A double junction model of irradiated silicon pixel sensors for LHC

V. Chiochia[a,*], M. Swartz[b], Y. Allkofer[a], D. Bortoletto[c], L. Cremaldi[d], S. Cucciarelli[e], A. Dorokhov[a,f], C. Hörmann[a,f], D. Kim[b], M. Konecki[e], D. Kotlinski[f], K. Prokofiev[a,f], C. Regenfus[a], T. Rohe[f], D.A. Sanders[d], S. Son[c], T. Speer[a]

[a]Physik Institut der Universität Zürich-Irchel, 8057 Zürich, Switzerland
[b]Johns Hopkins University, Baltimore, MD 21218, USA
[c]Purdue University, West Lafayette, IN 47907, USA
[d]University of Mississippi, University, MS 38677, USA
[e]Institut für Physik der Universität Basel, 4056 Basel, Switzerland
[f]Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

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Abstract

In this paper, we discuss the measurement of charge collection in irradiated silicon pixel sensors and the comparison with a detailed simulation. The simulation implements a model of radiation damage by including two defect levels with opposite charge states and trapping of charge carriers. The modeling proves that a doubly peaked electric field generated by the two defect levels is necessary to describe the data and excludes a description based on acceptor defects uniformly distributed across the sensor bulk. In addition, the dependence of trap concentrations upon fluence is established by comparing the measured and simulated profiles at several fluences and bias voltages.
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1. Introduction

The CMS experiment, currently under construction at the Large Hadron Collider (LHC) will include a silicon pixel detector [1] to allow tracking in the region closest to the interaction point. The detector will be a key component for reconstructing interaction vertices and heavy quark decays in a particularly harsh environment, characterized by a high track multiplicity and heavy irradiation. The innermost layer, located at only 4 cm from the beam line, is expected to be exposed to an equivalent fluence of $3 \times 10^{14}\,n_{eq}/cm^2/yr$ at full luminosity.

In these conditions, the response of the silicon sensors during the detector operation is of great concern. It is well understood that the intra-diode electric fields in these detectors vary linearly in depth reaching a maximum value at the p–n junction. The linear behavior is a consequence of a constant space charge density, N_{eff}, caused by thermodynamically ionized impurities in the bulk material. It is well known that the detector characteristics are affected by radiation exposure, but it is generally assumed that the same picture is valid after irradiation. In fact, it is common to characterize the effects of irradiation in terms of a varying effective charge density. In Ref. [2] we have proved that this picture does not provide a good description of irradiated silicon pixel sensors. In addition, it was shown that it is possible to adequately describe the charge collection characteristics of a heavily irradiated silicon detector in terms of a tuned double junction model which produces a double peak electric field profile across the sensor. The modeling is supported by the evidence of doubly peaked electric fields obtained directly from beam test measurements and presented in Ref. [3]. In this paper,

*Corresponding author.
E-mail address: vincenzo.chiochia@cern.ch (V. Chiochia).

we apply our model to sensors irradiated to lower fluences demonstrating that a doubly peaked electric field is already visible at a fluence of 0.5×10^{14} n$_{eq}$/cm^2. In addition, the dependence of trap concentrations upon fluence is established by comparing the measured and simulated profiles at several fluences and bias voltages.

This paper is organized as follows: Section 2 describes the experimental setup, Section 3 describes the carrier transport simulation used to interpret the data. The tuning of the double junction model is discussed in Section 4 with the results of the fit procedure. The conclusions are given in Section 5.

2. Experimental setup

The measurements were performed in the H2 line of the CERN SPS in 2003/04 using 150–225 GeV pions. The beam test apparatus is described in Ref. [4]. A silicon beam telescope [5] consisted of four modules each containing two 300 μm thick single-sided silicon detectors with a strip pitch of 25 μm and readout pitch of 50 μm. The two detectors in each module were oriented to measure horizontal and vertical impact coordinates. A pixel hybrid detector was mounted between the second and third telescope modules on a cooled rotating stage. A trigger signal was generated by a silicon PIN diode. The analog signals from all detectors were digitized in a VME-based readout system by two CAEN (V550) and one custom built flash ADCs. The entire assembly was located in an open-geometry 3T Helmholtz magnet that produced a magnetic field parallel or orthogonal to the beam. The temperature of the tested sensors was controlled with a Peltier cooler that was capable of operating down to $-30\,^\circ$C. The telescope information was used to reconstruct the trajectories of individual beam particles and to achieve a precise determination of the particle hit position in the pixel detector. The resulting intrinsic resolution of the beam telescope was about 1 μm.

The prototype pixel sensors are so-called "n-in-n" devices: they are designed to collect charge from n$^+$ structures implanted into n-bulk silicon. All test devices were 22×32 arrays of $125 \times 125\,\mu$m^2 pixels having a sensitive area of 2.75×4 mm^2. The substrate was 285 μm thick, n-doped, diffusively-oxygenated silicon of orientation $\langle 1\,1\,1 \rangle$, resistivity of about $3.7\,\text{k}\Omega$ cm and oxygen concentration in the order of 10^{17} cm^{-3}. Individual sensors were diced from fully processed wafers after the deposition of under-bump metalization and indium bumps. A number of sensors were irradiated at the CERN PS with 24 GeV protons. The irradiation was performed without cooling or bias. The delivered proton fluences scaled to 1 MeV neutrons by the hardness factor 0.62 [6] were 0.5×10^{14}, 2×10^{14} and 5.9×10^{14} n$_{eq}$/cm^2. All samples were annealed for three days at $30\,^\circ$C. In order to avoid reverse annealing, the sensors were stored at $-20\,^\circ$C after irradiation and kept at room temperature only for transport and bump bonding. All sensors were bump bonded to PSI30/AC30 readout chips [7] which allow analog readout of all 704 pixel cells without zero suppression. The PSI30 settings were adjusted to provide a linear response to input signals ranging from zero to more than 30,000 electrons.

3. Sensor simulation

A detailed sensor simulation was implemented, including a physical modeling of irradiation effects in silicon. Our simulation, PIXELAV [8,9,2], incorporates the following elements: an accurate model of charge deposition by primary hadronic tracks (in particular to model delta rays); a realistic 3-D electric field map resulting from the simultaneous solution of Poisson's equation, continuity equations, and various charge transport models; an established model of charge drift physics including mobilities, Hall Effect, and 3-D diffusion; a simulation of charge trapping and the signal induced from trapped charge; and a simulation of electronic noise, response, and threshold effects. A final step reformats the simulated data into test beam format so that it can be processed by the test beam analysis software.

The effect of irradiation was implemented in the simulation by including two defect levels in the forbidden silicon bandgap with opposite charge states and trapping of charge carriers. The model, similar to one proposed in Ref. [10], is based on the Shockley–Read–Hall statistics and produces an effective space charge density ρ_{eff} from the trapping of free carriers in the leakage current. The effective charge density is related to the occupancies and densities of traps as follows:

$$\rho_{eff} = e[N_D f_D - N_A f_A] + \rho_{dopants} \qquad (1)$$

where N_D and N_A are the densities of donor and acceptor trapping states, respectively; f_D and f_A are the occupied fractions of the donor and acceptor states, respectively, and $\rho_{dopants}$ is the charge density due to ionized dopants. Each defect level is characterized by an electron and hole trapping cross section, $\sigma_{e/h}^D$ and $\sigma_{e/h}^A$, for the donor and acceptor trap, respectively, and by an activation energy, E_D and E_A for the donor and acceptor trap, respectively. An illustrative sketch of the model is shown in Fig. 1. Trapping of the mobile carriers from the generation-recombination current produces a net positive space charge density near the p$^+$ backplane and a net negative space charge density near the n$^+$ implant as shown in Fig. 1(a). Since positive space charge density corresponds to n-type doping and negative space charge corresponds to p-type doping, there are p–n junctions at both sides of the detector. The electric field in the sensor follows from a simultaneous solution of Poisson's equation and the continuity equations. The resulting z-component of the electric field is shown in Fig. 1(b). It varies with an approximately quadratic dependence upon z having a minimum at the zero of the space charge density and maxima at both implants. A more detailed description of the double junction model and its implementation can be found in Ref. [2].