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Silicon Sensors for HEP Experiments

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Abstract

With increasing luminosity of accelerators for experiments in High Energy Physics the demands on the detectors increase as well. Especially tracking and vertexing detectors made of silicon sensors close to the interaction point need to be equipped with more radiation hard devices. This article introduces the different types of silicon sensors, describes measures to increase radiation hardness and provides an overview of present upgrade choices of HEP experiments.

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Silicon Sensors for Experiments in High Energy Physics

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Abstract. With increasing luminosity of accelerators for experiments in high energy physics the demands on the detectors increase as well. Especially tracking and vertexing detectors made of silicon sensors close to the interaction point need to be equipped with more radiation hard devices. This article introduces the different types of silicon sensors, describes measures to increase radiation hardness and provides an overview of present upgrade choices of experiments in high energy physics.

Keywords: silicon sensors, radiation hardness, HEP

1 Introduction

High energy physics (HEP) is probing the nature of matter. With large accelerators new particles are generated and huge detection systems identify the type and properties of those to challenge predictions of particle physics theories. The measurements agree very well with current theories, but more accurate measurements or detection of very rare events can help to identify the best descriptions of our universe. That pushes the acceleration systems to higher energy and luminosity. High luminosity comes with a large number of simultaneous tracks to be distinguished and a very harsh radiation environment. The detection systems closest to the interaction points are tracking and vertexing systems, which mainly rely on silicon sensors as sensitive elements and are strongly affected by increasing luminosity.

1.1 Radiation damage in silicon sensors

The upgrade of the LHC to the high-luminosity LHC will push the peak luminosity to $5 - 7.5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the integrated luminosity to $3000\,\mathrm{fb}^{-1}$ [1] for the CMS and ATLAS experiments. This results in an equivalent fluence of up to $2 \times 10^{16}\,\mathrm{n_{eq}/cm^2}$ for pixel sensors and $1 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$ for strip sensors (Fig. 1). The total ionizing dose reaches 10 MGy and 700 kGy, respectively.
The silicon sensors will suffer from radiation damage due to displacement damage in the bulk and ionization in the silicon oxide at the surface of the bulk silicon. Displacement damage generates vacancies and interstitials, which can

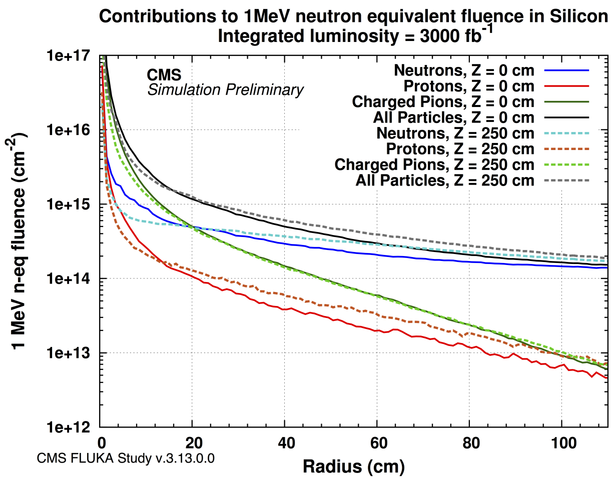


Fig. 1: Expected radiation environment for the CMS Tracker at the HL-LHC [2]. The expected equivalent fluence for different particle types and regions is plotted vs. the radial distance to the interaction point.

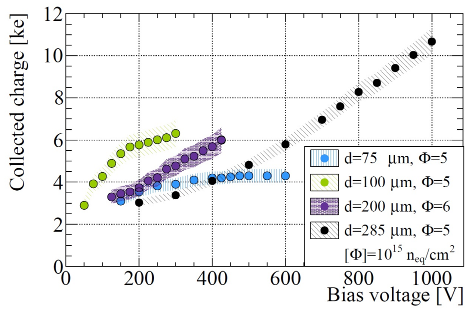
form higher order defects combining with themselves or with impurities (e.g. oxygen, carbon, phosphorus, boron) in the crystal lattice. These defects show up as energy levels in the band gap of silicon [3]. Depending on the energy level and the interaction cross sections these defect levels can act as generation centers for volume generated leakage current, as trapping centers to fix mobile charges for a short period of time (long enough to get lost for fast electronics) and as acceptors/donors modifying the effective space charge and the shape of the electric field. Ionizing radiation leads to a positive charge of the silicon oxide and generation/activation of interface traps which both alter the electric properties close to the surface [4, 5]. One effect for example is the attraction of mobile electrons to the positively charged oxide creating an accumulation layer of electrons, which could short circuit n-doped strips/pixels. This has to be prevented by measures to isolate the strips by p-stop or p-spray techniques [6, 7].

2 Silicon sensor types

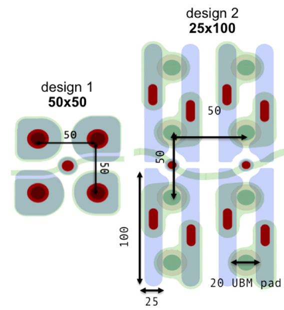
This section discusses silicon sensor types of current interest mainly for the upgrades of the LHC experiments.

2.1 Planar silicon sensors

Manufacturing of planar silicon sensors is a mature technology, which is being developed and applied since more than 35 years [8]. The sensors are based on structured pn-junctions operated under reverse bias. Sensors with structured p-type strips/pixels on an n-type bulk (p-in-n) collect holes and have been used in



(a) Collected charge vs. bias voltage for pixel sensors of different thicknesses. [10]



(b) Design of very small pixel cells using common punch-through connections for biasing without bump-bonded read-out chip. The dimensions are in µm [11].

Fig. 2: Illustration of the main developments for planar silicon sensors: thin devices and small pixel cells.

large scale detectors up to now. Trapping is much more severe for this kind of sensors due to the slower drift of holes and therefore higher trapping probability. To gain higher radiation resistance (as required for the strip trackers at HL-LHC or vertex detectors) electrons need to be read out [9] and n-in-p or n-in-n sensors are used. For even higher radiation one needs to increase the electric field strength in the sensors. Increasing the operation voltage has a practical limit, therefore thinner sensors are being developed, which exhibit more collected charge at moderate voltages compared to thick sensors after high irradiation (Fig. 2a). The initially smaller charge compared to thick sensors is accepted in view of increased longevity, reduced leakage current and lower material budget. For vertex detectors the high density of tracks requires higher granularity of the sensors and therefore smaller pixel cells (e.g. $2500\,\mu m^2$ cells in Fig. 2b). Small cells also allow to reduce the individual readout channel noise, which enables the detection of smaller signals after severe radiation damage.
The two general purpose experiments at LHC, ATLAS and CMS, will receive new tracking systems for the HL-LHC phase equipped each with $200\,m^2$ of n-in-p type silicon sensors [12, 13]. Also the vertex detectors will be replaced and equipped with several square meters of planar silicon pixel sensors. These big systems will be exceeded in size by the CMS High Granularity Calorimeter, which will be equipped with $600\,m^2$ of planar silicon pad sensors [14].

2.2 3D sensors

To overcome the penalty of less generated charge when reducing the drift distance in planar sensors, the electrodes were proposed to be manufactured in form of columns into the bulk [15]. These so called 3D sensors allow lateral drift to closely spaced columns, while keeping the thickness high and thus maintaining the charge generated by the penetrating particles. The devices typically show more than 50% charge collection efficiency after severe irradiation ($>5 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$) and low bias voltages between 150 V and 200 V. This sensor type requires specialized and lengthy process steps and is currently offered by three vendors. This sensor type exhibits an inefficiency for particle detection when the particle traverses one of the columns, which can be overcome by placing the sensors at an angle to the incoming particles. 3D sensors were first deployed in the ATLAS Inner B-Layer, for which production yields of about 65% were reached [16, 17].

2.3 HV-CMOS sensors

Monolithic Active Pixel Sensors (MAPS) combine sensitive elements and readout electronics and can overcome the limitations of hybrid systems such as connectivity (costly bump-bonding) and very low mass. The largest application of such MAPS is the future ALICE Inner Tracking System [18], which will be equipped with $10\,\mathrm{m^2}$ of these detectors. Although MAPS are widely used (from CMOS cameras to the STAR experiment [19]), they suffer a lot from radiation damage and the readout speed is slow compared to the requirements for proton collisions at LHC (40 MHz). A fairly new development is the usage of industrially available HV-CMOS processes to allow biasing of the substrate up to about 150 V leading to a collection of the charge carriers by fast drift and not by slow diffusion as for conventional CMOS processes. Therefore, HV-CMOS sensors are much more radiation hard and can be considered for applications in a much wider field including LHC experiments [20]. Still, there are several challenges to overcome like time resolution, power consumption and production of large sensors, which requires stitching for sizes larger than about $5\,\mathrm{cm^2}$. The first application of HV-CMOS sensors in a particle physics experiment is at Mu3e [21, 22].

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