BROWN

Environmental conditions stress tests on Low Gain Avalanche Diodes

Gaetano Barone[a], Diallo Boye[b], W Chen[b], Gabriele D'Amen[b], Spencer Ellis[a], Hijas Farook[b,c] Gabriele Giacomini[b], Spandan Mondal[a], Jennifer Roloff[b], Enrico Rossi[b], Trevor Russell[a], Alessandro Tricoli[b]

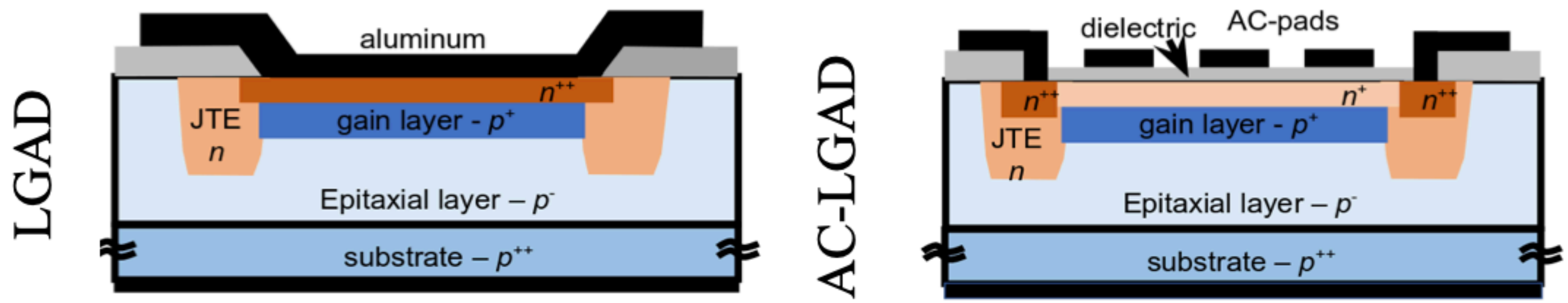
[a] *Brown University*

[b] *Brookhaven National Laboratory*

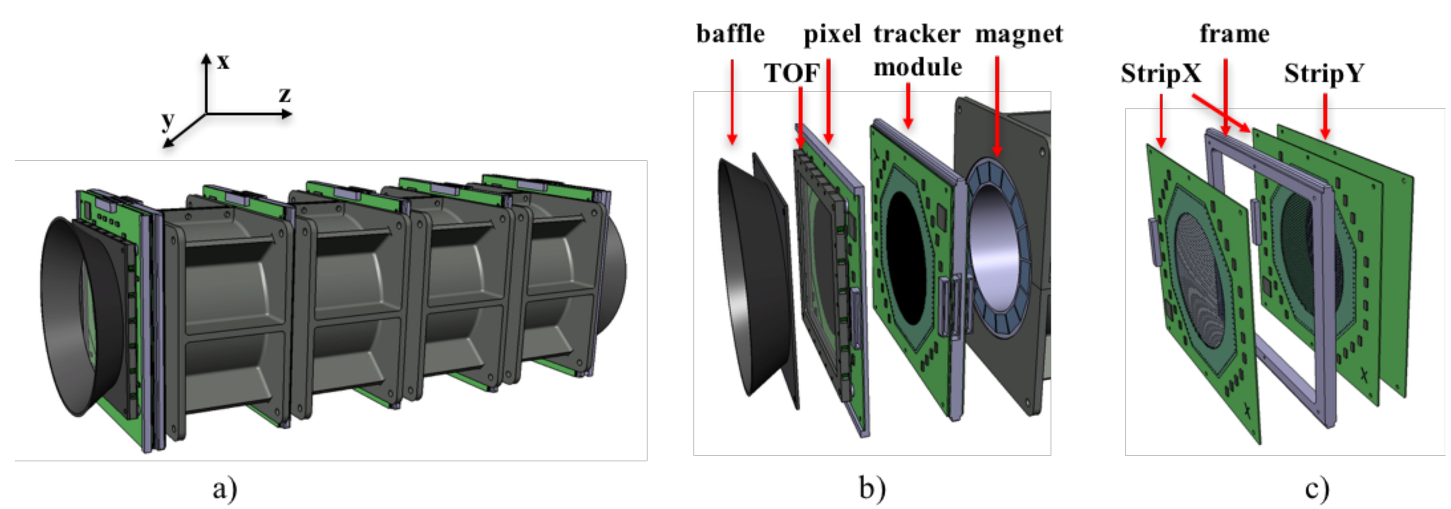
[c] *University of New Mexico*

Introduction

- Low Gain Avalanche Diodes (LGADs) and AC-coupled Low Gain Avalanche Diodes (AC-LGADs):



- O(30) ps timing performance and 4D extension with O(10) μm spatial resolution in RSD variant
- Considered for several applications in HEP: Electron-Ion Collider, LHCb Velo Upgrade, ATLAS & CMS High Granularity Timing Detector, Pioneer, …
- Application to space-based experiments starting to be investigated [1]
  - Low power operational needs and their radiation hardness make them suitable devices for providing pico-second-level timing for satellite-based spectroscopy
  - Ex: time-of-flight detector for Penetrating Particle Analyzer (baseline SiPM) [2]

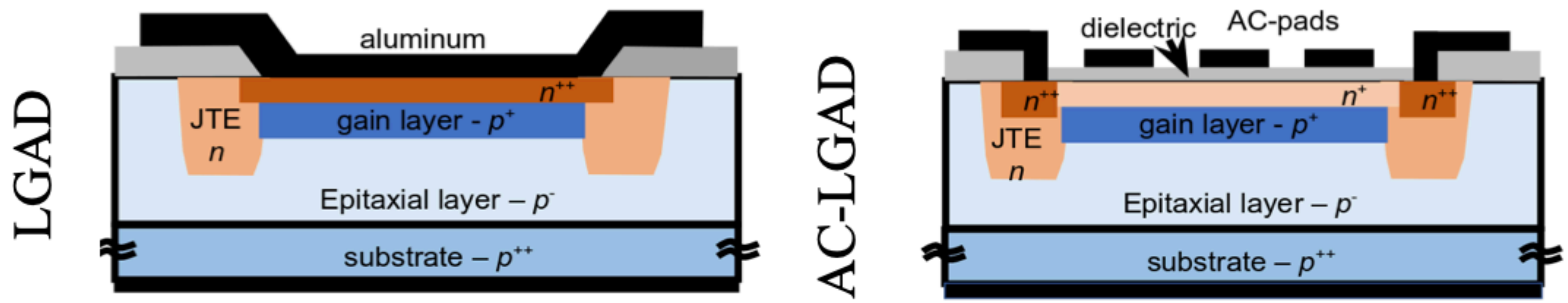


[1] **Characterisation and Stress tests of DC and AC LGAD sensors,** *P. Azzarello, G. Barone, D. Boye, W. Chen, G. D'Amen, J. Roloff , G. Giacomini , A. Tricoli, X. Wu, P.* Xi, IEEE Nuclear Science Symposium and Medical Imaging Conference (2022).

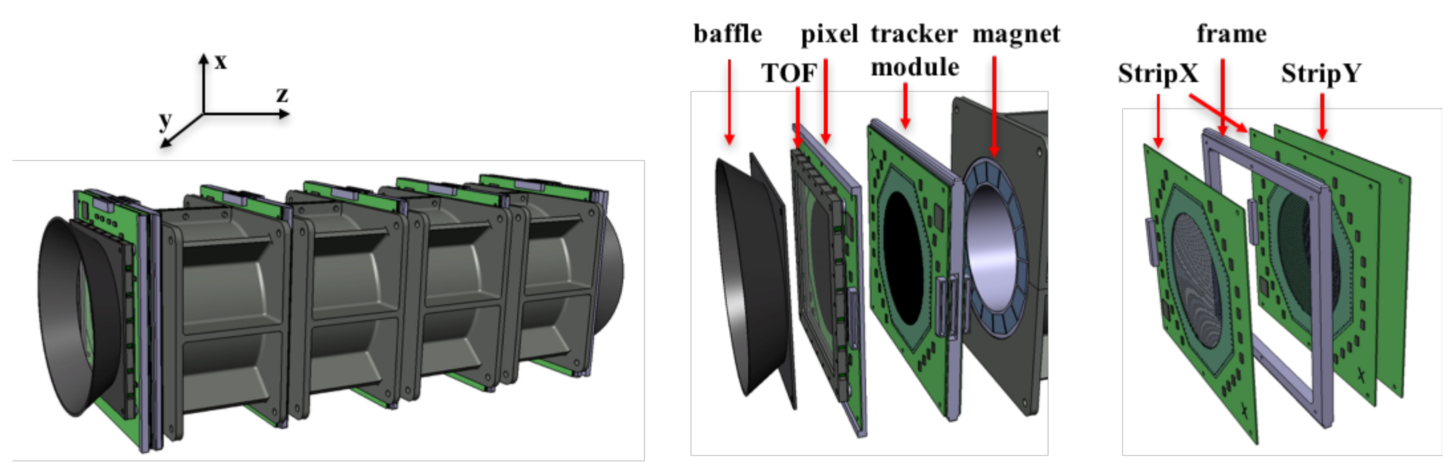
[2] **Penetrating Particle ANalyzer (PAN)** X.Wu et al., Adv. Space Res. 63, 8, 2672-2682 (2019) https://doi.org/10.1016/j.asr.2019.01.012

Introduction

- Low Gain Avalanche Diodes (LGADs) and AC-coupled Low Gain Avalanche Diodes (AC-LGADs):



  - O(30) ps timing performance and 4D extension with O(10) μm spatial resolution in RSD variant.
  - Considered for several applications in HEP: Electron-Ion Collider, LHCb Velo Upgrade, ATLAS & CMS High Granularity Timing Detector, Pioneer, …
  - Application to space-based experiments starting to be investigated [1]
  - Sensor fabrication can be specifically targeted
    - Tuning the sensor's size, the gain characteristics, and the depletion layers size.
  - Application-specific design can be targeted: specific needs are reached in terms of material budget, energy consumption, and climate-change resilience.



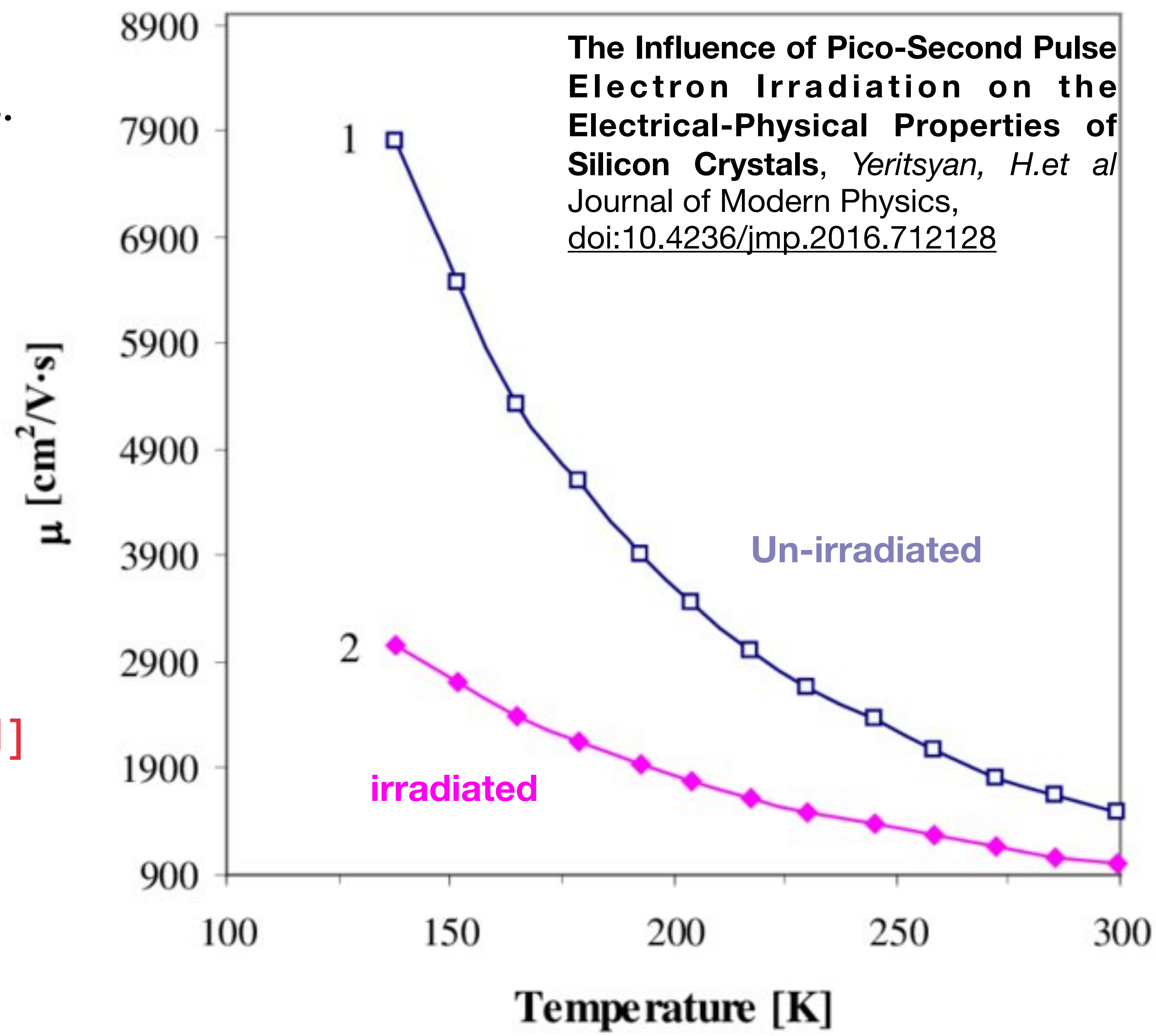
a) b) c)

[1] **Characterisation and Stress tests of DC and AC LGAD sensors,** *P. Azzarello, G. Barone, D. Boye, W. Chen, G. D'Amen, J. Roloff , G. Giacomini , A. Tricoli, X. Wu, P*. Xi, IEEE Nuclear Science Symposium and Medical Imaging Conference (2022).

[2] **Penetrating Particle ANalyzer (PAN)** X.Wu et al., Adv. Space Res. 63, 8, 2672-2682 (2019) https://doi.org/10.1016/j.asr.2019.01.012

Environmental conditions

- A large set of studies actively performed on LGADs & AC-LGADs
  - In cryogenic and laboratory-controlled conditions.
- Space applications require the study of LGAD behavior in a wide range of environmental conditions.
  - Temperature variations -100°C and +100°C
  - Payload limitations: temperature control not ensured
- Charge carrier mobility:
  - Decreases as temperature increases due to phonon scattering.
  - The mobilities decrease as the doping concentration increases due to the scattering from the dopants.
  - ➡ Gain reduction as a function of temperature increase [1]
- Need to ensure good sensor response and electrical characteristics at varying operating conditions.

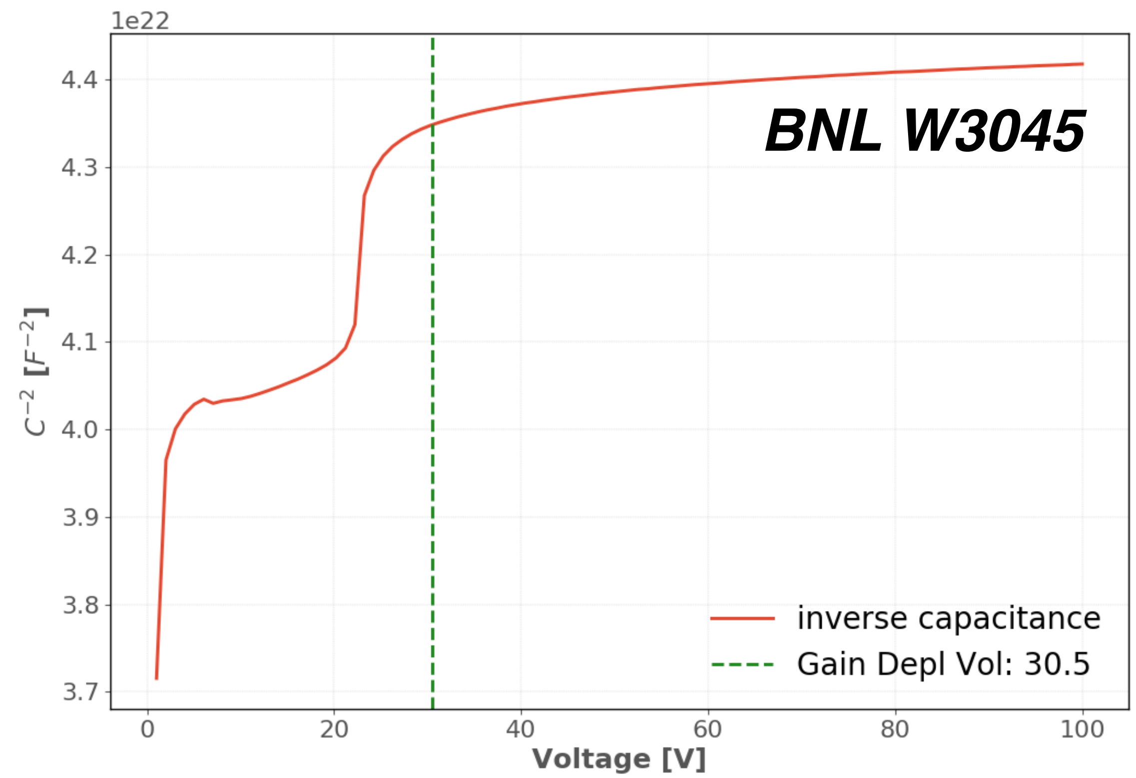


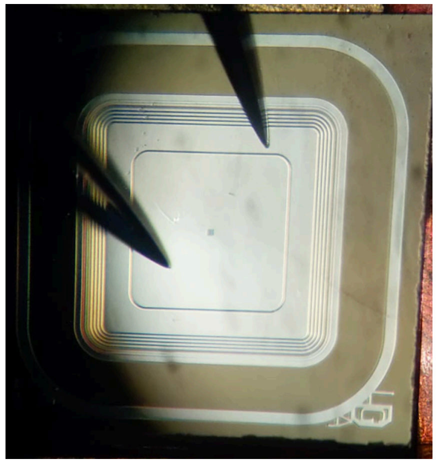
Silicon crystal (n-Si) charge carrier's mobility temperature dependence after electron pico-second beam irradiation (3.5 MeV).

[1] **Gain suppression mechanism observed in Low Gain Avalanche Detectors,** *Esteban Currás, Marcos Fernández*, ***Michael Moll*** **arXiv:2107.10022**

Sensors & setup

- BNL-produced sensors [1] with uniform p-type implants on the silicon surface.
  - 1.3 mm^2 with gain layers doses of 2.8×10^{12} cm^{-2} (50µm) and 2.25×10^{12} cm^{-2} (20µm), respectively, were tested.
  - With and without a passivation layer.
  - For the AC-LGAD sensors: strips with both fixed pitch and variable pitch for an active area of 0.5 cm× 0.5 cm from 50µm thick devices.
- Probe-station setups used in reverse bias:
  - Brookhaven climate chamber with two-needle probe-station readout (compliance at 10^{-6} A/V).
  - RD50's (CERN) characterization laboratory, with a two-needle probe station setup (compliance at 10^{-6} A/V).
- Thermal & humidity control:
  - RD50: ethanol chiller for cooling and heating in the ranges of $T = -30^{\circ}$C to $T = +30^{\circ}$C, dry air for humidity control ~20-30%
  - BNL: ambient chamber $T = -60^{\circ}$C to $T = +180^{\circ}$C with varying humidity.
  - N_2 is supplied to vary relative humidity and to prevent condensation when operating at cryogenic temperatures
- Thermalization and wait time:
  - Thermal imaging camera to ensure thermalization is reached.

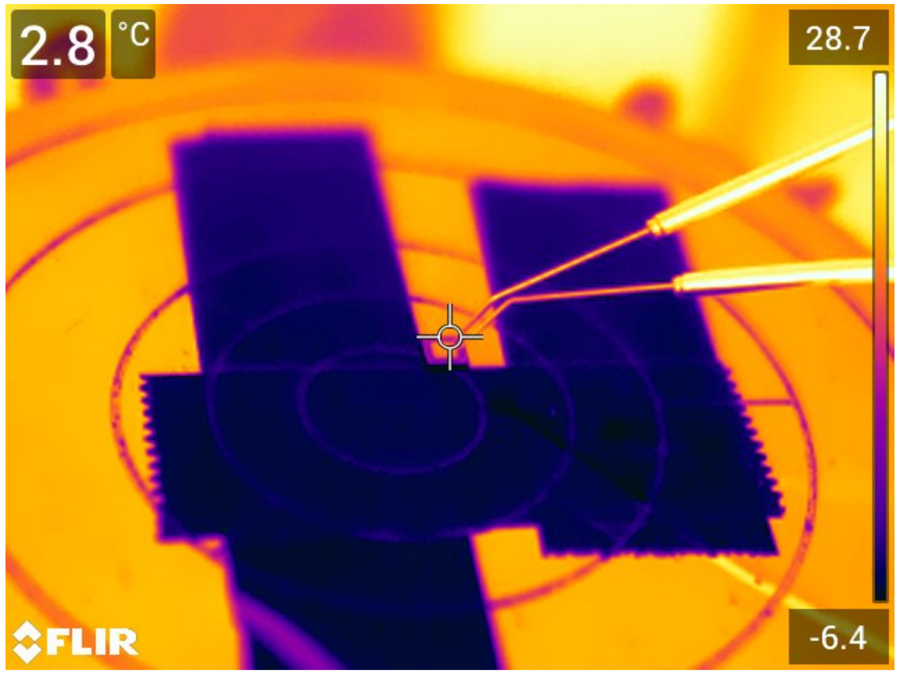


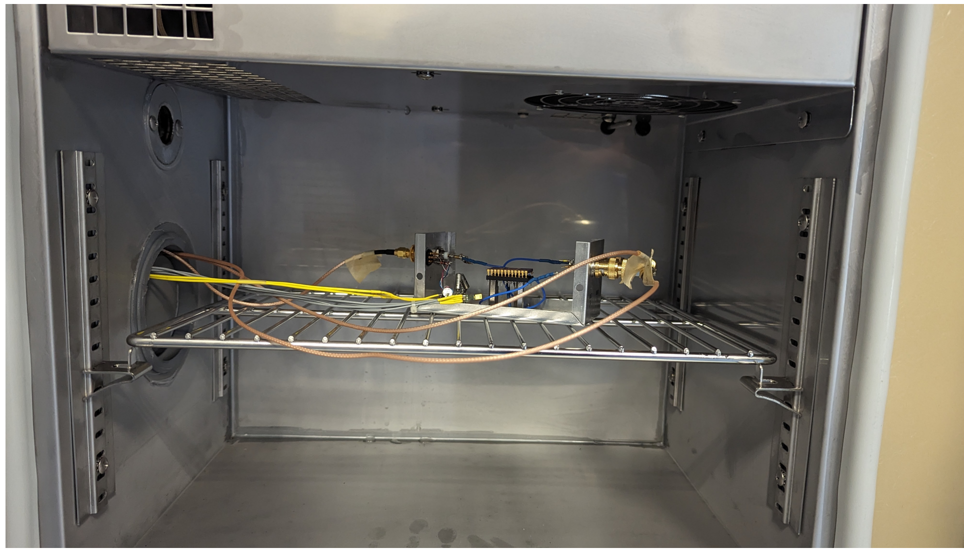


[1] **Development of a technology for the fabrication of Low-Gain Avalanche Diodes at BNL** *G. Giacomini, W. Chen, F. Lanni and A. Tricoli*, Nucl. Instrum. And Meth. In Phys. Res. *https://doi.org/10.1016/j.nima.2019.04.073*.

Sensors & setup

- BNL-produced sensors [1] with uniform p-type implants on the silicon surface.
  - 1.3 mm^2 with gain layers doses of 2.8 × 10^{12} cm^{-2} (50μm) and 2.25 × 10^{12} cm^{-2} (20μm), respectively, were tested.
  - With and without a passivation layer.
  - For the AC-LGAD sensors: strips with both fixed pitch and variable pitch for an active area of 0.5 cm× 0.5 cm from 50μm thick devices.
- Probe-station setups used in reverse bias:
  - Brookhaven climate chamber with two-needle probe-station readout (compliance at 10^{-6} A/V).
  - RD50's (CERN) characterization laboratory, with a two-needle probe station setup (compliance at 10^{-6} A/V).
- Thermal & humidity control:
  - RD50: ethanol chiller for cooling and heating in the ranges of $T = -30^{\circ}$C to $T = +30^{\circ}$C, dry air for humidity control ~20-30%
  - BNL: ambient chamber $T = -60^{\circ}$C to $T = +180^{\circ}$C with varying humidity.
  - N_2 is supplied to vary relative humidity and to prevent condensation when operating at cryogenic temperatures
- Thermalization and wait time:
  - Thermal imaging camera to ensure thermalization is reached.

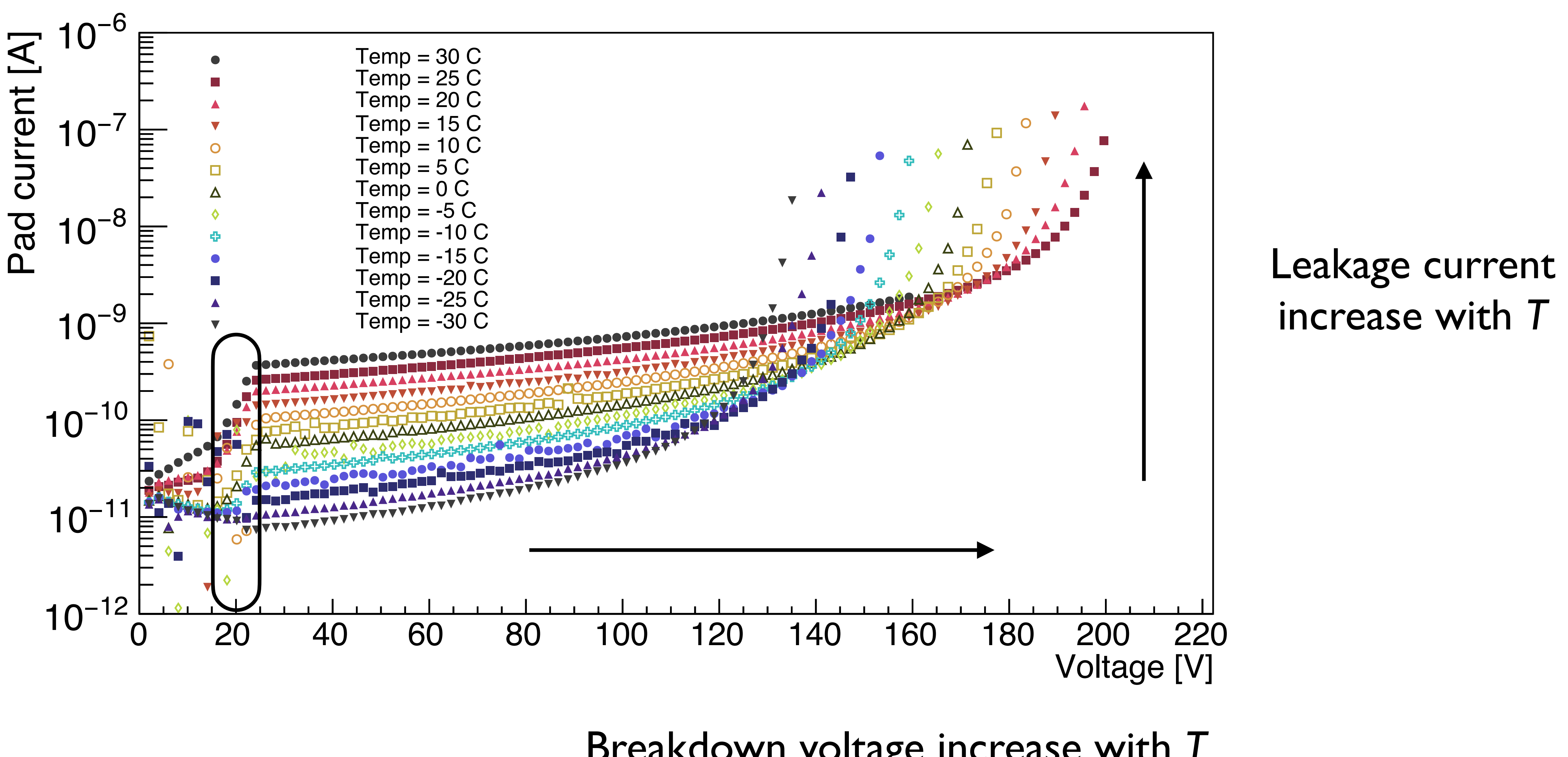




[1] **Development of a technology for the fabrication of Low-Gain Avalanche Diodes at BNL** *G. Giacomini, W. Chen, F. Lanni and A. Tricoli*, Nucl. Instrum. And Meth. In Phys. Res. *https://doi.org/10.1016/j.nima.2019.04.073*.

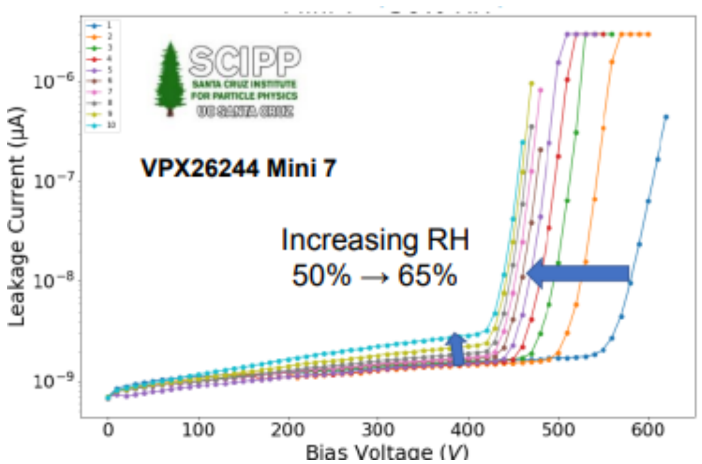
Thermal profile

- Measurement segmentation in *sweeps*
  - To stress test the sensors four sequential temperature scans are performed in intervals of 5◦C and a period of 60◦C.
  - After reaching a temperature of T = +30◦C all the $I(V)$ measurements are repeated by now decreasing the temperature by steps 5 ◦C.
  - Use each set of two measurements as a self-cross-check with respect to changing conditions (humidity)
  - Further stress tests are performed by abruptly changing the temperature changes between the cold and warm regimes.
- Depletion voltage is independent of the temperature, but leakage current and break-down are.



Environmental changes

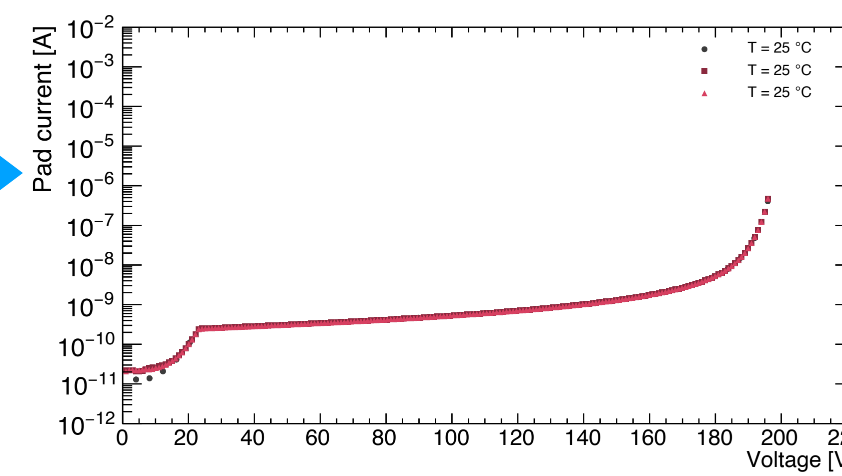
- Segmentation of temperature sweeps as a function causes that can impact the performance.
  - Humidity can reduce dielectric strength, influence from guard ring metals [1]



Humidity-controlled environments with dry-air desiccators

  - Static charge accumulation [2], ex: storage medium, handling

de-ioniser



  - Implant-related temperature dependence [3]

[1] **Humidity Sensitivity of Large Area Silicon Sensors: Study and Mitigation** ,*X. Fernández-Tejero et al,* HSTD12, Hiroshima 2019

[2] **Strip sensor performance in prototype modules built for ATLAS ITk,** *C. Helling et al,* https://doi.org/10.1016/j.nima.2020.164402

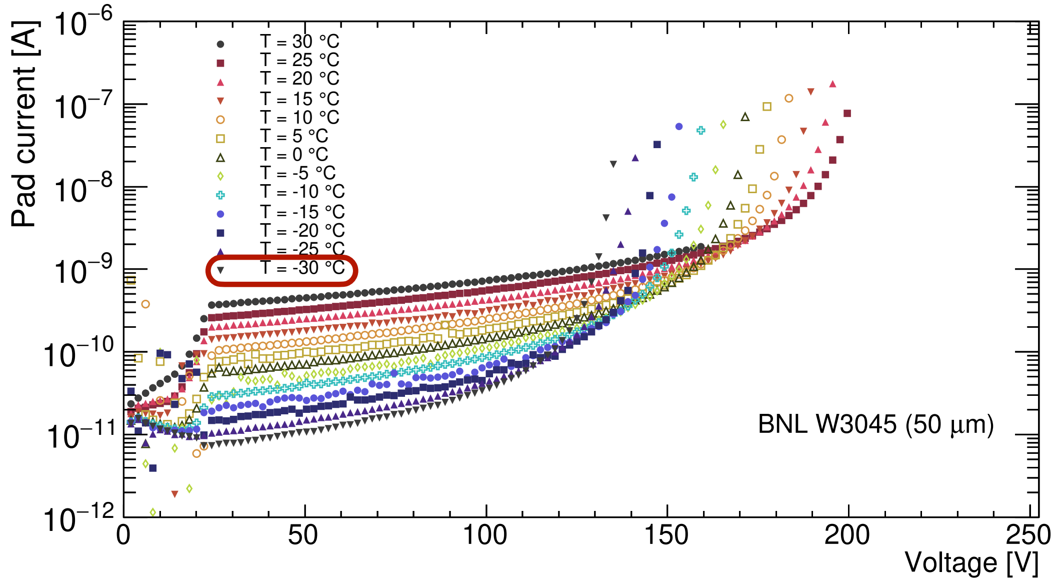
[3] **Study of impact ionization coefficients in silicon with Low Gain Avalanche Diodes,** *E. Rivera and Michael Moll,* https://arxiv.org/pdf/2211.16543.pdf

Thermal profile

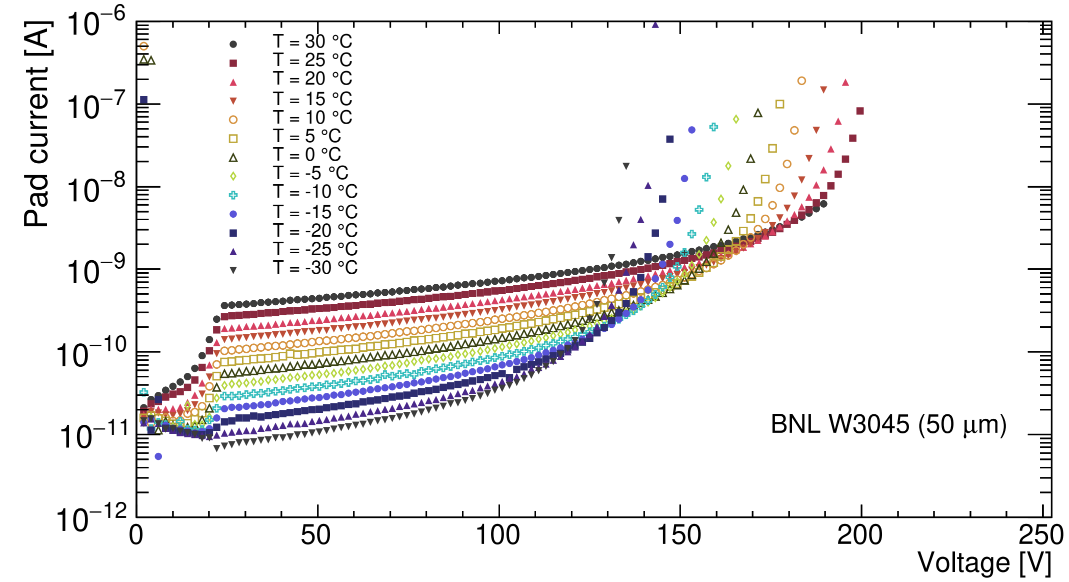
- Studies repeated for stability under rapidly changing conditions.
  - by abruptly changing the temperature changes between the cold (-30◦C) and warm regimes (+30◦C)

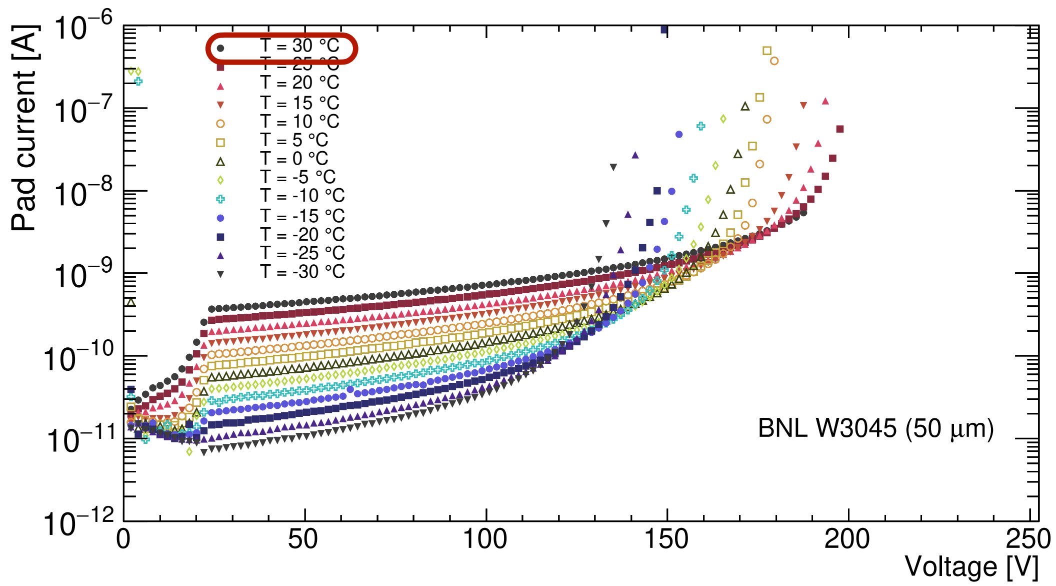
T

Sweep 1

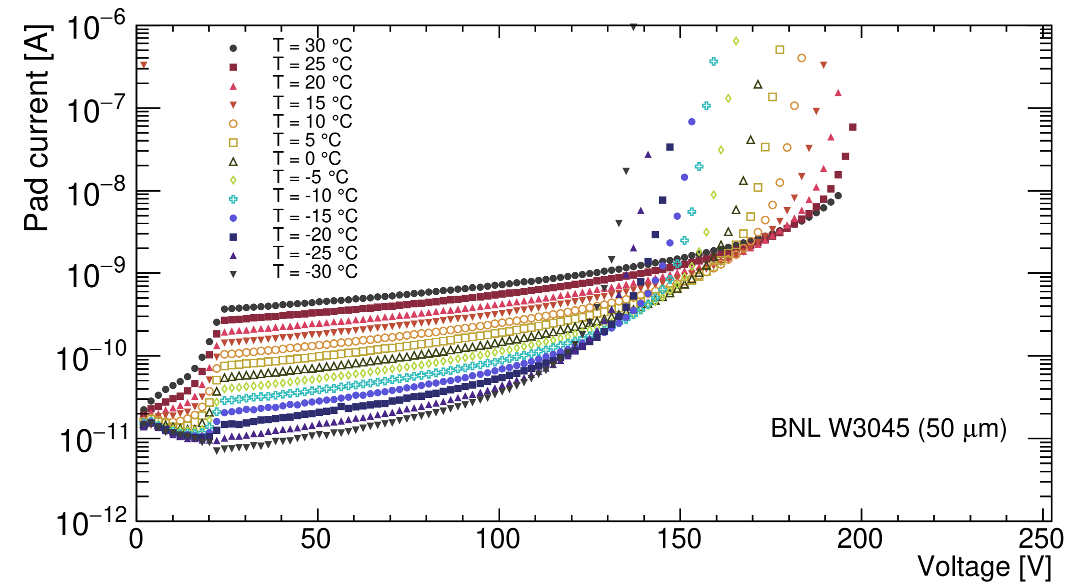


Sweep 3





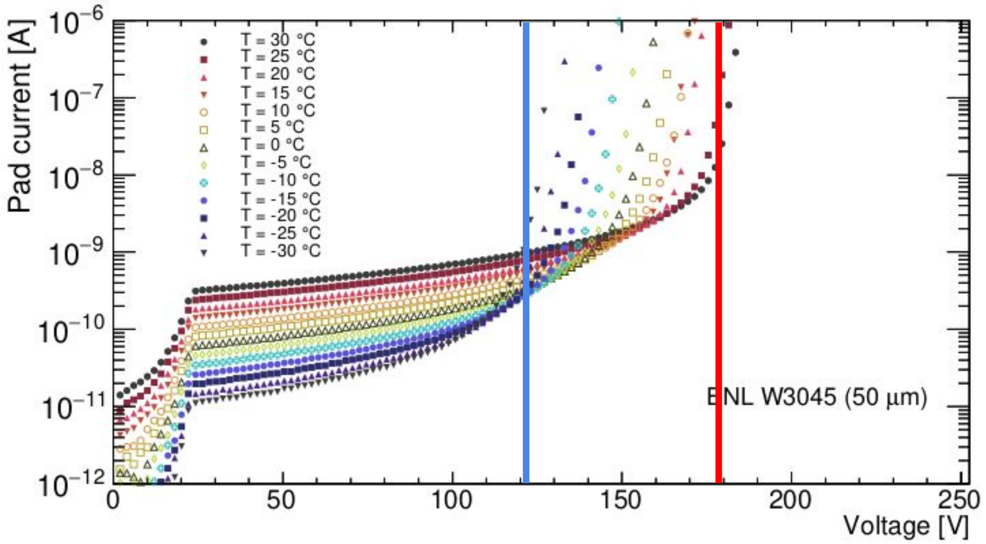
Sweep 2

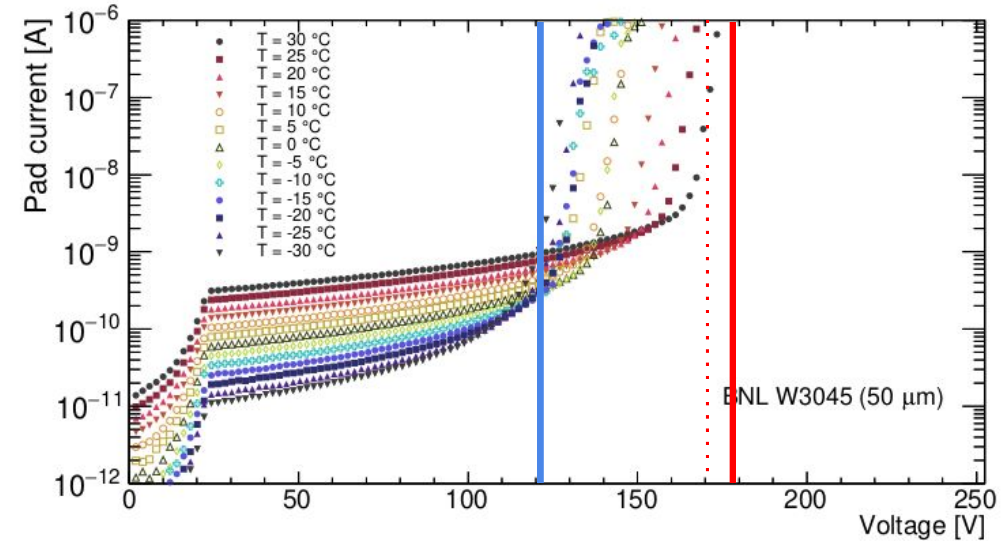


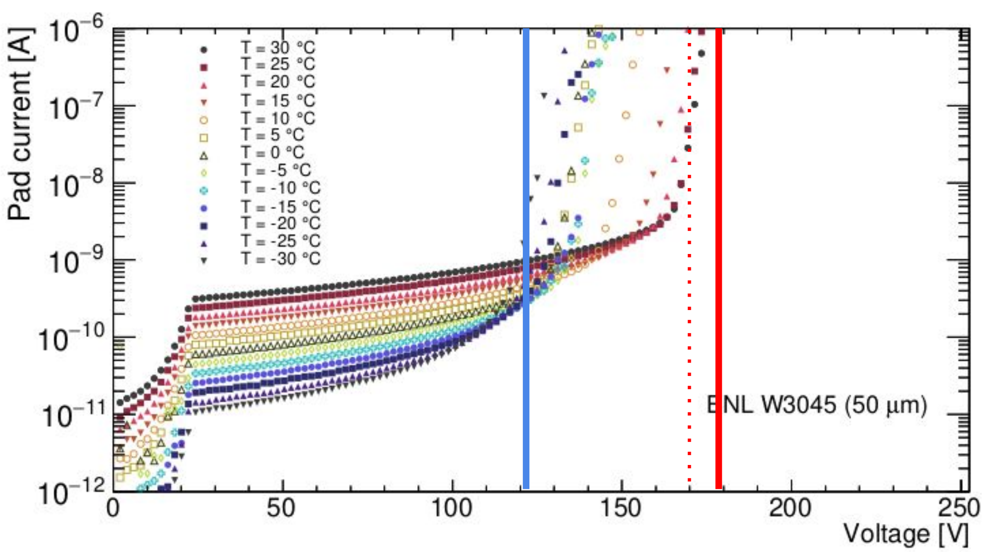
Sweep 4

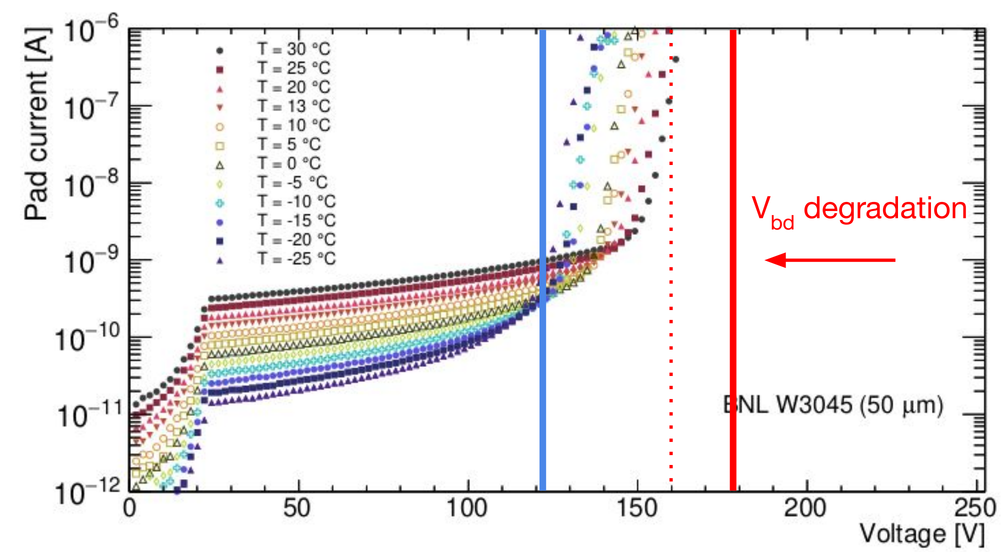
Thermal profile

- Testing in extreme scenarios: unpassivated sensors with the pad exposing bare metal.
  - Observing permanent performance degradations of LGAD breakdown biases.
  - De-ionization tests seem to point at a static charge accumulation or humidity-related impacts.





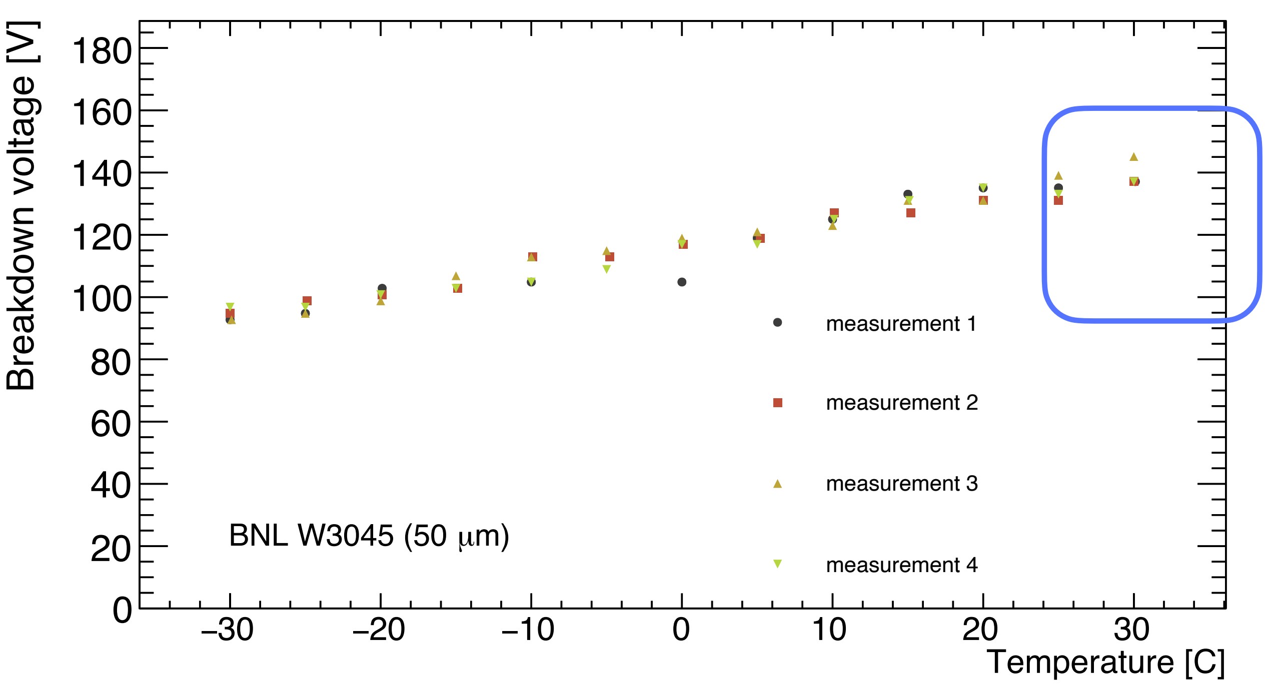




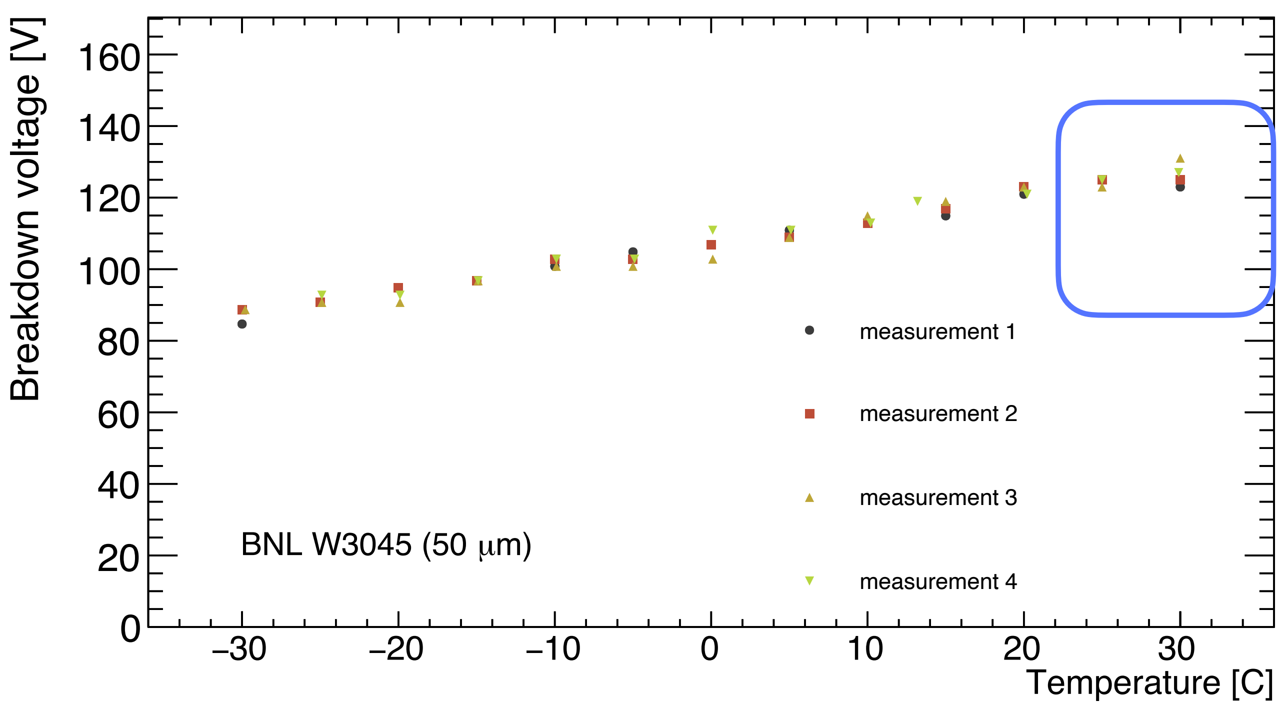
Thermal profile

- Studies repeated for stability under rapidly changing conditions.
  - Breakdown voltage extracted from two exponential fits with χ^2 as a discriminator.
  - Within a given thermal cycle we do observe the linear profile evolution of a diode.
  - These results show that the electrical characteristics of the BNL-produced sensors retain good operating performance at a wide range of temperatures.
  - Further tests with short thermalization times or abrupt temperature variations from $T = -30^{\circ}$C to $T = +30^{\circ}$C without relaxation times show a similar resilience.
  - The linear model loses validity at high temperatures where thermal effects might induce early breakdowns.

Sweep 1+2

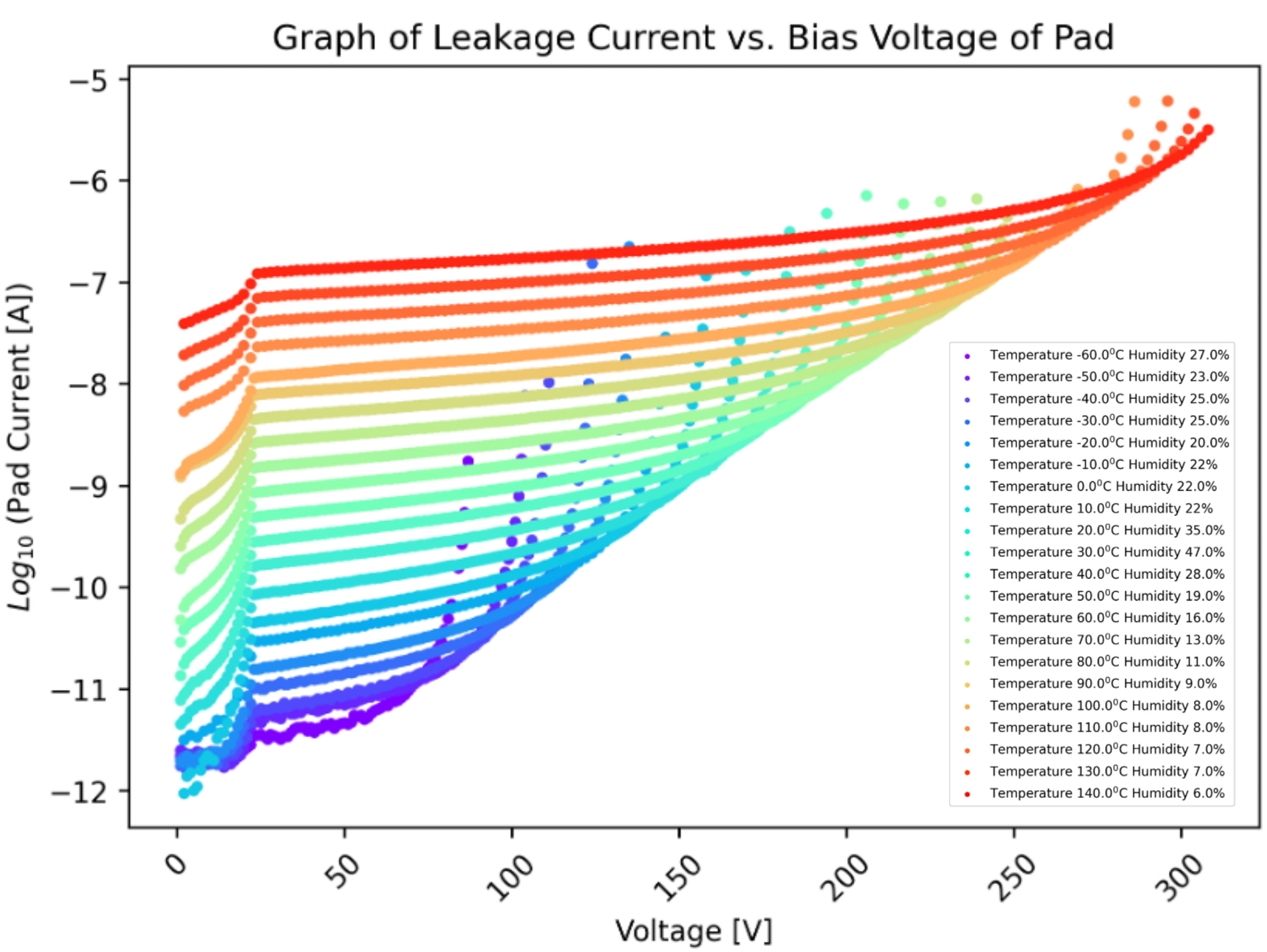


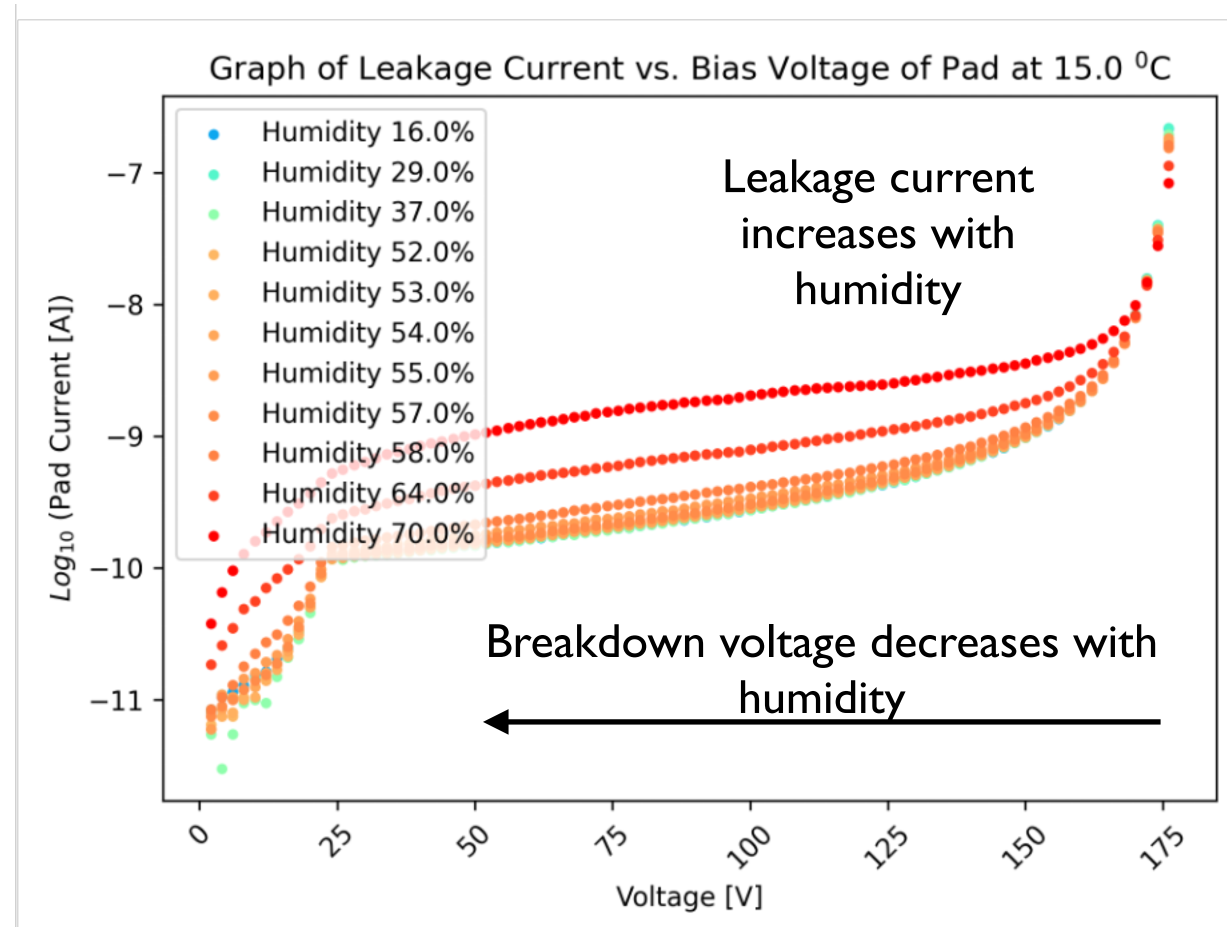
Sweep 3+4



Humidity investigations

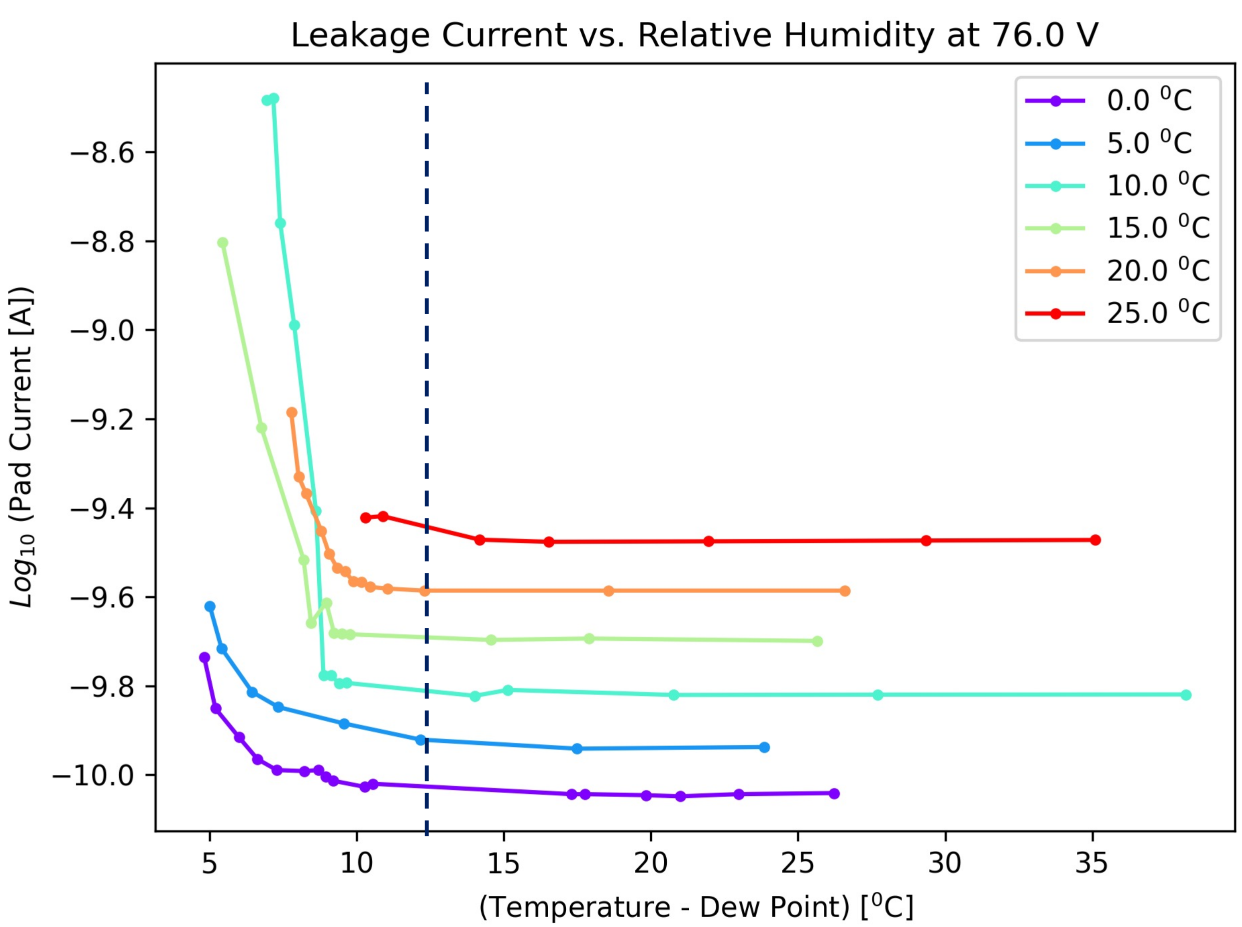
- $I(V)$ measurements are taken at temperatures from -60°C to 140°C with varying humidities.
  - Reaching higher temperatures is difficult with the cabling used.
  - Measurements repeated from low humidity to high and reversely.
  - Difficult to create higher humidity conditions with higher temperatures in the climate chamber.
- As expected leakage current and breakdown voltage increase with temperature, independently of the humidity.
  - At fixed temperatures, pad current remains the same until a *critical humidity*.
  - Leakage current increases when the dew point is around ~10°C less than the sensor temperature

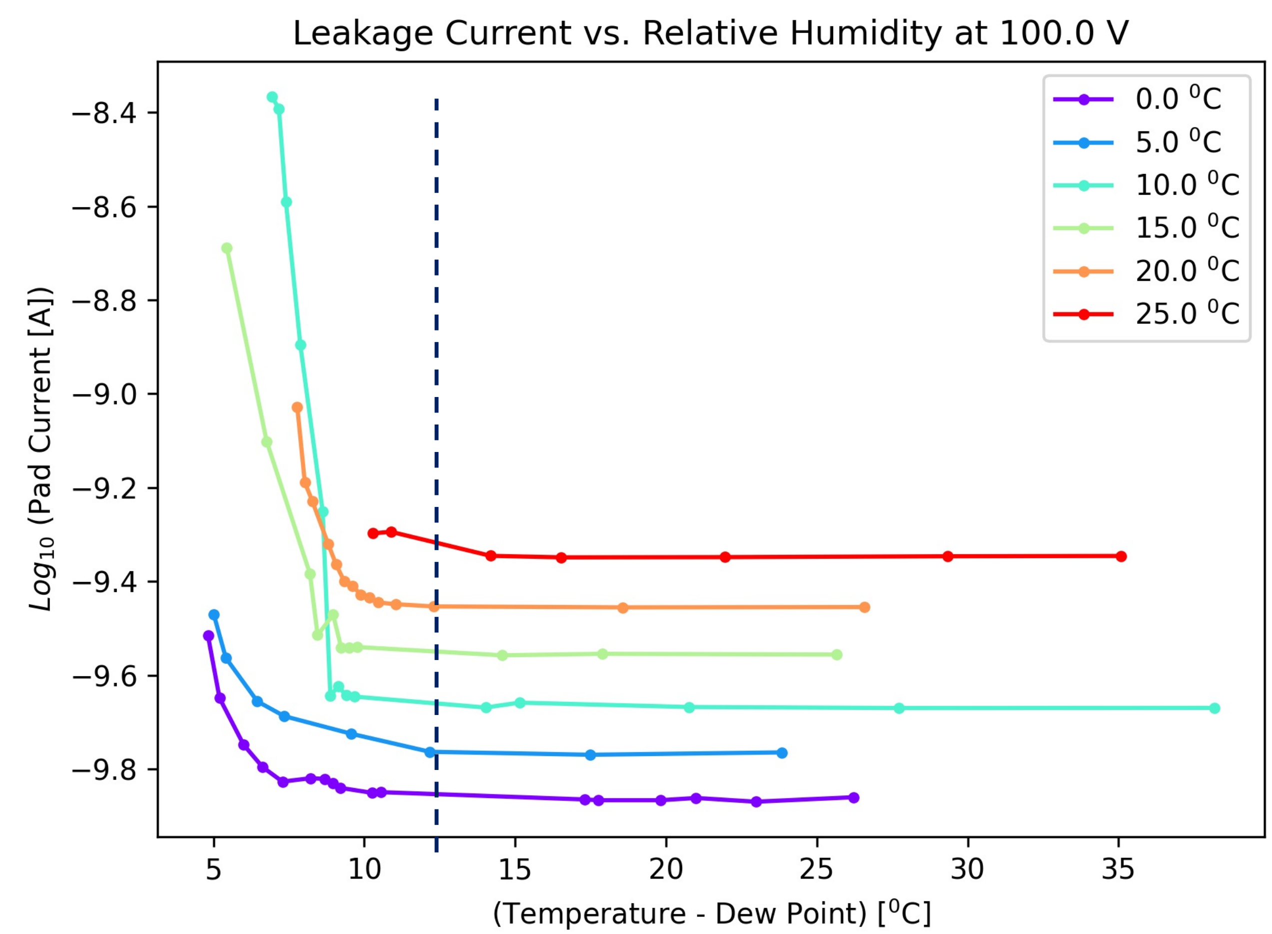




Humidity investigations

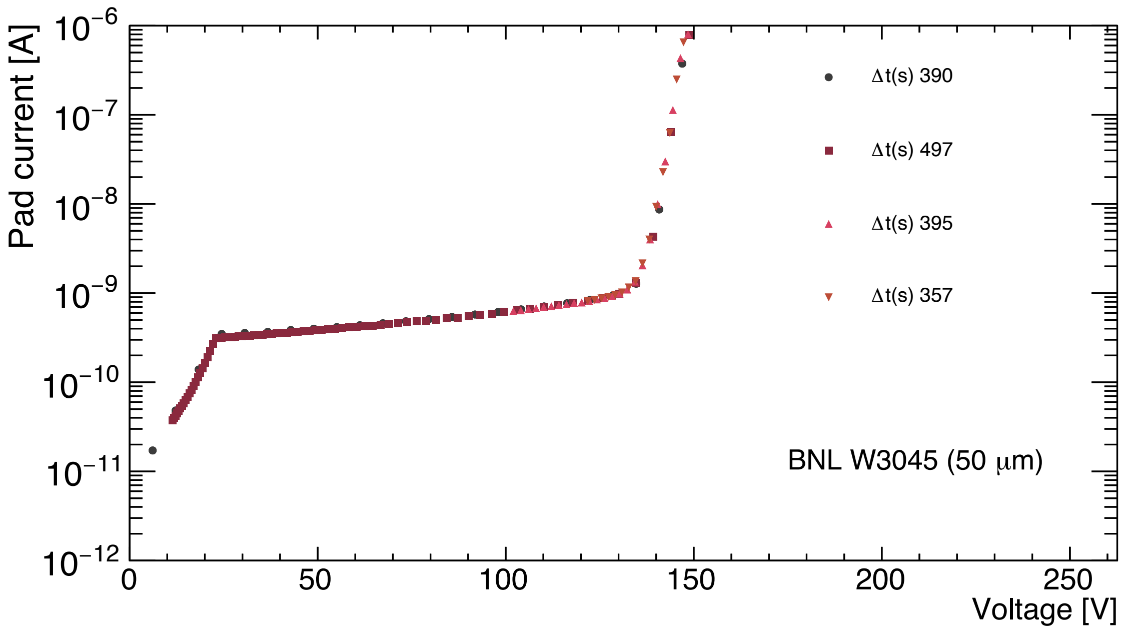
- As expected leakage current and breakdown voltage increase with temperature, independently of the humidity.
  - At fixed temperatures, pad current remains the same until a *critical humidity.*
  - Leakage current increases when the dew point is around ~10°C less than the sensor temperature
- Performance degradation with humidity:
  - Transient performance degradation.
  - Reversible, as cyclical tests were performed.

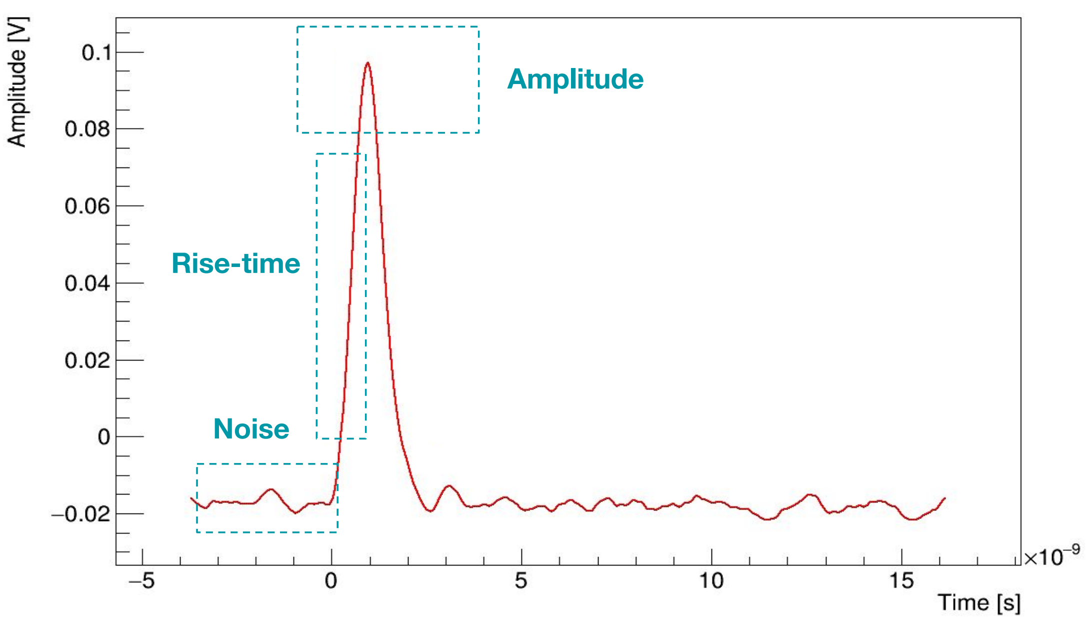




Conclusions

- Preliminary study on environmental conditions stress tests on (AC) LGADs
  - Prompted by investigation on applications of (AC) LGADs to space-based experiments.
    - Payload considerations, temperature control, current-draw limitations on satellites.
  - Ongoing systematic study on the impact of environmental operating conditions on physics performance.
  - Investigating mitigation strategies for environmental factors that degrade their performance
  - BNL-produced LGADs show good performance despite harsh operating conditions.
- Outlook:
  - Expand the phase space of environmental parameters.
  - Evaluation of long-term effects and prolonged operations under harsh conditions.
  - Confront results with ionization coefficients from TCAD models [1]
  - Analyze full effects on waveforms with TCT and test-beam setups.
- Lead to optimized sensor design for space-based applications.



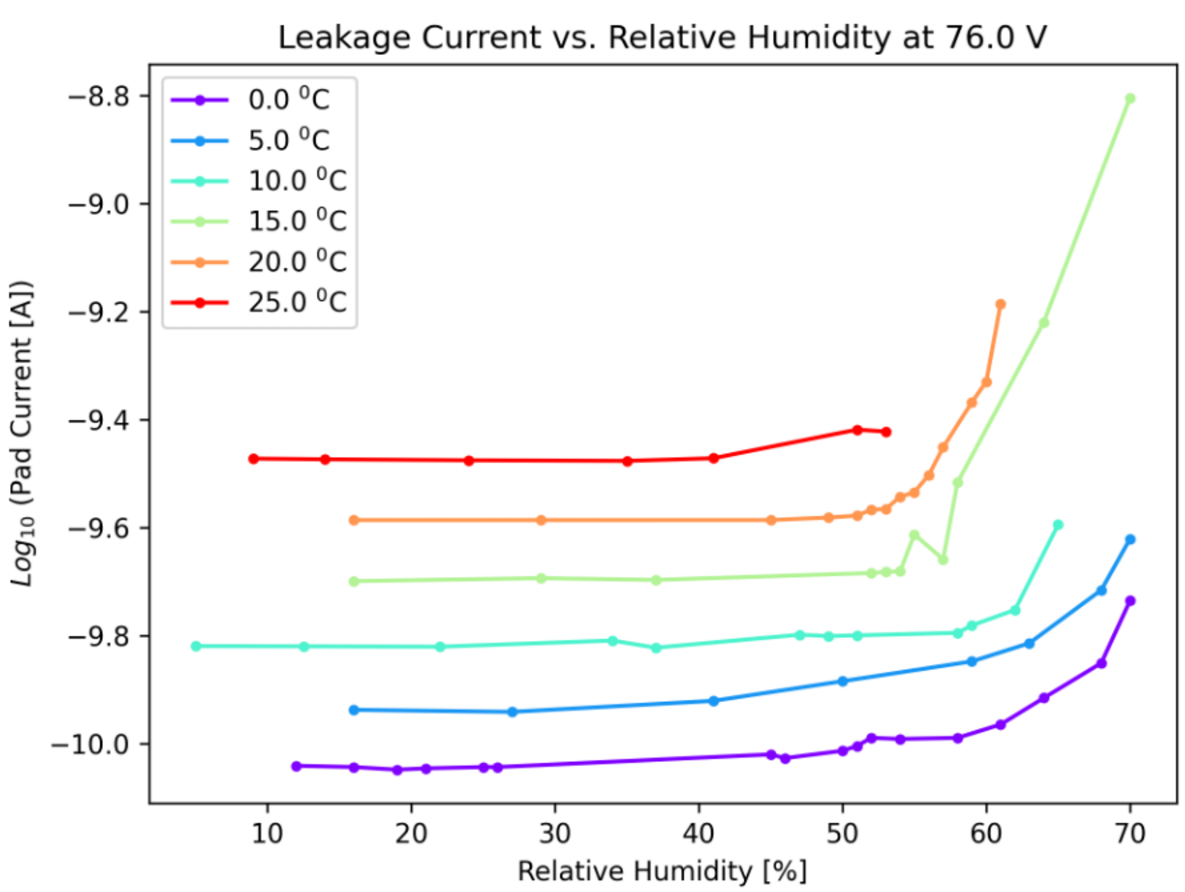


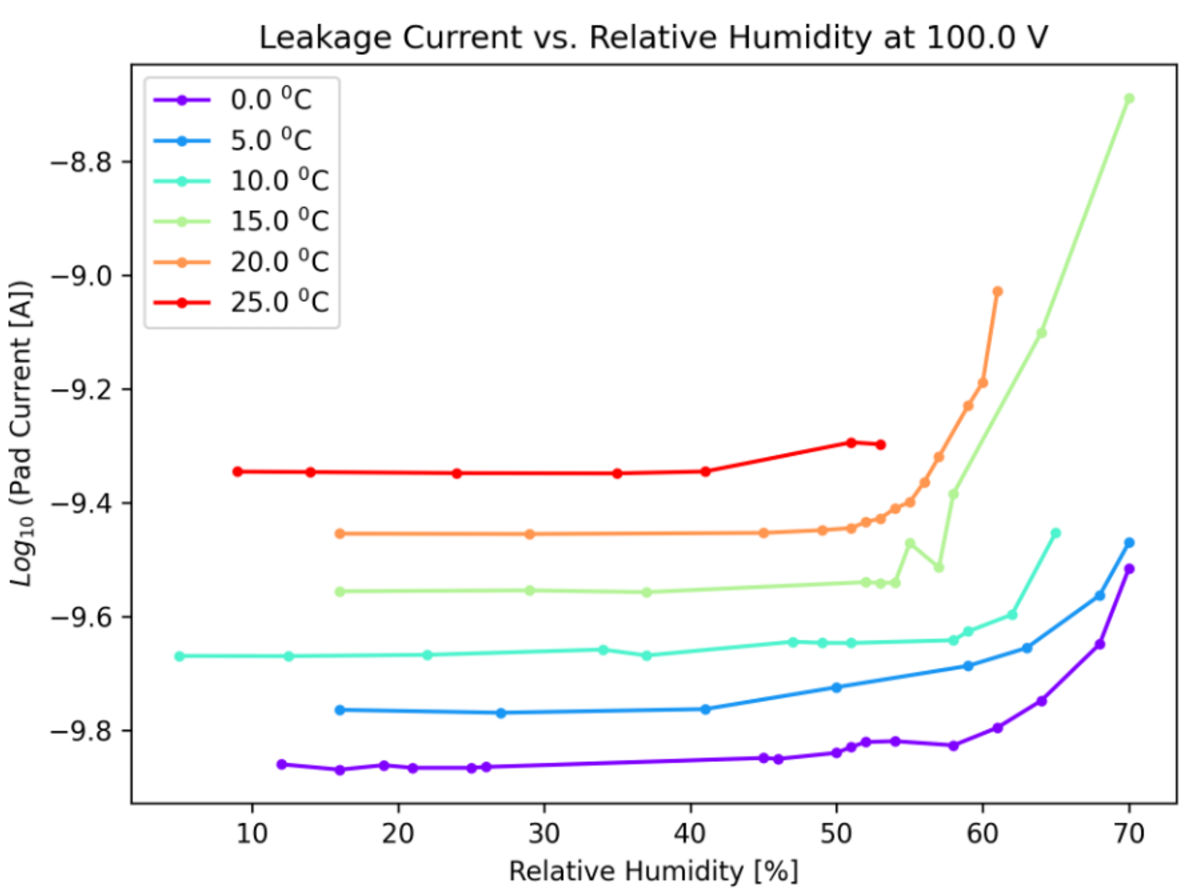
[1] **Study of impact ionization coefficients in silicon with Low Gain Avalanche Diodes,** *E. Rivera and Michael Moll,* https://arxiv.org/pdf/2211.16543.pdf

Additional material.

Humidity investigations

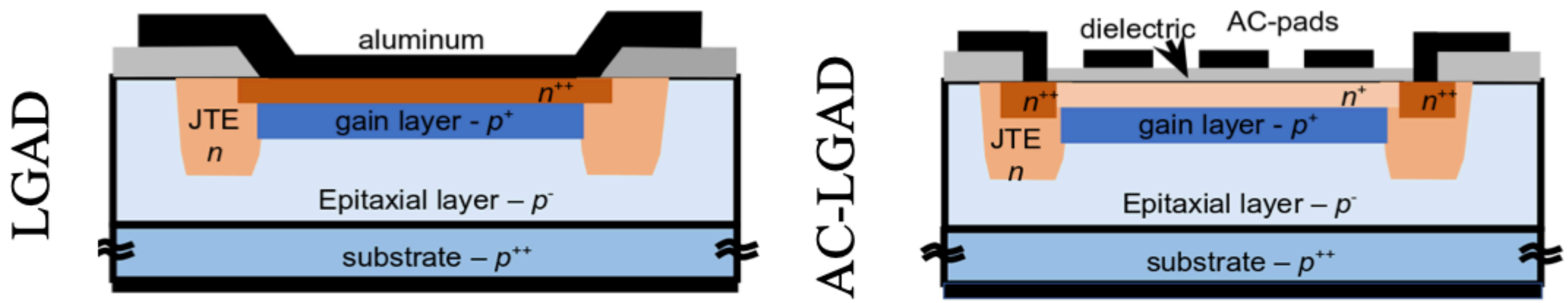
- *I*(*V*) measurements are taken at temperatures from -60°C to 140°C with varying humidities.
  - Reaching higher temperatures is difficult with the cabling used.
  - Measurements repeated from low humidity to high and reversely.
  - Difficult to create higher humidity conditions with higher temperatures in the climate chamber.
- As expected leakage current and breakdown voltage increase with temperature, independently of the humidity.
  - At fixed temperatures, pad current remains the same until a *critical humidity*.
  - Leakage current increases when the dew point is around ~10°C less than the sensor temperature





Introduction

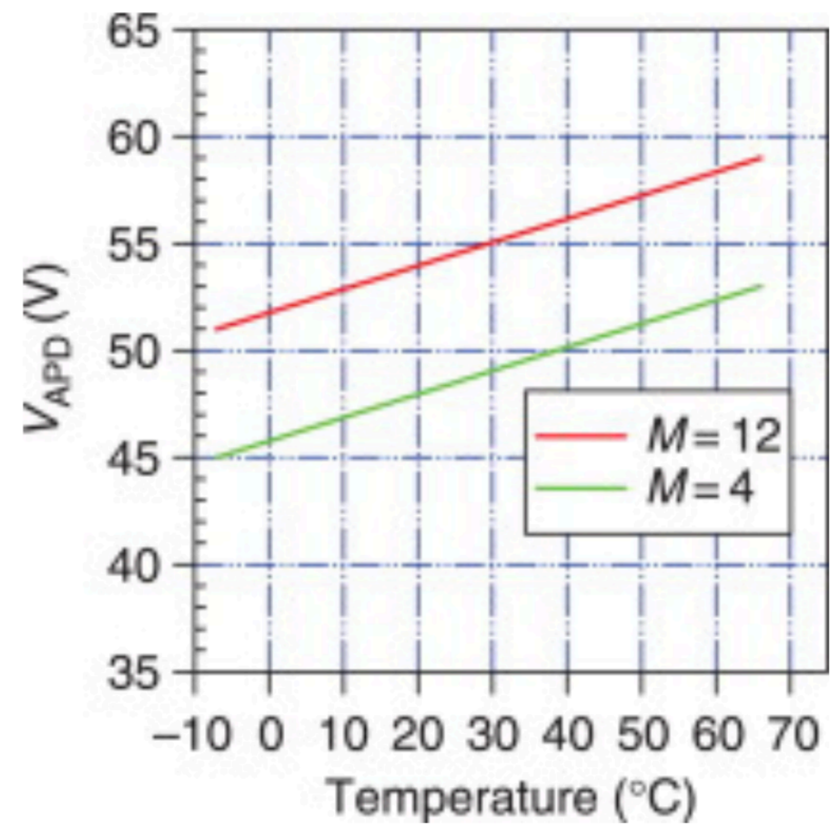
- Low Gain Avalanche Diodes (LGADs) and AC-coupled Low Gain Avalanche Diodes (AC-LGADs):



  - O(30) ps timing performance and 4D extension with O(10) μm in RSD variant.
  - Considered for several applications in HEP: Electron-Ion Collider, LHCb Velo Upgrade, ATLAS & CMS High Granularity Timing Detector, CMS, Pioneer, …
  - Application starting to be investigated for space-based experiments [1]
- Large set of studies actively performed on Resistive Silicon Devices and specifically LGADs & AC-LGADs
- Space applications require the study of LGAD behavior in a wide range of environmental conditions.
  - Temperature variations -100°C and +100°C
  - Cryogenic/temperature control not ensured (payload)
- Need to ensure good sensor response and electrical characteristics at varying operating conditions.
  - Leakage current is a function of T
  - Need easy-to-model
  - The behaviour of charge carriers in silicon strongly affected by T

Temperature mechanisms

- Avalanche as a function of temperature.
  - The ability of carriers to ionize depends on the bandgap and the band structure
    - In turn, they depend on the temperature.
  - Phonon scattering is affected by temperature.
    - At high temperatures carriers lose their energy when traveling through the multiplication region and require longer paths before they impact ionization.



M.M. Hayat, in Comprehensive Semiconductor Science and Technology, 2011