Available on CMS information server **CMS CR 1999/032**

CMS Conference Report

November 9, 1999

Does Radiation Improve Silicon Detectors?

Ph. Bloch and A. Peisert
CERN, Geneva, Switzerland
A. Cheremukhin, I. Golutvin and N. Zamiatin
JINR, Dubna, Russia

Presented by Anna Peisert

Abstract

Sensors designed for the CMS Preshower detector were irradiated with protons and neutrons to fluences equivalent up to $2x10^{14}$ n/cm^2. The leakage current and the capacitance as well as the charge collection efficiency and the noise were measured, before and after the irradiation, for most of the detectors. We noticed, that for some detectors of a lower quality, the breakdown voltage increases after type inversion and that their leakage current, charge collection efficiency and noise are comparable to good detectors. We explain this phenomenon by two effects: a change of the distribution of the electric field and a decrease of the carriers lifetime. Defects on the p-side do much less harm after type inversion, because the maximum of the E-field is now on the n-side. Defects on the n-side still generate charge carriers, but their lifetime is much shorter and most of them recombine before reaching by diffusion the space charge volume.

The article presents the measurements of the breakdown voltage, the charge collection efficiency and the noise before and after irradiation of such sensors compared with detectors of a high initial quality.

Presented at *the IEEE Symposium on Nuclear Science*
Seattle, October 1999

Submitted to *Transactions on Nuclear Science*

I. Introduction

The CMS Preshower detector will be built of about 5000 silicon sensors of a total surface of 18 m^2 [1,2]. An extensive research and development program was carried out together with potential manufacturers, Elma (Russia), Demokritos (Greece), ERSO (Taiwan) and Takion (Japan), during the last two years to develop specifications which would relate the initial parameters to detector's performance after 10 years of operation at the LHC. It is clear that a very high initial quality guarantees a good performance after irradiation, but the production yield becomes an important factor at this scale. In an attempt to increase it and to reduce the overall cost, we took a closer look at 3 sensors, which would normally be rejected: one with a breakdown voltage lower than 400 V, and two with a very high current at relatively low voltages. To our surprise, these sensors showed no signs of breakdown up to 700 V after the irradiation and their response to particles was similar to others.

In chapter II, we describe the Preshower design. The evaluation of new detectors is presented in chapter III and the improvement of their static parameters after the irradiation in chapter IV.
In chapters V and VI we present the measurements of the charge collection efficiency and of the noise after the irradiation and
in chapter VII we try to explain the improvement. Chapter VIII summarizes the status of the Preshower sensors production and the last section is reserved for a summary and conclusions.

II. The Preshower design

The Preshower sensors are made on 4" wafers. Originally the total surface was 60x60 mm^2, but recently we changed the design to 63x63 mm^2, to take advantage of the whole surface of the wafer. They have 32 strips at a pitch of 1.81 mm and 1.9 mm respectively for the two designs. The gap between the strips varies between 50 μm and 160 μm, depending on the manufacturer and on the production batch. In all designs the metal strips are 20 μm to 40 μm wider than the implants. Although in the future the sensors will be passivated, those, which were studied, are not.

An essential feature of the Preshower design is the direct coupling of the metal lines to the p^+ implant, which allows to considerably reducing the cost. The custom made electronics [3] includes a current compensation scheme to reduce the constant level caused by the leakage current.

Thirty-six detectors are subject of this study. Nineteen were irradiated with neutrons at the Dubna reactor [4], some in 2 or 3 steps, to fluences between 0.6×10^{14} cm^{-2} and 2.3×10^{14} cm^{-2}. The detectors were not biased and the irradiation was done at room temperature[1].
The other seventeen were irradiated with protons at the CERN PS to fluences between 2.8×10^{14} cm^{-2} and 3.2×10^{14} cm^{-2}. They were biased to 150 V and cooled down to –7 °C.

All detectors were stored at temperatures below –3 °C immediately after the exposure and they were tested 3 to 5 weeks later, unless explicitly specified.

III. Evaluation of the initial parameters

The following measurements are done before and after irradiation: the total leakage current and the depletion layer capacitance as a function of the bias voltage, the leakage current for each strip at the full depletion voltage and 150 V above, the breakdown voltage, the charge collection efficiency as a function of voltage and the strip noise, also at V_{fd} and at V_{fd}+150V. The measurements before irradiation are done at room temperature. For the capacitance measurement, we used a 590 Keithley CV analyzer with a generator of 100 kHz for non irradiated detectors and an HP 4284 LCR meter at a frequency of 5 kHz for the irradiated ones.

We deduce the breakdown voltage from the capacitance and current measurement and we define it as a voltage at which the leakage current shows a sharp increase, accompanied by an increase of the capacitance (or a decrease of its inverse square).

---

[1] Earlier measurements of detectors irradiated under bias in a reactor in Saclay show that there is no significant difference.

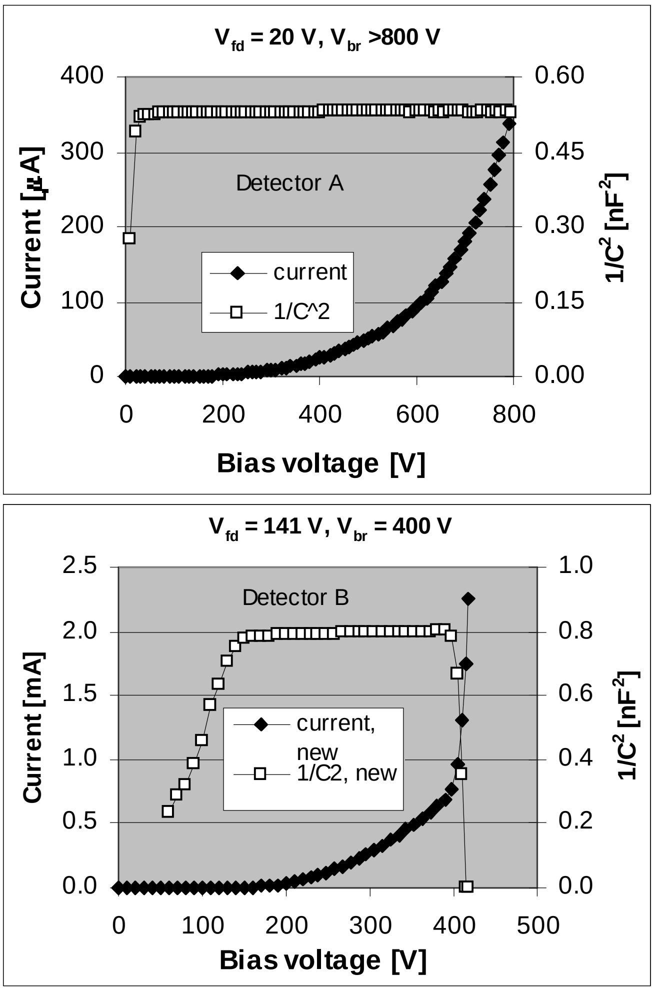

Figure 1: Leakage current and inverse square capacitance as a function of voltage before irradiation for detector A and B, measured at room temperature.

Figure 1 shows examples of measurements of two detectors: detector A with a breakdown voltage higher than 800 V and detector B with a breakdown voltage equal to 400 V. Out of fourteen sensors, which were tested before irradiation to at least 500 V, only detector B had a breakdown voltage below this value.

At the early stage of our research we did not dare to set the bias voltage to more than 200 V on non irradiated detectors,

so, unfortunately, for many of them we do not have an exact value of the breakdown voltage. We can judge their quality from the leakage current curve only. We found two sensors, called C and D, which had a high current at a relatively low bias voltage.

Figure 2 shows the results of measurements of these detectors together with 2 reference detector, called D1 and D2. Detector C has a very high current at voltages well below the full depletion and an additional increase starting at 63 V at which it depletes.

The current of detector D is low up to the full depletion voltage, 38 V, but increases steeply above this value.

After the irradiation, the detectors were tested up to 500 V at the beginning of our research and now we go to higher voltages. Out of 46 measurements (some detectors were irradiated and tested more than once), we found that only one, detector C, had a breakdown voltage of around 400 V, all others holding at least 500 V and most of them no breakdown was visible up to 650 V.

Detector C had a breakdown voltage at around 400 V after the first irradiation to $0.6x10^{14}$ n/cm^2, but improved after the second step of $0.58x10^{14}$ n/cm^2 and could hold up to at least 660 V.

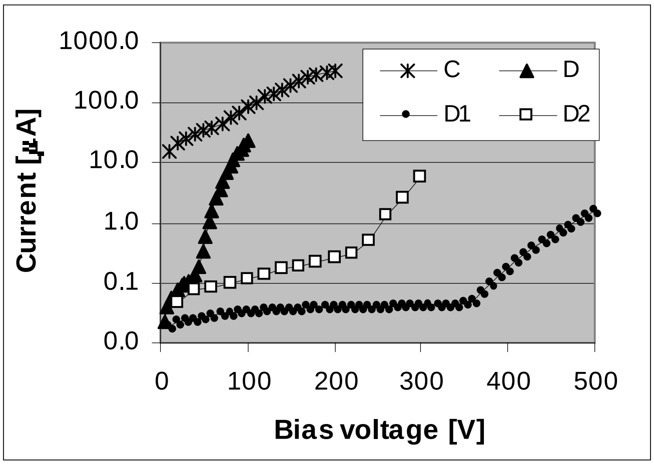

Figure 2: Leakage current of detectors C and D and of two reference detectors before irradiation, measured at room temperature.

IV. Detectors improvement after irradiation

Detector B

Figure 3 shows the leakage current and the inverse square capacitance of detector B after irradiation to 3.16x10^{14} p/cm^2.

The 1/C^2 curve has a slight slope after 500 V, but it does not resemble the curve from figure 1. We will see in the next chapter that the response of this detector to particles is good.

Detector C.

Figure 4 shows the inverse square of the depletion layer capacitance of detector C before irradiation, after 0.6x10^{14}n/cm^2 and after a second irradiation to a total fluence of 1.18x10^{14} n/cm^2. We see that the breakdown voltage, of about 400 V at 0.6x10^{14} n/cm^2, increases to over 700 V after the second irradiation.

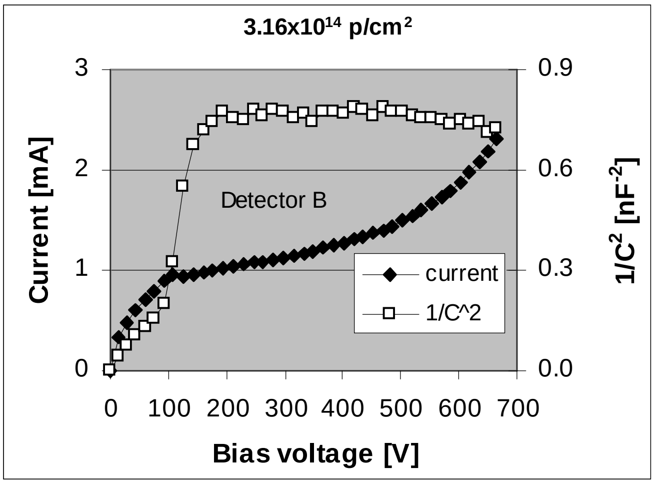

Figure 3: Leakage current and inverse square capacitance of detector B from figure 1 as a function of voltage after irradiation to 3.16x10^{14} p/cm^2. The measurement was done at about 0 ^{o}C.

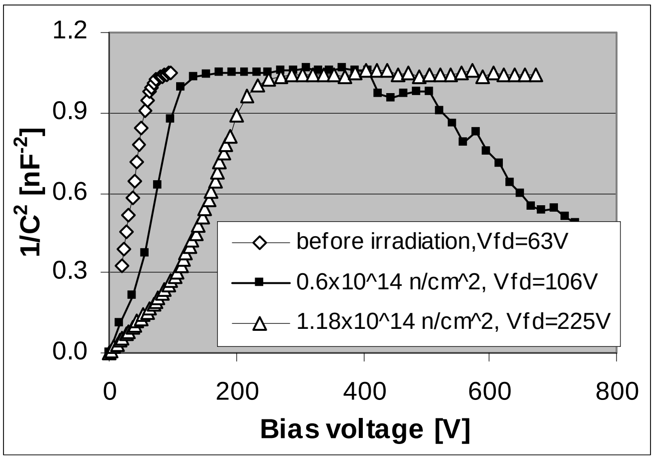

Figure 4: Inverse square of the depletion layer capacitance of detector C before irradiation, after 0.6x10^{14} n/cm^2 and 1.18x10^{14} n/cm^2.

Detector D

Figure 5 shows the leakage current as a function of voltage of detector D and of the reference detectors, all irradiated to 3x10^{14} p/cm^2, measured at –10 °C. Although detector D is still the worse, the difference is not so striking as on figure 2 and its response to particles is equally good, as will be shown later.

Figure 6 shows the leakage current and the inverse square capacitance of detector D, measured 10 months after at 0 °C. The detector holds 800 V.

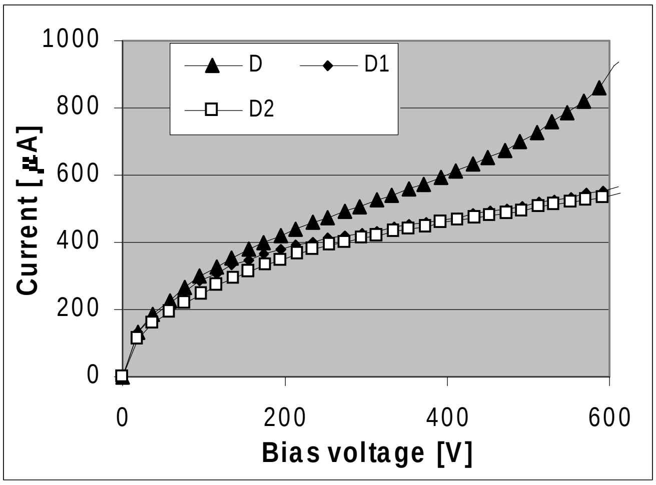

Figure 5: Leakage current of detector D of reference detectors, D1 and D2, irradiated to 3x10^{14} p/cm^2. The measurement was done at –10 °C.

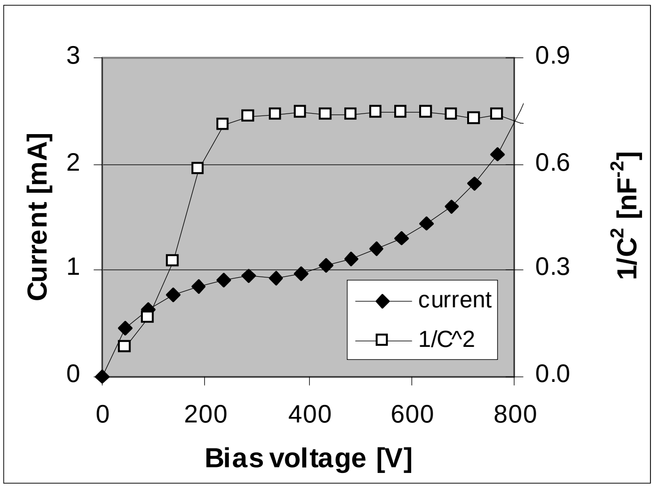

Figure 6: Leakage current and inverse square capacitance of detector D from figure 2, at 0 ^{o}C, measured 10 months after the measurement from figure 5.

V. Measurements with particles

The charge collection efficiency was measured using the SCT32 chip [5], with β particles from a ^{106}Ru[6]. The collected charge was normalized to charge produced in a non-irradiated detector, 300 μm thick, at 500 V.

Figure 7 shows the charge collected from detectors B and D and from 3 other detectors, of an initial higher quality, irradiated to similar fluences. The measurement error is of the order of 5% to 10%, coming from the error of the charge measurement (the signal to noise ratio in our set-up is of the order of 7:1) and from the detector's thickness uncertainty. The error of the fluence is of the order of 10 % for the neutron irradiation [4] and 6 % for the proton irradiation [7].

One can see that there is no difference in the performance of detectors B and D compared to the others. They reach the efficiency plateau at about 400 V and the plateau is over 150 V long for detector B and 250 V for detector D. Their charge loss is similar to other Preshower sensors and also comparable to values measured by other groups on silicon diodes [8,9] and calculated [10].

Detector C, described in the previous section was not tested with particles yet.

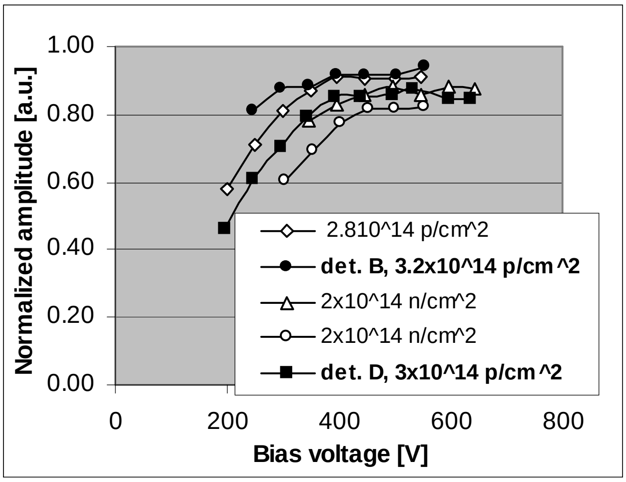

Figure 7: Charge collection efficiency of detectors B and D and of three other detectors with high initial parameters, irradiated to similar fluences.

VI. Noise measurements

A particular attention was given to the study of the noise, as strips with exceedingly high noise are inefficient, reducing the overall detector's efficiency. In case of the Preshower, the problem becomes very important, because one strip represents 3 % of the sensor's surface. The noise of Preshower detectors is dominated by the detector capacitance, about 37 pF, coming mainly from the big capacitance of the strip to the back plane. A non-negligible contribution for irradiated sensors comes from the leakage current, as the surface of one strip is about 1 cm^2.

To reduce this component for the tests with particles, for which we use a chip not optimized for our geometry, we operate irradiated detectors at temperatures around –30 ^{o}C, at which the current per strip does not exceed a few μA for the highest fluences. In this case the average noise measured with the SCT32 chip is of the order of 2800e$^-$ to 2900e$^-$ for non irradiated detectors, increasing to about 3000e$^-$ after the irradiation. We evaluate the noise of each detector as a function of fluence and bias voltage.

Figure 8 shows the equivalent noise charge measured at 600 V and 650 V for detectors A and B, respectively. The average value is the same for both detectors, with detector A, originally a better one, having one strip with a noise over two times higher than the average. Detector D also did not have particularly noisy strips up to very high voltages.

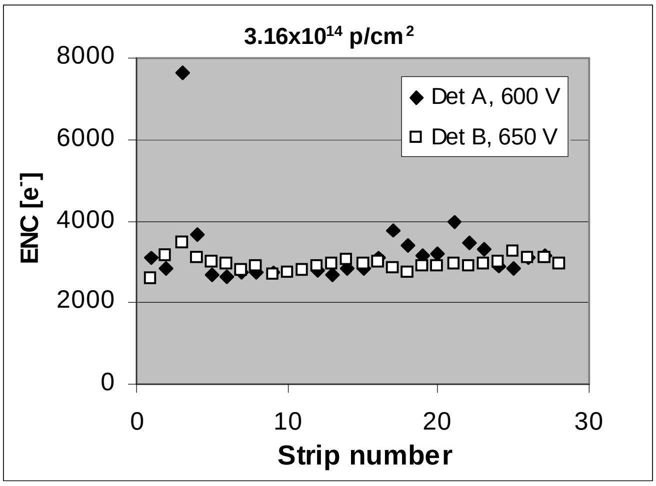

Figure 8: Equivalent noise charge of detectors A and B, irradiated to 3.16x10^{14} p/cm^2.

The analysis of the noise level before and after irradiation indicates that there is not always a good correlation between the strip noise and the strip current, before or after irradiation. Work on relating the appearance of noisy strips at high voltages after irradiation to the initial parameters is going on and will be reported in the future in a separate publication.

VII. Possible explanation

Initial I-V characteristics strongly depend on the following processing defects:

- Pinholes in the p$^+$ implantation, resulting in a short of the aluminium line to the n-bulk. This defect can cause an ohmic component of the current, visible already at low voltages. After the irradiation and the type inversion, the shape of the electric field is radically changed, having two maxima, one on each side of the sensor [11,12,13,14]. The value of the p-side maximum is lower than the one of the n-side and also lower than the value before the irradiation for the same bias voltage. This reduction of the electric field near the strips makes that the processing defects give a negligible contribution to the leakage current after strong irradiation.

- Presence and density of the fixed charge in SiO_2 and the homogeneity of the potential distribution between guard rings. This effect also becomes less important after type inversion, for the same reason. A high number of guard rings helps to improve the initial parameters, but is not essential, as some detectors with only one guard ring have very good performance.
- Defects on the n-side generate charge carriers, which can diffuse to the space charge region, if their lifetime is long and the n^+ implant layer relatively thin. One observes the so-called backplane injection effect: a strong current increase starting at full depletion voltage. At high voltages, it leads to a breakdown, as visible in figure 1. After a strong irradiation, however, the carrier lifetime is considerably reduced [11,12] and, although the electric field is very high near the ohmic contact, the backplane injection current is limited.
- Quality of the scribing process; generation and recombination centers introduced during scribing at the edge of the sensor could be the source of a higher current.

The evolution of I-V and C-V curves and the value of the breakdown voltage for detector B (figures 1 and 3) can be explained by defects on the ohmic n^+ side. Before the irradiation, a strong increase of the current at the full depletion voltage (not visible in this scale) indicates an injection of minority carriers from the n^+ region into the electric field space and can be related to the quality of the n^+ contact. At a high voltage, it leads to a breakdown. After the irradiation with $3.2\text{x}10^{14}$ p/cm^2, the lifetime of minority carriers is decreased and no breakdown is visible up to 600V. A high slope of the current above 400 V indicates that some carriers are still injected from the n^+ region.

In the case of detector C we, probably, have a mixture of the described defects. The high level of current before full depletion may be explained by pinholes in p^+ strips or by a big surface current through the guard rings. The fact that after a fluence of $0.6\text{x}10^{14}$ n/cm^2 there are still signs of a breakdown at about 400 V, proves the presence of defects in the n^+ layer. After the second irradiation, however, these defects have much less influence on the overall performance.

The increase of the leakage current at the full depletion voltage for detector D before irradiation indicates a shallow n^+ implantation with a relatively long carriers lifetime. After the irradiation, as explained earlier, the lifetime is reduced and the increase of the current above the full depletion is not as dramatic as before.

Figure 7 illustrates a good charge collection efficiency for all detectors, no matter how good their static characteristics are. The charge collection for minimum ionizing particles depends only on the electric field distribution in the detector and on the value of the lifetime of the charge carriers, which is a function of the fluence.

VIII. Towards the Preshower Sensors Production

In our understanding, the quality of the n^+ contact is a crucial parameter for a high voltage operation of silicon sensors. Originally, we thought that polishing the wafers on both sides would guarantee a high performance. Tests of sensors made on single-sided and double-sided polished wafers showed, however, that there is no difference in their performance neither before nor after the irradiation. A development program performed by Elma showed that the important parameters are the depth of the phosphorus layer and the uniformity of the donor atoms distribution. With a high and uniform doping, the lifetime of the minority carriers is short and the current generated in the defects near the surface will not reach the space charge volume. Results obtained using a special n^+ processing method are very encouraging. Figures 9 and 10 shows the I-V curves of six Preshower sensors, recently produced at Elma and of three irradiated detectors. The detectors have a surface of 63x63 mm^2.

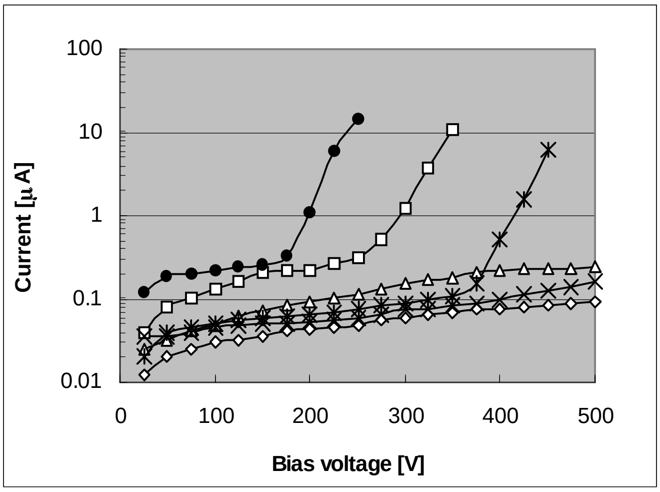

Figure 9: Leakage current as a function of voltage of six Preshower detectors, 63x63 mm^2, produced at Elma.

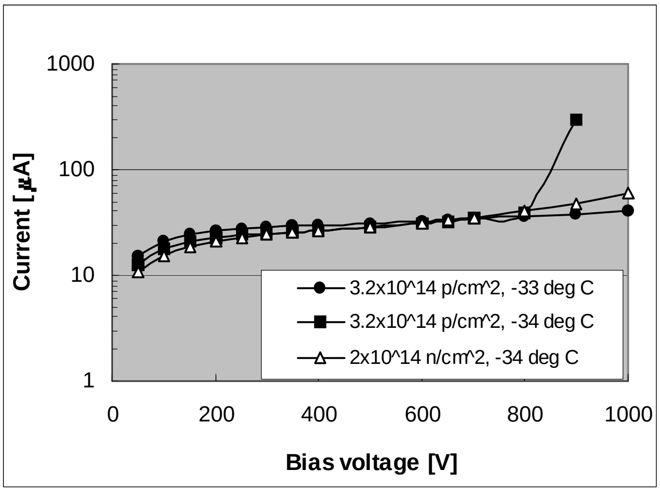

Figure 10: Leakage current as a function of voltage of other three sensors, 63x63 mm^2 , after irradiation.

IX. Summary and conclusions

An extensive research and development program was carried out during the last two years to work out specifications, which would guarantee a good detectors performance after irradiation to fluences expected at Preshower center, i.e. about 2x10^{14} n/cm^2. A special attention was paid to sensors of a relatively lower quality, because at the scale of 5000 pieces, a high production yield can considerably reduce the cost.

Detectors with a breakdown voltage over 500 V perform very well after irradiation. It turns out, however, that detectors, which have an initial breakdown voltage of around 400 V or lower, perform equally well. They have a long efficiency plateau and a noise comparable to others.

We found that processing defects responsible for low initial parameters, become much less important after a strong irradiation: on the p-side because of the change of the electric field distribution, and on the n-side, because of a decrease of the minority carrier lifetime.

We also found from our research, that the processing of the n-side is essential for our geometry. Thick and uniform implant layer reduce the charge diffusion to the active volume, increasing the breakdown voltage by several hundred volts.

Working towards the specifications for the Preshower silicon sensors, we are now in a position to try to set a lower limit for the breakdown voltage before the irradiation. Detectors made on 3 kΩcm to 5 kΩcm silicon, which we intend to use, deplete between 50 V and 100 V. For a safe operation we require a full efficiency plateau of at least 150 V, which results in a lower limit of the breakdown voltage of 200 V to 250 V. Although we are confident that most of our sensors will have a leakage current below 200 nA up to 500 V, by accepting those of a lower quality we will be able to reduce the cost without compromizing the performance.

X. Acknowledgements

We would like to thank the Elma experts, Dr. A. Sidorov and Dr. N. Egorov for usefull discussions.

We thank Shaun Roe from the Cern Atlas group for helping us to set up the SCT32 chip readout.

We are also grateful to Ögmundur Runolfsson and Kaspar Mühlemann for bonding all our detectors, some of them several times.

XI. References

[1] CMS Technical Proposal, Cern-LHCC 94-38

[2] CMS ECAL TDR, Cern-LHCC 97-33

[3] P. Aspell, “The design of the Pace integrated circuit for the LHC CMS Preshwoer Detector system”, Open University degree thesis, No. T401, Walton Hall, UK, 1997

[4] A. Cheplakov et al., “Radiation hardness of GaAs preamplifiers for liquid argon calorimetry at LHC”, MPI-PhE/96-15

[5] F. Anghinolfi et al., “SCTA – A Rad-Hard BiCMOS Analog Redout ASIC for Atlas Semiconductor Tracker”, Transactions on Nuclear Science, Vol. 44, No. 3 (1997) 298-302

[6] Ph. Bloch et al., “High Voltage Performance of Silicon Detectors Irradiated under Bias”, CMS NOTE 1998/058, accepted for publication in Nuclear Instruments and Methods A, 1999.

[7] E. León-Florián et al. “Particle fluence measurements by activation technique for radiation damage studies”, CERN-ECP-95-15

[8] L. Beattie et al., “Charge Collection Efficiency in Heavily Irradiated Silicon Diodes”, Nuclear Instruments and Methods A 412 (1998) 238-246

[9] C. Leroy et al., Proc. IVth Int. Conf. On Calorimetry in High Energy Physics, La Biadola, Isola d’Elba, Italy, 1993, eds. A. Menzione and A. Scribano, World Scientific, Singapore, 1994, p. 627

[10] Leroy et al., “Study of Charge Transport in non-irradiated and irradiated Silicon Detectors”, Cern-EP 98-105

[11] I. Golutvin et al., “Radiation Hardness of Silicon Detectors for Collider Experiments”, JINR Preprint No. E14-95-97

[12] L.J. Beattie et al., “Electric Field Profile in Si Detectors after Heavy Irradiation”, paper presented at the 8th European Symposium on Semiconductor Detectors, Schloss Elmau, June 14-17, 1998.

[13] Z. Li et al., “Charge Collection and Charge Pulse Formation in Highly Irradiated Silicon Planar Detectors”, paper presented at the 8th European Symposium on Semiconductor Detectors, Schloss Elmau, June 14-17, 1998.

[14] D. Passeri et al., “A CAD Investigation of Depletion Mechanisms in Irradiated Silicon Microstrip Detectors”, Nuclear Instruments and Methods A 426 (1999) 131-134