Curing early breakdown in silicon strip sensors with radiation

Luise Poley[a,b], Jammel Brooks[c,d], Emily Duden[c,e], Vitaliy Fadeyev[f], Hijas Farook,[g], Javier Fernandez-Tejero[a,b], Andrew Fournier[a,b], Martin Hoeferkamp[g], Jim Kierstead[c], David Lynn[c], Igor Mandić[h], Meny Raviv Moshe[c], Jack Osieja[a,b], Joey Sorenson[g], Bernd Stelzer[a,b], Stefania Stucci[c], Sally Seidel[g]

[a] *TRIUMF, Vancouver, BC V6T 2A3, Canada*
[b] *Simon Fraser University, Burnaby, BC V5A 1S6, Canada*
[c] *Brookhaven National Laboratory, Upton, NY 11973, USA*
[d] *Indiana University, Bloomington, Indiana, USA*
[e] *Brandeis University, Waltham, MA 02453, USA*
[f] *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA 95064, USA*
[g] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131, USA*
[h] *Experimental Particle Physics Department, Jožef Stefan Institute, SI-1000 Ljubljana, Slovenia*

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Abstract

In preparation for the forthcoming High-Luminosity phase of the Large Hadron Collider, the ATLAS experiment is working on major upgrades to its detector systems to effectively accommodate the increase in radiation levels and track density. The foremost among these upgrades entails the replacement of the current inner tracking detector with an advanced all-silicon Inner Tracker (ITk). In the outer region of the ITk apparatus is the Strip Detector.

Central to the new strip tracking system are the ITk Strip modules, comprising silicon sensors and hybrid Printed Circuit Boards housing the integral read-out Application-Specific Integrated Circuits (ASICs) as well as power distribution services. Thorough characterisation of the electrical characteristics of the silicon strip modules at various stages of the assembly procedure holds paramount significance in evaluating module performance. This rigorous evaluation ensures timely identification of any anomalies, thereby enabling proactive remedial measures. Notably, during the course of these electrical assessments, certain modules manifested breakdown phenomena occurring below the prescribed threshold of 500 V, mandated by the ITk Quality Control protocols.

Based on these observations, controlled exposure to low levels of radiation was suspected to elevate the breakdown voltage in susceptible sensors. This contribution presents results from two irradiation campaigns to investigate potentially beneficial effects of irradiation. One study investigates the effects of gamma irradiation on modules showing an early breakdown after gluing. For this study, modules were exposed to an ionising dose of 11 krad (corresponding to the dose accumulated after several days of operation in the HL-LHC) utilising a ^{60}Co source. The second campaign focuses on silicon sensor test structures with low breakdown voltage due to intentionally caused mechanical defects and their development after exposure to reactor neutrons. In both cases, preliminary findings suggest a discernible improvement in the breakdown voltage.

Keywords: ATLAS, silicon strip sensors, radiation damage, active sensor area

1. Introduction

For the Phase-II Upgrade of the ATLAS detector, the ATLAS Inner Detector will be replaced with a new, all silicon tracker - the ATLAS Inner Tracker (ITk), consisting of a pixel and a strip tracking detector [1]. The ITk strip tracker will be constructed from sensors with a size of about 100 cm^2 each. In order to meet the required 10:1 signal-to-noise-ratio at the detector's end of life, sensors will need to be operated at a reverse bias voltage of -500 V. Therefore, each sensor and detector module is repeatedly checked for a premature breakdown throughout the module assembly process.

Over the course of the initial production phase, some sensors have shown premature breakdown for different reasons:

- mechanical damage (cracks, chipped edges or corners, scratches) [2]
- humid environments [3]
- long-term application of bias voltage [4]
- static charge-up [5]

In addition to the effects above, assembled modules have shown additional cases of premature breakdown if the adhesive used for assembly spread onto the sensor guard ring [6].

During quality assurance tests performed to confirm the viability of gluing printed circuit boards directly onto the sensor, it was discovered that none of the sensors showed a premature breakdown after irradiation to $2{\cdot}10^{15}\,\mathrm{n_{eq}/cm^2}$ using 23 MeV protons (see figure 1).

Based on these observations using the simulated end-of-life fluence, irradiation was suspected to have a beneficial effect on premature sensor breakdown. Further measurements were conducted to study the development of early breakdown with radiation for sensors with a premature breakdown due to:

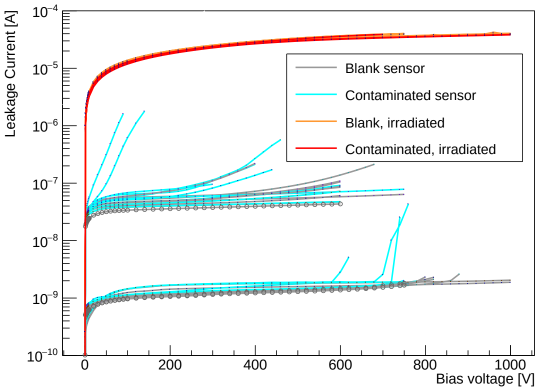


Figure 1: Sensor IV tests before/after gluing and before/after irradiation to $2{\cdot}10^{15}\,\mathrm{n_{eq}/cm^2}$, from [7]

- humidity sensitivity [8]
- static charge-up [5]

showing improved breakdown voltages in both cases after gamma irradiation to only 1.5 krad. This paper presents measurements of sensors and modules with physical damages to study their improvement with radiation with the aim to establish a predictable recovery of components during detector operation.

2. Module gamma irradiation

In order to study potential improvements in modules due to radiation, two ATLAS Long Strip modules with premature breakdown were irradiated. Figure 2 shows a typical example of a module with reduced breakdown voltage after assembly compared to the initial sensor tests.

It should be noted that, different from bare sensors, the origin of an early breakdown on a module can only be unambiguously identified for some of the causes:

- clear and identifiable mechanical damage
- glue on sensor guard ring, if not obscured by components glued onto the sensor
- static charge-up

Email address: `APoley@cern.ch` ()

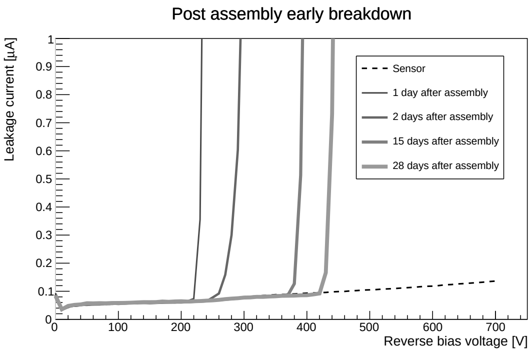


Figure 2: Reduced breakdown voltage measured for an LS sensor after assembly into a module

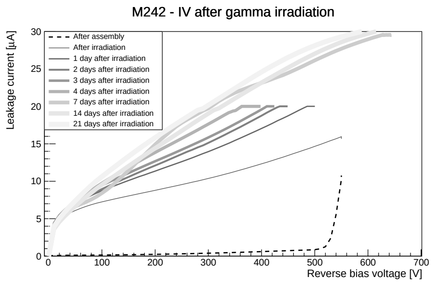
While it is possible to study individual sensors and select sensors with specific premature breakdown causes for irradiation studies, that cause is not necessarily known for modules. For the module results shown below, the corresponding sensors did not have any known causes for an early breakdown.

Two modules with premature breakdown were irradiated to 11 krad and showed the same behaviour as bare sensors undergoing the same treatment [5]: the total leakage current increased, but breakdown voltage occurred later (see figures 3a and 3b). The recovery was found to be stable over repeated measurements on subsequent days.

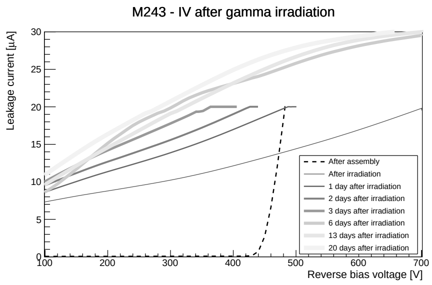
More measurements are planned to be performed for additional modules showing a premature breakdown as they become available during the ITk module production phase.

3. Intentional diode damage

In parallel to the treatment of assembled modules with gamma irradiation, diode test structures with a size of $2 \times 2\,\mathrm{mm}^2$ each were prepared with intentional damage to study its impact on the diode breakdown voltage and potential recovery with irradiation. The occurrence of mechanical damage on comparable structures has not been found to result in early breakdown in all cases (e.g. chipped corners of similar extent can lead to lowered breakdown voltage for some sensors, but result in a stable performance for others). Therefore, the location and depth (superficial or deep enough to produce debris) of the applied scratches was varied to compare their impact (see figures 4a to 4d) using a tungsten carbide scribe tip.



(a) Long Strip module 1

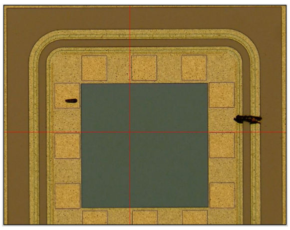


(b) Long Strip module 2

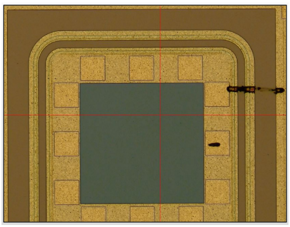
Figure 3: Two modules with premature breakdown showing higher breakdown voltage after gamma irradiation to 11 krad

The IV characteristics of each diode were tested after adding the intentional damage. Subsequently, the diode array was diced out of the larger sensor structure and tested again. All diodes were then irradiated using reactor neutrons. For this study, reactor neutrons were used, as previous measurements had shown [9], [10] that hadronic irradiation leads to a reduction of the active diode area away from the edge ring, which would provide an explanation for why peripheral damage does not cause premature breakdown after irradiation.

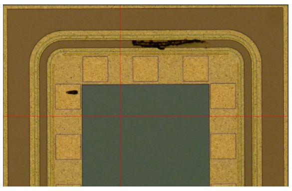
Diodes were exposed to increasing fluences, starting with the lowest achievable fluence of $1 \cdot 10^8\,\mathrm{n_{eq}/cm^2}$. In an iterative process, each diode will alternatingly be irradiated to the next higher magnitude of fluence and its IV



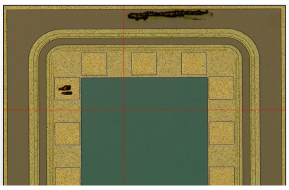
(a) Deep scratch from bias ring to guard ring



(b) Deep scratch from bias ring to edge ring



(c) Deep scratch between bias ring and guard ring



(d) Deep scratch between guard ring and edge ring

Figure 4: Examples of different scratches on diodes

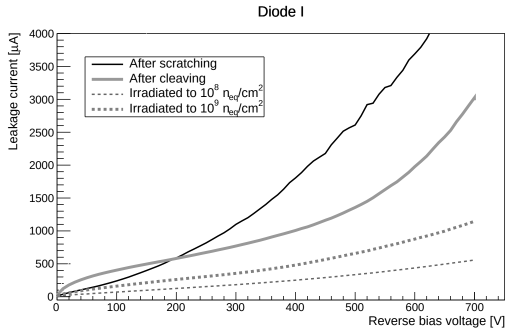
performance characterised. Additionally, the extension of the active area is determined after every other irradiation step to compare the depleted diode volume to the location of each diode's physical defects and its breakdown voltage [11].

It should be noted that while these irradiations were conducted with neutrons, the samples are expected to have received $\mathcal{O}$(krad) of ionising dose due to background irradiation in the reactor. Since studies of individual sensors were shown to improve premature breakdown after gamma irradiation up to doses of only 1.5 krad, the impacts or neutron and ionising radiation can not be distinguished completely.

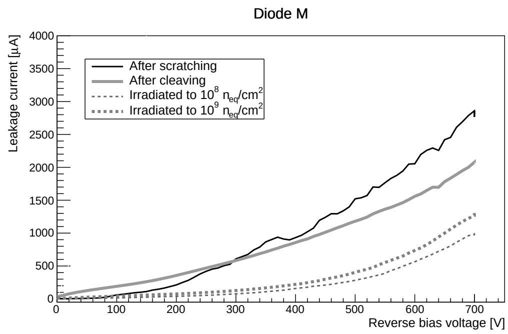
While the exact behaviour of all diodes depended on the location and the extent of the incurred damage, overall, it was observed that:

- sufficiently severe damage led to a lowered breakdown voltage
- lowered breakdown voltages generally improved over time
- diodes showing a lowered breakdown voltage after damaging showed improved IV characteristics even after irradiation to low fluences
- where the breakdown voltage improved with radiation, irradiation was also found to lead to overall lowered leakage current after irradiation

Figures 5a and 5b show two representative examples for this behaviour. These measurements indicate that, similar to the recovery observed for modules after gamma irradiation, test structures with intentionally caused premature breakdown show an improved breakdown voltage, even after exposure to low equivalent fluences.



(a) IV tests for diode with scratch between bias ring and guard ring (see figure 4c)



(b) IV tests for diode with scratch from bias ring to edge ring (see figure 4b)

Figure 5: IV characteristics for two diodes before and after irradiation to $1 \cdot 10^8\,n_{eq}/cm^2$ and $1 \cdot 10^9\,n_{eq}/cm^2$ with reactor neutrons. Both diodes show a recovery from the initial performance post damage even after being exposed to a low fluence of $1 \cdot 10^8\,n_{eq}/cm^2$. Afterwards, the current increases with higher fluence as expected.

It should be noted that while the measurements do indicate a recovery of the leakage current, it is uncertain whether this improvement translates directly into an increased working range of the sensor or if secondary effects, such as noise caused by current instability, would still impact its operation at higher bias voltages.

4. Test structures with severe physical damage

In addition to testing devices with minor damages, studies were performed using devices which were fully cracked through the active area (see figure 6)

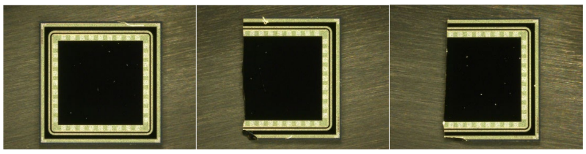


Figure 6: $4 \cdot 4\,\mathrm{mm}^2$ diodes used for this test; two of them were cracked through the centre

Four sets of diodes (each one consisting of one intact and two cracked diodes) were prepared and irradiated to the same fluence for all devices per set. The devices were irradiated to fluences of $1.92 \cdot 10^{14}, 4.97 \cdot 10^{14}, 6.58 \cdot 10^{14}, 1.20 \cdot 10^{15}\,\mathrm{n_{eq}/cm^2}$ using 500 MeV protons.

In all cases, the diodes showed a premature breakdown after cracking, but showed a comparable IV performance to the intact diode after irradiation. Figure 7 shows a representative example of the IV tests before and after breaking in comparison with the complete diode before and after irradiation.

Despite the severe damage they had incurred, all broken damage showed an improvement of the observed breakdown voltage after irradiation that made them comparable to intact diodes. Additionally, the broken diodes showed a lower absolute current than the intact diode after irradiation, approximately matching the reduction in active area by cleaving.

It should be noted that an attempt to map the shape of the active area of these devices in an X-ray beam failed, as positioning the beam

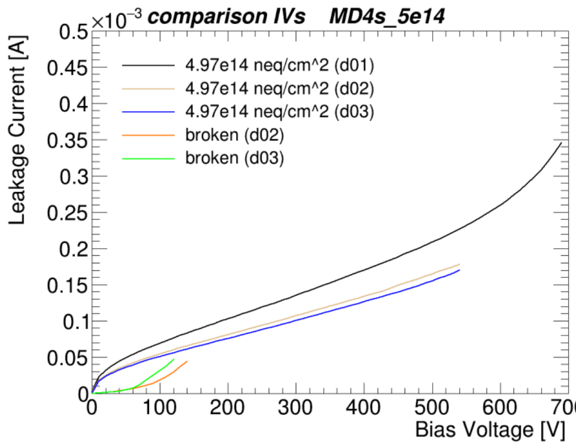


Figure 7: Comparison of 3 diodes (two broken, one intact) before and after irradiation

in the vicinity of the broken edge led to a sudden increase of the measured leakage current which remained at an elevated level even after the beam had been switched off. This measurement indicated that, while irradiation was found to alleviate an early breakdown in all cases, severe physical damage may have other, significant effects usually not observed due to inoperability in breakdown.

5. Conclusion and Outlook

Measurements were conducted to systematically evaluate the improvement of premature breakdown in silicon sensors via gamma, neutron and proton irradiation. In all cases, radiation was found to improve the breakdown voltage, even after severe physical damage.

Future measurements are planned to be conducted to study IV characteristics for increasingly higher fluences of the devices under investigation.

For any future modules showing an early breakdown after assembly, gamma irradiations are planned to be conducted to study the reliability of curing premature breakdown in modules with radiation.

In addition to investigations into the reliability of recovering premature breakdown, further measurements are planned to understand the underlying recovery mechanism as well as its extent.

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References

[1] The ATLAS Collaboration. Technical Design Report for the ATLAS Inner Tracker Strip Detector. Technical Report CERN-LHCC-2017-005. ATLAS-TDR-025, CERN, Geneva, 04 2017.

[2] Christoph Klein et al. ATLAS ITk Strip Sensor quality control and review of ATLAS18 preproduction sensor results. to be published in Proceedings: 13th International 'Hiroshima' Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD-13).

[3] J. Fernández-Tejero and others. Humidity sensitivity of large area silicon sensors: Study and implications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 978:164406, 2020.

[4] Paul Miyagawa et al. Analysis of the results from Quality Control tests performed on ATLAS18 Strip Sensors during on-going production. to be published in Proceedings: 13th International 'Hiroshima' Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD-13).

[5] Marcela Mikestikova et al. Gamma irradiation of ATLAS18 ITk strip sensors affected by static charge. to be published in PoS Proceedings for Vertex2023.

[6] C. Helling, L. Poley, et al. Study of n-on-p sensors breakdown in presence of dielectrics placed on top surface. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 924:147–152, 2019. 11th International Hiroshima Symposium on Development and Application of Semiconductor Tracking Detectors.

[7] Anne-Luise Poley. Studies of adhesives and metal contacts on silicon strip sensors for the ATLAS Inner Tracker, 2018. PhD thesis, presented 12 Apr 2018.

[8] J. Fernández-Tejero et al. Analysis of humidity sensitivity of silicon strip sensors for ATLAS upgrade tracker, pre- and post-irradiation. *Journal of Instrumentation*, 18(02):P02012, feb 2023.

[9] L. Poley et al. Mapping the depleted area of silicon diodes using a micro-focused X-ray beam. *Journal of Instrumentation*, 14(03):P03024–P03024, mar 2019.

[10] L. Poley et al. Mapping the in-plane electric field inside irradiated diodes. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 980:164509, 2020.

[11] Luise Poley, Andrew Blue, Vitaliy Fadeyev, and Dennis Sperlich. Active Region Extent Assessment with X-rays (AREA-X). *Journal of Instrumentation*, 17(11):T11009, nov 2022.