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Radiation damage and defects in NPN bipolar junction transistors irradiated by silicon ions with various energies

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ABSTRACT

The characteristic of incident particle is an important factor to evaluate the correlation of radiation damage. It is useful to investigate the influence of incident particle with various energies on radiation effects of BJTs. Radiation effects in bipolar junction transistors are examined under the irradiation with 10, 24 and 40 MeV Si ions in this paper. Based on the electrical performance degradation, it is shown that the change in the reciprocal of current gain is dominated by the ionizing damage during the heavy ion irradiations at low fluence, leading to a non-linear behavior. While at a higher fluence, displacement damage is the domain effect to show a linear curve. Deep level transient spectroscopy (DLTS) is used to analyze the characteristic of the deep level defects induced by irradiations. DLTS results show that for the BJTs under various Si ions irradiations, the types of deep level defects induced by Si ions are similar, while the concentration of the defects is different at the same displacement dose.

1. Introduction

Displacement damage refers to the dislodging of atoms from their normal lattice sites in a target material by impinging energetic radiation. Displacement defects produce permanent damage in material and device. The resulting damage causes degradation of the electronic and optical properties of materials and devices [1–5]. The degradation is generally due to the introduction of new energy levels in the semiconductor bandgap, which changes properties such as minority carrier lifetime [6–8]. Bipolar junction transistors (BJTs) are notably susceptible to displacement damage effects [9–10]. Displacement damage induced by incident particles irradiation in silicon BJTs would produce vacancy or interstitial related defect complexes that are effective recombination and trapping centers, leading to a decrease in minority carrier lifetime.

The common radiation source to research the displacement damage is heavy ion. The heavy ions can produce a large amount of vacancies and interstitial atoms, and the ionization damage can be neglected due to the very high charge density in small injected region. However, for heavy ion irradiations, the injected particles produce damage cascades and defect clusters at the end of range in silicon. In the end of the incident particle range, the defect density can be 4–7 orders of magnitude higher than spatially averaged defect concentration [11]. If there is an overlap between the end of the incident particle and the radiation sensitive region, the radiation damage of the BJT in this case should be much higher than the BJT irradiated by the particle with a very large range (through the device). Therefore, the range of the incident particle can strongly affect the degradation of the device performance. On the other hand, if the incident particle range is lower than depth between the surface and base region of BJT's chip, the displacement dose of the incident particle will vary a lot, especially, in the end of the range. In this case, the radiation damage of BJTs could not be the same as those with constant displacement dose at a given dose or fluence. Therefore, incident particle range in BJTs is an important factor to evaluate the correlation of radiation damage induced by various particles. It is useful to investigate the influence of incident particle range on radiation effects of BJTs.

The changes of the transistor performance are caused by microscopic defects induced by displacement irradiation. These displacement defects can be well characterized by microscopic methods like the Deep Level Transient Spectroscopy (DLTS) [12–13]. Therefore, based on the DLTS technology, this investigation is focused on the effects and defects of displacement damage in NPN BJTs irradiated by various energies Si ions. The aim of this study is to characterize the influence of the range of the incident particle on degradation of the device performance, and to show the critical defects for degrading current gain.

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2. Experimental details

The 3DK2222A NPN BJTs are a kind of typical high frequency and low noise bipolar transistors in Chinese models, which are fabricated from the same single diffusion lot and manufacturer to minimize uncertainties caused by doping differences, and are used as the tested samples in this study. For the 3DK2222A transistors, doping levels of the emitter (n+), the base (p+) and the epitaxial layer (n−) are $1.0 \times 10^{20}\,cm^{-3}$, $1.0 \times 10^{18}\,cm^{-3}$ and $7.0 \times 10^{14}\,cm^{-3}$, respectively. The thickness is about 1.2 μm, 1.5 μm and 12 μm for the emitter (p+), base (n+) and the epitaxial layer (p−) of the 3DK2222A BJTs, respectively. The minimum characteristic frequency of the 3DK2222A BJT is 150 MHz. Fig. 1 shows the representative cross-sections of the 3DK2222A BJT.

The irradiation facility utilized in investigation is the EN tandem accelerator in the State Key Laboratory of Nuclear Physics and Technology, Peking University, China. A scanning beam of 10 MeV, 24 MeV and 40 MeV Si ions is performed at room temperature in a vacuum chamber in order to realize the different incident range. The flux is chosen as 1.0×10^{6} ions/cm^2·s for all of three energies Si ions irradiations. There are three repeat irradiated samples to ensure the reproducibility and consistency of the data. The BJTs under irradiations and DLTS test were de-sealed, and all the terminals are grounded during irradiation.

All the electrical characteristics were measured using Keithley 4200-SCS semiconductor characterization system. In-situ electrical measurement of the tested BJTs under the dark condition was finished within one minute after each given radiation fluence to reduce the self-annealing effect. The delay time between the irradiation and measurements was approximately within 5 seconds or less.

Radiation defects in the BJTs were measured utilizing a PhysTech HERA-DLTS (High Energy Resolution Analysis Deep Level Transient Spectroscopy) system after irradiations. Due to that DLTS accuracy varies inversely to the doping concentration, the lower doped collectors are chosen to characterize the displacement induced defects in order to increase the test accuracy of DLTS. The DLTS scans were measured in a liquid helium cryostat, and the scan temperature is from 30 K to 320 K. The DLTS scans were performed with a reverse bias voltage (V_R) of −10 V and a pulse voltage (V_P) of −0.1 V (i.e., a fill pulse of 9.9 V) for NPN BJTs. Test period (T_W) is 204.8 ms, and a fill pulse width (t_P) of 100 ms was chosen to ensure complete trap filling. Based on this setting, the DLTS probed region is from 0.5um to 3um below BC junction.

For every detected level, the energy, cross section and trap concentration can be evaluated using the results of the separation analysis, the emission time constants and the amplitudes in Arrhenius plots. The energy level is related to the temperature of the peak position, and the trap concentration (N_T) can be related to the peak height in the DLTS spectra. The concentrations of defects have been estimated from the DLTS measurements using the following relation:

$$N_T = 2N_D \frac{\Delta C_0}{C_R} \tag{1}$$

where N_T is the trap concentration, N_D is the doping concentration, ΔC_0 is the saturation value of the DLTS peak and C_R is the reverse capacity of the junction. In the Arrhenius plots, the slope yields the activation energy, and the intercept can be utilized to calculate the capture cross section (σ), for a trap induced by the radiation damage in the BJTs.

3. Results and discussions

3.1. SRIM calculation results

The SRIM, Stopping and Range of Ions in Matter, is a useful software to calculate the stopping power and range of ions in matter [14]. Figs. 2 and 3 show the displacement and ionization absorbed dose of various energies Si ions versus depth in 3DK2222A BJT, respectively. The data above is obtained by the detailed calculation with full damage cascades module in SRIM software. Based on the calculated results, it is clear that the end of range for 40 MeV Si ions far exceeds the base and the DLTS-probed region, and displacement and ionization absorbed dose change slightly with the depth of the device chip. 24 MeV Si ions can also exceed the base and the DLTS-probed region, but the displacement and ionization absorbed dose change obviously with the depth of the device chip. 10 MeV Si ions can only exceed the base region, and the end of range is in the DLTS-probed region. In the DLTS-probed region, the ions with lower range (10 MeV Si ions) can produce more vacancies, interstitials and cascades than the ions with higher range (40 MeV Si ions). The more the number of generated vacancies, the more the number of stable displacement defects is. From the results irradiated by 10 MeV Si ions, it can show the influence

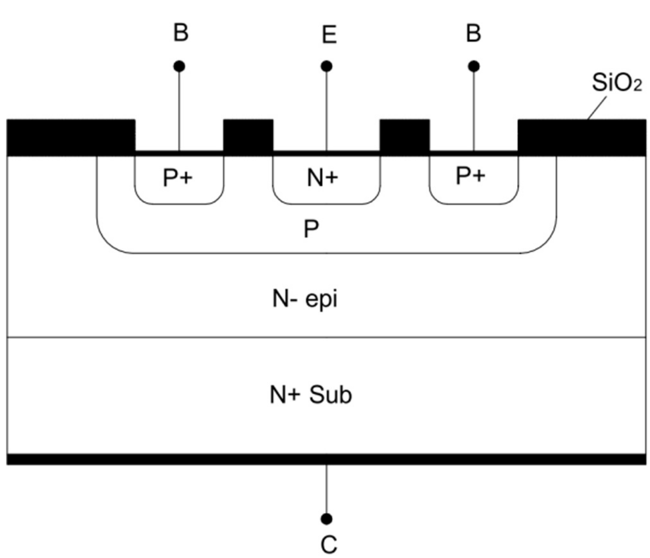

Fig. 1. Representative cross-sections of the 3DK2222A BJT.

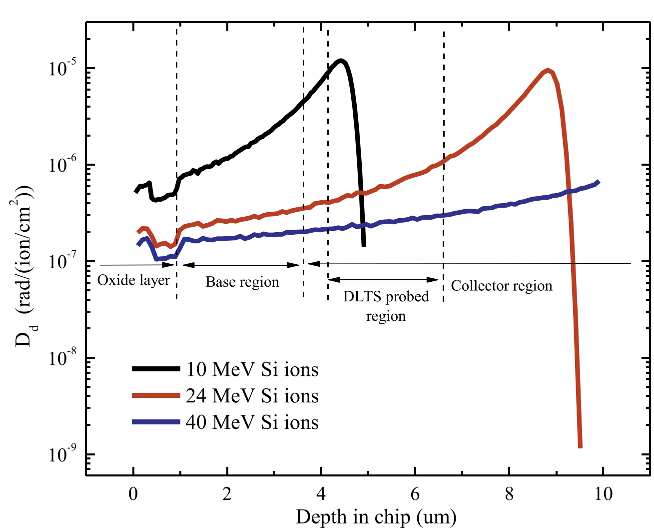

Fig. 2. Displacement absorbed dose of various energies Si ions versus depth in 3DK2222A BJT.

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