Investigation into the charge collection efficiency of prototype microstrip sensors for the CBM Silicon Tracking System

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Abstract.

Double-sided silicon microstrip sensors are known to be sensitive to the radiation dose received during operation. The lifetime fluence for the Silicon Tracking System of the CBM experiment is estimated as $10^{14}$ 1 MeV n$_{eq}$ cm$^{-2}$. In order to maintain the signal-to-noise ratio sufficiently high during all the time of operation we study the newest sensor prototypes irradiated to the single and double lifetime doses. The results of the tests are addressed in this paper.

1. Introduction

The Compressed Barionic Matter (CBM) \cite{1} experiment is planned as a part of the future FAIR facility in Darmstadt, Germany \cite{2}. The aim of CBM is to explore the phase diagram of strongly interacting matter at high net baryon densities and moderate temperatures. The Silicon Tracking System (STS) \cite{3} is the core tracking detector of the CBM experiment. STS will be placed in the 1 Tm dipole magnet 30 cm downstream of the target. It will provide track reconstruction and momentum determination of the charged particles. Signals registered by the charge sensitive electronics will be used to determine interaction points of the charged particles with the silicon sensors. During the operation of CBM, STS will cope with up to $10^3$ charged particles per central Au-Au collision. As a result of the high interaction rates of up to 10 MHz, sensors are expected to be sufficiently radiation hard to survive fluences up to $10^{14}$ 1 MeV n$_{eq}$ cm$^{-2}$.

STS will employ double-sided double-metal n-type silicon microstrip sensors. They are planned to be produced in different sizes: 2.2$\times$6.2, 4.2$\times$6.2, 6.2$\times$6.2 and 12.2$\times$6.2 cm$^2$ outer dimensions. Prototype sensors are shown in Fig. 1. On each sensor, there are 1024 strips per side with 58 $\mu$m pitch. To maintain a good position resolution in the bending plane of the magnet and to avoid excessive fake interaction points, strips on the p-side are oriented by 7.5$^\circ$ with respect to the sensor edge. Corner strips on both edges are interconnected via second metal layer so that sensor read-out routing lines can be achieved from one sensor edge only, matching the detector module concept.

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2. Sensors characterization before and after irradiation

In order to evaluate the sensor performance the following procedures have to be accomplished before and after irradiation [4]:

- the study of the electrical characteristics of a sensor by measuring the leakage current as a function of the reverse bias voltage (IV) and the bulk capacitance (CV curve);
- the determination of the signal-to-noise ratio by measuring the signal amplitude from the radioactive source and the baseline width in the attached read-out electronics.

In particular the signal-to-noise ratio is the figure of merit for the detector performance. In this ratio the signal is defined as a mode of the particle energy distribution and the noise is estimated as the root-mean-square of the baseline variation in a particular channel.

2.1. Experimental setup

For the test purposes the prototype sensors are installed into printed circuit boards (PCB), which are populated with pitch-adapters in order to adjust the step of the traces from 58 µm to 130 µm. In-built R-C-L filters are mounted on the PCB after the high voltage input. In order to protect the wire-bonds, non-conductive glue was applied. A particular PCB configuration is shown in Fig. 2, the group of 128 central strips per side is ready for the charge collection measurements.

The measurements were performed in a custom made light-tight thermal enclosure with the temperature and humidity control. The top view of the setup is depicted in Fig. 3. Radiators with fans are placed aside, scintillator and photomultiplier are under the sensor. Right above of the sensor there is a collimator with the radiation source. In order to suppress the leakage current during data taking and to avoid annealing, sensors were constantly kept at the temperature of -10°C and at a relative humidity of 30 – 50%.

Figure 1. Silicon microstrip sensors in four different sizes: 2.2×6.2, 4.2×6.2, 6.2×6.2 and 12.2×6.2 cm².

Figure 2. Sensor installed into a printed circuit board (PCB).

Figure 3. Top view of the radiation source setup.

The detection of minimum ionizing particles (MIPs) is an ultimate task for the silicon sensors. To mimic MIPs, a ⁹⁰Sr β-source was used. It produces electrons with a continuous energy spectrum and \( E_{\text{max}} = 2.28 \text{ MeV} \). A plastic scintillator (2.5 cm thick) with an attached photomultiplier was used to produce external trigger signals. The most energetic particles were selected by requiring a sufficiently high signal amplitude in the scintillator. In order to keep the interaction region of the same size as the sensitive area, a system of collimators was implemented in the setup.

A dedicated read-out chip was designed for the STS. STS-XYTER is suitable for the signal detection from double sided silicon microstrip sensors [5]. This chip is currently under evaluation.
thus we can not use it for charge collection studies yet. For the purpose of the laboratory tests the Alibava system [6] was involved. This system uses the Beetle ASIC [7] which was applied for the LHCb Vertex Detector, Silicon Tracker and RICH [8]. Front-end boards of the Alibava were customized according to our needs: the fan-out with two 68-pin ERNI connectors was wire-bonded to the pitch adaptor of the Beetle chip.

2.2. Electrical and signal measurements
As it was mentioned above, the IV and CV measurement must be performed before and after irradiation. A particular example of electrical characteristics is shown in Fig. 4. The leakage current is strongly dependent on the temperature, it has been lately normalised to 20°C and to the sensor size. As one can see on the plots, the bulk capacitance does not change with the irradiation, but the leakage current increases by a factor of 1000, as expected.

![Figure 4. Comparison of the leakage current (left) and the bulk capacitance (right) as a function of the applied voltage for non-irradiated and irradiated sensors.](image)

The noise level was estimated as the baseline width for each channel. All edge and noisy channels are removed from the analysis. The events with a single channel amplitude higher than 5σ of the noise level fill the signal distribution histogram. Geometrical considerations show that for the small crossing angles (i.e. close to perpendicular incidence) the total charge should not spread by more than 3 neighbouring strips. The search algorithm for the charge clusters starts from the strip with the highest signal-to-noise ratio and then moves to the left and to the right, stopping whenever the signal falls below the threshold.

![Figure 5. Spectra amplitude of non-irradiated sensor (left) and irradiated up to 2×10^{14} 1 MeV n_{eq} cm^{-2} with spectra (right).](image)
The most probable value obtained from the charge distribution is interpreted as the collected charge. Sample spectra of a $^{90}\text{Sr}$ source are presented in Fig. 5. The signal-to-noise ratio for one-strip clusters of non-irradiated $2.2 \times 6.2 \text{ cm}^2$ sensors are shown in Fig. 6. $P$- and $n$-side read-out are denoted with p and n, the sensor name is composed of the vendor coding (c for CiS and h for Hamamatsu). Beyond the full depletion of the sensor, the signal-to-noise ratio remains constant. The systematic uncertainty is found to be much larger than statistical one. The error bar on the next figures represent uncertainty correlated between voltage scan points.

![Figure 6](image)

**Figure 6.** Signal-to-noise ratio for non-irradiated $2.2 \times 6.2 \text{ cm}^2$ sensors from different vendors at three applied voltages a) CiS and b) Hamamatsu. c) Dependence of the charge collection on the applied voltage in terms of signal-to-noise ratio. For the sake of illustration points were shifted on the X-axis by 3 V.

### 2.3. Charge collection efficiency after irradiation

The sensors were irradiated at the KIT Irradiation Center (Karlsruhe, Germany) with protons of $E_{\text{kin}} = 22.9 \text{ MeV}$ produced by the Compact Cyclotron [9]. There, sensors are scanned in 1 mm spaced rows by the 7 mm wide beam. In order to dissipate the heat and to minimize annealing effects, nitrogen flow at the temperature of -40$^\circ\text{C}$ was supplied during irradiation.

![Figure 7](image)

**Figure 7.** Dependence of the charge collection efficiency of the irradiated sensor on the applied voltage.

The radiation causes defects in the silicon lattice which act as traps for the charge carriers. To compensate this damage, one should apply higher bias voltage in order to speed up the charge collection in the sensor medium. In Fig. 7 one can see how the charge collection efficiency
saturates to 100% with sufficient bias voltage applied. The 100% level of charge collection efficiency was defined as the charge collected by the non-irradiated sensor from the same vendor of given thickness. Fig. 8 depicts the signal-to-noise ratios obtained with different sensors.

Nevertheless, with an expected radiation environment of the CBM experiment it is still possible to collect almost 100% of the signal with increasing of the bias voltage. On Fig. 9 one can see performance of the sensors irradiated up to twice the lifetime fluence.

![Figure 9: Charge collection efficiency for the \textit{p}\textsuperscript{-} and \textit{n}\textsuperscript{-}side of irradiated sensors.](image)

3. Conclusions
The latest prototypes of the silicon microstrip sensors for the STS are found to be sufficiently radiation hard to survive the lifetime particle flux without critical performance degradation. At radiation levels reaching once and twice the expected nominal life-times of the STS detector, i.e. neutron equivalent fluences of $1 \times 10^{14}$ and $2 \times 10^{14} \text{ MeV n}_{eq} \text{ cm}^{-2}$, the signal-to-noise ratio after irradiation drops down from about 23 to 12. The sensor prototypes from two vendors show a reduction of the charge collection efficiency by 10% to 20% after being irradiated to the double lifetime non-ionizing dose.

Acknowledgments
Supported by HGS-HIRe.

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