Analysis of humidity sensitivity of silicon strip sensors for ATLAS upgrade tracker, pre- and post-irradiation

J. Fernández-Tejero[a,b,*], A. Affolder[c], E. Bach[d], M.J. Basso[e], A. Bhardwaj[e], V. Cindro[f], A. Dowling[c], V. Fadeyev[c], C. Fleta[d], A. Fournier[a,b], K. Hara[g], C. Jessiman[h], J. Keller[h], D. Kisliuk[e], C. Klein[h], T. Koffas[h], J. Kroll[i], V. Latonova[i,j], K. Mahtani[e], I. Mandic[f], F. Martinez-Mckinney[c], M. Mikestikova[i], K. Nakamura[k], R.S. Orr[e], L. Poley[a,b], E. Staats[h], B. Stelzer[a,b], J. Suzuki[g], M. Ullán[d], Y. Unno[k], J. Yarwick[c], I. Zatocilova[i]

[a] *Department of Physics, Simon Fraser University, 8888 University Drive, Burnaby, B.C. V5A 1S6, Canada*
[b] *TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada*
[c] *Santa Cruz Institute for Particle Physics (SCIPP), University of California, Santa Cruz, CA 95064, USA*
[d] *Centro Nacional de Microelectrónica (IMB-CNM, CSIC), Campus UAB-Bellaterra, 08193 Barcelona, Spain*
[e] *Department of Physics, University of Toronto, 60 Saint George St., Toronto, Ontario M5S1A7, Canada*
[f] *Experimental Particle Physics Department, Jožef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*
[g] *Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan*
[h] *Physics Department, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario, K1S 5B6, Canada*
[i] *Academy of Sciences of the Czech Republic, Institute of Physics, Na Slovance 2, 18221 Prague 8, Czech Republic*
[j] *Faculty of Mathematics and Physics, Charles University, V Holesovickach 2, Prague, CZ18000, Czech Republic*
[k] *Institute of Particle and Nuclear Study, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

Abstract

During the prototyping phase of the new ATLAS ITk large area strip sensors, a degradation of the device breakdown voltage at high humidity was observed. Although the degradation was temporary, showing a fast recovery in dry conditions, the study of the influence of humidity on the sensor performance was critical to establish counter-measures and handling protocols during production testing in order to ensure the proper performance of the upgraded detector.

*Corresponding author
Email address: `Xavi.Fdez@cern.ch` (J. Fernández-Tejero)

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The work presented here has the objective to study for the first time the breakdown voltage deterioration in presence of ambient humidity of ATLAS ITk production layout sensors with different surface properties, before and after proton, neutron and gamma irradiations. The sensors were also exposed for several days to high humidity with the aim to recreate and evaluate the influence of the detector integration environment expected during the Large Hadron Collider (LHC) Long Shutdown 3 (LS3) in 2025, where the sensors will be exposed to ambient humidity for prolonged times.
Keywords: Humidity Sensitivity, Large Area Silicon Sensors, Radiation-hard detectors, HL-LHC

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1. Framework

The ATLAS collaboration is working on a major upgrade of the current Semiconductor Tracker (SCT) [1], that will be replaced by the new Inner-Tracker (ITk) [2], able to withstand the extreme operational conditions expected for the forthcoming High-Luminosity Large Hadron Collider (HL-LHC) upgrade [3]. During the prototyping phase of the new large area silicon strip sensors, the community observed a degradation of the breakdown voltage when the devices with final technology options were exposed to high humidity, recovering the electrical performance prior to the exposure after a short period in dry conditions [4, 5]. These findings helped to understand the humidity sensitivity of the new sensors, defining the optimal working conditions and handling recommendations during production testing.

In 2020, the ATLAS strip sensor community started the pre-production phase [6], receiving the first sensors fabricated by Hamamatsu Photonics K.K. (HPK) using the final layout design. The work presented here is focused on the

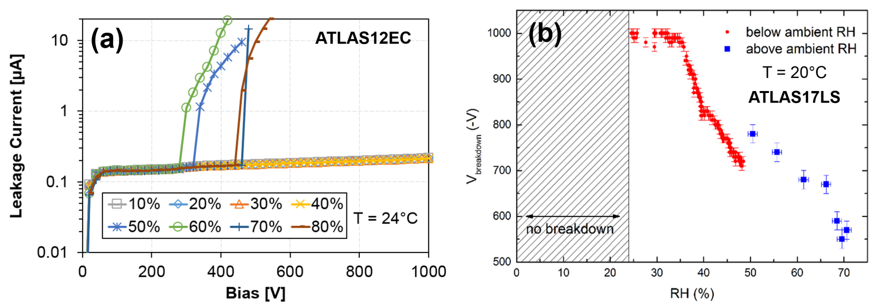

Figure 1: (a) Reverse leakage current of an ATLAS12EC large area prototype at different humidity conditions, and (b) breakdown voltage dependence with humidity of an ATLAS17LS prototype. Figures adapted from [5].

analysis of the humidity sensitivity of production layout sensors with different surface properties, before and after irradiation, providing new results on their influence on the humidity sensitivity.

2. Humidity sensitivity of large area silicon strip sensors

2.1. Breakdown voltage dependence

During the prototyping phase, participating institutes reported a degradation of the breakdown voltage when the leakage current of End-cap ATLAS12EC and Barrel ATLAS17LS prototype sensors, fabricated by HPK and Infineon Technologies AG, was measured at ambient humidity conditions (Figure 1). The sensor community started an extensive investigation campaign, accumulating more evidences of the inverse relation between relative humidity and sensor breakdown voltage.

Several palliative treatments were attempted, observing a fast recovery of the sensor performance in dry storage, and after baking or cleaning treatments. Although the recovery of the sensor performance was demonstrated, the reduction of breakdown voltage when the sensors were biased at high humidity was not mitigated. Thermal images of sensors in breakdown behaviour at high humidity revealed hotspots in the sensor edge, suggesting that the separation between guard/edge ring structures in combination with the passivation thickness could

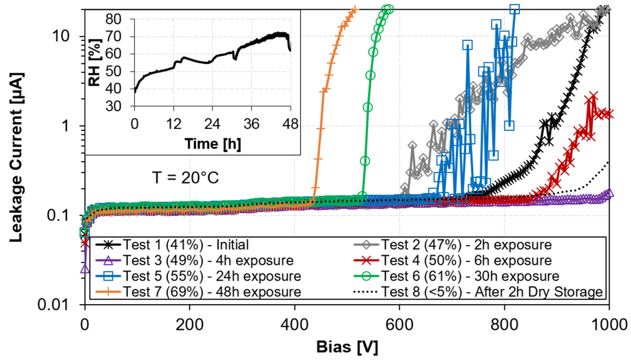

Figure 2: Breakdown voltage degradation of a large area sensor exposed to high humidity (inner plot) for 48h. Last measurement (Test 8) performed at low humidity. Figure adapted from [5].

be responsible for the humidity sensitivity. The hypothesis proposed was that, in presence of high humidity, the surface of the sensor accumulates positive hydrogen ions, inducing the appearance of electron/hole inversion/accumulation layers between the n+ and p+ implants of the guard ring and dicing edge, respectively, causing the premature breakdown when the device is biased at high humidity.

2.2. High humidity exposure

With the objective to evaluate the risks of permanent degradation of sensors exposed to high humidity, biased and unbiased prototype sensors were exposed to high humidity for several days. The experiment demonstrated that biased sensors can develop permanent damages when exposed to high humidity for long periods of time, but unbiased sensors show only a temporary degradation, recovering the performance prior to the exposure after hours/days in dry conditions (Figure 2).

2.3. Influence of irradiation

While at the prototyping phase the influence of the irradiation on the humidity sensitivity was unclear, a first study of an ATLAS12EC prototype sensor

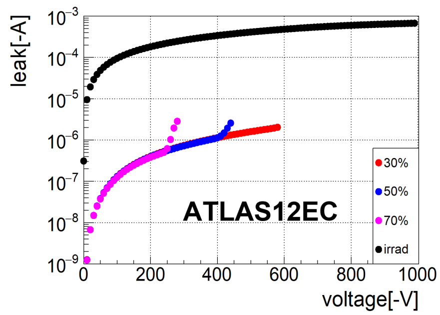

Figure 3: Prototype ATLAS12EC irradiated with protons up to 5x10^{14} n_{eq}/cm^2 shows no breakdown voltage below 1 kV at high humidity (>30%) and low temperature (-20C).

irradiated with protons up to 5x10^{14} n_{eq}/cm^2 showed no breakdown below 1 kV at high humidity (>30%) and low temperature (-20C) (Figure 3). These results suggested a progressive mitigation of the humidity sensitivity for the high radiation environment expected for the HL-LHC.

3. Devices under test

With the aim to investigate the humidity sensitivity of production layout ATLAS ITk silicon strip sensors, several sensors were selected during the preproduction phase. Additionally, HPK fabricated a special batch with different surface properties. Some of these sensors were irradiated with protons to different low fluences, or with neutrons+gammas to fluences expected at the end of the HL-LHC lifetime.

All the sensors used in this work are ATLAS full-size Barrel Short-Strip (SS) sensors with final layout designs for HL-LHC, also called ATLAS18SS [6]. The sensors are n^+-on-p type, ∼10x10 cm^2 size and 320 μm thickness. The active area is divided in 4 segments containing 1,282 parallel strips per segment with a strip length of 24,155 μm and a strip pitch of 75.5 μm.

3.1. Non irradiated sensors

In total, sensors with 6 different surface characteristics were used for the study before irradiation, coming from the special batch fabricated by HPK.

	Special Treatment	Additional Treatment	Special Masking	Thicker Passivation	p-spray Addition (cm^{-2})	Proton irrad (n_{eq}/cm^2)	Neutron+Gamma irrad (n_{eq}/cm^2 + Mrad)
Type A	X					1x10^{13}, 5x10^{13}, 1x10^{14}	
Type A'	X	X					
Type B	X		X				
Type C	X			X			1.6x10^{15} + 66
Type D high	X				8x10^{11} (target value)		1.6x10^{15} + 66
Type D low	X				4x10^{11} (target value)		1.6x10^{15} + 66

Table 1: Sensor types used to study the humidity sensitivity before and after irradiation.

Table 1 shows the different process modifications applied, in comparison with the default production technology.

3.2. Sensors irradiated with protons, neutrons and gammas

With the objective to study the evolution of the humidity sensitivity in working conditions, several production-like sensors (Type A) were irradiated to 3 different low proton fluences. Additionally, sensors with different passivation thickness (Type C) and p-spray addition (Type D high/low) were irradiated with neutrons and gammas up to fluences expected at the end of the HL-LHC lifetime. Table 1 also shows the different irradiations and fluences applied to each sensor type.

4. Results

This section shows and discusses the IV characteristics of the sensors measured at different relative humidity, before and after irradiation. Additionally, all the sensors were exposed to high humidity unbiased for several days to study its influence.

4.1. Humidity sensitivity pre-irradiation

For the study before irradiation, the leakage current was measured up to 1 kV at room temperature (20 C). For each sensor, a first IV was performed at low humidity (<10%), followed by a second IV at cleanroom humidity (35-45%), a third IV at high humidity (50-60%) and again several consecutive measurements

	Breakdown at Low RH (<10%)	Breakdown at Cleanroom RH (35-45%)	Breakdown at High RH (50-60%)	IVs at low RH needed to recover (training)	Breakdown after 40h exposure (30-50%)
Type A (production)	>1 kV	650 V	450 V	2-3 IVs	>1 kV
Type A'	>1 kV	640 V	380 V (Worst)	3-4 IVs	>1 kV
Type B	>1 kV	570 V (Worst)	470 V	>7 IVs (Worst)	>1 kV
Type C	>1 kV	580 V	520 V	1 IV (Best)	>1 kV
Type D high	>1 kV	640 V	590 V	2-3 IVs	>1 kV
Type D low	>1 kV	760 V (Best)	680 V (Best)	2 IVs	>1 kV

Table 2: Breakdown voltage at different RH, training effect and influence of 40h exposure to high humidity for all sensor types before irradiation.

at low humidity to study the recovery of the sensors when tested in dry conditions, also called the training effect. Each measurement took around 10 minutes and the time between the measurements was less than 20 minutes. Finally, in order to study the influence of the exposure to high humidity, all the sensors were exposed unbiased to 30-50% humidity for 40 hours, and measured again at low humidity.

Figure 4 shows the IV curves obtained for each sensor, and for each step detailed above. To facilitate the comparison, Table 2 summarizes the measured breakdown voltage for all the cases and training needed to recover the sensors at low humidity.

Initially, at low humidity, all sensor types show breakdown voltages higher than 1 kV, and low and stable leakage current. For reference, the ATLAS specifications establish that sensors measured at low humidity with breakdown voltage above 500 V and leakage current at 500 V below 0.1 μA/cm^2 are considered good sensors. Then, all the sensor types show IV characteristics at low humidity fulfilling the requirements imposed by ATLAS.

At cleanroom humidity (35-45%), all the sensor types show a clear deterioration of the breakdown voltage. In particular, the sensor with special masking (Figure 4(c)) shows the lowest breakdown voltage, 570 V in cleanroom conditions. On the other hand, the sensor with a low dose of p-spray (Figure 4(f)) shows the best results with a breakdown voltage of 760 V. However, all the sensor types still show breakdown voltages above 500 V, fulfilling the ATLAS

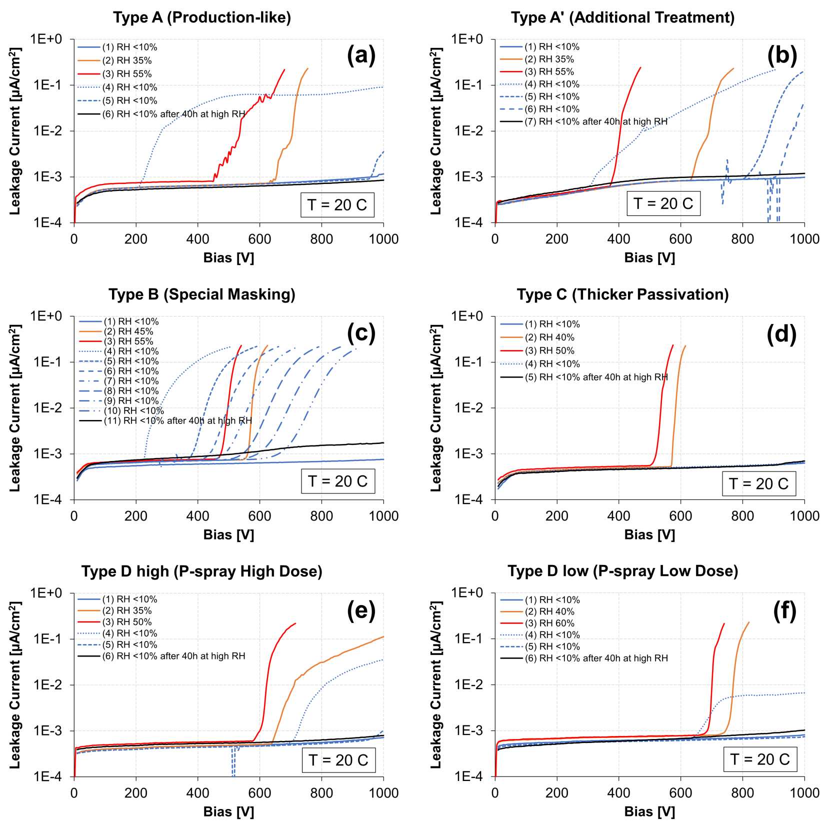

Figure 4: IV curves at different RH and after 40h exposure to high humidity for all sensor types before irradiation: (a) Type A, (b) Type A', (c) Type B, (d) Type C, (e) Type D high and (f) Type D low.

specifications.

As expected, at high humidity (50-60%) the deterioration of the breakdown voltage is even higher. The sensor with additional treatment (Figure 4(b)) has the lowest breakdown at 380 V, and again the sensor with a low dose of p-spray (Figure 4(f)) shows the best results, keeping the breakdown voltage at 680 V even at high humidity. At these humidity conditions, only the sensors with thicker passivation (Type C) or p-spray addition (Type D low and high) still fulfill the ATLAS specifications, showing breakdown voltages above 500 V.

All the sensors were measured again at low humidity several consecutive times (training), showing improved breakdown voltages after each new measurement. In general terms, all the sensors showed a fast recovery, needing only 1-3 consecutive IVs to show again a breakdown voltage above 900 V. However, the sensor with special masking (Figure 4(c)) was not recovered, even after 7 IVs.

Finally, the sensors were exposed unbiased to high humidity (30-50%) during 40 hours, and measured again at low humidity (<10%). Similarly to the results obtained with prototyping sensors (Figure 2), the breakdown voltage was clearly deteriorated when the sensor was biased at high humidity but, even with different surface characteristics, the breakdown voltage was not influenced by the exposure to high humidity if the devices were not biased.

As suggested in [5], positive charges can be accumulated in the passivation layers in presence of humidity due to the fact that electrons can move easily in the oxides under the applied potential. Then, the presence of these positive charges in the passivation-air interface could lead to the formation of a conducting electron inversion layer in the silicon-oxide interface, extending the guard ring potential towards the sensor edge and reducing the breakdown voltage of the device. This hypothesis seems to be reinforced by the good results obtained with sensors with thicker passivation or p-spray addition. At a given humidity condition, thicker passivation layers can reduce the influence of the positive charges in the creation of conducting electron inversion layers, requiring higher humidity to deteriorate the breakdown voltage. Similarly, the addition of p-spray to the silicon bulk surface can help to minimize the accumulation of positive charges in presence of humidity, requiring higher humidity to deteriorate the breakdown voltage. Although none of these solutions seem to completely mitigate the humidity sensitivity, the results indicate that the breakdown voltage is less influenced by humidity when the sensors have thicker passivation layers or p-spray treatments.

4.2. Humidity sensitivity post-irradiation

For the study of the humidity sensitivity after irradiation, the leakage current was measured at -20 C up to 700 V for the production-like (Type A) sensors irradiated to low fluences (1x10^{13} n_{eq}/cm^2, 5x10^{13} n_{eq}/cm^2 and 1x10^{14} n_{eq}/cm^2), and up to 500 V for the sensors with thicker passivation (Type C) and p-spray addition (Type D high/low) irradiated to high fluences with neutrons (1.6x10^{15} n_{eq}/cm^2) and gammas (66 Mrad). The leakage current of the sensors irradiated to low fluences was initially measured at low humidity[1] (<10%), followed by a measurement at 35%, and again at low humidity to study the recovery. Since the low temperature and high humidity conditions, in presence of warm air inside the probe station chamber, induce the appearance of condensation and ice on the sensor surface and edges, the measurement of sensors irradiated to high fluences was only performed at low temperature and low humidity. Finally, all the sensors were exposed 90 hours to 40-60% humidity and measured again at low humidity to study the influence of the exposure. Figure 5 shows the IV curves obtained for all the irradiated sensors and for all the steps detailed above.

Production-like sensors irradiated to low fluences (Figure 5(a), (b) and (c)) show no breakdown below 700 V at low humidity. However, at high humidity (and in presence of condensation/ice) the breakdown voltage was reduced to 250 V, 300 V and 350 V for the sensors irradiated to 1x10^{13} n_{eq}/cm^2, 5x10^{13} n_{eq}/cm^2 and 1x10^{14} n_{eq}/cm^2, respectively. However, the breakdown voltage was

[1] Relative humidity is measured in the air apart several centimetres away from the cold sensor

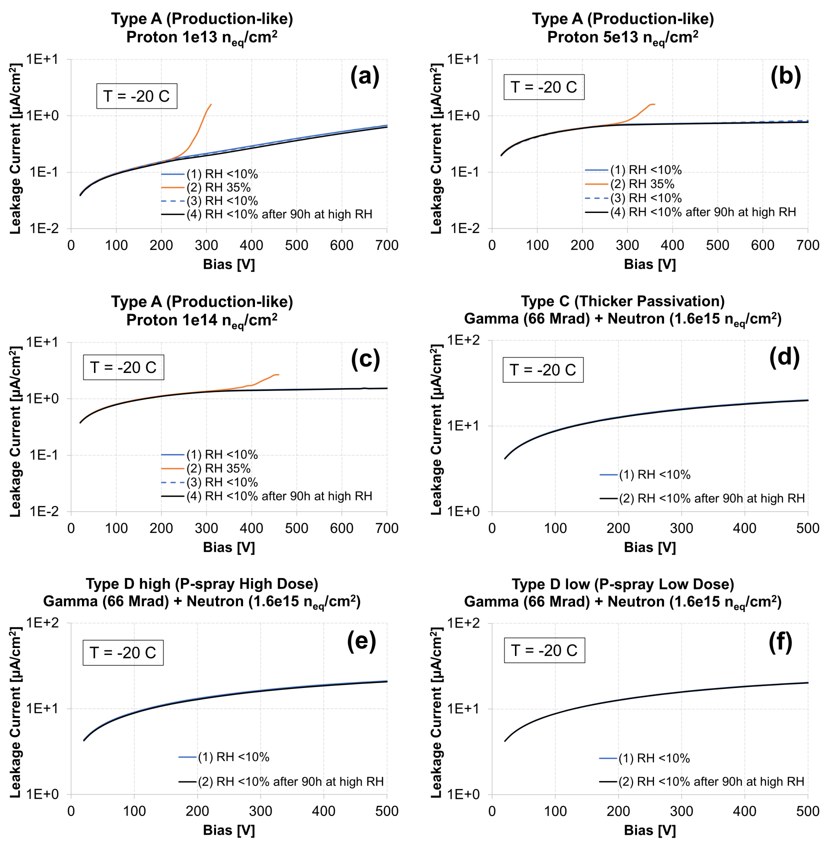

Figure 5: IV curves at different RH and after 90h exposure to high humidity for sensors irradiated with protons and neutrons+gammas: (a) Type A (protons 1x10^{13} n_{eq}/cm^2), (b) Type A (protons 5x10^{13} n_{eq}/cm^2), (c) Type A (protons 1x10^{14} n_{eq}/cm^2), (d) Type C (neutrons 1.6x10^{15} n_{eq}/cm^2 + gammas 66 Mrad), (e) Type D high (neutrons 1.6x10^{15} n_{eq}/cm^2 + gammas 66 Mrad) and (f) Type D low (neutrons 1.6x10^{15} n_{eq}/cm^2 + gammas 66 Mrad).

rapidly recovered at low humidity for the three fluences, showing no breakdown below 700 V for the first IV performed after the measurement at high humidity. Similarly to the observed for non-irradiated sensors, 90 hours of exposure to high humidity had no effect on the IV characteristics, showing identical curves and no breakdown below 700 V at low humidity, before and after exposure. Although the presence of ice on the surface of the sensor at low temperature and high humidity could influence the breakdown mechanisms, the results suggest that the sensitivity to humidity variations is lower for sensors irradiated to higher fluences.

Sensors with thicker passivation and p-spray addition irradiated to high fluences show no breakdown below 500 V at low humidity (Figure 5(d), (e) and (f)), also showing identical leakage current for the different surface properties. As observed for lower fluences and non-irradiated sensors, the exposure of 90 hours to high humidity had no effect on the breakdown voltage at low humidity, showing identical IV curves before and after the exposure.

5. Conclusion

ATLAS ITk strip sensors with different surface properties have been tested at different humidity conditions, showing different levels of breakdown voltage deterioration. Although none of them mitigated completely the humidity sensitivity, thicker passivation layers and p-spray treatments helped to improve considerably the performance of the sensor, showing higher breakdown voltages at high humidity. These results seem to confirm the hypothesis made in previous studies, suggesting that thicker passivation layers can reduce the influence of the positive charges, accumulated on the surface in presence of humidity, in the creation of conducting electron/hole inversion/accumulation layers in the silicon-oxide interface between the guard ring and the edge, that can reduce the breakdown voltage of the device. Similarly, the presence of p-spray can reduce the accumulation of positive charges on the surface, also helping to avoid the appearance of conducting channels.

Additionally, a subset of these sensors were irradiated with protons and neutrons+gammas, showing less sensitivity to humidity variations for higher fluences. These results suggest that in working conditions the humidity sensitivity will be reduced by the radiation effects, and mitigated eventually. Irradiated sensors with different surface properties showed very similar leakage current values, confirming that thicker passivation layers or p-spray addition have a minimum impact on the device leakage current.

Finally, all the sensors (pre- and post-irradiation) were exposed unbiased to high humidity several days, showing a fast and complete recovery of the breakdown voltage when measured again in dry conditions. These results confirm that there is little risk of permanent deterioration when unbiased sensors are exposed to ambient humidity, as expected during module/petal assembly and detector integration for the HL-LHC upgrade.

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