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Silicon Detectors for Future Experiments - RD50 Status Report

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In 2001 the Large Hadron Collider (LHC) and High Luminosity Large Hadron Collider (HL-LHC) were facing the challenging construction of experiments that have to withstand radiation levels never dealt with before in a particle detector. The innermost tracking layers, closest to the beam, are expected to reach an instantaneous luminosity of 7.5×10^{34} cm^{-2}s^{-1}, being the result of 200 simultaneous proton-proton interactions per bunch crossing, and fluence levels of $2{\times}10^{16}$ n_{eq}/cm^2. The LHC experiments' upgrades utilize silicon for the tracking detection layers, which have to withstand a huge amount of radiation at the end of the experiment lifetime without losing the detectors' performance. Therefore, in 2001, there was a need to study the precise damage that those detectors were going to receive, as well as to simulate, understand and mitigate the radiation effects in the silicon detectors.

RD50 is a CERN-based collaboration that started in 2002. The collaboration is dedicated to study radiation-hard semiconductor devices for very high luminosity colliders. The collaboration is finishing its activity by the end of 2023 with 65 institutes and more than 400 members, leaving more than 20 years of radiation damage studies and leading the development of new technologies for radiation-hard semiconductor devices, as well as detector technologies and 4D detectors. The collaboration is organized into four research areas: material characterisation, detector characterisation, new detectors and full detector systems.

During 20 years, different silicon detector layouts and materials have been extensively studied before and after irradiation. The trap centres created inside the silicon have been parametrized, which provided valuable information for the implementation of radiation effects for simulation software tools. There have been strategies to mitigate the radiation damage, as well as new measurement techniques to study the electric field inside the sensor bulk. Silicon detector concepts, including monolithic, 3D and LGAD detectors, have been thoroughly investigated for use inside the HL-LHC. As a result, 3D detectors were installed inside the ATLAS IBL layer, and LGADs are being introduced in the timing detectors of the CMS and ATLAS Phase-II upgrades.

This text aims to summarise more than 20 years of RD50 results as well as some current research.

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1. Introduction

The RD50 collaboration is a CERN-based collaboration for the development of radiation hard semiconductor devices for very high luminosity colliders. It started in 2002 as a continuation of the ROSE collaboration[1] and focusing in the radiation fluences that were facing the Large Hadron Collider (LHC) upgrades[2]. The activity of RD50 will finish at the end of 2023, with 65 institutes and more than 400 members, but most of its current research will continue in the new DRD3 collaboration[3]. This proceeding shows a short summary of the RD50 collaboration.

2. Overview of RD50

2.1 Material characterization

Bulk radiation damage in silicon is parametrized by NIEL (Non-Ionizing Energy Loss) scaling, which is very useful to quantize different particle damage in terms of 1-MeV neutron equivalent. Not all the radiation scales exactly with neutron radiation[4] though, since neutrons generate primary knock on atoms while low energy protons might be more prone to displace atoms in the crystalline lattice through Coulomb scattering. Better approximations for point and cluster defect simulations were developed, which result in a more precise NIEL scaling[5].

Thermally Stimulated Current (TSC) and Deep Level Transient Spectroscopy (DLTS) are two measurement techniques that give detailed information about the energy levels of traps in the silicon band gap generated by radiation damage, and they have been extensively characterized[6]. Different trap centres inside the silicon show different effects, for instance E205a(-/0) and H152K increase the charge trapping and decrease charge collection efficiency[7] while H152(-/0), H140(-/0) and H116(-/0) defects are responsible for causing long term annealing effects[8].

P-type and n-type wafer substrates show different behaviours after irradiation. N-type wafer substrates present type inversion effects[9] and collect holes, whose mobility is slower than electrons, therefore they are more prone to be trapped. To avoid those effects, the Phase-II upgrade for the ATLAS and CMS experiments use p-type bulk silicon[10, 11]. Float Zone or Magnetic Czochralski techniques to fabricate wafer ingots induce different oxygen atom concentrations inside the wafer and show different performance after irradiation. There has been extensive characterization for different wafer types as well as annealing studies to understand better those effects[12, 13].

The RD50 collaboration studies have been focused in silicon mainly but there has been interest in other materials. Especially, Silicon Carbide (SiC) has already been considered in the past but it presented low charge collection efficiency compared to silicon[14]. Today SiC has other applications in nuclear fusion reactors (plasma diagnostic), aerospace detectors and medical dosimetry[15]. SiC productions with intrinsic gain (LGAD SiC) aim to have charge multiplication in the detector[16].

2.2 TCT Transient Current Technique

Transient Current Technique (TCT) is a measurement technique where charge is typically generated with a laser or alpha radioactive source and read out through an amplifier connected to an oscilloscope. This technique gives information about the electric field shape as well as drift velocities inside the detector. There have been modifications to this technique, such as the edge-TCT [17], that shines the laser onto the edge of the detector, which shows the electric field along the thickness of the bulk. An evolution of this technique is the Two Photon Absorption TCT (TPA-TCT), that employs lasers with wavelength in the quadratic absorption regime of silicon. This enables the experimenter to only generate charge in a very small volume around the laser focus and leads to the three dimensional resolution of the method[18, 19].

2.3 Simulations

Reproducing silicon detectors' behaviour with simulation tools allows the experimenter to understand better the sensors' behaviour. Radiation damage is typically not implemented in simulation software kits, but the integration of energy trap levels can imitate the radiation effects. Commercial TCAD (Technology Computer Assist Devices) software solves the Poisson equation in each node of the mesh generated in the simulated structure. TCAD software tools can not simulate the radiation damage but the user can introduce energy trap levels inside the silicon structure. Several models have been described among the RD50 collaboration, taking into account the bulk and surface damage generated by radiation. Some of the radiation trap models are based on that reported by Eremin, Verbitskaya and Li (EVL)[20] traps, which accommodate very well the double junction effect after irradiation. Based on EVL energy trap levels are the KIT model [21], Indian model [22] and Penta Trap Hamburg model [23]. The University of Perugia has a different trap model which takes into account surface damage as well as bulk damage [24] and is suited for LGADs.

Besides commercial TCAD software, other software tools were developed by members of the RD50 collaboration to take into account radiation damage in semiconductors. Weightfield2 is ROOT-based software that calculates the weighting field of the silicon cross section[25]. It can simulate from silicon LGADs to diamond or 3D detectors. TRACS[26] is a simulator of transient currents and charge collection in semiconductor detectors based on the Shockley–Ramo theorem. KDetSim[27] is a full 3D package for charge collection simulations in semiconductor detectors and has been developed using the ROOT framework. It solves the Poisson and Laplace equations for a given space charge for different materials. The simulation of induced current takes into account all relevant physics processes such as drift, diffusion, impact ionization and trapping.

2.4 3D detectors

3D detectors are semiconductor detectors where the electrodes are located in columns through the thickness of the silicon bulk. They were firstly proposed at 1997 by S. Parker et al.[28]. The columns are etched along the bulk with a Deep Reactive Ion Etching (DRIE), and then filled with n++ or p++ type material. The drift distance of electrons and holes, as well as the depletion voltage, is defined by the distance between columns, and the generated charge is given by the thickness of the wafer. 3D detectors have low leakage current (since the depletion voltage is defined by the distance between columns), low trapping and fast signals.

3D detectors were installed in the Insertable B-Layer (IBL) of the ATLAS experiment in 2013 and they will be introduced in the Phase-II upgrades of ATLAS and CMS. 3D detectors are also applicable as timing detectors since the drift distance is defined by the distance between columns[29].

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2.5 Monolithic detectors

The silicon detectors for the ATLAS and CMS upgrades are hybrid detectors, the sensitive part is fabricated in a different foundry than the readout chip, and they have to be bonded together. Monolithic Active Pixel Sensors (MAPS) are detectors fabricated in CMOS foundries where the electronic components are processed with the sensitive silicon volume.

RD50 has a common project called RD50 Multi Project Wafer (RD50 MPW) of Depleted Monolithic Active Pixel Sensors (DMAPS). There has been three designs, RD50-MPW1, RD50-MPW2 and RD50-MPW3 [30–32]. They show good results under irradiations with neutrons up to $2 \times 10^{15}\ \mathrm{n_{eq}/cm^2}$ [33].

Within the collaboration, there are other DMAPS fabrications which allow experimenters to explore other DMAPS technologies and CMOS facilities and to prove the radiation tolerance of the DMAPS detectors[34].

2.6 LGADs

Low Gain Avalanche Detectors (LGADs) are planar silicon detectors with internal gain. They have similar behaviour to Avalanche Photo Diodes (APDs), although with moderate gain. They are typically built as n-on-p diode structures with a boron multiplication layer underneath the n++ readout electrode. When the multiplication layer is depleted, it maintains an electric field close to silicon breakdown ($\sim 3 \times 10^5\ \mathrm{V\,cm^{-1}}$). When electrons reach the multiplication layer, they start an avalanche that generates more electron hole pairs. The extra generated electron hole pairs constitute the gain ($\sim$ 100), typically lower than APDs, and therefore LGADs are called low gain.

LGADs were first presented as high energy particle detectors in an RD50 workshop [35, 36] in 2012. LGADs are used as timing detectors because when fabricated in thin wafers the detectors have short drift distance and therefore the signal is very fast (thus they are also known as Ultra Fast Silicon Detectors [37, 38]). Since 2012, there has been a big development of LGADs for timing detectors, and currently LGADs are the baseline detectors for the ATLAS and CMS Phase-II upgrade timing detectors (the High Granularity Timing Detector HGTD and Endcap Timing Layer ETL respectively).

When irradiated, LGADs show a huge degradation of the gain[39]. The degradation is due to acceptor removal. The acceptor removal constant has been characterized [40], helping to predict the degradation caused by the radiation. The acceptor removal also impacts the performance of High Voltage CMOS detectors, and the study of epitaxial wafers with low resistivity epitaxial layers TSC measurements helped improve understanding of the acceptor removal process[41].

Due to the high electric field at the edge of the implant layers, edges of LGADs have to be protected from early breakdown, typically with a deep n++ implant called a Junction Termination Extension (JTE) [42]. With a JTE, the edge is not active (does not show multiplication) which reduces the LGAD fill factor. The inactive edge of LGADs prevents segmentation (pixels or strips), since for a large fraction of the total area no multiplication happens. Different techniques to mitigate the reduced fill factor have been studied. The iLGAD (inverted LGAD) is a p-on-p LGAD detector that has the multiplication at the backplane (not at the segmented area). iLGADs work very well with thick wafers, but it is challenging to process the backplane when using a thin wafer. Another technique to segment LGADs yields Trench Isolated LGADs, LGADs separated by a trench etched with DRIE. Other techniques to increase the fill factor are pixelated AC-LGADs or DC-RSD (Direct Coupling-Resistive Silicon Detectors). Deep Junction DJ-LGADs have a deeper and more doped multiplication layer, therefore avoiding the high electric field at the edge and increasing the active LGAD area[43].

When inducing high charge close to the multiplication region, a plasma mechanism starts and screens the gain. This gain suppression has been observed with alpha particles, red laser and TPA-TCT measurements with LGADs[44].

3. Conclusions

During more than 20 years, the RD50 collaboration has been studying silicon detectors response to high radiation fluences. New techniques such as TPA-TCT emerged for studying in more detail the electric field of the silicon. There have been a lot of improvements in simulation software to better predict silicon effects of radiation damage. Monolithic detectors, 3D detectors and LGADs have been characterised to understand the behaviour after irradiation.

Most of the HL-LHC upgrades are in production, and a new generation of colliders is envisaged. They will define the requirements for the new generation of high energy particle detectors, and a new collaboration will lead the development of the new detector generations. RD50 leaves more than 20 years of results for radiation hard semiconductor devices with a better understanding of radiation damage in silicon detectors.

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