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Bias dependence of synergistic radiation effects induced by electrons and protons on silicon bipolar junction transistors

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HIGHLIGHTS

- Bias cases can affect the total number of ionization traps.
- For displacement damage, bias cases can produce the injection annealing effect.
- Electrons show enhancement or mitigation effects during sequential exposures.
- Transition fluence is dependent on the bias case.

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ABSTRACT

Bias dependence on synergistic radiation effects caused by 110 keV electrons and 170 keV protons on the current gain of 3DG130 NPN bipolar junction transistors (BJTs) is studied in this paper. Experimental results indicate that the influence induced by 170 keV protons is always enhancement effect during the sequential irradiation. However, the influence induced by 110 keV electrons on the BJT under various bias cases is different during the sequential irradiation. The transition fluence of 110 keV electrons is dependent on the bias case on the emitter–base junction of BJT.

1. Introduction

Bipolar junction transistors (BJTs) have important applications in electrical circuits and system in the spacecraft, and are susceptible to the space radiation environment. It is important to research the radiation response of the BJTs to find better radiation hardening and design methods before employing them for specific applications in space (Pease, 2003; Madhu et al., 2008; Kulkarni et al., 2006; Gnana Prakash et al., 2004; Johnston and Rax, 2006; Liu et al., 2012). Charged particles are abundant in space, and can be more likely to be injected in the semiconductor devices. Space charged particles, such as protons and electrons, produce the synergistic radiation damage, including both ionization and displacement damage in semiconductor devices. Bulk traps induced by displacement damage increase by decreasing the bulk carrier lifetime (Messenger and Ash, 1992). Ionization damage also affects by increasing the densities of semiconductor oxide interface traps and net positive oxide charge (Pease, 2003). However, the mechanism of synergistic irradiation induced by protons and electrons in BJTs is still not clear nowadays. Therefore, the study on the synergistic radiation effects is helpful to understand the damage mechanism on the BJT, and valuable to employ the transistors in the space radiation environment.

The synergistic effects of the ionization damage and the displacement damage, are complex and generally nonlinear. Measurement under various biasing conditions on the device is an important method to study the mechanism of the synergistic radiation damage. On another hand, for the space application, electronic devices are usually biased in the specific circuit during the irradiation. Measurements under bias conditions can simulate the radiation damage on tested devices in space to some extent. The bias dependence in sequential radiation damage on bipolar junction transistor will be served as the focus of this study.

In order to distinguish the impact on the BJT induced by proton and electron, the individual radiation effects induced by 110 keV electrons and 170 keV protons, and the sequential radiation effects in the 3DG130 NPN BJTs are carried out under various bias

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conditions in this study. Sequential exposures will produce both the ionization damage in the oxide layer induced by 110 keV electrons (Li et al., 2010a) and the displacement damage in Si bulk induced by 170 keV protons (Li et al., 2010b), resulting in a synergistic radiation effect in BJTs. This results will provide support for the mechanism of the synergistic radiation effects on the bipolar transistors.

2. Experimental details

The 3DG130 NPN BJT is a kind of typical high fluency low noise bipolar transistors of the Chinese models, and is sensitive to both ionization and displacement damage. Therefore, in this study, 3DG130 NPN BJT is chosen as the sample to investigate the combined radiation damage in bipolar junction transistor. The thickness of the insulating silicon dioxide (SiO_2), the emitter (n+), the base (p+) and the epitaxial layer (n−) of 3DG130 BJT is about 600 nm, 1.2 μm, 2.1 μm and 10 μm, respectively. The doping concentration is obtained from the manufacturer and confirmed by current–voltage (*C*–*V*) measurements. Doping levels of the emitter (n+), the base (p+) and the epitaxial layer (n−) are about 1×10^{20} cm^{-3}, 1×10^{18} cm^{-3}, 1×10^{15} cm^{-3}, respectively.

The irradiation facility is an accelerator at Harbin Institute of Technology, China, which can perform the individual, simultaneous and sequential irradiation for protons and electrons in a vacuum chamber. To ensure the test accuracy, there is a Faraday cup nearby the sample during irradiation, which is used to measure the particle beam current. During the irradiation process, a temperature monitor is placed near the irradiated sample to display the temperature on device. Based on the temperature data, the device temperature keeps +20 ± 2 °C during the irradiation.

The samples were mounted inside a package with removable upper lid for irradiation. Electrical characteristics and applied bias were performed by Keithley 4200-SCS semiconductor characterization system. In-situ electrical measurement of tested BJT under the dark condition was finished within one minute after each given irradiation fluence to reduce the self-annealing effect during a long time. The delay time between the irradiation and measurements was approximately within 5 s or less.

All samples have been irradiated in the same conditions apart from the bias configurations. There are three repeat irradiated samples to ensure the reproducibility and consistency of the data for each bias case. Based on the work conditions of 3DG130 BJT, the bias conditions on the tested bipolar transistors were sets as following:

(1) zero bias case ($V_{BE}=V_{BC}=0$ V),
(2) forward bias case ($V_{BE}=0.7$ V, $V_{BC}=0$ V),
(3) reverse bias case ($V_{BE}=-4$ V, $V_{BC}=0$ V).

3. Results and discussion

3.1. SRIM calculation results

The ionization and displacement doses per unit fluence of protons and electrons as a function of the chip depth of NPN BJTs are plotted in Figs. 1 and 2, respectively. The ionization/displacement doses per unit fluence represent ability of a charged particle inducing a certain kind of radiation effects. In general, the higher the doses per unit fluence for a radiation effect, the larger the ability for a charged particle to induce the effect, as illustrated in the MOS devices mentioned in reference (Schwank et al., 2008; Paillet et al., 2002).

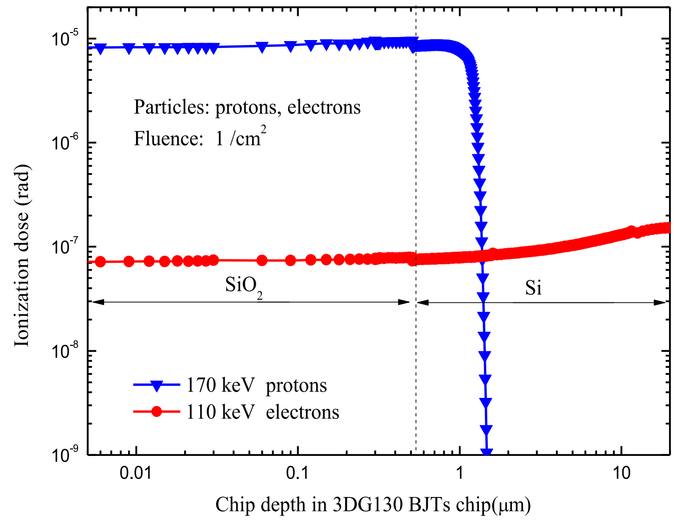

Fig. 1. The ionization dose per unit fluence of protons and electrons as a function of chip depth in 3DG130 BJTs.

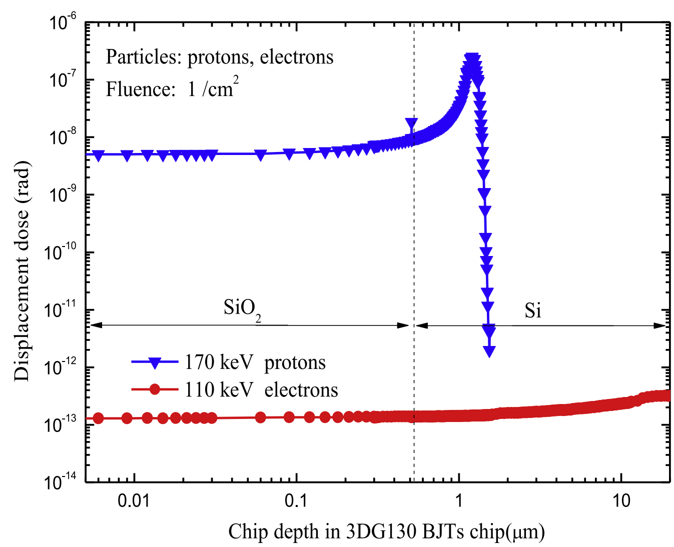

Fig. 2. The displacement dose per unit fluence of protons and electrons as a function of chip depth in 3DG130 BJTs.

As shown in Figs. 1 and 2, 110 keV electron travels through the oxide layer and the Si bulk to cause ionization damage in these two regions. Moreover, the energy threshold of electrons for displacement damage is believed to be about 200 keV in p-type silicon and 150 keV in n-type (Brucker et al., 1966). Therefore, 110 keV electrons mainly cause ionization damage to the BJTs and displacement damage induced by 110 keV electrons can be negligible.

For 170 keV protons, the maximum range is 1.75 μm, arriving at the base region. The distribution of displacement doses per unit fluence for 170 keV protons exhibits a maximum in the base region. Moreover, based on Li et al. (2010b), 170 keV protons can result in severe displacement damage, and cause lower ionization damage to the device. Hence, 110 keV electrons cause ionization damage to the BJTs, while 170 keV protons will mainly induce displacement damage.

3.2. Degradation in current gain caused by individual Irradiations

Current gain (h_{FE} or β) is one of the most important electrical parameters for bipolar junction transistors. Current gain degradation also is one of the most concerned radiation effects on