Long-term Humidity Exposure of ATLAS18 ITk Strip Sensors

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Abstract

The ATLAS collaboration is upgrading its detector for High-Luminosity LHC (HL-LHC) operations scheduled to start in 2029. This involves making a new all-silicon tracker, called Inner Tracker (ITk), with instrumented strip area of 165 m^2.

The strip sensor type is n-on-p, chosen because of its radiation hardness and a relative fabrication simplicity. So far it has not been used in large-scale experiments. Many years of R&D investigations and pre-production experience showed that it works well, with the specification of the maximum operational voltage of 500 V. The sensors, however, show sensitivity to ambient humidity, e.g. reduced breakdown voltage at relative humidity (RH) values of about 40% and above. This is an issue for testability, but not for real operations, where RH is very low. Therefore, the collaboration adopted the strategy of dry storage, testing, and shipment for sensors and related assembled components: modules, staves, and petals. A few days long exposure to ambient air during assembly was shown to be tolerable.

The dry handling strategy becomes much more difficult to implement during the tracker integration, when barrels and disks are put together in large-size cleanrooms with RH range between 50 and 70%. The duration of each of numerous integration steps is several weeks, followed by testing. The effect of such long humidity exposures on the sensor properties was unknown. Therefore, we commenced a study of repeated sensor exposures to 75% RH. We chose 32 sensors for the study from different deliveries, and with different pedigrees in terms of initial performance on reception and recovery procedures used. Progressively longer exposures ranged between 4 and 266 days in duration. The cumulative exposure time was up to 2 years. No performance deterioration was seen, as evaluated by the visual inspection, IV characteristics, and other checks. We report the details of the tests, results, and implications.

Keywords: silicon, detector, humidity, breakdown

1. Introduction

The ATLAS ITk construction project is on-going, aiming to upgrade the ATLAS detector [1] for the HL-LHC era and associated requirements. After many years of R&D for Strip Sensors the design version called ATLAS18 was developed [2]. It satisfies the project Specification requirements, as verified by pre-production experience [3]. Currently over half of the Strip Sensors needed are already produced. The sensors have a feature that the breakdown voltage (V_{bd}) is dependent on the ambient humidity. Typically, V_{bd} is reduced at the RH levels of 40-50% [4, 5, 6]. This is not a problem for operations, where a very dry environment is anticipated.

During the sensor tests where humidity matters, such as current-voltage (IV), capacitance-voltage (CV), and Long-Term Stability (LTS) tests, RH is maintained under 10% [1]. This is straightforward to achieve in relatively small enclosures required for sensor, module and stave/petal tests, using either desiccant units or external gas line hookup to dry air or nitrogen.

The setups for assembly of the large-scale tracker objects, such as disks and cylinders, are different. They need large cleanroom volumes [7], which are impractical to keep dry at all times. Therefore, although the sensors will remain unbiased during such integration, it is important to investigate a question of the long-term sensor tolerance to the ambient humidity. Given the Specifications for the cleanrooms and the construction schedule, we investigated the following question: After a several months long exposure to RH of 50% to 70%, would the ATLAS18 sensors still have the acceptable V_{bd} (above 500 V), as shown by the IV tests performed in a dry environment (RH<10%)?

2. Sensor Samples and Exposure Setups

At first we selected 8 sensors distributed between 5 pre-production batches available to us. In order to control the humidity a "flat bed" type of setup was made, using a "humidor" device[1] (Figure 1). Although it was meant for a different application, the functionality of maintaining the target humidity, coupled with outputting the droplet-free moisture, matched our requirements.

Once a sufficient number of production sensors became available, we augmented the sample set with additional 16 sensors from 13 fabrication batches. They were selected predominantly from the sensors that underwent recovery procedures at the time of reception tests.

The recovery procedures included UV irradiation, dry storage, which tend to improve the breakdown voltage, as well as "baking", that helps with the stability test performance and IV test run after the stability. The UV exposures were 1-2 hours long and baking was 17-20 hours long. Further details of the procedures are described elsewhere [8]. The recovered sensors were included to check that their improved performance is maintained with time.

The full list of the sensors in this investigation and their recovery history is shown in Table 1. In order to add the 2nd set of sensors we rearranged the setup as vertically stacked shelves and improved its hermeticity (Figure 2).

The exposures were planned with ever-increasing time, in order to catch a possible onset of performance problems. In order to imitate the tracker integration conditions, the sensors were kept unbiased in the humid conditions. IV tests were run after each exposure for the evaluation. Initially we also alternated the presence of ambient light during the exposures. The longest continuous exposure was 266 days and the longest cumulative time in high humidity was 963 days (Table 2).

After first 2 brief tests we set the target humidity to 75%, to be above the expected range in the assembly cleanrooms. This target was maintained throughout the

Table 1: Composition of test sensors. The sensors are grouped and color-coded according to the primary issue and the recovery method: green for the relatively benign IV features recovered by Dry storage, blue for the IV problems recovered with UV, yellow for the early breakdown occurring immediately after LTS, that was recovered by Baking, orange for the Stability test issue recovered by Baking, and magenta for the Stability issue recovered by re-running the test.

Sensor reference		Test, Issue	Recovery method	
Batch	Wafer		Main	Others
VPX32411	W00039	None	None	
VPX32418	W00146	None	None	
VPX32418	W00151	None	None	
VPX32418	W00180	None	None	
VPX32419	W00186	None	None	
VPX32420	W00234	None	None	
VPX32426	W00383	None	None	
VPX32426	W00412	None	None	
VPA38186	W01307	None, IV feature	Dry storage	Ion blower
VPA37911	W00997	None, IV feature	Dry storage	
VPA38692	W01757	None, IV feature	Dry storage	Ion blower
VPA38186	W01591	None, IV feature	Dry storage	
VPA38700	W01308	IV	UV	
VPA38701	W01961	IV	UV	Baking (17.5 hr)
VPA38886	W01989	IV	UV	Baking (17.5 hr)
VPA39550	W02630	LTS/V_{bd}	Baking	UV
VPA38901	W02436	LTS/V_{bd}	Baking	UV, Ion blower
VPA38901	W02443	LTS/V_{bd}	Baking	Ion blower
VPA38901	W02464	LTS/V_{bd}	Baking	UV
VPA39577	W02990	LTS/V_{bd}	Baking	
VPA39578	W03010	LTS/V_{bd}	Baking	
VPA39576	W02957	LTS/variance	Baking	
VPA39576	W02972	LTS/variance	Baking	
VPA41724	W04399	LTS/variance	LTS repeat	

Table 2: Humidity exposures.

Exposure Number	Start Date	Individual Exposure [days]	Cumulative Time [days]	Average RH [%]	Ambient Light
Initial 8 sensors					
1	2021-03-07	4	4	66.9	ON
2	2021-03-11	16	20	66.9	ON
3	2021-03-27	39	59	74.8	ON
4	2021-05-05	7	66	77.5	OFF
5	2021-05-12	70	136	72.6	OFF
6	2021-07-22	146	282	74.5	OFF
7	2021-12-17	214	496	75.7	OFF
8	2022-07-20	266	762	74.4	ON
9	2023-04-14	201	963	75.3	ON
Additional 16 sensors					
1	2022-10-20	15	15	75.4	ON
2	2022-11-04	67	82	74.7	ON
3	2023-01-10	90	172	73.0	ON
4	2023-04-14	201	373	75.3	ON

[1] Model "Cigar Oasis Magna 3.0" from www.cigaroasis.com .

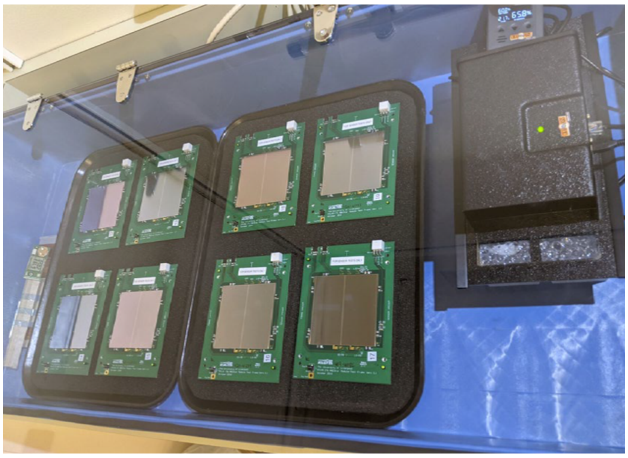

Figure 1: Initial "flatbed" setup for 8 sensors.

2 years of this investigation, with the exception of 3 occasions when the humidor ran out of water (Figure 3). The built-in humidity readings of the humidor were confirmed from the ones from SHT31 meter. The setup temperature varied between 19 °C and 23 °C.

3. Main Tests

The repeat IV tests in dry environment (<10% RH) are the main method in our investigation. They were done for our sensors at several stages: during the usual sensor QC verification, after performance recovery attempts (if any), before the humidity exposures, and after each exposure. The breakdown voltage was the primary performance parameter tracked. It was evaluated with the standard software that checks for the change in the current slope with voltage [9].

In most cases we did not find the breakdown within the voltage scan range of up to 700 V. An example compilation of the IV graphs for such a sensor is shown in Figure 4. We observed the effect of the performance recovery work where applicable. In some cases, the initial V_{bd} improvements with repeat tests was found, a typical occurrence. The IV plot compilation for such a sensor is shown in Figure 5. We note that we only observed such changes during the regular QC tests and the pre-exposure re-assessment. The evaluation after each humidity exposure showed very stable results, that were compliant with our specification and did not change with time (Table 3). This observation addresses the main goal for this study.

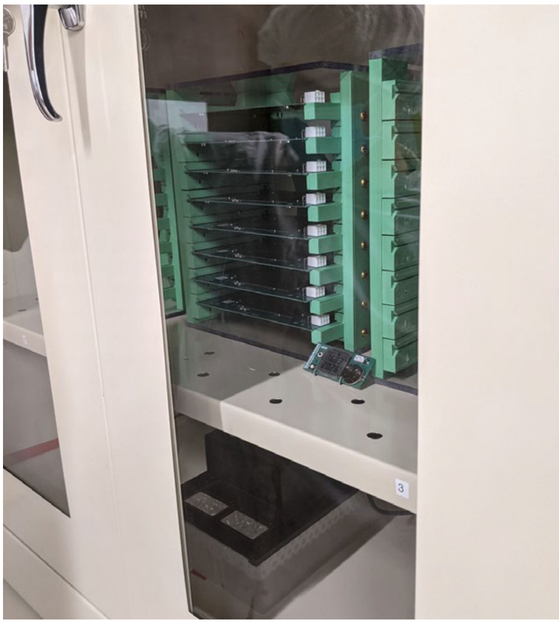

Figure 2: Final setup with 24 sensor positioned in vertically arranged shelves.

4. Additional Tests

4.1. Visual Inspections

The sensors were visually inspected several times during the exposures. The inherent motivation was to check for any signs of corrosion that was seen in the past with a different vendor [10]. It can appear in case of chemical residue remaining after some of the processing steps.

The main inspection tool was Keyence VHX-500 station with magnification of several hundred times. The same procedure was applied as during the regular QC tests, including scans of the sensor edges and the active

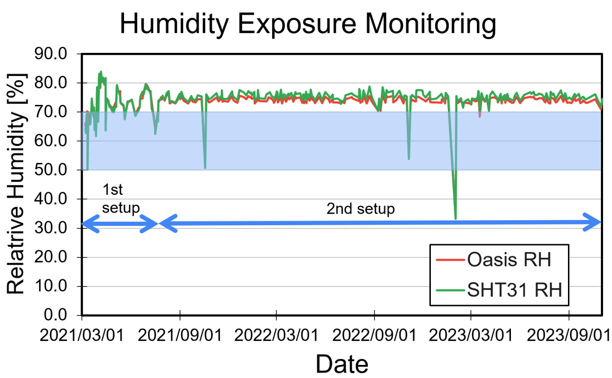

Figure 3: Record of humidity readings throughout the exposures.

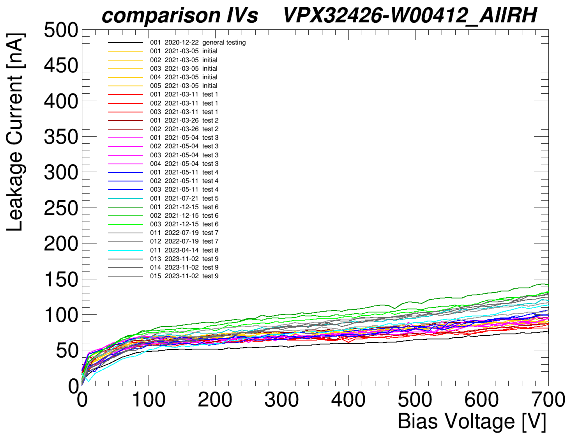

Figure 4: A combination of all test results throughout this study for a typical sensor.

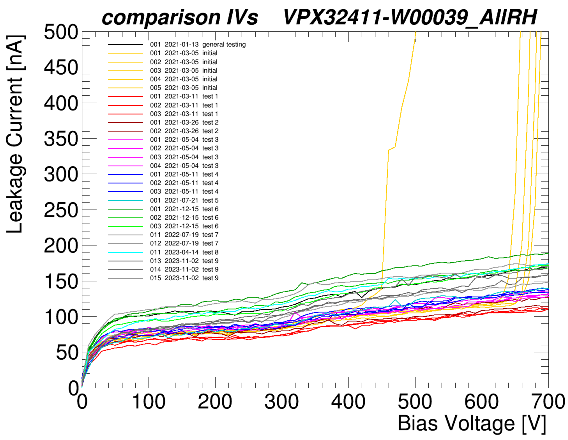

Figure 5: A combination of all test results throughout this study for a sensor that exhibited an improvement of the breakdown voltage in the initial tests.

area. The last time the sensors were inspected at the end of all exposures.

We have not observed any sign of the corrosion, on any sensor. This observation affirms the high quality of the fabrication and suitability of the chosen technology.

Somewhat confusingly, we initially saw small droplets on the surface of the first set of sensors. They were eventually tracked to small-scale intermittent oil contamination in the dry air lines used in some of the test setups (but not the main IV and humidity-exposure cabinet). The reason for the contamination is likely temporary storage of the sensors in a different setup during the setup upgrade change. The following observations confirm the nature of the oil contamination, as tested on one of the sensors from the original set:

Table 3: Breakdown voltage (V_{bd}) derived from the IV tests during the normal QC testing, before the long-term humidity exposures, and after each exposure. The sensor sequence in the table is the same as in Table 1. The V_{bd} values below the specification limit are colored in red, and the detected breakdowns above the limit are shown in green.

Sensor reference		V_{bd} [V]										
Batch	Wafer	QC Tests	pre-exposure	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
VPX32411	W00039	>700	450→660	>700	>700	>700	>700	>700	>700	>700	>700	>700
VPX32418	W00146	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700
VPX32418	W00151	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700
VPX32418	W00180	>700	310→640	>700	>700	>700	>700	>700	>700	>700	N/A	>700
VPX32419	W00186	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700
VPX32420	W00234	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700
VPX32426	W00383	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700
VPX32426	W00412	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700	>700
VPA38186	W01307	290→530	>700	>700	>700	>700	>700					
VPA37911	W00997	490→>700	>700	>700	>700	>700	>700					
VPA38692	W01757	510→>700	>700	>700	>700	>700	>700					
VPA38186	W01591	170→>700	>700	>700	>700	>700	>700					
VPA38700	W01308	130→660	>700	>700	>700	>700	>700					
VPA38701	W01961	280→>700	500→>700	>700	>700	>700	>700					
VPA38886	W01989	180→>700	>700	>700	>700	N/A	>700					
VPA39550	W02630	350→>700	>700	>700	>700	>700	>700					
VPA38901	W02436	250→530	530	530	530	530	540					
VPA38901	W02443	260→>700	>700	>700	>700	>700	>700					
VPA38901	W02464	180→>700	>700	>700	>700	>700	>700					
VPA39577	W02990	390→670	680→>700	>700	>700	>700	>700					
VPA39578	W03010	610→>700	>700	>700	>700	>700	>700					
VPA39576	W02957	480→>700	>700	>700	>700	>700	>700					
VPA39576	W02972	>700	>700	>700	>700	>700	>700					
VPA41724	W04399	400→>700	>700	>700	>700	>700	>700					

- The droplets were removable with a cleanroom Q-tip
- They did not disappear in dry storage, but we could "bake" them away at 150 C

We could reproduce the contamination size and features by spraying the oil on test pieces, which confirms the interpretation. They could also be removed by baking (Figure 6). The presence of the droplets was unfortunate, however we should note that the sensor performance was not affected by this phenomenon.

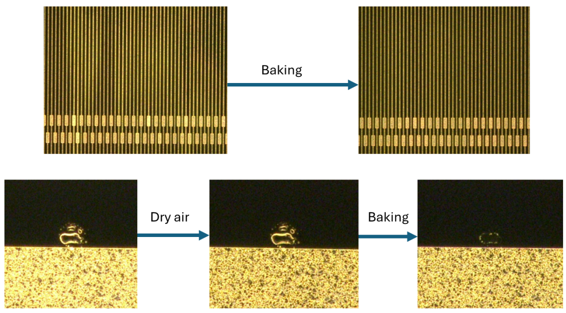

Figure 6: Effect of dry air and baking application to the typical oil residues on the surface.

We also performed a direct deposition of the de-ionized water droplets on the sensor surface to check for the water pooling possibility. However, the droplets typically evaporate in seconds in the environment of about 50% RH. This indicates that a long-term water presence on the sensors is not feasible in a typical tracker assembly environment[2]

[2] An example video of water droplets evaporation

4.2. *Stability Tests*

After the last humidity exposure we performed another Stability test as an additional check on the sensor operation. They were performed at 450 V bias, in dry environment (<10% RH), at ~21 °C. The relative current variance during the standard 40-hour test was 3-6% for all sensors (Figure 7). This is the same range as observed in the usual reception QC tests, and it is well within the specification of < 15%.

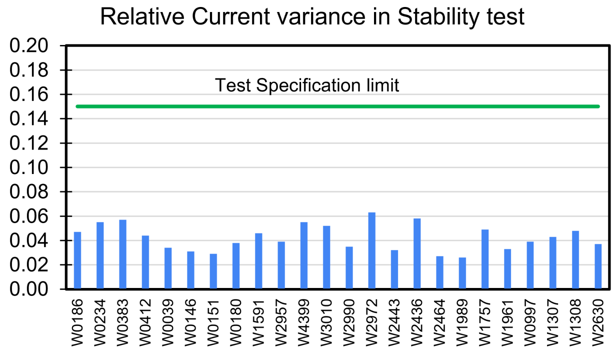

Figure 7: Relative current variance measured in the Long-Term Stability test performed at the end of all exposures for all 24 sensors. Also shown is a specification limit for the maximum allowed variance.

4.3. *Humidity Dependence*

During some of the testing periods we varied the humidity environment in the test enclosure to re-assess the influence of the humidity on V_{bd} and to add statistics to the previous studies [4, 5]. The voltage scan range was the same as for the other tests, up to 700 V. The results are shown in Figure 8, where the value of 700 V was used in cases when no breakdown was found. As expected, V_{bd} typically is reduced at RH of 30-50%. In a few cases there was a V_{bd} reduction for RH of 13-20%, and a few cases of sensors without breakdown up to 55%. However, in all cases the sensors performed well at the ITk test specification of RH ≤10%, confirming the validity of the chosen procedures.

5. Conclusions

We investigated the ATLAS ITk Strip Sensors susceptibility to long-term humidity exposure. This performance aspect is relevant to the large-scale assembly

under a microscope is shown at the following link: https://drive.google.com/file/d/1HLDHC-KYDYCPXciN7IHt_Fvb-6_XLo19/view .

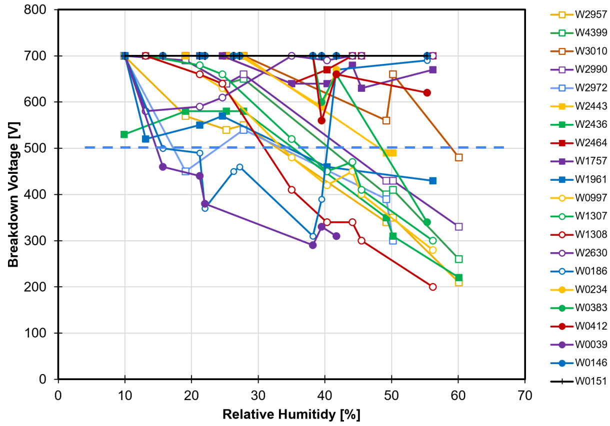

Figure 8: Dependence of the breakdown voltage on the relative humidity in the ambient environment in the test performed at the end of the exposures.

of the final tracker parts, which will be repeatedly subjected to the high ambient humidity for several months at a time. The target RH of 75% in our investigation was intentionally maintained above the 50%-70% specification for the final assembly rooms. The longest single exposure was 266 days, and the longest cumulative exposure was 3 years. The following features were observed:

- The breakdown voltages tested in dry atmosphere did not change throughout the repeat exposures.
- The presence of ambient light during the exposures did not affect the results.
- The long-term stability tests after all the exposures showed typical good results.
- In repeat visual inspections we have seen no sign of corrosion. Water droplets deposited on the surface evaporate in seconds, suggesting no long-term water presence.
- There was an expected general dependence of V_{bd} on RH in humid environment with some variability. All sensors performed well at the ITk chosen dry test threshold of 10% RH.

These results mean that the sensor technology is compatible with the tracker assembly plans involving multi-month exposure to ambient humidity, as long as the dry environment is maintained during the test time. We attribute the results to the high sensor quality and dedicated passivation features designed to reduce the humidity sensitivity.

6. Acknowledgments

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