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An upgraded drift–diffusion model for evaluating the carrier lifetimes in radiation-damaged semiconductor detectors

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ABSTRACT

The transport properties of a series of n- and p-type Si diodes have been studied by the ion beam induced charge (IBIC) technique using a 4 MeV proton microbeam. The samples were irradiated with 17 MeV protons at fluences ranging from 1×10^{12} to 1×10^{13} p/cm^2 in order to produce a uniform profile of defects with depth. The analysis of the charge collection efficiency (CCE) as a function of the reverse bias voltage has been carried out using an upgraded drift–diffusion (D–D) model which takes into account the possibility of carrier recombination not only in the neutral substrate, as the simple D–D model assumes, but also within the depletion region. This new approach for calculating the CCE is fundamental when the drift length of carriers cannot be considered as much greater that the thickness of the detector due to the ion induced damage. From our simulations, we have obtained the values of the carrier lifetimes for the pristine and irradiated diodes, which have allowed us to calculate the effective trapping cross sections using the one dimension Shockley–Read–Hall model. The results of our calculations have been compared to the data obtained using a recently developed Monte Carlo code for the simulation of IBIC analysis, based on the probabilistic interpretation of the excess carrier continuity equations.

1. Introduction

Since its development in the early 1990's [1], the ion beam induced charge (IBIC) technique has found widespread applications to measure and study the transport properties of semiconductor materials and devices [2]. Different theoretical frames have been developed for calculating the charge pulse signal produced by semiconductor detectors. Those models include the use of TCAD simulations [3], the solution of an adjoint carrier continuity equation [4], or the implementation of a simple one-dimensional charge transport by drift and diffusion [5]. In this paper, the drift–diffusion model is revisited to consider the possibility of carrier recombination not only in the electroneutral part of the detector, as stated in [5], but also in the depletion region. The results are applied to a series of Si diodes subjected to radiation damage produced by high energy protons. The present work has been done in the framework of the IAEA Coordinated Research Project F11016 "Utilization of ion accelerators for studying and modeling of radiation induced defects in semiconductors and insulators".

2. Experimental

The samples studied in this work consist of 300 μm thick n- and p-type Floating Zone Si diodes with doping concentration of $\sim 10^{12}$/cm^3 fabricated by the Helsinki Institute of Physics (HIP). Fig. 1 shows a scheme of a p-type diode with the doping profile (red line) extracted from the *C–V* curve determined at the Sandia National Laboratories (SNL) [6]. The inset represents the width of the depletion region vs. reverse bias voltage, as found out in [6].

The irradiations were carried out at the external beam of the compact cyclotron of the CNA, placing the samples 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 [7]. The homogeneous proton beam (∅ = 15 mm) was partially blocked with a 2 mm thick graphite collimator (∅ = 10 mm), which was connected to a Brookhaven 1000c current integrator for fluence measurements. A second collimator made of 2 mm thick Al

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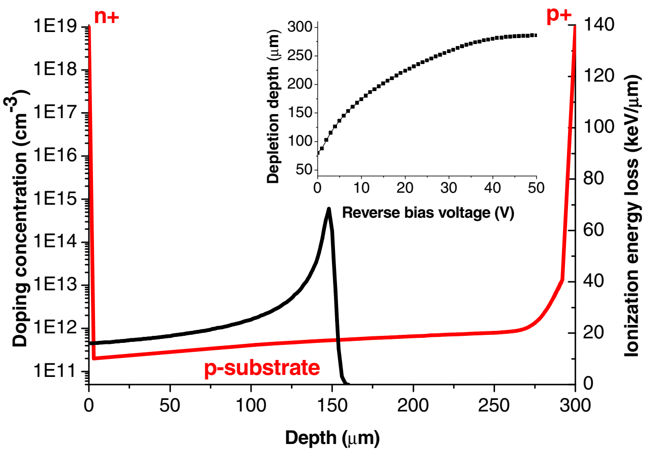


Fig. 1. In red, doping concentration profile of one n+-p-p+ diode. In black, ionization profile of 4.07 MeV protons in Si. The inset shows the width of the depletion region vs. bias voltage (from [6]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(∅ = 200 μm) was placed in front of the diode to limit the damaged volume, which otherwise would increase the leakage current to unacceptable values after the irradiation. The diodes were irradiated at fluences between 1×10^{12} p/cm^2 and 1×10^{13} p/cm^2.

The study of the defects was accomplished at the microbeam line of the 3MV Tandem accelerator of the CNA, approximately one week after irradiation, with the samples stored at room temperature. IBIC analysis was performed with a 4.07 MeV proton beam, whose ionization profile in Si, as evaluated by SRIM code, is superimposed to the doping profile in Fig. 1 (black line). To avoid creating additional damage during the measurements, the beam was slightly focused to a spot of 10×10 μm^2 and the proton rate was kept below 200 Hz. First, the damaged areas were localized through the 1×1 mm^2 IBIC mappings, as shown in Fig. 2, and then point measurements were performed in the center of the perturbed regions to extract the data. 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 in 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. No significant changes in the position of the pulser signal for bias voltages between 42 V and 0.5 V were observed during the measurements.

3. Calculation of the measured charge collection efficiency

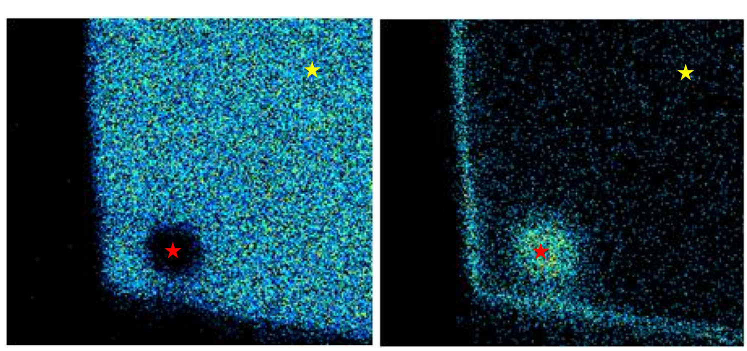
As shown by M. Breese in his pioneer paper about the theory of ion beam induced charge collection [5], the measured (normalized) charge collection efficiency (CCE) can be expressed in a partially depleted device as:

$$\mathrm{CCE} = \mathrm{CCE_{Drift}} + \mathrm{CCE_{Diffusion}} = \frac{1}{E_i}\left(\int_0^w \frac{dE}{dx}dx + \int_w^{R_p} \frac{dE}{dx} e^{-\frac{x-w}{L_{diff}}} dx\right) \quad (1)$$

where E_i, R_p and dE/dx are the initial energy, the projected range and the ionizing energy loss of the incident ion in the material of the diode, respectively; w is the depletion width of the device, which is assumed in the following to be smaller than the ion penetration range, and L_{diff} is the minority-carrier diffusion length, which is related to the carrier lifetime τ_{min} by $L_{Diff} = \sqrt{D_{min} \times \tau_{min}}$, where D_{min} is the diffusion coefficient. The first integral (drift term) represents the contribution from the charge carriers generated within the depletion region and collected as drift current. The second integral (diffusion term) represents the contribution from the minority carriers created in the electroneutral substrate that reach the edge of the depletion region as diffusion current. This simple drift–diffusion model is often used to explain the bias voltage-dependent CCE and to characterize p–n or Schottky junction devices [2,3,8]. A basic assumption for the validity of Eq. (1) is that carrier recombination has to be negligible within the depletion zone, which is fulfilled when the drift times are much shorter than the carrier lifetimes. In that case the measured efficiency should be 100% when the range of the ions is smaller than the depletion thickness (i.e. the CCE only contains the drift term). As will be shown in the next section, this behavior is indeed found for pristine samples, but is not observed in samples irradiated with given proton fluences. In that case, carrier recombination occurs within the active volume of the diodes and the calculation of the CCE using (1) is not accurate. Assume a detector with parallel-plate geometry, the total induced signal charge Q_s for a packet of charge Q_0 with lifetime τ will be [9]

$$Q = Q_0\left[\int_0^{t_{cmin}} \frac{\mu_{min} \cdot \varepsilon}{w} \cdot e^{-\frac{t}{\tau_{min}}} + \int_0^{t_{cmaj}} \frac{\mu_{maj} \cdot \varepsilon}{w} \cdot e^{-\frac{t}{\tau_{maj}}}\right] dt \quad (2)$$

where t_{cmin} and t_{cmaj} are the minority and majority carrier collection times, respectively, $\mu_{min,maj}$ are the corresponding carrier



a)V=30 volts (100-95% CCE) b) V=30 volts (95-90% CCE)

Fig. 2. 1×1 mm^2 IBIC maps recorded around a point irradiated to 1×10^{13} p/cm^2. The damaged spot is clearly visible near the corner of the diode. The red and yellow stars indicate the positions of the point measurements for the irradiated and pristine areas, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)