Test Results on Heavily Irradiated Silicon Detectors for the CMS Experiment at LHC


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Abstract

We report selected results of laboratory measurements and beam tests of heavily irradiated microstrip silicon detectors. The detectors were single-sided devices, produced by different manufacturers and irradiated with different sources, for several total ionizing doses and fluences up to 4 x 10^{14} 1-MeV-equivalent neutrons per cm². Strip resistance and capacitance, detector leakage currents and breakdown performance were measured before and after irradiations. Signal-to-noise ratio and detector efficiency were studied in beam tests, for different values of the detector temperature and of the read-out pitch, as a function of the detector bias voltage. The goal of these test is to optimise the design of the final prototypes for the Silicon Strip Tracker of the CMS experiment at the CERN LHC collider.

I. INTRODUCTION

The LHC at CERN, to be completed by 2005, will collide protons at 14 TeV center-of-mass energy. The CMS detector at the LHC has been designed to detect cleanly the diverse signatures of new physics and, more generally, to perform precise measurements of physics processes at the TeV energy scale. Robust tracking and detailed vertex reconstruction within a strong magnetic field are powerful tools to reach these objectives. The CMS Tracker [1] will consist of three subsystems, the Pixel Detector System, the Silicon Strip Tracker, and the Micro-Strip Gas Chamber Tracker, each best matched to the task of satisfying the stringent resolution and granularity requirements in the regions of high, medium, and lower density of particles produced by the LHC collisions. The subsystems are arranged in concentric cylindrical volumes, each corresponding to the three occupancy regimes: ≈ 20 cm, between ≈ 20 and ≈ 60 cm, and from ≈ 70 cm to 120 cm from...
Figure 1: Radiation levels in the CMS Tracker region, at selected distances (7, 21, 49, 75, 111 cm) from the beam line. \( z \) is the coordinate along the beam. The Silicon Strip Tracker extends between 22 and 60 cm. All values correspond to an LHC integrated luminosity of \( 5 \times 10^5 \text{ pb}^{-1} \).

The technology for the radiation resistance of silicon micro-strip detectors has been thoroughly investigated by several groups [4]. The design of the micro-strip devices for the SST will be based on single-sided \( p^+ \) implants in an initially \( n^- \) type bulk silicon which offers a great advantage in terms of cost and industrial production capability. This choice, however, presents a significant challenge due to heavy radiation damage.

The radiation damage can be divided into two classes: surface damage and bulk damage. The former occurs when the holes produced by ionizing radiation in the surface oxide layer either become trapped in the oxide or interact with atoms at the silicon-oxide interface to form interface states. Fixed positive charge in the oxide modifies the oxide field, while interface states give rise to new energy levels in the forbidden gap which can modify device behaviour [5]. These changes can lead to a decrease in the inter-strip isolation, causing unwanted signal charge sharing and increase in the inter-strip capacitance, which is the major contribution to the electronic noise of the system. The bulk damage is due to hadrons, and leads to the creation of defects in the silicon lattice. This affects the leakage current, which increases proportionally to the received fluence and is strongly dependent on the temperature [6]. Another effect of the bulk damage concerns the decrease in charge collection efficiency caused by the charge trapping at radiation-induced levels in the silicon bulk [7]. It is estimated [6] that the resulting ballistic deficit will be tolerable.

The bulk damage also influences the effective doping...
concentration of the substrate, which is determined by the concentration of space charge in the depletion region. Since irradiation results in an accumulation of negative space charge in the depletion region due to the introduction of acceptor defects which have energy levels deep within the forbidden gap, n-type detectors become progressively less n-type with increasing hadron fluence until they invert to effectively p-type and then continue to become more p-type beyond this point, apparently without limit [8, 9]. The inversion fluence depends strongly on the initial resistivity of the substrate. Detectors should be operated at low temperature. The entire volume of the SST will be kept at -10 °C during the LHC running [2, 9, 10].

Several test structures and detector prototypes were used to validate the design choices and processing technologies for the detectors foreseen for the SST. Here we will present a selection of the results for single-sided, p+ on n-bulk, 300 μm thick, high bulk resistivity (> 6 kΩ·cm), AC-coupled, polysilicon-biased devices, with two guard rings. Other detector parameters are summarized in table I. The detectors were manufactured by CSEM [11] and Hamamatsu [12]. Irradiations were performed with fast neutrons from nuclear reactors [13, 14] and with 24-GeV protons from the CERN PS. The irradiation conditions such as detectors bias voltage and temperature are also summarized in table I.

The capacitive coupling of each strip to the adjacent ones is determined by the shape of the electric potential between the p+ implants and is strongly influenced by the fixed charge at the Si-SiO2 interface. The role of various designs and technologies has been investigated before and after irradiation. The experimental setup used to measure the capacitive couplings between strips is described in [15]. Figure 2 shows the value of the total capacitive coupling per unit length,

\[ C_{tot} = C_b + 2(C_{1n} + C_{2n}), \]  

(1)

as a function of the strip width over pitch ratio. \( C_b \) is the capacitance to the back, while \( C_{1n} \) and \( C_{2n} \) describe the couplings to the first and the second neighbouring strips, respectively. The measurements were performed at 100V bias voltage and 1 MHz frequency on detectors with high resistivity (> 6 kΩ·cm) substrates. This bias voltage was enough for the detector to be substantially over-depleted and for the

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<th>Pitch (μm)</th>
<th>Width (μm)</th>
<th>Number of Strips</th>
<th>Depletion Voltage (V)</th>
<th>Breakdown Voltage (V)</th>
<th>Leakage Current (nA)</th>
<th>Fluence (10¹⁵ cm⁻²)</th>
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<td>HAMAMATSU</td>
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<td>Neutrons [14]:</td>
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<td>0.05, 0.17, 0.31, 1.7</td>
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<td>T&lt; -8°C, 150 V bias</td>
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II. LABORATORY MEASUREMENTS ON PROTOTYPES

A. Strip Resistance and Capacitance

The resistance between p+ strips is very high (>100 MΩ) before irradiation. After type inversion lower values (10-100 MΩ) for the inter-strip resistance have been observed for all the detectors studied. However, the contribution to the detector noise [15] is still negligible.

The strip series resistance depends on the geometry and the resistivity of the metal line. Standard aluminium-silicon resistivity has been measured around 27 mΩ·μm, which results in a series resistance of the order of 90 Ω for metal electrodes 12 μm wide, 1.5 μm thick and 62.5 mm long.

The capacitive coupling of each strip to the adjacent ones is determined by the shape of the electric potential between the p+ implants and is strongly influenced by the fixed charge at the Si-SiO2 interface. The role of various designs and technologies has been investigated before and after irradiation.
The concentration of positive fixed charge in the oxide increases up to the saturation value with irradiation. The higher concentration of negative charge at the interface results in a stronger inter-strip coupling. A reduction of inter-strip capacitance can be obtained in all devices by increasing the bias voltage, since a higher field on the $p^+$ side confines the electrons at the interface to the middle of the gap between two implants. Figure 4 shows the inter-strip capacitance versus the bias voltage for CSEM detectors after neutron irradiations [15]. As already mentioned before, the neutrons, responsible for the bulk damage, were accompanied by gamma rays in the MeV energy range, which were responsible for the surface damage, thus for the change in the inter-strip capacitance. The detectors were at 20 °C temperature and they were not biased.
during the irradiation. The inter-strip capacitances measured after irradiation show a very strong bias dependence. At full depletion the coupling is still high but it sharply decreases by increasing the bias voltage. Asymptotic values at most 25% higher with respect to the pre-irradiation values can be reached for a bias voltage 1.5 higher than the depletion voltage.

The possibility of minimizing the effects of both the bulk and the surface damage, by using detectors with low resistivity (1 kΩ·cm) substrates and <100> lattice orientation, is currently under study.

B. Breakdown Performance

The breakdown characteristics of several series of devices from different manufacturers have been measured before and after irradiation. Breakdown voltage distribution for devices (CSEM) before irradiation is shown in figure 5. Most of the detectors fulfill the requirement of breakdown voltage above 500 V. Similar performances are obtained after proton and neutron irradiation. As an example, figure 6 shows the leakage current as a function of bias voltage after neutron irradiation for Hamamatsu detectors, at -10°C temperature. Measured values of the leakage current at maximum bias voltage after irradiation are compatible with the maximum tolerable leakage current of 25 µA/cm² at a temperature of -10°C [2]. Detector leakage current variations are linear with the fluence. The damage constant α normalized at 20°C is $(4\pm1)\times10^{-17}$ A/cm, to be compared with an expected value of $(2.9\pm0.2)\times10^{-17}$ A/cm [16].

C. Possible Design Improvements

Laboratory measurements indicate some problems of the simple edge design (n-well on the cutting area and two guard-rings) we have adopted for all the detectors tested in this work. When a high reverse bias is applied to both the detector active area and the external guard-ring, intense electric fields may lead to avalanche breakdown on the outer side of the external guard-ring causing physical breakdown of the device.

Another problem is related with surface generated leakage current and carrier generation current from the edge, where generation-recombination centers are induced by cutting. This current is a source of extra noise. With the simple edge design the external guard-ring collects the surface current, while the n-well creates a barrier for hole injection.

Improvements can be achieved by shaping the electric field using a series of floating p⁺ rings (a multi-guard structure) around the guard-ring. A particular scheme (figure 7) has been tested making use of multi-guard structures, optimised by means of device characterisation, irradiation tests and simulations [17, 18]. The overall results may be used to give prescriptions on the geometrical arrangement and doping of the multi-guard structure in order to optimise the breakdown behaviour [19].
III. TEST BEAM RESULTS

A series of beam tests has been carried out on heavily irradiated detectors. Here we will present results obtained with the 100 GeV muon beam of the X5 CERN experimental area. The silicon sensors were mounted in detector modules, formed by one or two silicon detectors, and a read-out hybrid, which houses the front-end electronics [20]. Each micro-strip is read out by a fast charge sensitive preamplifier, wire-bonded to the strip, followed by a shaper, with peak mode readout and 50 ns shaping time. The strip length varies from 6.25 to 12.5 cm, depending on whether a module consists of one or two silicon sensors. In the latter case, the micro-strips of the two sensors were wire-bonded to form a single electrical unity. The modules under test were inserted in a "cold box", in which cooled nitrogen was circulated and where the temperature could be varied from -20 °C to room temperature; the temperature, monitored inside the box, was stable within ±0.5 °C. The box was inserted in the middle of a silicon telescope made of four planes of double-sided microstrip detectors [21]. This telescope allows a tri-dimensional tracks reconstruction with a resolution in both coordinates 5.4 pm. The set of algorithms used for cluster finding and for determining the cluster charge and noise are described in [22]. Pedestal, single-channel noise, common-mode noise, signal common-mode-subtracted and cluster selection were calculated on an event-by-event basis using pre-determined thresholds.

A. Signal-to-Noise Ratio

Signal-to-Noise (S/N) is defined as the ratio of the most probable value of the Landau fit to the cluster signal distribution with the average single strip noise. The most important noise contributions in our detectors come from: the thermal noise, due to the strip and bias resistances; the amplifier noise, seen as a noise source applied to the input of the amplifier, which depends linearly from the capacitive load seen at the amplifier input towards the detector. An estimation of the relative contribution to the noise of the system can be found in [23]. The influence of the strip pitch and width on the S/N ratio has been investigated. Non-irradiated detectors from Hamamatsu with different readout pitch values, ranging from 60 to 240 pm and comparable width/pitch ratios (0.21-0.33), show similar behaviour of S/N as a function of bias voltage (figure 8). This because the noise is dominated by amplifier noise, that depends on the total capacitance, which is (figure 2) nearly constant for the set of detectors of figure 8. Similar performance was observed also for CSEM detectors.

Since in a typical LHC collision a significant fraction of particles will cross the detectors at non-orthogonal incident angles, the effect of inclined tracks has been studied in detail. The amount of charge released in the silicon and the number of fired strips is expected to increase while the average single strip noise should remain unaffected. The observed S/N ratio is compatible with the predicted 1/cos θ dependence of the cluster charge and a constant strip noise [2].

The surface radiation damage produces an increase of the noise, as a consequence of the increased inter-strip capacitance (Figure 4), while the bulk damage causes a decrease of the charge collection efficiency [15]. These two effects can be partly reduced by increasing the bias voltage above the full depletion value. The S/N ratio for irradiated devices approaches a plateau value at high bias voltages. Figure 9 shows the S/N ratio as a function of bias voltage for Hamamatsu detectors irradiated with 24 GeV protons and fluences up to 1.6 × 10^{14} p/cm^2. Figure 10 shows the S/N as a function of the bias voltage in over-depletion units for two non-irradiated detectors (made by CSEM and SGS [25]) and two CSEM detectors irradiated with neutrons at fluences of 1 and 2 × 10^{14} neutrons per cm^2. The detectors were kept at -10 °C temperature. The depletion voltage is around 60V
Extrapolation to LHC conditions

+ CSEM not irradiated
- vb=200V
* vb=150V
- vb=100V
Q Vb= 50V

SGS

irradiated

CSEM irradiated 1 \times 10^{14} \text{n/cm}^2
CSEM irradiated 2 \times 10^{14} \text{n/cm}^2

Another important parameter which determines the behaviour of the detectors is the temperature at which the silicon is operated. This influences both the amount of charge collected and the noise. An increase in the S/N ratio up to 20% has been observed for irradiated detectors going from room temperatures to the operating temperature of -10 °C. As an example, figure 11 shows the S/N ratio as a function of temperature for various bias voltages, for a CSEM detector irradiated with neutrons at \(1 \times 10^{13} \text{n/cm}^2\). A similar behaviour is observed also for Hamamatsu detectors, and for higher fluences.

**Figure 10:** Signal-to-noise ratio as a function of bias voltage in over-depletion units, for two non-irradiated detectors (CSEM, SGS), and two detectors (CSEM) irradiated at \(1 \times 10^{14} \text{n/cm}^2\) and \(2 \times 10^{14} \text{n/cm}^2\), respectively. The readout pitch is 50 μm, the strip length is 12.5 cm. The operating temperature is -10 °C. The blue band is an analytical extrapolation (see text) to the experimental conditions foreseen at the LHC.

**Figure 11:** Signal-to-noise ratio as a function of temperature at various bias voltages for a detector from CSEM irradiated at \(1 \times 10^{13} \text{n/cm}^2\). The readout pitch is 50 μm, the strip length is 11 cm.

**Figure 12:** Efficiency vs. S/N for irradiated CSEM detectors of 50μm pitch, 6.22 cm length, at various temperatures.

### B. Detector Efficiency

The global hit efficiency is defined as the ratio between the number of reconstructed and predicted hits. The latter are calculated from the number of tracks crossing the detector within its geometrical acceptance and away from dead or noisy strips. Figure 12 shows the dependence of this efficiency on signal-to-noise ratio at various temperatures for detectors irradiated with neutrons at \(1 \times 10^{13} \text{n/cm}^2\), for particles impinging orthogonally to the detector surface.

It is worthwhile to note that in Figure 12 even when S/N is
2099

Figure 13: Efficiency as a function of bias voltage. CSEM detectors of 75 µm pitch, 11 cm length, at -10°C temperature, irradiated with neutrons.

7.5 we have an efficiency greater than 95%. Figure 13 shows the dependence of the efficiency on bias voltage for a CSEM non-irradiated detector and for two CSEM detectors irradiated at $1 \times 10^{14}$ n/cm$^2$ and $2 \times 10^{14}$ n/cm$^2$, respectively. At full depletion, the efficiency is compatible with 100% for both irradiated and non-irradiated detectors.

The charge collection efficiency has been measured as a function of cluster position between two strips for different levels of radiation. The cluster charge distribution indicates good uniformity of charge collection even in heavily irradiated devices (Figure 14).

The measurement of ghosts, namely the fraction of hits not associated with tracks, has also been performed. A high ghost rate could spoil the pattern recognition task and the track finding efficiency. Values well below 1% were obtained, which is considered tolerable. The ghost rates do not depend on the operating conditions such as bias voltage and irradiation level [2].

Both the response function and the spatial resolution have been studied in a wide range of detectors. The experimental data show no significant discrepancy with respect to the expected performance [2].

IV. CONCLUSION

A wide R & D program has been developed since a few years with the aim of assessing the performance of detectors suitable for the CMS Silicon Strip Tracker. The selected results presented in this paper confirm that the design options chosen so far can meet the requirements needed for CMS experiment. Laboratory measurements and beam test results, carried out before and after irradiation, confirm good performance of the current detectors design. Standard detector production shows acceptable performance on breakdown voltage values before and after irradiation allowing a safe high voltage operation. Nevertheless a more efficient breakdown protection is foreseen with the use of multi-guard solution.

The behaviour of total strip capacitance has been well understood in terms of detectors geometry, and the effect of radiation damage has been investigated. After irradiation, performances similar to non-irradiated detectors can be reached using over depletion bias voltage.

Signal to noise ratio has been studied in beam tests with different detectors geometry. The operation under real conditions shows good performance of detectors produced by different manufacturers. Besides measurements also analytical studies have been carried out. Extrapolation to the expected LHC condition shows acceptable S/N value with a hit efficiency greater than 95%.

V. REFERENCES


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