Analysis of unstable leakage current in ATLAS18 Strip Sensors after long-term tests

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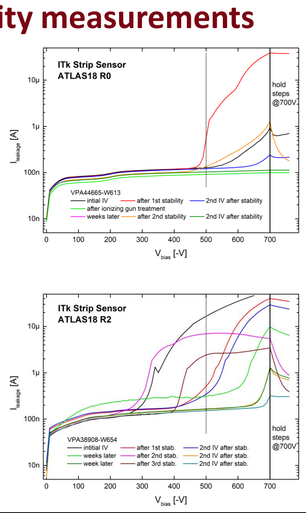
Abstract

With the upgrade of the LHC to the High-Luminosity LHC (HL-LHC), the Inner Detector will be replaced with the new all-silicon ATLAS Inner Tracker (ITk) to maintain tracking performance in a high-occupancy environment and to cope with the increase in the integrated radiation dose. Comprising an active area of 165m^2, the outer four layers in the barrel and six disks in the endcap region will host strip modules, built with single-sided micro-strip sensors and glued-on hybrids carrying the front-end electronics necessary for readout. Before being shipped out for module building, a total of 24010 ATLAS18 n$^+$-in-p strip sensors, of which 17888 sensors are to be installed in the experiment, were tested at different institutes in the collaboration for mechanical and electrical compliance with technical specifications, the quality control (QC), while technological parameters were verified on test structures from the same wafers before and after irradiation, the quality assurance (QA). Reverse bias leakage current characteristics of every single sensor and leakage current stability measurements on a sample basis are an important part of QC procedure. During these measurements, a recurring pattern of performance degradation and recovery in leakage current and sensor breakdown after long-term testing has been observed for a subset of sensors. A comprehensive analysis of those changes observed during Sensor QC will be shown. Mitigation and recovery procedures, such as ionizing guns, exposure to UV light and sensor baking, developed by the sensor community and applied at different QC sites will also be highlighted, including their impact on sensor performance.

Motivation: sensor breakdowns after leakage current stability measurements

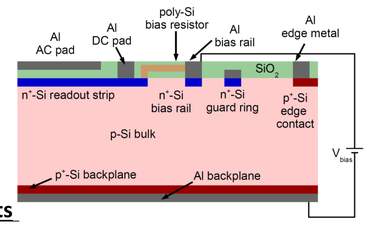
- sensors which had the IV characteristic tested after leakage current stability measurements (see Section "ITk Strip Sensor testing") were often found to have shift of breakdown compared to initial IV
  - sensors either broke down earlier or later
  - sometimes both for same sensor when testing repeatedly
  - could occur even if no breakdown was observed initially
- most sensors improved when testing IV multiple times after stability
- sensor recovery methods were found to be effective, but not for all sensors
- occurrences were often more common in whole production batches

➢ behavior not predictable before sensors were tested
➢ need for comprehensive analysis, now that almost all sensors have been tested



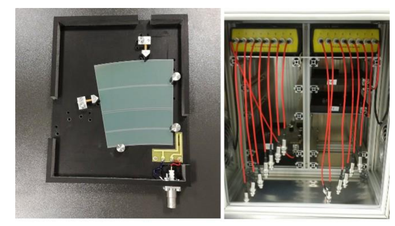
ITk Strip Sensor testing: IV, leakage current stability, and recovery treatments

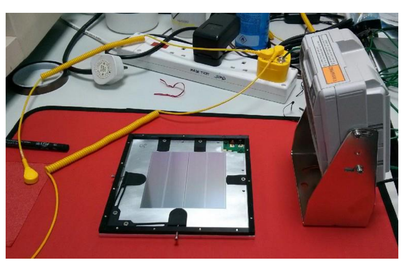
- ITK Strip Sensors are single-sided n$^+$-in-p silicon sensors with AC-coupled readout strips, produced by Hamamatsu Photonics [1]
- two types of square barrel sensors with different strip lengths for the inner and outer barrel layer (short/long strip, SS/LS)
- six trapezoidal sensor layouts for endcap petals (R0-R5)



Sensor Quality Control (QC) – IV and leakage current stability measurements

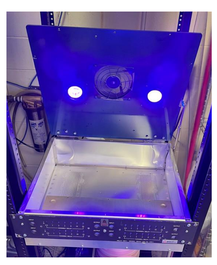
- current-voltage (IV) characteristic is measured for every sensor
  - measurement up 700V reverse bias in dry environment
  - $V_{breakdown}$ > 500V and $I_{leakage}$ @500V < 0.1µA/cm^2
- leakage current stability (or long-term stability, LTS) is tested on a 10-20% sample basis per batch
  - sensors held at high voltage (450V) for 24h+

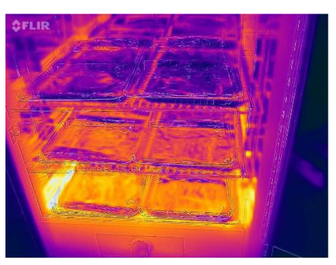




changes in sensor performance

- influence of environmental conditions and long-term testing on ITk Strip Sensors have been studied since the prototyping phase and continued during sensor production
  - among others, surface charge build-up and elevated ambient humidity found to adversely affect sensor performance





recovery methods

- different methods of sensor recovery were developed to mitigate performance changes
  - ionizing guns / ion blowers, UV-A/UV-C irradiation, sensor baking

for more details on ITk Strip Sensor QC, see HSTD14 talk by P. Federičová

Analysis of sensor behavior

- analyze data of production batches on ITk Production Database
- only select sensors with finished QC and for which LTS was performed
- investigate change of breakdown voltage based on testing sequence
  - not all tested sensors follow same testing sequence, e.g. not all sensors had follow-up IV scan after stability

IV of sensors with LTS on record, initial IV done before LTS

IV measured after LTS, without recovery treatment in-between

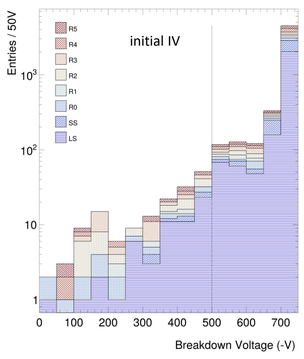
2nd IV right after first follow-up scan, without recovery treatment in-between

most recent IV on record for sensors with LTS, including recovered sensors

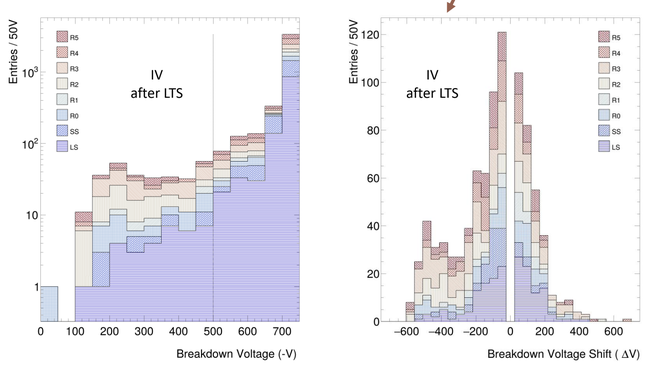
(most recent) IV results of all production sensors

	initial IV before LTS	IV after LTS	2nd IV after LTS	last IV	IV all sensors
SS	0.85 (8)	1.63 (12)	1.48 (5)	0.11 (1)	**0.55 (10)**
LS	2.37 (61)	2.97 (33)	0.76 (1)	0.35 (9)	**0.7 (44)**
R0	5.92 (21)	10.88 (31)	2.97 (7)	3.1 (11)	**2.34 (24)**
R1	2.77 (9)	4.48 (12)	1.8 (2)	1.23 (4)	**0.87 (9)**
R2	11.01 (38)	20.65 (64)	4.07 (10)	4.06 (14)	**3.28 (33)**
R3	8.21 (45)	17.37 (87)	7.85 (30)	2.55 (14)	**1.86 (37)**
R4	4.85 (31)	3.69 (21)	2.67 (7)	0 (0)	**1.19 (24)**
R5	5.04 (30)	6.04 (32)	3.21 (11)	1.34 (8)	**1.24 (25)**
% fails (# total)	**3.84 (243)**	**6.77 (292)**	**3.56 (73)**	**0.96 (61)**	**1.20 (206)**

relative (total) IV failure rate ($V_{breakdown}$ < 500V)

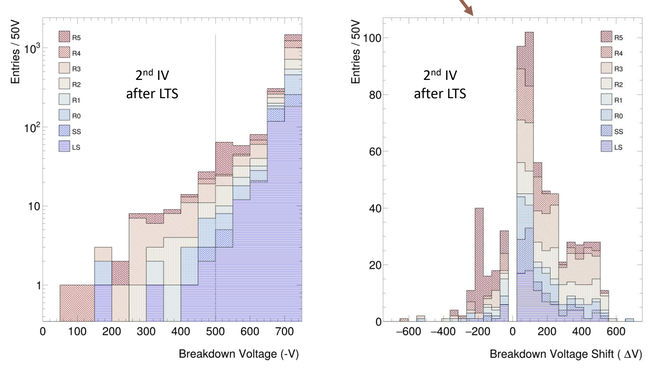


negative shift = lower breakdown (sensors without breakdown shift excluded)



- IV measurements performed right after stability measurements have a significant fraction of sensors shifting breakdown to lower voltage
- sensors with breakdown degradation are more likely to be from one of the endcap types
- 381 scans showed improved IV performance, 665 were worse, 3243 had little-to-no change
  - caveat: sensors selected for stability often include those with existing breakdowns, either within specification (>500V) or slightly below, to investigate stability of observed breakdown

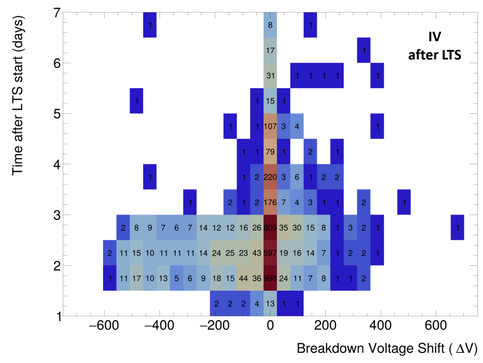
sensors improved without additional recovery treatments

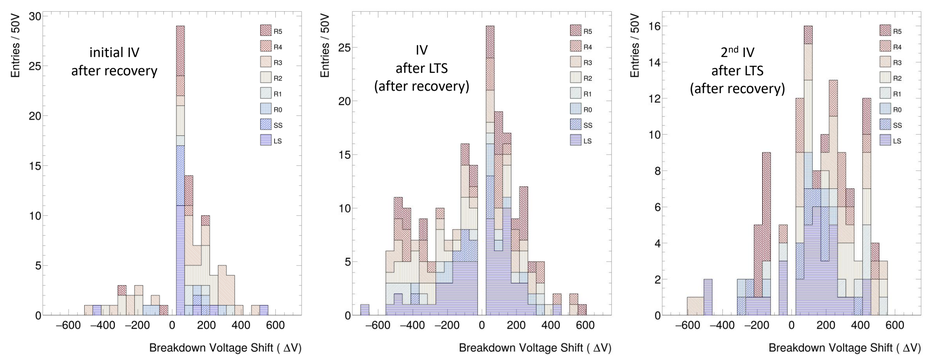


- IV measurements performed as a direct follow-up to the previous one show improved breakdowns for vast majority of sensors with shifting breakdown
  - for these sensors no additional recovery treatments were performed, only the IV characteristic was measured an additional time
- 561 scans showed improved IV performance, 176 were worse, 1312 had little-to-no change
- sensors with unstable IV performance that still had breakdown after the 2nd follow-up IV were often selected for additional recovery treatments

Impact of sensor recovery

- the unstable IV performance is likely the result of surface charge build-up in the sensor during the long-term HV reverse bias as part of the stability measurements
- analysis of the breakdown shift in relation to the follow-up IV waiting period show only a slightly larger fraction of improved IVs having been performed later
  - IV scans on sensors with stable performance could be conducted at any time after the stability measurement
  - sensor recovery from storage alone is therefore unlikely or only possible on much longer timescales than feasible during Sensor QC





- using additional recovery treatments (ion blower, UV, sensor baking) resulted in improved performance and more stable IV behavior
  - IV measurements after LTS showed almost equal number of sensors with improved/worse breakdown (122:114)
  - an additional follow-up IV, again, further improved sensor breakdown
  - over the course of the post-recovery testing, most sensors were found to be stable

Conclusions

- ITk Strip Sensors were found to exhibit unpredictable and unstable leakage current behavior after long-term tests as part of QC procedure
- a comprehensive investigation and analysis of the observed behavior was performed
  - shift of breakdown voltage was identified to occur depending on the testing sequence performed for affected sensors
  - the occurrence and breakdown shift patterns at different stages of testing were analyzed
  - the effect of sensor recovery treatments was found to yield an improvement in sensor performance and a more stable IV behavior for a majority of sensors

Acknowledgments

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References

[1] Y. Unno, et al., Specifications and pre-production of n+-in-p large-format strip sensors fabricated in 6-inch silicon wafers, ATLAS18, for the Inner Tracker of the ATLAS Detector for High-Luminosity Large Hadron Collider, J. Inst. 18 (03) (2023) T03008.