Silicon Sensor Quality Control for the HGCAL Upgrade of the CMS Detector

Robert Laughlin • Karem Peñaló Castillo • Alexander Wade • Supervising Professor: Rachel Yohay, PHD
Florida State University, Department of Physics

Introduction

The Large Hadron Collider (LHC) is the most powerful particle accelerator in the world. When complete, the High Luminosity Large Hadron Collider (HL-LHC) upgrade to the LHC will integrate 10 times the luminosity of the LHC. To detect the energies of particles produced by proton-proton collisions in the HL-LHC, the High Granularity Calorimeter (HGCAL) will replace the current endcap calorimeters [1]. The semiconducting materials used in the calorimeter can be used to track charged particles.

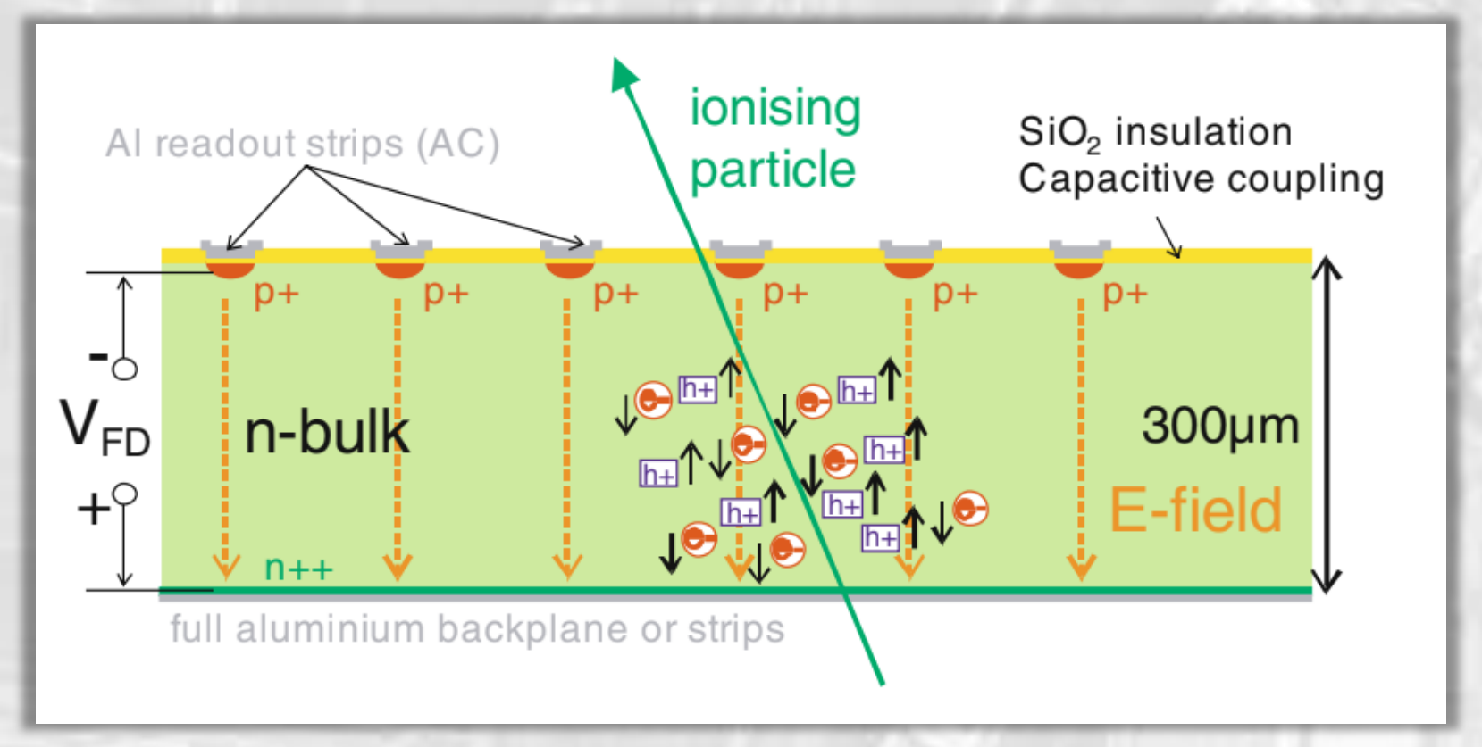

Fig. 1. The p-n junction of a silicon sensor. Electron hole pairs are created by ionizing particles moving through the p-n junction of the detector. The charge created can be collected at the electrode to detect the particle [2].

The silicon sensors in the HGCAL will be able to detect the energy deposited by charged particles moving through them. Hamamatsu Photonics K.K. is producing these sensors. Before launching the multi-year production of these sensors, the electrical characteristics of the latest prototype sensors need to be tested using the ARRAY probe station to determine how well they will perform over the ten-year run in the HL-LHC, which will expose the sensors to high levels of radiation. The ARRAY probe station is a probe card-based system which connects all the pads on the sensors with pogo pins in order to test the current and capacitance characteristics over the range of bias voltage concerned [3].

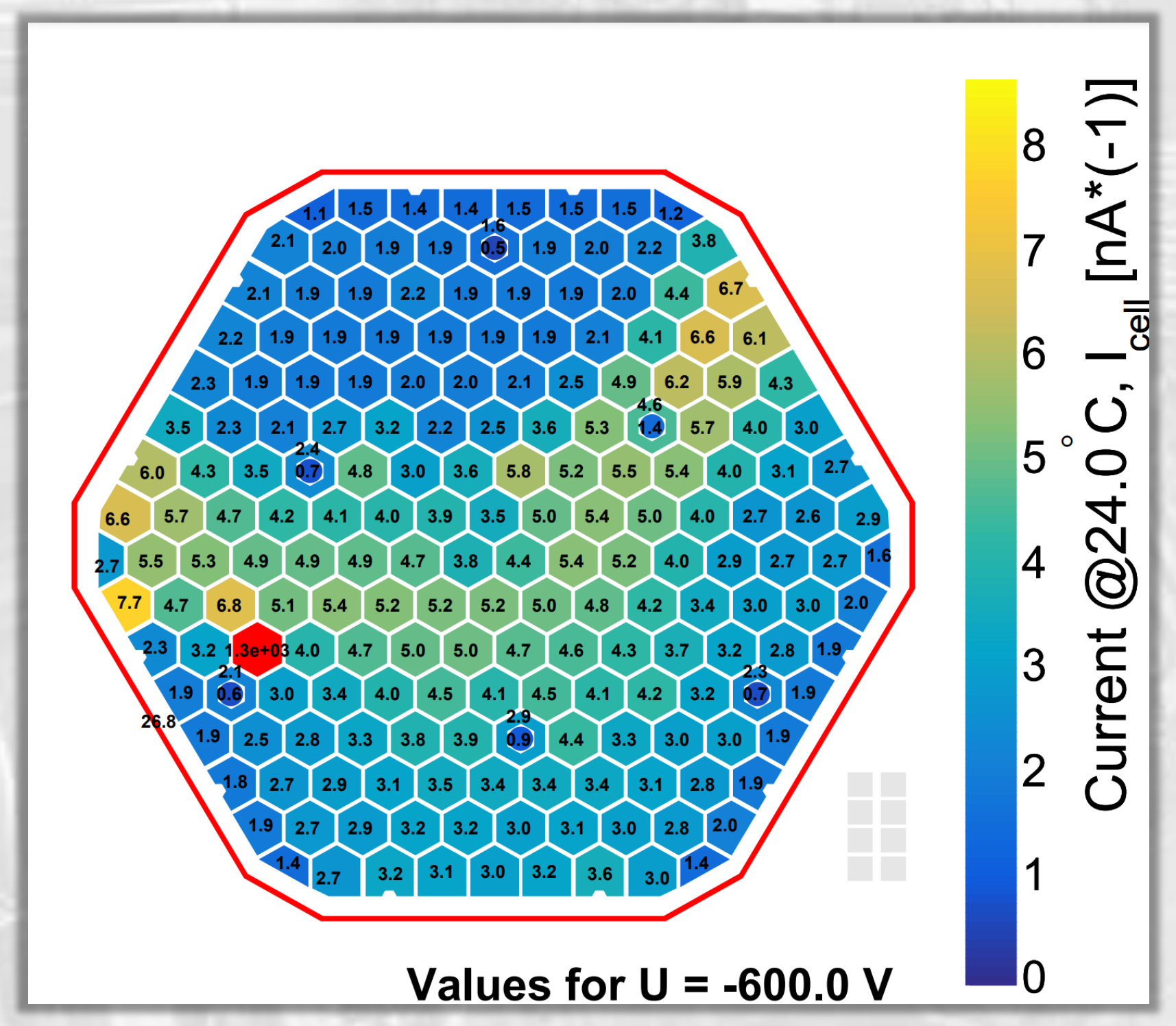

Fig. 2. Hexplot of a low-density sensor from the N_4792 series tested in this research depicting the current read-out on a per-cell basis at a reverse bias of 600 V generated from the automatic analysis after a loop test on the ARRAY probe station.

Purpose

The prototype sensors are diced while attached to a dicing frame and tested for quality control before and after the sensors are removed from their dicing frame. Around half of the previously passing sensors fail the sensor requirements after these sensors were removed from their dicing frame. All the failing sensors fail on a single requirement: I(800) < 2.5x I(600), meaning that the total current at a reversed bias voltage of 800 volts is less than 2.5 times the total current at 600 volts, which exists to ensure that the sensors will be able to withstand the bias voltage and the end of their operation. The sensors should exhibit diode characteristics, modeled by the Shockley diode equation, which is provided below; however, this behavior is not present in failing sensors.

$$I_D = I_s\left(e^{\frac{qV_D}{kT}} - 1\right)$$

Identifying the cause for this failure will help determine if the failure is a result of a bad sensor or, if the cause of the failure is a result of some outside factor, guide our research on eliminating the outside interference.

Methods

Our research team theorized that the failure of these sensors is a result of charge build-up on the sensor during handling and testing. To investigate the cause of the failure our research team investigated the effect of the duration of tests, the humidity of the environment during tests, and the presence of a deionizing blower during tests on the total current with increasing bias voltage. Our research team took a small sample of failing sensors in the N4792 series (200 μm thickness) , two failing sensors and a control sensor, to investigate the cause of the breakdown.

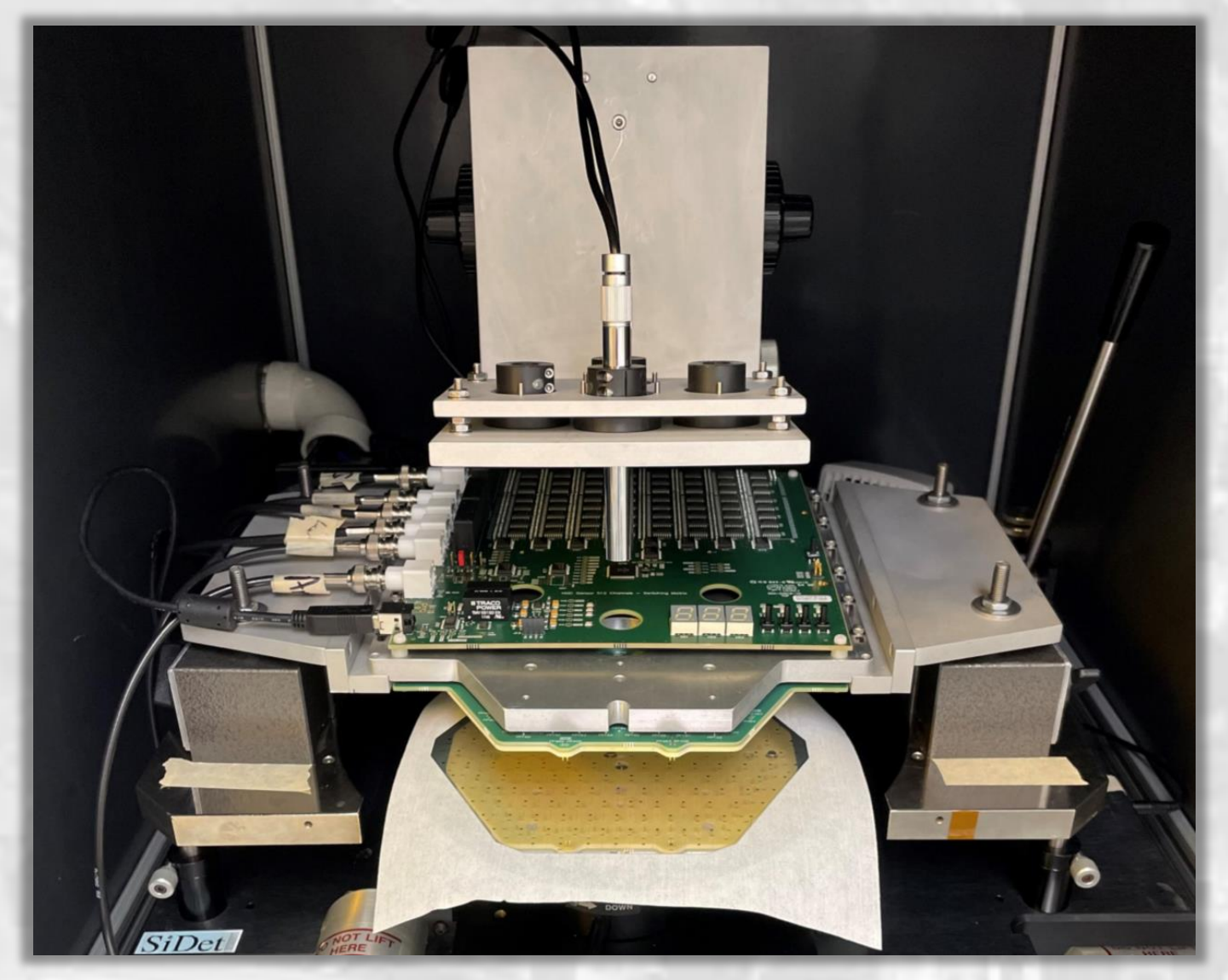

Fig. 3. The ARRAY sensor probe card contacts the sensor's cells. The ARRAY probe station applies a bias voltage through the front side of the sensor which is transmitted internally to the back side of the sensor. The current is then measured through the pins on the probe card [3].

Results

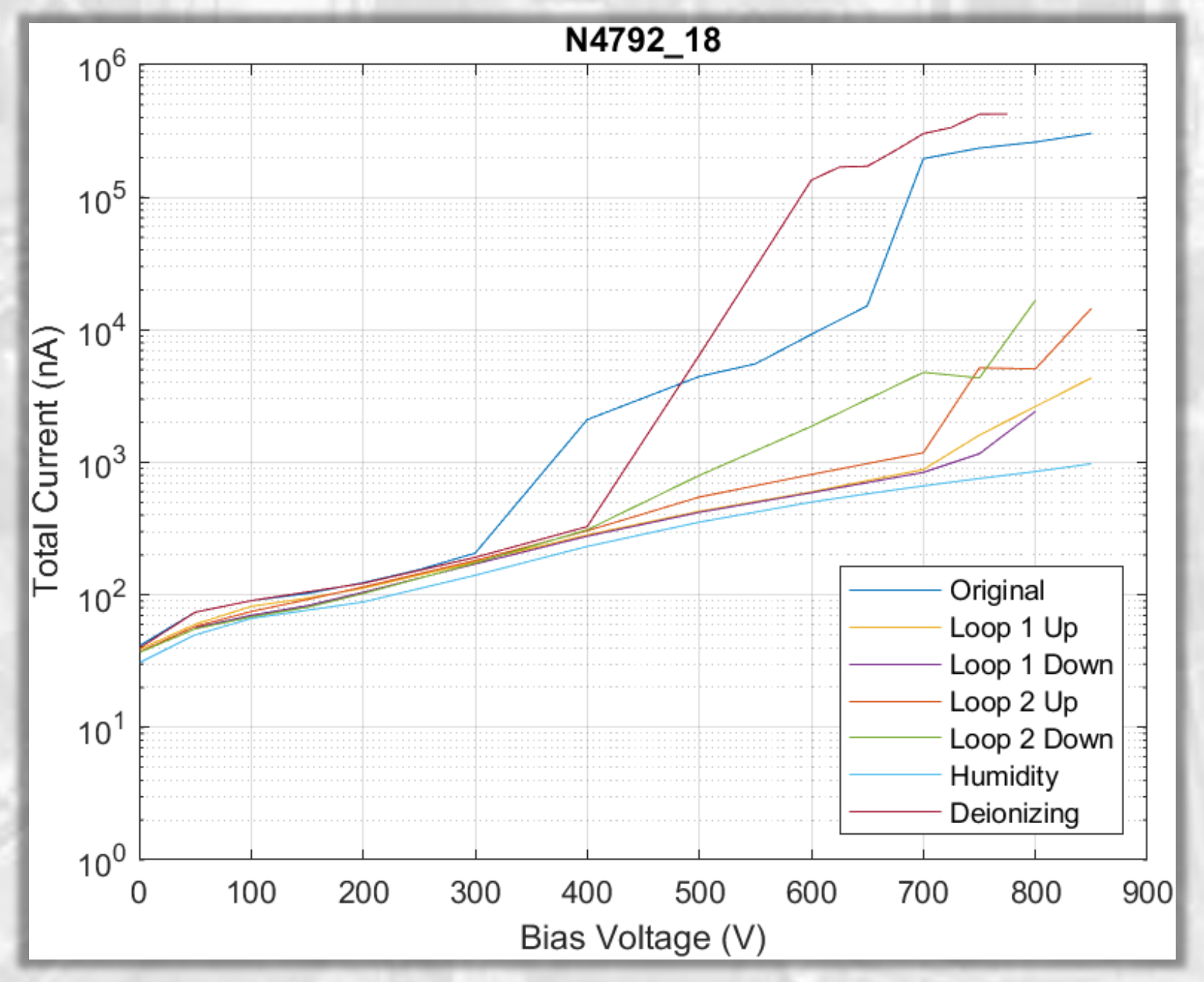

Fig. 4. Results of sensor N4792_18: The total current increases over successive loops at high voltages, and still fails the requirement. The sensor passes the I(800) < 2.5x I(600) requirement at low humidity. The sensor hits compliance at 775 V during the deionizing blower test, completely failing the requirement.

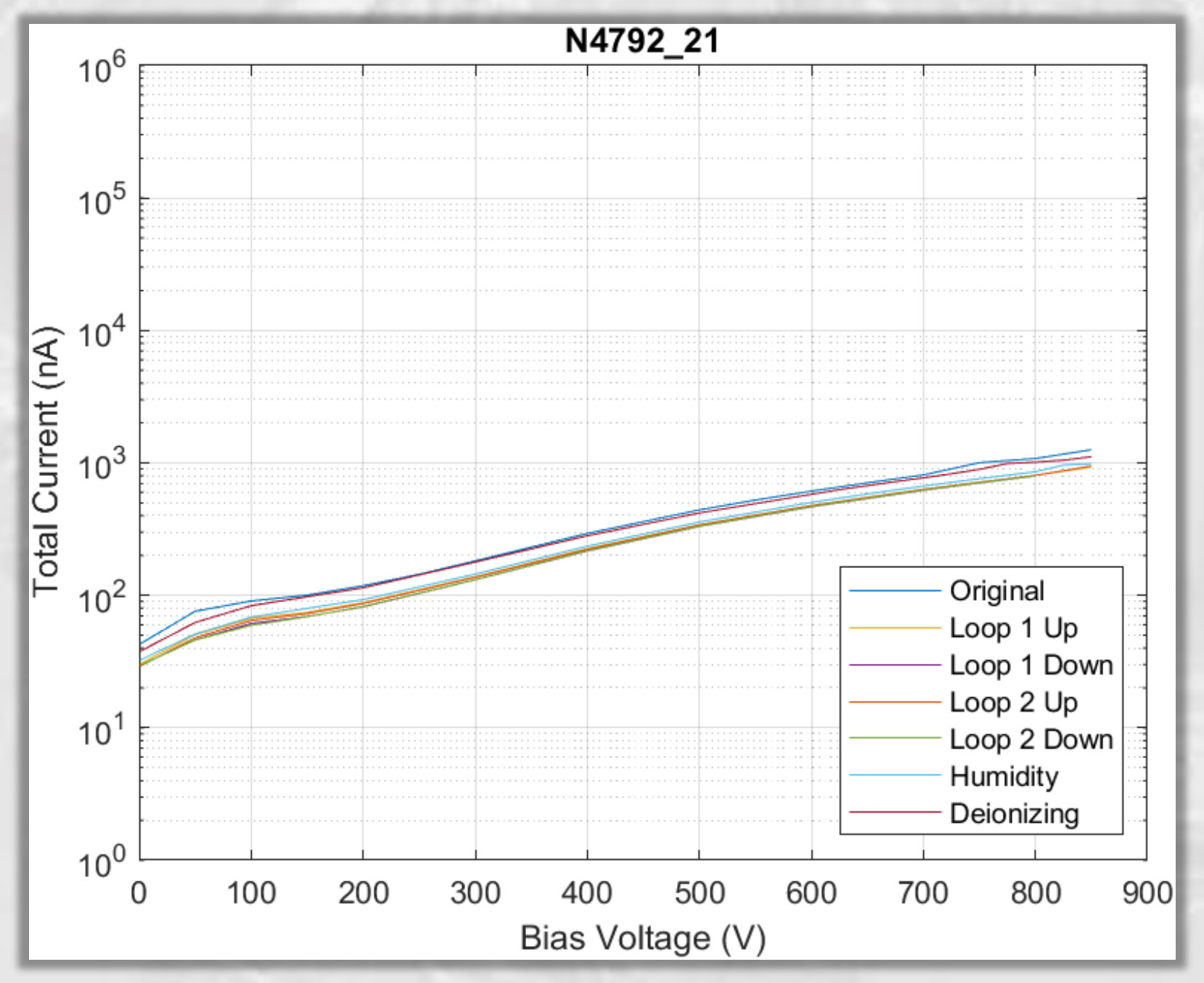

Fig. 5. Results of sensor N4792_21: The control sensor behaves consistently across each test, experiencing only small variation across the different tests. The control sensor meets the I(800) < 2.5x I(600) sensor requirement for each test.

	I(600) to I(800) Ratio			
	Original	**Loop**	**Humidity**	**Deionizing**
N4792_18	× 25.5	× 6.95	✓ 1.70	× N/A
N4792_19	× 3.86	×5.61	✓ 1.88	× 150
N4792_21	✓ 1.77	✓ 1.70	✓ 1.70	✓ 1.75

Discussion

The loop test behavior changes over successive tests indicating that the poor behavior of the sensor is related to the amount of handling of the sensor, which possibly indicates charge buildup on the sensor over successive tests. It is notable that in the time between the original test and the loop test, where the sensor remained untouched, the sensor began to behave closer to the expected diode behavior. This could point to handling as leading to the poor sensor behavior.

Our results indicate that the poor sensor behavior goes away when the humidity of the environment the sensors are tested in is decreased to around 8%. This implies that the cause of the poor sensor behavior lies in the environment in which the sensor is tested and not an inherent flaw with the sensor. As the HGCAL will operate in similarly low humidity environment, there is no reason to reject sensors for their poor performance at higher humidity levels.

The deionizing blower appears to not significantly affect the control sensor; however, it has a significant negative impact on failing sensors. This indicates that the failing sensors behavior is related to their ionization, but not in the way we expect.

Conclusion

Our research team theorized that the cause of the breakdown of the diode characteristic behavior of sensors, causing the failure of the I(800) < 2.5x I(600) requirement, was a result of charge build-up on the sensor during handling and testing. Charge build-up on the sensor does seem to affect the diode behavior. Whether it is the primary cause has not yet been determined. Handling and testing also seem to be related to poor sensor behavior.

The corrected behavior at low humidity indicates that future sensor tests should take place in a low humidity environment to differentiate poor sensors from environmental effects.

In the future, studying the result of combining the different tests and the effect of the testing procedure on other sensor requirements will allow for further refining Sensor Quality Control procedure and a better understanding of the underlying cause for the poor sensor behavior.

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References

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