ATLAS ITk strip sensor quality control procedures and testing site qualification

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ABSTRACT: The high-luminosity upgrade of the Large Hadron Collider, scheduled to become operational in 2029, requires the replacement of the ATLAS Inner Detector with a new all-silicon Inner Tracker (ITk). Radiation hard n^+-in-p micro-strip silicon sensors were developed by the ATLAS ITk strip collaboration and are produced by Hamamatsu Photonics K.K. Production of the total amount of 22 000 ITk strip sensors has started in 2020 and will continue until 2025. The ATLAS ITk strip sensor collaboration has the responsibility to monitor the quality of the fabricated devices by performing detailed measurements of individual sensor characteristics and by comparing the obtained results with the tests done by the manufacturer. Dedicated Quality Control (QC) procedures were developed to check whether the delivered large-format sensors adhere to the ATLAS specifications.

The institutes performing the QC testing of the pre-production and production ATLAS ITk strip sensors (QC sites) had to initially be qualified for multiple high-throughput tests by successfully completing Site Qualification process. The QC procedures and the qualification process are described in this paper.

KEYWORDS: Silicon detectors, HL-LHC, Quality Control.

Contents

1. Introduction

The upgrade of the Large Hadron Collider (LHC) into the High-Luminosity LHC (HL-LHC), with the peak instantaneous luminosity reaching 7.5×10^{34} cm^{-2}s^{-1} [1], will require replacement of the entire current 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]. The individual modules of the ITk strip detector include 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 9.8×9.8 cm^2, implementing short strips (24.1 mm) for the inner two 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 strips lengths vary from 15 mm to 60 mm depending on the radius. The pitch of a barrel sensor is 75.5 μm, while it varies around the mean value of 75 μm for the endcap sensors [3]. Production of the total amount of 22 000 ITk strip sensors has started in HPK in 2020 and will continue until 2025.

The ATLAS ITk strip sensor collaboration monitors the quality of the fabricated sensors by performing electrical and metrology measurements of individual sensors. Dedicated QC procedures were developed to check whether the delivered large-format sensors adhere to the ATLAS specifications.

2. Strip Sensor Quality Control Procedures

The QC tests are performed by the sensor QC sites before the sensors are sent to the module assembly sites, which will use them to build the modules. As it is practically impossible to test all sensor’s properties against specifications, the QC protocol was designed to ensure the sufficient quality of the sensors selected for the module assembly, while keeping the human and financial resources on the manageable level.

Sensors are produced in technological batches, within which many sensors are undergoing the individual manufacturing steps at the same time. The experience is that a variation of the individual sensor characteristics within the same batch is smaller than across different batches. For this reason, the sensor QC procedures are split up in tests to be carried out on each individual sensor, and tests done on a few selected sensors of each batch.

The tests on every sensor focus on checking the integrity and condition of the sensor and its structures using visual methods, while basic electrical behavior is verified through current-voltage (IV) and capacitance-voltage (CV) tests. Tests on sample sensors are introduced to check for quality of sensors of a given batch, to verify the uniformity of channel responses across a sensor and across sensors in a batch. The individual QC tests are listed in Table 1 and described in detail in the following paragraphs.

QC tests on every sensor	**QC tests on sample of sensors (2-10%)**
Human Visual Inspection (Vis.Insp.)	Leakage Current Stability (Curr.Stab.)
Machine Visual Capture (Vis.Cap.)	Full Strip Tests (Full Str.)
Metrology (sensor bow and thickness)	Detailed Strip Tests
IV and CV	

Table 1. List of QC tests performed on every sensor and on sample of sensors.

Schematic diagram of a sensor distribution during the ITk assembly is shown in Figure 1. The QC testing sites are marked in yellow. All the endcap sensors and half of the barrel sensors are shipped from HPK to CERN, while the second half of the barrel sensors is going to High Energy Accelerator Research Organization (KEK). KEK and University of Tsukuba provide the QC testing (Vis.Cap., Metr., Full Str.) of sensors in the clean laboratories of HPK. Additional QC tests (Vis.Insp., Curr.Stab., IV, Thickness) of these sensors are performed on sample basis at SCIPP. Half of the endcap sensors are shipped from CERN to Prague for the QC testing and half to Canada where sensors are split for testing between Carleton University, Simon Fraser University (SFU) and Canada's particle accelerator center TRIUMF. The barrel sensors from CERN deliveries are shipped to Rutherford Appleton Laboratory (RAL) and distributed between Queen Mary University of London (QMUL) and University of Cambridge for testing. After sensor delivery at CERN and KEK, the QC sites have 4 months to perform all required acceptance QC tests. The accepted sensors are then distributed to the individual module assembly sites, where the sensors are used to build the modules.

The average speed of the QC testing required during the production phase of the ATLAS ITk strip project corresponds to ~75 barrel and ~50 endcap sensors tested per week.

2.1 Human Visual Inspection

Human Visual Inspection serves to spot obvious defects before investing time and effort in more elaborate testing of the sensor. The sensor is quickly visually inspected by eye and by microscope for chips, scratches, deposits, or other features on the sensor surface and along the edges. Accepted sensor should appear intact, with edge chipping under 40 μm.

2.2 Metrology and Visual Capture

The goal of the metrology is to verify that sensor thickness meets specifications of the ATLAS ITk strip collaboration and bow is suitable for building of the module and its mounting on the local support structure. Non-contact coordinate measuring machine with an optical sensor or a dynamic range laser sensor is used to probe vertical profile of the freely lying sensor. Measuring points form a grid with interval ≤ 10 mm in x and y axes, resulting in an 11x11 points in the case of a square barrel sensor, or an equivalent grid for endcap sensors. The measuring resolution is required to be better than 5 μm RMS. The sensor bow is defined as the difference between the minimum and maximum measured *z*-height after subtracted a fitted plane.

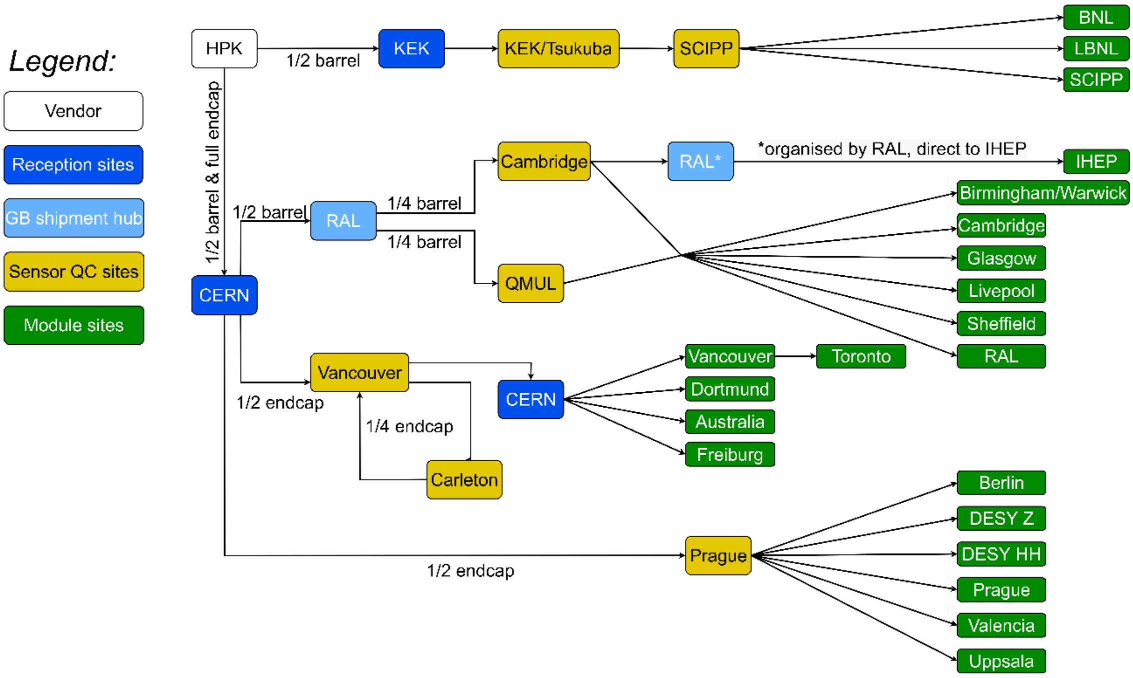

Figure 1. Part flow diagram for the strip sensors used for the ATLAS Inner Tracker assembly.

Thickness is measured using a micrometer on the halfmoons, which are the special testing structures positioned on each individual wafer around the main sensor, or directly on the main sensor by using the chosen contactless method. As an example, in Prague or Carleton the sensor thickness is determined as the lowest z-value measured in the vertical profile scan of the sensor surface. While this method assumes a constant thickness of the sensor in all of its points, ideal subtraction of the origin plane defined by the points measured on the metrology table in a close vicinity of measured sensors, and sufficiently fine grid of measurement points, the obtained results are in a very good agreement with a micrometre measurement of halfmoons. The acceptance criterium for the sensor thickness is 320 ± 15 μm, while the sensor bow is required to be below 200 μm.

The goal of Visual Capture is to provide a very detailed snapshot of the sensor upon its arrival to the sensor QC testing site, which can be used for a future reference in case any defective behavior is found in the following sensor testing or during further detector assembly. The QC sites are equipped with setup that is capable of a fully automatic image capture of entire sensor without intervention. The required minimum resolution is 10 kdpi (2.54 μm/pixel).

The metrology and Visual Capture setup used in KEK/Tsukuba is shown in Figure 2, together with the evidence of the resolution achieved on it. The machines available at the University of Cambridge and in Prague can be seen on Figure 3. While the KEK/Tsukuba developed the system with an automatic wafer loader, sensors are measured on the special jigs at University of Cambridge to avoid any potentially dangerous manipulation with these sensors, or they are positioned directly on the glass metrology table in Prague.

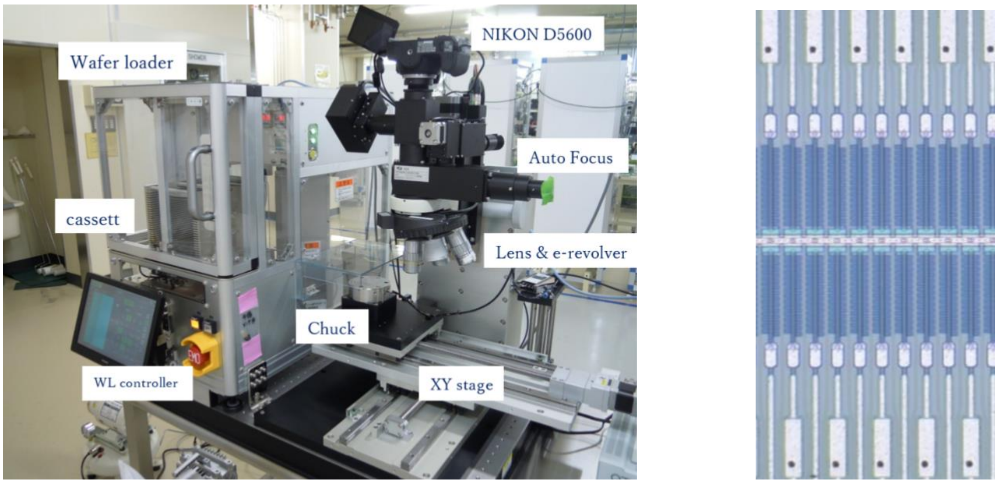

Figure 2. Metrology and Visual Capture setup installed in the clean laboratory of HPK and used by the KEK/Tsukuba QC testing site (left). Evidence of the resolution achieved with this setup (right).

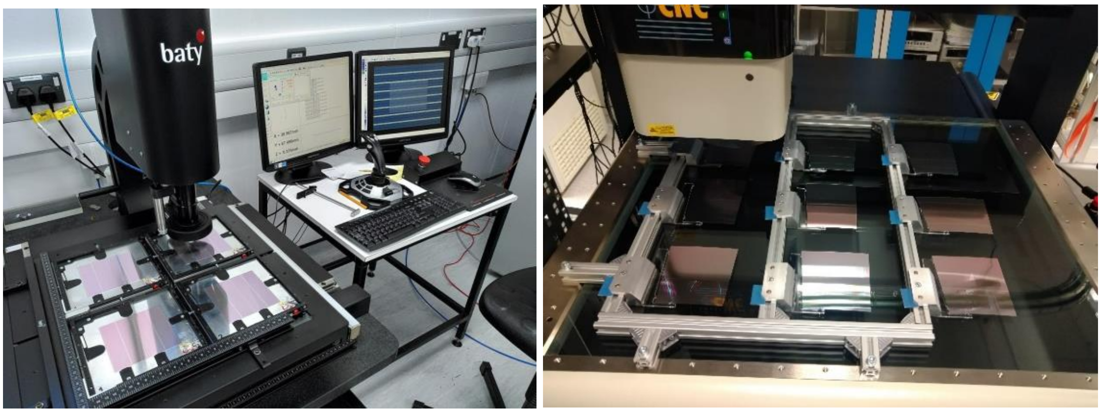

Figure 3. BATY Venture 3030 measurement system installed at University of Cambridge (left) and OGP SmartScope CNC 500 machine used for metrology and Visual Capture tests in Prague (right).

2.3 IV, CV and Current Stability Tests

To verify the sensor basic electrical behavior before its further processing the IV and CV characteristics are tested on every sensor.

The measurements are carried out in controlled environmental conditions with relative humidity RH < 10% and temperature T = 21+/-2°C. Firstly, the IV is performed up to -700 V bias voltage at 10V/10 s increments. The maximum voltage is kept for at least 30 seconds, during which multiple measurements are taken to ensure the sensor is stable. If the leakage current appears to be reducing during this step, this provides an indication that the sensor may be trainable and hence attain better electrical performance (reduced leakage current, higher breakdown voltage). The upper limit of the leakage current is set to 10 μA on the Source Measure Unit used for the IV measurement. Secondly, the CV measurement is performed, at intervals of at least 3x the R-C time of the series resistor and DC blocking capacitor. A frequency between 1 and 5 kHz is used, with the setup having a proven flatness in the frequency response. An AC amplitude of 100 mV is recommended, ensuring the LCR meter achieves the desired resolution.

The measurement is performed either in a probe station on one sensor at a time or in dedicated setups taking automated measurements on up to 20 sensors concurrently, that requires switching equipment with an automatic changeover between IV and CV measurements. In the probe station the sensor contacts are direct, the high voltage is applied on the sensor backplane via chuck through a protection resistor (1MΩ) and current or capacitance is measured by contacting the bias pad by the probe needle installed on the micro-manipulator. In the latter case, sensors are positioned in special jigs where the electrical contacts via wire-bonds are used. For tests in probe station the wire-bonder specialist is not needed and the time for the sensor positioning into the jig is saved, while in case of the automated measurements of multiple wire-bonded sensors the operator interaction time is saved.

The current stability test is performed to check the sensor leakage current variation over tens of hours. Simultaneous measurements of multiple sensors mounted and wire-bonded on sensor jigs or module frames are carried out inside an ESD safe dry cabinet with an active control to ensure stable and dry environmental conditions. The constant bias voltage of 450 – 500 V is ramped up and kept steady and the sensor currents are measured with time interval of 30 s or less. Between 10% and 20% of all main sensors are required to be tested for the leakage current stability. The selection for this test is semi-random. Typically, sensors having a non-ideal IV behavior, like sensors with a breakdown voltage between 500-700V or sensor that appear to be trainable or sensors with visual features are selected for this test. The rest of the sensors is selected randomly from a batch.

The R0 endcap sensor sitting on the jig designed for the leakage current stability measurement, as well as the individual examples of the ESD safe dry cabinets and the experimental setups used for this test are shown in Figure 4.

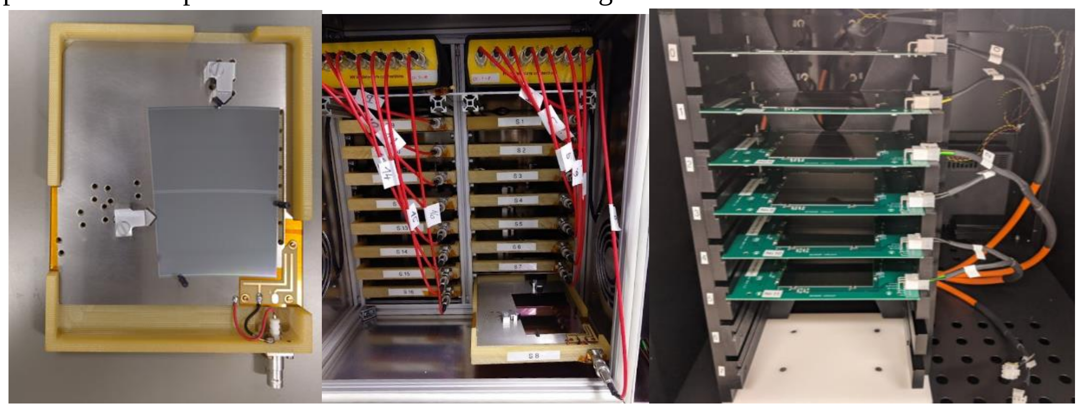

Figure 4. The R4 endcap sensor installed on the jig designed for leakage current stability tests (left). Dry storage cabinets with slots for sensor jigs or module test frames used for the leakage current stability tests in Prague (middle) and SCIPP (right).

Infrastructure necessary for testing electrical properties of ITk strip sensors contains precise High Voltage Source Measure Units (SMUs) able to provide voltage between 0 and - 700 V and to measure electrical current with a resolution better than 10 nA, a LCR meter capable of measuring in 0.5 – 5 kHz interval with at least 0.1 nF resolution, a switch matrix with a multiplexer with leakage less than 5 nA at 500 V and >10 GΩ isolation, with a multiplexing factor to match the number of sensors used, a light-tight ESD safe dry cabinet equipped with necessary patch panels, racks or shelves designed for the used sensor jigs, and T/RH monitoring and control system ensuring stable environment conditions inside the cabinet. For both IV and CV tests, the SMU needs to include a series resistance of at least 1 MΩ to limit inrush currents and prevent sparking in case of contact issues.

Common automated LabVIEW scripts control was developed to be used in all collaborating institutes for all the test procedures including control measuring devices and switching equipment, as well as of the system monitoring the environmental conditions inside the dry cabinet. Data are cashed during the measurement to enable recovery in case of power cuts and are saved automatically afterward.

2.4 Full Strip Tests

The goal of the full strip test is to verify the manufacturing process quality and uniformity of electrical characteristics throughout the wafer surface. Each individual strip of a sensor is contacted and it's impedance to ground is measured to identify potential presence of metal shorts, broken implants, faulty bias resistors or low inter-strip isolation, and pinholes or punch-throughs in the dielectrics. Between 2 and 5% of sensors from each individual batch are selected to be measured at the full strip test. Sensors that pass IV/CV tests but whose visual inspection shows defects and where it is not possible to say with certainty whether defects affect the sensor performance or not are primarily tested. The number of identified defective channels is compared with information provided by HPK.

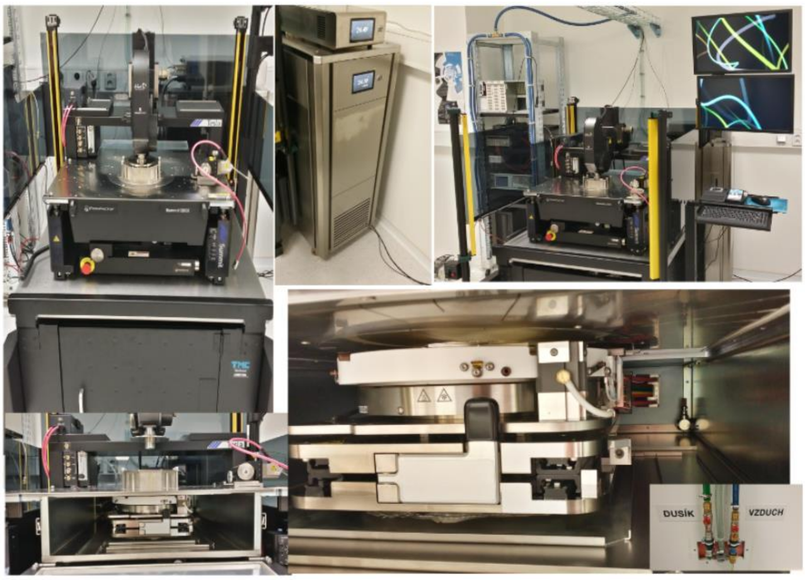

Figure 5. Semi-automatic Probe station Tesla 200mm installed in Prague.

To access all strips, a computer controlled semi-automatic probe station is required, see Figure 5, with the precise control of the chuck movements in all axes. The switch matrix with the multiplexer, which is compatible with the voltages > 100 V and has a leakage < 1 nA and an inter-channel insulation > 1 GΩ, is required to enable DC current measurements, as well as measurements with the LCR meter. The DC current meter needs to have a resolution better than 10 nA. The LCR meter must be capable of the measuring at frequencies between 10 and 100 kHz, while the resolution of 5 pF or better in the 20-100 pF range is required. While the endcap sensors with contact pads positioned on an arch can be tested only by a single needle, the multichannel probe card is used to speed up the testing of barrel sensors from approximately 14 hours to less than 2.5 hours. The LabVIEW scripts, which provide the automatic control of the measurement, including the alignment of the sensor in the probe station, configuration of the individual measuring instruments, as well as a data acquisition, were developed and used by all

QC sites. The temperature and relative humidity during the measurement are monitored and/or controlled.

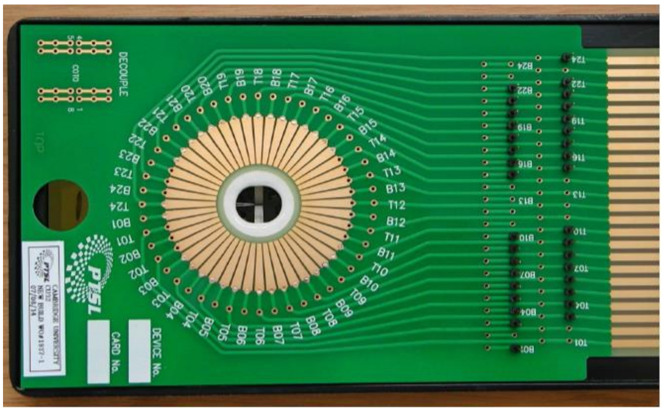

Figure 6. The 32-channel probe card used for full strip test of barrel sensors at University of Cambridge.

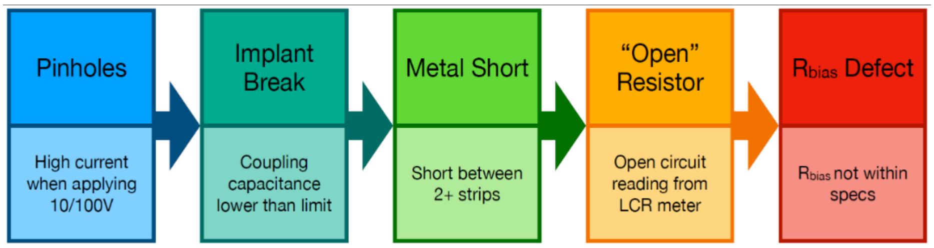

Figure 7. Schematic of defect searched by strip test.

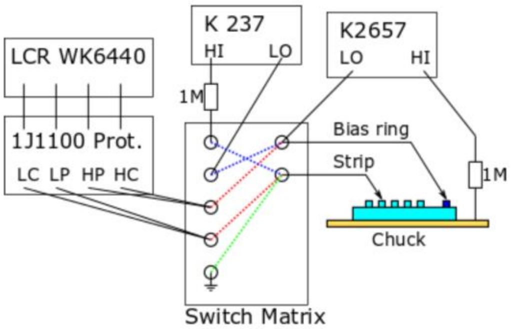

Figure 8. Scheme of the measurement setup used for full strip test in Prague.

During the full strip test the sensor is biased to -150 V to achieve the full strip isolation of strips. In case of endcap sensors, the GND or LO connection to the bias ring is supplied through a probe on PCB that is fixed on the chuck, and it is moving with the chuck. The channel under investigation is contacted by means of a single needle or a multi-channel probe card. The multi-channel card used at University of Cambridge is shown in Figure 6. The full strip test protocol [4] is performed on each individual strip: a DC voltage of 10V is applied by a SMU or a voltage source and a current meter and the current is measured. The series resistor of 1MΩ for current limiting is included. If no shorts are detected, the DC voltage is raised to 100V and the current is recorded. Afterwards, the strip is grounded and subsequently connected to a LCR meter in the R-C series mode to establish the coupling capacitance and the bias resistance. After completing the R-C measurement the strip is grounded and the next strip is measured. The schematic of the procedure and the possible defects are shown in Figure 7.

As an example, the schematic of the measurement setup used for the full strip test in Prague is shown in Figure 8.

3. Site Qualification Process

Although most of the ATLAS institutes have an extensive experience with sensor studies and measurements, the institutes performing the QC testing of the pre-production and production ATLAS ITk strip sensors had to initially be qualified for multiple high-throughput tests by successfully completing a two-step Site Qualification Process. In the first qualification step, the QC sites had to show that all infrastructure required for the test to be performed in these sites is available. This step included certification of the clean laboratories to ISO class 7 cleanliness standard or better, as well as a presentation of availability of necessary measurement devices and their spares. A control of sufficient dry storage capabilities and availability of the distribution systems for the vacuum, compressed air, and nitrogen, was also the part of the first step. In the second step, the capability of properly performing all QC test procedures on prototype sensors had to be demonstrated by providing a detailed test description and a procedural documentation including photos or videos.

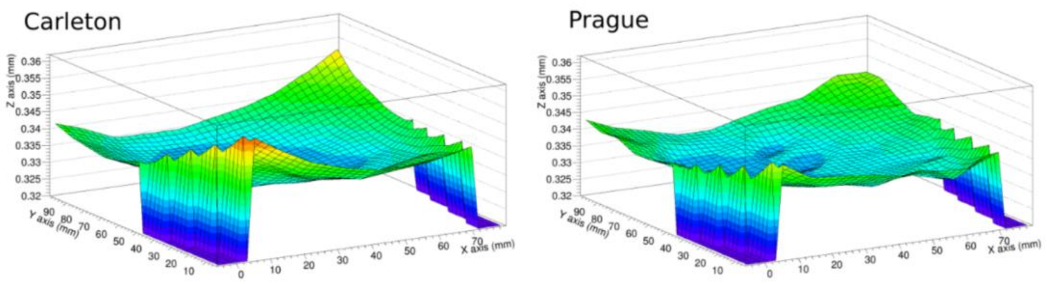

Figure 9. A comparison of metrology measurements performed on the same reference sample at Carleton University and in Prague. The sensor thickness and bow measured at Carleton University were 329 um and 29 µm, respectively, while the sensor thickness of 328.6 µm and bow of 21.4 µm were measured in Prague.

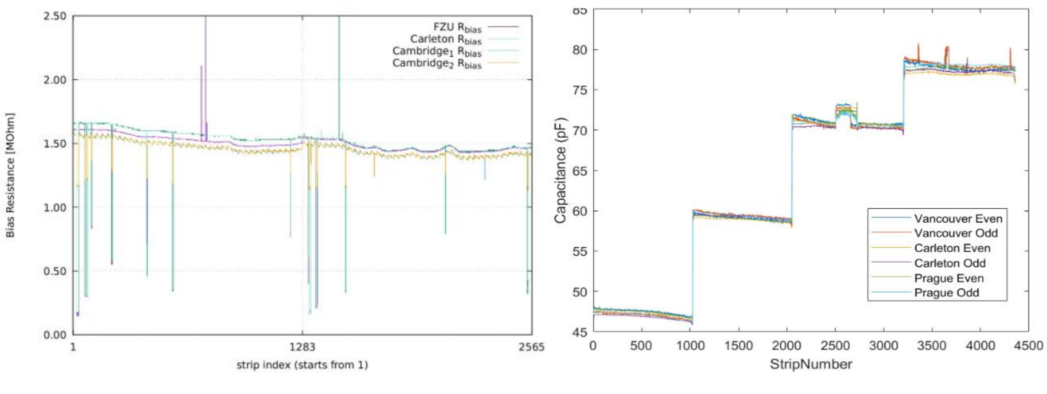

Figure 10. Comparison of bias resistance and coupling capacitance measured on each individual strip of the same reference sample in Prague, at Carleton University, and at University of Cambridge. The coupling capacitance measured on odd and even strips is distinguished. A very good agreement between the results obtained by the participating sites was found.

To cross-check the results obtained by individual QC sites, reference samples with identified defects were exchanged among these sites and results of their measurements were compared. The excellent agreement was achieved among the participating QC sites that matched well the data provided by the manufacturer. An example of results from metrology measurements is shown in Figure 9. A reference sample was measured independently at multiple QC sites, with the equivalent or very similar positions tested on the sensor surface, to compare the obtained results. The same or very similar measurement points have been used in all testing sites. The prototype sensor with many identified defects was intentionally chosen as a reference sample for the full strip test and was examined by different institutes. This sensor had an atypically large number of defects, which is not representative of the delivered good sensor quality. It was obtained from the manufacturer solely for the purpose of qualifying the ATLAS test setups. The comparison of the bias resistance and the coupling capacitance measured on the individual strips of this reference sample in Prague, at University of Cambridge, and at Carleton University, shown in Figure 10, demonstrates a sufficient ability to identify the electrical strip defects in all three sites. The QC sites also demonstrated that the probes do not cause any mechanical damage to the sensor AC pads contacted during the automatic full strip test, see example in Figure 11.

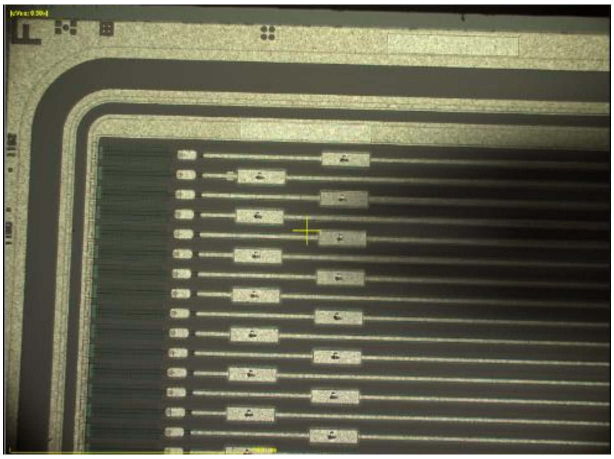

Figure 11. Visual evidence that the probes are reasonable and not causing any significant damage to AC pads of the sensor tested by the full strip test. The small dot marks were caused by probing in HPK, while the longer "line" marks were created during the full strip test performed in Prague.

Finally, the QC sites had to demonstrate overall safe handling of the delivered sensors, as well as the ability to correctly process the data, including upload of results into the ITk Production Database.

4. Conclusions

The QC procedures were developed by the ATLAS ITk strip sensor collaboration to continuously monitor the quality of delivered main sensors that will be used in the ATLAS Inner Tracker. The visual inspection, the metrology measurement, the machine visual capture, as well as several tests of critical electrical properties of silicon strip sensors represent the most important steps of the QC testing. As these procedures will be carried out on a large quantity of main sensors during the pre-production and production phases of the project, the individual QC sites had to go through an extensive qualification process.

Despite of the pandemic related restrictions, the qualification process lasted less than 1 year, as all seven QC sites have successfully passed the qualification criteria by June 2021. The individual QC sites demonstrated capability of properly performing all defined QC test procedures on prototype and pre-production sensors. Moreover, most of the QC sites have achieved a sensor testing throughput required for the sensor deliveries during the production phase of the project, which started in August 2021.

Acknowledgments

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