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Enhanced efficiency of segmented silicon detectors of different thicknesses after proton irradiations up to $1 \times 10^{16}\, n_{eq}\, cm^2$

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ABSTRACT

Silicon sensors are used as tracker and vertex detectors in all the main current high energy physics experiments because of their unsurpassed performance in terms of granularity, resolution and speed while offering relatively low mass. The anticipated future upgrade of the present Large Hadron Collider (the Super LHC, sLHC) will require similar performance in terms of speed and low mass, but with increased granularity and a factor of ten more radiation tolerance. The radiation hardening of silicon detectors, given the sLHC requirements, is being investigated from many angles: different silicon materials, different electrode geometries and varying the thickness of the active substrate. It has been proposed that possible advantages could be achieved with detectors thinner than the accepted standard of 300 μm. The charge collection properties of microstrip detectors made on thin (140 μm) and standard p-type devices is here presented after various proton irradiation fluences up to $1 \times 10^{16}\, n_{eq}\, cm^{-2}$. This is about the maximum dose expected for the pixel layers (excluding the innermost b-layer) located at the lower distance from the p–p collisions, where the reduction in thickness of the silicon sensors is a beneficial feature, due to the requirements for low mass at the innermost space points.

1. Introduction

It is accepted that one the of most challenging issues for the experiments in the future sLHC will be the radiation tolerance of the tracking and vertexing silicon detectors [1,2]. In fact, these devices will be extensively used in the inner volume of the two general purpose (ATLAS, CMS) upgraded experiments to cover a total surface up to $\sim 200\, m^2$ in both. The hadron radiation dose in this inner volume depends on the radial position and will be a factor of ten higher (for $6000\, fb^{-1}$ of integrated luminosity) than the present LHC, with a maximum fluence above 2×10^{16} 1 MeV neutron equivalent $(n_{eq})\, cm^{-2}$. This dose is so severe that the ability to use silicon sensors fabricated with the standard planar technology is questioned. The most exposed will be the pixel sensors located at the smaller distance from the interaction region. These devices also need to be as light as possible, in terms of material in the tracking volume, to present the least distortion to the particle tracks. The possibility of enhanced radiation tolerance by means of thinning the devices with respect to the accepted 300 μm standard (see e.g. [3]) matches the requirement for low mass in the pixel sensors. A possible drawback is the smaller signal associated with the thin detectors. The sLHC sensors will be used for tracking minimum ionising particles (mip). The mip signal is proportional to the path length in non-irradiated silicon, so thinner devices deliver a smaller signal by the ratio of the thicknesses of the sensors. Nonetheless the small size of individual pixel elements is associated with low electronics noise due to the reduced input capacitance to the readout electronics. The smaller noise allows operating the sensors with a lower signal while keeping a signal over noise (S/N) ratio adequate for fully efficient tracking. These effects point in the direction of some possible advantage associated with the choice of silicon pixel detectors thinner than the standard 300 μm for the sLHC applications.

2. Effects of the detector thickness on the radiation tolerance of silicon detectors

It is well accepted that n-side readout of segmented silicon detectors results in a much improved radiation tolerance with respect to the more standard p-side readout (see e.g. [4–6]). This is due to a shorter collection time of the electron with respect to the hole signal that significantly reduces the charge trapping. The charge trapping increases with fluence [7] to the point that the charge carrier lifetime is shorter than the time required to contribute to the signal (the collection time, t_c). In practice, this results in a detector with a collection distance shorter than the

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actual thickness of the devices. As an example, using a trapping time calculated according the parameterisation in [7], the collection distance for carriers travelling at the saturation velocity of electrons in silicon is about 24 μm after $1\times10^{16}\,n_{eq}\,cm^{-2}$. In a situation where the collection distance is significantly shorter than the detector thickness, thinner detectors could have an advantage with respect to standard 300 μm ones, due to a possible higher average strength of the electric field over the active volume of the irradiated sensor for the same applied voltage. This would result in a shorter t_c, with less trapping and consequently higher signal.

3. Experimental results

A comparative study of the charge collection properties of neutron irradiated thin and thick silicon microstrip detectors has been reported in [8,9]. The investigated neutron doses are up to $2\times10^{16}\,n_{eq}\,cm^{-2}$. In the sLHC applications, the radiation damage at the inner radii is though mainly due to charged hadrons emerging from the proton–proton collisions [10], therefore a comparison of the performance after proton irradiations is more directly relevant.

Small size ($\sim1\times1\,cm^2$) 80 μm pitch (128 strips) silicon AC coupled detectors have been designed by the University of Liverpool (in the framework of the RD50 collaboration [11]) and processed by Micron Semiconductor Ltd. on 140 and 300-μm-thick p-type high resistivity and high purity silicon wafers. These sensors where processed with n^+-doped readout strips (n-in-p) for improved radiation tolerance. They have been characterised after irradiation with the charge collection measurement set-up in the semiconductor detector centre of the University of Liverpool (LSDC). A radioactive ^{90}Sr source provides fast electrons with energy deposition in silicon comparable to minimum ionising particles. The readout is based on the SCT128 40 MHz analogue chip [12]. The system is calibrated with a non-irradiated 300 μm thick sensor with known most probable energy deposition from a mip ($\sim$24,000e^-). The set-up is also equipped with a high voltage source and current measurement unit. A Keythley 237 model was used (with an upper limit of 1100 V), later upgraded with an ISEG SHQ222 to a maximum applicable voltage of 2000 V. This upgrade has been dictated by the extremely good voltage breakdown performances of irradiated Micron detectors that can in many cases withstand higher voltage than the previous limit of 1100 V.

The thin and thick sensors have been irradiated in pairs to the various nominal fluencies (with an estimated error of 10%). After irradiation the sensors have been stored at temperatures well below 0 °C to suppress annealing. The measurements were performed in a freezer at about −25 °C, unless differently indicated.

Fig. 1 shows the charge collected as a function of the bias voltage (CC(V)) for detectors irradiated with protons to various fluences up to $1\times10^{16}\,n_{eq}\,cm^{-2}$. The proton irradiations were performed in two different facilities: the IRRAD1 at the CERN/PS, with 24 GeV/c protons [13] and the Compact Cyclotron of the University of Karlsruhe, with 26 MeV protons [14]. The 24 GeV/c protons have a radiation damage factor of 0.52 and the 26 MeV protons of 1.85 relative to 1 MeV neutrons. The irradiations at the Cyclotron are always performed at sub-zero temperatures, preventing any annealing of the electrical properties of the detectors after irradiation. At the IRRAD1 facility, most of the sensors were irradiated in a cool-box (with the temperature ranging between 0 and 5 °C), with practically no annealing. Only the irradiation to $3.1\times10^{15}\,n_{eq}\,cm^{-2}$ has been performed with the sensors kept at the area temperature ($\sim$30 °C), allowing for an annealing corresponding to about 10–15 days at 20 °C. It is expected that this annealing time has a beneficial effect on the charge collection [15,16], so the CC(V) characteristic of the sensor irradiated at the above dose are enhanced with respect to the performance immediately after irradiation (and compared to all the other measurements of Fig. 1). Fig. 1 documents the degradation of the CC(V) with fluence, and the fact that the damage of the two different energies protons are well comparable. It is noticeable that the charge collected after the highest dose goes up to about 6000e^-, significantly more than the less the 2000e^- figure expected from the anticipated collection distance of 24 μm.

Figs. 2–5 show the comparison of the CC(V) by 140 and 300 μm FZ n-in-p detectors irradiated with 24 GeV/c protons to 1.9, 3.1, 5.6, $10\times10^{15}\,n_{eq}\,cm^{-2}$. After the two lowest doses, the CC(V) of the thin and thick devices is similar at the lower voltages (although a slightly faster rise of the signal is observed in the pair irradiated to $1.9\times10^{15}\,n_{eq}\,cm^{-2}$) until saturation of the charge collected by the 140 μm thick detector. After the two highest doses, the thin devices show a more important faster rise of the signal with voltage, exhibiting a superior charge collection than the standard ones at the whole range of applied voltages. It should be remarked that the collected charge goes up to over 8000e^-, again much higher than the expectations from the measurements of the charge trapping.

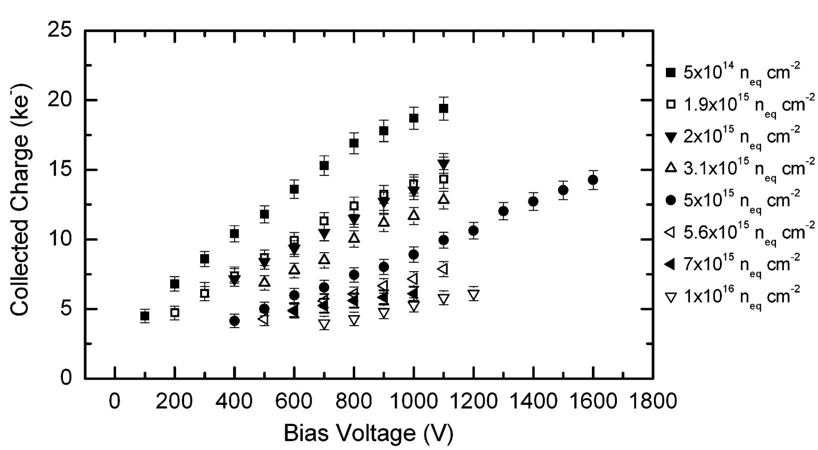

Fig. 1. Collected charge as a function of the bias voltage (CC(V)) for standard (300 μm thick) n-in-p detectors irradiated in cold with 24 GeV/c (open symbols) and 26 MeV (solid markers) protons. The only exception is the $3.1\times10^{15}\,n_{eq}\,cm^{-2}$ series irradiated with 24 GeV/c protons at the area temperature of 30 °C. As a consequence, the CC(V) at this dose appears slightly enhanced.