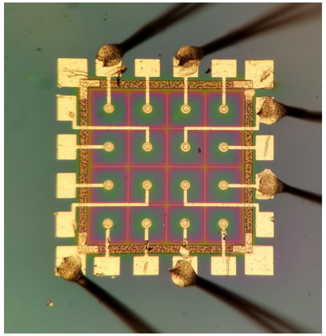
Development of (V)UV-Sensitive GaN Geiger-Mode Photodiodes



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DE-SC0019133

center for compound semiconductors

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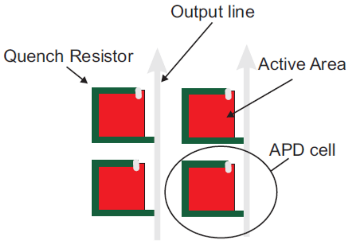
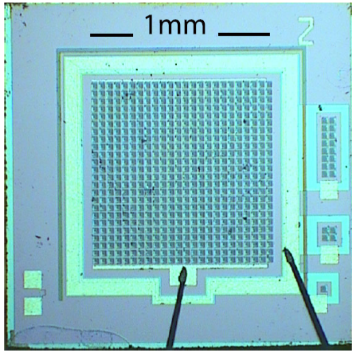
School of Physics
&
Center for Relativistic Astrophysics

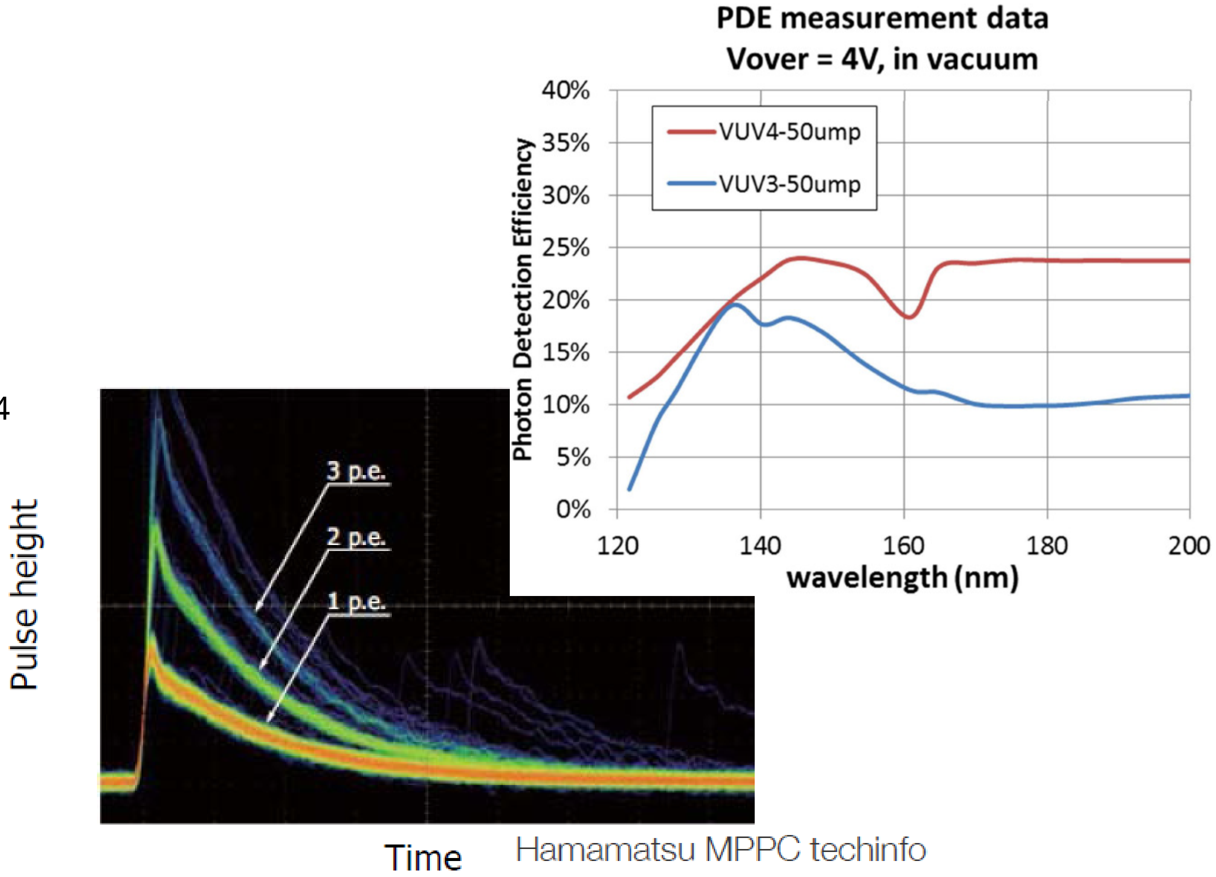
Georgia Tech | Physics
College of Sciences

The Silicon Photomultiplier or G-APD





MEPhI/Pulsar SiPM 2004

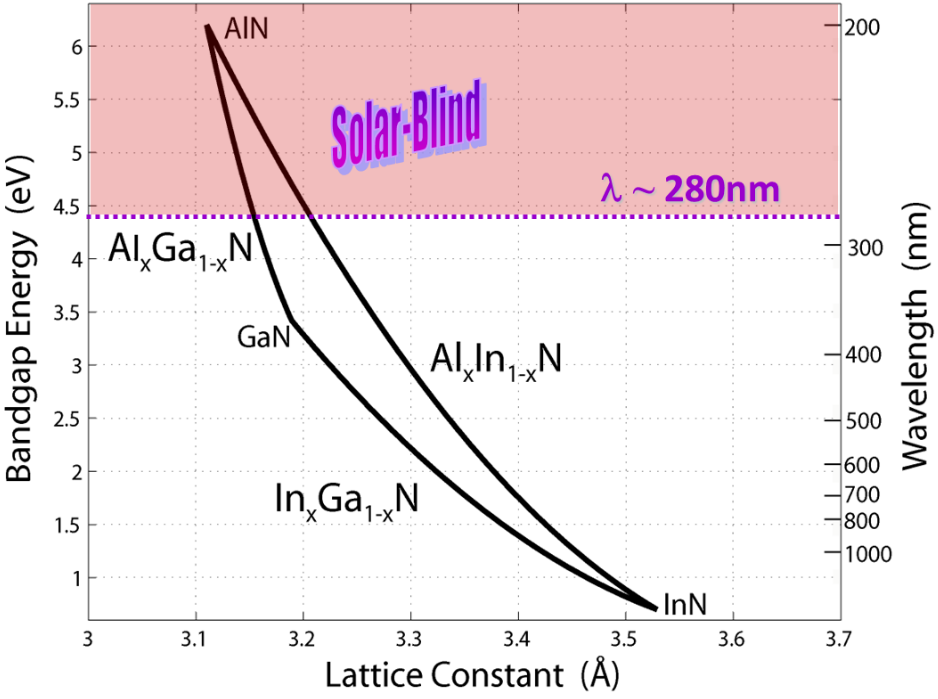


Hamamatsu MPPC techinfo

Can the SiPM concept be transferred to GaN?

Why GaN?

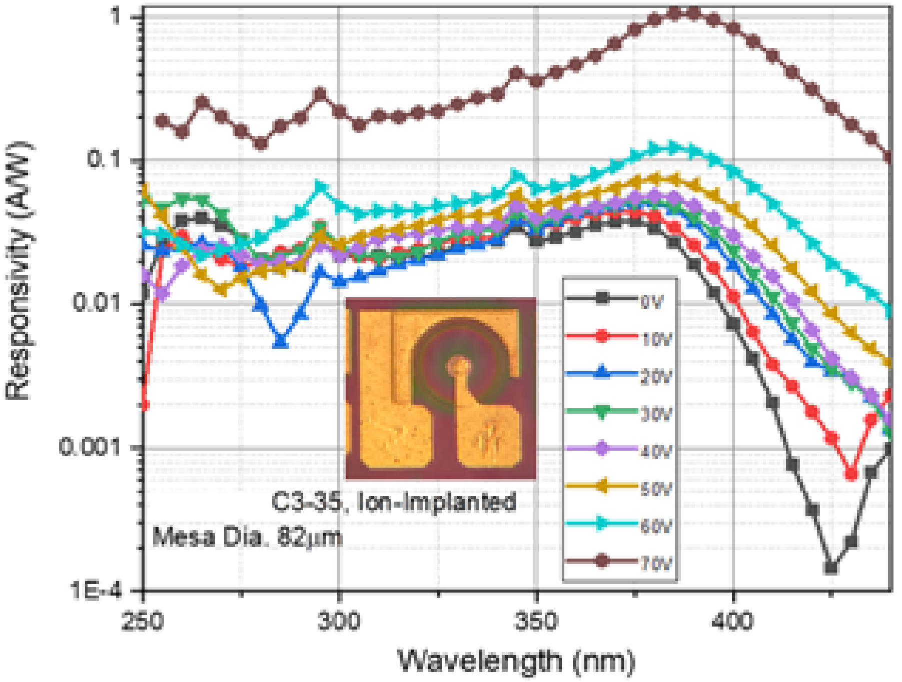
- Large bandgap
  - Tunable bandgap -> tunable spectral response
  - Potential for high UV-VUV sensitivity with little to no red sensitivity
- Sufficiently clean substrates are available
  - Geiger-mode is possible
- Increasing use of GaN in high-power electronics, LEDs, Lasers
  - Increasing supply of GaN-substrates
  - Cleaner substrates
  - Lower cost



The GaN Technical and Intellectual Challenge

- **Geiger-mode in GaN is unexplored**
  - Breakdown probability?
  - Temperature dependencies?
  - Electric field dependencies?
  - Quenching?

- **Device Fabrication**
  - Uniform breakdown characteristics
  - Low dark-count rates
  - Scalability
  - Arrays
  - …

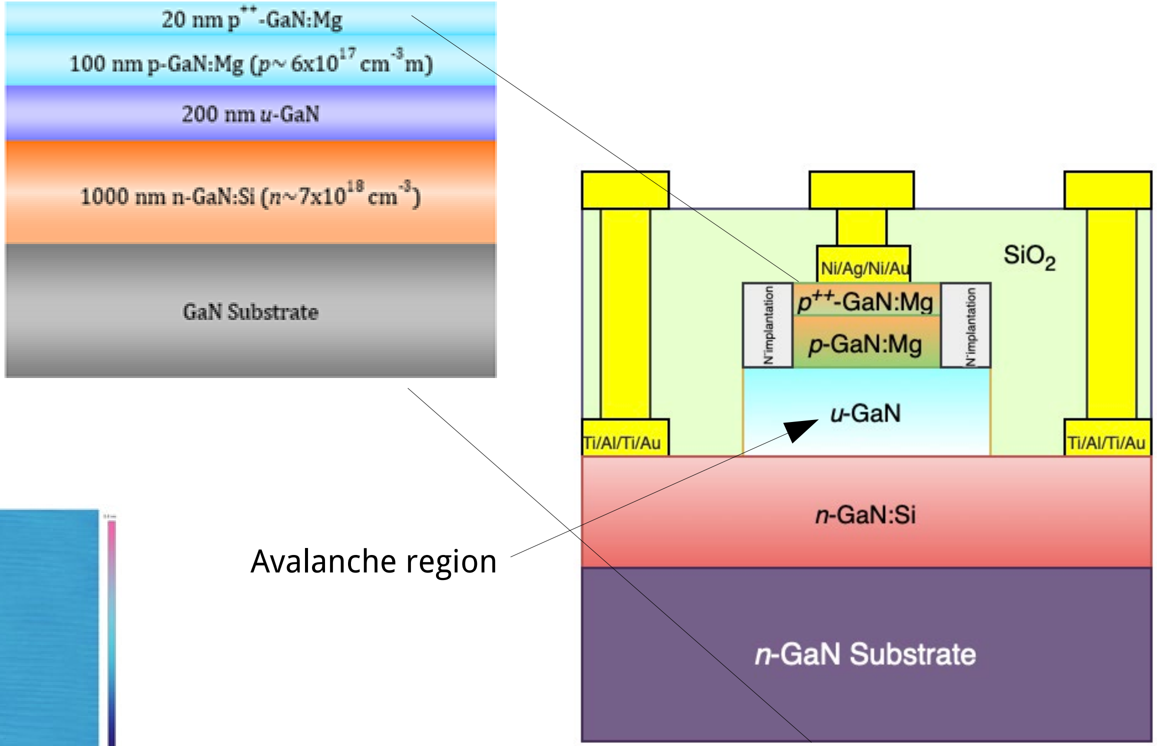


Spectral response of a 82 um-dia. Georgia Tech GaN APD

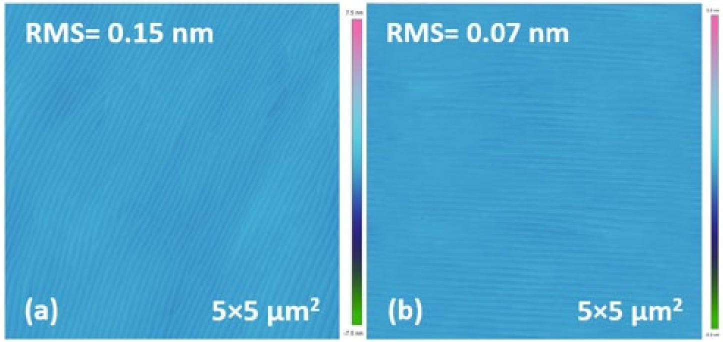
Georgia Tech GaN Structures

https://doi.org/10.1117/12.2576888

- epitaxial growth

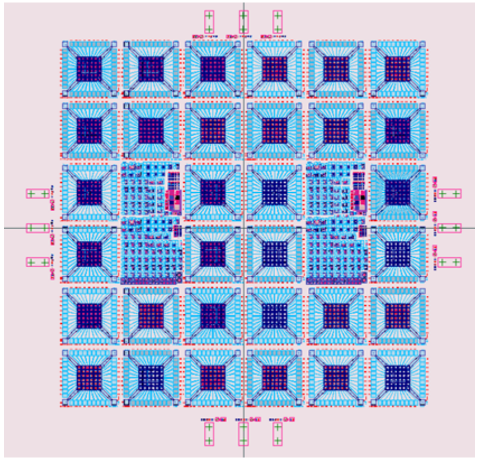


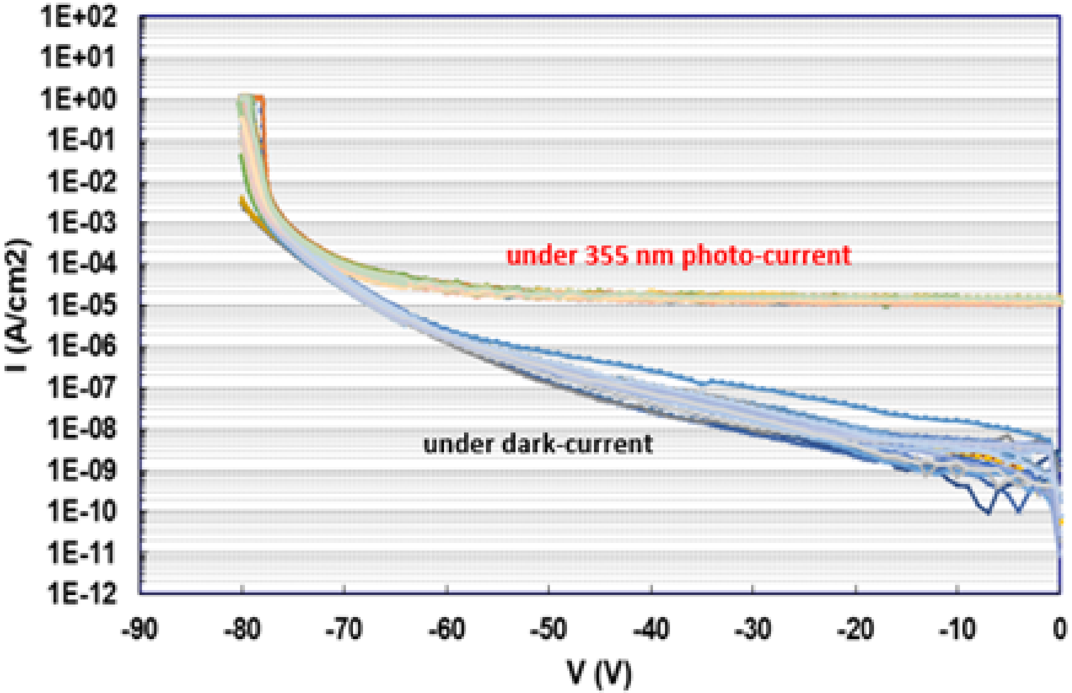
surface roughness:



Growth on: u-GaN/sapphire n-GaN bulk substrate

IV-Curves



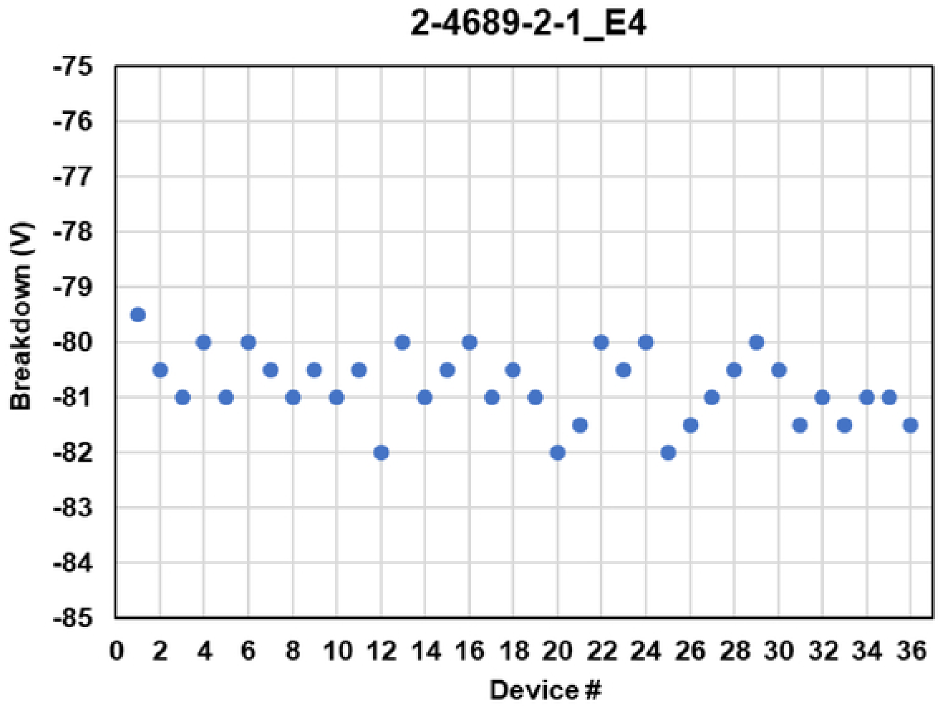


36 diode array of 60 um cells

- Uniform dark current characteristics
- Uniform light response

https://doi.org/10.1117/12.2576888

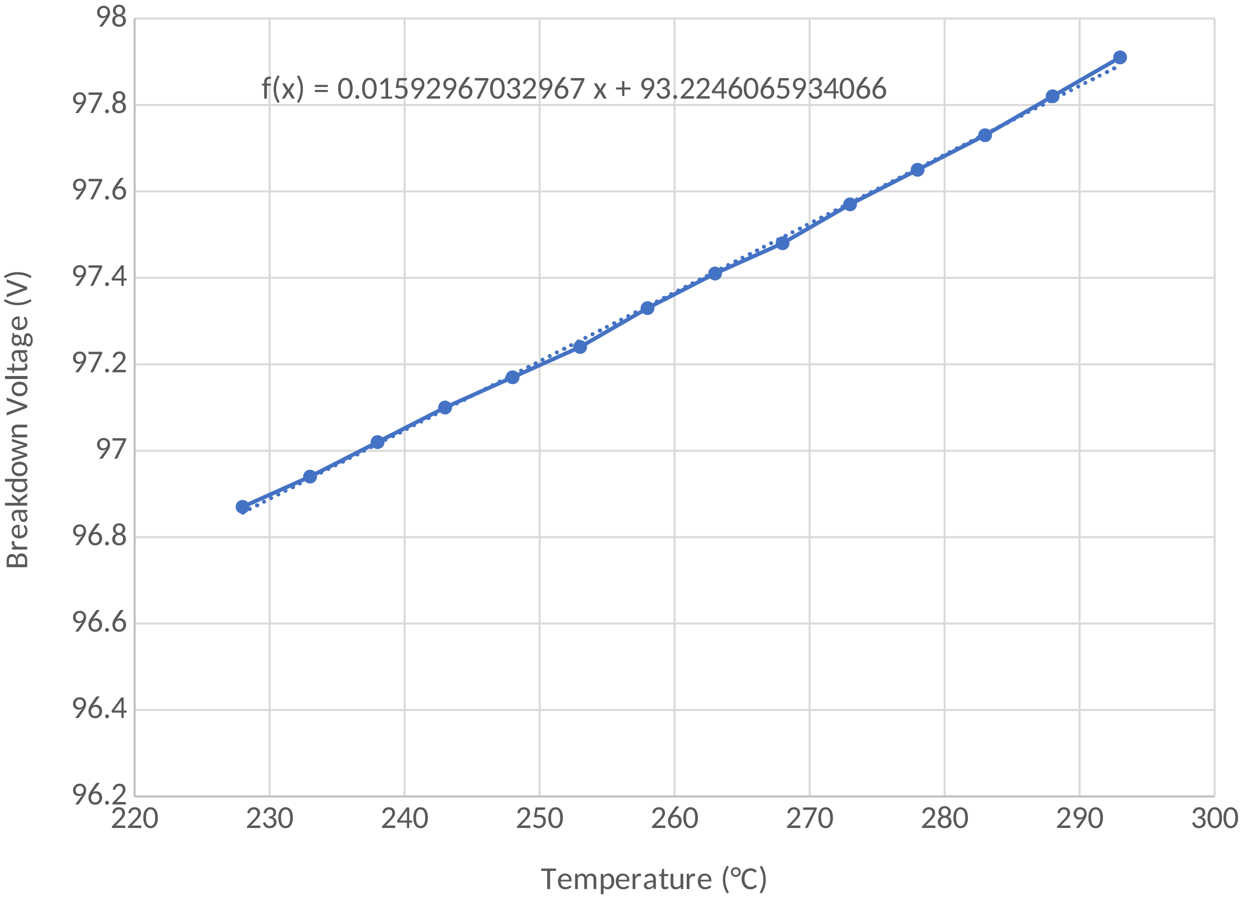
Breakdown Voltage Uniformity



- Uniform breakdown characteristics (<1% variations)

Breakdown Voltage vs. Temperature

- Breakdown voltage shifts 0.02%/K (SiPMs 0.1%/K)



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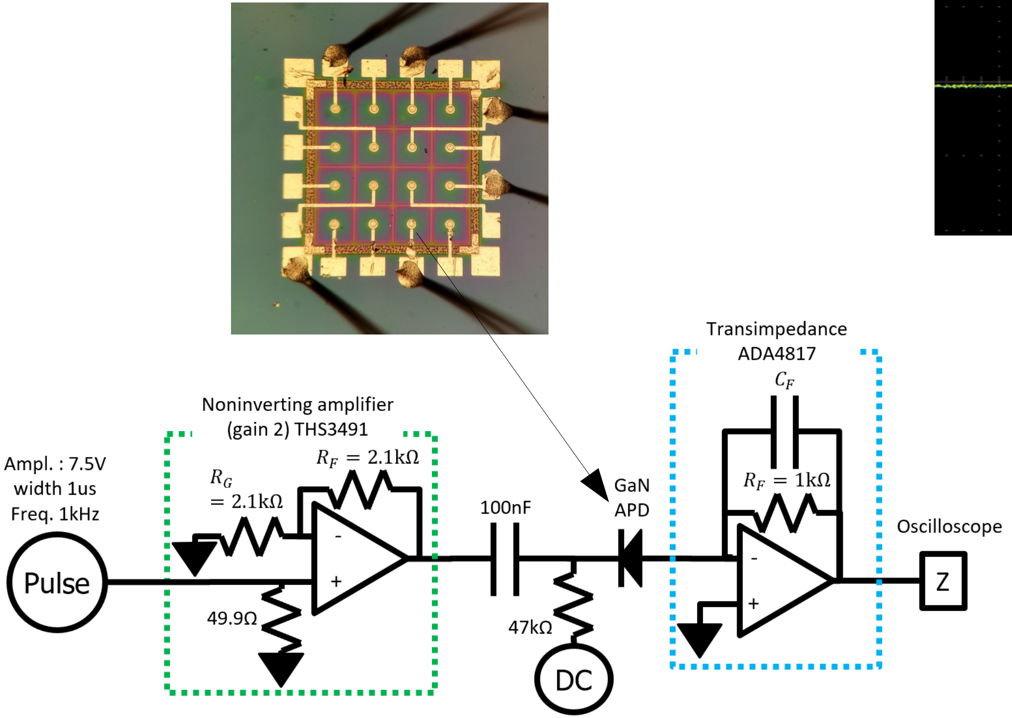
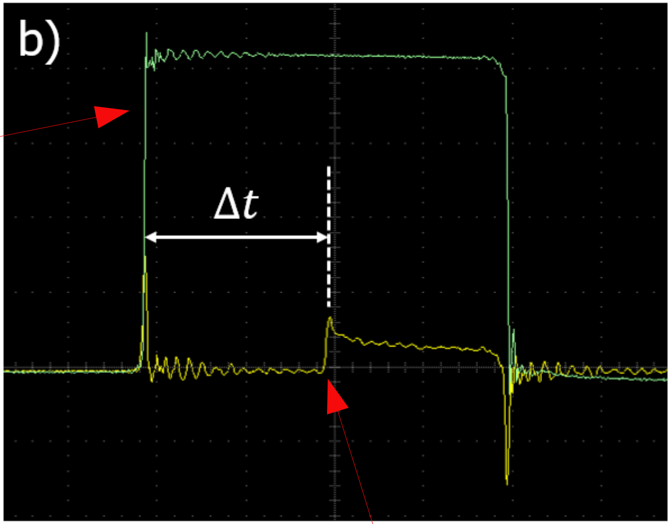
Geiger Mode Measurements

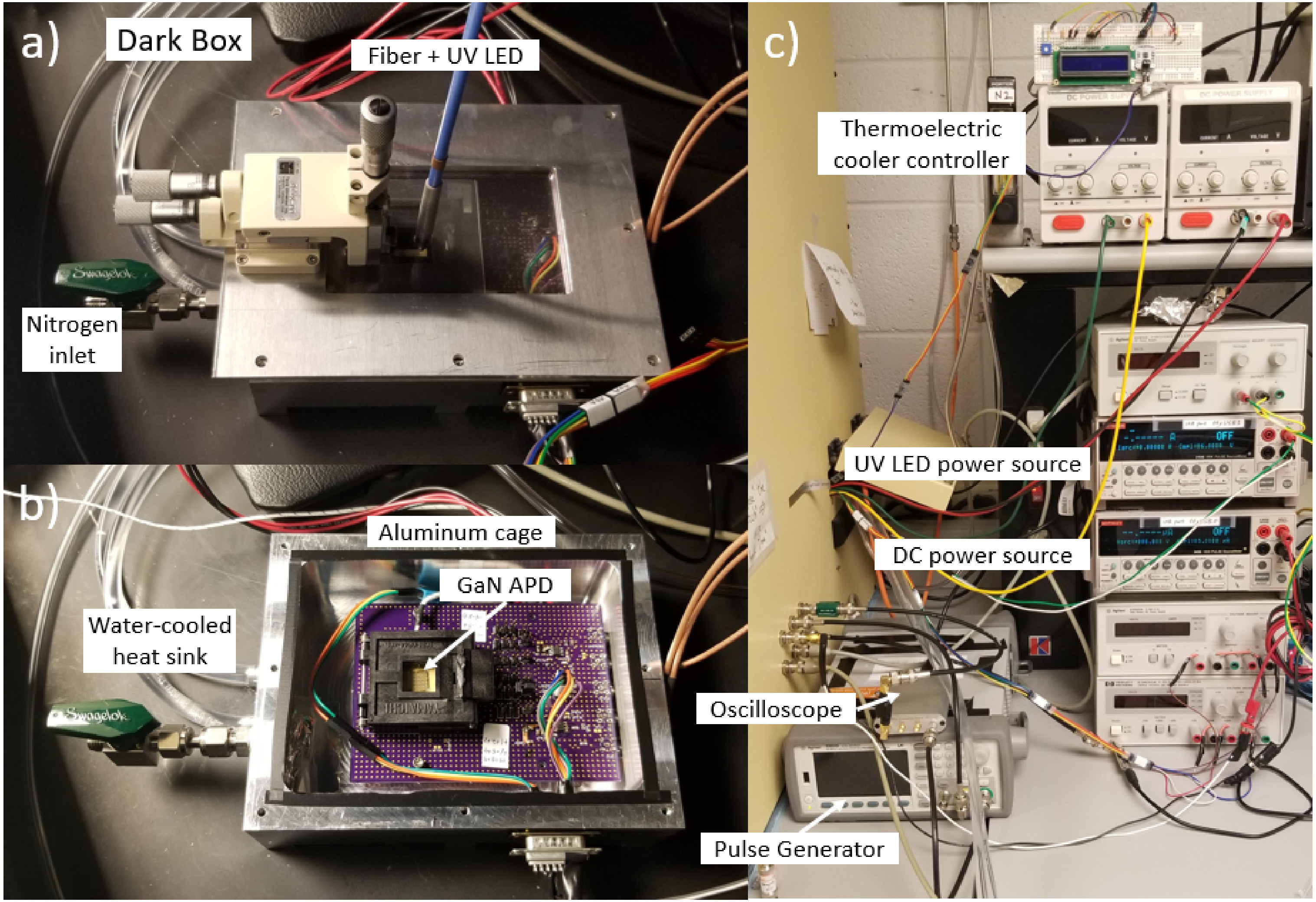
- New territory
  -> Develop setups from scratch





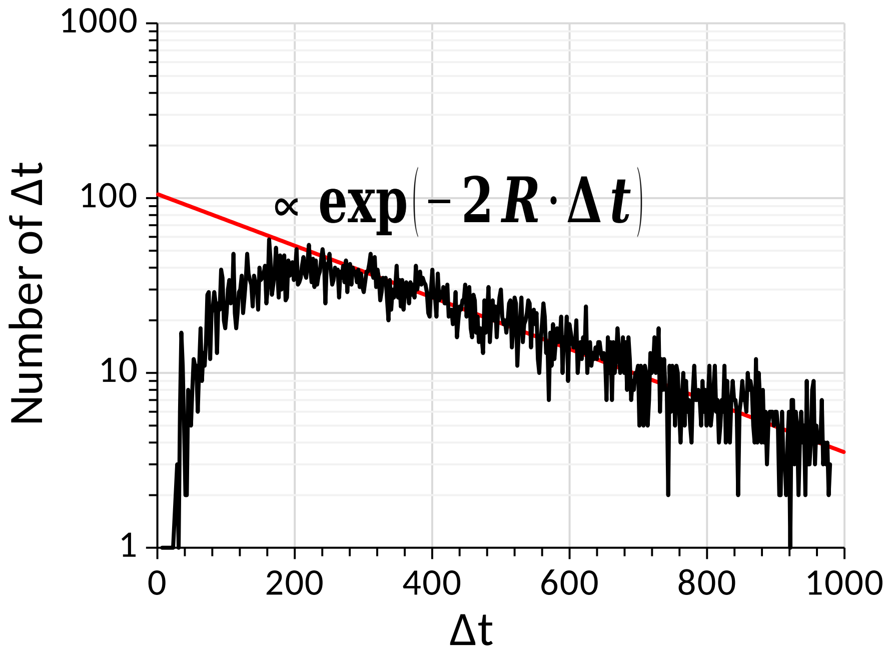
bias pulse

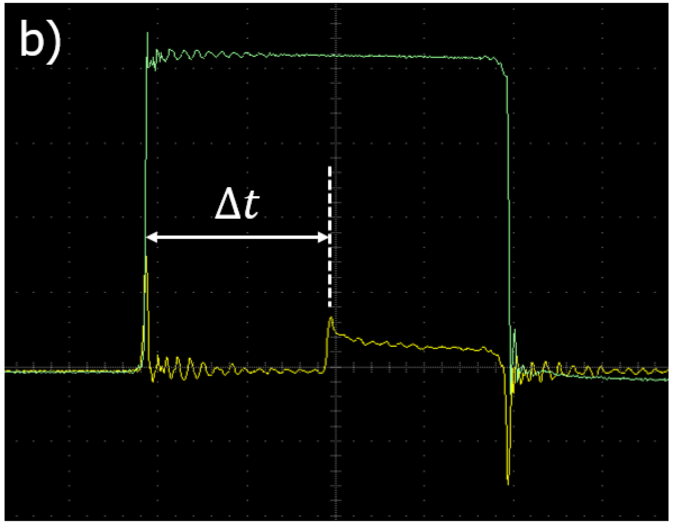
dark-count breakdown


a)
Dark Box
Fiber + UV LED
Nitrogen inlet
b)
Aluminum cage
GaN APD
Water-cooled heat sink
c)
Thermoelectric cooler controller
UV LED power source
DC power source
Oscilloscope
Pulse Generator

Count Rate Measurements

Determine count rate from Δt distribution





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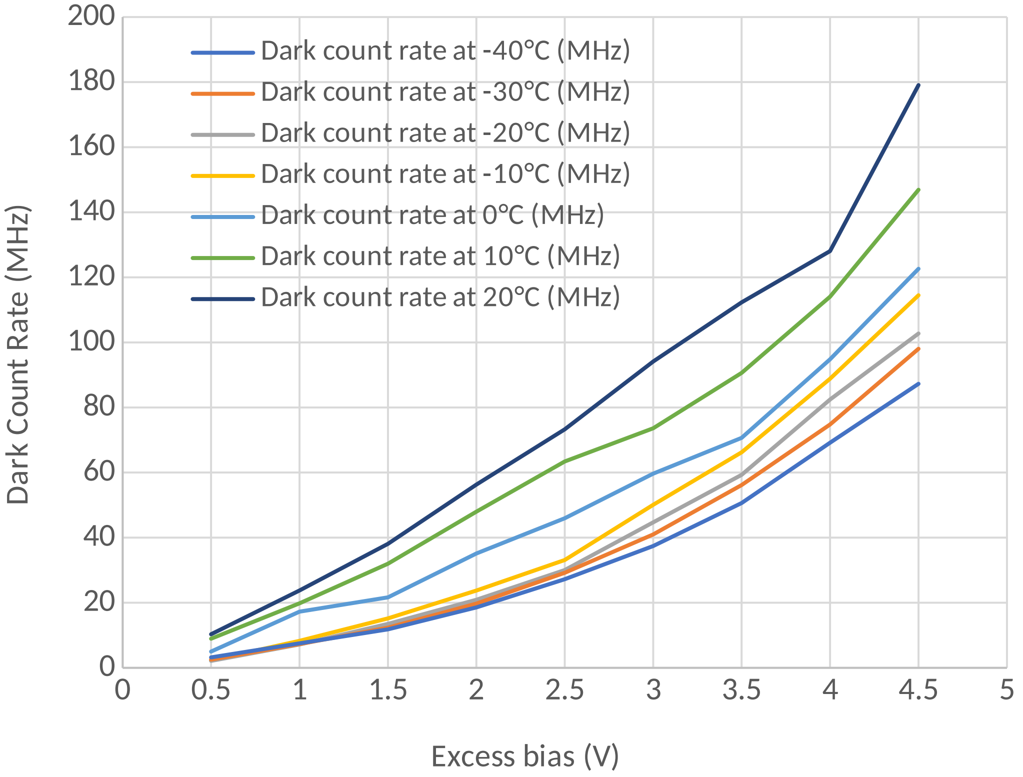
Dark-Count Rates

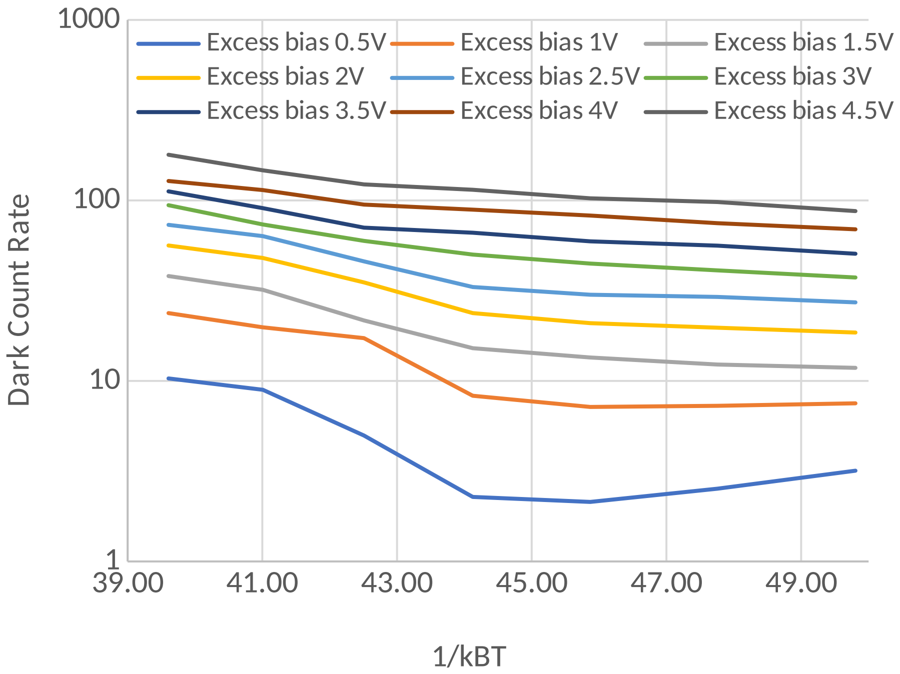
- Temperature range -40°C – 20°C
- Overvoltages 0.5 V - 4 V
- Dark count rates (DCR) > 10 MHz



High dark-count rate prevents operation at higher overvoltages (cf. early SiPMs)

Dark-Count Rates

- Temperature range -40°C – 0°C
- Overvoltages 0.5 V - 4 V
- Dark count rates (DCR) > 10 MHz
- Activation energies ~0.2 eV -> DCR dominated by trap-assisted tunneling (Poole-Frenkel)



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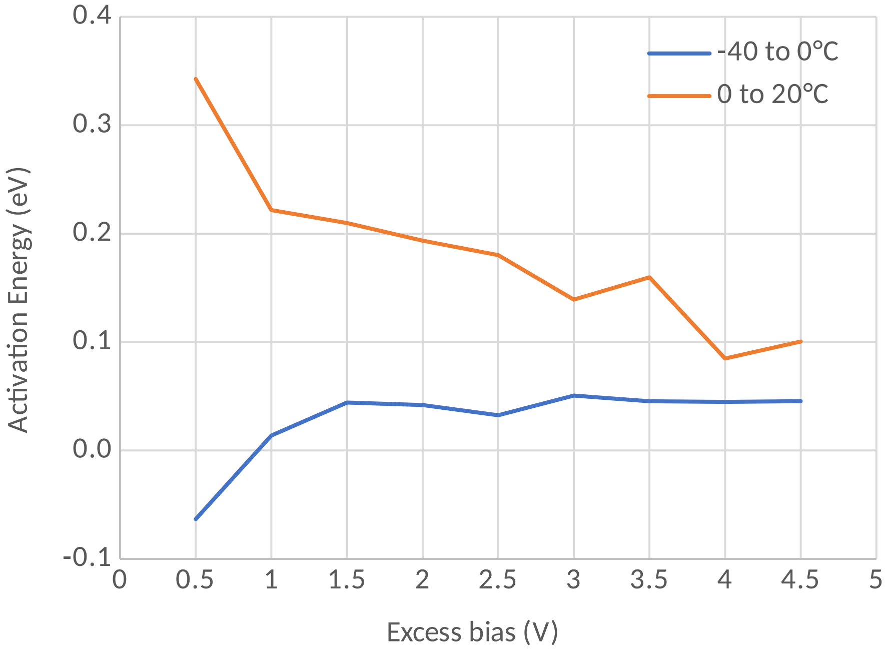
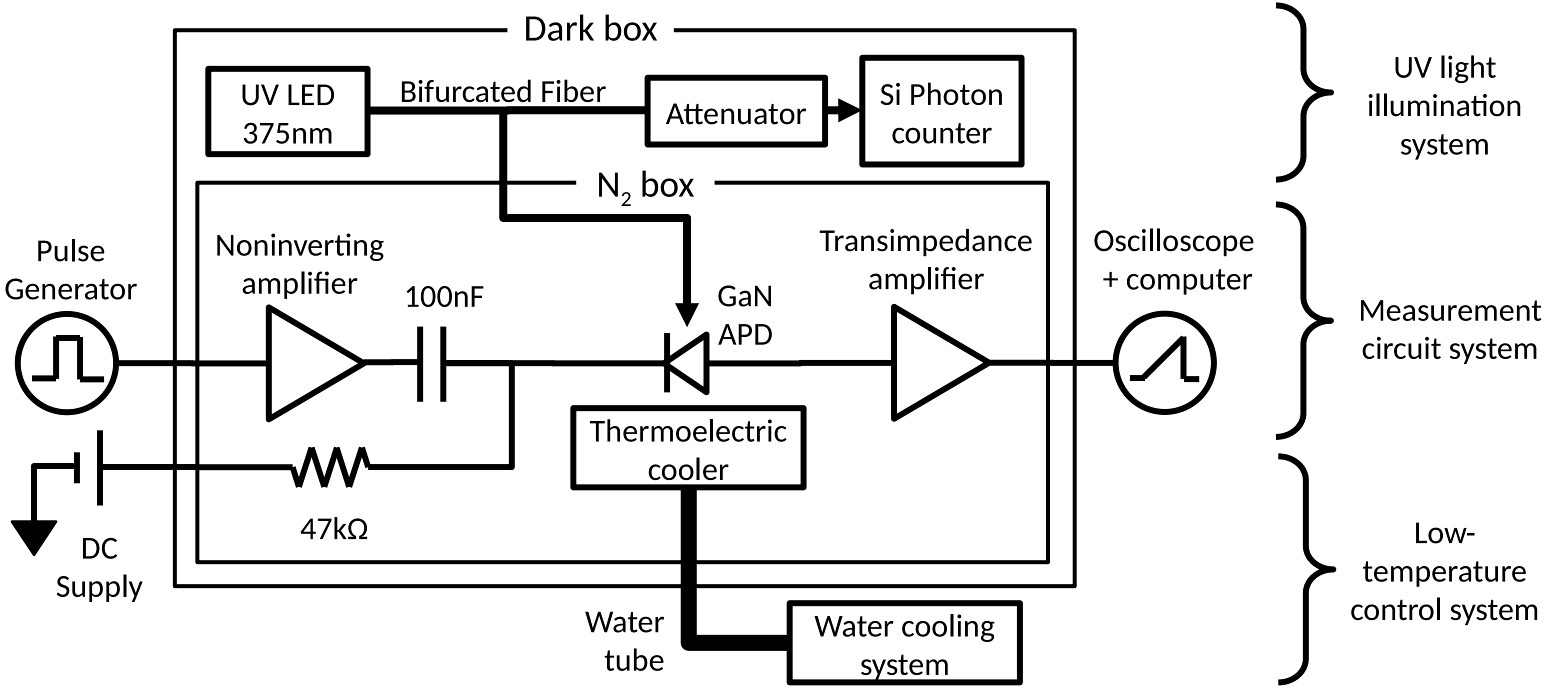
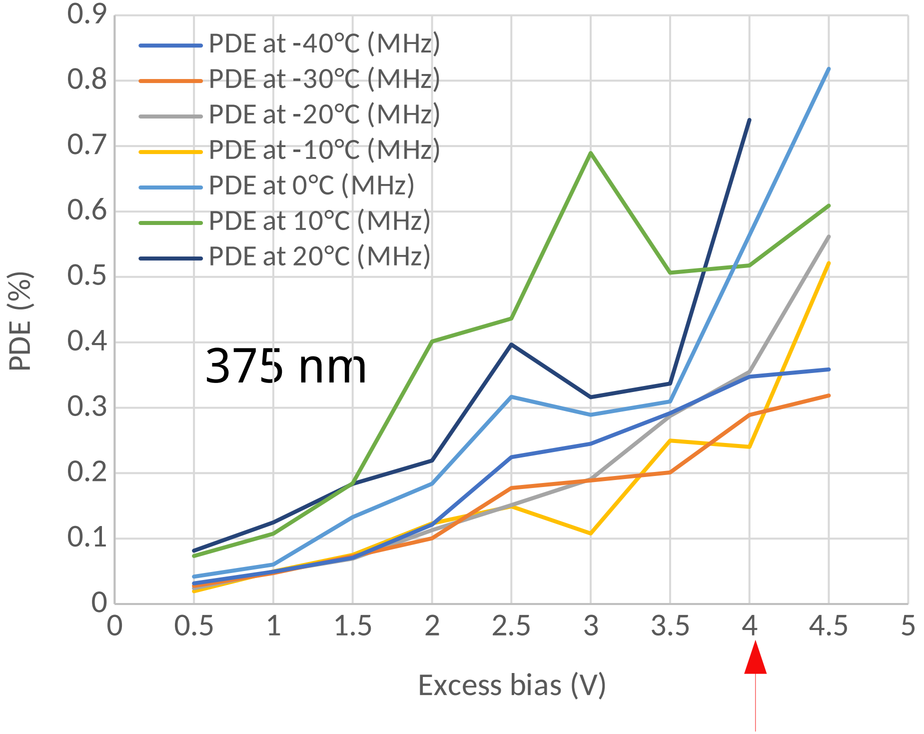


High dark-count rate prevents operation at higher overvoltages (cf. early SiPMs)

Photon Detection Efficiency: Setup

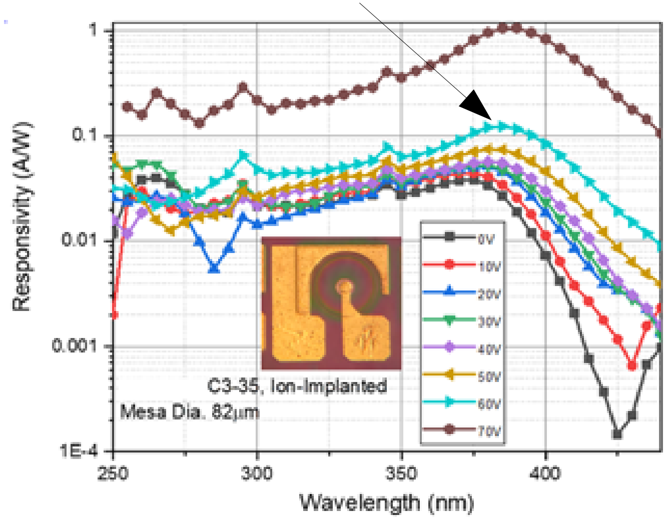


Photon Detection Efficiency



375 nm

45% QE

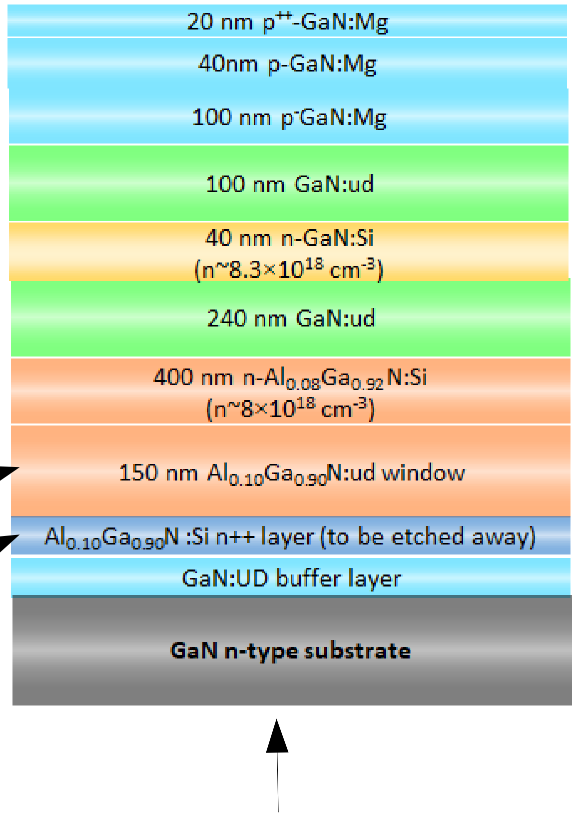


~1% breakdown probability at 4V overvoltage (~5% above breakdown voltage)

Operation at higher overvoltages will result in higher breakdown probabilities

Next Steps

- Reduce DCR -> Eliminate Poole-Frenkel tunneling
  - Impurity states in “intrinsic layer”
  - Residual crystalline defects
  - Growth studies have shown we can reduce “unintentional impurities” in the avalanche region
  - Employ low-defect III-N substrates
  - Further studies of ion-implantation
- AlGaN “window” for better UV sensitivity
- Back-side illumination designs
- Selective etching for substrate removal
- Provides for “flip-chip” mounting to Si bias/readout circuit



Light
(after substrate removal)

Summary

- GaN G-APDs have the potential for high (V)UV sensitivity.
- We succeeded in operating GaN diodes in Geiger mode.
    - All things considered the results are very encouraging.
- High DCR prevents operation at high breakdown probability.
    - Device can only operate <5% above breakdown -> latest SiPMs operate 10%-20% above breakdown -> lots of room for improvement.
    - Identified trap assisted tunneling as dominant DCR mechanism.
- The situation is very similar to early silicon SPADs and SiPMs.
    - No fundamental limitations identified.
    - The same methodology that improved SiPM characteristics can also improve GaN.

Look forward to our next generation of GaN SPADs.