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Radiation hard silicon particle detectors for HL-LHC—RD50 status report

S. Terzo, On behalf of the RD50 Collaboration[1]

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, D-80805 München, Germany

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ABSTRACT

It is foreseen to significantly increase the luminosity of the LHC by upgrading towards the HL-LHC (High Luminosity LHC). The Phase-II-Upgrade scheduled for 2024 will mean unprecedented radiation levels, way beyond the limits of the silicon trackers currently employed. All-silicon central trackers are being studied in ATLAS, CMS and LHCb, with extremely radiation hard silicon sensors to be employed on the innermost layers. Within the RD50 Collaboration, a massive R&D program is underway across experimental boundaries to develop silicon sensors with sufficient radiation tolerance. We will present results of several detector technologies and silicon materials at radiation levels corresponding to HL-LHC fluences. Based on these results, we will give recommendations for the silicon detectors to be used at the different radii of tracking systems in the LHC detector upgrades. In order to complement the measurements, we also perform detailed simulation studies of the sensors.

1. Introduction

The High Luminosity upgrade of the Large Hadron Collider (HL-LHC) foreseen in 2024 will allow to deliver about 3000 fb^{-1} in ten years of operations [1]. The expected high radiation environment will be one of the main challenges for the innermost detectors of the experiments at HL-LHC which will be exposed to particle fluences up to $1–2 \times 10^{16}$ n_{eq}/cm^2 in the case of the innermost pixel layers [2] and up to 10^{17} n_{eq}/cm^2 in the forward calorimeter regions [3]. RD50 is a CERN R&D collaboration active since 2001 with the aim of developing radiation hard silicon detectors for HL-LHC and future collider experiments. It involves over 280 members from 50 different institutions worldwide organised in four research areas: Defect and Material Characterisation, Detector Characterisation, New Structures and Full Detectors Systems. In the following the activities of the collaboration are presented together with a selection of recent results. More details can be found in Refs. [4,5].

2. Defect and material characterisation

High energetic particles create defects in the semiconductor lattice leading to trapping of charge carriers, increase of the leakage current, change of the effective doping concentration and of the electric field in silicon sensors. After high radiation doses these effects result in a significant deterioration of the detector performance. Dedicated techniques such as TSC (Thermally Stimulated Current) or DLTS (Deep Level Transient Spectroscopy) allow to identify defects induced by radiation and measure their electrical properties. An example of TSC measurement, shown in Fig. 1, compares the defects measured for n-type and p-type silicon after irradiation with 23 MeV protons to a fluence of 10^{14} n_{eq}/cm^2 [6]. The investigation of radiation damage in p-type silicon is of particular interest since this material is a baseline for both pixel and strip detectors in the upgrades of the main experiments at HL-LHC.

3. Device simulations

The properties of the measured defects in silicon are of fundamental importance to define the inputs for detector simulations. The radiation models developed inside the RD50 collaboration approximate the bulk damage with two [7,8] or three [9] deep levels. The defect concentration and cross section is then tuned to match experimental data. Good agreement was achieved between simulations and data as reported in Ref. [10] for CMS strip sensors irradiated up to a fluence of 1.5×10^{15} n_{eq}/cm^2. A different approach is also under investigation to reproduce IV, CV and CCE characteristics with a simple fluence dependence independently of the specific material type or irradiation [11]. The aim is to overcome the limitation of the present radiation models at high radiation fluences ($> 3 \times 10^{15}$ n_{eq}/cm^2). In this new model the TCAD

E-mail address: Stefano.Terzo@mpp.mpg.de
[1] RD50 collaboration: http://rd50.web.cern.ch/.

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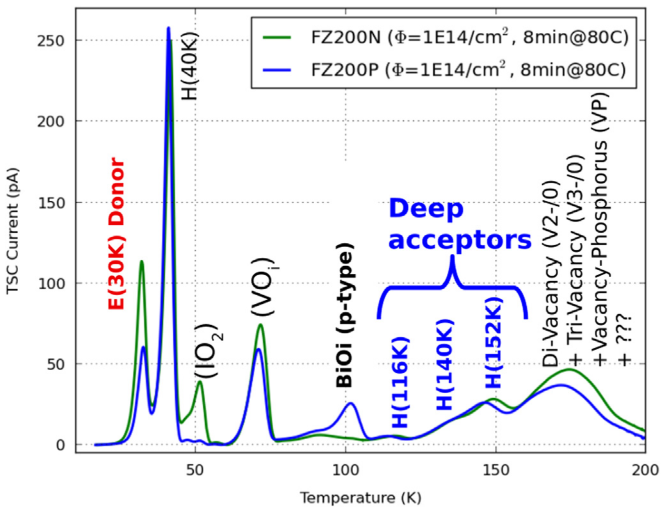

Fig. 1. TSC spectrum of 200 μm thick n-type (green) and p-type (blue) Float Zone silicon diodes irradiated to a fluence of 10^{14} n_{eq}/cm^2 with 23 MeV protons at the Karlsruher Institut für Technologie (KIT). Measurements were performed after an annealing time of 8 min at 80 °C. Identified defects are marked. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

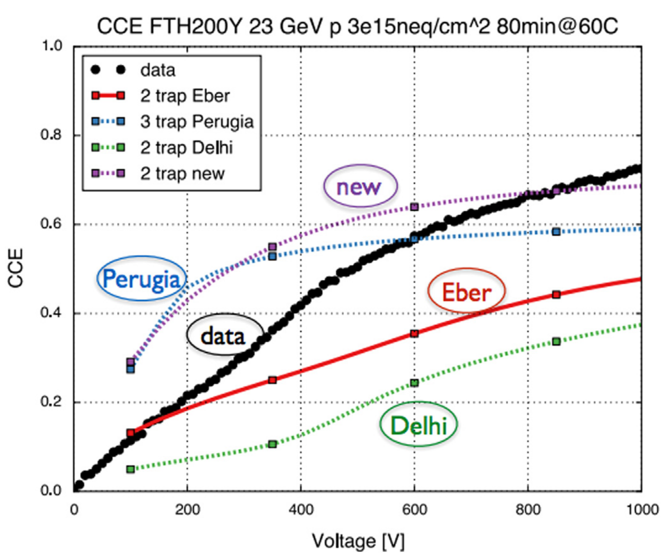

Fig. 2. CCE of 200 μm thick p-type diodes irradiated to a fluence of 3×10^{15} n_{eq}/cm^2 and operated at −20 °C. Synopsis TCAD simulations with the new approach and other radiation models (Perugia [9], Eber [7] (Synopsis), Delhi [8] (SILVACO)) are compared to data of samples irradiated at KIT.

inputs are defined minimising the deviation between simulations and measurements over a large voltage range:

$$F = w_1 \int_{V_{min}}^{V_{max}} \left(1 - \frac{I_{sim}}{I_{meas}}\right)^2 dV + w_2 \int_{V_{min}}^{V_{max}} \left(1 - \frac{C_{sim}}{C_{meas}}\right)^2 dV$$

where V_{max} (V_{min}) is the maximum (minimum) of the voltage range, I_{sim}, C_{sim} (I_{meas}, C_{meas}) are the simulated (measured) current and capacitance, respectively and $w_{1,2}$ are weighting factors. First results of this novel approach compared to measurements of diodes irradiated with 23 MeV protons to a fluence of 3×10^{15} n_{eq}/cm^2 show a very good agreement for IV and CV measurements at the same time. As shown in Fig. 2, the new model gives also a good approximation of the CCE at high bias voltages (around 800 V), while measurements at lower bias voltage are overestimated.

4. Detector characterisation

A powerful detector characterisation tool, developed by the JSI[2] group within the RD50 collaboration, is the Edge-Transient Current Technique (E-TCT) [12]. This technique is a modification of standard TCT measurement [13] and consists of focusing fast infrared laser pluses (< 1 ns) in silicon detectors from the side. The electron–hole pairs generated by the laser at different depths drift in the electric field inducing a current in the electrodes connected to the readout. The initial signal, measured shortly after the laser pulse, is proportional to the sum of both carrier velocities which is in turn proportional to the electric field ($I \propto v_e + v_h \propto E$) up to the charge carrier velocity saturation. In Fig. 3 the sum of the carrier velocities in a 300 μm thick n-in-p silicon strip sensor irradiated with neutrons to fluence of 10^{16} n_{eq}/cm^2 is measured throughout the bulk depth with E-TCT measurements [14]. For high bias voltages the velocity at the strip side exhibits a non-negligible increase without saturation, which can be attributed to charge multiplication. A second smaller peak is also observed on the backside. This peak is less prominent than in proton irradiations to the same fluence and disappears after a neutron fluence of 10^{17} n_{eq}/cm^2 as shown in preliminary measurements presented in Ref. [15]. Even at these high irradiation fluences a rather large field is still observed in the sensor bulk.

5. New structures and full detector systems

Different technologies to fulfil the requirements for tracking and calorimetry applications in the different detector layers at HL-LHC are investigated by the RD50 collaboration. These includes cost-effective solutions for moderate radiation levels such as HV-CMOS and n-in-p planar sensors as well as more radiation hard solutions suited for the innermost detector layers such as 3D and thin planar silicon sensors. The work of the collaboration is also focused on sensors with intrinsic gain which are particularly interesting for precise timing applications.

5.1. HV-CMOS

HV-CMOS sensors consist of deep n-well collecting electrodes in a usually low resistivity p-type substrate. The signal is thus obtained by charge drift in a thin depleted region which allows to reduce the trapping effects after irradiation. The CMOS circuity is implemented inside the n-well with deep sub-micron technology. E-TCT measurements of irradiated HV-CMOS diodes are shown in Fig. 4 [16,17]. An increase of the collected charge after irradiation up to a fluence of 7×10^{15} n_{eq}/cm^2 is observed. This effect is especially large for proton irradiated samples and is probably due to acceptor removal in the low resistivity ($\sim 10\,\Omega$ cm) bulk material. For a radiation fluence of 2×10^{16} n_{eq}/cm^2 a collected charge similar to the one before irradiation is instead measured with a bias voltage of 80 V. An activity on TCAD simulations of HV-CMOS is also ongoing within the collaboration and first results of diodes were presented in Ref. [18]. The HV-CMOS technology allows to produce also strip and pixel structures which can be operated as monolithic detectors or as hybrid pixel sensors with an integrated pre-amplification stage.

[2] Jožef Stefan Institute, Ljubljana.

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