ATLAS ITk Strip Sensor Quality Control and Review of ATLAS18 Pre-Production Sensor Results

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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 165 m^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. The strip sensors are manufactured as n^+-in-p devices from high-resistivity silicon in 8 different shapes, from square in the barrel staves to a stereo annulus wedge-shape in the endcap discs, developed to withstand a total fluence of 1.6×10^{15} n_{eq}/cm^2 and a total ionising dose of 66 MRad. In 2020 the ITk Strip Sensors project has transitioned into the pre-production phase, where 5% of the production volume, a total of 1101 ATLAS18 wafers, was produced by Hamamatsu Photonics. Before being shipped out for module building, the ATLAS18 main sensors were tested at different institutes in the collaboration for mechanical and electrical compliance with technical specifications, the quality control (QC), while fabrication parameters were verified using test structures from the same wafers, the quality assurance (QA). The sensor QC evaluation program, test results and statistics, as well as experience gained from pre-production will be summarised in this contribution.
KEYWORDS: LHC, ATLAS, ITk, Strip Sensors

1. Introduction

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 become operational in 2029. Therefore the Inner Detector will be replaced with the new all-silicon ATLAS Inner Tracker (ITk) [2], consisting of the inner Pixel Detector and the outer Strip Detector. The Strip Detector is further divided into the cylindrical barrel region around the interaction point, consisting of four layers of staves made of 14 modules per face of the stave, and six disks in the forward end-cap region arranged from petals with nine endcap modules on each face, with a total silicon area of 165 m^2. Modules for the ITk Strip Detector are composed of one sensor with one or two PCBs (hybrids), hosting the read-out ASICs (ABCStar & HCCStar) and power board, 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.

ITk strip sensors are single-sided n^+-in-p sensors with square 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 two inner barrel layers is half the length of outer layer sensors, hence them being called short-strip (SS) or long-strip (LS) sensors. For end-cap sensors there are six different layouts with a small angular offset compared to the radial direction (R0-R5). 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 the implants for strip isolation. The top sensor layer is passivated with openings for probing and wirebonding.

In past years, multiple iterations of prototype sensors for extensive testing had been manufactured by *Hamamatsu Photonics K. K.* (HPK) [3–6]. Commencing in 2020, prior to full production of the sensors and in addition to another 60 prototype short-strip sensors (ATLAS18SS), “Pre-Production” of sensors delivered a total of 1041 wafers – equal to 5% of the sensors needed, including a margin for anticipated losses. All past and present sensors submissions are summarised in Tab. I. Aside from the ramp-up of sensor fabrication for the ITk, Pre-Production served as a means to establish the part flow routine between institutes, finalise QC and QA testing procedures [7,8] with the necessary throughput rates, as well as verify the sensor quality of the finalised layouts. A summary of QC test results and a review of the processes with regards to the ongoing production will be presented in the following.

Table I. Overview of past and present sensor submissions for the ITk Strip Detector.

	Order type	Sensor type	Contractor	Sensors	Area	Status
Prototype	ATLAS07	barrel SS	HPK	143	$1.4\,m^2$	completed [3]
	ATLAS12	barrel SS	HPK	120	$1.1\,m^2$	completed [4]
	ATLAS12EC	end-cap R0	HPK	135	$1.2\,m^2$	completed [5]
	ATLAS17LS	barrel LS, final size	HPK	70	$0.7\,m^2$	completed [6]
	ATLAS17LS	barrel LS, final size	HPK	60	$0.6\,m^2$	completed
	ATLAS17LS	barrel LS, final size	IFX	~~40~~	~~$0.4\,m^2$~~	cancelled
	ATLAS18SS	barrel SS, final layout	HPK	60	$1.4\,m^2$	completed
	Pre-Production	all 8 types	HPK	1,041	$9.2\,m^2$	completed
	Production	all 8 types	HPK	20,800	$190.3\,m^2$	ongoing

2. ITk Strip Sensor part flow and QC procedure

The sensors for the ITk Strip Detector are all produced by HPK and then separated depending on their sensor type and final destination for module assembly, as shown in Fig. 1. All 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 are carried out for every sensor, while more detailed measurements are done on a sample basis.

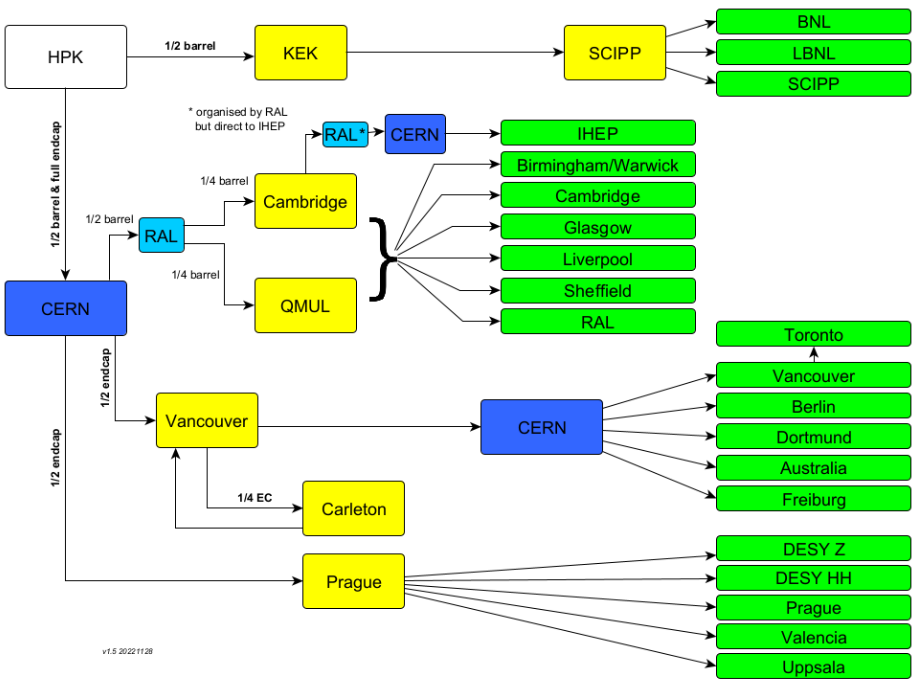


Fig. 1. Sketch the main sensor part flow for QC (sites shown in yellow) and module assembly (green).

Half of the barrel sensors first stay in Japan, where a subset of QC measurements are carried out at HPK on a fully automated machine operated remotely by KEK and Tsukuba. Those sensors are subsequently sent to Santa Cruz (SCIPP) for the outstanding QC tests and then distributed to the US module assembly sites. The other half of the barrel and all of the end-cap sensors are sent to CERN for further distribution. Those barrel sensors are split between the UK QC sites in London (QMUL) and Cambridge for testing and, afterwards, shipment to the UK module assembly sites. The end-cap sensors are tested in half by Prague, while one quarter is shipped to each Vancouver (SFU/TRIUMF) and Ottawa (Carleton). Assembly of end-cap modules takes place at various institutes in Europe, in Canada, and in Australia.

2.1 Tests performed on all sensors

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. The planarity of every main sensor has been measured using contactless methods such as provided by a *coordinate measurement machine* (CMM) or a precision measuring microscope, which allows the mapping of the sensor height and thus a measurement of its planarity. This is done on a grid of at least 11×11, which corresponds to 9.44 mm spacing between points distributed on the full sensor surface. The slope of the suspended sensor on the microscope plate or a jig is corrected by subtracting the result of planar fit of the raw data points.

The measurement of the leakage current with increasing bias voltage (IV) is conducted by ramping up the reverse bias voltage in increments of 10 V in a range from $V_{\text{bias}} = 0\,\text{V}$ to 700 V, applied to the sensor backplane through the edge metal contact (see [9, 10] for detailed schematics). Current is measured with nA precision with 10 s intervals in between steps at ambient temperature of $T \simeq 21\,^{\circ}\text{C}$ in the air-conditioned cleanroom and at $V_{\text{bias}} = 500\,\text{V}$ should not exceed $0.1\,\mu\text{A/cm}^2$. Moreover, IV curves are checked for onset of sensor breakdown or micro-discharge and only sensors with $V_{\text{breakdown}} > 500\,\text{V}$ are accepted. As an additional check, the maximum bias voltage is held for at least 30 s and the leakage current behaviour during those hold steps is taken into consideration when selecting samples for the long-term stability test. To determine the full depletion of the silicon strip sensors, the bulk capacitance C_{bulk} is measured as a function of the bias voltage V_{bias} (CV). Data points are taken in steps of 10 V with a delay of 5 s after raising the voltage before the actual measurement in order to allow the current to settle in the test circuit. The AC voltage has an amplitude of 100 mV with a frequency of 500 Hz to 5 kHz.

As a consequence of the humidity sensitivity observed in extensive studies of prototype sensors [10–12], electrical tests are required to be performed in dry conditions with RH < 10 %. Therefore, in order to conduct electrical tests – IV, CV, and the Stability test detailed in the following paragraph – in a low-humidity environment, the sensors tested at QC sites are mounted on jigs in dry storage while addressing the individual sensors through switching systems with matrix or multiplexer units. This is also done to increase the weekly testing throughput and facilitate sensor handling.

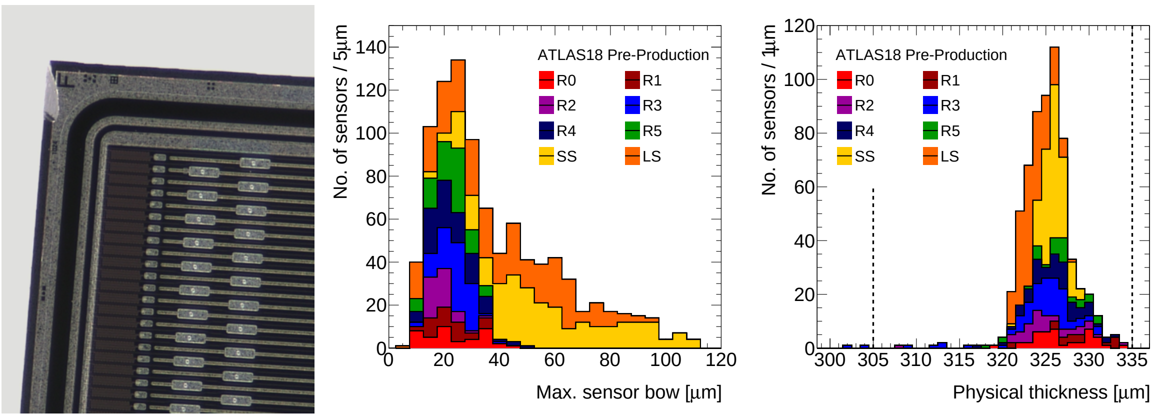
2.2 Tests performed on a subset of sensors per batch

If the metrology setup allows, physical sensor thickness is extracted from that data, otherwise the thickness is determined on a sample basis using caliper measurements of halfmoons, wafer pieces remaining after the main sensors are diced off containing test structures and mini sensors [9]. The acceptable range of thickness is $320\,\mu\text{m} \pm 15\,\mu\text{m}$. On 10 % to 20 % of sensors per batch, leakage current stability (Long-term Stability, LTS) will be monitored over at least 40 hours at V_{bias} = 400-500 V and temperature-corrected fluctuations should not exceed 15%. Sensor selection for LTS takes into consideration prior IV performance and sensors that performed close to the failing criteria or showed transient behaviour during the hold steps are prioritised. For 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 pinholes and punch-throughs to channels through spikes in strip current when applying a voltage, and measure the poly-silicon bias resistor (R_{bias} = 1-2 MΩ) as well as the coupling capacitance ($C_{\text{coupling}} > 20\,\text{pF/cm}$) between metal strips and implants. Only 1% of strips per segment or no more than 8 consecutive strips are allowed to have parameters outside of the quoted specifications. Where applicable, e.g. on barrel sensors, this test is conducted using a multi-channel probe card.

3. QC test results

3.1 Mechanical test results

Of all 1041 Pre-Production sensors, only 10 sensors showed major irregularities during their visual inspection. 4 of those sensors had a mismatch between the listed serial number and their scratch marks, a redundant form of sensor identification. No further mechanical or electrical defects were seen on those sensors and after resolving this issue with HPK, those sensors were cleared. The number of sensors that outright failed the visual inspection due to noticeable mechanical defects were limited to 6. Half of those had deep scratches that also affected their electrical test results. One sensor had a chipped corner, as shown in Fig. 2(a), while a second sensor broke into pieces during handling. The last sensor has a built-in short between its bias rail and guard ring, leading to high currents. Other common, but minor, issues observed during visual inspection were limited to superficial scratches on the surface or debris that could be removed.



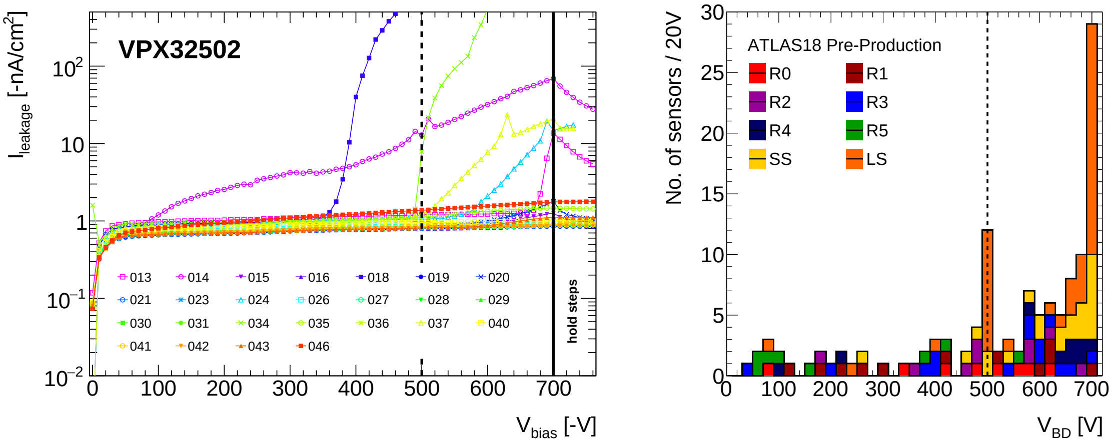
(a) (b) (c)

Fig. 2. (a): Sensor with chipped corner found during visual inspection. (b): Maximum sensor bow of Pre-Production sensors. The allowed limit of 200 µm exceeds the upper limit of the displayed axis as all sensors were well below that value. (c): Histogram of measured physical thickness with upper and lower limits of specification range shown as dashed lines.

The metrology measurement was passed by every sensor, as can be seen in Fig. 2(b). For the majority of sensors the maximum bow was below even 50 µm and therefore well within the limit defined by the specifications. Only two sensor failed the thickness measurement, with results of 302 µm and 304 µm, respectively (see Fig. 2(c)).

3.2 Electrical test results

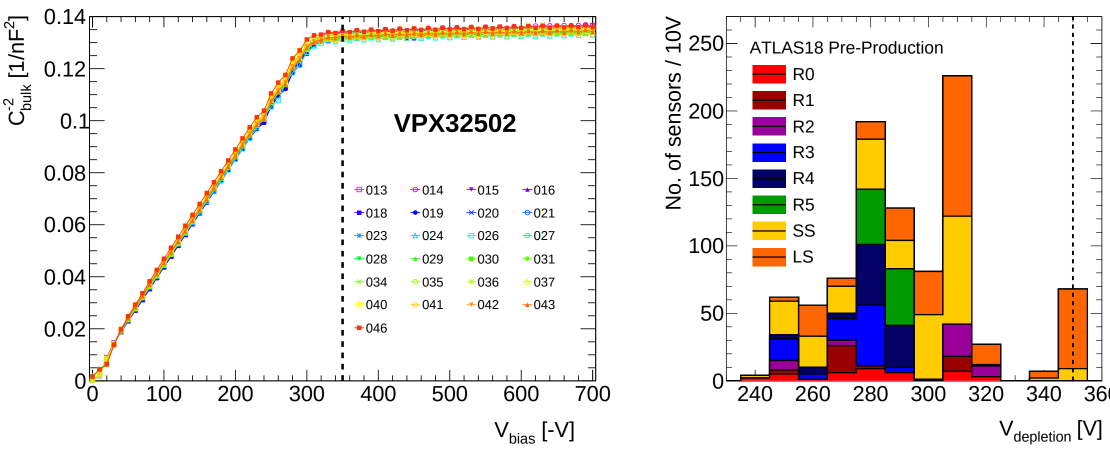
Of all the QC measurements performed on Pre-Production sensors, the IV scan has been the test which the largest fraction of sensors failed by a large margin. Additionally, the mode of failure was exclusively from early onsets of breakdown below 500 V, rather than exceeding the current limit. A summary of all observed sensor breakdowns based on the most recent IV scans is shown in Fig. 3(b). In total, 36 sensors failed the QC test criteria for IV measurements.



(a) (b)

Fig. 3. (a): Example IV curves of a Pre-Production batch; some of the sensors with breakdown have visibly decreasing current during hold steps suggesting possible improvements after voltage training. (b): Histogram of breakdown voltage of Pre-Production sensors measured in the most recent IV scan, not including sensors without breakdown up to 700 V. The dashed lines in both plots illustrate the specification of $V_{\text{breakdown}} > 500\,\text{V}$.

It has to be noted that many of the sensors initially failing the IV scans were re-tested at a later date, some even multiple times. This was done due to observed improvements of the sensor performance during either their long-term stability test or IV scan (see Fig.3(a)). As a result of this, many of the sensors have a breakdown voltage close to the specification limit as their most recent test result, explaining the larger peak in the histogram for those values. All in all, despite the overall larger number in comparison to other QC tests, only a small fraction of 3.5% actually failed the IV test, with a much larger fraction of tested sensors showing an onset of breakdown with $500\,\text{V} < V_{\text{breakdown}} < 700\,\text{V}$.

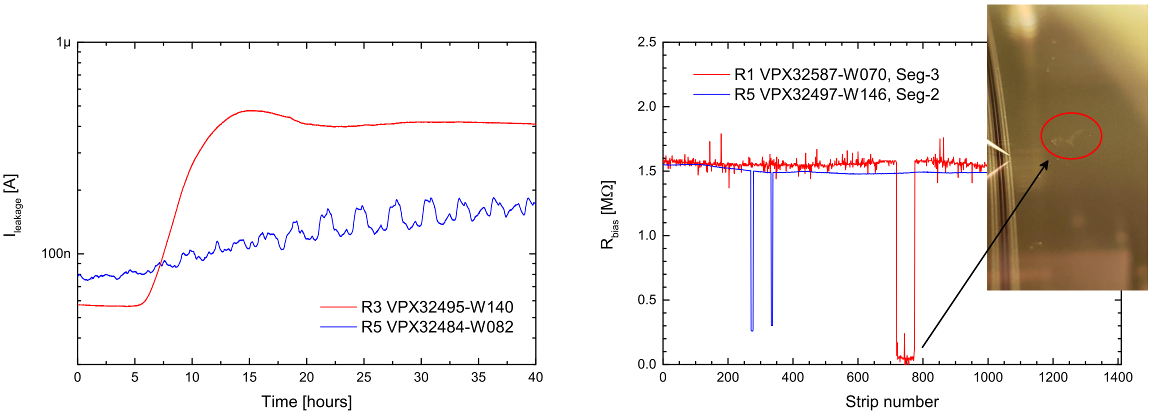


(a) (b)

Fig. 4. (a): Example CV curves of a Pre-Production batch. (b): Histogram of depletion voltage of all Pre-Production sensors measured in CV scans. The dashed line illustrates the acceptable limit of $V_{\text{depletion}} < 350\,\text{V}$.

For CV scans, the vast majority sensors have a full depletion voltage well below the required 350 V, as can be seen in Fig. 4. However, there has been one shipment of barrel sensors, in particular, that had a significant number of sensors either within close margins of said requirement or even exceeding it, albeit by less than 5 V. This occurrence has been brought up in a discussion with the manufacturer and as a result the internal process criteria at HPK were tightened to prevent this from happening in the future. Furthermore, in subsequent CCE measurements it has been confirmed that even those sensors with $V_{\text{depletion}}$ just above the specification show acceptable performance to be used in Pre-Production module assembly.

Of all sensors tested for their leakage current stability and based on the most recent tests for those that were tested more than once, only 4 sensors uniquely fail the LTS scan, i.e. without failing their prior IV scan. Most commonly, the leakage current of failing sensors would rapidly increase at some point during the scan and then stay at an elevated level for the remainder of the test (see Fig. 5(a), red curve). During striptests, 4 of the sampled sensors were found to be out-of-specification, all but one due to large regions of consecutive strips with low R_{bias} or C_{coupl}, as demonstrated in Fig. 5(b). Typically, for good sensors the total number of bad strips, if any at all, did not exceed 10.



(a) (b)

Fig. 5. (a): Example of two different sensors that failed long-term stability. (b): R_{bias} measured for one segment of a sensor that failed its striptest and the artefact visible on the sensor surface upon closer inspection of the affected region.

4. Discussion: QC testing procedures and workflow

Over the course of Pre-Production QC, the part flow routines for main sensors has been refined as well as QC testing procedures at all sites were finalised. One of the most important aspects that was introduced with the beginning of Pre-Production was the usage of the ITk Production Database (ITkDB). Not only are all test results for all ITk components and the assembled modules reported within the database, but it is also used to keeps track of sensor shipments and through that location of components. Moreover, it works as a means of information and data sharing between institutes. The ITkPD will continue to be used for those purposes throughout all of production.

For QC testing beyond Pre-Production, various aspects have already been improved upon based on the experiences gained while testing those sensors. The initial visual inspection and capture of the sensor surface has proven to be valuable tool to document the mechanical state of the sensors and refer back to, if the sensor fails any of the electrical tests. As an example, for a sensor with out-of-specification strips observed in striptests, the visual capture images serve as a look-up tool to check for visible irregularities in the affected area that might have been overlooked during the initial inspection.

Moreover, in order to get an accurate picture of the electrical performance of sensors, sufficient storage time in a dry environment seems to be necessary, despite all efforts to ship sensors in dry conditions while being vacuum sealed in moisture barrier bags. Complementary to this, during Pre-Production and the early stages of Production, it has been seen on multiple occasions that performing additional IV scans can be needed to either make use of beneficial training effects ([10]) or confirm behaviour seen in a prior stability measurement. This sensor training and dry storage has been part of a larger effort to provide means of sensor recovery for those that initially fail to meet some QC criteria. The difficulty with such repeated tests and treatments, however, is that they can be difficult to fit into the already time-constraint Production schedule.

5. Conclusion of Pre-Production QC

Throughout 2020, a total of 1041 Pre-Production sensors, distributed between 7 sites, underwent the full ITk Strip Sensor Quality Control. Using the mechanical and electrical tests detailed in the previous sections, the quality of the final layouts for all 8 types of sensors manufactured by HPK has been verified. Test yields for all QC tests are summarised in Tab. II.

Table II. Summary of Pre-Production QC yield based on sensor samples for each test and accounting for multiple test failures of individual sensors.

QC Test	Vis. Insp.	Metrology	Thickness	IV	CV	LTS	Striptest
Yield (Fails)	99.6% (4)	100%	99.7% (2)	96.5% (36)	100%	99.3% (4)	99% (4)

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