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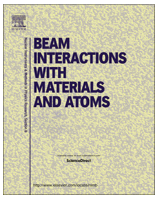

Comparative study by IBIC of Si and SiC diodes irradiated with high energy protons

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ABSTRACT

The transport properties of a series of Si and SiC diodes have been studied using the Ion Beam Induced Charge (IBIC) technique. Structural defects were induced into the samples during the irradiation with 17 MeV protons. The experimental values of the charge collection efficiency (CCE) vs bias voltages have been analyzed using a modified drift-diffusion model, which takes into account the recombination of carriers in the neutral and depletion regions. From these simulations, we have obtained the values of the carrier's lifetime for pristine and irradiated diodes, which are found to degrade faster in the case of the SiC samples. However, the decrease of the CCE at high bias voltages is more important for the Si detectors, indicative of the lower radiation hardness of this material compared to SiC. The nature of the proton-induced defects on Si wafers has been studied by Positron Annihilation Spectroscopy (PAS) and Doppler Broadening Spectroscopy (DBS). The results suggest that the main defect detected by the positrons in p-type samples is the divacancy while for n-type at least a fraction of the positron annihilate in another defect. The concentration of defects is much lower than the number of vacancies predicted by SRIM.

1. Introduction

Silicon has a high-quality and robust native oxide that provides a well-controlled interface to the underlying silicon, while protecting the bulk from environmental contamination. This property of silicon is unique among semiconductors and it is a key ingredient to understand why this material is prevailing for the fabrication of electronic devices and detectors. However, in hostile environments, like nuclear reactors, particle accelerators and outer space, radiation damage is the main driver in the search for new materials [1]. Silicon carbide (SiC) is one of the most attractive semiconductor materials for the development of high-temperature, high-power and high-frequency devices [2]. Moreover, SiC has been already used as radiation detector [3] and have the advantage of much higher radiation tolerance compared to silicon [4]. In this paper we present a comparative study by Ion Beam Induced Charge (IBIC) of the radiation hardness of Si and 4H-SiC detectors irradiated with high energy protons. Besides, the nature of the proton-induced defects on Si wafers from which the diodes were fabricated has been studied by Positron Annihilation Spectroscopy (PAS) and Doppler Broadening Spectroscopy (DBS).

The present work has been done in the framework of the IAEA Coordinated Research Project (CRP) No: F11016 [5], whose main objective is to obtain a deeper theoretical knowledge and experimental data on defects created in semiconductor and insulator materials by the use of accelerator-based light and heavy ion irradiation. To create the damage we have employed 17 MeV protons, which is the higher proton energy available among the participants of this CRP, with the distinctive feature that these ions traverse completely the samples, without leaving residual hydrogen in the crystals. As the defect profile is homogeneous, during an IBIC experiment all minority and majority carriers will have a certain probability to be trapped across the path to their respective electrodes and the detection properties, like the charge collection efficiency (CCE), can be evaluated in terms of the lifetime of both charge carriers. On the contrary, the irradiations carried out in

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other laboratories (ANSTO, RBI, JAEA and SNL) along this CRP utilized heavier ions and/or lower energies [6–9], which generate a much shallow and non-constant damage profile. In these conditions, most of the majority carriers generated by IBIC will move across a defect-free region, while the lifetime of minority carriers will depend on the carrier position. Therefore, this will not be an adequate parameter to describe the radiation hardness of the detector. Instead, the capture coefficients $\alpha_{n,p}$ will provide the key parameters for the characterization of the effects of radiation damage in the semiconductors [10]. The methodology and experiments concerning the CCE degradation in Si and SiC diodes after irradiation with MeV ions (others that 17 MeV protons) are described in [11,12], respectively.

2. Experimental

2.1. Materials

The Si samples consist of 300 μm thick n- and p-type Floating Zone Si diodes and wafers with bulk doping concentration of $\sim 10^{12}/\text{cm}^3$ fabricated by the Helsinki Institute of Physics (HIP). The full depletion voltage were ~30 and 40 V for the n- and p-type diodes, respectively, and the saturated leakage current was about 10 nA for both types. A more complete description of these samples can be found in [11,13,14]. The SiC diodes were provided by the Japanese Atomic Energy Agency (JAEA). Basically they consist on a ~47 μm thick n-type 4H-SiC epilayer grown on 4H-SiC substrate. The Schottky contact, with dimensions 1 mm × 1 mm × 80 nm, was created by Ni sputtering on top of the SiC epilayer while the ohmic contact was Ni sintered at 950 °C at the substrate back side. The doping concentration of the epilayer, estimated at JAEA from the *C–V* measurements, is $5 \times 10^{14}\ \text{cm}^{-3}$. The relationship between depletion layer thickness (w) and reverse bias voltage (V_B) is given by $w\,(\mu\text{m}) = 1.50013\ \text{V}^{0.5}$, as obtained in [15] for SiC diodes from the same batch.

2.2. Proton irradiation

To create structural damage, the samples were irradiated using the external beamline of the 18/9 compact Cyclotron of the National Accelerator Centre (CNA) in Sevilla (Spain). The Si and SiC diodes were placed in air at 15 cm from the 150 μm thick kapton exit window. Although the cyclotron delivers 18 MeV protons, the actual proton energy at the sample's surface after traversing the kapton foil and the air was 17 MeV, as calculated using the SRIM code [16]. Since the proton beam current cannot be measured directly on the diode, the proton fluence was indirectly determined by knowing the ratio between the amount of beam impinging on a 10 mm diameter carbon collimator placed right after the exit window and connected to a Brookhaven 1000c current integrator, and the amount of beam passing through this collimator. A second collimator made of 2 mm thick Al with 0.2 mm diameter hole was placed in front of the Si diodes in order to limit the irradiated volume, which otherwise would increase the leakage current to unacceptable levels. Due to the wide bandgap of the 4H-SiC material ($E_g = 3.23$ eV) compared to Si ($E_g = 1.17$ eV), the increase of the leakage current of the SiC diodes after irradiation is not a big concern and, therefore, their full volume was irradiated by removing the Al collimator. The fluences given to the Si and SiC detectors range between $10^{12}\ \text{p/cm}^2$ and $10^{13}\ \text{p/cm}^2$. The vacancy profile induced by the 17 MeV proton beam, evaluated by the SRIM code, was practically flat for all the samples, with ~200 vacancies/cm/ion in the Si diodes assuming a displacement energy of 21 eV and ~150 vacancies/cm/ion in the SiC diodes supposing a displacement energy of 35 eV and 21 eV for Si and C, respectively.

For PAS and BD measurements, the n-type and p-type FZ Si wafers used to fabricate the diodes were irradiated in air, at 8 cm from the 125 μm thick Al exit window. In order to guarantee the lateral homogeneity of the beam over the $8 \times 8\ \text{mm}^2$ surface of the samples, a 50 μm thick W foil was placed immediately after the exit window. At 4 cm from this foil, a graphite collimator with a 1 cm diameter hole was placed to define the beam size. As the beam slightly diverges from the collimator to the sample position due to the interaction with the air, the actual beam size and homogeneity at the sample's distance was measured with a radiochromic film. The beam energy calculated by SRIM at the sample surface was 15.7 MeV, which produces practically the same vacancy profile as 17 MeV protons. To determine the proton fluence, the wafers were stuck with carbon tape to an electrically floating graphite plate connected to a current integrator. Irradiation was performed for the fluences 10^{15}, 4.26×10^{15} and $8.5 \times 10^{15}\ \text{p/cm}^2$.

All the analysis for diodes and wafers were carried out several days after irradiation, during which the samples were kept at room temperature, so only permanent damage induced by the displacement of atomic nuclei will be considered.

2.3. IBIC measurements

IBIC analysis of the Si diodes was performed in the microbeam line of the CNA with a 4.07 MeV proton beam. Using a slightly focused $10 \times 10\ \mu\text{m}^2$ beam with a low count rate (<200 Hz), the damaged areas were first localized through the $1 \times 1\ \text{mm}^2$ IBIC mappings, as shown in Fig. 1, and then point measurements were performed in the center of the perturbed regions to extract the data. The IBIC signal was recorded as a function of the applied bias voltage using a Canberra 2003BT preamplifier, a Tennelec TC245 amplifier with a shaping time of 2 μs and the OMDAQ ADC/MCA system from Oxford Microbeams Ltd. It is important to emphasize that, despite the use of the 200 μm collimator, the increase of the leakage current I_c after the 17 MeV proton irradiation is not negligible. Then, the actual bias voltage V_B applied to the Si diodes can be notably different from the voltage indicated by the front panel digital display of the bias supply (Vread) and is determined by $V_B = \text{Vread} - I_c \times R_L$, where $R_L = 110\ \text{M}\Omega$ is the detector load resistor. As the range of 4.07 MeV protons in Si is ~150 μm (approximately half of the detector thickness), by setting the reverse bias voltage it was possible to work in conditions in which all the

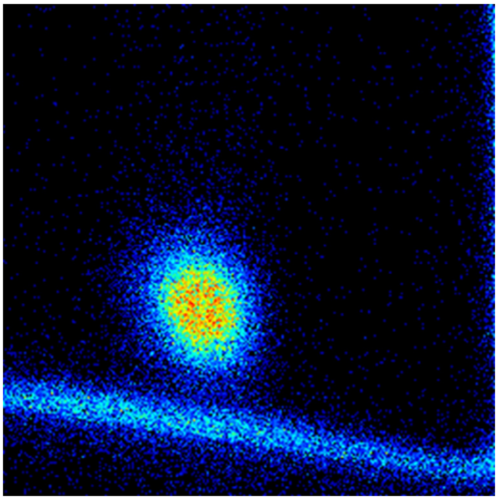

Fig. 1. $1 \times 1\ \text{mm}^2$ CCE mapping for n-type Si diode around the spot irradiated to $5 \times 10^{12}\ \text{p/cm}^2$ recorded using a low bias voltage ($V = 5$ V) to increase the sensitivity. The damaged region is clearly visible near the bright line coming from the guard ring.

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