Silicon Detectors for the LHC Phase-II Upgrade and Beyond – RD50 Status Report

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Abstract. A large R&D program has been underway to develop silicon sensors with sufficient radiation tolerance for LHC-Phase-II trackers and the next generation of collision experiments. Key areas of recent RD50 research include new technologies such as CMOS and Low Gain Avalanche Detectors (LGADs), where a dedicated multiplication layer to create a high field region is built into the sensor. We also seek for a deeper understanding of the connection between macroscopic sensor properties such as radiation-induced increase of leakage current, effective doping concentration and trapping, and the microscopic properties at the defect level. Another strong activity is the development of advanced sensor types, like 3D silicon detectors. We will present the state of the art in silicon detectors at radiation levels corresponding to LHC-Phase-II fluences and beyond. Based on our results, we will give an outlook towards the silicon detectors to be used for particle detectors at future colliders like the FCC.

1. Introduction

Silicon detectors are used in all major high energy physics (HEP) experiments at locations closest to the inter-action point, to obtain track information with high spatial- and time-resolution. The lifetime of detectors in regions with a high particle flux is eventually limited by radiation damage, which reduces the particle detection efficiency and increases the leakage current, in turn requiring a higher voltage supply and stronger cooling of the detectors. The most challenging environment for silicon detectors to-date is the Large Hadron Collider (LHC), which will be upgraded to the High Luminosity LHC (HL-LHC) during the Long Shutdown 3 (LS3). The particle fluence in the most inner regions of the detectors will increase to 10^{16} $\mathrm{n_{eq}/cm^2}$ (HL-LHC). The total integrated luminosity will be higher by about a factor of ten. In the course of the LHC upgrade, the ALTAS and CMS experiments will be upgraded (Phase II upgrade) and their inner trackers will be replaced by all silicon trackers that can withstand the high radiation fluence. RD50 is a joint collaboration between the experiments, sensor manufacturers and experimental- and solid-state-physicists to develop silicon sensors for the Phase II upgrades of the experiments. RD50 played a major role in the development of p-type silicon sensors, the development of radiation hard timing detectors and the mitigation of radiation effects by co-implantation of foreign atoms. As the design of the detectors for the HL-LHC is approaching finalization the focus of the collaboration shifts towards detector technologies for future accelerator projects like the Future Circular Collider (FCC). Foreseen radiation levels at the FCC are as high as $8 \times 10^{17}\,\mathrm{n_{eq}/cm^2}$ [1]. Current technologies could not withstand such high radiation fluence, so that further research and development of novel techniques is needed. RD50 activities are grouped into four main fields of research: Defect and material characterization, device characterization, new structures and full detector systems. In the following, selected results of latest research of the RD50 collaboration in the first three fields are presented.

2. Defect Characterization: Acceptor Removal

Depending on the particle types and energies, radiation creates damage clusters (neutrons), point-defects (low energy electrons and gammas) or a mixture of both (protons). Silicon atoms are removed from their lattice site, creating vacancies and interstitials which can migrate through the lattice and undergo a multitude of nuclear reactions with other defects and impurities forming defect complexes which affect the overall device properties. RD50 characterizes these defect states and their impact on the device operation and seeks ways to mitigate their effects, e.g. by co-doping of foreign atoms. Over the years several defects have been identified, which are shown schematically in fig. 1 a) at their respective location in the silicon bandgap. Shallow defects are mainly responsible for charge carrier trapping, reducing the collection efficiency of detectors, whereas deep levels act as carrier-generation centers, and are found to be responsible for increasing the leakage current. In recent years the $\mathrm{B_iO_i}$ (boron interstitial - oxygen interstitial) defect is of high importance because it is responsible for a process called acceptor removal. In p-type sensors, boron is used as a dopant. A silicon atom which is removed from its lattice site can interact with a boron atom (Watkins replacement mechanism), which subsequently forms the $\mathrm{B_iO_i}$ defect with an oxygen atom [2, 3]. In this process the boron loses its properties as an acceptor and the $\mathrm{B_iO_i}$ defect contributes with positive space charge, changing the overall charge state by a factor of two. The change of effective doping concentration is parameterized by [3]

$$N_{eff}(\Phi_{eq}) = N_{A,0}\exp\left(-c_A\Phi_{eq}\right) + g\Phi_{eq}. \tag{1}$$

The first term describes the inactivation of boron atoms, with the acceptor removal coefficient c_A. The second term describes the formation of acceptor like defects with the introduction rate g. Fig. 1 shows two defect spectra, recorded with the Thermally Stimulated Current (TSC) technique. One can see, that the boron defect was found with higher concentration after proton than after neutron irradiation [4]. The $\mathrm{B_iO_i}$ defect is not affected by thermal annealing of the devices [4].

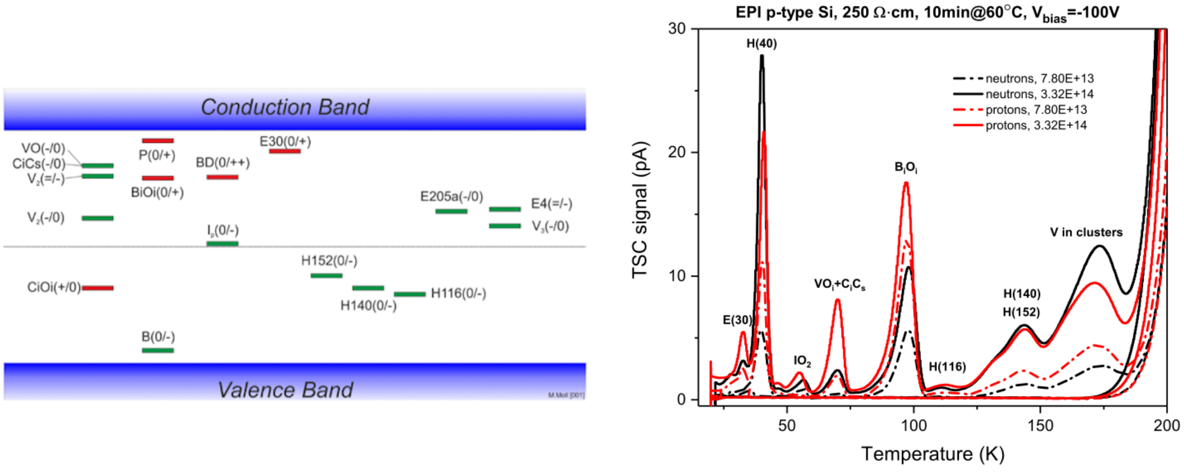
Acceptor removal is especially important for Low Gain Avalanche Detectors (LGADs, see sec. 3). In LGADs a multiplication region is formed by a shallow, highly doped boron implant. Removal of boron reduces the gain of the devices and is currently limiting the radiation hardness of LGADs. A possible way to mitigate the effect of acceptor removal was found to be the co-implantation of carbon into the gain layer [7, 8]. Carbon competes with boron about the formation of complex defect states and thus reduces the amount of deactivated boron. The efficiency of carbon co-implantation to mitigate radiation damage depends on the specific design of the gain layer, the carbon dose and the thermal annealing procedure. It was found that a deep gain layer, with a concentrated high doping density and carbon co-doping, is most radiation hard. An undesirable effect, which is currently being investigated, is that, depending on the carbon dose, a certain fraction of boron is deactivated after co-implantation, effectively reducing the gain already before irradiation.

3. New Structures

To increase the spatial and timing resolution and to increase the radiation hardness of detectors novel sensor designs are being developed. The most promising developments of recent years are Low Gain Avalanche detectors, 3D-detectors and HV-CMOS sensors.

3.1. Low Gain Avalanche Detectors

LGADs feature a highly p-doped gain layer, to create a small region of very high electric field in which charge carrier multiplication through impact ionization can occur. LGADs have a



(a) (b)

Figure 1. a) The most relevant defects at their respective position in the silicon bandgap. Red: donors and Green: acceptors. [5, 6] b) TSC spectra for EPI diodes after proton (red) and neutron (black) irradiation with 7.8×10^{13} n_{eq}/cm^2 (dashed) and 3.3×10^{14} n_{eq}/cm^2 (solid) and annealing for 10 minutes at 60°C [4].

gain of about 10-50, which is lower than the typical gain of Avalanche Photo Diodes (APDs) to avoid breakdown of the devices. Due to their high signal charge at low thicknesses, LGADs will be used as timing detectors in the ATLAS [9], CMS [10] and LHCb [11] experiments. LGADs are radiation hard up to a fluence of about 10^{15} n_{eq}/cm^2. A comparison of the timing resolution of LGADs from different manufacturers after irradiation to 2.5×10^{15} n_{eq}/cm^2 (NDL: 1.5×10^{15} n_{eq}/cm^2) can be seen in fig. 2. The timing resolution before irradiation is in the order of $20 - 30$ ps [13] and is eventually limited by fluctuations of the signal shape originating from inhomogeneous charge deposition inside the sensor bulk.

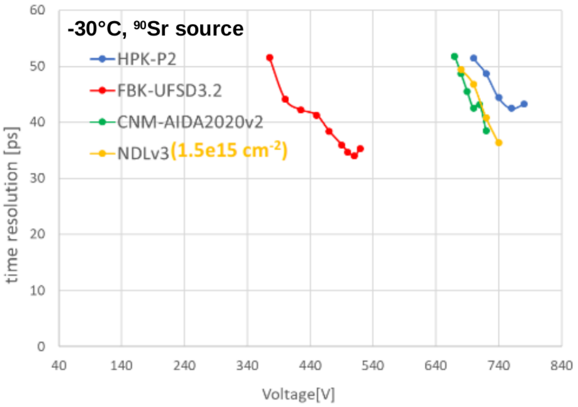
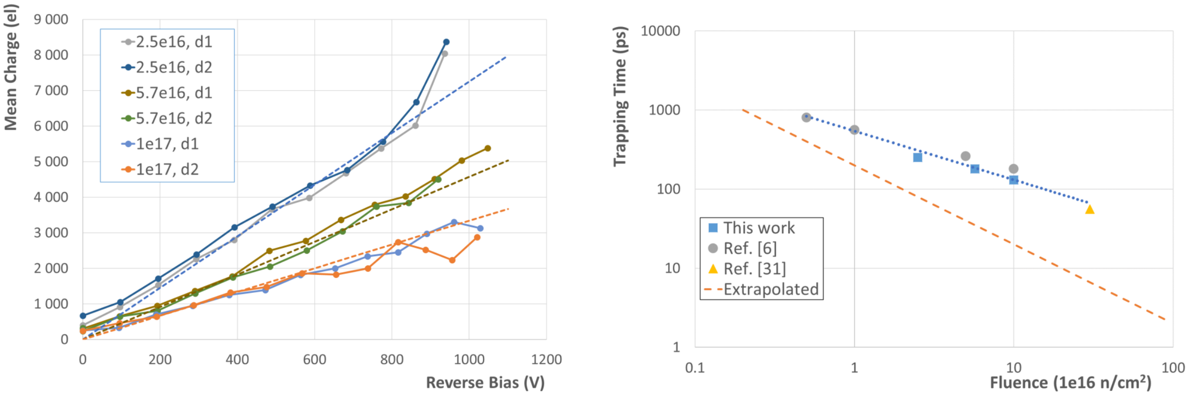


Figure 2. Comparison of the time resolution of LGADs from HPK, FBK, CNM and NDL as a function of bias voltage. Except for NDL, all devices have been irradiated to a fluence of 2.5×10^{15} n_{eq}/cm^2. Measurements were carried out at $-30°C$ using a radioactive source. [12]

Few studies have been carried out at extremely high fluences ($> 10^{17}$ n_{eq}/cm^2). Fig. 3 shows measurements of the collected charge as a function of bias voltage and the trapping time as a function of fluence for 75 μm-thin epitaxial LGADs after neutron irradiation. LGADs were used for these studies, not to exploit their gain feature (which is lost due to radiation damage at much lower fluences), but because they are thin planar detectors. At extreme fluences drift paths of carriers are short, so planar detectors have to be thin, to profit from a higher electric field at a given bias voltage and a higher weighting field. A linear dependence of the signal charge with voltage is observed. The IV characteristics of the devices at high fluence under forward and reverse bias become similar. The trapping time was observed to be larger than anticipated from low fluence extrapolations. There are indications that LGADs are more likely to break down in test-beam measurements due to single events with an exceptionally high charge deposition inside the device. Further studies are ongoing to find the cause of these failures [14, 15]. Besides the radiation hardness of LGADs, an open question is, how to solve the so-called 'fill factor problem'. Currently, LGAD pads are separated by a p-stop implant and a Junction Termination Extension (JTE) at each side of the gain implant to shape the electric field at the boundaries and avoid high electric field peaks, leading to device breakdown. The no-gain region between LGAD pads can be as large as $50 - 60$ μm. Four approaches are currently being investigated to overcome this limitation:



(a) (b)

Figure 3. a) Mean charge as a function of reverse bias voltage for different fluences. b) Comparison of trapping times measured at high fluences with extrapolated values from lower fluence measurements. Measurements were carried out with 75 μm thin EPI LGADs after neutron irradiation. [16].

- Trench isolated LGADs use an etched trench with a depth of several micrometers to isolate pad-regions. With this design it is possible to reduce the no-gain region down to about 6 μm. No negative effect on the leakage current or high voltage stability was observed [17].
- AC-LGADs use a continuous gain layer and thus, in principle, allow for a fill factor of 100%. The read-out pads are AC coupled to a resistive n-layer. The position and timing resolution depend critically on the design of the read-out pads and charge sharing between pads. Resolutions of 40 ps and 1 to 17 μm can be achieved [18, 19, 20]
- Inverse-LGADs also use a continuous gain layer which is located at the back side of the device allowing for a finer segmentation of the DC-coupled read-out pads. The design allows for a 100% fill factor, but the signal shapes become more complex due to the drift of charge carriers to the multiplication layer and the subsequent drift of multiplied charges [21, 22].

- Deep Junction-LGADs use a continuous gain layer which is implanted some micro-meters below the sensor surface, avoiding high field regions at the read-out pads and increasing the drift distance of multiplied charges [23, 24].

3.2. 3D detectors

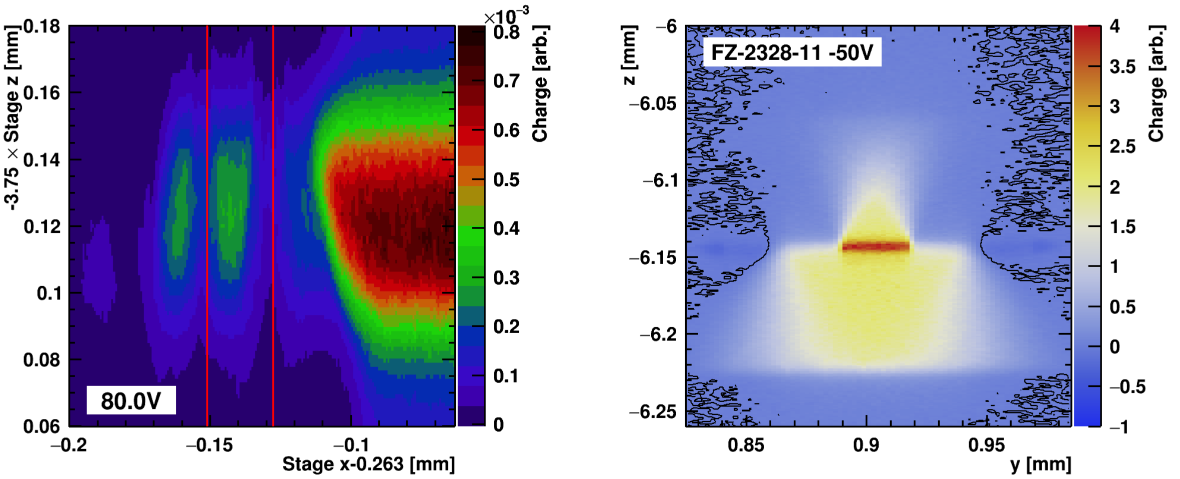
3D detectors decouple the drift distance from the sensor thickness by forming p- and n- columns in the sensor bulk. Typical device thicknesses can be as high as 280 to 300 μm with drift distances of 25 to 50 μm. This design makes 3D detectors radiation hard with a very good timing resolution. The timing resolution is limited by the inhomogeneous electric and weighting field. Current development is ongoing to overcome this limitation in the form of 3D trenches [25, 26]. The radiation hardness of standard 3D-detectors was tested at fluences of 3×10^{17} $\mathrm{n_{eq}/cm^2}$ [27]. The charge collection efficiency decreased to about 20% with an inhomogeneous charge collection depending on the position on the device.

3.3. HV-CMOS

Traditionally pixel sensors are fabricated in a hybrid-design, with separated sensor and readout chip, connected by bump-bonding. The HV-CMOS technique integrates basic read-out electronics on a pixel-level into the sensor design. In the large-fill-factor design, the drift region and read-out electronics are separated by a deep n-well. This design allows for reduced read-out noise and cheaper fabrication on high-resistivity wafers by commercial suppliers. RD50 started the development of an own HV-CMOS chip in 2017 with successful fabrication of two versions on multi-project-wafers (MPW) in the 150 nm technology with LFoundry. The design of MPW2 was improved with respect to its predecessor in terms of leakage current and voltage stability. MPW2 is currently being tested with IV/CV and TCT measurements as well as beam tests. The device has been successfully tested after irradiation to a fluence of 2×10^{15} $\mathrm{n_{eq}/cm^2}$ [28, 29]. A further version (MPW3) is under development. RD50 has developed a custom read-out architecture, based on the CaRIBOu read-out board [30].

4. Two-Photon-Absorption TCT

The Transient-Current-Technique (TCT) is commonly used to characterize silicon sensors by injecting pulsed laser light into the sensor to create electron-hole-pairs and study the resulting transient signal. Usually laser light in the visible (red) or near infrared range is used to excite carriers by single photon absorption (SPA). Within RD50 the use of two photon absorption - TCT (TPA-TCT) to characterize silicon sensors before and after irradiation has been developed. First measurements [31, 32, 33] were carried out at the laser facility of UPV/EHU, Bilbao [34]. After the initial success, a tabletop setup was developed [35], making use of a 1.55 μm laser with a pulse duration of 300 fs to create charge carriers by TPA. Strong focusing optics (NA=0.5 to 0.7) ensure that carriers are only created at the focal point of the objective. The beam radius at the focal point was measured to be $w_0 = 1.4$ μm with a Rayleigh-length of $z_{0,Si} = 12.5$ μm for NA=0.5, and $w_0 = 0.9$ μm, $z_{0,Si} = 6$ μm for NA=0.7 [36]. It is possible to take measurements with true 3D-resolution. The resolution is best perpendicular to the beam axis and can for example be used to study the no-gain region in LGADs, as is shown in fig. 4 a). The beam focal point is moved in depth (z) and across (x) the inter-pad region of an HPK2 LGAD (IP5). The neighboring pad is floating. P-stop and JTE implants can be identified in the measurements (red lines). Fig. 4 b) shows a measurement of a strip detector (FZ-2328-11) at 50 V. The back side of the detector is located at $z \approx -6.225$ mm and the top side at $z \approx -6.14$ mm. Neighboring strips are biased but not read out. The laser light is injected in z-direction from the back side of the device. The strip metalization can be identified as the red coloured region of highest charge. The high charge collection at the strip metalization and the charge that is apparently collected above the strip metalization are artefacts of the reflection of the laser light back into the sensor bulk.



(a) LGAD inter-pad region

(b) Strip detector

Figure 4. TPA-TCT: Charge as a function of depth in the sensor (z) and a second spatial coordinate (x or y) measured with a) an HPK2 LGAD and b) a strip detector.

5. Summary

The RD50 collaboration contributes in many fields to the development of radiation hard detector technologies. Some recent results were presented. Current sensor technologies are still operational after irradiation to fluences expected at future collider projects but suffer from a strong degradation of the collection efficiency. 3D detectors and LGADs have a high timing resolution ($\sim$ 30 ps) but, especially LGADs, need to be developed with improved radiation hardness. Research is ongoing to mitigate the acceptor removal effect by co-doping of carbon. The HV-CMOS technology is a promising candidate to produce inexpensive, low-noise detectors with low material budget. Two MPW chips have been produced and tested successfully and a third generation is under development. New sensor characterization techniques like TPA-TCT, with increased spatial resolution, will help to develop ever smaller and more complex devices.

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