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Radiation hardness of p-type silicon detectors

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ABSTRACT

Finely segmented silicon detectors made with n-side readout on p-type substrate have emerged as the most promising choice for the replacement of the tracker systems for the CERN LHC upgrade to higher luminosity. They have practically assumed the status of baseline devices for the silicon microstrip layers of the upgrades, and are now also being considered as possible candidates even for the innermost pixel layers. A review of the reasons for the success of the p-type bulk devices is presented here.

1. Introduction

In the CERN Large Hadron Collider (LHC) experiments the innermost silicon tracker detectors will be exposed to hadron fluences of about 10^{15} 1 MeV neutron equivalent (n_{eq}) cm^{-2} for an integrated luminosity of $500\,fb^{-1}$. A strong physics case for extending the integrated luminosity has been proposed and well received by the high-energy physics community [1]. This goal should be achieved by upgrading the instantaneous luminosity of the machine by a factor of about ten from the present $10^{34}\,cm^{-2}\,s^{-1}$. The planning assumptions for the upgrade to the super LHC (SLHC) are presently as follows [2]:

- Phase I: reaching $2\times10^{34}\,cm^{-2}\,s^{-1}$ around 2013;
- Phase II: reaching $10^{35}\,cm^{-2}\,s^{-1}$ incrementally from around 2017.

The structure of the physics events is determined by the centre-of-mass energy and will not change, while the background from minimum bias events will increase by more than one order of magnitude. In the upgraded experiments, there is no physics reason to improve spatial and momentum measurement precision, so the key point is to maintain tracking and vertexing performance of the present LHC detectors. This fact alone has a big impact on the sensor design. The granularity of the detectors will have to increase considerably to keep a similar hit occupancy to the present LHC, due to the increase in the number of interactions per bunch crossing from ~20 to 300–400. Another known challenge of the SLHC will be its unprecedented radiation environment. A factor of ten higher radiation damage is expected in the vertex and inner tracker layers of the upgraded detectors. The needed radiation tolerance will be up to $2\times10^{16} n_{eq}\,cm^{-2}$ for the pixel sensors closest to the beam line (B-layer).

Fig. 1 shows the simulated fluences [3] after $3000\,fb^{-1}$ as a function of the radial distance from the interaction point, of charged hadrons and backscattered neutrons for the preliminary layout of the upgraded ATLAS detector at the SLHC [4]. A factor of two safety margin is attached by ATLAS to these values for qualification purposes, so the required radiation tolerance is twice that reported in Fig. 1. The flux is composed of backscattered neutron from the calorimeter volume and charged hadron from the interactions. The neutron and charged hadron fluences are equal just above 20 cm radius; at inner radii the flux is dominated by charged particles, while at outer distances by neutrons. The pixel sub-detector includes the B-layer at 3.7 cm and three pixel layers at 5, 7 and 11 cm radii. The required radiation tolerance is 25, 14, 7.8 and $3.6\times10^{15} n_{eq}\,cm^{-2}$ from the B-layer to the outer radius, respectively. The innermost of the three short strips layers at 38 cm radius needs to be tolerant to about $7\times10^{14} n_{eq}\,cm^{-2}$, while the first layer of long strip detectors is located at 85 cm, requiring a tolerance to $3.2\times10^{14} n_{eq}\,cm^{-2}$. An extensive research activity has been started already for a few years to confront the challenge presented by these extremely high fluences. Very encouraging results have been obtained. In particular, planar p-type sensors have been proven capable to sustain radiation levels corresponding to most of the sensor layers anticipated in the tentative layout of the new experiments. The status of the development of radiation hard p-type silicon sensors for the SLHC is reviewed here. Most of these results have been obtained in the framework of the CERN-RD50 [5] collaboration.

2. Radiation hardening of silicon detectors

After the development of the planar processing in the 1980s [6,7], segmented silicon detectors have been used to cover ever larger areas in high-energy physics experiments (see Ref. [8] for a review). The reason for this success is their low mass, high speed

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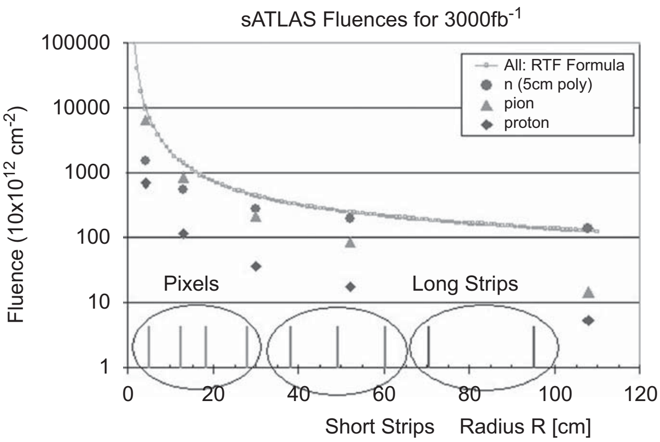

Fig. 1. Anticipated fluences as a function of radius in the present tentative layout of the upgraded ATLAS detector at SLHC.

and resolution. All the more recent experiments use mainly silicon sensors for tracking and vertexing. The radiation environment of present and future hadron machines is however very challenging due to the damage induced by fast hadrons to the silicon crystal. The created electrically active defects can change the effective doping concentration ($N_{\rm eff}$) and therefore the full depletion voltage ($V_{\rm FD}$), the reverse bias leakage current ($I_{\rm R}$) and the increase in charge carrier trapping. The increase in $V_{\rm FD}$ leads to higher operating voltages, the increase in $I_{\rm R}$ to higher power dissipation (with the risk of the uncontrolled rise of the current due to self-heating of the silicon, called thermal run-away) and electronics noise, and finally the increase in charge trapping to a severe reduction of the signal induced by minimum ionising particles (mip's). The combination of these effects would eventually make the detectors inoperable after a certain dose.

2.1. N-side readout for improved radiation tolerance

During the preparation for the LHC, the qualification of silicon detectors in terms of radiation hardness relied on the ability of providing a bias voltage significantly higher (50%) than the $V_{\rm FD}$ [9]. According to this approach, silicon detectors could not be used for several inner layers of the anticipated layout of the various experiments because the expected final $V_{\rm FD}$ is well in excess of 1000 V.

On the other hand, change of $V_{\rm FD}$ is not the most direct method for evaluating the performances of the sensors. The measurement of the charge collected as a function of the bias voltage (CC(V)) with a segmented detector is a better measurement of its functionality. To adequately assess the radiation tolerance, the evaluation of the CC(V) after various doses of irradiation is the more accurate method. Because the CC(V) is influenced by the characteristic of the readout electronics, a readout system compatible with SLHC requirement (especially in terms of shaping time and clock speed) should be used. All the measurements reported here have been performed with a readout system based on an SCT128 40 MHz clock (LHC speed) analogue amplifier. The signal was induced by fast electrons (mip's) from a ^{90}Sr radioactive source, triggered by a plastic scintillator. The CC(V) characteristic is the most probable value of the energy spectrum recorded by a flash ADC as a function of the bias voltage. The system is normalized to the most probable value of a non-irradiated 300-μm-thick detector (~24,000 electrons).

With the CC(V) characteristics, a substantial advantage can be demonstrated with the appropriate choice of the readout geometry of a segmented detector. The segmented electrodes can be obtained with n-type or p-type implantation on n-type silicon (n-in-n or p-in-n) or n-type implantation on p-type silicon (n-in-p). In these sensors, the signal is mainly formed by the electron current in the case of n-side readout and by the hole current in the case of p-side readout. It has been proposed that for the same value of $V_{\rm FD}$ (only dependent on the substrate type and radiation dose) the n-side readout (both n-in-n and n-in-p) can provide a better signal after irradiation [10,11]. This is due to the stronger electric field at the n-side in irradiated silicon sensors, resulting in faster collection of electrons with respect to holes.

An important difference between n-in-n and n-in-p detectors is that in the first case, double-sided processing is needed to implant edge protection structures on the backside (guard rings) with significant impact on the complexity and cost (up to 50% higher) of the processing with respect to p-type substrates that only require front-side guard ring implants. This turns out to be a very important factor for experiments where a large coverage area is required due to cost reduction and easier handling of single-sided devices.

3. P-type detectors for high-energy physics

P-type sensors require at least one more processing step than p-in-n sensors. The segmented n-type electrodes (strips or pixels) need to be isolated by means of an interposed implantation. The most used methods are p-stop implants, blanket p-spray or a combination of the two methods [12,13]. This was the reason for choosing p-in-n geometry in high-energy physics experiments until the LHC. In the past, n-side readout has been implemented in double-sided detectors for bi-dimensional information [14,15], but when single-sided devices where envisaged, p-in-n was preferred due to the simpler production processing. The hadron accelerators have evolved significantly in terms both of energy and luminosity, and the more recent machines require a larger area to be covered by much improved radiation-tolerant sensors. P-type silicon detectors for n-side readout with single-sided devices were proposed to face the novel radiation environment [16,17] with reduced processing costs. The first attempt was made with full-size ($6\times6\,{\rm cm}^2$) ATLAS barrel detector geometry. The devices were produced by Micron Semiconductor Ltd [18] with individual p-stop isolation. This work proved the feasibility of this type of devices. The first comparison of CCE with p-in-n sensors after a radiation dose of $4\times10^{14}\,{\rm p\,cm}^{-2}$ was performed, confirming the expectations of superior charge collection [19]. The size of these devices did not easily allow further studies at much higher fluences; therefore a program for developing small-size ($1\times1\,{\rm cm}^2$, 80 μm pitch, 128 strips) strip detectors has been started by the University of Liverpool in collaboration with CNM Barcelona [20].

A few of these miniature devices have been irradiated at different fluences up to $7.5\times10^{15}\,{\rm cm}^{-2}$ with 24 GeV/c protons in the CERN-PS [21]. The CC(V) measurements after such an unprecedented dose gave new perspectives for using planar silicon devices in the SLHC environment, fully confirming the advantages of the n-side readout as the more efficient radiation hardening method. A very clear energy spectrum (Fig. 2) with a most probable value of ~7000 electrons at 800 V was measured, despite a predicted $V_{\rm FD}$ higher than 3000 V (in the most favourable case of oxygen-enriched silicon) or 9000 V (for standard silicon) [22]. These results indicated that planar silicon sensors with n-side readout were capable of operating after doses of hadron irradiation much higher than that predicted by the changes of the $V_{\rm FD}$ and well within the requirements of SLHC. These early results originated a wide R&D effort to perform systematic investigations of p-type sensors after irradiation to various doses of protons and