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Radiation tolerant semiconductor sensors for tracking detectors

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On behalf of the RD50 Collaboration[1]

Abstract

The CERN RD50 collaboration "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders" is developing radiation tolerant tracking detectors for the upgrade of the Large Hadron Collider at CERN (Super-LHC). One of the main challenges arising from the target luminosity of $10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$ are the unprecedented high radiation levels. Over the anticipated 5 years lifetime of the experiment a cumulated fast hadron fluence of about $10^{16}\,\mathrm{cm^{-2}}$ will be reached for the innermost tracking layers. Further challenges are the expected reduced bunch crossing time of about 10 ns and the high track density calling for fast and high granularity detectors which also fulfill the boundary conditions of low radiation length and low costs. After a short description of the expected radiation damage after a fast hadron fluence of $10^{16}\,\mathrm{cm^{-2}}$, several R&D approaches aiming for radiation tolerant sensor materials (defect and material engineering) and sensor designs (device engineering) are reviewed and discussed. Special emphasis is put on detectors based on oxygen-enriched Floating Zone (FZ) silicon, Czochralski (CZ) silicon and epitaxial silicon. Furthermore, recent advancements on SiC and GaN detectors, single type column 3D detectors and p-type detectors will be presented.

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Keywords: Radiation damage; Semiconductor detectors; Silicon particle detectors; Defect engineering; SLHC

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1. Introduction

The Large Hadron Collider (LHC) at CERN is expected to deliver first proton–proton collisions before the end of 2007. At the end of the following commissioning phase the design luminosity of $10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ at proton energies of 7 TeV shall be reached for the two multipurpose experiments ATLAS and CMS. The exposure of all detector components to high radiation levels arising from the high luminosity operation has been well anticipated. A long R&D phase preceding the construction of the detector components gives presently confidence that the detectors will survive an integrated luminosity of $500\,\mathrm{fb^{-1}}$, corresponding to a 10-year operation of the LHC. However, it is obvious that the main part of the presently used detectors would not survive or would not be operational for the proposed upgrade of the machine to a 10 times higher luminosity (Super-LHC or SLHC) with a proposed accumulated luminosity of $2500\,\mathrm{fb^{-1}}$ [1,2]. A dedicated R&D program is therefore urgently needed and partly already under way to develop new detector technologies for the innermost tracking layers and replacements for most of the outer detector components.

Fig. 1 gives an indication about the cumulated hadron fluences after an integrated luminosity of $2500\,\mathrm{fb^{-1}}$. For the innermost tracking layers fluences of more than $1\times10^{16}\,\mathrm{cm^{-2}}$ are expected. Besides these unprecedented high radiation levels the increase in the track density and the proposed reduction of the bunch crossing time from 25 ns to about 10 ns will pose the most severe challenges. Faster detectors with finer granularity are therefore needed. This means for example that the pixel detectors will have to cover the tracking volume to higher radii (see shaded areas in Fig. 1) pushing the microstrip detector

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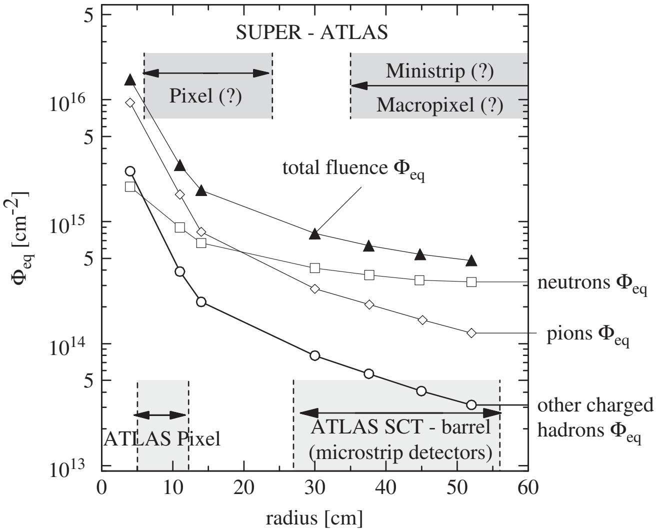

Fig. 1. Hadron fluences expected in the inner SUPER-ATLAS detector after 5 years (2500 fb^{-1}). The data have been taken from a calculation for the ATLAS detector [3] and are scaled to the expected SUPER-ATLAS integrated luminosity. While the exact SUPER-ATLAS geometry is not yet known, the presented data can be used as a rough estimate.

system further outside. The microstrip detectors themselves will have to be reduced in strip size making the difference between microstrip and pixel detectors less and less distinct as, e.g. expressed in the naming of some newly developed devices as “macropixel” or “ministrips”. In any case the increased granularity will call for more cost effective technologies than presently existing since otherwise a detector upgrade could not be afforded.

The RD50 collaboration “Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders” [4] was formed in 2002 with the aim to develop semiconductor sensors matching the above mentioned SLHC requirements. These efforts are now closely linked to the increasing upgrade activities of ATLAS and CMS which are expressed by the increasing frequency of their upgrade workshops [5,6].

Only some specific topics of the RD50 scientific program will be described. More detailed information can be found in Refs. [4,7], in recent conference proceedings [8–11] and in literature cited there.

2. Radiation damage and strategies to cope with it

2.1. Radiation damage

The radiation damage to silicon sensors can be divided into two general types of damage. The first is caused by Ionizing Energy Loss (IEL) and produces surface damage. Positive charge is accumulated in the oxide (SiO_2) and interface states at the Si/SiO_2 interface are created as a consequence. This can influence the detector capacitance, rise the noise and might have a negative impact on the breakdown behavior. The second type of damage is arising from Non-Ionizing Energy Loss (NIEL) which is causing the creation of crystal defects in the silicon bulk. It is this type of damage which is presently the main concern and which expresses itself in the following three detector deterioration effects:

- A change of the effective doping concentration with severe consequences for the electric field profile and the operating voltage needed for full depletion.
- A fluence proportional increase of the leakage current, increasing the electronic noise and the power consumption and dissipation.
- An increase of the charge carrier trapping leading to a reduction of the effective drift length both for electrons and holes and thus to a reduction of the charge collection efficiency (CCE) of the detector.

Since there are only very little experimental data regarding the impact of an irradiation to a fluence of $10^{16}\,\mathrm{cm}^{-2}$ quantitative values can only be extrapolated from experiments performed at lower fluences. Assuming an annealing of 14 days at room temperature after exposure to a 1 MeV neutron equivalent charged hadrons fluence of $10^{16}\,\mathrm{cm}^{-2}$ the following can be extrapolated. The leakage current density rises to a level of $\approx 400\,\mathrm{mA/cm^3}$ (20 °C) or $\approx 25\,\mathrm{mA/cm^3}$ (−10 °C) [12] rendering cooling of the detectors inevitable to reduce noise and power consumption. The effective trapping times for holes and electrons is reduced to less than 200 ps corresponding to a drift length of about 30 μm for electrons and only 7 μm for holes [13,14]. The difference between hole and electron drift length is thereby mainly arising from the three times higher drift velocity of the electrons.

While for the leakage current and the trapping no strong variations between different (defect engineered) silicon materials have been observed, the change of the effective doping concentration is strongly influenced by the choice of the silicon material (see Section 3). In standard n-type FZ silicon the net space charge changes from positive to negative due to the radiation-induced generation of deep acceptors. Accordingly, it is expected that the depletion of a type inverted p^+–n detector starts from the n^+-contact. Following this assumption and taking, e.g. the data given in Ref. [15] for FZ silicon the depletion depth would be reduced to about 50 μm for a detector operating at 500 V. This number must be taken with care however. On the one hand, the increase of the effective space charge depends strongly on the used silicon material and on the other hand the formation of the electric field is not as simple as stated above. A so-called “double-junction” is appearing after irradiation with high fluences [16,17] being formed by electric fields growing from the front and the back contact. This makes further experimental and simulation work necessary to understand the electric field distribution and its impact on the CCE in highly irradiated devices.

Each of the above-mentioned effects is changing in time at room temperature (annealing). While the leakage current and the electron trapping are annealing in a beneficial way,