

Stress Tests on Low Gain Avalanche Diodes and AC-Coupled Low Gain Avalanche Diodes

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▶ Low-Gain Avalanche Detector (LGAD)

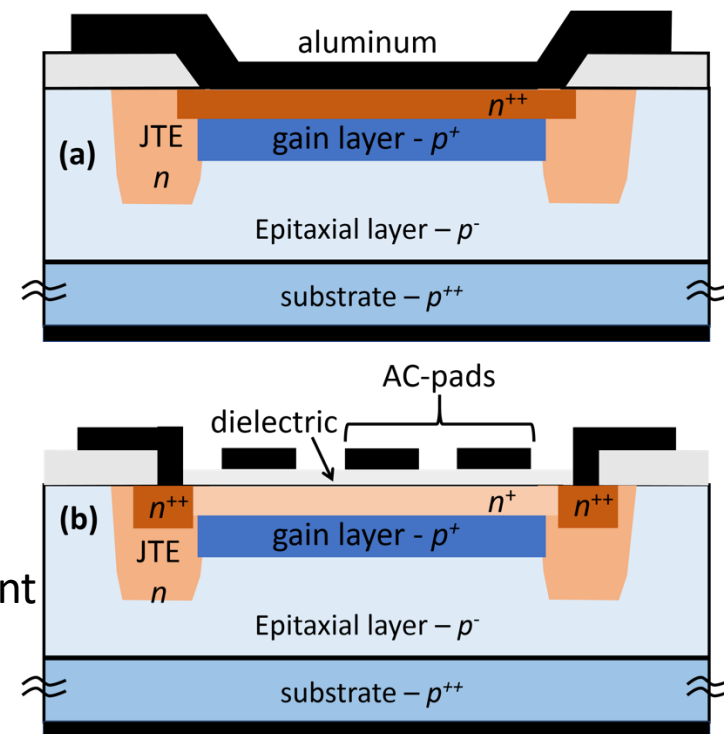
- ▶ Direct electrical connection
- ▶ Segmented gain layer
- ▶ Excellent timing resolution
- ▶ Limited spatial resolution

▶ Capacitive-Coupled LGAD (AC-LGAD)

- ▶ Capacitive coupling
- ▶ Continuous, large-area, less-doped n-resistive implant
- ▶ Excellent timing resolution
- ▶ High spatial resolution

▶ Applications

- ▶ HL-LHC upgrade: CMS MIP Timing Detector, ATLAS High Granularity Timing Detector
- ▶ Future collider: FCC, Muon Collider
- ▶ Space-based experiments



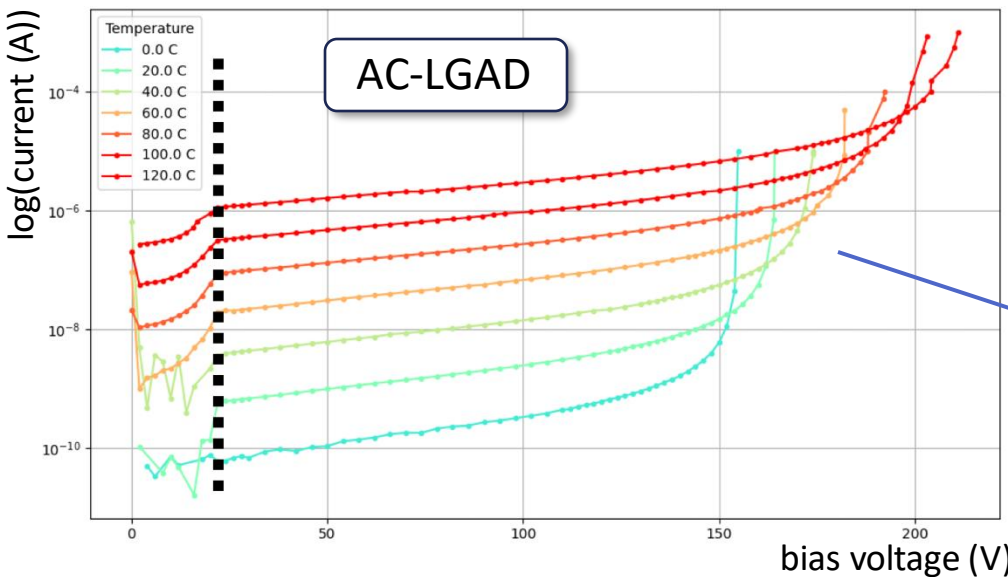
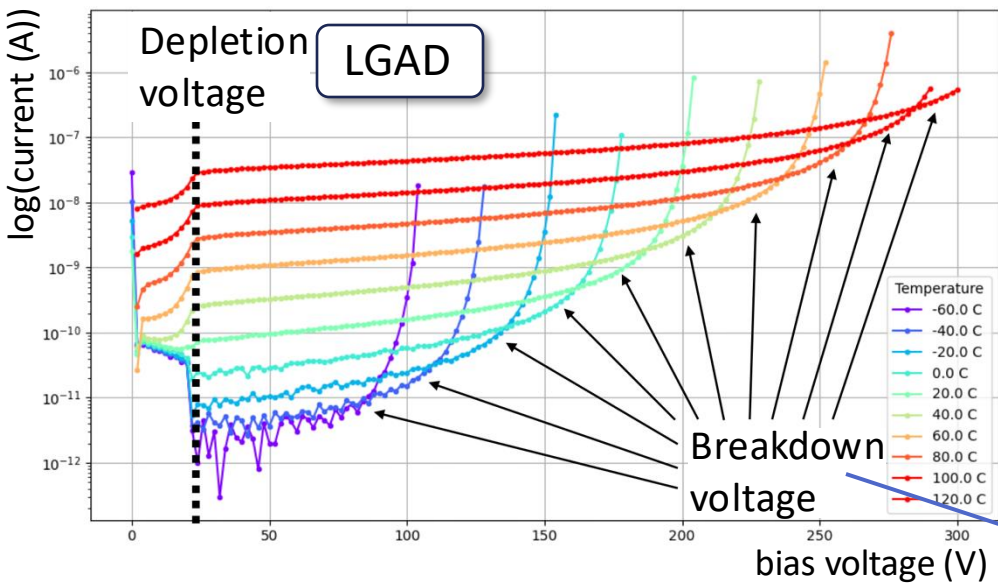
Goal:

- ▶ Understand how **environmental factors** and **sensor fabrication**
 - ▶ affect sensor performance and
 - ▶ how these factors correlate

- ▶ **Characterization** of **LGAD/AC-LGAD** performance of various environment conditions:
 - ▶ LGAD: [Talk at PSD13](#), [Talk at RD50](#)
 - ▶ AC-LGAD: [Talk at DRD3](#), [Talk at CPAD](#)

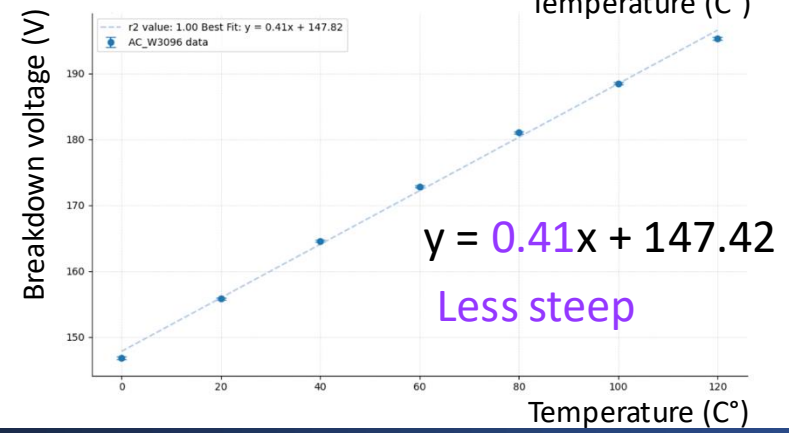
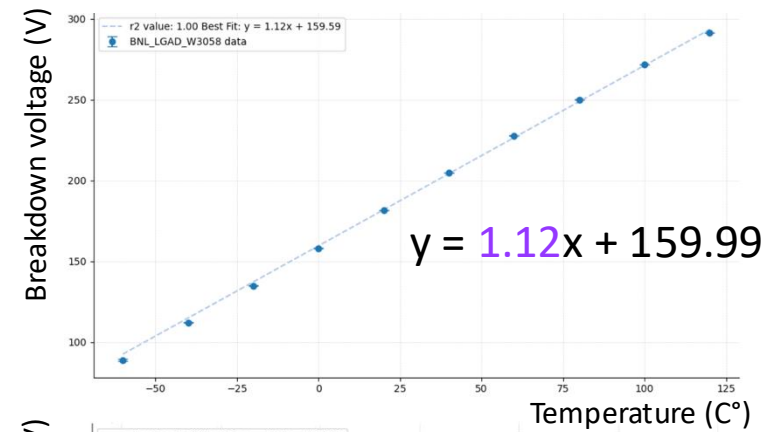
- ▶ Focus of **this talk**:
 - ▶ Progress in the **understanding** of the collected data
 - ▶ Progress in understanding how environmental factors and sensor fabrication affect sensor performance with the help of machine learning method

Recap of test results



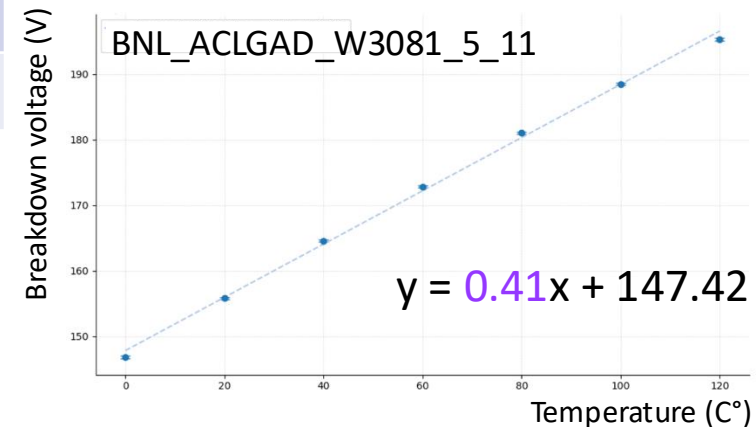
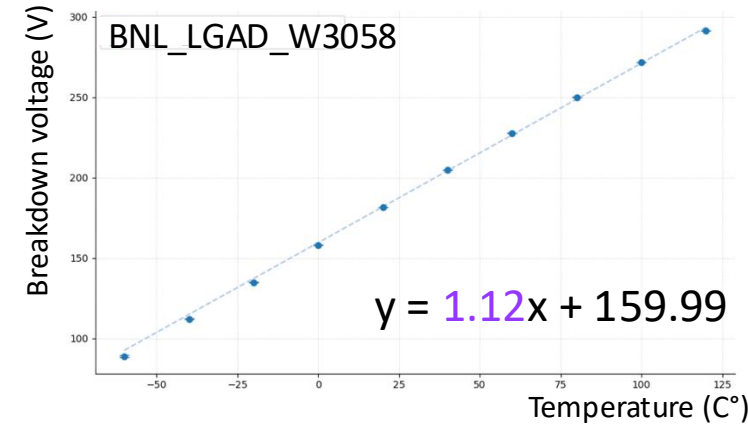
Temperature

- ▶ Depletion voltage: Constant
- ▶ Leakage current: Exponential
- ▶ Breakdown voltage: Linear



Understanding of test results

Sensor	Thickness (μm)	Slope ($\text{V}/^\circ\text{C}$)
BNL_LGAD_W3045	50	1.09
BNL_LGAD_W3058	50	1.12
BNL_ACLGAD_W3081_5_11	20	0.41
BNL_LGAD_W3076_5_13	20	0.47
BNL_LGAD_W3076_12_13	20	0.38
BNL_LGAD_W3076_9_13	20	0.47

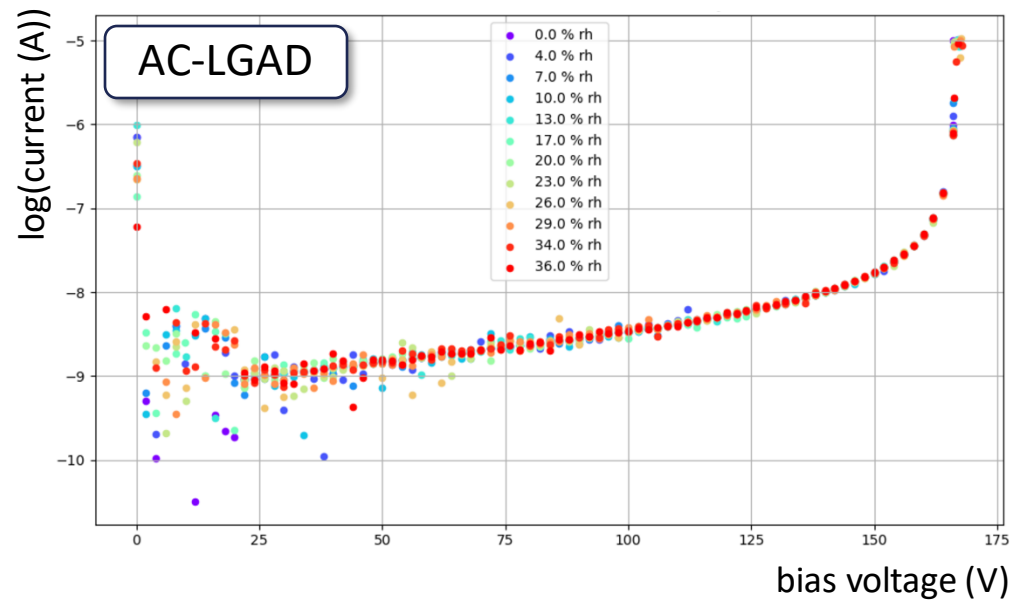
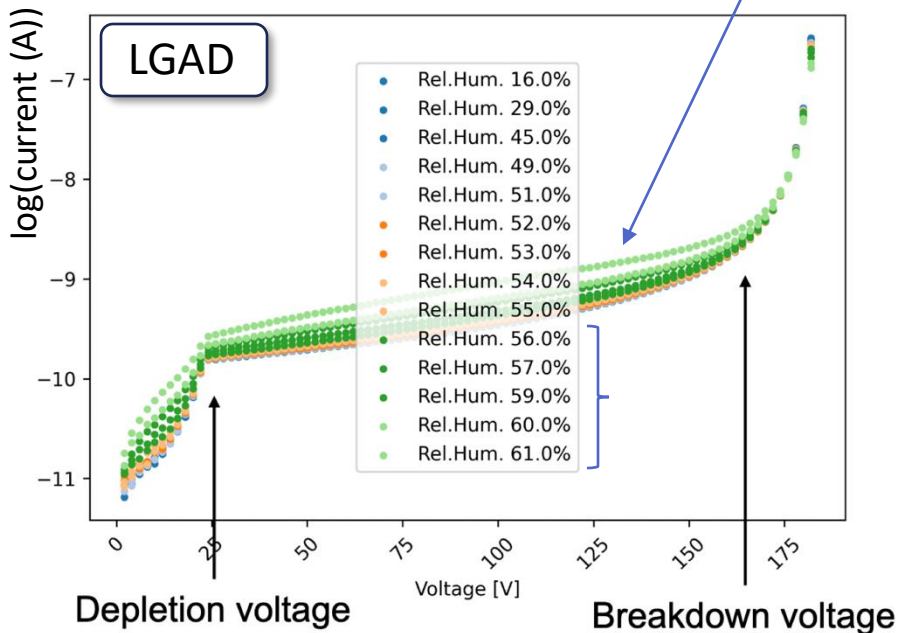


- ▶ Breakdown voltage may tend to change more rapidly for **thick** sensors
- ▶ **Other factors** such as annealing time, and etc.: under investigation

Recap of test results

Humidity

- ▶ Depletion voltage: Constant
- ▶ Breakdown voltage: Constant
- ▶ Leakage current: Increase at high humidity

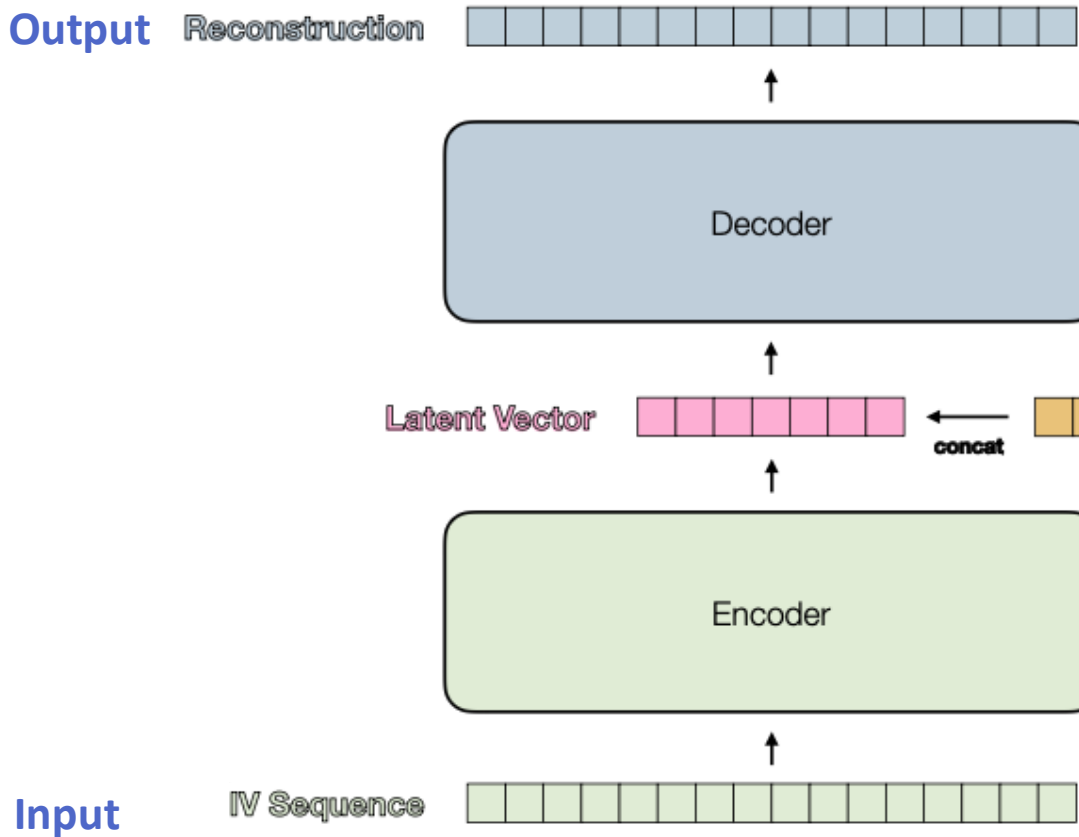


Humidity not high enough to observe the increase in leakage current

Uncover effects of environmental factors



- ▶ **Goal:** Understand the effect **environmental factors**
- ▶ **Autoencoder** can help



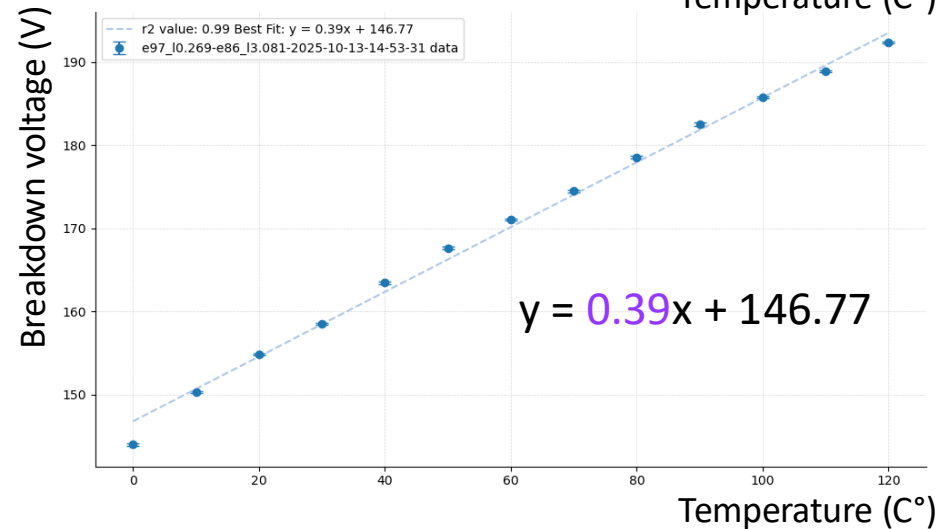
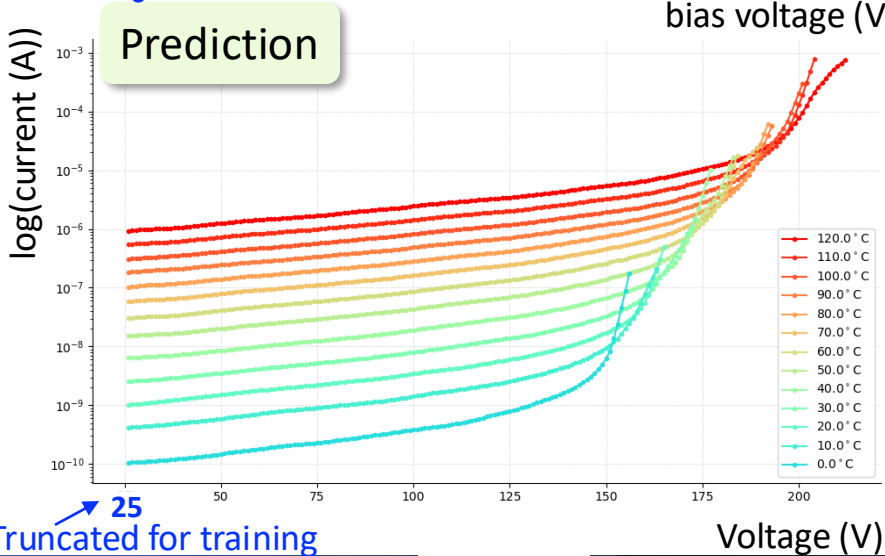
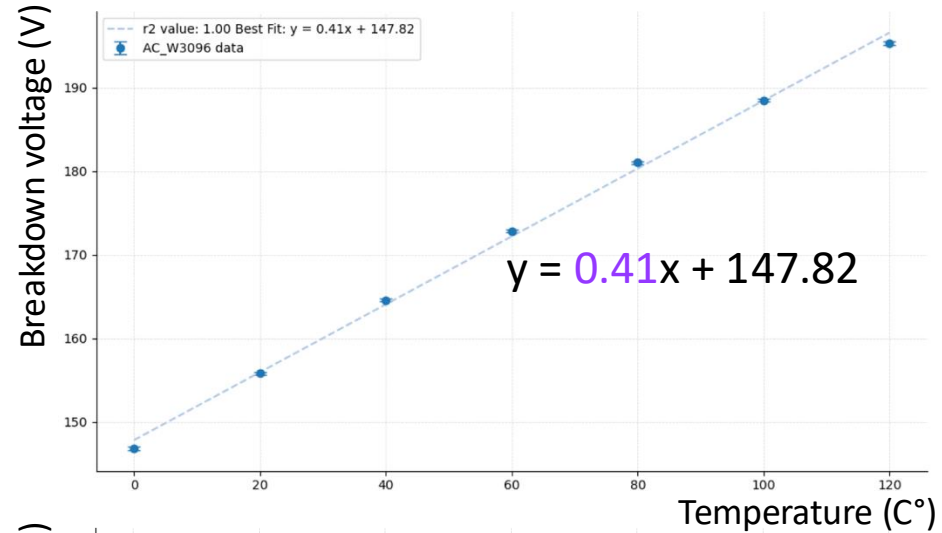
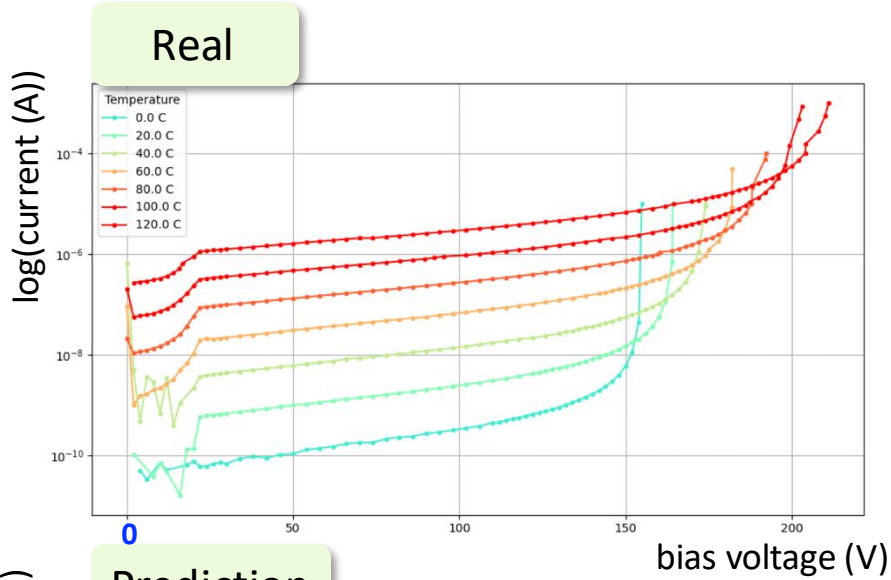
Environmental Variables

- ▶ Temperature
- ▶ Humidity
- ▶ Ramp type
- ▶ Sensor ID
- ▶ Sensor thickness
- ▶ Sensor type (LGAD/AC-LGAD)

Preliminary Results



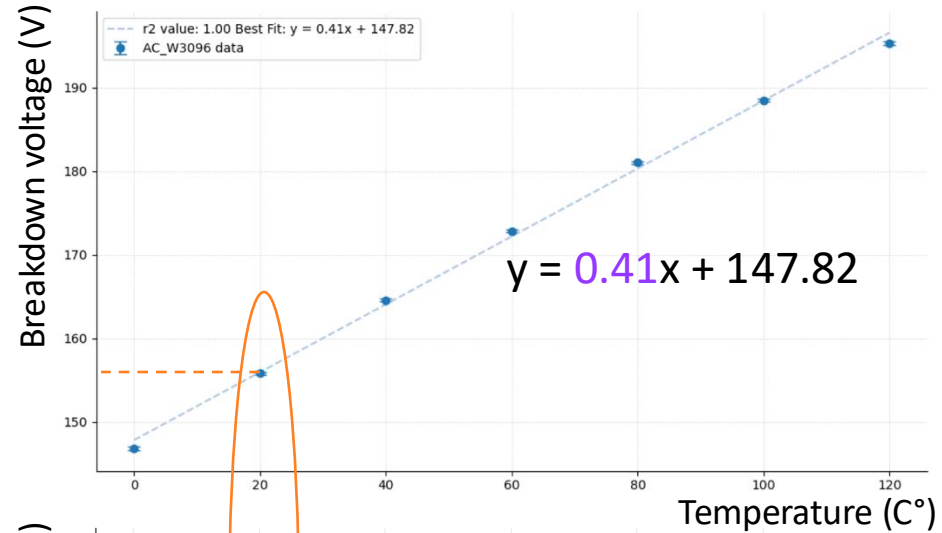
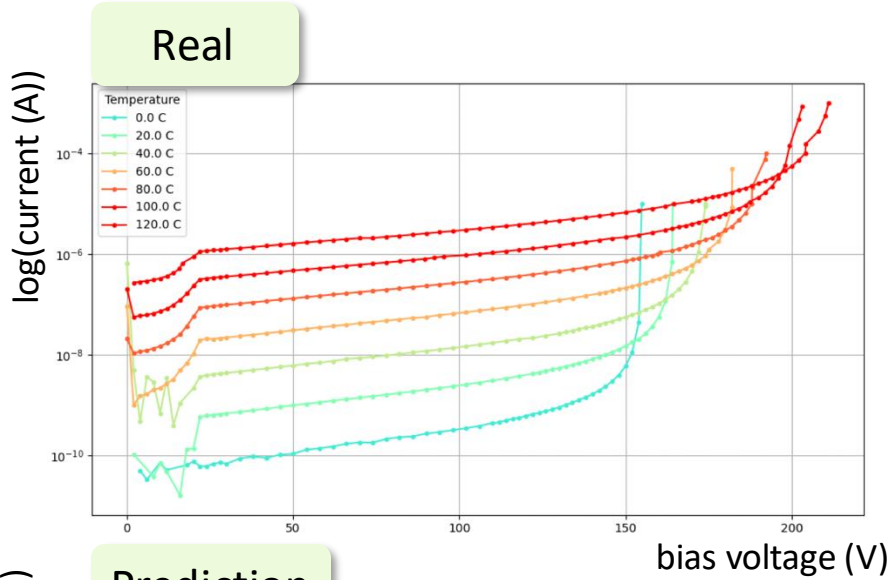
► Prediction of IV curve for various temperatures



Preliminary Results



Prediction of IV curve for various temperatures

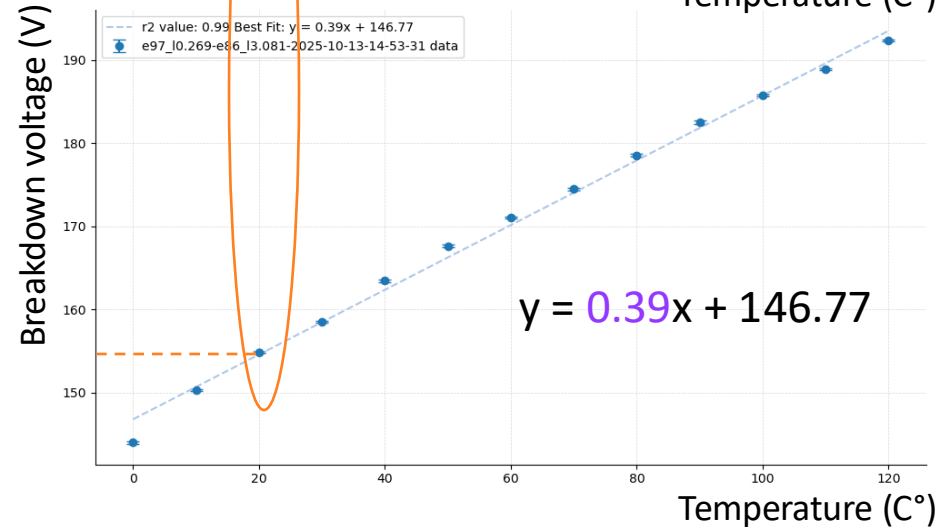


Prediction

- ▶ Reconstructed breakdown voltage correctly **reflects the real data**
- ▶ Correctly predicts the linear trend
- ▶ Best fit slope close to the actual value
- ▶ Able to interpolate

log(current (A))

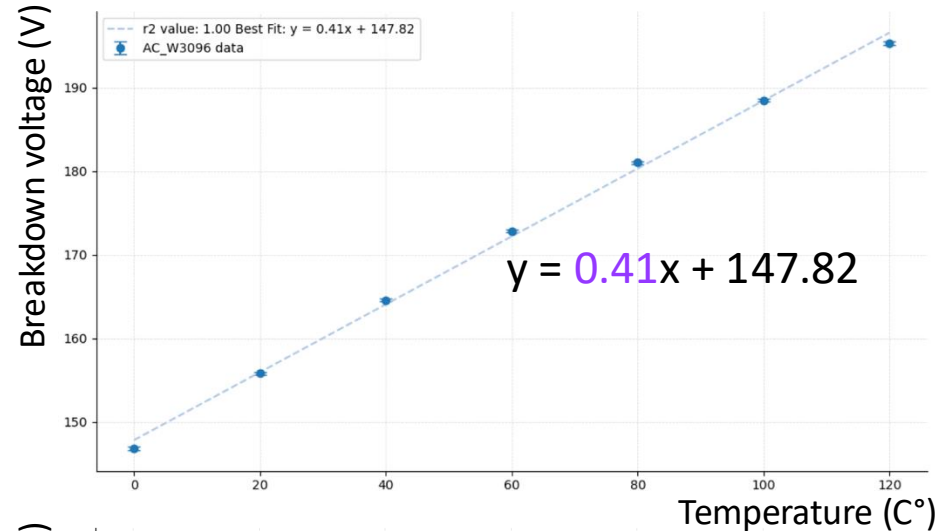
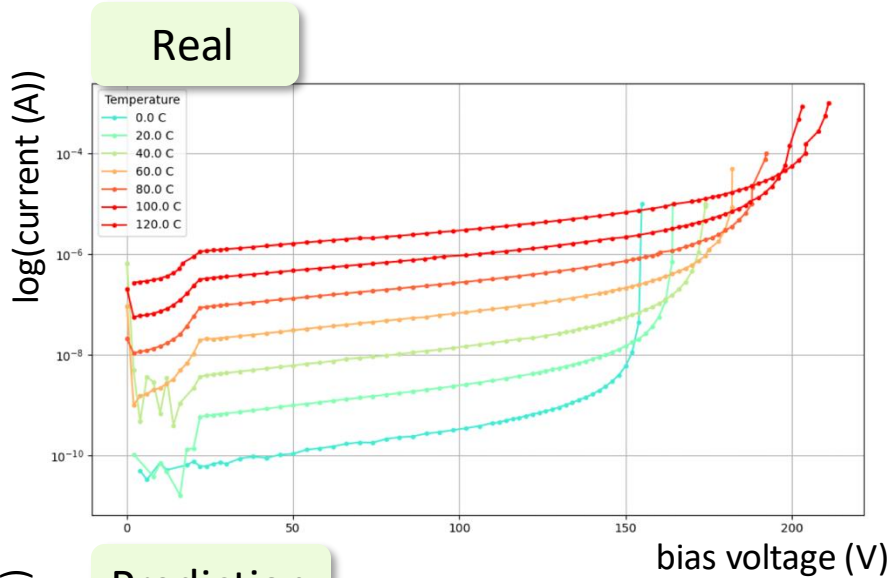
Voltage (V)



Preliminary Results

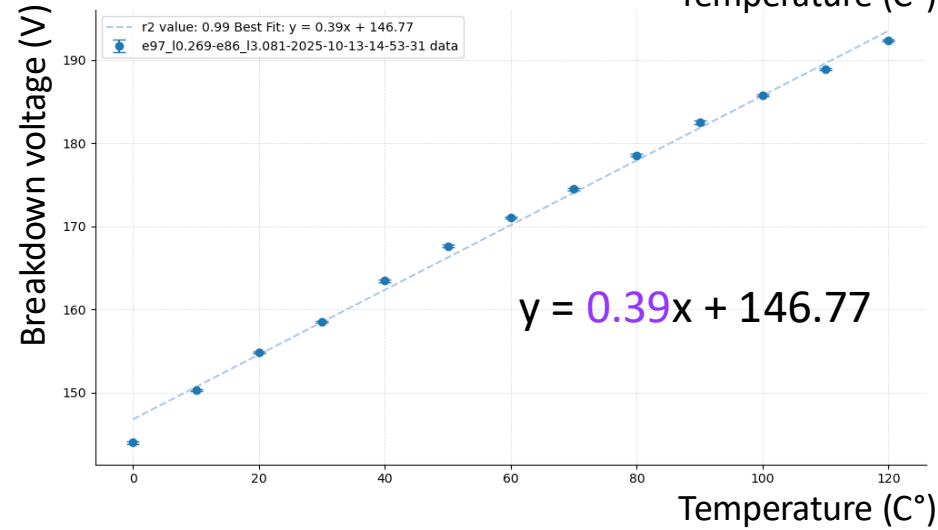


► Prediction of IV curve for various temperatures



Prediction

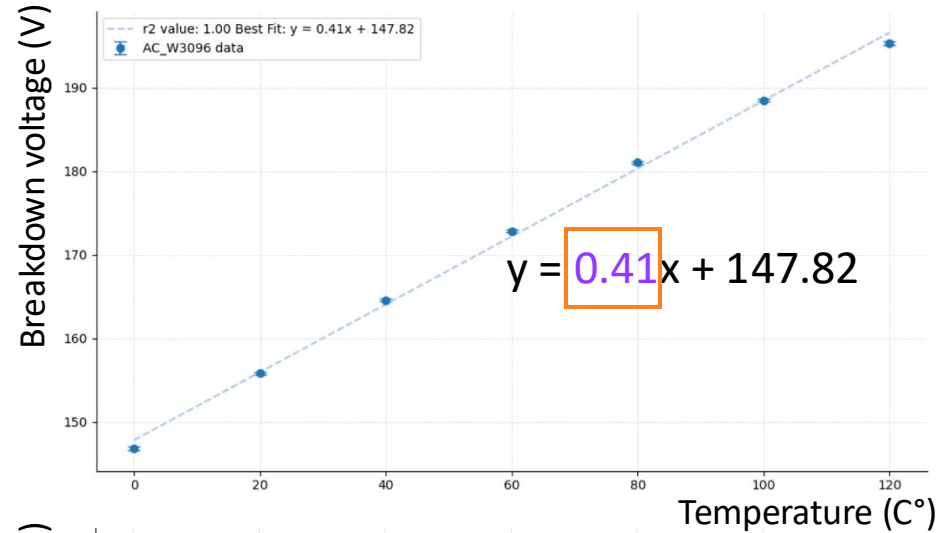
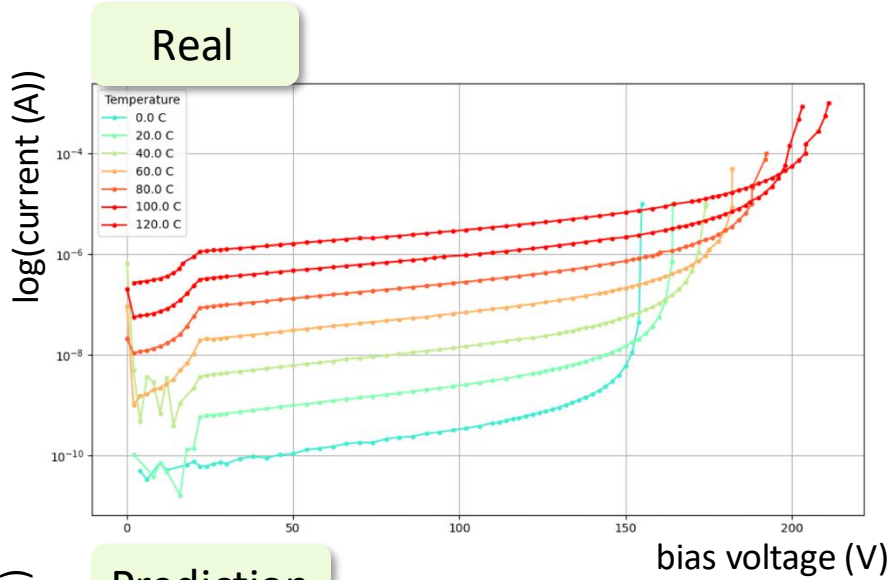
- Reconstructed breakdown voltage correctly reflects the real data
- Correctly predicts the **linear** trend
- Best fit slope close to the actual value
- Able to interpolate



Preliminary Results

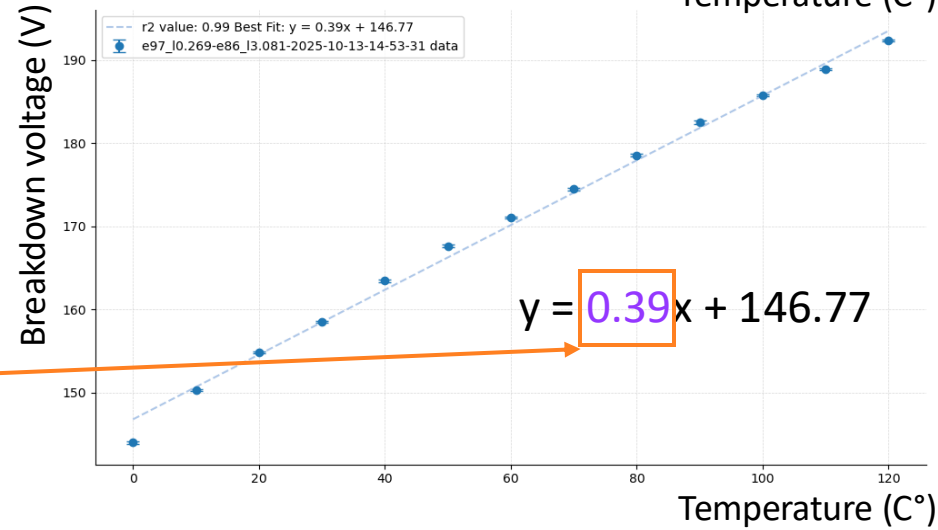


► Prediction of IV curve for various temperatures



Prediction

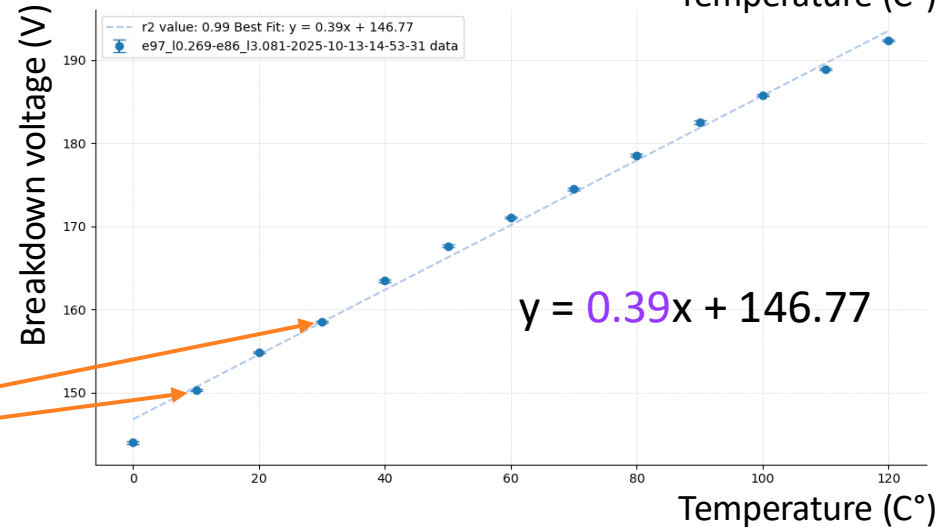
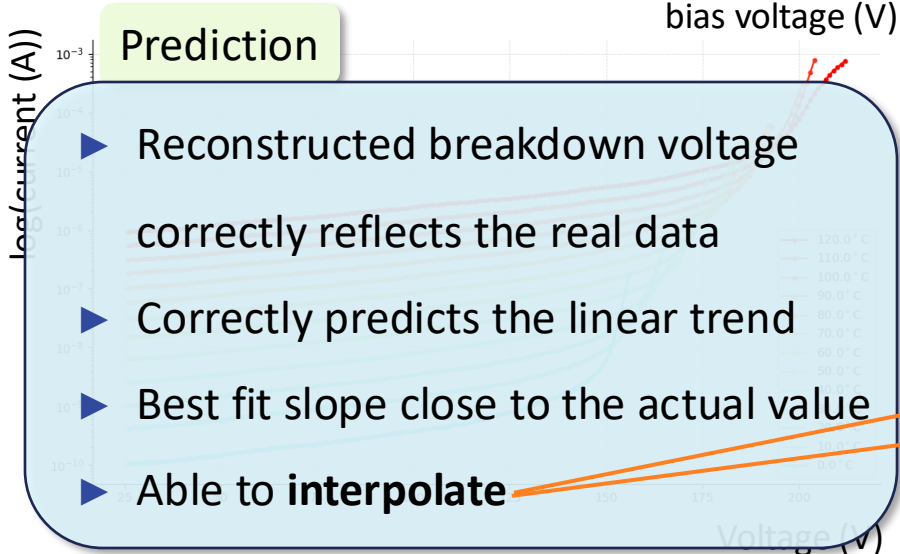
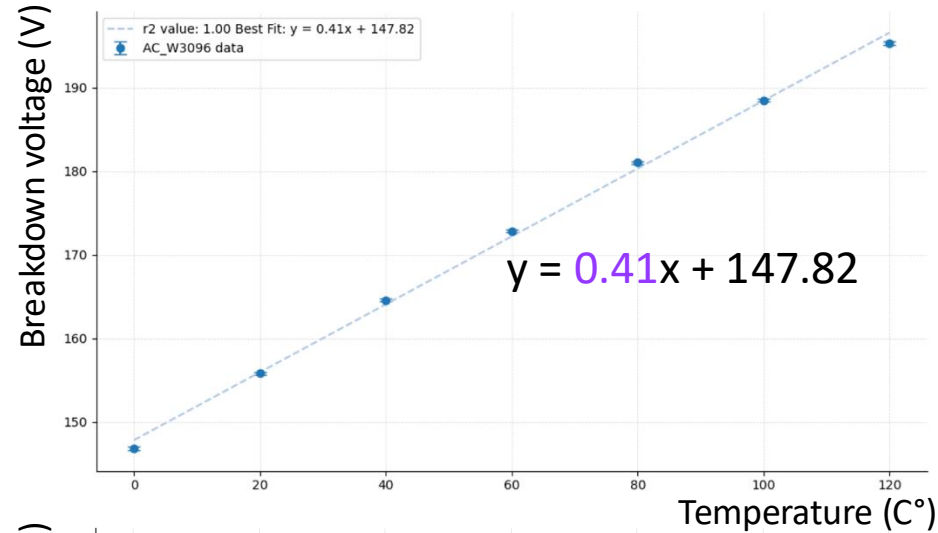
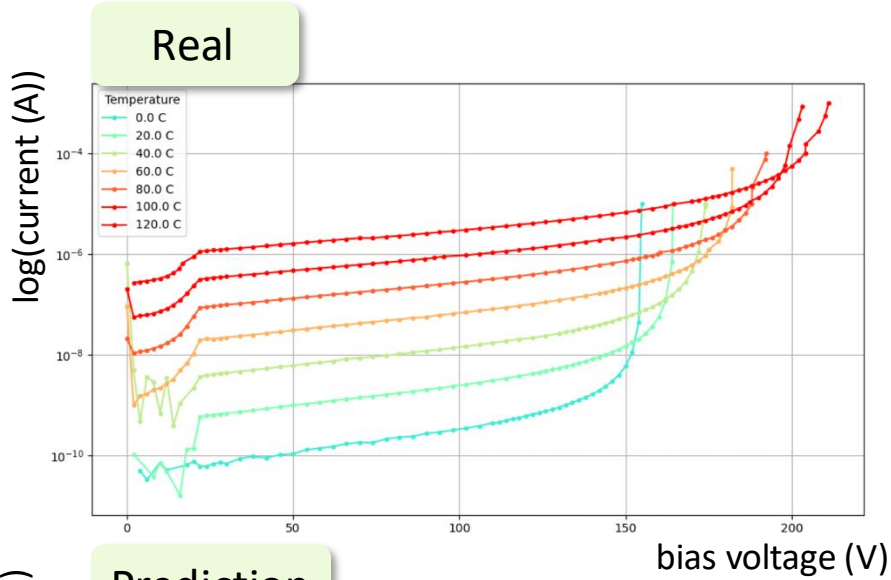
- Reconstructed breakdown voltage correctly reflects the real data
- Correctly predicts the linear trend
- Best fit **slope** close to the actual value
- Able to interpolate



Preliminary Results



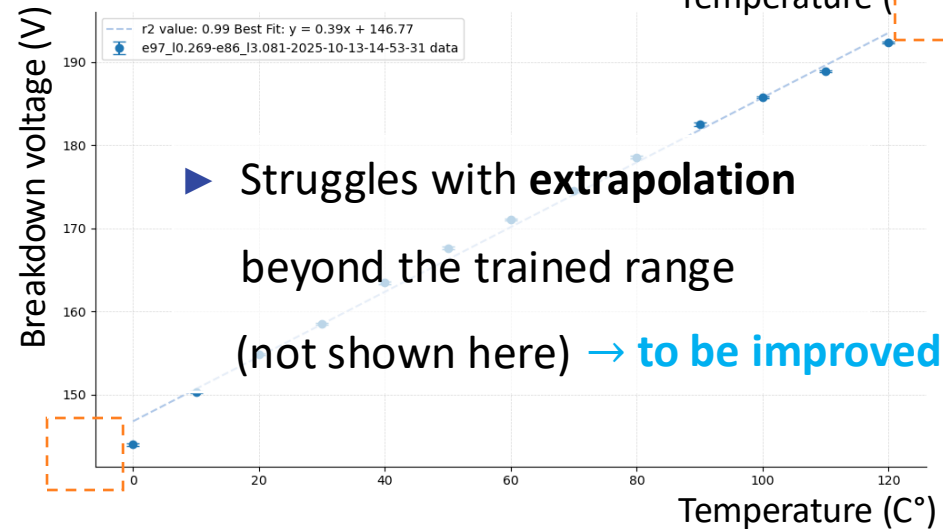
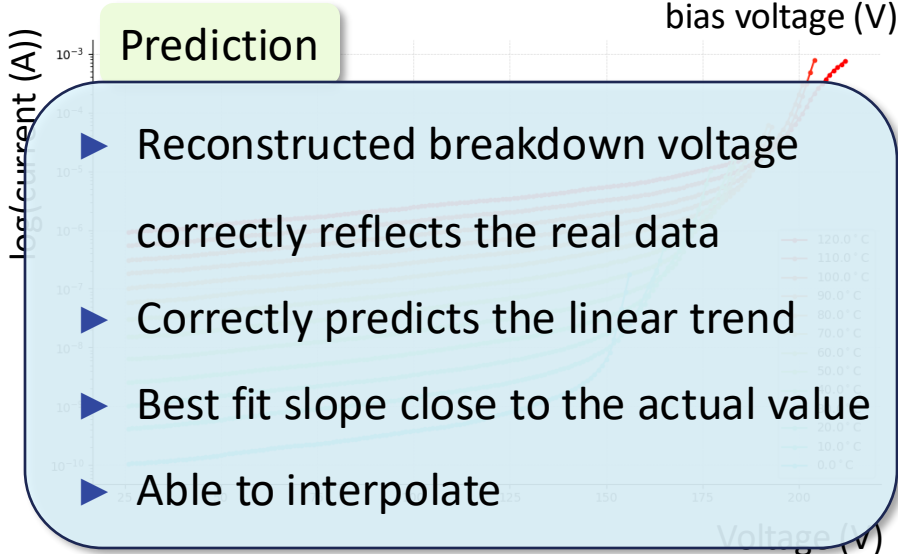
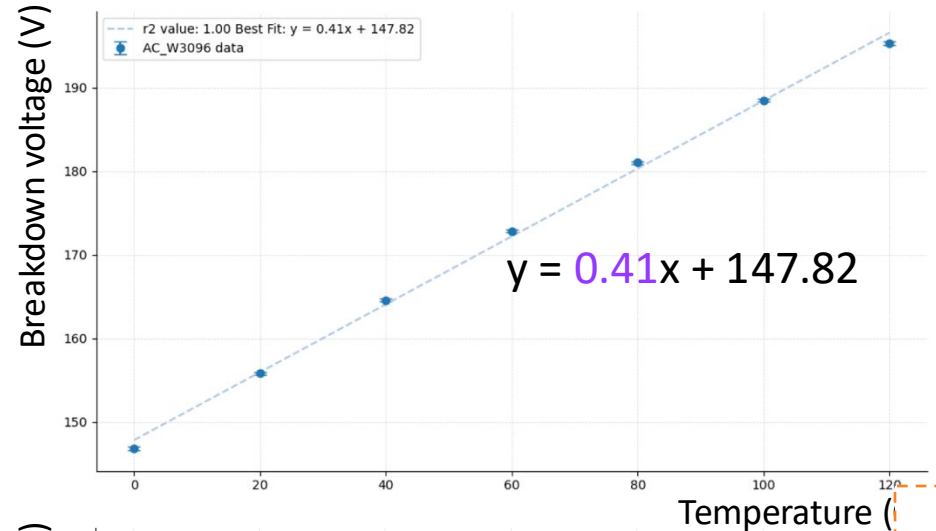
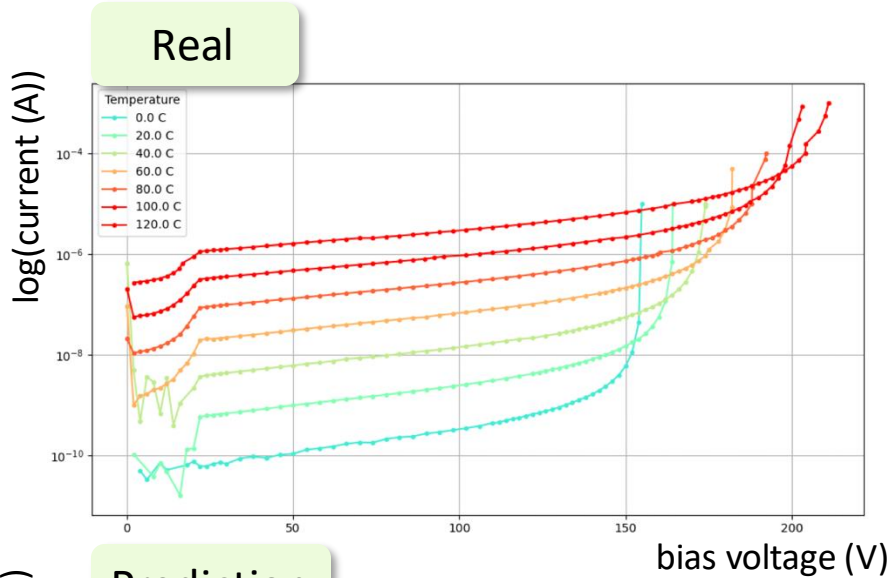
Prediction of IV curve for various temperatures



- ▶ Reconstructed breakdown voltage correctly reflects the real data
- ▶ Correctly predicts the linear trend
- ▶ Best fit slope close to the actual value
- ▶ Able to **interpolate**

Preliminary Results

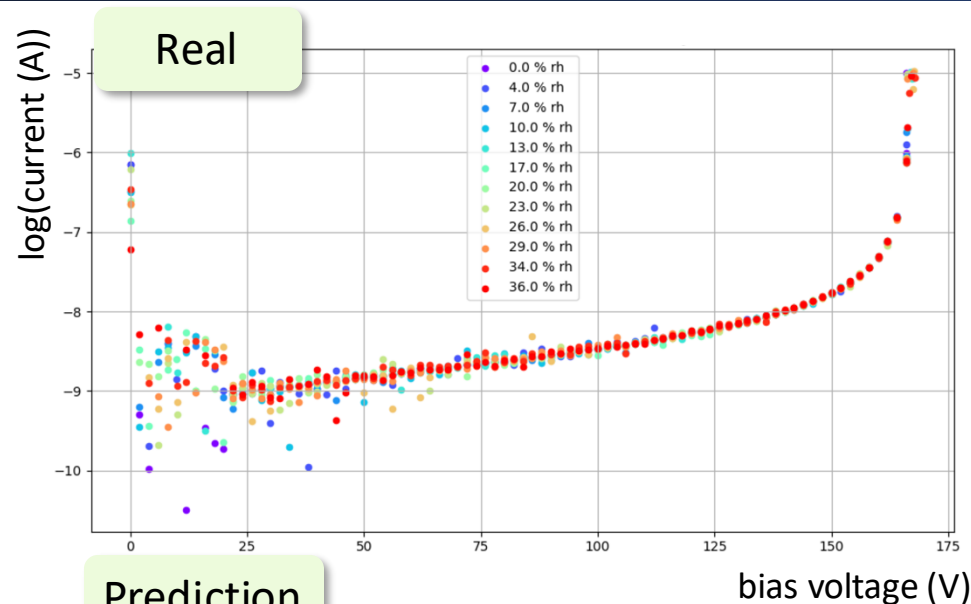
Prediction of IV curve for various temperatures



- ▶ Reconstructed breakdown voltage correctly reflects the real data
- ▶ Correctly predicts the linear trend
- ▶ Best fit slope close to the actual value
- ▶ Able to interpolate

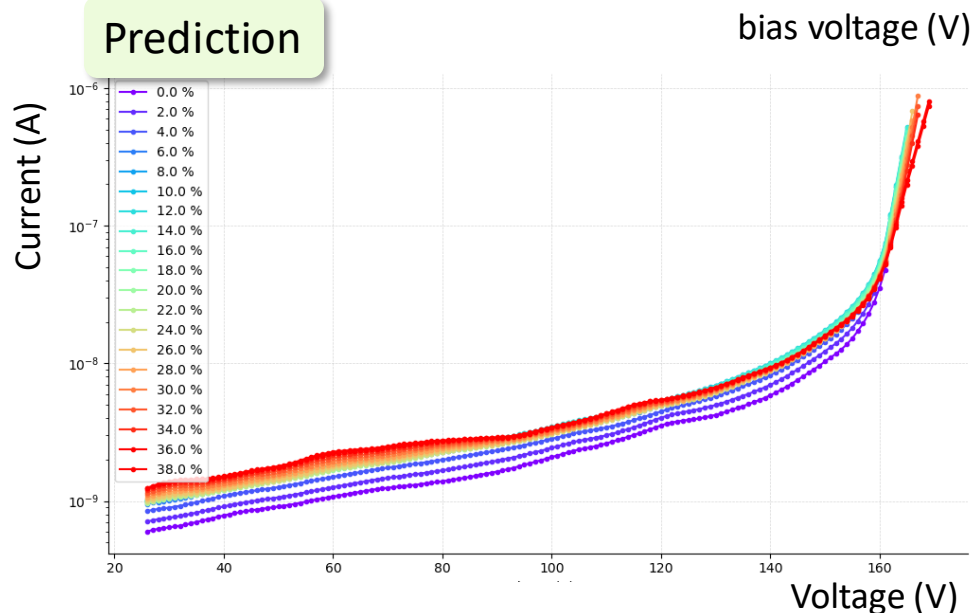
- ▶ Struggles with **extrapolation** beyond the trained range (not shown here) → **to be improved**

Preliminary Results



► IV prediction for various **relative humidities**

► Post-depletion IV curve and breakdown voltage **constant** to humidity change



► Some **small variations** in the predicted IV curve with respect to humidity change

→ **to be improved**

- ▶ Improve the ML prediction of IV curve and breakdown voltage
 - ▶ Collect **more data** with more sensors
 - ▶ More sensors are coming through a DRD3 production run at BNL
 - ▶ Further simplify the model to allow better **generalization**
- ▶ Test **irradiated sensors**, sensors with different doping profiles and thickness
- ▶ Extend the study to the signal response of LGAD and AC-LGAD with respect to
 - ▶ Beta source (Sr), test beam, TCT
- ▶ Create physics simulation of LGAD/AC-LGAD for further study

We welcome more collaborators!

Part of a DRD3 project



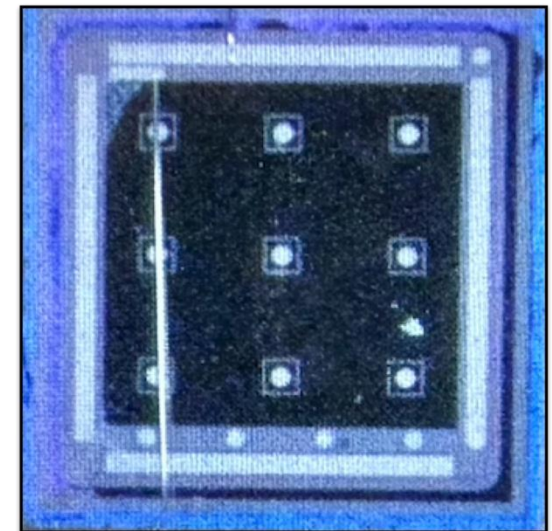
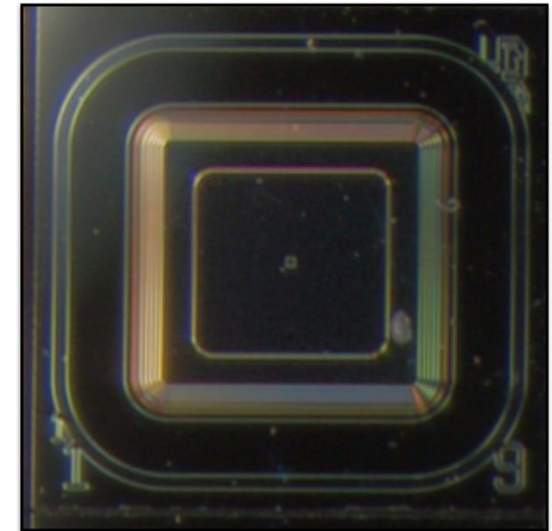
Thank you for your attention!

- ▶ **Sensor fabrication**

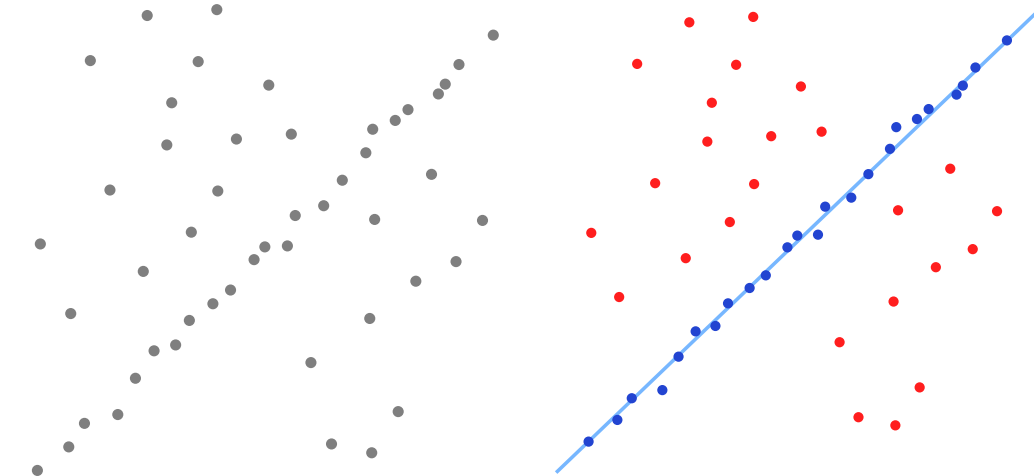
- ▶ Sensor size
- ▶ Gain characteristics
- ▶ Depletion layers size

- ▶ Enable **application-specific designs**

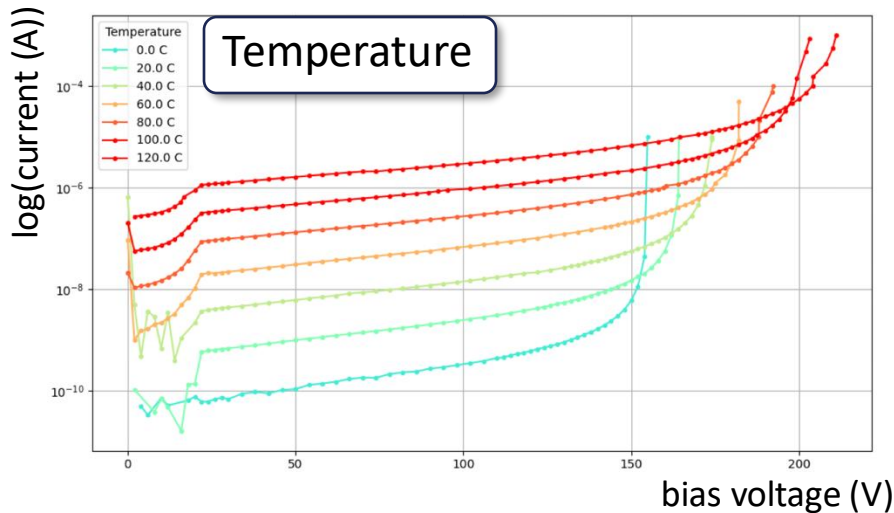
- ▶ Material budget
- ▶ Energy consumption
- ▶ Resilience to changes in the environment
 - ▶ Space applications:
 - ▶ Temperature variations: $-100\text{ }^{\circ}\text{C}$ to $+100\text{ }^{\circ}\text{C}$



▶ RANdom SAmple Consensus (RANSAC)



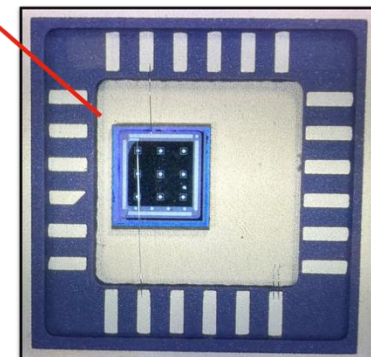
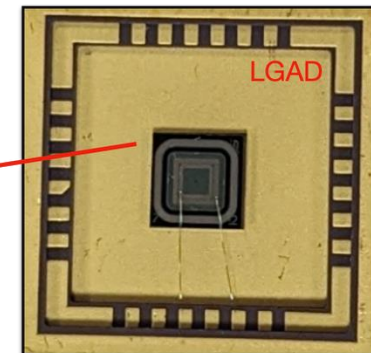
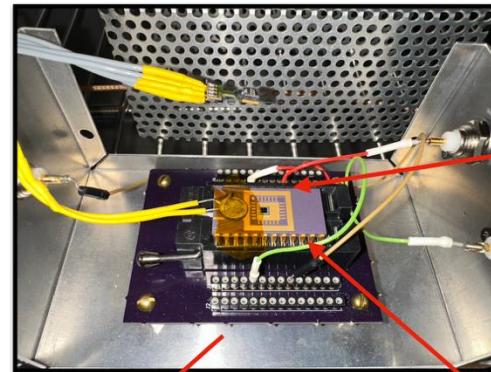
- ▶ Dataset with outliers
- ▶ Use random subsets for the fit
- ▶ Goodness of fit: RMS
 - ▶ Samples with mostly inliers
→ smallest RMS

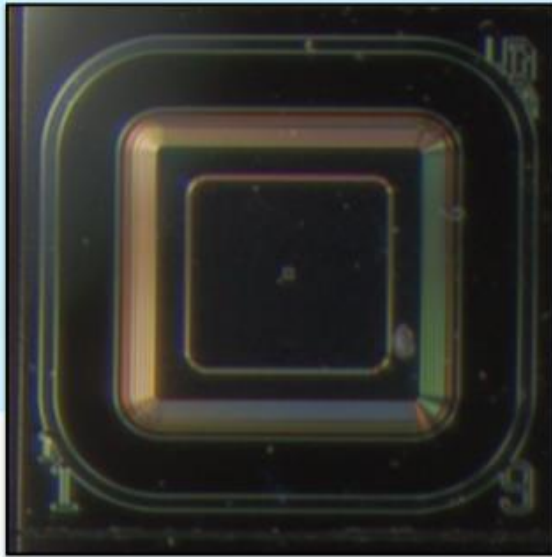


▶ Robust for noisy data:
important at low temperatures

Backup – Training data

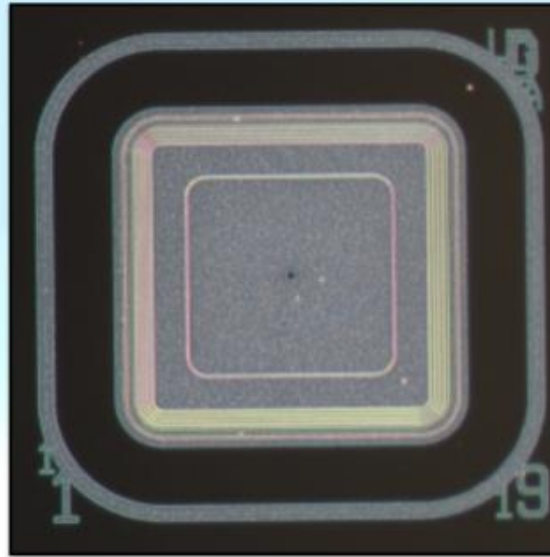
- ▶ Training sample: 369 IV curves
- ▶ IV scan under various temperatures and relative humidities
- ▶ 5 LGADs, 1 AC-LGAD: different thickness and area of gain layer





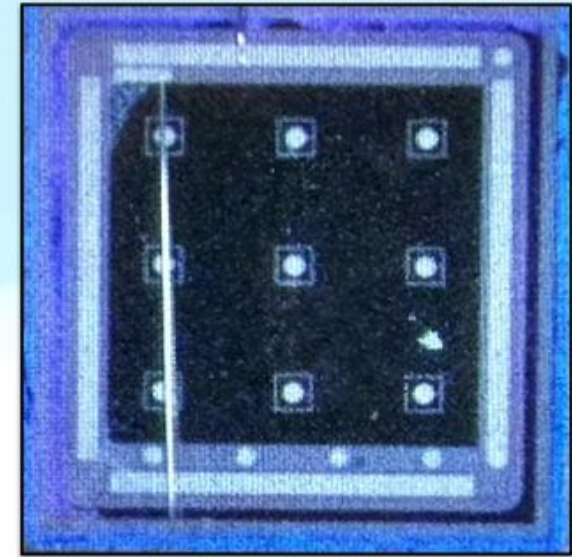
W3045

- First production at BNL
- 1.3 mm² active area
- 2.8 x 10¹² cm⁻², 380 keV gain layer
- High-dose shallow phosphorous layer
- Implants done through naked silicon oxide
- 50 μm thick



W3058

- Newer production at BNL
- 1.3 mm² active area
- 2.95 x 10¹² cm⁻², 380 keV gain layer
- High-dose shallow phosphorous layer
- Implants done through 15 nm of silicon oxide
- 50 μm thick



W3081

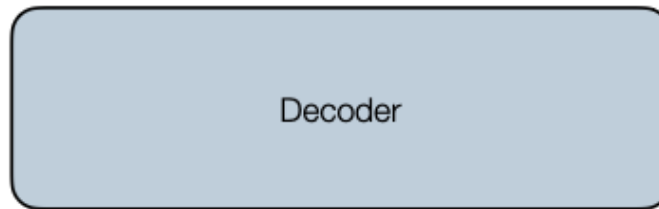
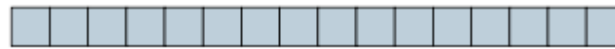
- AC-LGAD production at BNL
- 1.3 mm² active area
- 2.45 x 10¹² cm⁻², 380 keV gain layer
- Medium-dose shallow phosphorous layer
- Implants done through 15 nm of silicon oxide
- 20 μm thick
- Unintentionally much higher annealing time (~100x)

5

[Talk at CPAD](#)

▶ Step 1: train an autoencoder

Output Reconstruction



▶ Decodes representation and output reconstruction



Latent Vector



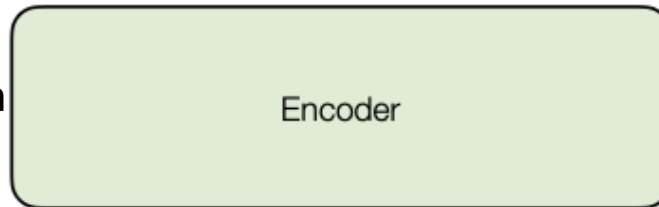
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Environmental Variables

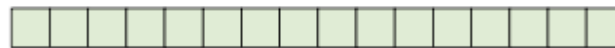


▶ Learns curve representation



Input

IV Sequence



- ▶ Temperature
- ▶ Humidity
- ▶ Ramp type
- ▶ Sensor ID
- ▶ Sensor thickness
- ▶ Sensor type (LGAD/AC-LGAD)

- ▶ Step 2: Train a separate MLP

