Tests of electronic devices and semi-conductor detectors under high neutron flux

Gh Gregoire
Institute of Physics, Université catholique de Louvain, Belgium
Ghislain.Gregoire@fynu.ucl.ac.be

Abstract. We present a study of the radiation damages induced by neutrons in a large batch of microstrip silicon sensors and test structures. The paper first describes the context of the research in the framework of an international collaboration preparing an experiment near a high intensity proton collider. The radiation hardness of the silicon sensors is essential to withstand the high neutron fluence to be encountered near the interaction point. The structure of the sensors is explained in a second section. The generation of the neutron beam and its characterization is briefly given. The last part shows systematic comparisons of some electrical parameters of the sensors before and after irradiation by neutrons. It also compares the relative behavior between batches from different manufacturers.

1. Introduction
The highly aggressive radiative environment around present and future particle accelerators requires the evaluation of radiation damages in all materials used in their construction or operation. In particular, the electronic devices, the structural materials and the associated equipments must be tested to check whether they will resist to the subsequent dose during their foreseen operation. The problem is however not limited to fundamental research facilities, but is also present in space activities, where the operations of spacecrafts result in integrated fluence of the same order of magnitude as those around high intensity accelerators: this is especially the case if their orbits cross the Van Allen radiation belts around the Earth.

In this context, our group has been involved in testing the resistance to neutron-induced radiation damages of various equipments from bare semiconductor sensors to complete operational power supplies and active electronic components.

The advantage of using neutron beams instead of proton beams is that their interactions with matter do not directly generate ionization losses. In most cases, it allows to keep the equipment partly or fully operational during the irradiation. Another important fact in the favor of neutron beams is that their damages give direct access to the so-called displacement damages, which are those believed to be permanent.

The present communication will present partial results on the resistance of silicon sensors exposed to neutron beam. These results were partially obtained in the context of work performed for the CMS collaboration at CERN.

2. Overview of the silicon tracker for the CMS experiment
The CMS experiment is presently being built at CERN around one intersection point of the future LHC accelerator. It is essentially a very large barrel-shape structure (21 meters in length with a diameter of about 14 meters) composed of several layers of specific subdetectors.

Each layer is mostly sensitive to a specific type of particle, the outermost layers being those reached by the most penetrating particles. One of the innermost structures is the tracker, whose goal is to provide three-dimensional coordinates along the many tracks originating from the interaction point. The sensitive elements of the tracker are semiconductor microstrip silicon sensors arranged in concentric cylinders and end plates around the beam axis (Fig. 1).

![Figure 1. Sketch and dimensions of the silicon tracker.](image)

In total, there are about 24200 sensors for the whole tracker. They are arranged in modules, which are the smallest fully operational devices in the tracker in the sense that a module contains all the associated electronics circuitry (multichannel preamplifiers, control circuits, optical transceivers, power supply and bias lines, mechanical support) (Fig. 2). The silicon sensors of the numerous modules cover a total area of about 206 m².

![Figure 2. Photograph of a complete module equipped with two silicon sensors (large grey rectangles). They are supported by a lightweight carbon fiber frame. The four preamplifier chips are the small brown squares right to the centre of the picture.](image)
It is obvious that the production, testing and assembly of such a large quantity of silicon sensors is a big enterprise and the management issues are not negligible.

Tendering was performed at the world level. At the same time, the physicists involved in the design and the physics issues defined the technical specifications of the sensors. These specs were discussed with the interested industries and a lot of feedback was done before reaching agreed conditions of contract. Two manufacturers were eventually selected for the whole production of sensors. The technical conditions of the contract specify the physical and electrical parameters essential for the good performance of the sensors during the foreseen operation period of the LHC (10 years) (Table 1).

| Tests     | Before irradiation | After irradiation |
|-----------|--------------------|-------------------|
| $V_{dep}$ | $100{<}V_{fd}{<}250$ V | $V_{fd}{<}300$ V |
| $I_{leak}$ | ~ $3{\times}10^{-17}$ A/cm | $V_{break}{>}$ 500 V |
| $R_{poly}$ | 1.5±0.5 MΩ | 1.5±0.5 MΩ |
| $C_{ac}$   | 1.2-1.3 pF/cm/µm | 1.2-1.3 pF/cm/µm |
| $I_{id}$   | < 1 nA | |
| $C_{int}$  | 1.2 pF/cm | 1.2 pF/cm + 10% |
| $R_{int}$  | >1 GΩ | >20 MΩ |

Table 1. Specifications of the essential electric parameters of the microstrip detectors. $V_{dep}$ is the depletion depth; $I_{leak}$ is the leakage current at full depletion and $\alpha$ is the slope of the fluence dependence of the normalized leakage current. $R_{poly}$ is the value of the biasing polysilicon resistors, $I_{id}$ is the leakage current of the coupling capacitor. $C_{ac}$ and $R_{int}$ are respectively the interstrip capacitance and resistance.

To check that the delivered product comply with these specifications a complex organization of laboratories was set-up to assess the performances of the sensors (Fig. 3).
Their tasks were to check the quality of the production, the long-term behavior of the sensors and the sensitivity to radiation damages generated by protons and neutrons. The present communication deals only with the procedures at the level of the Irradiation Qualification Centres.

3. The structure of the silicon strip microstrip sensors
Although having many different rectangular or wedge shapes to cope with the cylindrical geometry of the tracker, the microstrip sensors share common features. They are cut from 5 or 8-inch diameter wafers with two thicknesses of 320 and 500 microns. A sensor is obtained from the central part of a wafer and processed to implant the electrode structures for 512 to 768 strips; each strip has a couple of connecting pads and a polysilicon resistor in series with the bias supply line (Fig. 4).

![Figure 4. Longitudinal cut of a silicon sensor along a strip. The bias ring is common to all strips and feeds all then individual bias resistors.](image)

The half-moon cut-offs from the wafers, - the so-called test structures- follow the same processing line to implant all the characteristic elements of a sensor: minidetectors, MOS structures, capacitances, polysilicon resistors and diodes. The test structures are essential for the qualification as they share the same physical origin, same processing operations and same electrical characteristics as the central sensor from a given wafer. This fact even allows destructive testing, like an irradiation, without harm to the expensive sensor, while still giving fully meaningful data on its operation in real conditions.

The equivalent circuit of a microstrip silicon detector involves the component typical of any semiconductor detector: ideal diode with its associated equivalent capacitance and leakage resistance. The connection to an external charge preamplifier is done via a coupling capacity in parallel with a (possible) leakage resistor. The bias line is common to all strips and feeds a set of 512 polysilicon resistors (Fig. 5).
In addition to those elements common to any particular strip, there are parasitic interstrip resistances and capacitances. Their impedances depend on the electric field in the bulk of the semiconductor. It is essential to check that their values remain acceptable after high doses of radiation since they could be responsible for crosstalk between strips.

4. Electrical characteristics of a sensor or a test structure
For the Irradiation Qualification Centers, the characterization of a sensor, or a test structure, is performed before and after irradiation in conditions approaching as much as possible the real situation in CMS.
The electrical measurements are done with the help of a semiautomatic probe station Suess PA-200 (Fig. 6), assisted by several ancillary devices (capacitance meter, electrometer, high and low voltage supplies) linked to the needles of the probe station by a programmable switching matrix (Fig. 7).

Figure 6. The Suess PA-200 semiautomatic probe station.

Figure 7. Scheme of the electronic devices linked to the probe station to characterize the electrical properties of sensors and test structures.
The strategy of a complete set of tests is illustrated in Fig. 8 with the approximate durations of the main steps.

5. The high-flux neutron beam
The neutron production target is located in an underground cave near the vault of the Louvain-la-Neuve cyclotron (Fig. 9). The accelerator delivers a 10 microamperes deuteron beam impinging a water-cooled 10-mm thick beryllium target. A 50-micron thick stainless window closes the target chamber.

In order to harden the neutron energy spectrum, a stack of three different materials performs a simple filtering. A 20-mm thick polyethylene plate moderates the lowest energy neutrons; a 1-mm thick cadmium sheet then captures the remaining slow neutrons and a 1-mm thick sheet of lead attenuates the subsequent contribution of capture gamma rays. A GEANT-3 simulation of the neutron production process estimates the contamination of the beam. (Table 2)

| Particle type | Fraction | Average energy (MeV) | Maximum energy (MeV) |
|---------------|----------|----------------------|----------------------|
| Neutron       | 1.0      | 20.4                 | 50                   |
| Proton        | 1.5 $10^{-4}$ | 12.6                | 25                   |
| Electron      | 1.6 $10^{-4}$ | 1.6                 | 6                    |
| Gamma         | 2.4 $10^{-2}$ | 1.9                 | 10                   |

Table 2. Estimated relative contaminations of the neutron beam after the hardening filter.
Figure 9. The high flux neutron beam line near the Louvain-la-Neuve isochronous cyclotron.

The neutron energy spectrum was obtained by activation of selected target foils of 1 mm thickness. The choice of a specific target is based on the production cross-section of the daughter nucleus and its relatively long half time. The selected target materials are listed in Table 3.

| Reaction                  | Energy range (MeV) | Gamma ray energy (keV) | Relative gamma intensity | Half life of residual nuclide | Natural abundance of target |
|---------------------------|--------------------|------------------------|--------------------------|-------------------------------|----------------------------|
| $^{27}$Al(n,α)$^{24}$Na  | 7-27               | 1369                   | 1                        | 14.9 h                        | 1                          |
| $^{58}$Ni(p)$^{59}$Co    | 2-20               | 811                    | 0.995                    | 70.9 d                        | 0.683                      |
| $^{58}$Ni(n,2n)$^{57}$Ni | 12-40              | 1378                   | 0.779                    | 1.5 d                         | 0.683                      |
| $^{59}$Co(p,p)$^{60}$Co  | Thermal            | 1117-1332              | 1                        | 5.27 y                        | 1                          |
| $^{59}$Co(n,2n)$^{58}$Co | 14-50              | 811                    | 0.995                    | 70.9 d                        | 1                          |
| $^{59}$Co(n,3n)$^{57}$Co | >20                | 122-136                | 0.855                    | 271.8 d                       | 1                          |
| $^{93}$Nb(n,2n)$^{92m}$Nb| 9-30               | 934.5                  | 0.991                    | 10.2 d                        | 1                          |

Table 3. Target materials and reactions used for the activation measurements.

From the activity of the residual nuclides and based on the known neutron production cross sections, one obtains the energy spectrum of the neutron beam (Fig. 10) and its absolute normalization with respect to the primary deuteron beam [1].
The shapes of the neutron beam spots at various downstream positions along the beam axis were obtained with standard radiographic plates and, after development, by densitometry. All beam profiles are peaked on the primary beam axis.

The estimation of the dose is done with alanine dosimeters. Their small size and linear response at high doses make them particularly suitable in the present case. The dosimeters are read by a Bruker E-Scan system and the absolute calibration is traceable to the NIST with a set of reference dosimeters.

A quantitative evaluation of the radiation damages is obtained with the displacement $D$, defined as the normalized integral of a spectral displacement function $D(E)$ weighted by the beam energy spectrum. The function $D(E)$ in turn takes into account the various interaction cross sections, $\sigma_k(E)$, the subsequent recoil energy distribution $f_k(E, E_r)$ and the probability $P(E_r)$ to get a non-ionizing collision.

$$
D = \frac{\int \frac{d\Phi(E)}{dE} D(E) dE}{\int \frac{d\Phi(E)}{dE} dE} = \frac{\int \frac{d\Phi(E)}{dE} D(E) dE}{\Phi_{tot}}
$$

with

$$
D(E) = \sum_k \sigma_k(E) \int dE_r f_k(E, E_r) P(E_r)
$$

A value of $D$ for 1-MeV neutrons is found to be 95 MeV mb. It is used as a normalization to define a hardness factor $\kappa$ for any neutron beam with any energy distribution. It allows comparisons between beams of very different energy spectra and energies. This is very useful since the neutron energy distribution around CMS is known from simulations only, and is very different from all experimentally available beams.

A graph of the presently known values of the hardness factor is shown in Fig. 11. The points with error bars were obtained in Louvain-la-Neuve with the monoenergetic neutron beam near the cyclotron.
5. The environment of the sensors during irradiation

The build-up of damages in the silicon sensors corresponds to an important increase in the reverse current of a biased semiconductor detector. Since this current also corresponds to a serious increase of the noise, the silicon sensors of the tracker in CMS are kept at about -20°C at all times during the operation.

To mimic the actual conditions in CMS, the sensors and test structures are also maintained at low temperatures during their exposure in the neutron beam. These environmental conditions are obtained by placing the devices inside a Styrofoam cold box directly placed in the beam. A flow of cold and dry air is permanently maintained inside the box: the relative humidity is automatically maintained at about 1% while the temperature is stabilized to about -20°C within about 0.5 °C. The description of this system is given elsewhere [3][2].

Inside the cold box, sensors and/or test structures are fixed on PMMA frames and bonded to metallic pads to supply the bias voltage. Up to five frames can be stacked along the beam direction. Up to three stacks can be put side by side inside the box cold; each stack is then exposed in turn to the neutron beam by remotely operated lateral displacements of the box.

6. Modeling the radiation damages

The so-called NIEL model assumes that the permanent radiation damages are due to non-ionizing displacements of atoms in the crystal lattice [4][3]. Quantitatively the damages are then empirically expressed in terms of an effective dopant concentration given by the following expression involving the equivalent fluence $\Phi_{eq}$ for 1-MeV neutrons:

$$N_{eff}(\Phi_{eq}, t_a, T_a) = N_{eff,0} \left( 1 - r(1 - e^{-\Phi_{eq}}) \right) - \Phi_{eq} \left( g_e - g_a e^{-\frac{1}{\tau_{ce}}} - g_{\gamma} (1 - e^{-\frac{1}{\tau_{ce} T_a}}) \right)$$

In this expression, the first term in brackets represents de donor removal by the incident neutrons with the characteristic constants $r$ and $c$. The quantity $g_c$ corresponds to the fraction of the flux which
generates permanent damages. The constants $g_a$ and $t_a$ appear in a term expressing the "beneficial  
"annealing of damages at a temperature $T_a$ for a duration $t_a$. The last terms in the second line, with the  
constants $g_y$ and $k_y$ define the so-called "reverse annealing" which corresponds to a creation of  
defaults during the annealing.

The concentration of dopant appears in all expressions defining the electrical characteristics of a  
depleted diode, like the capacitance, the depletion voltage and the reverse current.

\[ C_{\text{back}}(V) = \frac{dQ}{dV} = S \sqrt{\frac{q\varepsilon_0|N_{\text{eff}}|}{2(V_{bi} + V)}} \]

\[ V_{\text{dep}} = \frac{q}{2\varepsilon_0} \left| N_{\text{eff}} \right| q^2 V_{bi} - V_{bi} \]

\[ J_{\text{leak}}(V) = -\frac{q}{\tau_s} \left[ \frac{2\varepsilon_0}{q|N_{\text{eff}}|} \right] \left( \sqrt{V_{bi} + V} - \sqrt{V_{bi}} \right) \]

Although the model is useful to evaluate the electrical characteristics, it does not always agree with  
experimental data (Fig. 12). This figure shows that the depletion voltage is correctly predicted for sensors of a  
given manufacturer, while in disagreement for those from another manufacturer.

![Graph of Manufacturer 1](image1)

![Graph of Manufacturer 2](image2)

Figure 12. Comparison between the predicted (red points) and the measured (blue points) values of the depletion  
voltages for sensors of two different manufacturers.

7. Measurements of the capacitance and depletion voltage

The figure 13 shows the characteristics CV curves for two sets of sensors.
Figure 13. Capacitance versus voltage curves for two batches of sensors. The upper row corresponds to those made by the manufacturer #1, the lower row from manufacturer #2. For each row, the picture at left (right) is for sensors before (after) the irradiation. The dashed lines represent the maximum depletion voltages according to the conditions of contract.

Figure 14. Coupling capacitance versus voltage curves for two batches of sensors. The upper row corresponds to those made by the manufacturer #1, the lower row from manufacturer #2. For each row, the picture at left (right) is for sensors before (after) the irradiation.
Figure 15. Polysilicon bias resistors versus voltage for two batches of sensors. The upper row corresponds to those made by the manufacturer #1, the lower row from manufacturer #2. For each row, the picture at left (right) is for sensors before (after) the irradiation.

It is immediately seen that before the irradiation, the sensors from manufacturer #1 show larger fluctuations of the depleted thickness than for those of manufacturer #2. On the other hand, after the irradiations, the detectors from manufacturer #2 all meet the required constraint, while a sizeable fraction of, - if not all-, sensors from #2, do not meet the conditions and should be rejected.

The coupling capacities and the polysilicon bias resistors were shown to be unaffected by the irradiations (Figs. 14 and 15).

8. Measurements of the interstrip impedances
As indicated before, the interstrip resistances and capacitances are key parameters, which could give rise to unwanted crosstalk between strips. It is then essential to check that the interstrip resistance does not drop below with requirement stated in the conditions of contract (Fig. 16). This condition is met here in all cases. In the same conditions, the interstrip capacitance was also shown not to exceed a safe value.
Figure 16. Interstrip resistance curves versus bias voltage for two batches of sensors. The upper row corresponds to those made by the manufacturer #1, the lower row from manufacturer #2. For each row, the picture at left is for sensors before the irradiation. The graphs at right are distributions of the interstrip resistances at a bias voltage of 400 Volts DC.

Figure 17. The distributions of the leakage current in the dielectric of the coupling capacity for two batches of sensors. The upper row corresponds to those made by the manufacturer #1, the lower row from manufacturer #2. For each row, the picture at left is for sensors before the irradiation. The graphs at right are distributions of the same quantity after irradiation.
It is also seen that the observed leakage currents are in general much smaller that the maximum allowed limit of 1 nA.

9. Conclusions
Many more experimental results could be shown, but, even with the presentation of a very partial sample of sensors, it is shown that the compared behavior of sensors before and after irradiations is a powerful tool to check production batches of different origins.

The irradiation of sensors, and their detailed characterization, proved thus very effective in detecting, monitoring and correcting anomalies at different levels of the production processes:

• the quality of the raw silicon material,
• the handling of the wafer in the industry (dicing, manipulations...),
• the manufacturing process and the long term stability of the final sensor.

With severe constraints at the production level, it is thus possible to obtain silicon sensors, which are able to withstand high doses of radiations, like those encountered in space or in "hot" laboratories.

References

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