PROCEEDINGS OF SCIENCE

Quality Control for ATLAS Inner Tracker Strip Sensor Production

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With the upgrade of the LHC to the High-Luminosity LHC (HL-LHC), scheduled to be installed in 2024, the Inner Detector will be replaced with the new all-silicon ATLAS Inner Tracker (ITk) to maintain tracking performance in this high-occupancy environment and to cope with the increase of approximately a factor of ten in the integrated radiation dose. The outer four layers in the barrel and six disks in the endcap region will host strip modules, built with single-sided strip sensors and glued-on hybrids carrying the front-end electronics necessary for readout.

The strip sensors are manufactured as n-in-p strip sensors from high-resistivity silicon, which allow operation even after fluences expected towards the end of the proposed lifetime of the HL-LHC. Prototypes of different sensor designs have been extensively tested electrically as well as in testbeam setups, yielding generally good results. Since pre-production is scheduled to start at the end of 2019, it is necessary to have a quality control (QC) procedure for strip sensors to confirm that manufactured sensors comply with specifications necessary for operation in the HL-LHC, ranging from generic electric properties to reliability of long-term operation. An overview over the QC procedure and its results will be given as well as details about the ongoing challenges.

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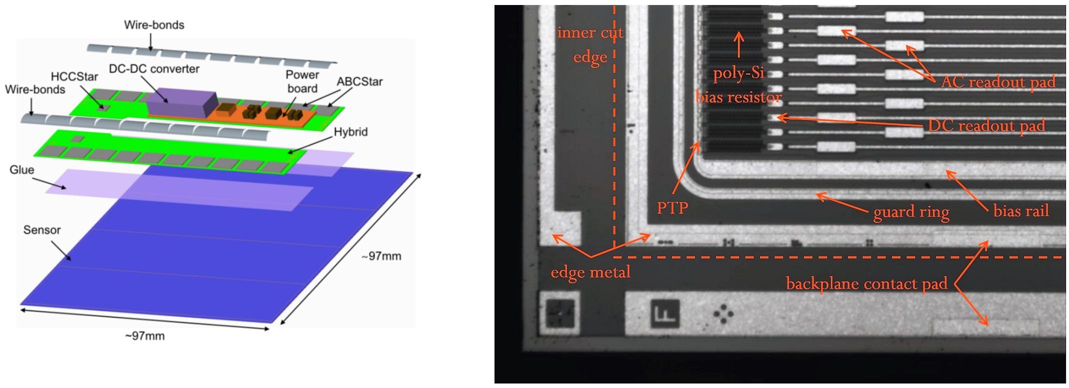
1. Introduction: The ATLAS Inner Tracker Strip Detector

The current ATLAS Inner Detector [1] will have reached the end of its lifespan and will be rendered inoperable with the increased luminosity, associated data rate, and radiation damage in the HL-LHC upgrade, scheduled to be installed in 2024 [2]. Therefore the Inner Detector will be replaced with the new all-silicon ATLAS Inner Tracker (ITk), consisting of the inner Pixel Detector and the outer Strip Detector. Modules for the ITk Strip Detector are composed of one sensor and one or two PCBs (hybrids) hosting the read-out ASICs (ABCStar & HCCStar), glued directly to the sensor. The power board provides switch-able sensor HV bias and delivers power to the front-end read-out ASICs using DC-DC conversion. An exploded view of a strip module is shown in Fig. 1(a) as an example.



(a) (b)

Figure 1: (a): Exploded view of a short-strip barrel module with its components denoted [2]. (b): Picture of the corner of an ATLAS12 prototype sensor containing reference to all relevant structures. The shown sensor is an "Outer Cut" type, whereas the final layout will contain "Inner Cut" sensors with reduced edge metal and therefore inactive region, indicated by the dashed line.

ITk strip sensors are single-sided n^{+}-in-p sensors with rectangular shape in the barrel region and wedge shape with curved edges at constant radius in the end-cap. The strip length of sensors in the inner barrel layer is half the length of outer layer sensors. For end-cap sensors there are six different layouts with radially oriented strips. The properties of all sensor layouts are detailed in [2]. Top metal layer strips are AC-coupled to the strip implants through a thin insulating layer, with p-stop traces running in between along the full length for strip isolation. The top sensor layer is passivated with openings for probing and wirebonding. Multiple iterations of prototype sensors for extensive testing have been manufactured by Hamamatsu Photonics [3, 4, 5], a picture of the corner of one is shown in Fig. 1(b).

2. Sensor Quality Control

Sensor pre-production is scheduled to start in late 2019. For this, sensors have to undergo Quality Control (QC) so as to make sure only sensors which adhere to specifications are used in the module production process. Basic mechanical and electrical tests will be carried out for every sensor, while more detailed measurements will be done on a sample basis.

Each individual sensor, after reception at the QC site, is checked for cracks, chips, or other irregularities, and an image of the entire sensor surface is captured at high-resolution. In addition to the aforementioned, sensor bow defined as the maximum difference in z should not exceed 200 µm when measured with a non-contact Coordinate Measurement Machine (CMM), a measurement of which an example is shown in Fig. 2.

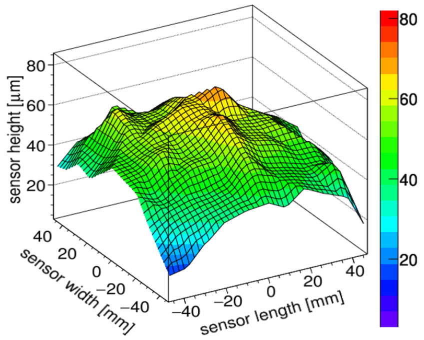
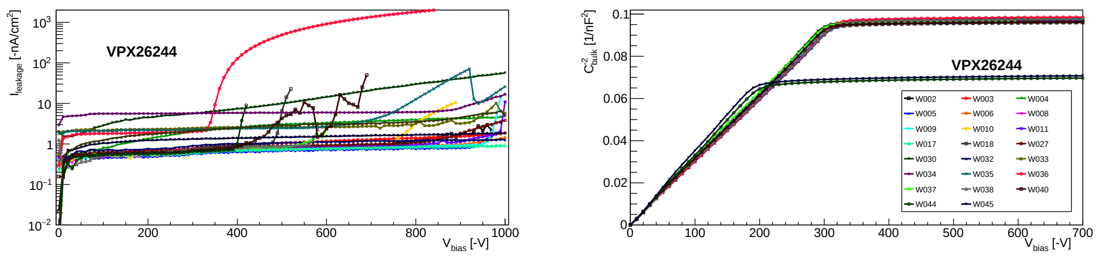


Figure 2: Example bow measurement on a full-size barrel sensor performed with a CMM [4].

Subsequently, reverse bias leakage current (IV) and sensor bulk capacitance (CV) measurements are carried out for each individual sensor from $V_{\text{bias}} = 0\,\text{V}$ to $-700\,\text{V}$ in a well-controlled cleanroom or dry air/nitrogen atmosphere at room temperature, on either custom made jigs or a probe station. For the IV scan, current should not exceed $0.1\,\mu\text{A}/\text{cm}^2$ when measured with nA precision in steps of 10 V with 10 sec intervals in between steps. An example for IV measurements of a batch of ATLAS17 long-strip (LS) sensors is shown in Fig. 3(a).



(a) (b)

Figure 3: Electrical test results for ATLAS17LS sensor batch VPX26244: (a) Leakage current measured as a function of applied V_{bias} and (b) $1/C_{\text{bulk}}^2$ versus V_{bias} plot of CV measurement results.

For CV measurements, the bias voltage is increased by 10 V with 5 sec intervals and measured with an LCR meter at a frequency from 500 Hz to 5 kHz. For all sensors the extracted full depletion voltage is not to exceed $-330\,\text{V}$. Fig. 3(b) shows results of CV measurements plotted as $1/C_{\text{bulk}}^2$ versus V_{bias} for the same batch of ATLAS17LS sensors, two of which where intentionally manufactured with reduced active thickness as is observable in the plots.

In addition to the aforementioned tests, on 10 % to 20 % of sensors per batch leakage current stability will be monitored over 24 hours at $V_{\text{bias}} = -700\,\text{V}$. Owing to the experience with prototype sensors, as further detailed in section 3.1, current stability tests will be carried out in dry nitrogen atmosphere and current variations should not exceed 3 %.

PoS(VERTEX2018)056

On 2 % to 5 % of sensors per batch, a Full Strip Test will be performed. This is a test sequence on each individual strip using a probe station, which can identify shorts and pinholes to channels through spikes in strip current when applying a voltage, and measure the poly-silicon bias resistor ($R_{\text{bias}} = 1\text{-}2\,\text{M}\Omega$) as well as the coupling capacitance ($C_{\text{coupling}} > 20\,\text{pF/cm}$) between metal strips and implants. Where applicable, e.g. on barrel sensors, this test is conducted using a multi-channel probe card. Results of such a measurement can be seen in Fig. 4.

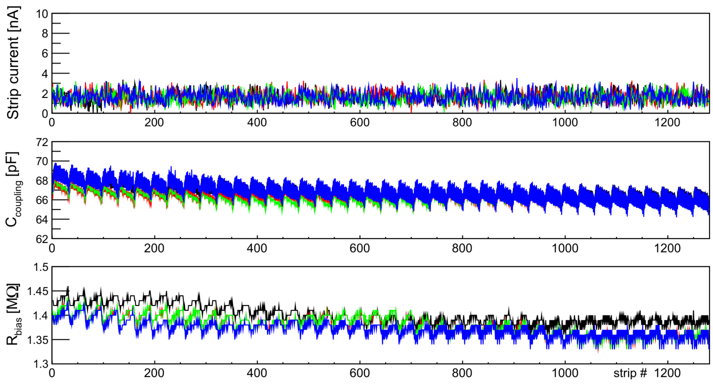


Figure 4: Results of a Full Strip Test performed for all 5120 strips of a barrel sensor. The visible periodic small variations are induced by the stray impedance in the probe card surrounding the active channel.

Additional checks of inter-strip capacitance (C_{is}) or resistance (R_{is}), and punch-through protection (PTP), which would require contacting sample channels across each sensor, will be mostly carried out on test structures manufactured on the same wafers as the full-size sensors. For these, between adjacent strips C_{is} should not exceed $1\,\text{pF/cm}$ and R_{is} be in the GΩ range. PTP is verified by measuring the sudden change in current when increasing the voltage over the bias resistor.

More detailed information on all Sensor QC tests can be found in the ITk Technical Design Report [2] and results for various prototypes have been published in [3, 4, 5].

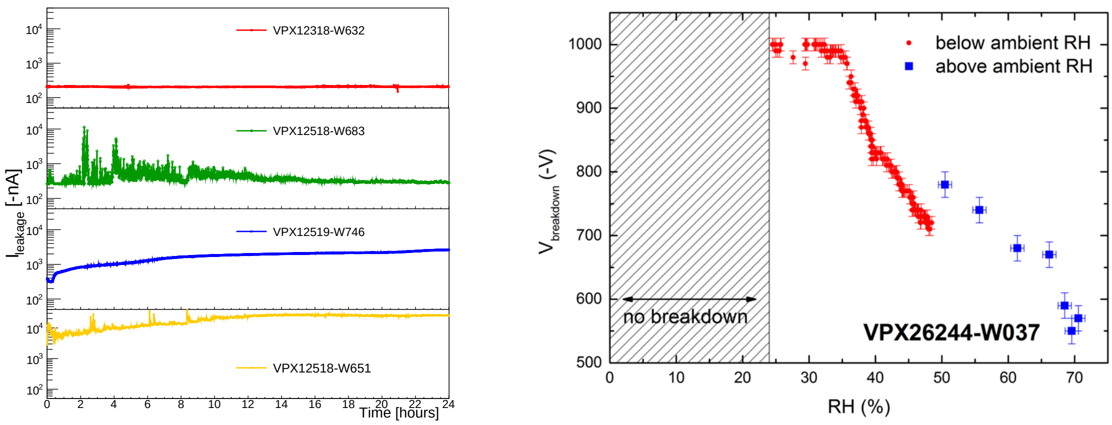
3. Ongoing challenges with current prototype sensors

3.1 Current instability and humidity sensitivity

Long-term reliability is one of the key points in ITk sensor development. However, many prototype sensors did not fulfil current stability criteria, even more so in ambient atmosphere. Sensor behaviour ranged from the required stable leakage current to erratic fluctuations, continuously increasing current, and abrupt breakdowns, as can be seen in Fig. 5(a). Similarly, the onset of sensor breakdown would often shift depending on previous electrical tests and environmental conditions.

Further investigations were conducted with respect to the humidity dependence of sensor behaviour and repeated IV scans of sensors at room temperature show systematic decrease of breakdown voltage ($V_{\text{breakdown}}$) with increasing humidity, as shown in Fig. 5(b). However, similarly systematic results are difficult to produce on many sensors, in particular those which already fail specifications due to low breakdown or leakage current instability. Instead, the only commonality is an overall positive response, e.g. increased $V_{\text{breakdown}}$, to low relative humidity (RH) $< 10\,\%$.

As a result of these findings, efforts are being made to minimise the sensor exposure to ambient humidity during storage, Sensor QC tests, and module production.

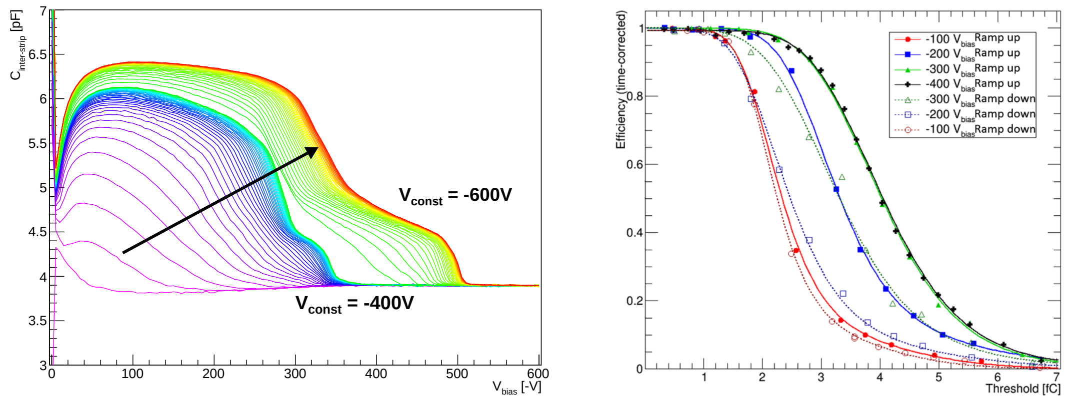


(a) (b)

Figure 5: (a): Different modes of sensor leakage current behaviour observed in 24 h stability measurements at $V_{\text{bias}} = -700\,\text{V}$. (b): Development of $V_{\text{breakdown}}$ in a single sensor with varying relative humidity in the surrounding atmosphere obtained from repeated IV scans.

3.2 Effects of long-term biasing

The input capacitance to front-end electronics is dominated by C_{is}, thus making it an important characteristic. Repeated C_{is} measurements were performed with constant bias level (V_{const}) between individual C_{is} scans, to emulate long-term detector operation. The result was a significant increase in C_{is} for $V_{\text{bias}} < V_{\text{const}}$ (Fig. 6(a)). The cut-off point for this increase is only depending on V_{const} and the effect is reversible within a few days at room temperature and ambient humidity. Similarly, extended periods of biasing in testbeam scans have resulted in a significant decrease in tracking efficiency for $V_{\text{bias}} < V_{\text{const}}$ due to increased charge sharing between neighbouring strips (Fig. 6(b)).



(a) (b)

Figure 6: (a): Increase of C_{is} observed in repeated measurements over 70 h with $V_{\text{const}} = -400\,\text{V}$ for the first and $V_{\text{const}} = -600\,\text{V}$ for the second half of the time. (b): Difference in testbeam tracking efficiency during threshold scans performed for an endcap module at different bias voltages in the beginning (*Ramp up*) and at the end (*Ramp down*) of a measurement series. The module has been constantly biased at $-400\,\text{V}$ for approximately five days between voltage ramps.

The nature of this effect and the long recovery time point towards charges trapped in oxide or Si/SiO_2 interface as the cause, similar to the effect of radiation damage in the oxide. Due to the reversibility of this effect, the energy levels of the trap states in SiO_2 are currently being further investigated using Deep Level Transient Spectroscopy (DLTS) in combination with simulation results from TCAD. Arrhenius plots that have been extracted from DLTS curves, utilising inverse Laplace transformation in order to cope with the long recovery time, are shown in Fig. 7. The displayed data points and their linear fits represent the temperature dependence of the two shortest trapping time constants observable in the spectra [6].

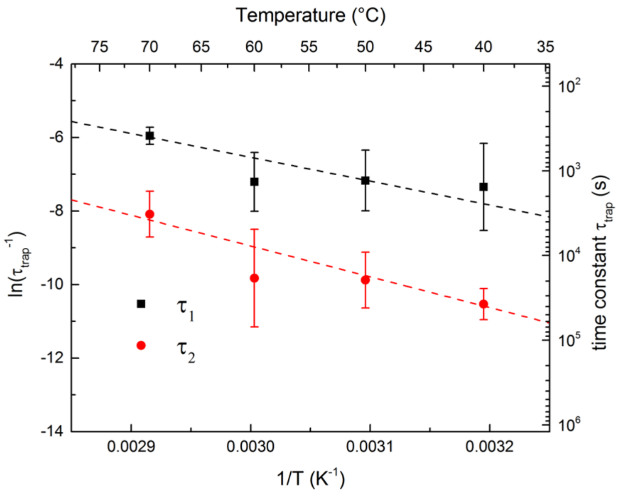


Figure 7: Arrhenius plots of the two shortest trapping time constants extracted from sensor C_{is} DLTS curves with inverse Laplace transformation with linear fits to the data points.

4. Summary and conclusion

The Sensor Quality Control procedure for ATLAS ITk strip sensor production and example results on full-size prototype sensors have been presented in this proceeding. Mechanical and electrical tests as well as specifications for the sensors, including further details such as environmental conditions, were defined using the prior experience from measurements on prototype sensors. Further investigations concerning long-term effects and their influence on tracking results are still ongoing, however, overall prospects with respect to the start of sensor pre-production are positive.

References

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