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Charge collection efficiency degradation on Si diodes irradiated with high energy protons

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ABSTRACT

The charge collection efficiency (CCE) of several p-type Si diodes has been determined by the Ion Beam Induced Charge (IBIC) technique with 4 MeV protons. In addition, the time evolution of the collected carriers has been recorded as a function of the reverse bias voltage. The diodes were irradiated in our cyclotron with 17 MeV protons and fluences ranging from 3.3×10^{11} to 1.65×10^{13} p/cm^2. The high energy irradiation was selected because of the practically constant value of the proton stopping power across the samples, leading to a uniform vacancy profile with depth. It is observed that the CEE decreases linearly with radiation fluence while the leakage current increases with ion dose. From these results, the diffusion length of minority carriers, the damage constant and the damage coefficient of p-type Si diodes have been evaluated.

1. Introduction

The study of radiation effects in semiconductor electronics and detectors is fundamental to evaluate the lifetime and performance deterioration of the semiconductor devices working in high radiation environments like nuclear reactors, particle accelerators and outer space [1,2]. While the effect of radiation induced defects on properties of semiconducting and insulating materials and devices has been studied for 50 years, there are still important gaps in the understanding of what types of defects are formed, how they can be detected and their effects on electrical and structural properties. The present work has been done in the framework of the IAEA Coordinated Research Project (CRP) No: F11016, 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. In this paper we present a study by the Ion Beam Induced Charge (IBIC) technique of the damage produced by 17 MeV protons (the higher proton energy available among the participants of this CRP) in silicon diodes at low ion fluencies. A review of the IBIC theory and applications can be found in [3].

2. Experimental

The samples studied in this work consist of a 6 × 6 mm^2 Floating Zone p-type Si diodes fabricated by the Helsinki Institute of Physics (HIP). They are formed by a 3 μm n$^+$ top layer, followed by a 300 μm intrinsic substrate with doping concentration of 10^{12}/cm^3 and a 7 μm p$^+$ back layer. Ohmic contacts were deposited on the top n$^+$ and the back p$^+$ regions by Al evaporation. The thickness of the Al contacts was 422 ± 10 nm, as determined by RBS using a 2 MeV He^{2+} beam. Fig. 1 shows a scheme of the diode with the doping profile extracted from the C–V curve determined at the Sandia National Laboratory (SNL) [4]. Also included in Fig. 1 is the ionization profile produced by the 4 MeV proton beam used for the IBIC measurements (see below). The inset represents the width of the depletion region *vs*. reverse bias voltage, as found out in [4].

The external beam of our cyclotron was used to irradiate the diodes at several fluences. The samples 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 [5]. 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

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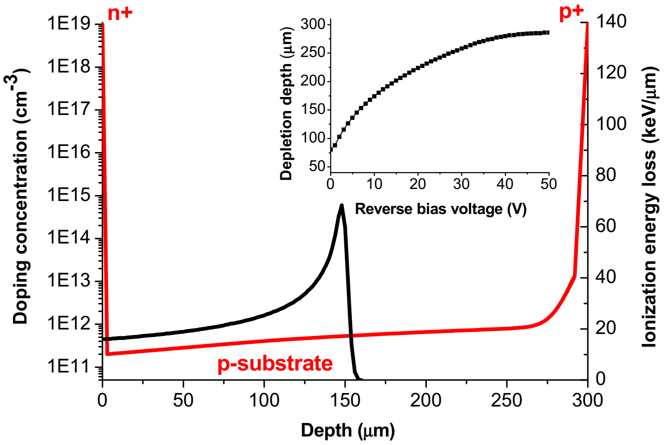

Fig. 1. In red, doping concentration profile of the n+-p-p+diode. In black, ionization profile of 4.07 MeV protons in Si. The inset shows the width of the depletion region *vs.* bias voltage (from [4]).

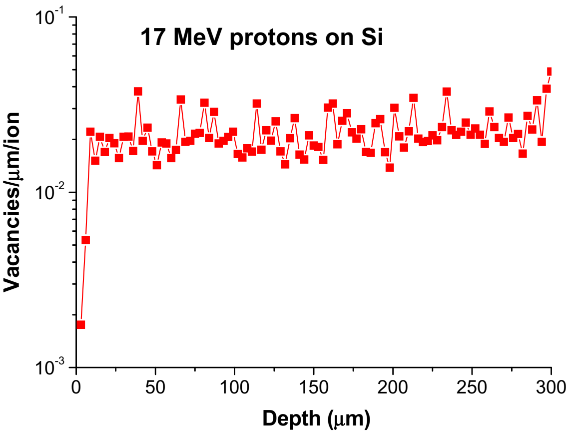

Fig. 2. Vacancy profile in Si generated by 17 MeV protons.

through this collimator. The proton flux was typically 3×10^{10} p/cm^{2}s. A second Al collimator with 0.55 mm diameter was placed in front of the diodes in order to limit the irradiated volume, which otherwise would increase the leakage current to unacceptable levels. The diodes were irradiated to fluences of 3.3×10^{11}, 1.65×10^{12}, 3.3×10^{12} and 1.65×10^{13} p/cm^2, respectively.

The IBIC measurements were performed in our microbeam line using a 4.07 MeV proton beam. To avoid creating additional damage during the measurements, the beam was slightly focused to a spot of 50×50 μm^2 and the proton rate was kept below 500 Hz. The signal height 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. A triple alpha source (^{244}Cm, ^{241}Am and ^{239}Pu) with about 1 μCi activity was placed inside the vacuum chamber, in that way the alpha spectrum was simultaneously recorded together with the IBIC signals providing an absolute calibration of the full electronic chain. Moreover, in order to correct for the possible changes on the overall electronic gain due to the variation of the detector capacitance at different bias, a calibrated pulser was connected to the “Test” input of the preamplifier. We did not observe any significant change in the position of the pulser signal for bias voltages between 42 and 0.5 V. Finally, in order to obtain further information about the transport of free carriers to the collecting electrodes, the time dependence of the signal current was measured by connecting the “Energy output” of the preamplifier to the input of a 2 GHz LeCroy 204Mxi-A digital oscilloscope.

3. Results and discussion

Fig. 2 shows the vacancy profile induced by the 17 MeV proton beam, as evaluated by SRIM, assuming a displacement energy in Si of 21 eV. As observed, the high energy protons create a vacancy profile that is practically constant all along the Si diode, leading to a uniform distribution of active defects in the detector volume. In these conditions, the increase in reverse diode bias current due to the creation of mid-gap states after irradiation can be written as [6]:

$$I_d = I_0 + \alpha \cdot \phi \cdot Ad \qquad (1)$$

where I_0 is the leakage current before irradiation, α is a damage coefficient dependent on particle type and energy, ϕ is the particle fluence and the product of detector area and thickness Ad is the irradiated detector volume. At 40 volts, where the leakage current saturates, the damage coefficient for 17 MeV protons is $\alpha \approx 7.8{\cdot}10^{-17}$ A/cm, which is about 2.6 times higher that the value found in the ATLAS inner silicon detector irradiated with 650 MeV protons [7]. The displacement energy is linked to nonionizing energy loss (NIEL), which is not proportional to the total energy absorbed. The displacement damage *vs.* energy for neutrons, protons, pions and electrons, relative to 1 MeV neutrons, has been compiled by Lindstrom [8]. From this data, the relative damage for 17 MeV protons is 2.9 larger compared to 650 MeV protons, in good agreement with our experimental results.

The reverse bias voltage dependence of the total collected charges measured for a non-irradiated diode is shown in Fig. 3. As observed, for voltages from 40 to 7 V, the CCE is practically 100% and this value decreases for lower voltages until reaching 55% at 0 volts. If trapping and recombination are negligible within the depletion zone, the CCE can be calculated as [3]:

$$\mathrm{CCE} = \frac{100}{E_i}\left(\int_0^w \frac{dE}{dx}dx + \int_w^{R_p} \frac{dE}{dx} e^{-\frac{x-w}{L_{\mathrm{diff}}}} dx\right) \qquad (2)$$

where E_i = 4.07 MeV and R_p = 156 μm are the initial energy and the projected range of the incident protons in the material of the diode, respectively, dE/dx is the ionizing energy loss that we have estimated using SRIM, w is the width of the depletion layer and L_{diff} is the diffusion length of minority carriers (electrons) within the electroneutral region. The first term in Eq. (2) represents the drift current and the second term corresponds to the diffusion current.

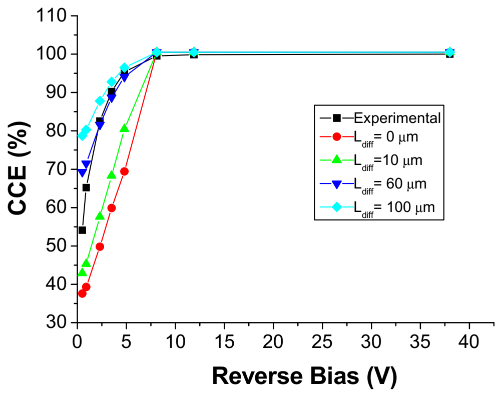

Fig. 3. CCE of a pristine diode as a function of bias voltage determined with a 4 MeV proton beam. Calculations from the drift-diffusion model for different L_{diff} values are also included.

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