Impact of environmental stresses on Low Gain Avalanche Diodes

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

[a]**Brookhaven National Laboratory**
[b]**Brown University**
[c]**University of New Mexico**

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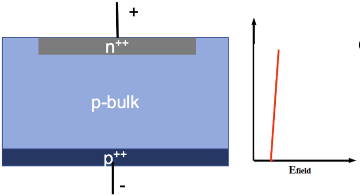
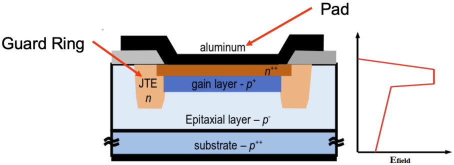
Introduction: Low Gain Avalanche Detectors

LGAD caracteristics and its applications

- Good candidate for timing measurements.
- Variety of applications, such as HEP, Nuclear Physics, medical imaging etc.
- Application to space-based experiments starting to be investigated.



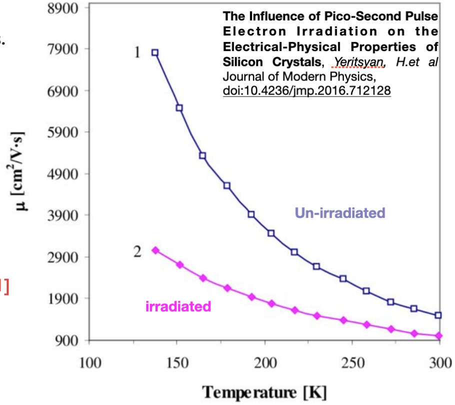


- Standard Silicon Diode
- Gain = 1
- Signal/Noise Ratio is low

- Standard Silicon Diode
- Gain $\sim 10 - 100$
- Signal/Noise Ratio very high
- Timing resolution $\sim$ 30ps

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.

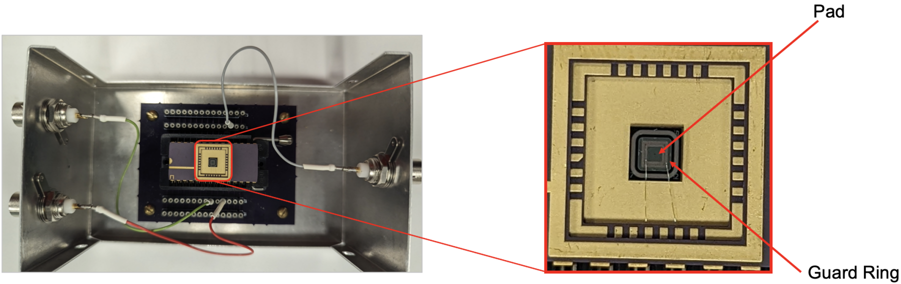


Silicon crystal (n-Si) charge carrier's mobility temperature dependence after electron pico-second beam irradiation (3.5 MeV).

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

DC-LGAD made at Brookhaven National Laboratory

- 50 μm thickness sensor is mounted to a readout chip.
- Sensor is biased with high voltage.
- Leakage currents from pad and guard ring of the sensor are measured.
- With and without a passivation layer.

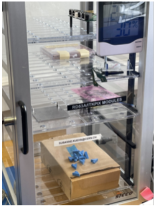


Sensors and Setups

- Different setups are used in our study.
  - BNL setup.
  - RD50 setup.

	BNL setup	RD50 setups
Probe-station setups used in reverse bias	climate chamber with two-needle probe-station readout (compliance at 10−6 A/V).	characterization laboratory, with a two-needle probe station setup (compliance at 10−6 A/V).
Thermal and humidity control	ambient chamber $T = -60^\circ C$ to $T = +180\ ^\circ C$ with varying humidity. The setup is kept inside an ambient chamber for **thermal cycle**	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%
	N2 is supplied to vary relative humidity and to prevent condensation when operating at cryogenic temperatures	

Humidity and temperature are measured inside the metal box (BNL)



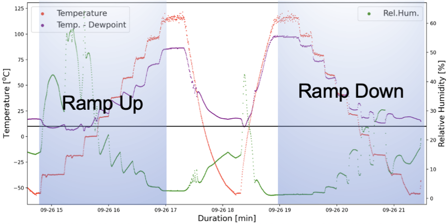
Humidity-controlled environments with dry-air desiccators(CERN)

Thermal cycle

- Temperature of the ambient chamber is cycled at an average rate of 1.81 °C/mn.
- Humidity is maintained in such manner that dew point is always 10 0C less than the operating temperature of the ambient chamber.

Program	Temperature	Bias Voltage	IV Measurements
Day	-60 °C to 120°C	-50 V	Steps of 20°C: Ramping up and ramping down
Night	21 °C	-150 V	No measurement
Weekend	10 °C to 120°C	off	No measurement

- The temperature range is driven by the limitations of ambient chamber and electrical components



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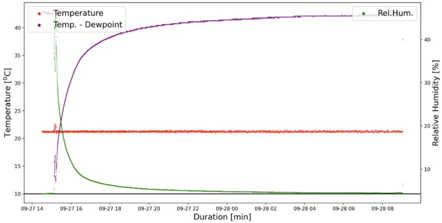

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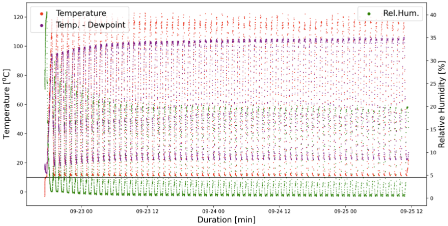
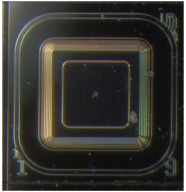
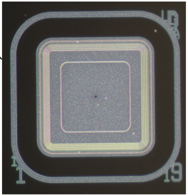
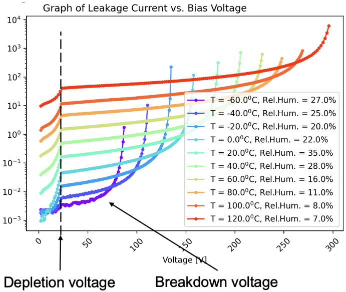


Use of different wafers: W3045 vs W3058

- Sensors testing from two different wafers fabricated at BNL
- W3045: First production, no passivation, no termination.
- W3058: Latest production, Silicon nitride/oxide passivation, Improved termination and contact





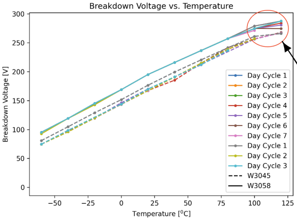


Observation

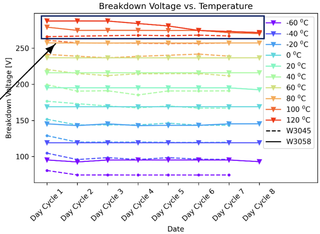
- Depletion voltage is independent of temperature.
- Breakdown voltage increases with temperature
- Leakage current of plateau increases with temperature

Breakdown voltage results

- Breakdown voltage is estimated by two linear fits on the IV curve.

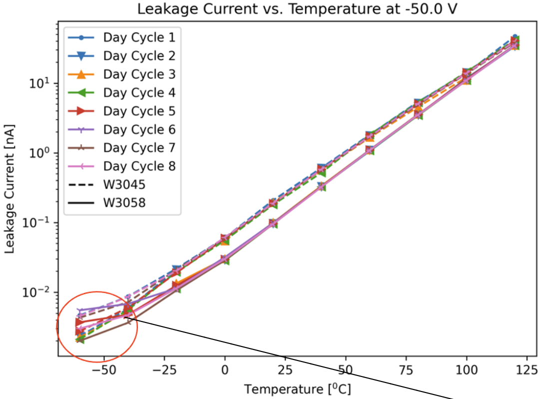


- This discrepancy is a primary result of fitting code artifact



- Breakdown voltage increases linearly with the temperature
- New sensor shows improvement in breakdown voltage compared to the old sensor
- Breakdown voltage is consistent over different thermal cycles in the new wafer.

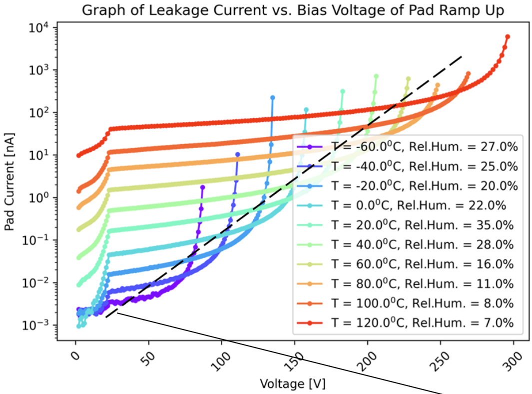
Results: Leakage Current vs Temperature



- Leakage current exponentially increases with the temperature.
- Leakage current is consistent over different thermal cycles.
- Leakage current of the new sensors is lower compared to older sensors.

- Current in pA range

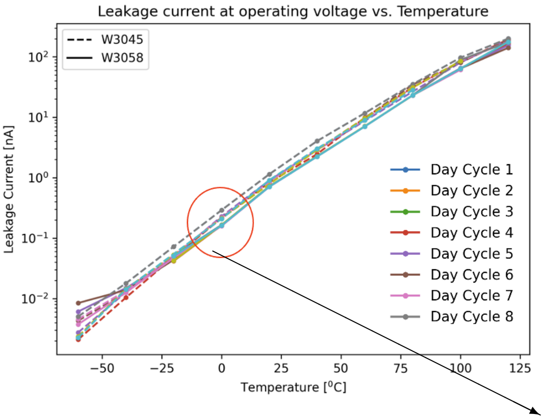
Operating Voltage



- Sensors are operated at the highest voltage before breakdown such that the carrier velocity saturates (in order to improve time response)
- Operating Voltage = Breakdown Voltage – 20 V.

- Operating Voltage

Leakage Current at Operating Voltage

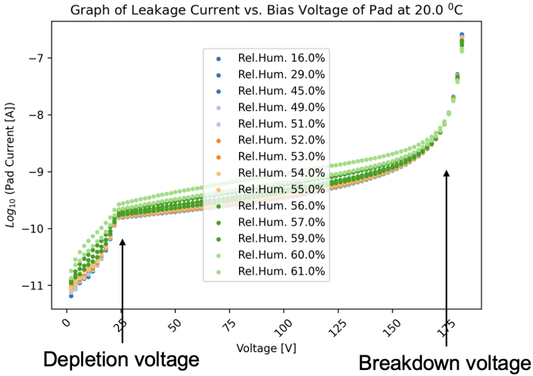


- Leakage current of the new wafer is lower compared to the older wafer at the operating voltage
- New wafer shows consistent leakage current over different thermal cycles showing an excellent improvement from its predecessor

- Dispersion of the leakage current at 0°C over different thermal cycles
  - $\sigma_{W3045} = \pm 12.5\%$
  - $\sigma_{W3058} = \pm 1.3\%$

Results: Leakage Current and Relative Humidity

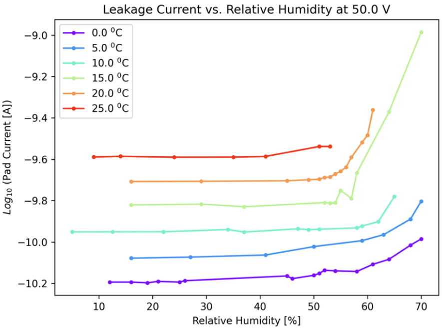
- We keep the temperature constant at 20 0C and vary the humidity

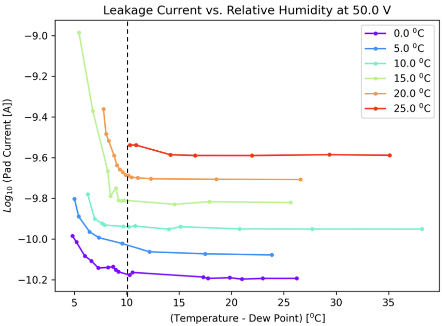


- Depletion voltage is independent of humidity
- Breakdown voltage is independent of humidity
- Leakage current of plateau increases with humidity

Results: Leakage Current and Dewpoint

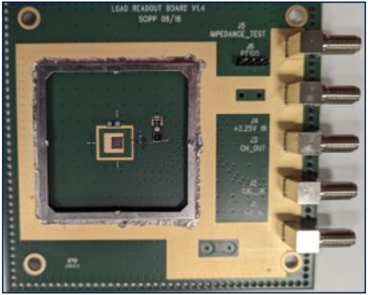
- We repeated the above measurements at different temperatures



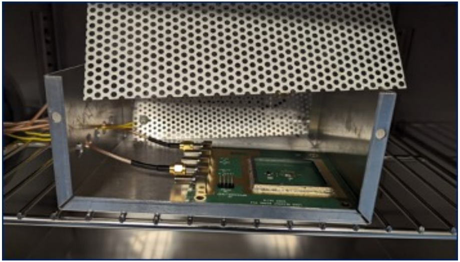


- When dewpoint reaches 10°C closer to the temperature, a critical point humidity, the leakage current increases rapidly

- DC-LGAD sensor is mounted to a readout board to measure analog signal pulses
- This setup is kept inside the ambient chamber together with IV setup and thermal cycled simultaneously



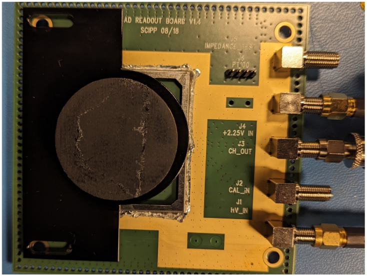
LGAD READOUT BOARD V1.4 SCIPP 08/18



LGAD Readout board inside the ambient chamber

Experimental Setup: Analog Signal Analysis

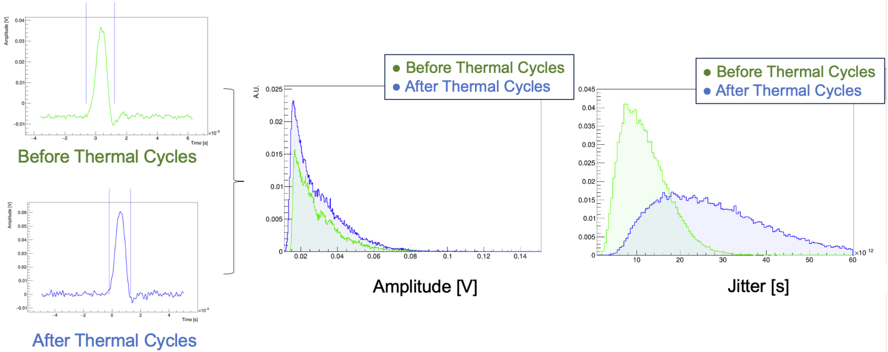
- Analog signal analysis is performed before and after thermal cycling
- We use a Sr90 as signal source and measure the analog pulse using Waverunner 9404M-MS oscilloscope
- Signals are recorded outside the ambient chamber in an uncontrolled environment at room temperature inside a dark hood



Sr 90 Beta source is used to generate signal pulses

Analog signal pulses recorded by oscilloscope

- Sample waveform of a signal measured before and after 8 thermal cycles.



Summary of Analog Signal

- Signal amplitude is consistent before and after thermal cycles.
- We observe the noise of the signals to have increased significantly.
- This discrepancy can be attributed to the electronics of readout board being impacted due to thermal cycling.

Thermal Cycles	Amplitude [mV]	Noise [mV]	Slew Rate [MV/s]	Jitter [ps]
Before Thermal Cycles	20.9°C	0.48	36.5	9.68
After 8 Day Cycles + 2 Weekend Prog.	19.1°C	0.99	31.2	26.3

As this is a work in progress, we anticipate to perform a more comprehensive analog signal analysis in the future

Conclusion and Outlook

- Two different BNL-made LGAD sensors have been tested for weeks at extreme and rapidly changing temperature and humidity conditions.
- The results from the two sensors show consistent response of leakage current, and depletion, breakdown and operating voltages as functions of temperature and humidity.
- no deterioration of performance is seen in LGADs after weeks of thermal-cycling
- The new LGADs with an improved termination design shows slightly better performance than the old sensor design

Parameters	**Depletion Voltage**	**Breakdown Voltage**	**Leakage Current**
Temperature	Independent	Dependent	Dependent
Humidity	Independent	Independent	Critical Humidity

- Thermal cycles will continue for several more weeks and performance will be assessed to test the limits of LGADs. Similar tests will be performed in the future for AC-LGADs and for sensors after irradiation.

Backup

BACKUP

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

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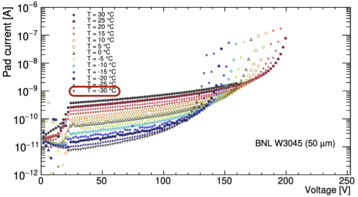
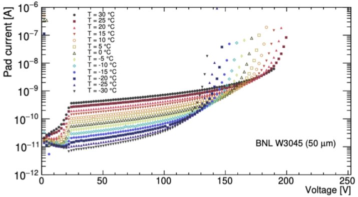
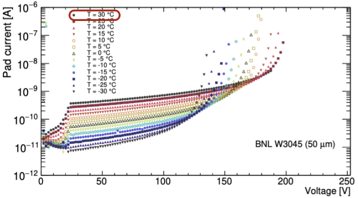
Sweep 1

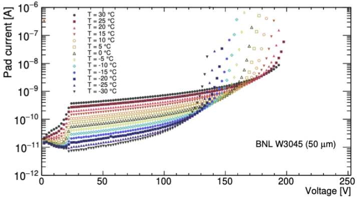


Sweep 3



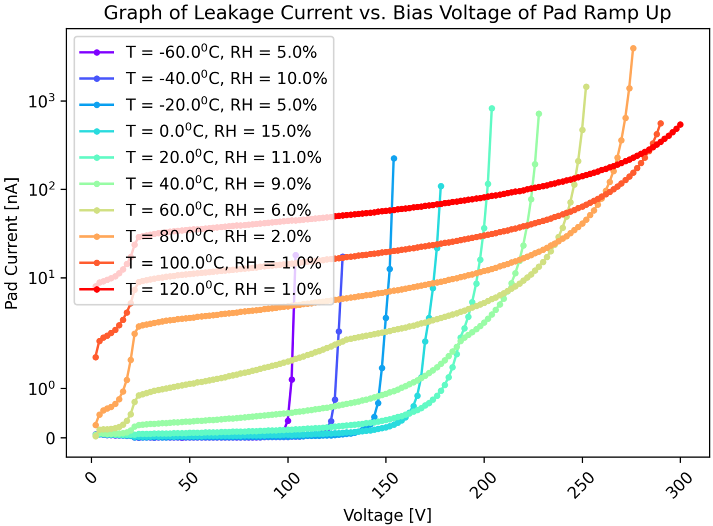


Sweep 2

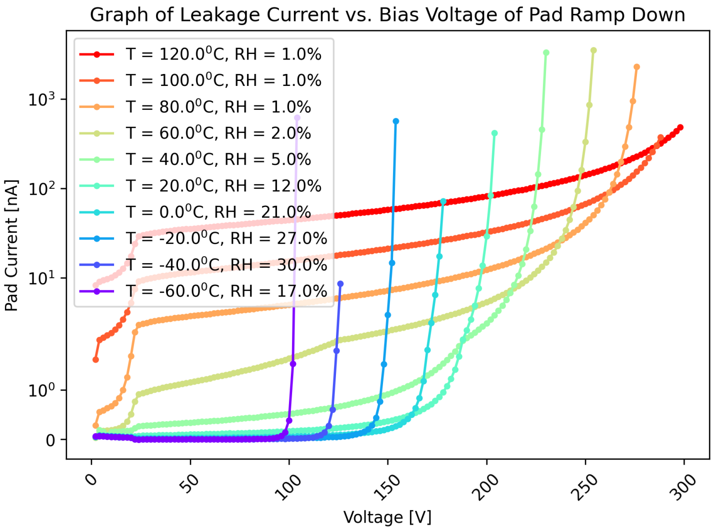


Sweep 4

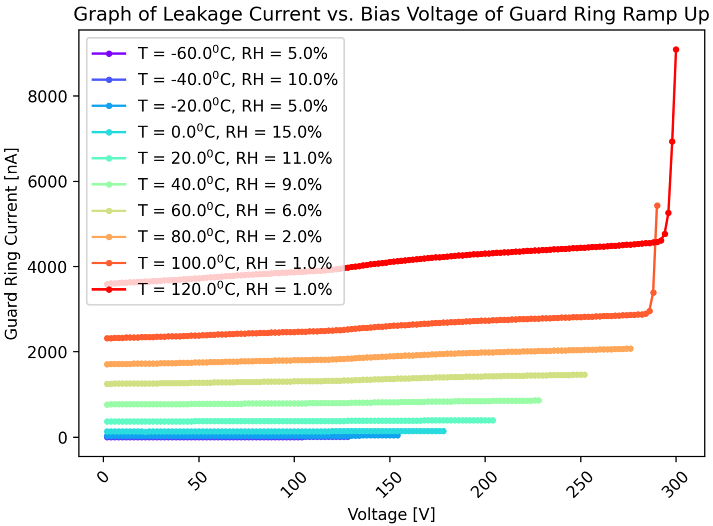
Pad current vs Bias voltage: Ramp up



Pad current vs Bias voltage: Ramp down



Guard Ring current vs Bias voltage: Ramp up



Guard Ring current vs Bias voltage: Ramp down