

Gamma irradiation of ATLAS18 ITk strip sensors affected by static charge

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ABSTRACT: Construction of the new all-silicon Inner Tracker (ITk), developed by the ATLAS collaboration to be able to track charged particles produced at the High-Luminosity LHC, started in 2021 and is expected to continue until 2028. The ITk detector will include ~18,000 highly segmented and radiation hard n⁺-in-p silicon strip sensors, which are being manufactured by Hamamatsu Photonics. Upon their delivery, the ATLAS ITk strip sensor collaboration performs detailed measurements of sensors to monitor quality of all fabricated pieces.

QC electrical tests include current-voltage (IV) and capacitance-voltage (CV) tests, full strip tests, and a measurement of the long-term stability of the sensor leakage current. While most sensors demonstrate excellent performance during QC testing, we have nevertheless observed that a number of sensors from several production batches failed the electrical tests.

Accumulated data indicates a strong correlation between observed electrical test failures and high electrostatic charge measured on the sensor surface during initial reception tests. This electrostatic charge enhances the risk of "Local trapped charge" events during manufacturing, shipping, and handling procedures, resulting in failed electrical QC tests. To mitigate the above-described issues, the QC testing institutes modified the sensor handling procedures and introduced sensor recovery techniques. Despite the implementation of various recovery techniques, it is still possible that some affected sensors will not be identified by the sensor QC testing, or that "Local trapped charge" events could occur in later manipulation stages of the sensor.

In the presented study, we have investigated whether the total ionizing dose (TID) expected in the real experiment can effectively resolve early breakdown or low interstrip isolation caused by the electrostatic charge. Selected charge-affected sensors were irradiated with gamma rays from the ⁶⁰Co source for a number of TID values. The results of this study indicate that the negative effects of the electrostatic charge on the critical sensors characteristics disappear after a very small amount of an accumulated TID, which actually corresponds to one or two days in the experiment. This finding gives us confidence in mitigating the issue of electrostatic charge during the operation of the ITk strip sensors in the real experiment.



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1. Introduction

The upgrade of the Large Hadron Collider (LHC) into the High-Luminosity LHC (HL-LHC), with the peak instantaneous luminosity reaching $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [1], will require the replacement of the existing ATLAS Inner Detector with a new all-silicon tracker containing a new type and design of silicon sensors. The innermost part of the new Inner Tracker (ITk) will consist of pixel detectors, whereas the outer radii will be made of strip detectors [1, 2]. Each individual module of the ITk strip detector includes a single-sided micro-strip sensor made with n^+ -strips implanted on p-type silicon bulk (n^+ -in-p). The ITk strip detector will consist of 2 types of barrel sensors of a square geometry $9.8 \times 9.8 \text{ cm}^2$, implementing short strips (24.1 mm) for the inner two barrel layers and long strips (48.3 mm) for the outer two barrel layers, and of 6 types of endcap sensors with roughly trapezoidal shapes and strips forming a fan geometry. The endcap strip lengths vary from 15 mm to 60 mm depending on the radius. The pitch of a barrel sensor is $75.5 \text{ }\mu\text{m}$, while it varies around the mean value of $75 \text{ }\mu\text{m}$ for the endcap sensors [3]. Aluminum strips are AC-coupled to the implant strips, which are biased through poly-silicon bias resistors. The ITk detector will include 17,888 strip sensors covering 165 m^2 of silicon with a total of ~ 60 million strips. Production of the total amount of 20 800 ITk strip sensors (including spares) has started in HPK in 2021 and is scheduled for completion in 2025.

Upon delivery, the ATLAS ITk strip sensor collaboration performs detailed measurements of individual production sensor characteristics to monitor the quality of all fabricated devices. Several institutes involved in the complex testing program (the Quality Control or QC) conduct mechanical and electrical measurements of the sensors to ensure that their characteristics are within the specifications defined by the collaboration. QC electrical tests include current-voltage (IV) and capacitance-voltage (CV) tests conducted on each individual sensor. Additionally, full strip test and a measurement of long-term stability of the sensor leakage current are performed on a sample comprising 2-10% of the total sensors. The full strip test checks the uniformity of electrical characteristics throughout the wafer surface. Each individual sensor strip is contacted and its impedance to ground is measured to identify potential presence of metal shorts, broken implants, faulty bias resistors or low inter-strip isolation, as well as pinholes or punch-throughs in the dielectrics. The current stability test is performed to check the sensor leakage current variation over tens of hours. During production, measurements of the surface electrostatic charge were added for each individual sensor.

By now, approximately 50% of production sensors have been delivered and tested. While most sensors have demonstrated high quality performance in QC tests, several sensors from different production batches failed the electrical QC tests. Early breakdowns were observed in IV tests, where the Breakdown Voltage (V_{BD}) was measured to be below the required 500 V, whereas areas with low interstrip isolation in full strip tests as well as current instabilities during the long-term current stability studies were also observed. Additionally in some occasions, IV failures were observed after the long-term leakage current stability test.

Accumulated data indicate a strong correlation between observed electrical failures and a high electrostatic charge, reaching several hundreds of volts per inch, measured on the surface of the sensors and of the plastic sheets used for sensor mechanical protection during the initial reception test (see Figure 1). The electrostatic charge enhances the occurrence of "Local trapped charge" events during handling procedures, manufacturing steps, and shipping, resulting in failed

electrical QC tests. Electrostatic charge accumulated on the surface of the sensor in the strip area can lead to the loss of interstrip isolation whereas charge accumulated close to the edge and bias ring can cause instability of the leakage current or low breakdown voltage. To mitigate the above-described issues, the QC testing institutes modified the sensor handling procedures and introduced sensor recovery techniques, such as irradiating the sensor surface with UV-A (315-400 nm wavelength) or UV-C light (100-280 nm), applying an intensive flow of ionized gas, or subjecting the sensors to high-temperature exposure at 150 °C for 16 h. In many cases, simply storing the sensors in a dry environment for a few days or weeks helps to cure the sensors. Additional information about sensor recovery techniques can be found in [4]. However, despite the implementation of these methods, there is still a possibility that some affected sensors may go unnoticed during the QC testing process, or that "Local trapped charge" events could occur during later manipulation of the sensor.

So, the question arises: will the sensor issues caused by electrostatic charge be ‘cured’ by ionization in the real experiment? If so, how quickly? To investigate whether the total ionizing dose (TID) expected in the real experiment can effectively resolve early breakdown or low interstrip isolation caused by the electrostatic charge, the affected sensors were irradiated with the gamma rays from a ^{60}Co source. To determine the TID and the corresponding duration of the real experiment required for such a cure, irradiation to several TID values was planned.



Figure 1. Electrostatic charge measurement on sensor surface during initial reception tests. Displayed value is in units of kVolts.

2. Sensor selection and irradiation

In this experiment, we chose three sensors that exhibited early breakdown in IV tests and 3 sensors with low interstrip isolation area identified in the full strip test for the gamma irradiation study. Our plan was to irradiate only two from each category (early breakdown and low interstrip isolation) and keep one sensor from each category as a reference sample. The reference sample will undergo no irradiation but will be subjected to identical conditions in terms of transport, storage, and handling as the irradiated sensors. The selected sensors along with their breakdown Voltage (V_{BD}) and the number of strips with low interstrip isolation are given in Table 1. Initial IV tests were conducted as part of the standard sensor QC testing and were repeated after two-months of storage in a drying cabinet, just before irradiation.

Sample	Initial V_{BD} / V_{BD} just before irradiation [V]	Sample	Low interstrip isolation area # of affected strips in initial test / in test just before irradiation)
R1-W607	150 / 160	R1-W635	40 / 40
R1-W617	150 / 150	R1-W620 - R	26 / 18
R1-W650 - R	150 / 200	R3-W1014	28 / 24

Table 1. Selected samples for the irradiation study. R1 and R3 indicate the sensor type and Wxxx represents the wafer number. Samples highlighted in red with an ‘R’ denote the reference sample.

Figure 2 shows the full strip test results of bias resistance (R_{BIAS}) of the R1-W635 and R1-W620-R sensors tested just before planned irradiation. The low interstrip isolation manifests as areas with low R_{BIAS} values in the full strip test measuring setup. The required value of R_{BIAS} according to the ATLAS specification is 1.5 ± 0.5 M Ω .

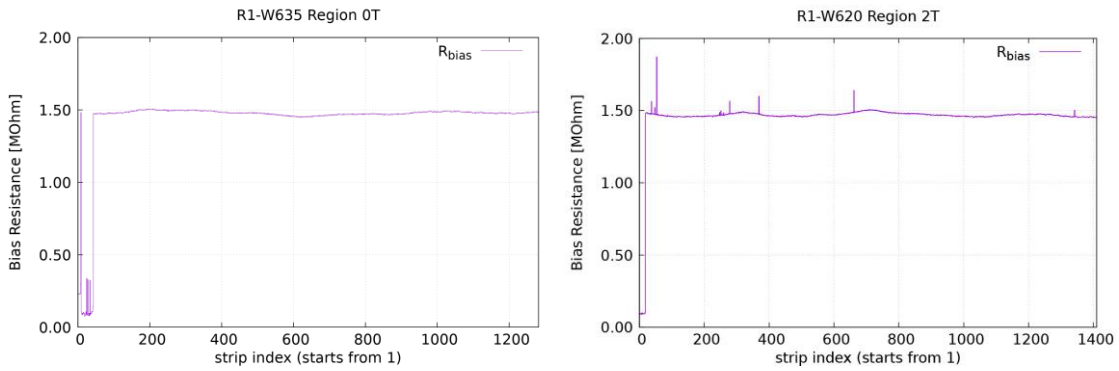


Figure 2. Full strip tests of R1-W635 (left) and R1-W620-R (right) sensors measured after 2 months of dry storage, i.e. just before irradiation.

The target TID values chosen for this experiment were 11, 49, 195, 590, 1200 krad, corresponding approximately to one week, one month, six months, one year, and two years of sensor exposure in the real experiment according to the simulations. The worst-case scenario for curing sensors affected by electrostatic charge is in regions in the ITk detector where the TID is minimal, as it would take longer to get sensors cured in these areas. Specifically, this applies to the central region of the outermost barrel cylinder, with 5.9 Mrad target dose including 1.5 safety factor, see Figure 3.

The sensors were irradiated by a ^{60}Co gamma radionuclide source installed at UJP PRAHA a.s. [6] with dose rate of 1 krad/min. The sensors were irradiated individually in a custom made charged-particle equilibrium (CPE) box constructed with an outer layer of 1.5 mm of Pb and an inner layer of 1 mm of Al, following the recommendations of ESCC [7]. A photo of the CPE box with a sensor is shown in Figure 4. While using the CPE box during the irradiation, the dose enhancement from low-energy scattered radiation is minimized by producing electron equilibrium and a uniform distribution of energy deposited in the sample is ensured. The reference samples were physically moved inside the CPE box, taken out, but were not subjected to irradiation.

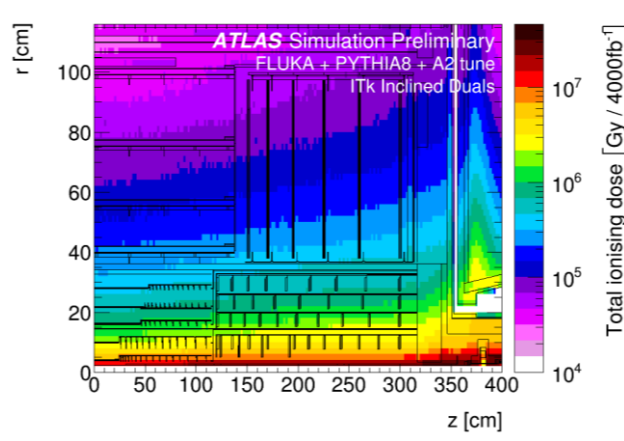


Figure 3. Total expected ionizing dose per 4000 fb^{-1} of integrated luminosity in the ATLAS Inner Tracker [5].

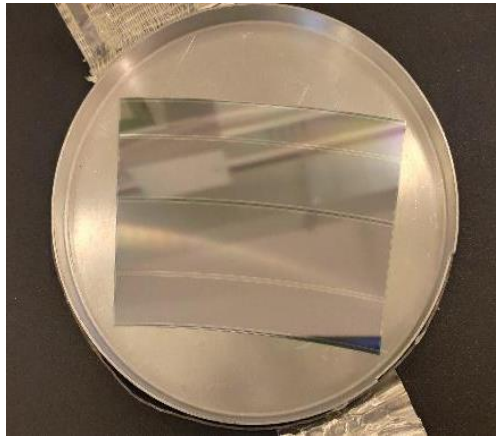


Figure 4. Photo of sensor positioned in CPE box. The top cover of the box is not shown.

3. Results

The measurements of IV characteristics after irradiation with TID of 11 krad for sample R1-W617 are shown in Figure 5a. The IV characteristics measured before irradiation, with breakdown voltage of 150V, are also displayed. Early Break Down (BD) of sensors W617 and W607 (not shown in the plot) was no longer present after gamma irradiation to 11 krad. In Figure 5b, IV characteristics of the reference sample R1-W650-R are shown. Reference sensor R1-W650-R, which was transported and handled alongside the other sensors and was not subjected to irradiation, did not recover, as seen from the green line corresponding to the measurement on June 2nd 2023. Its breakdown voltage increased only slightly, to 250V, in comparison to the initial measurements. The leakage current of sensors irradiated to 11 krad (R1-W607 and R1-W617) increased two orders of magnitude. Such an increase of current is expected since the measurement was performed at room temperature. In the real experiment sensors will be operated at temperatures below $-30 \text{ }^\circ\text{C}$. According to the previous study [8], the increase of the total current, which comprises both surface and bulk components, after gamma irradiation is due to the increase of the surface part of the total current. The bulk leakage current increases only very little after a TID as small as 11 krad. Annealing at $60 \text{ }^\circ\text{C}$ for 80 minutes did not decrease the current.

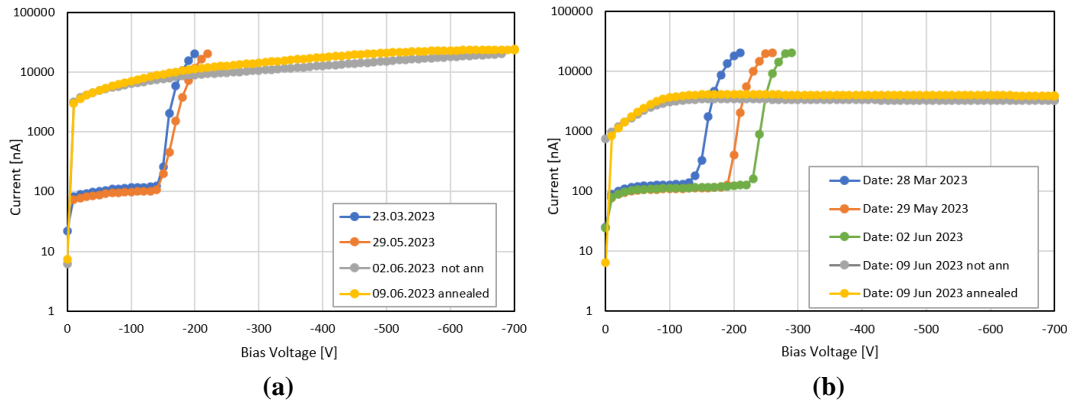


Figure 5. IV characteristics measured before and after gamma irradiation for R1-W617 (5a) and for reference sample R1-W650-R (5b).

As gamma irradiation resolved issues successfully during the initial planned step of irradiation with TID of 11 krad (approximately one week in the real experiment), no further irradiations to higher TID values were needed. Instead, the reference samples were irradiated to an even lower TID of 1.5 krad, corresponding to one day in the real experiment. Figure 5b shows measurements performed after gamma irradiation of the reference sample W650 to 1.5 krad (gray and yellow lines measured on June 9th). The early BD observed before irradiation was no longer present even after this small irradiation. Annealing again did not help to decrease the leakage current in this case.

The full strip tests done after irradiation to TID of 11 krad are shown in Figure 6. The gamma irradiation with TID of 11 krad completely cured the low interstrip isolation areas on the sensor R1-W635 and R3-W1014. Figure 7 show reference sample R1-W620-R after TID of 1.5 and 3 krad. The reference sample R1-W620-R irradiated only to the TID of 1.5 krad has a bias resistance value of the affected strips just above the required limit of 1 M Ω , but it was not fully recovered. An additional gamma irradiation with TID of 1.5 krad was thus applied to sensor R1-W620-R and the results are shown in Figure 7 (right). After the TID of 3krad, the area of low interstrip isolation, manifested by a lower bias resistance value, disappear. The few strips with increased bias resistance are issues related to non-ideal probe contact.

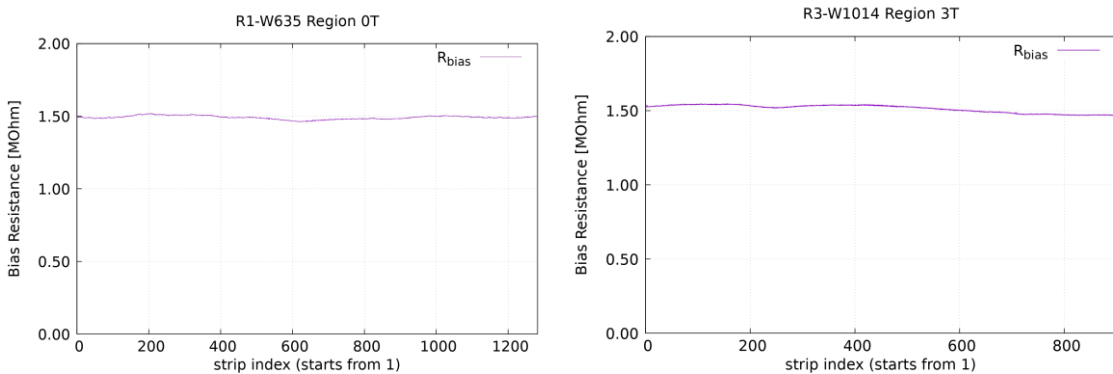


Figure 6. Full strip tests of R1-W635 (left top) and R3-W1014 (right top) R1-W620-R (right) sensors measured after gamma irradiation of 11 krad.

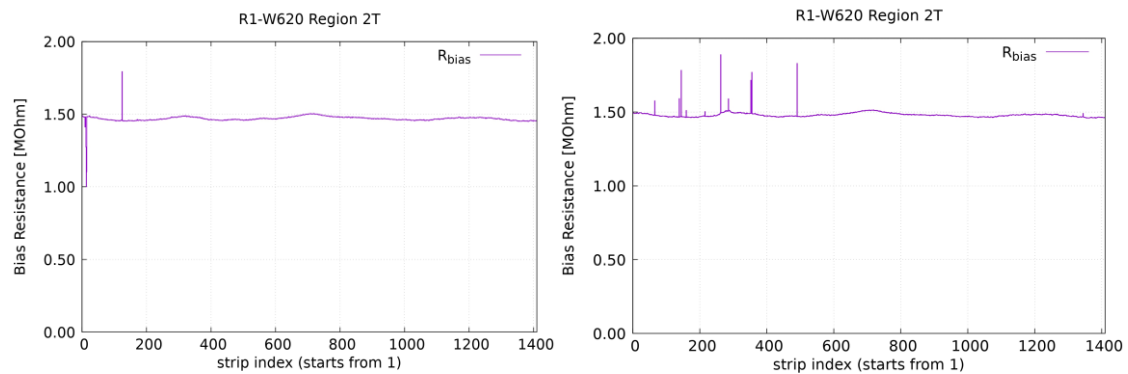


Figure 7. Full strip tests of R1-W620-R sensor measured after the total delivered ionizing dose of 1.5 krad (left), and 3 krad (right).

4. Conclusions

The results of this study indicate that the negative effects of the electrostatic charge accumulated on the sensor surface completely disappear after a very small amount of delivered total ionizing dose, which corresponds to one or two days of operation in the real experiment. These findings give us confidence that any issues related to accumulation of electrostatic charge on the ITk sensor surface will be very quickly mitigated in the conditions of the real experiment.

Acknowledgements

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