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Silicon sensors for HL-LHC tracking detectors

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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) in 2021 in order to harvest the maximum physics potential. After the upgrade, unprecedented levels of radiation will require the experiments to upgrade their tracking detectors to withstand hadron fluences equivalent to over 10^{16} 1 MeV neutrons per cm^2. Within the RD50 Collaboration, a massive R&D program is underway to develop silicon sensors with sufficient radiation tolerance. Recent defect characterization and Edge-TCT measurement results improved the understanding of irradiated detector performance. RD50 results show that sensors with n-side readout, easiest made with p-type silicon, have a superior radiation hardness due to the high overlap of electric and weighting field after irradiation, larger contribution of electrons to the total signal and finally due to charge multiplication which may enhance the collected charge at high bias voltages in this type of detector. A further area of activity is the development of advanced sensor types like 3D silicon and thin pixel detectors designed for the extreme radiation levels expected for the inner layers.

1. Introduction

The upgrade of LHC to High Luminosity LHC (HL-LHC) is foreseen after 2021. It is expected that the general purpose experiments ATLAS [1] and CMS [2] will collect data corresponding to about 3000 fb^{-1} of integrated luminosity during the operation of HL-LHC. This inevitably means also high radiation levels and current radiation field simulations foresee that the innermost detectors will have to withstand displacement damage equivalent to irradiation with 2×10^{16} cm^{-2} of 1 MeV neutrons. Such radiation levels require the development of new detectors which is the mission of the RD50 collaboration. RD50 is an international collaboration based at CERN with over 260 members from 48 institutions [3]. The work in the collaboration is divided into several subjects dealing with defect and material characterization, studies of novel detector structures and measurements with full detector systems.

As mentioned, part of the research is oriented towards the understanding of the radiation damage on a microscopic level by studying properties of radiation induced defects and their influence on the detector performance. Important progress has been made on this subject in recent years and the main defects correlated with changes of detector performance, the influence of oxygen and the annealing behaviour have been identified [4,5]. Closely related to defect characterization is the work of the simulation task group, recently formed within RD50, aiming to simulate the macroscopic behaviour of an irradiated detector from defect parameters using commercial (TCAD) or custom made software. Assuming that two effective deep levels are responsible for changes of N_{eff} and charge trapping and considering the influence of leakage current on charging of the defects, it was possible to reproduce the double peak electric field shapes in irradiated detectors and the dependence of charge collection efficiency on fluence and bias voltage taking into account also the impact ionization phenomena [6]. Properties of radiation induced defects were tested also in measurements of detrapping times using the TCT measurement method [7] and agreement with TSC measurements was found.

An important effort within RD50 is devoted to measurements for the selection of detector material. There are several materials still being tested within RD50: Float Zone (FZ), Magnetic Czochralski (MCz) [8] and epitaxial silicon. Although it is known that with detectors made of p-type FZ silicon the requirements for HL-LHC could be met, there are still several questions to be answered and optimizations to be performed in terms of performance and price, for different parts of the tracker with different radiation levels and composition of the radiation field. For example, measurements in Ref. [9] showed that in n-type MCz the increase of full depletion voltage V_{fd}, caused by irradiation with charged hadrons, decreases after irradiation with neutrons, although the

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total equivalent fluence has increased. Therefore, if used in the part of the tracker with a mixed radiation field, a smaller increase of V_{fd} in n-MCz detectors could be expected, because the effective space charge increase introduced by charged hadrons, is compensated by irradiation with neutrons.

At fluences higher than Φ_{eq}~1×10^{15} n_{eq}/cm^2 detectors with segmented readout electrodes made of n-type silicon have higher charge collection efficiency, than those with p-side readout [10–12]. Also it is important to note that at such high fluences there are no significant differences between various types of detector materials. The reasons for the better performance of n-side readout are known: the favourable overlap of electric and weighting field after irradiation, larger contribution of electrons to the signal and finally due to charge multiplication which may enhance the collected charge at high bias voltages in this type of detector.

RD50 is a large and active collaboration and it is not possible to cover all the results in such a short publication. In the following text E-TCT measurements and charge multiplication effects will be described in slightly more detail as they recently improved the understanding of heavily irradiated detectors.

2. Edge-TCT

Edge-Transient Current Technique (E-TCT) is a modification of standard TCT measurements [13–16]. In E-TCT sub-nanosecond pulses of focused infrared laser light ($\lambda=1064$ nm) are directed to the segmented silicon detector from the side. A segment (e.g. strip) close to the detector side is connected to a time resolved readout. With side illumination, the signals induced by movement of the charge, created at a known depth in the detector, can be measured. The magnitude of the induced current measured shortly (e.g. 600 ps) after the laser pulse, before the carriers could move far from the place of creation or are lost by trapping, is proportional to the sum of drift velocities of electrons and holes $I(t=600\text{ ps})\propto(v_e+v_h)$, where $v_{e,h}$ are the carrier velocities. The sum of drift velocities is proportional to the electric field but one should keep in mind that this relation is not linear and saturates at high values of electric field. Fig. 1a shows the velocity profile at different bias voltages measured in a n-in-p strip detector before irradiation and Fig. 1b after irradiation to $\Phi_{eq}=1\times10^{16}$ n_{eq}/cm^2. The detector produced by Hamamatsu Photonics, Japan was irradiated with neutrons in the TRIGA reactor in Ljubljana [17]. The velocity profile before irradiation (Fig. 1a) has the expected form: at low bias voltages, the non-zero carrier velocity is measured next to the readout electrodes which drops to zero in the undepleted region deeper in the detector. A similar "expected" behaviour is found also after irradiation to fluences of the order of 10^{14} n_{eq}/cm^2. The picture is strikingly changed at high fluence as shown in Fig. 1b because of two main features: first a clear increase of carrier velocity is seen at both sides of the detector and second, there is non-zero electric field in the whole detector volume, although the bias voltage is much below V_{fd}. E-TCT measurements therefore directly confirm the double-peak electric field in heavily irradiated detectors. Such a shape of the electric field is only possible if the effective space charge changes sign within the detector bulk. For example, a simple model which would lead to this field profile of the electric field [16] would have a negative space charge at the strip side, positive space charge on the back side separated by a neutral region. The double-peak electric field shape is even more visible after irradiation with charged particles (24 GeV protons or 190 MeV pions) and in MCz material [15] and is related to the oxygen concentration in the detector material. The E-TCT results help to understand the relatively high charge collection efficiencies measured in detectors irradiated to very high fluences, which could not be explained with "standard" parameters: full depletion voltage and effective trapping times [18,19].

3. Charge multiplication

One of the exciting research subjects of the RD50 collaboration certainly is the charge multiplication effect. It is now widely accepted and confirmed [20–23] that in irradiated detectors at sufficiently high bias voltage, multiplication due to impact ionization of electrons contributes to the charge collection efficiency. The reason is the high peak electric field near the n–p junction because of the high concentration of effective space charge introduced in the detector by irradiation. The effect is increased by geometrical effects in the n-in-p type strip detectors because the junction and therefore the high field is at the segmented electrode. It is interesting that irradiated detectors can operate in the multiplication regime because the process is closely related to electric breakdown. The main reason is that in operating conditions considered here, only electrons undergo significant multiplication effects because of much larger multiplication factors [26]. Electrons are attracted to the high field region but are eventually collected by the electrode while holes created by multiplication drift out of the high field and do not contribute more electrons so the multiplication factor stays finite. Another important reason is the negative feed-back effect in irradiated silicon [28]: holes created in the multiplication process get trapped in the radiation induced defects and so reduce the negative space charge

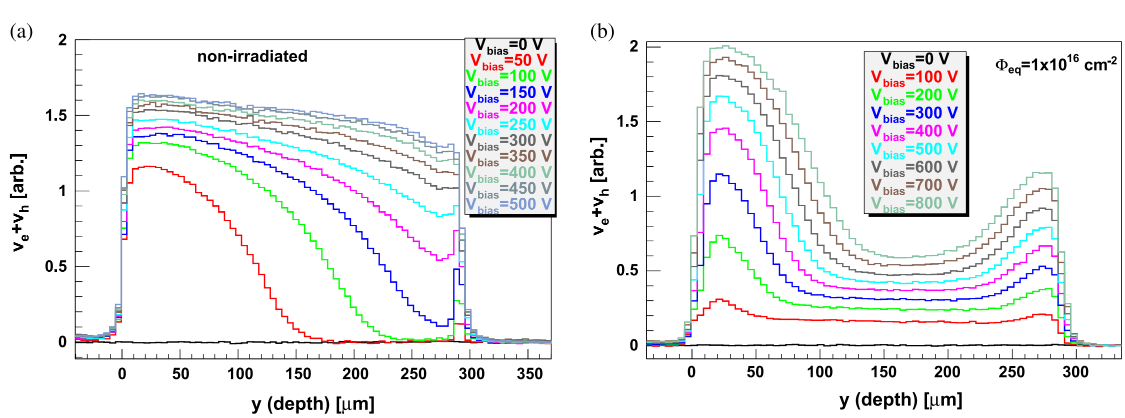

Fig. 1. Velocity profiles measured with 300 μm thick n-in-p strip detectors (a) before irradiation and (b) after irradiation with $\Phi_{eq}=1\times10^{16}$ n_{eq}/cm^2 neutrons and annealed for 80 min at 60 °C. The detector is oriented so that readout strips are at $x=0$ μm and backplane at $x=300$ μm. The curves are ordered as the bias voltages: the almost flat curve at $v_e+v_h=0$ corresponds to measurement at V_{bias}=0 V, and the highest curve to the highest bias voltage.