The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

May 21, 2003

Performance of Si sensors irradiated to 5×10^{14} n/cm².

Ph. Bloch, A. Peisert

Cern, Geneva, Switzerland

A. Cheremukhin, A. Dmitriev, N. Zamiatin

JINR, Dubna, Russia

A. Go

NCU, Chung-li, Taiwan

I. Evangelou, P. Kokkas, N. Manthos

University of Ioannina, Ioannina, Greece

Abstract

The expected particle fluence in the inner part of the CMS Preshower is calculated to be 1.6×10^{14} cm⁻² for neutrons and 0.4×10^{14} cm⁻² for charged hadrons. Since the error of the calculation is high and/or unexpected accidental beam miss-alignments might happen we have irradiated Preshower silicon sensors to fluences up to 5×10^{14} n/cm² to verify that they hold voltages necessary to reach the full charge collection efficiency. All irradiated sensors showed no signs of breakdown up to 1000 V, the maximum voltage applied. For all but one the operating voltage was lower than 900 V and a charge collection efficiency plateau was at least 200 V long. No noisy channels were observed at the extreme voltages.

The measured charge collection efficiency was $71 \pm 12\%$ and $59 \pm 12\%$ for sensors irradiated to 3×10^{14} n/cm² and 5×10^{14} n/cm², respectively. These values are consistent with the extrapolation from previous measurements made on sensors irradiated to 2.3×10^{14} n/cm².

The work presents the results of static and dynamic measurements and shows that our design and the technology are very robust.

1. Introduction

The maximum neutron fluence in the volume of the Preshower detector is expected to be $1.6 \times 10^{14} \text{ cm}^{-2}$ of 1 MeV equivalent neutrons and $0.4 \times 10^{14} \text{ cm}^{-2}$ of charged hadrons [1]. The silicon sensors were designed to sustain and be operational up to this fluence. In our previous work [2] we showed that sensors irradiated to $2.3 \times 10^{14} \text{ n/cm}^2$ are fully operational with a charge loss of about 19%. Since the fluence calculations bare a certain error and, in addition to that, one can not exclude accidents which would provoke a higher irradiation, we irradiated a couple of sensors to $3 \times 10^{14} \text{ n/cm}^2$ and $5 \times 10^{14} \text{ n/cm}^2$ and thoroughly checked their performance.

In chapter 2 we describe the sensors and the set-ups used for the measurements are presented in chapter 3. The results of static measurements and of charge collection efficiency measurements are shown in chapters 4 and 5 respectively. The last chapter is reserved for a summary and conclusions.

2. The Sensors

Preshower silicon sensors which were subject of this study are single sided, DC coupled strip detectors with a total area of $63 \times 63 \text{ mm}^2$. They have 32 strips at a pitch of 1.9 mm. The surface is passivated with openings for bonding and probing. The sensors were designed to hold a voltage of at least 500 V, necessary for operation after irradiation to $2 \times 10^{14} \text{ n/cm}^2$ [2]. To achieve it the metal lines are designed wider than the implants, all elements have rounded corners and the active area is surrounded by a series of guard rings.

In order to reduce the backplane current injection, limiting the breakdown voltage, the backplane n^+ layer is at least $2.5 \text{ }\mu\text{m}$ thick [3].

Table 1: Summary of parameters of sensors irradiated and tested

Sensor	Irradiation date	Φ (10^{14} n/cm^2)	$V_{fd}(0)$ (V)	ρ ($\text{k}\Omega \times \text{cm}$)	$V_{fd}(\Phi)$ (V) from CV	$V_{op}(\Phi)$ (V) from CCE
A	Nov. 01	3.1	109	3.4	500	670
B	Nov. 01	3.1	54	6.8	462	695
C	Nov. 01	4.9	52	7	665	800
D	Nov. 01	4.9	105	3.5	648	820
E	May 02	3	181	2	505	750
F	May 02	3	57	6.4	600	745
G	May 02	5	192	1.9	751	>1000
H	May 02	5	57	6.4	768	

Eight sensors of initial resistivity between $1.8 \text{ k}\Omega \times \text{cm}$ and $6 \text{ k}\Omega \times \text{cm}$ were irradiated in a reactor in Dubna [4] in two runs, in November 2001 and in May 2002. The neutron flux from the reactor is $1.14 \times 10^{10} \text{ cm}^{-2}$. The irradiation to $5 \times 10^{14} \text{ n/cm}^2$ took about 12 hours.

The irradiation was done at room temperature and the sensors were stored at -8°C right after. They were at room temperature for about 10 hours, time to travel to CERN, where the measurements were done.

Table 1 shows the list of sensors irradiated and tested and their full depletion voltage before irradiation and after.

3. The Set-ups

3.1 Static measurements

For the static measurements we used a probe card with 32 pins connected to a relay board, which can switch from strip to strip, keeping the remaining 31 strips connected to ground. A Keithley 237 high voltage source/monitor unit was used for biasing the sensor and a Keithley 2410 source/monitor unit was used as an amperometer.

The depletion layer capacitance was measured with an HP 4182 LCR unit with the generator set to 1 kHz.

All measurements were done in a commercial freezer at about -34°C . This enabled us to keep the leakage low and to reduce therefore the noise.

3.2 Charge collection measurements

The charge collection efficiency was measured with a system based on the Deltastream chip [5]. It is composed of an array of 32 preamplifiers and shapers with a peaking time of 25 ns, followed by a sample and hold and a multiplexer. The chip was mounted on a hybrid coupled to a probe card [6] which made contact to the strips. This system does not require bonding and is therefore very convenient for quick, laboratory tests.

Although the readout chip was designed for high detector capacitance, about 50 pF for full size sensors, the equivalent noise charge was about 3000 e^{-} and a signal-to-noise ratio for a minimum ionizing particle from non-irradiated sensors was about 7:1.

The most reliable way to measure the charge deficit is to compare the mip signal from irradiated sensors to the one obtained from a non irradiated sensor. If one uses the same electronics there is even no need to calibrate the gain of the amplifier and the signal scales only with the thickness of the sensors, a parameter easy to measure.

Our previous measurements on sensors irradiated up to $2.3 \times 10^{14} \text{ n/cm}^2$ made with β particles from a ^{106}Ru source showed a charge deficit of about $8.5\%/10^{14} \text{ n/cm}^2$ [2]. Assuming that the charge deficit is linear with the fluence we expect to collect about 75% and 58% of generated charge from sensors irradiated to $3 \times 10^{14} \text{ n/cm}^2$ and $5 \times 10^{14} \text{ n/cm}^2$, respectively. For the lower fluence one would have a signal-to-noise ratio of 5:1 and one could still determine the Landau peak, but for the higher fluence the signal would be buried in the noise.

For this study we used a 1060 nm laser as an ionization source. At this wavelength the light traverses the sensors of a typical thickness of 320 μm and simulates particles. The signal used for triggering the laser was 10 ns wide with the leading and trailing edges of 2 ns.

The charge generated, proportional to the trigger signal amplitude, can be varied depending on the needs. We set the laser to generate a charge equivalent to about 4 minimum ionizing particles which gave a comfortable signal-to-noise ratio of 14:1 even on sensors irradiated to the highest fluence.

The use of the laser light of this wavelength brings however a major inconvenience when working at low temperatures. The water vapor deposited on cold surfaces absorbs this wavelength, causing the input signal to be lower than expected. It is therefore not easy to make an absolute calibration.

There are certainly ways to get the atmosphere in the freezer perfectly dry, but our lab is not equipped with such a system. We use commercial freezers with no control of the humidity. We decided nevertheless to do the measurements to verify the following points: the sensors reach the full depletion, there is a charge collection plateau of at least 100 V, the signal on the plateau is stable and no noisy strips appear when applying these extremely high voltages.

We assumed that the water vapor deposition is slow and the measurement of charge vs. voltage on a single strip, which is done without opening the freezer, is fast. As we will see in chapter 5 these assumptions were justified. We could therefore answer the crucial questions and we even attempted to make an absolute measurement of the charge loss due to trapping.

The laser light was split in three using a passive splitter and one of the outputs was used for monitoring. The light was converted on a photodiode and the charge was digitized with a charge integrating ADC.

The signal obtained from the sensors was normalized to a unit light output of the monitoring diode. It was also normalized to a unit thickness of the sensor.

4. Static measurements

The leakage current and the depletion layer capacitance were measured as a function of voltage up to 1000 V for all strips. Figure 1 shows the inverse square capacitance as a function of voltage for detectors F and H irradiated to $3 \times 10^{14} \text{ n/cm}^2$ and to $5 \times 10^{14} \text{ n/cm}^2$, respectively. Both are made on $6.4 \text{ k}\Omega \times \text{cm}$ material and are $320 \text{ }\mu\text{m}$ thick. From these curves we calculate the full depletion voltage as a crossing of two straight lines fitted to two parts of the curves, as shown in the figure. We obtain values of about 600 V for detector F and 770 V for H. Full depletion voltages calculated from the $1/C^2$ -V curves for all sensors are presented in Table 1 . We estimate the error of this measurement to about $\pm 10 \text{ V}$.

Figure 1: Inverse square capacitance for sensors F and H irradiated to $3 \times 10^{14} \text{ n/cm}^2$ and $5 \times 10^{14} \text{ n/cm}^2$, respectively, as a function of voltage. The straight lines are fits used for calculating the full depletion voltage.

All sensors tested reach the full depletion and the capacitance is constant beyond this point. We do not observe difficulties in fully depleting highly irradiated sensors, reported by

authors of reference [7] for fluences of $\sim 10^{14}$ particles/cm² and higher and tested at room temperature.

Figures 2 and 3 show the leakage current, measured at -34° C, of sensors irradiated to 3×10^{14} n/cm² and 5×10^{14} n/cm², respectively. Sensors A, B, C and D were irradiated in November 2001 and E, F, G and H in May 2002. One can see that the current of sensors irradiated in November 2001 is lower than of those irradiated later thanks to the longer time of the beneficial annealing.

Figure 2: Leakage current for 4 sensors irradiated to 3×10^{14} n/cm², measured at -34° C. Sensors A and B were irradiated in November 2001 and E and F in May 2002.

Figure 3: Leakage current for 4 sensors irradiated to 5×10^{14} n/cm², measured at -34° C. Sensors C and D were irradiated in November 2001 and G and H in May 2002.

For all irradiated sensors the I-V curves exhibit a slope at voltages beyond full depletion. It is partly due to self heating of the sensor because of a poor heat evacuation in our set-up. Figure 4 shows the measurement of the leakage current as a function of voltage starting from 0 V (“up” curve) and starting from 1000 V (“down” curve) for sensor D. For the “down” measurement we applied each value of the bias voltage for a very short time not to let the sensor to heat up. One can see that the slope beyond 700 V is lower, but it remains.

Figure 4: Leakage current measured as a function of voltage starting from 0 V (up) and starting from 1000 V.

The residual slope is due to an increased surface component between the strips and the guard ring, which in our measurements is floating. This hypothesis is supported by the distribution of the current across the strips, shown in figure 5. Edge strips which have a 30 times longer border with the guard ring draw a higher current.

Figure 5: Distribution of the strip current at 1000 V for sensor D.

5. Charge collection measurements

Seven out of eight irradiated sensors were tested with the laser. On each sensor we measured the charge as a function of voltage for a couple of strips.

Figure 6: Laser induced signal for 3 strips of sensor E irradiated to $3 \times 10^{14} \text{ n/cm}^2$.

Figure 6 shows the signal from 3 strips of sensor E irradiated to $3 \times 10^{14} \text{ n/cm}^2$. The laser was positioned first over strip 31 and then moved to strips 30 and 29. Since the x-stage on which the laser fiber is mounted does not work at -34°C the operation of fiber alignment with respect to the opening in the aluminium and moving from strip to strip was done manually with the lid open. During each operation more and more humidity got into the freezer and, as one can see, the collected charge decreased. However, looking at individual strip measurement, made without opening the freezer, one sees a stable signal. One can therefore test the stability of sensors for high voltage.

Figure 7 shows the laser induced signal for sensors A and B irradiated to $3 \times 10^{14} \text{ n/cm}^2$. For this measurement our goal was to check the stability of the operation, the limiting voltage and the noise so no attention was paid to have the same settings of the laser and no normalization for the thickness was done.

From figure 7 one sees that there is no plateau in the conventional sense. Although with a low slope the signal increases continuously with the voltage. A similar behavior was observed by authors of references [8], [9] and [10]. A possible explanation of this phenomenon is that with an increased voltage the drift velocity of holes increases and they induce more signal.

Authors of reference [8] explain this effect by an increase of the carriers lifetime with the bias voltage.

In order to establish the operating point we looked at the variation of the slope of the signal-voltage curve and define the operating point as the voltage at which this slope decreases by 50% with respect to its maximum value. The operating voltage of a sensor is then the average of the values measured for the strips. Defined as that the operating voltages of sensors A and B from figure 7 are $670 \pm 30 \text{ V}$ and $695 \pm 30 \text{ V}$, respectively. Increasing the biasing voltage above these values would give a small charge increase, of the order of a few percent. One has a comfortable range of operation of 350 V.

Figure 7: Laser induced signal for sensor A and B irradiated to $3 \times 10^{14} \text{ n/cm}^2$.

Figure 8 shows similar plots for sensors C and D irradiated to $4.9 \times 10^{14} \text{ n/cm}^2$. The operating points are $800 \pm 30 \text{ V}$ and $820 \pm 30 \text{ V}$ for C and D respectively.

All sensors tested hold the voltage and work fine up to the maximum of 1000 V. No noise excess was observed at these extremely high voltages.

Operating points, $V_{\text{op}}(\Phi)$ (V) from CCE, are listed in Table 1 for all sensors.

Figure 8: Laser induced signal from sensors C and D irradiated to $4.9 \times 10^{14} \text{ n/cm}^2$.

Comparing sensors A and B of initial resistivity of $3.4 \text{ k}\Omega \times \text{cm}$ and $6.8 \text{ k}\Omega \times \text{cm}$, respectively, and irradiated to the same fluence at the same time, we see that there is no

difference in operating voltage. The same conclusion can be drawn for the two other pairs: C-D and E-F.

In spite of the difficulties with controlling the light absorption on the surface we made an attempt to measure and normalize the charge collected on two sensors, E and G, irradiated to $3 \times 10^{14} \text{ n/cm}^2$ and $5 \times 10^{14} \text{ n/cm}^2$, respectively. They were placed in the freezer which was at room temperature, the cooling was switched on and the measurement was taken when the temperature reached -34° C without opening the freezer's lid.

Figure 9: Normalized charge as a function of fluence for neutron irradiated sensors.

This operation was time and effort consuming, because we had to scan across the strip to be sure the fiber is well aligned with the window, letting each time the sensor to warm up to room temperature to eliminate the vapor. This explains why we did it only for two sensors.

The measured signal was normalized to the signal from a non irradiated sensor of the same thickness and we obtained a charge collection efficiency of $71 \pm 12\%$ and $59 \pm 12\%$, for sensors E and G, respectively. The error estimate is based on our previous work [2]. As we can not guarantee that, in spite our efforts, there was no water vapor on the surface, these numbers represent the lower limits of the corresponding efficiency.

The results are plotted in figure 9 together with the data from references [2], [7], [8], [11] and [12].

6. Summary and conclusions

The CMS Preshower silicon sensors were designed to work up to a fluence $2 \times 10^{14} \text{ n/cm}^2$. The results of tests of sensors irradiated to this fluence were described in our previous papers. Recently we have irradiated eight sensors to $3 \times 10^{14} \text{ n/cm}^2$ and $5 \times 10^{14} \text{ n/cm}^2$ to verify their performance in case they receive a much higher fluence. Electrical parameters as well as their response to charge generated by a laser light were measured.

Sensors, around $320 \mu\text{m}$ thick, irradiated to $3 \times 10^{14} \text{ n/cm}^2$, have a full depletion voltage calculated from the capacitance measurement at 1 kHz of around 480 V after 12 months of storage at -8° C . The operating voltage is about 680 V for these sensors.

Sensors irradiated to 5×10^{14} n/cm² deplete at about 650 V and they need around 800 V to reach the efficiency plateau.

The sensors under test were made on wafers of different resistivities, ranging from 2 k Ω ×cm to 7 k Ω ×cm. We see no difference in the operating voltage between sensors made on the lower and the higher initial resistivity wafers.

Charge collected from sensors irradiated to 3×10^{14} n/cm² and 5×10^{14} n/cm², normalized to charge from a non-irradiated sensor, was $71 \pm 12\%$ and $59 \pm 12\%$, in agreement with the extrapolation from previous measurements on sensors irradiated to 2.3×10^{14} n/cm².

All irradiated sensors hold at least 1000 V and their operation is very stable. The noise, provided they are cooled to reduce the leakage current, is comparable to non irradiated sensors.

Acknowledgments

We would like to thank E. Kulagin from JINR for irradiating the sensors and for help with the neutron fluence monitoring.

Special thanks go to Youri Musienko from the CMS collaboration for fruitful discussions and interesting suggestions.

References

- [1] The CMS ECAL Group, “The Electromagnetic Calorimeter Project Technical Design Report, CERN/LHCC 97-33.
- [2] Ph. Bloch et al., “Silicon sensors for the CMS Preshower Detector,” Nucl. Instr. Meth., A 479 (2002) 265.
- [3] Ph. Bloch et al., “Investigation of Silicon Sensor Quality as a Function of the Ohmic Side Processing Technology”, IEEE Trans. Nucl., Sci., Vol. 49 (2002) 321-325.
- [4] A. Cheplakov et al., “Radiation hardness of GaAs preamplifiers for liquid argon calorimetry at LHC”, MPI report, PhE/96-15.
- [5] P. Aspell et al., “DeltaStream: A 36 channel low noise, large dynamic range silicon detector readout ASIC optimized for large detector capacitance.” 7th Workshop on Electronics for LHC Experiments, Stockholm, 22 Oct. 2001.
- [6] I. Evangelou et al., “Noise measurements on Si sensors”, Nucl. Instr. Meth., A 493, (2002) 25-29.
- [7] E. Borchini et al., “Electrical characteristics and charge collection efficiency of silicon detectors irradiated with very high neutron and proton fluences, Nucl. Phys. B (Proc. Suppl.) 61B (1998) 481-486
- [8] L. Beattie et al., “Charge collection efficiency in heavily irradiated silicon sensors”, Nucl. Instr. Meth., A 412, (1998) 238-246.
- [9] S. Marti i Garcia et al., “A model of charge collection for irradiated p⁺n detectors”, Nucl. Instr. Meth., A

473, (2001) 128-135.

[10]I. Stavitski et al., “Charge collection efficiency of standard and oxygenated silicon microstrip detectors”, Nucl. Instr. Meth., A 485, (2002) 105-108.

[11]C. Leroy et al., “Study of electrical properties and charge collection of silicon detectors under neutron, proton and gamma irradiations”, Proc. IVth Int. Conf. on Calorimetry in High Energy Physics, World Scientific, Eds. A. Menzione and A. Scribano (1994) 627.

[12]M.M. Angarano et al., “Study of radiation damage and substrate resistivity effects from beam test of silicon microstrip detectors using LHC readout electronics”, Nucl. Instr. Meth., A 488, (2002) 85-93.