide trapped charges, and give more enhanced synergistic effects. These results will help to assess the reliability of BJTs in the space radiation environment.

## 1. Introduction

Bipolar junction transistors (BJTs) have important applications in analog or mixed-signal integrated circuits (ICs) and BiCMOS (Bipolar Complementary Metal Oxide Semiconductor) circuits due to their current drive capability, linearity and excellent matching characteristics, some of which are still employed for space application and suffer from the ionizing and displacement damage [1–4], require accurate evaluation of irradiation response. There are a large number of protons in space environment from trapped radiation belts and solar flares. Moreover, the range of proton energy is from the dozens of keV to hundreds of MeV, which will affect the BJTs simultaneously. These protons with different energies cause the degradation of BJTs and finally impact the reliability of the whole electronic system [5]. Moreover, damage defects that limit the radiation response of BJTs can also significantly affect their reliability outside of a radiation environment.

Previous work [6–9] have extensively investigated the irradiation effects on current gain degradation of BJTs caused by protons, neutrons, electrons and Co-60 gamma rays, respectively. As mentioned in reference [10], 70 keV protons mainly cause the ionization damage on BJTs, while 170 keV protons primarily produce displacement damage on BJTs. Unlike low-energy protons, high-energy protons can produce both displacement defects in silicon bulk and ionization damage in the oxide layer of BJTs [11–13]. Displacement defects are effective recombination and trapping centers, leading to a decrease in the minority carrier lifetime [13]. The ionizing damage will increase the densities of semiconductor-oxide interface traps and net positive oxide charge in BJTs, leading to an increase in surface recombination current of the base [11]. Both ionization and displacement defects will result in the degradation of current gain of BJTs [11–15].

☆ The project supported by the National Natural Science Foundation of China (No. 11575049 and No. 61404038).
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https://doi.org/10.1016/j.microrel.2018.01.010
Received 12 September 2017; Received in revised form 15 January 2018; Accepted 20 January 2018

Importantly, the gain degradation mechanisms for BJTs induced by the combined proton irradiation with different energies are complicated. However, few references are available on the combined radiation effects of protons with different energies for the NPN BJTs. In general, the study of the combined-radiation induced effects on semiconductor devices is important. On the one hand, it is helpful to understand the damage behavior caused by the combined radiation; on the other hand, it is useful to assess the reliability of the devices in the space radiation environment, where protons with different energies can induce the irradiation damage on the devices simultaneously.

This investigation focuses on revealing the synergistic effects of the irradiated 3DG112 NPN BJTs by the combined 170 keV and 70 keV protons with 5 MeV protons. The deep level transient spectroscopy (DLTS) is very useful to detect irradiation defects [16,17]. In this work, DLTS is employed to attempt to provide direct results for the synergistic-effect mechanisms.

## 2. Experiment

The 3DG112 BJTs used as samples in this study, are a type of high radio frequency and low power silicon NPN transistors. The BJT is a typical vertical structure, which is insulator ($SiO_2$), emitter, base and epitaxial layer from top to bottom, respectively, as shown in Fig. 1. The insulator ($SiO_2$), emitter ($n^+$), base (p) and epitaxial layer (n) are approximately 600 nm, 1 μm, 1.3 μm and 12 μm, respectively. The device has an emitter comb structure. The emitter area is approximately $50 \times 80\ \mu m^2$, and the resulting current density is $1.5 \times 10^5\ A/cm^2$. In order to minimize uncertainties caused by device construction and doping differences, a large number of NPN 3DG112 transistors are obtained from single diffusion lots from the same manufacturer.

70 keV, 170 keV and 5 MeV protons are chosen as the incident particle since 70 keV, 170 keV and 5 MeV protons mainly cause ionization damage, displacement damage and both, respectively. The 70 keV, 170 keV proton irradiation test facility used in this investigation is an accelerator at Harbin Institute of Technology, while the 5 MeV proton exposures were performed using the EN Tandem Accelerator in the State Key Laboratory of Nuclear Physics and Technology, Peking University. The flux of 70 keV, 170 keV and 5 MeV protons is $2.0 \times 10^8\ p/(cm^2 \cdot s)$. The irradiations were carried out in an evacuated chamber with a specially designed Faraday cup, which is used to measure the heavy ions beam current. From these measurements, the flux and the fluence were determined for the irradiation experiments. Irradiation experiments are divided in two groups, namely individual irradiation and combined irradiation. The two different combined irradiations are firstly 70 keV protons and then 5 MeV protons (case 1), and firstly 170 keV protons and then 5 MeV protons (case 2).

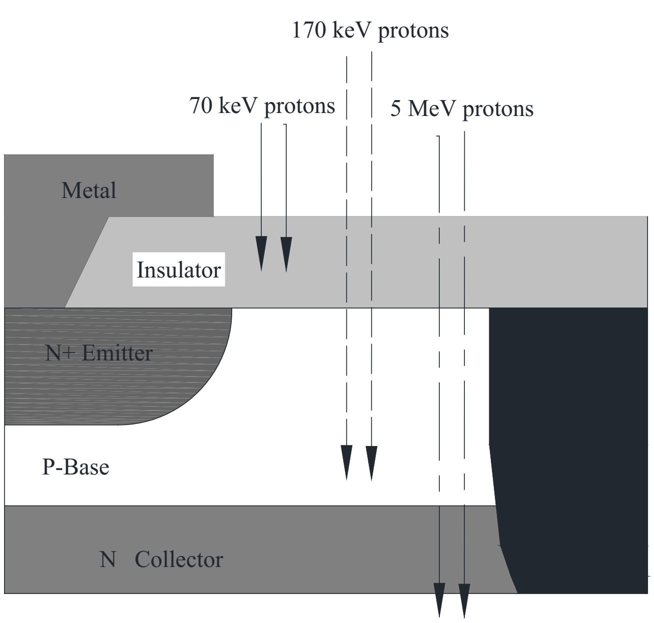


**Fig. 1.** A schematic showing the range of 70 keV, 170 keV and 5 MeV protons in NPN BJTs.

The NPN BJTs were grounded during proton exposures. Gummel curves were measured in-situ using a KEITHLEY 4200-SCS semiconductor parameter measurement system. Each measurement was performed within 1 min. The delay time between irradiation and measurements was approximately within 5 s or less. Irradiation and measurements were carried out at room temperature, and all the samples were decapped.

DLTS results from the base-collector junctions of NPN BJT transistors, with the emitter shorted to the base, were used to characterize the irradiation defects. The capacitance transients (ΔC) were measured with a 1 MHz DLTS spectrometer operated with a temperature scan from 30 K to 310 K. The reverse bias voltage and the filling pulse amplitude were −10 V and +10 V, respectively. The depletion of the NPN collector during DLTS measurements was about 0.49 μm and 2.90 μm for 0 V and −10 V, respectively.

## 3. Results and discussion

### 3.1. Calculation results

According to the Geant4 code (Geant4.9.6), the range, the ionizing absorbed dose $D_i$ and displacement absorbed dose $D_d$ in the NPN BJTs caused by 70 keV, 170 keV and 5 MeV protons could be obtained. The ionizing absorbed dose $D_i$ and displacement absorbed dose $D_d$ produced by monoenergetic irradiation are calculated using the following equations:

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

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

where, $D_i(t)$ and $D_d(t)$ are separately the ionizing dose and the displacement dose per unit fluence as a function of depth in chip of the NPN BJTs, rad; $t$ is the chip depth, μm; $1.6 \times 10^{-8}$ is the unit conversion parameter, rad·g/MeV; Φ is the fluence of incident particles, $p/cm^2$; $LET(t)$ and $NIEL(t)$ are separately the ionizing and displacement energy loss as a function of depth in chip of the device and could be calculated by Geant4 code [18,19], $MeV \cdot cm^2/g$.

From Figs. 1 and 2, it can be seen that 70 keV protons with the maximum range of 0.67 μm only arrive at insulator layer, deducing that 70 keV protons can give little displacement damage on the base and mainly cause ionization effects in the oxide layer. The distribution of displacement doses per unit fluence for 170 keV protons is 1.22 μm and exhibits a maximum in the base region. This implies that the 170 keV protons could result in severe displacement damage in the base region. Moreover, it is observed from Fig. 2(a) that the ionizing dose for 170 keV and 70 keV protons almost the same in the insulator region, implying that both 70 keV and 170 keV protons will cause similar ionization damage on the device. However, there are obvious difference in displacement dose per unit fluence for the two protons, showing different displacement damage ability. 5 MeV protons can travel through the oxide layer and the Si bulk, and cause ionization and displacement damage in these two regions, respectively.

### 3.2. Electrical characteristics

Gummel characteristics were measured for the NPN transistors before and after irradiation in a common-emitter configuration, applying a sweep in $V_E$ from 0 to −1.2 V and keeping $V_B = V_C = V_{CB} = 0$ V. The change in current gain (Δβ) is defined as the transistor current gain after