Studies of Radiation Effects in the NA60 Silicon Pixel Detectors

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Abstract

NA60 is a fixed target experiment at the CERN SPS, which studies dimuon production in proton and ion induced collisions. Downstream of the target system a silicon pixel telescope made with p-on-n silicon sensors measures the charged tracks originating from the interactions. During the 2003 data taking period with indium-indium collisions at 158 GeV per incident nucleon, a significant radiation dose with a very inhomogeneous distribution has been accumulated in the pixel telescope, leading to partially type-inverted silicon sensors. Measurements of the depletion voltage and leakage current performed during this run are shown and compared with simulation results. It is also shown that the operation of partially type-inverted sensors poses no major problem.

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1 The NA60 silicon pixel telescope

The NA60 silicon pixel telescope [1] consists of 16 detector planes placed downstream of the target system. The planes comprise either 4 single chip assemblies, in case of the planes closest to the target, or 8 single chip assemblies, for the downstream planes. Figure 1 shows the arrangement of the planes, chosen to get an optimal coverage of the geometrical acceptance of the muon spectrometer, located further downstream behind a hadron absorber.

The single chip assemblies are made from ALICE1LHCB readout chips and ALICE pixel sensors. The sensors have p-type pixel implants on a high-resistivity (15 k Ω cm) n-type bulk.

Figure 1: The complete vertex telescope consists of eight 4-chip and eight 8-chip detector planes.

2 Expected effects of the radiation damage

To predict the behaviour of the silicon sensors during the running of the experiment, the effects of the radiation damage in the pixel planes were simulated, prior to the data taking [2], from the expected number of ions incident on the target and the number of tracks per collision, provided by the VENUS event generator [3]. The simulation results presented in this section include the effects of self-annealing, incorporated taking into account the measured time structure of the irradiation.

Figure 2 shows the calculated fluence for the complete indium ion run, in the most upstream and the most downstream planes of the pixel telescope. The simulation is based on the tracks generated by VENUS and takes into account the number of ions incident on the target, as continuously measured during the data taking period. We see that the fluence shows a strong dependence on the distance from the beam axis, with the central pixels being subject to 10 times higher fluences than the outermost pixels of the same sensor chips. The dependence on the distance from the target, along the beam axis, is much weaker.

Figure 2: Simulated fluence after the complete indium run (5×10^{12} ions incident on the target) in the most upstream (0) and the most downstream (15) planes of the pixel telescope.

2.1 Leakage current

The radiation-induced increase in the leakage current, ΔI , can be described by

$$\Delta I = \alpha \Phi_{\text{eq}} V \quad (1)$$

where Φ_{eq} is the 1 MeV neutron equivalent fluence, α is the current related damage rate and V is the volume. Since the irradiation lasted several weeks, the self-annealing during the irradiation cannot be neglected. The annealing behaviour is taken into account by introducing a time-dependent damage rate, using the parametrisation

$$\alpha(t) = \alpha_I \cdot \exp\left(-\frac{t}{\tau_I}\right) + \alpha_0 - \beta \cdot \ln(t/t_0) \quad (2)$$

explained in [4]. The experimentally measured values for the parameters were also taken from [4].

Figure 3 shows the simulated leakage current for the first plane at the end of the run, assuming an annealing temperature of 20°C over the whole data taking period. Following the behaviour of the fluence, the leakage current is expected to be negligible in the outermost pixels and reaches approximately 10 nA per pixel in the most central region.

Figure 3: Simulated leakage current at room temperature, including self-annealing, in the most upstream plane of the pixel telescope after the complete indium run (5×10^{12} ions incident on the target).

2.2 Depletion voltage

The radiation-induced change of the effective doping concentration, N_{eff} , leads to a change in the depletion voltage, V_{dep} , according to

$$V_{\text{dep}} = \frac{d^2 N_{\text{eff}} q_e}{2 \epsilon_0 \epsilon_r} \quad , \quad (3)$$

with the sensor thickness d , the elementary charge q_e and the dielectric constant $\epsilon_0 \epsilon_r$. It has been shown [5] that, under irradiation, the effective doping of n-type silicon decreases until it reaches a point of type inversion and then gets effectively p-doped with a constantly growing doping concentration. Furthermore, it was found that the change of the doping concentration can be written as a sum of three contributions with different annealing behaviours [4]:

$$\Delta N_{\text{eff}} = N_C (\Phi_{\text{eq}}) + N_A (\Phi_{\text{eq}}, t(T_a)) + N_Y (\Phi_{\text{eq}}, t(T_a)) \quad . \quad (4)$$

Here N_C is the stable damage part, N_A the short term (beneficial) annealing component and N_Y the reverse annealing contribution. While N_C depends only on the accumulated fluence, N_A and N_Y have a time dependence, which itself depends on the annealing temperature T_a . For all three contributions we have used the parametrisations and the experimental values given in [4]. Figure 4 shows the effective doping of the bulk, before annealing, as a function of the 1 MeV neutron equivalent fluence. The change in the sign of the doping concentration is equivalent to a transition from n-type to p-type material. At this transition point the depletion voltage (Fig. 5) reaches a minimum and then rises continuously with increasing accumulated fluence.

Figure 4: Effective doping concentration as a function of the 1 MeV neutron equivalent fluence, before annealing. At a fluence of approximately $3 \cdot 10^{12} \text{ n}_{\text{eq}}\text{cm}^{-2}$ the material undergoes type inversion.

Figure 5: Depletion voltage versus the 1 MeV neutron equivalent fluence. The voltage needed for full depletion decreases until type inversion and then increases almost linearly.

Due to the inhomogeneous radiation field in NA60, the change in the effective doping is expected to lead to the following behaviour in the p-on-n type sensors:

- At the beginning, the voltage needed for full depletion decreases with increasing fluence. Since the depletion region starts growing from the pixel implants, in principle the sensors can also be operated with partial depletion.
- After a certain fluence, the n-type bulk is converted to p-type material. Due to the inhomogeneity of the radiation field this is expected to happen earlier for the pixels close to the beam axis, while for the outer pixels it might never occur. In the region where this transition has happened, the depletion region starts growing from the backplane, while between the pixel implants and the

bulk there is no longer a diode transition (Fig. 6). Therefore, it is necessary to fully deplete the sensor for the pixel to be operational.

- After the point of type inversion the doping concentration of the now p-type bulk, and therefore also the depletion voltage, is constantly growing. Again, due to the form of the radiation field, the innermost pixels are expected to have the highest depletion voltage after type inversion.

Figure 6: Sensor behaviour before (top) and after (bottom) type inversion. After type inversion the depletion region grows from the backside of the sensor (as indicated by the arrows).

Figure 7 shows the simulated depletion voltage for a 4-chip pixel plane at the end of the run, i.e. after 5×10^{12} ions incident on the target. The outer regions of the plane show nearly the initial depletion voltage. At a radius of approximately 1.2 cm the point of type inversion is reached, indicated by a zone of very low depletion voltage. Going even further inwards, the depletion voltage of the now type-inverted sensor grows constantly, reaching nearly 200 V for the innermost pixels.

It should be noted that the electric field reaches its maximum at the pn-junction. As a consequence, when the point of type inversion is reached, together with the position of the pn-junction the maximum of the electric field also moves from the readout side to the back of the sensor. Therefore, for the central, type-inverted pixels the electric field is maximal close to the backplane and decreasing towards the pixel electrodes, in contrast to the initial state, where the electric field reaches its maximum at the readout side. We will, therefore, have completely different field configurations in different regions of the same silicon sensor. Furthermore, it will be necessary to operate the pixels overdepleted after type-inversion, to provide a non-zero field close to the pixel implants and guarantee an efficient charge collection in all the pixels.

3 Measurements during the indium run

3.1 Number of incident ions

The number of ions incident on the targets was measured with the beam tracker, a detector made of four silicon microstrip sensors and operated at cryogenic temperatures to sustain extreme radiation doses [6]. It is placed in the beam line, from 10

Figure 7: Simulated depletion voltage for a 4-chip plane at the end of the run.

to 30 cm upstream of the target system, and measures the transverse coordinates of the incident beam particles with an accuracy of $20\,\mu\text{m}$, thanks to the 24 strips of $50\,\mu\text{m}$ pitch of each sensor. The backplanes of each sensor, with an active area of $6 \times 14.5\,\text{mm}^2$, cover the beam profile and can be used to count the number of particles crossing the sensor on a burst by burst level. The integrated number of ions is shown in Fig. 8 versus the number of days of the run. After an initial phase of relatively low intensity, a period of stable running with approximately $1 - 2 \times 10^{11}$ ions per day was reached. The total number of ions during the complete data taking period was approximately 5×10^{12} .

Figure 8: Number of incident ions versus run duration.

3.2 Non-ionising energy loss

A dosimeter plane has been placed at the end of the vertex telescope, 40 cm downstream of the centre of the target system, to measure the radiation dose during the heavy-ion run. The measurements of the fluence were obtained with four silicon pin-diodes at different distances from the beam axis. Their I-V characteristics were measured under well-defined conditions before and after irradiation and then related to the 1 MeV n_{eq} fluence that would result in the measured increase in the leakage current. Furthermore, aluminium probes in the form of concentric rings around the beam axis were placed on the dosimeter plane and their $\text{Al} \rightarrow {}^{22}_{11}\text{Na}$ activation measured through gamma spectroscopy. This activation can be translated into a particle fluence using the appropriate activation cross sections for the particles predominantly produced in the collisions. It is important to notice that the cross sections for the activation $\text{Al} \rightarrow {}^{22}_{11}\text{Na}$ are significant only for particles of energies above ~ 30 MeV [7], while the silicon diodes are also sensitive to particles of lower energies, particularly neutrons.

Figure 9: Measured and simulated fluence at the downstream end of the pixel telescope. A dosimetry plane with silicon diodes and aluminium probes was exposed to the radiation field during the first 20 days of the run. The measurements are compared with simulations of primary charged tracks (VENUS) and a full FLUKA description of the collisions and of the target region materials.

The results of the measurements are shown in Fig. 9 together with the outcome of the simulations. We start by noting the significant difference between the fluences measured by the aluminium foils and by the pin diodes, especially at high distances from the beam axis, where low-energy particles from secondary processes contribute the most. The VENUS-based calculation and the aluminium measurements, both neglecting low-energy particles, are in good agreement with each other. Contrary to the VENUS simulation, the FLUKA [8, 9] simulation includes secondary processes, such as decays and re-interactions, as well as back-scattering of low-energy particles

from the hadron absorber and the vertex magnet of the NA60 experiment. These calculations are, therefore, in much better agreement with the total fluences measured by the silicon pin diodes.

3.3 Leakage Current

The detector current of every plane was constantly monitored throughout the whole data taking period. Figure 10 shows the current of a 4-chip plane versus the time in the run. Panel ‘a’ shows the measured current as well as the current we would have measured for a constant temperature of 20 °C, if we correct the temperature variations using the expression

$$I \propto T^2 \exp\left(-\frac{E_g}{2kT}\right) \quad (5)$$

where T is the temperature and E_g is the gap energy. The temperature has been measured by two Pt100 sensors soldered on each pixel detector plane. Since the Pt100 sensors were not placed on the silicon sensors but on the carrier hybrid, the measured temperature is not exactly the real temperature of the pixel sensors. A temperature difference of 5 K has been observed in measurements with an infrared camera and was taken into account in this analysis. The time evolution of the corrected leakage current follows exactly the pattern expected from the VENUS simulation, shown in Fig. 10 b, which takes into account the integrated number of ions incident on the target, shown in Fig. 8, and self-annealing effects during the irradiation period.

Figure 10: Leakage current of a 4-chip plane for the whole data taking period. Panel ‘a’ shows the raw current measurement and the current values corrected for a constant temperature of 20 °C. Panel ‘b’ shows the corresponding calculated leakage current, taking into account the measured number of ions for each day and the annealing during the data taking period.

The absolute value of the leakage current is higher than predicted by the VENUS simulation. This is consistent with the fact that this simulation neglects secondary

particle production from re-interactions, back-scattering and decays, processes which, as we have seen before (Fig. 9), significantly contribute to the accumulated fluence. Furthermore, we should keep in mind that the leakage current depends exponentially on the temperature and, hence, a small difference between the real and estimated temperatures would also lead to sizeable changes in the calculated values.

3.4 Depletion Voltage

Data sets have been taken with reduced bias voltages to assess the depletion voltage of the sensor. The measurements shown here have been performed after approximately 35 days of ion run, corresponding to 4.2×10^{12} ions delivered on the target. In the p-on-n sensors one expects that after type inversion only completely depleted pixels work without problems. Figure 11 shows the hitmaps that were integrated during a run with a low bias voltage (30 V) for two different planes. In spite of the fact that the density of tracks is highest at small distances from the beam axis, we clearly see a reduced number of hits in the centre of the planes, in the region which suffers the highest radiation damage.

Figure 11: Hitmaps at a bias voltage of 30 V for the first small plane and the first big plane.

To better quantify this effect we measured the pixel occupancies for different bias voltages and normalised them with the occupancy obtained at full depletion. The result is shown in Fig. 12 for two different bias voltages, as a function of the distance from the beam axis. For large radii the multiplicities are identical to those measured at full depletion, whereas closer to the beam axis the multiplicities drop. The radius of this transition ring increases when decreasing the bias voltage. The fact that the normalised occupancy is nearly constant and close to 1 for all radii

above the transition region shows that it is possible to operate a sensor which is only partially type-inverted, in spite of a drastically changing field configuration over the sensor chip, i.e. no difference can be seen in the hit detection efficiency between type-inverted and not type-inverted pixels.

Figure 12: Multiplicity vs. the distance from the beam axis for two different bias voltages. The multiplicities were normalised with the multiplicity measured in a run at full depletion.

The dependence of this behaviour on the bias voltage of the sensor is shown in Fig. 13 for all measured bias voltages in a single plane. The plot shows the applied bias voltage versus the radius below which the particle tracks are no longer efficiently detected. This point was determined from the 50%-point of an error function fitted to the data. We interpret it as the point below which the type-inverted pixels are no longer depleted and, therefore, are no longer properly working. As expected from the simulations the radius of the region of non-working pixels increases when lowering the bias voltage, consistent with a higher depletion voltage for smaller radii. The solid curve in Fig. 13 shows the depletion voltage vs. the radius, as expected from the VENUS simulation. For small radii one can see a very good agreement with the measurement, whereas for the most external pixels the measured depletion voltage is systematically higher than the expectation. This discrepancy is consistent with the difference between the fluence expected from the VENUS-based estimate and the measurements done with the pin diodes.

Figure 13: Depletion voltage vs. the radius for a 4-chip plane. The points show the depletion voltage as determined from multiplicity measurements, while the solid curve represents the result of the VENUS simulation.

4 Summary

The effects of the radiation damage on the silicon pixel sensors of the NA60 experiment have been studied. Simulations predicted a very inhomogeneous radiation damage, leading to type inversion in the most central pixels of every plane, whereas the outermost regions should keep their initial behaviour.

During the data taking period the leakage current of the pixel detector planes was monitored and the depletion voltage for the different pixels was determined from hit multiplicity measurements in a bias voltage scan. We have observed that the detectors can be operated without visible efficiency losses, even when a big fraction of their pixels is type-inverted. The two-dimensional segmentation of the pixel detectors offers the possibility to study the spatial dependence of the depletion voltage. The measurements show that, after irradiation, the depletion voltage is higher for pixels closer to the beam axis, as expected. If the applied bias voltage does not reach the value needed for the depletion of the whole sensor, the pixels closer to the beam axis lose efficiency, whereas the outer pixels work normally.

The behaviour of the measured depletion voltages and leakage currents is in qualitative agreement with the simulated patterns. The damage, especially in the outer regions of the planes, is a bit more severe than calculated, an observation consistent with an underestimation of the non-ionising energy loss in these regions. This is not surprising, since the fluence estimates were done with a simple simulation, ignoring secondary tracks emitted by re-interactions or by back-scattering from the materials surrounding the pixel planes.

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