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Development of radiation hard sensors for very high luminosity colliders - CERN - RD50 project -

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Abstract

The requirements at the Large Hadron Collider (LHC) at CERN have pushed today's silicon tracking detectors to the very edge of the current technology. Future very high luminosity colliders or a possible upgrade of the LHC to a 10 times increased luminosity of 10^{35} cm^{-2} s^{-1} will require semiconductor detectors with substantially improved properties. Considering the expected total fluences of fast hadrons above 10^{16} cm^{-2} and a possible reduced bunch-crossing interval of ≈10 ns, the detector must be ultra radiation hard, provide a fast and efficient charge collection and be as thin as possible. The newly formed CERN RD50 project is aiming to provide detector technologies, which are able to operate safely and efficiently in such an environment. This article describes the approaches and first results of RD50 to develop ultra radiation hard sensors by optimizing existing methods and evaluating new ways to engineer the silicon bulk material, the detector structure and the detector operational conditions as well as investigating the possibility to use semiconductor materials other than silicon.

Keywords: radiation damage; semiconductor detectors; defect engineering

1. Motivation

During the last decade advances in the field of sensor design and improved base materials have pushed the radiation hardness of the current silicon detector technology to impressive performance. It should allow operation of the tracking systems of the Large Hadron Collider (LHC) experiments at nominal luminosity (10^{34}cm^{-2}s^{-1}) for about 10 years [1-3]. However, the predicted 1 MeV neutron equivalent fluences of fast hadrons, ranging from 3×10^{15} cm^{-2} at a radius of R = 4cm to 3×10^{13} cm^{-2} at R = 75cm for an integrated luminosity of 500 fb^{-1}, will lead to substantial radiation damage of the sensors and degradation of their performance. For the innermost silicon pixel layers a replacement of the detectors may become necessary before 500 fb^{-1} has been reached. One option that has recently been discussed to extend

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the physics reach of the LHC, is a luminosity upgrade to 10^{35}cm^{-2}s^{-1}, envisaged after the year 2012 [4]. An increase of the number of proton bunches, leading to a bunch crossing interval of the order of 10 – 15ns is assumed to be one of the required changes. Present pixel detector technology, applied at larger radius (e.g. $R > 20$cm), may be a viable but very cost extensive solution. However, the full physics potential can only be exploited if the current b-tagging performance is maintained. This requires a tracking layer down to $R \approx 4$cm where one would face fast hadron fluences above 10^{16}cm^{-2} (2500fb^{-1}). The current silicon detectors are unable to cope with such an environment. The necessity to separate individual interactions at a collision rate of the order of 100 MHz may also exceed the capability of available technology.

In order to meet these challenges and to have a reliable detector technology, both for particle sensors and electronics, available for an LHC upgrade or a future high luminosity hadron collider, focused and coordinated R&D projects have to be launched now. As a side effect, any increase of the radiation hardness and improvement in the understanding of the radiation damage mechanisms achieved before the luminosity upgrade will be highly beneficial for the interpretation of LHC detector parameters and a possible replacement of pixel layers. Following these motivations the CERN-RD50 project ”Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders” [5, 6] was initiated and approved in June 2002 by the CERN Research Board.

2. Radiation Damage

The three main macroscopic effects on high-resistivity silicon detectors following energetic hadron irradiation are:

- Change of the effective doping concentration N_{eff} with severe consequences for the operating voltage needed for total depletion.
- Fluence proportional increase in the leakage current, caused by the creation of generation-recombination centers.
- Deterioration of charge collection efficiency (CCE) due to charge carrier trapping leading to a reduction of the effective drift length both for electrons and holes.

A detailed description of the radiation effects is beyond the scope of this article and can be found elsewhere (e.g. [7-10]). Recent research on radiation hard silicon detectors was focused on the understanding of the detector behavior after exposure to neutron or charged hadrons fluences of up to 10^{15} cm^{-2}. Beyond this fluence (up to the maximum expected fluence of 1.6×10^{16} cm^{-2} for an upgraded LHC [4]) only little or no data exist. However, already after an 1MeV neutron equivalent fluence of 10^{15} cm^{-2} severe changes to the detector macroscopic parameters are observed which are summarized in the following (data calculated for an annealing of ~14 days at room temperature).

The sign of the space charge changes from positive to negative due to the radiation induced generation of deep acceptors. Accordingly, the depletion of the type inverted detector starts from the n-contact and the overall negative space charge of non-oxygenated silicon requires more than 1000 V for a full depletion of a 300 μm thick detector [7]. Storing at room temperature leads to reverse annealing, a further increase of the negative space charge and depletion voltage respectively (see e.g. [7]). The leakage current increases to $I/V \approx 40$ mA/cm^3 (20 °C) [11] making cooling of the detectors inevitable to reduce noise and power consumption. Due to the high concentration of trapping centers the effective carrier drift length at an electric field strength of 1 V/μm is reduced to about 140-190 μm for electrons and to about 50-80 μm for holes [12, 13]. The combination of trapping and incomplete depletion leads to a strong deterioration of charge collection efficiency (CCE) and consequently signal to noise ratio, both for pixel and strip detectors.

3. Approaches to obtain radiation hard sensors

Based on achievements of past and present R&D projects (e.g.[14-17]) and recent discoveries in radiation hard semiconductor device technologies, three fundamental strategies have been identified by RD50 to develop radiation harder tracking detectors:

- **Material engineering** stands for the deliberate modification of the detector bulk material. One approach is defect engineering of silicon, which e.g. includes the enrichment of the silicon base material with oxygen, oxygen dimers or other impurities. Another approach is the use of other semiconductor materials than Si such as e.g. SiC.

- **Device engineering** stands for the improvement of present planar detector structures by e.g. modification of the electrode configuration or thinning of the bulk material and the development of new detector geometries such as “3D detectors”.

- **Variation of detector operational conditions.** Investigations of the optimum detector operational conditions include for example the operation of silicon detectors at low temperatures or under forward bias.

Although these three approaches might be followed within RD50 along separate research lines it is expected that the ultimate radiation hard detector will be achieved by a judicious combination of two or more of the above-mentioned strategies. Of course this solution will depend strongly on the specific application, the radiation environment and financial restrictions.

Following the above strategies and taking into account the big size of the collaboration as well as the vast scientific program, a scientific organization as presented in Table 1 was chosen (details in [6]). It consists of two major research lines and six sub-projects and implies that the operational conditions are evaluated within every project.

Obviously the different research projects cannot be strictly separated and a strong interaction is expected and encouraged. Furthermore, there are certain studies that are common to several research projects which are organized in working groups dealing e.g. with common mask designs, inter-calibration of microscopic and macroscopic measurement equipment and setups, device simulations or organization of irradiation experiments.

Table 1.: Scientific organization of RD50. The two research lines are coordinated by the spokesperson and deputy and are each subdivided into three projects managed by project conveners.

Material Engineering	Device Engineering
• Defect/Material Characterization	• Pad Detector Characterization
• Defect Engineering	• New Structures
• New Materials	• Full Detector Systems

In the following a brief overview of the six RD50 research projects will be given.

4. Material Engineering

4.1. Defect Engineering

The presently most successful example for defect engineered silicon is oxygen-enriched silicon. It was introduced to the HEP community as DOFZ (Diffusion Oxygenated Float Zone silicon) by the RD48 (ROSE) collaboration in 1998 [16] and consists of diffusion of oxygen (e.g. for 24h at 1150°C) into the silicon bulk from an oxide layer grown via a standard oxidation step. RD48 found that the built-up of negative space charge (corresponding to an increase of depletion voltage after type inversion) after irradiation with high energetic charged hadrons is strongly suppressed. A reduction by a factor 3 in the damage parameter β (slope of N_{eff} vs. particle fluence) was reported [18]. This beneficial effect was recently found to be even more pronounced after gamma irradiation [19, 20] as shown in Fig. 1. While the standard silicon type inverts and shows a strong built-up of negative space charge the effective space charge of the oxygenated silicon remains almost constant and even a small generation of donors is observed. However, after neutron irradiation no effect [9, 10] or only small influences [21] of the oxygenation on the

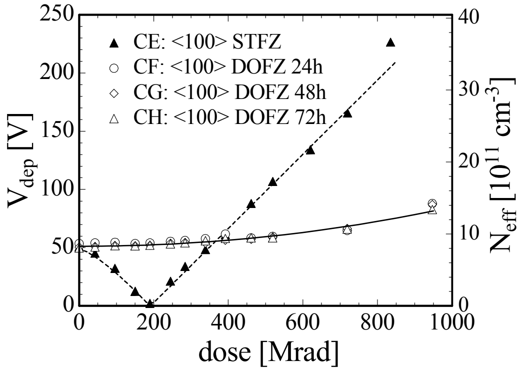

Fig. 1. Co^{60}-gamma irradiation of standard and oxygenated (DOFZ) silicon detectors [20].

radiation hardness have been observed. The leakage current after hadron irradiation is not influenced by the oxygen content [22] while after gamma-irradiation it is reduced in oxygen enriched silicon [20].

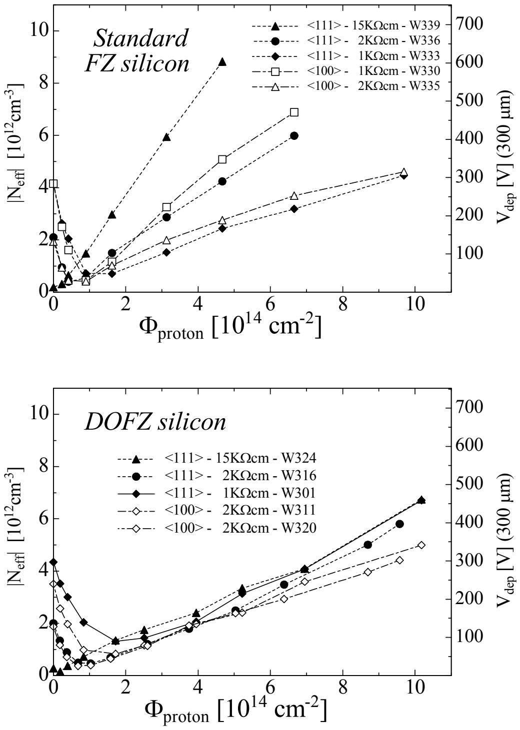

Fig. 2. Proton irradiation of standard (upper figure) and oxygenated (lower figure) detectors produced by ST Microelectronics (Italy) from Wacker (Germany) silicon.

Recent investigations also show that radiation hardness is not as clearly depending on the oxygen concentration as thought in the beginning. This is demonstrated in Fig. 2. Two identical sets of silicon wafers originating from different ingots were processed with and without an oxygenation step. As a result a wide variation is observed for the standard silicon set while for the oxygenated set only little difference is seen. Furthermore, some standard samples show exactly the same behavior as their oxygenated counterparts. A confusing result, which several groups also have observed for oxygenated and standard detectors produced by Sintef (Norway) (e.g [23]). These experiments clearly demonstrate that besides the oxygen content also other up to now not identified parameters play an important role. This and other open questions regarding oxygen-rich silicon are discussed in more detail in [9, 10].

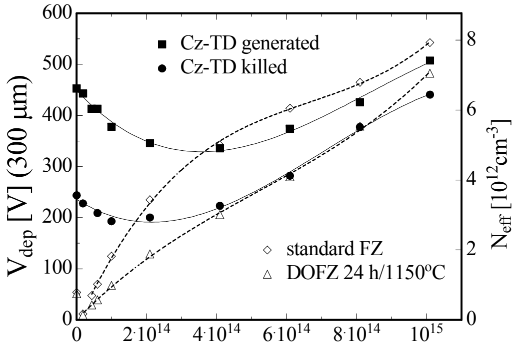

Fig. 4. Pion irradiation of standard FZ, oxygenated FZ (open symbols) and two types of high resistivity Czochralski silicon (filled symbols) [21].

Czochralski silicon (CZ) with a resistivity that is suitable for detector applications has only recently become available. Since it is grown in a quartz crucible it has high oxygen content in the order of some 10^{17} to 10^{18}cm^{-3}. First irradiation experiments with charged hadrons show remarkable and very promising results [21]. As shown in Fig. 4. the overall change of depletion voltage is smaller than in oxygenated or standard FZ silicon. Even more surprising are TCT (Transient Current Technique) measurements showing that the material is not type inverted after a fluence as high as 10^{15} cm^{-2} (190MeV pions) [24]. Therefore the increase in depletion voltage is believed to be due to the formation of donors (most probably thermal donors), which overcompensate the radiation-induced acceptors. Since also the price of this material is expected to be lower than for FZ material [25], CZ is a good material for p^+-n detectors since even after high fluences the high electric field will remain on the p^+-electrode (no type inversion). Meanwhile first full size strip detectors have been produced and successfully tested [25, 26] and irradiation tests are under way. The only known drawback of a material with very high oxygen content is that it requires special attention to avoid thermal donor creation (and thus a change of effective doping concentration) during processing.

Other approaches under investigation by RD50 are the use of epitaxial silicon (showing similar radiation hardness properties as CZ silicon [21]) or silicon enriched with oxygen dimers [27], hydrogen or other impurities like e.g. germanium.

4.2. Defect and Material Characterization

Defect and material characterization as well as computer simulations of defect formation and defect properties are indispensable tools to achieve a profound understanding of the radiation damage process. Only on such basis can the link between microscopic defects and macroscopic detector properties be fully understood in order to defect engineer the sensor material in a coordinated way.

Only recently has a clear correlation between radiation induced defects in silicon and changes of macroscopic detector properties been revealed [28]. It was shown that the values of the detector depletion voltage after gamma irradiation can be coherently predicted using defect parameters described in [28, 29]. One of the characterized defects was tentatively attributed to be the long searched V_2O (Di-Vacancy-Oxygen). A defect accredited to play a key role in the radiation damage process not only after gamma, but also after hadron irradiation [7, 30]. Computer simulations (AIMPRO) have predicted that this defect has an acceptor level at 0.57eV below the band gap [31], which coincides well with the value of 0.55eV given in [28]. However, another group within RD50 also claims to have possibly identified the V_2O defect [32] having an acceptor level at 0.46eV and a second acceptor level at 0.20eV above the conduction band. The later observation coincides with the prediction in [31] that V_2O should have a second acceptor level, which however is expected to be at 0.11eV above the conduction band. Both groups are now working together within RD50 to solve this riddle. Independent of the disclosure of the physical and chemical structure of the observed defects the finding of a defect with electrical properties explaining macroscopic detector properties in itself is a huge step forward in the understanding of radiation damage.

The material and defect characterization group within RD50 is furthermore working on issues like thermal donors (formation, stability, influence on defect generation during irradiation etc.), presence of hydrogen and its influence on oxygen diffusion and defect formation and the impact of the nitrogen and carbon content on defect kinetics. Theoretical solid state physicists are working on the simulation of the physical properties of defects in silicon as well as on defects in other new materials, currently under investigation in RD50. Last but not least, microscopic characterization techniques are improved and developed (e.g.[33]).

4.3. New Materials

It is well possible that a fluence of $10^{16}cm^{-2}$ corresponds to the operating limit of silicon sensors for temperatures close to room temperature. Other sensor materials are therefore under investigation. Diamond detectors are investigated by the RD42 collaboration [15] and silicon carbide (SiC) and semi-insulating GaN, which have recently been recognized as potentially radiation hard, are now studied by RD50.

In Table 2 we list some characteristics of 4H-SiC compared with diamond, silicon and GaN. The relatively large band gap leads, as for diamond and GaN, to a very low leakage current. Since the ionization energy lies between those of diamond and silicon also the resulting average e-h pair generation of 51/μm for a minimum ionizing particle (*mip*) lies between those of silicon (110/μm) and diamond (36/μm). Finally, the displacement threshold of 25eV indicates a potentially higher radiation hardness than silicon. However, this has to be tested since SiC is not monoatomic but a compound material.

Semi-insulating 300μm-thick SiC substrates equipped with ohmic contacts were tested in the past with a ^{90}Sr β-source [34]. A response of ~2000e$^-$ (500V) has been measured corresponding to a charge

Table 2: Properties of Diamond, 4H-SiC, Si and GaN crystals.

Property	**Diamond**	**4H-SiC**	**Si**	**GaN**
E_g [eV]	5.5	3.27	1.12	3.39
μ_e [cm^2/Vs]	1800	800	1500	1000
μ_h [cm^2/Vs]	1200	115	450	30
e-h energy [eV]	13	8.4	3.6	~8-10
Displacem. [eV]	43	25	13-20	~10-20
Density [g/cm^3]	3.52	3.21	2.33	6.15
Radiation length X_0 [cm]	12.2	8.7	9.4	2.7
e-h pairs / X_0 [10^6 cm^{-1}]	4.4	4.5	10.1	~2-3

collection distance of ~39μm. Due to polarization effects, most probably caused by a high defect concentration in the bulk, this signal was found to decay very quickly and irreversibly down to 800e$^-$. This undesirable effect led to the conclusion that SiC is no promising material for particle detection.

However, epitaxial 4H-SiC with very high crystal quality is now available and Schottky barrier detectors have been studied with α-particles from an ^{241}Am source [35-37]. 100% charge collection efficiency (CCE) has been measured observing no polarization effects. Radiation damage of these devices has been tested with a ^{60}Co γ-source and 8.2MeV electrons up to a dose of 40MRad and with 24GeV/c protons up to a fluence of $\approx 9\text{x}10^{13}\text{cm}^{-2}$. Although the effective space charge density (N_{eff}) was observed to decrease from the initial value of $7.7\text{x}10^{15}\text{cm}^{-3}$ to $1.4\text{x}10^{15}\text{cm}^{-3}$ after the highest electron dose of 40 MRad, no influence on the CCE was observed [36]. Also after the highest gamma dose and proton fluence a CCE of 100% was observed at room temperature. Furthermore, the leakage current decreased after irradiation [37].

First studies on the response of epitaxial 4H-SiC Schottky barriers to β-particles from a ^{90}Sr-source have been performed in the framework of RD50 [38, 39]. Schottky diodes of 1-2mm diameter have been manufactured on epitaxial wafers produced by CREE (Durham, USA). The thickness of the active epilayer with $N_{eff}\sim 6\text{x}10^{14}\text{cm}^{-3}$ was 21μm. The charge collection signal is stable and reproducible, showing an absence of priming and polarization effects. The collected charge increases as a function of $V^{1/2}$ and saturates at approximately 240V, with a maximum value of ~1100e$^-$, corresponding to ~100% charge collection efficiency over the total epilayer thickness. RD50 is now planning to measure the charge collection efficiency of 4H-SiC detectors produced with thicker epilayers in the range 30-70μm and to produce microstrip and pixels devices with epitaxial 4H-SiC to investigate the feasibility of position sensitive detectors with this material.

RD50 is also developing GaN based detectors. First tests of SI-GaN Schottky detectors with alpha particles showed a CCE of 100% (for details see[40]).

5. Device Engineering

5.1. Pad Detector Characterization

The research activity within this project is focused on systematic studies of the macroscopic pad detector properties by means of IV/CV and CCE (laser, mips and alpha particles) measurements during isothermal and isochronal annealing experiments performed after irradiation with different particle types and fluences. In a first step these activities will be performed with devices remaining from previous research activities (e.g. RD48) and later on with newly developed or defect engineered material. The main goal is to measure and parameterize the change of detector properties up to the maximal expected fluence for an upgraded LHC ($1.5\times10^{16}\text{cm}^{-2}$). Such parameterization is not only useful for calculations of LHC-like damage scenarios but is also an input for understanding basic radiation damage processes as well as testing the NIEL (Non Ionizing Energy Loss) - hypothesis. Lately several violations of this hypothesis have been observed and still a wide range of particle types and energies has not been investigated with respect to the NIEL. Of special interest are e.g. irradiations with low energy protons for which a NIEL violation is predicted [41] and with high energetic neutrons in order to unravel the charged hadron-neutron puzzle of oxygenated silicon [7]. Also irradiations with very high energy electrons have so far only rarely been performed [42].

5.2. New Structures

There are several approaches to optimize the detector structure to achieve, even after the bulk material has been severely radiation damaged, a sufficiently high CCE in a required collection time.

An optimized multi-guard ring systems allows to push the operation voltage up to ~1000V and thus allows for full depletion up to higher irradiation fluences. However, the hazard of a breakdown is still present and the power consumption is raised. Detector structures requiring only a reasonable low operation voltage are therefore under development.

So-called “3D-detectors“ [43] and “Semi-3D detectors” (for details see [44]) offer this feature. The electrodes of a 3D-detector are an array of vertical columns that are penetrating the detector bulk. The

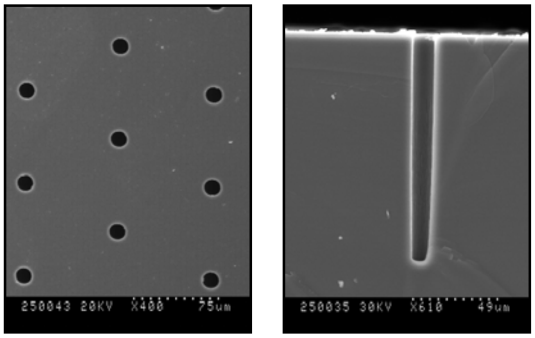

Fig. 5.: Holes in silicon obtained by inductively coupled plasma, diameter 10μm, pitch 85μm . Top view (left) and cross-section of a 130μm deep hole (right) [45].

first processing step is therefore the formation of holes by dry etching, electrochemical etching or laser drilling [45] (see Fig. 5.) with a diameter of ~5-10μm and a pitch of ~30-100μm. These holes are then filled with p$^+$ and n$^+$ electrode material (or are metallized) to form p$^+$-n junctions (or Schottky contacts). Such a structure has still the same ionization layer as standard planar detectors (e.g. 300μm), but due to the smaller distance between the electrodes the depletion voltage is smaller and the charge collection is much faster.

Thinning down planar detectors to about 50μm thickness is another approach and different thinning techniques are investigated (e.g.[46]). Thin detectors offer a low material budget and have a reduced depletion voltage. However, the collectable charge is strongly reduced (e.g.[47]), which sets higher requirements on the readout electronics.

5.3. Full Detector Systems

The Full Detector Systems subgroup of RD50 is the subgroup closest to the application of the improved radiation hard detectors into future HEP experiments. Its goals are the investigation of miniature and full size strip and pixel detectors made with different silicon substrates and detector geometries, using LHC speed electronics. Already, there have been studies performed with prototypes of the future LHC-b vertex locator detector using both p-strip and n-strip read-out and irradiated at the CERN PS. CCE studies confirmed the superiority of n-side read-out after irradiation, and showed limited signal loss (20%) even after a fluence of 7x10^{14}pcm^{-2}[48, 49]. Other CCE studies performed on segmented detectors have also observed an improvement for oxygenated silicon material compared with standard silicon. Since the charge collected at a given voltage is reduced both by the trapping, for which n-side read-out helps, and by the changes to the effective doping concentration, for which oxygenated silicon material helps, the combination of these techniques yields a good performance of tracking detectors up to the fluences expected for the LHC.

As mentioned previously, similar studies have to be performed on such detectors using the findings of the other subgroups of RD50 to study their performance at fluences characteristic of the post-LHC era.

6. Conclusion

A need for R&D on ultra radiation hard tracking detectors for very high luminosity colliders has been identified and consequently the R&D collaboration “CERN-RD50” was formed. RD50 follows various scientific approaches to tackle this challenge including Defect Engineering, Device Engineering and the Optimization of Operational Conditions. It is expected that in order to achieve ultra radiation hard sensors a combination of the above mentioned approaches depending on the radiation environment, application and available electronics will be the best solution for the next generation high luminosity tracking detectors. First scientific results and an outline of future work have been given.

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