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Identification and Recovery of ATLAS18 Strip Sensors with High Surface Static Charge

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Abstract

The new all-silicon Inner Tracker (ITk) is being constructed by the ATLAS collaboration to track charged particles produced at the High-Luminosity LHC. The outer portion of the ITk detector will include nearly 18,000 highly segmented and radiation hard silicon strip sensors (ATLAS18 design). Throughout the production of 22,000 sensors, the strip sensors are subjected to a comprehensive suite of mechanical and electrical tests as part of the Quality Control (QC) program. In a large fraction of the batches delivered to date, high surface electrostatic charge has been measured on both the sensors and the plastic sheets which sheathe the sensors for shipping and handling rigidity. Aggregate data from across QC sites indicate a correlation between observed electrical failures and the sensor/plastic sheet charge build up. To mitigate these issues, the QC testing sites introduced recovery techniques involving UV light or flows of ionizing gas. Significant modifications to sensor handling procedures were made to prevent subsequent build up of static charge. This publication details a precise description of the issue, a variety of sensor recovery techniques, and trend analyses of sensors initially failing electrical tests (IV, strip scan, etc.).

1. Introduction

A complete replacement of the ATLAS Inner Detector [1] by the Inner Tracker (ITk) [2] is necessitated by the upgrade of the Large Hadron Collider (LHC) to the High-Luminosity LHC (HL-LHC). The ITk, responsible for the detection and reconstruction of particle tracks, will be a fully solid state sub-detector of ATLAS comprised of radiation hard n^+-in-p silicon pixel and strip sensors. The "strips" portion of the ITk detector relies on 8 sensor layouts, 2 for the barrel region and 6 for the endcap, with a total requirement of nearly 18,000 strip sensors installed[3]. Hamamatsu Photonics K.K has begun production of 22,000 sensors (which accounts for losses) in 2021 and is scheduled to complete the production of the ITk strip sensors in 2025.

A quality control (QC) program has been established in order to verify the mechanical and electrical characteristics of each individual strip sensor. The QC test suite includes an initial visual inspection, surface metrology and total sensor thickness measurement, image capture of the sensor surface, current-voltage (IV) and capacitance-voltage (CV) performance, determination of the long-term stability (LTS) of leakage current, and full strip test [4, 5].

2. Association of QC Failures with Static Charge

During the fourth monthly delivery of sensors, QC sites observed a fourfold increase in the failure rate of

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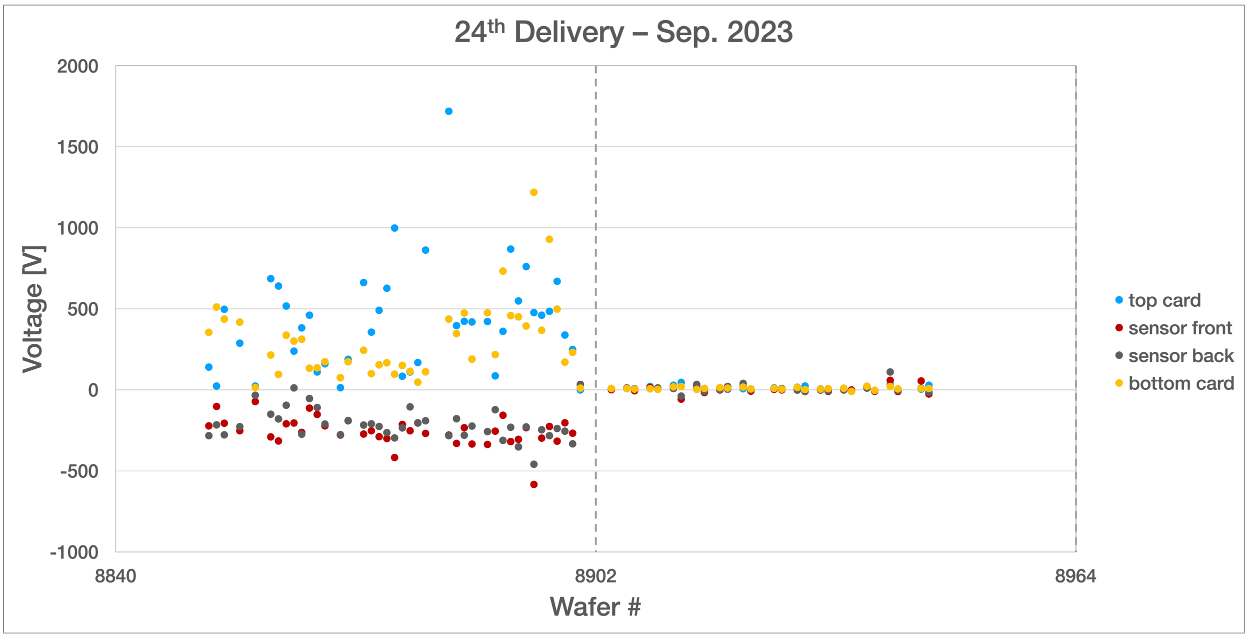

Figure 1: Surface static charge measured on two batches of sensors from the same delivery. The first batch, left of the hashed line, have high static charge on the sensors and sheets. In the second batch, right of the hashed line, the static charge is drastically lower.

sensors undergoing QC testing. In particular, 3 specific failure modes contributed to this elevated failure rate [6]: early breakdown measured in the IV, loss of inter-strip isolation [7], and significant instability in the leakage current measured over long time periods of 40 hours. An association with high surface static charge and at least the first two of these failure modes is apparent. Surface static charge is measured upon reception of the senors at the QC sites using electrostatic field meters. A suspected cause of the static charge build-up is mechanical vibrations or "rubbing" of sensors inside their packaging material during the shipping process. This possibility was confirmed in a dedicated test by rubbing the plastic packaging sheets on the sensor surface and observing an increase in the static potential.

The IV test consists of ramping the sensor's bias voltage from 0 V to -700 V in 10 V steps with a 10 second delay between steps. A sensor is considered to pass the IV test if the onset of breakdown is above (greater in magnitude than) -500 V and if the leakage current at 500 V is <100 nA/cm^2.

When few or no sensors in a batch have high static charge then the IV failure rate for that batch is low, typically much less than 10%. However, an increase in IV failure rate (>10%) is associated with batches where many or all sensors have surface static charge well above 200 V.

During the full strip test a sensor is biased to between -150 – -250 V and each individual strip is probed. First, leakage current of the coupling oxide is measured with 10 V and 100 V applied to the strip. The channel fails if >200 nA is measured at either of these voltages. Next, a series measurement of the strip bias resistance and coupling capacitance is made after switching an LCR meter into the circuit.

Similar to the case with IV testing, an increase in strip test failure rate is observed in batches with high surface static charge. The dominant mode of failure in the strip test is a measured bias resistance below the specified range of 1–2 MΩ. The low bias resistance measurement is considered an indication of low inter-strip isolation. This inference is drawn from the fact that the measured bias resistance will be reduced by a factor corresponding to the number of strips affected. That is, when a group of strips have poor isolation, their respective bias resistors act in parallel and the measured bias resistance is reduced.

It was previously observed that long-term dry storage can help recover the sensor performance [7]. However, the QC sites have a limited time to evaluate the performance of each delivery. What follows is a description of alternative measures which have been considered.

3. Mitigation Strategies

In an effort to reduce the overall failure rate, QC sites cross-checked existing procedures and developed improved handling techniques. Various measures which were found to reduce the instance of static charge build up include:

1. **Static charge measurement:** The surface static charge of the sensor and packaging cards is measured by an electrostatic field meter upon sensor reception and unpacking. This was not originally part of the QC procedures but has been adopted as part of QC initial reception. Sensors with high static charge may be specially selected to undergo LTS or strip testing.
2. **Electrical grounding:** Grounding mats and bracelets are used in laboratories of QC sites in order to prevent the build up of static charge while handling sensors.
3. **"Matte-matte" orientation:** Sensors are packaged in paper envelopes and sheathed between two stiff protective cards. The cards have two distinct sides: shiny and matte. When sensors are stored in a particular orientation, with both matte sides of their packaging cards facing towards the sensor, the build up of static charge is reduced.

A dependence of surface static charge on the sensor's packaging material has been observed. Figure 1 demonstrates the effect of the packaging cards. In a single delivery two back-to-back batches of sensors are packaged with the two kinds of packaging cards. In the batch packaged with "old style" cards (left of hashed line) the static charge measured on the sensor and cards is on the order of many hundreds of volts and in extreme cases >1000 V. However, the second batch, packaged in the"new style" cards (right of hashed line), shows very little static charge, typically <100 V.

4. Sensor Recovery Techniques

Alongside the above described mitigation strategies, certain recovery techniques have been found to improve a sensor's electrical performance. The improvement is often enough to bring a sensor within the thresholds set for QC. Hence, recovered sensors may be considered as acceptable for use within the ITk from the standpoint of the QC testing. A variety of recovery techniques have been examined. The following are the most effective:

1. **Ion-blower treatment:** Sensors may be treated for short periods of time, on the order of minutes, with streams of ionized gas even before any QC failures take place especially if their measured static charge is greater than 100 V. This treatment is also used as a recovery technique on sensors which fail either the IV or the strip test.
2. **UV-A treatment:** Exposure of the sensor to a UV-A light source (370–410 nm) for a long period of time, up to 12 hours, can be used to recover sensors failing IV and strip test.
3. **Additional LTS testing:** In cases of IV failure it has been observed that prolonged exposure to high voltage, just below the onset of breakdown, has a "training" effect which causes an increase to the sensor breakdown voltage. The prescription is essentially the same as the LTS test, hence, additional LTS testing after an IV failure may recover that sensor.
4. **UV-C treatment:** A more extreme treatment than the UV-A, used to recover inter-strip isolation. Sensors may be exposed to a UV-C light source (180–250 nm) for short periods of time <10min. This is typically a "last resort" technique if other treatments fail to recover the sensor.

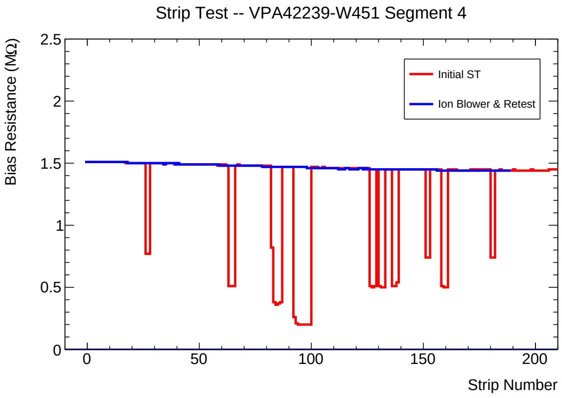

Figure 2: Bias resistance of the first ~200 strips of the topmost segment of a sensor as measured in the strip test. The initial measurement is shown in red and re-test after ion-blower treatment shown in blue.

An example of a strip test recovery is demonstrated in figure 2. Shown here is a sample of the strip test in the first ~200 strips of the topmost segment of a sensor. After the initial test (shown by the red curve) many regions each comprised of a couple to nearly a dozen strips have apparent low bias resistance. As previously explained, this is an indication of poor inter-strip isolation, most clearly seen in doublets and triplets of strips whose measured bias resistance is reduced by a factor of 2 or 3 compared to the nominal value of

1.5MΩ. Localized surface static charge may be high enough to invert the surface just below the SiO_2 interface. With strong enough inversion, a conducting channel will form between strips interfering with the p-stop isolation structures and effectively eliminating inter-strip isolation. After the ion blower treatment (shown by the blue curve) it is apparent that this localized static charge has been eliminated and the inter-strip isolation is recovered in all regions where it had previously been compromised. Analogous examples of such recoveries for both IV and strip test failures using the UV-A and ion blower treatment are in [6].

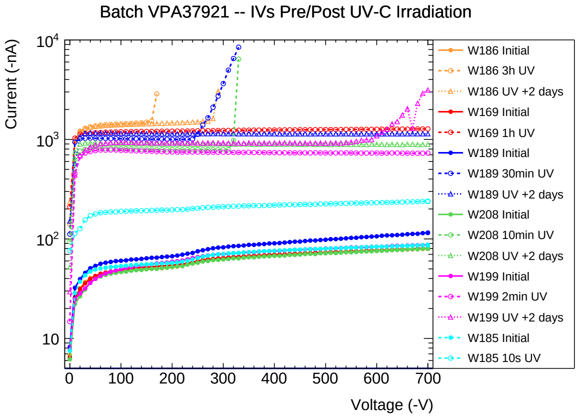

Figure 3: The effect on IV from UV-C exposure.

As a recovery technique, exposure to a UV-C light source is reserved for challenging cases of low inter-strip isolation which cannot be recovered in any other way. While very effective at restoring inter-strip isolation, the treatment has the undesirable side-effect of greatly increased leakage current by up to a factor of 20. The effect of UV-C exposure on sensor leakage current was tested using the lamp from a *SAMCO UV-1* bench-top UV-Ozone cleaning system (other features of the system such as heating and gas flow were disabled). The results of this testing are shown in figure 3. Various wafers from a single batch with poor strip isolation were selected for UV-C treatments of various exposure times ranging from as little as 10 seconds up to 3 hours. In the shortest exposure time (10 s) the sensor leakage current increased by about a factor of 2. After a few minutes of exposure, the leakage current appears to saturate with relatively minimal increases for greater exposures. Additionally, it can be seen that prolonged exposures to UV-C light will not only increase the total leakage current, but also induce an early onset of breakdown. For this reason, the UV-C light exposure should be extremely short, that is, less than a few minutes.

5. QC Failure Rates Over Time

Strategies for mitigating and treatments for recovering sensors with high static charge have been implemented by the QC sites. These, along with site specific setups are detailed in [6]. The summary of the QC site efforts is that sensors failing IV and strip test can be typically recovered in two dominant ways, particularly when the root cause appears to be high static charge accumulation. Exposure of sensors to a constant stream of ionized gas for short periods of time (on the order of minutes) or to a UV-A light source for longer exposures (>8 hours) often leads to improvement of the sensor performance.

Recovery of sensors has greatly decreased the total failure rate as shown in figure 4. Initial failure rate is the rate of sensors failing any QC tests before any recovery techniques are attempted whereas the final failure rate is the rate of failures after recovery. Following the third delivery, the initial failure rate drastically increased and the need for recovery became apparent. Hence, there were no recovery efforts throughout the first three deliveries. The figure demonstrates that the recovery efforts of the QC sites have been effective at keeping failure rates below 10% in every single delivery and below 5% in all but 4 deliveries[1]. More generally, the overall trend is a reduction of the fraction of sensors with issues toward the end of the time period shown.

6. Summary

High surface static charge has been an ongoing cause of QC failures throughout the production of ATLAS18 ITk strip sensors. Failure in the IV and full strip tests are the dominant causes of high static charge. Despite this issue, QC sites have developed strategies for recovering many failed sensors and have maintained failure rates below 10%. The most effective recovery strategies are exposure to streams of ionized gas or UV-A light sources. Finally, an overall downward trend of QC failure rates has been observed in the most recent deliveries which is assumed to be attributed to measures implemented by the manufacturer.

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[1] On average, about 2.1% of individual sensors are rejected, including those affected by the static charge. An entire group of sensors, referred to as a batch, is rejected if the QC and/or the quality assurance (QA) test fails [8, 9]. To date, 5 batches (VPA37921, VPA38206, VPA38906, VPA46225, VPA42646) and a partial batch (VPA46223) have been rejected. Including these batches, the total rejection rate is about 3.7%. Rejected sensors are to be replaced towards the end of production.

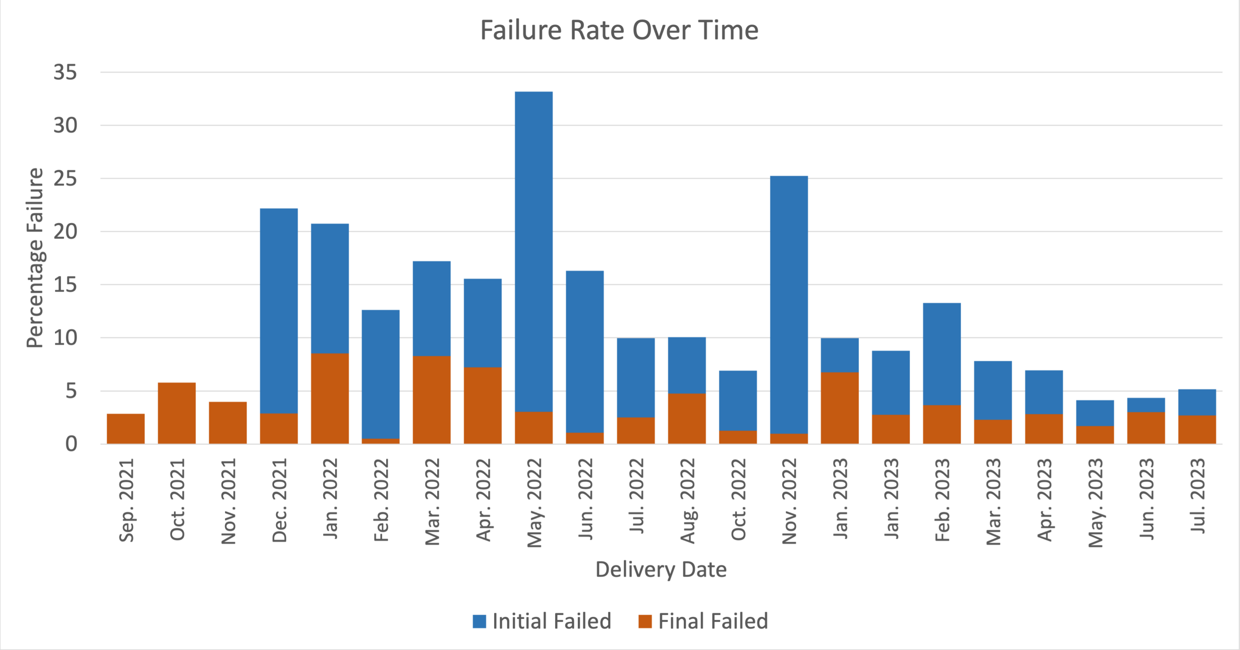

Figure 4: A summary of sensor failure rate over time for the first 22 deliveries. The "Final Failed" rates are much lower than the "Initial Failed" rates and reflect the recovery efforts implemented by QC sites.

7. Acknowledgements

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