Environmental conditions stress tests on Low Gain Avalanche Diodes

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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]


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  - 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.

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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.

Sensors & setup

  - 1.3 mm\(^2\) with gain layers doses of \(2.8 \times 10^{12}\) cm\(^{-2}\) (50\(\mu\)m) and \(2.25 \times 10^{12}\) cm\(^{-2}\) (20\(\mu\)m), 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\(\times\) 0.5 cm from 50\(\mu\)m 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 \(T = -30\) C to \(T = +30\) C, dry air for humidity control ~20-30%
  - BNL: ambient chamber \(T = -60\) C to \(T = +180\) 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.

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• 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.

![Graph showing leakage current and breakdown voltage changes with temperature]
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]
  - Static charge accumulation [2], ex: storage medium, handling
  - Implant-related temperature dependence [3]


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)

**Sweep 1**

![Graph 1](BNL W3045 (50 µm))

**Sweep 2**

![Graph 2](BNL W3045 (50 µm))

**Sweep 3**

![Graph 3](BNL W3045 (50 µm))

**Sweep 4**

![Graph 4](BNL W3045 (50 µm))
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.

Sweep test (stress evolution)

- LGAD W3045
- Sweep A, C: temperature increased from -30 to +30°C
- Sweep B, D: temperature decreased from +30 to -30°C
- Subsequent sweeps alternate increase and decrease
- Time between subsequent T-points has to account for thermal inertia
- Observed permanent degradation in $V_{bd}$
- Current too high?
Thermal profile

- Studies repeated for stability under rapidly changing conditions.
  - Breakdown voltage extracted from two exponential fits with $\chi^2$ 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 $T = -30$ C to $T = +30$ 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 1+2 Graph]

Sweep 3+4

![Sweep 3+4 Graph]
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 $\sim$10°C less than the sensor temperature.

Graph of Leakage Current vs. Bias Voltage of Pad

Graph of Leakage Current vs. Bias Voltage of Pad at 15.0 °C

Leakage current increases with humidity

Breakdown voltage decreases with humidity
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.

![Leakage Current vs. Relative Humidity at 76.0 V](image1)

![Leakage Current vs. Relative Humidity at 100.0 V](image2)
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.

Additional material.
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![Graphs showing leakage current vs. relative humidity at different temperatures and voltages.](image-url)
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- 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.

\[ V_{APD}(V) \] vs temperature (°C)

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