Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research A 581 (2007) 314–317
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

RD50 status: Developing radiation tolerant materials for ultra radiation-hard tracking detectors

R. Bates*

Department of Physics and Astronomy, University of Glasgow, Scotland, UK

This work is presented on behalf of the CERN RD50 collaboration

---

Abstract

The need for ultra-radiation hard semiconductor detectors for the tracker regions in high energy physics experiments at a future high luminosity hadron collider, like the proposed LHC Upgrade, has led to the formation of the CERN RD50 collaboration. The R&D directions of RD50 follow two paths: understanding radiation effects and finding mitigation through the use of new silicon materials, device engineering and optimised operations, all of which are covered in this paper. An emerging picture of a possible design of a future tracking detector is presented.

PACS: 85.30.De; 29.40.Wk; 29.40.Gx; 61.82.FK

Keywords: Radiation hard; Semiconductor detectors; Particle physics

---

1. Introduction

The proposed running luminosity for the two general purpose experiments (ATLAS and CMS) based on the LHC is $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which corresponds to an integrated luminosity for 10 years of operation of $500\,\mathrm{fb}^{-1}$. For this luminosity the simulation of the ATLAS experiment predicts an integrated radiation fluence at a radius of 4 cm from the interaction point of $3\times10^{15}\,\mathrm{cm}^{-2}$ 1 MeV equivalent neutrons. The radiation fluence falls with increasing radius from the interaction point; while the particle mix changes as the fraction of backscattered neutrons increases at larger radius.

A proposal for an upgrade of the present LHC machine, known as super-LHC or SLHC [1,2], is now seriously being considered. This will increase the luminosity by an order of magnitude over the present design. Associated with such a luminosity increase is an increase in the bunch crossing rate from 25 to 10 ns. The integrated luminosity for the proposed 5 years of operation will be $2500\,\mathrm{fb}^{-1}$. The expected fluence inside a detector for such high luminosities has been predicted by scaling simulation data from the present ATLAS design and is shown in Fig. 1 [3]. The expected integrated radiation fluence 4 cm from the interaction point is as high as $10^{16}\,\mathrm{cm}^{-1}$ 1 MeV equivalent neutrons. The average number of charged tracks per bunch crossing inside the tracker acceptance also increases by an order of magnitude.

The challenges of the higher radiation environment, high bunch crossing rate and higher track multiplicity all necessitate new tracking detectors for the general purpose experiments. Such detectors will have to have not only a higher radiation tolerance but also high granularity and faster collection times and readout electronics than presently used in the LHC based experiments.

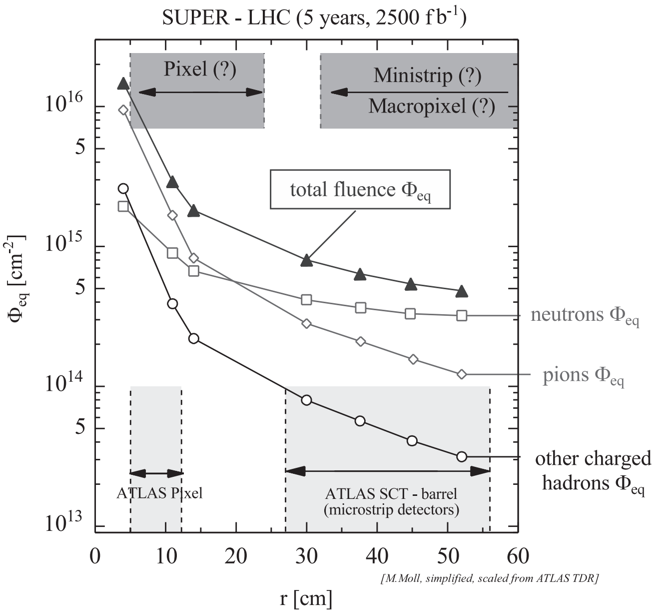
The CERN based RD50 collaboration was formed in 2002 to address the requirements for such a detector upgrade for SLHC operation. The devices developed within RD50 are also applicable to upgrades of present detectors based on the LHC; for example the LHCb VELO and the ATLAS pixel detector b-layer replacement.

Only a few specific research topics covered by the RD50 collaboration are covered here. More comprehensive information can be found in Refs. [4,5].

---

*Tel.: +44 141 330 6435; fax: +44 141 334 5881.
E-mail address: r.bates@physics.gla.ac.uk

0168-9002/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2007.07.131



[M.Moll, simplified, scaled from ATLAS TDR]

Fig. 1. The expected radiation fluence, after 5 years of SLHC running, as a function of radial distance from the interaction point inside the ATLAS detector.

2. Radiation damage fundamentals

The detrimental effects of radiation on a semiconductor detector can be divided into two groups. The first is the long term ionisation effects of the device; which is typically characterised as a build up of positive charge at the silicon–silicon oxide interface on the surface of the detector. This will change the electrical performance of the device for quantities dependent on the surface characteristics. Such characteristics are the inter-strip resistance and capacitance and the high voltage electrical behaviour of a detector.

The second effect is caused by non-ionising energy loss (NIEL) mechanisms inside the bulk of the detection material. The macroscopic effects from NIEL are an increase in device leakage current, a change in the effective doping density of the material, and a reduction in the charge collection efficiency of a detector.

The leakage current increase results in a higher shot noise component in the readout chain. Fortunately this increase is mitigated to an extend at (S)LHC experiments by the requirement for fast shaping times. However, the high currents increase the power dissipated inside the detector volume and increase the voltage drops on the detector's bias resistors and external power cables.

The radiation induced change in effective doping density is due to the destruction of donor levels and the creation of acceptor levels inside the material. As a consequence the near intrinsic n-type bulk material of standard silicon detectors behaves as if p-type. This effect is known as space charge sign inversion (SCSI). As a consequence the electric field profile inside the device changes; for example in a standard strip detector with p-type strips and an n^--type bulk, after SCSI the high field region moves from under the strips to under the uniform back contact.

The reduction in the charge collection efficiency results in a reduction in the measured signal and therefore in a drop in the signal-to-noise ratio of a detector. For a given charge carrier the collected charge as a fraction of deposited charge (Q_c/Q_0) for a fully depleted detector is

$$\frac{Q_c}{Q_0} = \exp - \frac{\tau_c}{\tau_t} \tag{1}$$

where τ_c and τ_t are the carrier collection and effective trapping times, respectively. The carrier trapping time is reduced by radiation introduced trapping and scattering centres inside the material. The trapping time has been shown to be inversely proportional to fluence, with little difference observed for electrons of holes [6,7]. However, the drift velocity for electrons and holes, (μ_n and μ_p), are different with $\mu_n = 4.45 \times 10^6\,\mathrm{cm\,s^{-1}}$ and $\mu_p = 1.6 \times 10^6\,\mathrm{cm\,s^{-1}}$. As a consequence the charge collection times of electrons are about 3 times faster than for holes. Therefore the collected charge is higher after irradiation if electrons are collected rather than holes. This can be achieved by attaching the amplifier to a segmented n-type doped contact which is positively biased with respect to the p-type contact.

The effect on the above properties as a function of time has to also be taken into account. The leakage current and electron trapping have been shown to fall with time (known as annealing) while the hole trapping increases slightly [8]. The effective doping concentration either falls before SCSI or increases after SCSI, an effect known as reverse annealing.

The RD50 collaboration has aimed at increasing the understanding of the microscopic effects of radiation and the macroscopic observables in a detector up to the radiation fluences relevant for SLHC. The knowledge of radiation effects are applied to new silicon materials and device engineering to obtain detectors that can be operated at the highest fluences.

A detailed description of the underlying microscopic defects is beyond the scope of this article and can be found elsewhere (e.g. Refs. [3,9]).

3. New silicon materials

Silicon detectors with a high oxygen interstitial concentration have been shown to exhibit a lower rate of increase in effective doping density as a function of proton fluence than standard float zone (FZ) silicon [9]. The materials studied in the past were oxygen doped FZ material (DOFZ). Within the framework of RD50 detectors fabricated from epitaxial silicon (EPI) grown on a highly doped Czochralski (Cz) substrate and from high resistivity Cz or Magnet Cz (MCz) silicon have been fabricated [7,12]. The oxygen concentration in Cz and MCz are uniform throughout the depth of the material, at $10^{18}\,\mathrm{cm^{-2}}$ while the DOFZ material has a non-uniform oxygen doping as a function of depth at an average doping density an order of