Test results on heavily irradiated silicon detectors(*)

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Summary. — The performance of silicon micro-strip detectors after heavy irradiation have been investigated using a muon beam. Large-area sensors have been irradiated with neutrons and protons, read-out with fast shaping time electronics, and operated at low temperature. The paper presents a study of the charge collection efficiency, signal-to-noise ratio and hit reconstruction efficiency of these silicon devices.

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1. Introduction

All major LHC experiments plan to use silicon detectors as a baseline element for the tracking system. Semiconductor micro-strip devices designed for CMS consist of $p^+$ on $n$ single-sided sensors. Such detectors will be exposed to radiation levels unprecedented in high-energy physics experiments. The primary $p$-$p$ interactions will produce a high flux of charged particles, photons and neutrons: it is foreseen that after 10 years of LHC running the innermost silicon barrel layer will have been irradiated up to an overall integrated fluence of about $1.6 \times 10^{14}$ 1 MeV-equivalent neutrons/cm$^2$ [1, 2].

The absorbed dose will cause type inversion and an increase of the depletion voltage. In addition, over-depletion of the device will be required to fully collect the charge and to lower the noise due to the increased inter-strip capacitance [3].

The most important parameters needed to evaluate the tracking performance of silicon devices are the signal-to-noise ratio ($S/N$), the charge collection efficiency (CCE) and the hit reconstruction efficiency (HE). Radiation-induced defects in the silicon bulk may trap


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charge carriers and reduce the available signal, leading to a marginal signal-to-noise ratio in the final system. This effect may be enhanced when very fast read-out electronics is used to cope with the 25 ns bunch crossing interval of LHC.

In order to ensure long-term operation of the detectors, it is mandatory to study their performance after heavy irradiation.

In this paper we report the study of the CCE, S/N and HE of very heavily irradiated silicon micro-strip detectors in a beam test.

2. – Detector description

Detectors [1] used in this study were designed in INFN Pisa and processed by the CSEM company (Neuchatel, CH). They were manufactured on n-type high resistivity silicon wafers with a \( (111) \) lattice orientation, \( 4'' \) in diameter and \( 300 \mu \text{m} \) thick. The devices are single-sided sensors with an active area of \( 53 \times 64 \text{mm}^2 \) and \( 1024 \) \( p^+ \) strips, \( 14 \mu \text{m} \) wide, with \( 50 \mu \text{m} \) or \( 61 \mu \text{m} \) strip pitch. The implant strips are AC coupled to the read-out electronics through an array of integrated capacitors the insulator of which is a multilayer of \( \text{SiO}_2 \) and \( \text{Si}_3\text{N}_4 \). Wafers have a bulk resistivity of \( 4-10 \text{K}\Omega \cdot \text{cm} \) and depletion voltage \( V_d \) of 40–80 V. The whole active surface of the detector is surrounded by an inner guard ring which is used to bias the strips through integrated polysilicon resistors. Surrounding it there is an external guard ring and along the edge of the device a \( n^+ \) implant is used to reduce the cut line contribution to the leakage current.

Since high-voltage operation is needed to fully deplete silicon detectors after irradiation, we have selected detectors with a breakdown voltage, before irradiation, exceeding 500 V.

3. – Irradiation

Both neutrons and protons were used to irradiate detectors.

Neutron irradiation was performed on 8 detectors at the Tapiro nuclear reactor (ENEA, Italy), at room temperature (25–30 °C) and not under bias. Four neutron fluences were chosen (1–4 × 10\(^{14}\) n/cm\(^2\)) in order to study the detector performance. For each fluence two devices were exposed together with test structures.

The current density gives a damage constant value \( [4] \) of \( \alpha_{20^\circ\text{C}} = (3.0 \pm 0.5) \times 10^{-17} \text{Acm}^{-1} \) and the measurement of the depletion voltage shows that all detectors were type inverted. These results are in agreement with the values found in literature [5].

Proton irradiation was performed on 24 detectors using a beam of 24 GeV/c momentum available at the PS accelerator (CERN). During irradiation all devices were kept at \(-10^\circ\text{C}\) and under bias voltage (150 V). Detectors were uniformly irradiated at the same fluence of \(~ 3.2 \times 10^{14} \text{proton/cm}^2\) to perform a statistically significant analysis.

The depletion voltage measured after irradiation has an average value of 300 V in agreement with the value foreseen in [1]. The measurement of the leakage current as a function of the bias voltage was performed on all irradiated devices. Breakdown was not observed up to 700 volts, as shown in fig. 1. This will allow us to safely over-deplete detectors in the LHC environment. In order to reduce the annealing effects, after irradiation all sensors were kept at \(-25^\circ\text{C}\).