# UV hybrid photon detector based on GaN photocathodes and Si Low Gain Avalanche Diode

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# Motivation

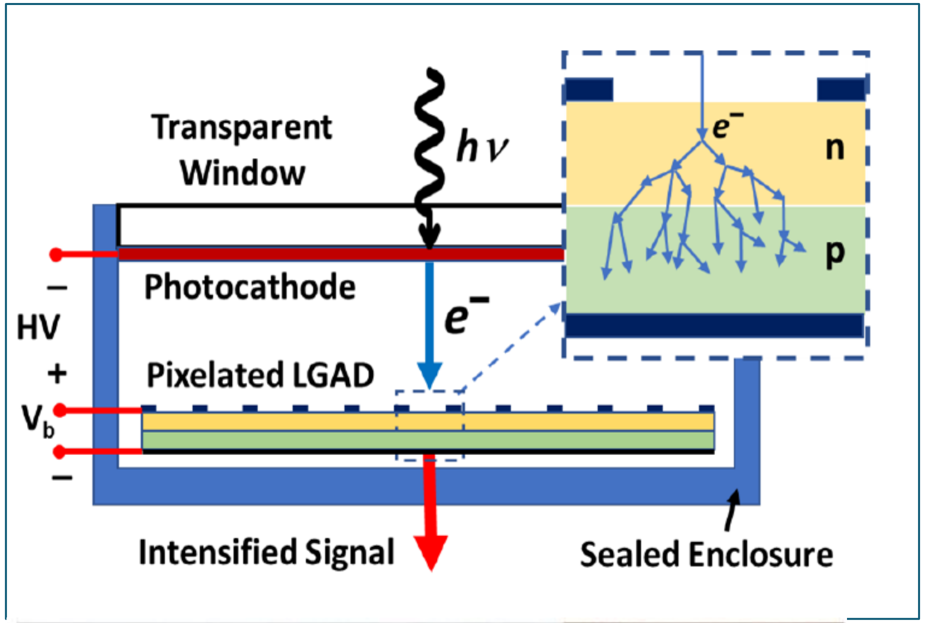
- Why? Single photon crucial for applications in high energy physics, space exploration and quantum optics

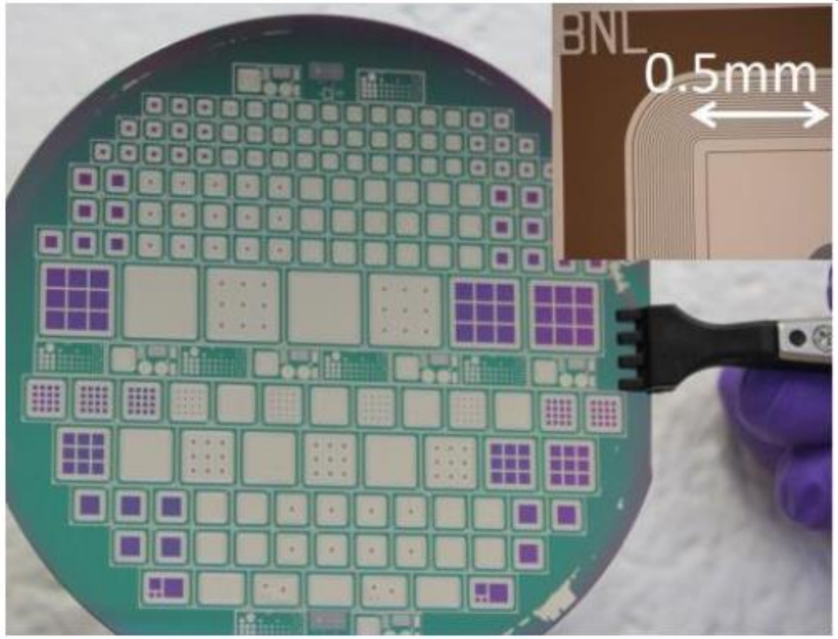
- Large area state-of-the-art photon detectors (LAPPD, Planacon, Hamamatsu) Use photocathode materials that provide high Quantum Efficiency for single-photon detection but require ultra-high vacuum (UHV) conditions due to air sensitivity, adding complexity to manufacturing processes.

- First test for the use of III-Nitride photocathodes with LGAD amplification for single keV photon detection with detector assembled in open air.

# LGAD choice

- Hybrid configuration with photoelectrons generated at the cathode and accelerated towards LGAD to be further amplified
- Total gain of the device will depend on the accelerating voltage and LGAD gain
- LGADs offer intrinsic low noise, high time resolution (~picoseconds), operation at very high repetition rates, low voltage operations, low cost of manufacturing

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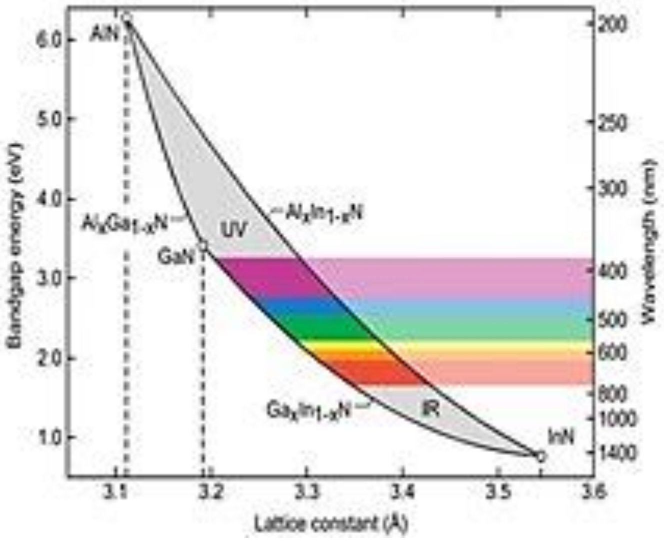
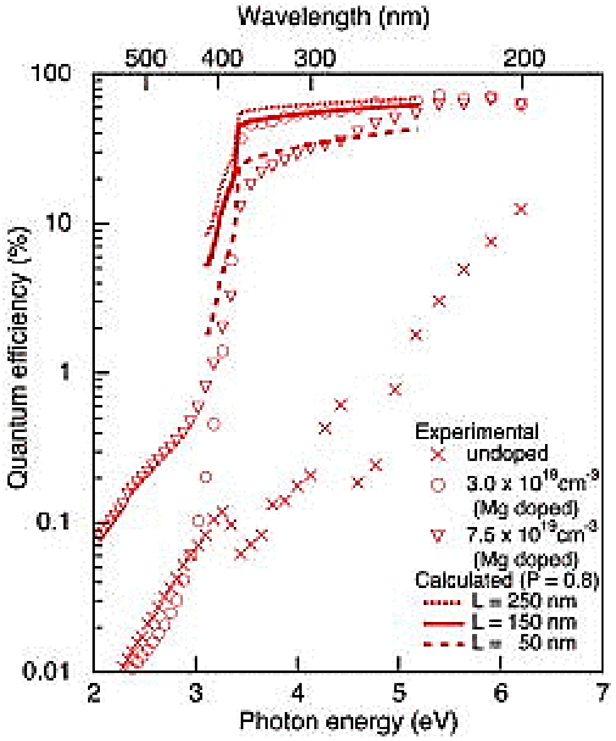
# GaN Photocathode choice

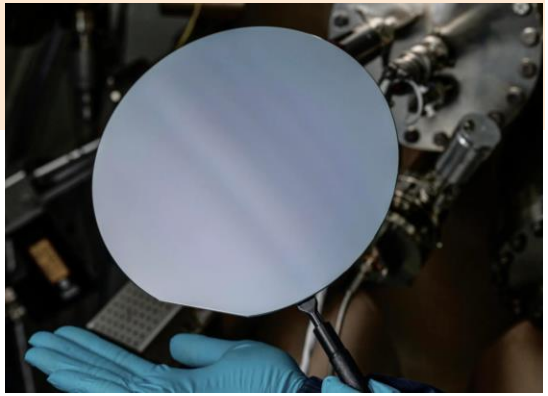
- GaN activated to Negative Electron Affinity by Cs vapor exposure has been studied for few decades and is it know to provide UV photon detection with large quantum efficiency.

- Alloying with Al and In allows band gap tuning and selection of the operational spectral range.

- It is one of the material of interest for the development of radiation hard detectors due to its large band-gap.



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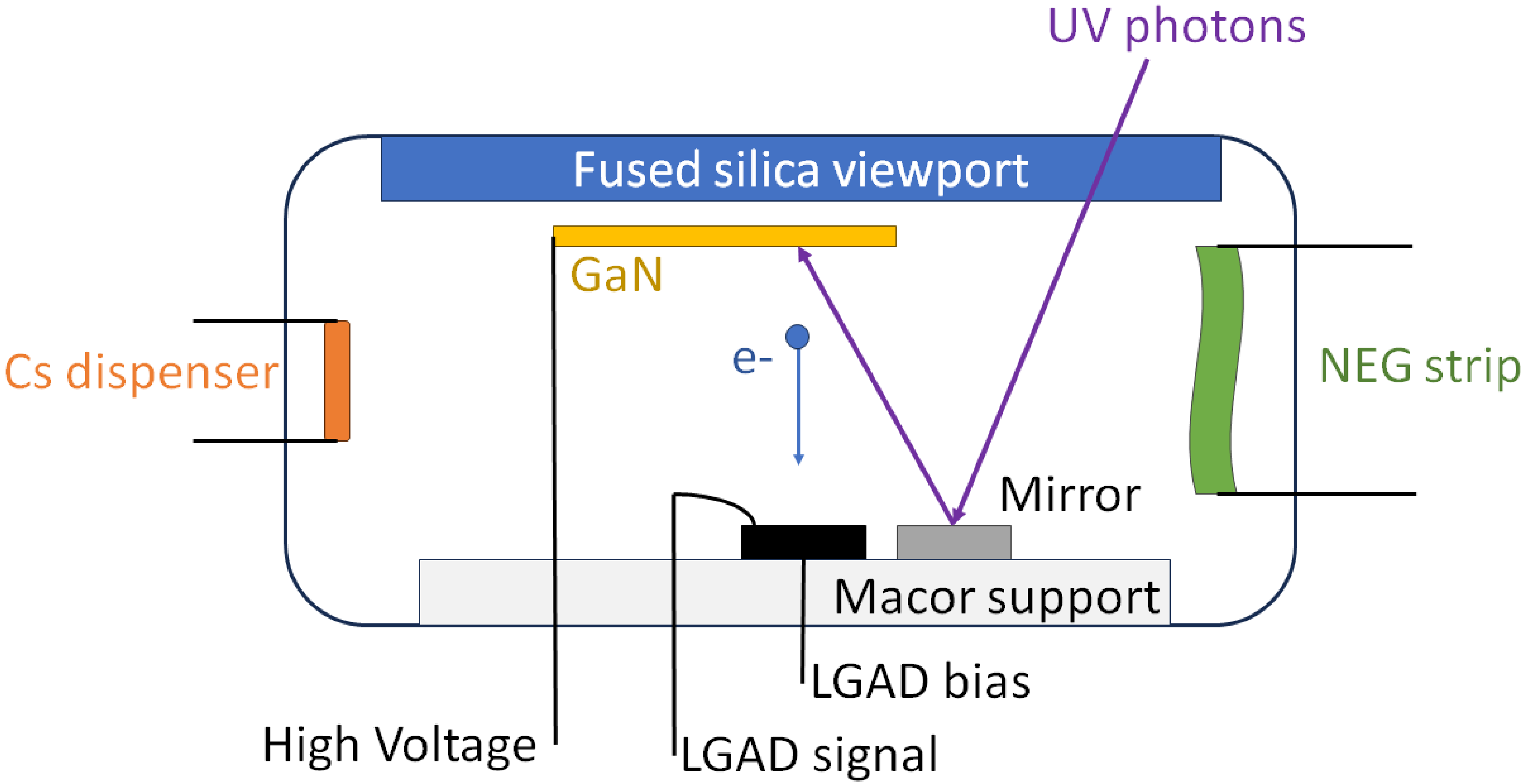
# Hybrid Photon Detector (HPD) Test Setup

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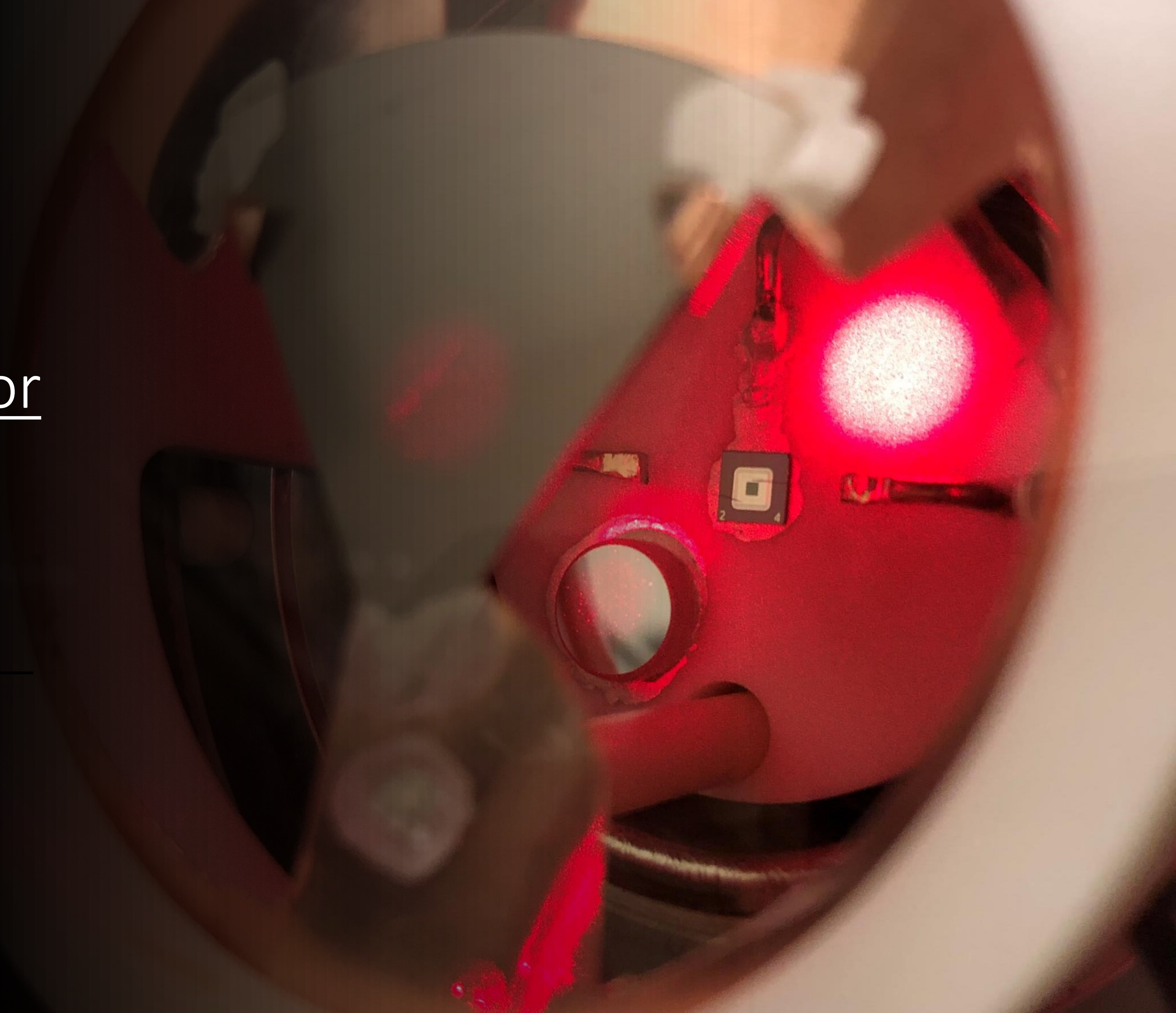
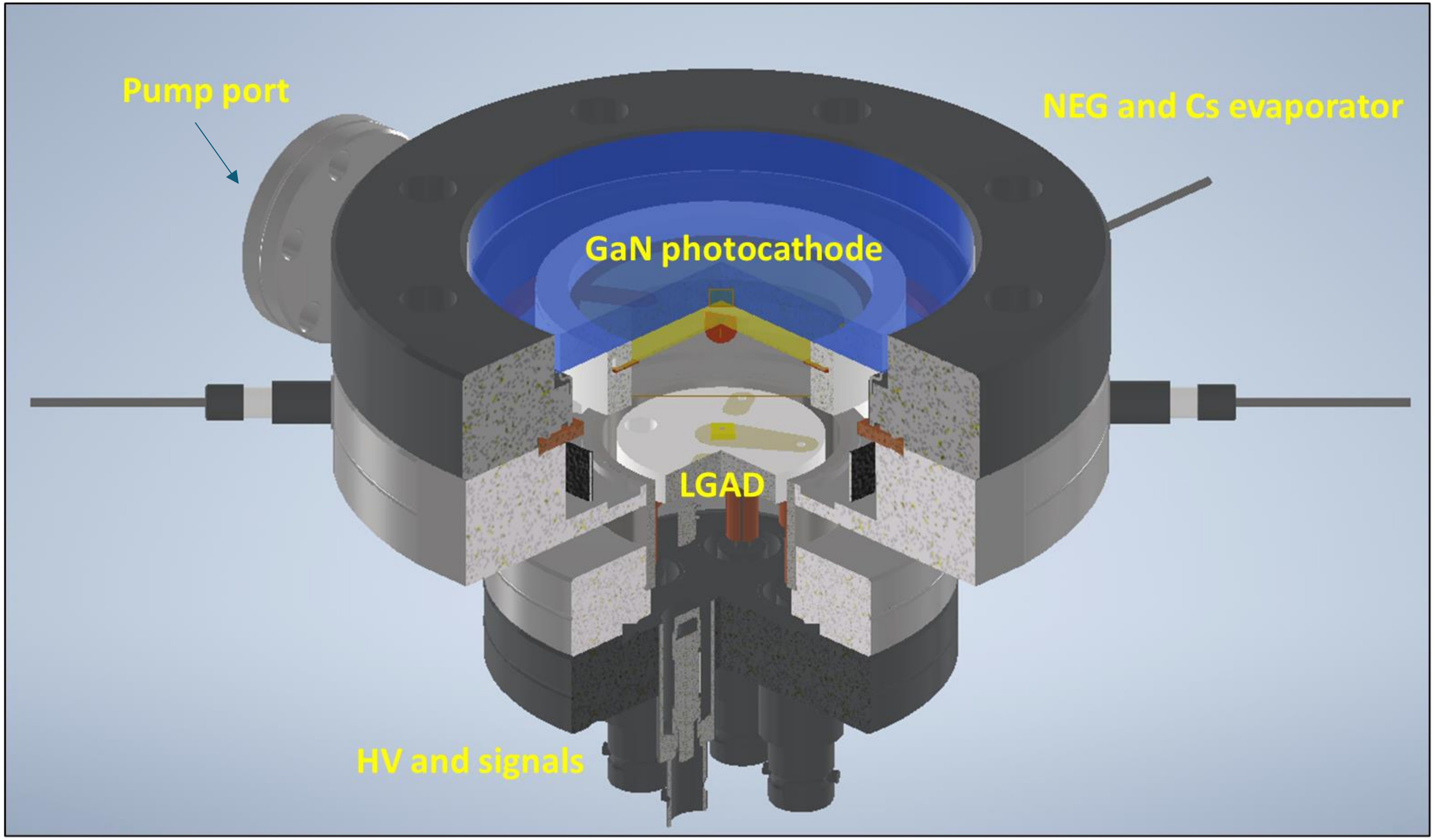
# Hybrid Photon Detector (HPD) Results



# 3D design of the HPD



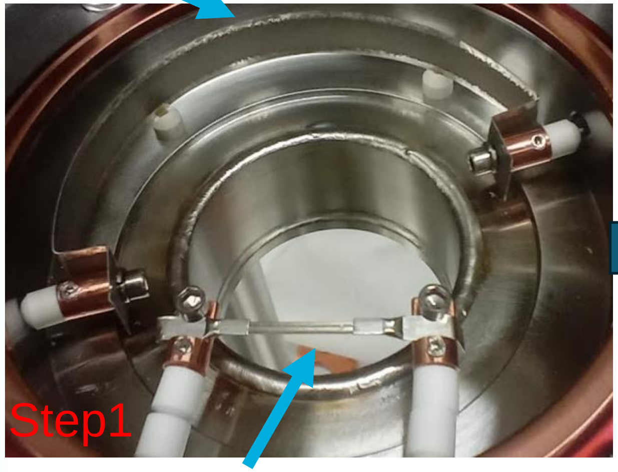

**Vacuum vessel made with Off-The-Shelf UHV components**

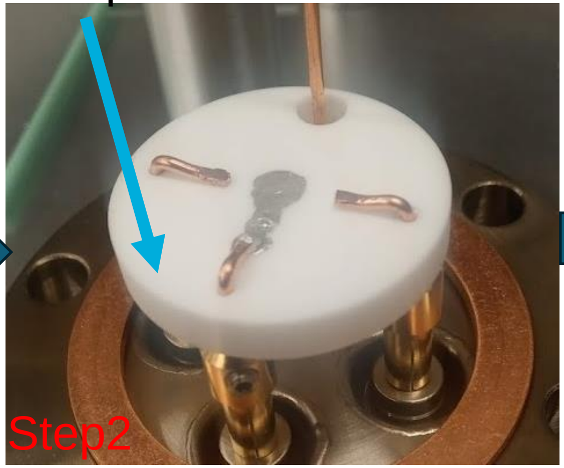
# Air- Assembly of the HPD

NEG

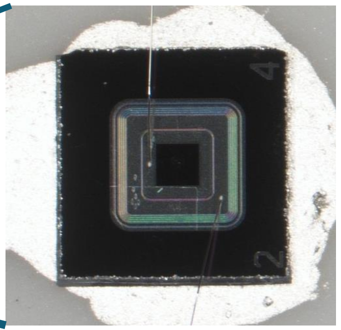
Macor plate

LGAD







Cs dispenser

$0.65 \times 0.65\ mm^2$

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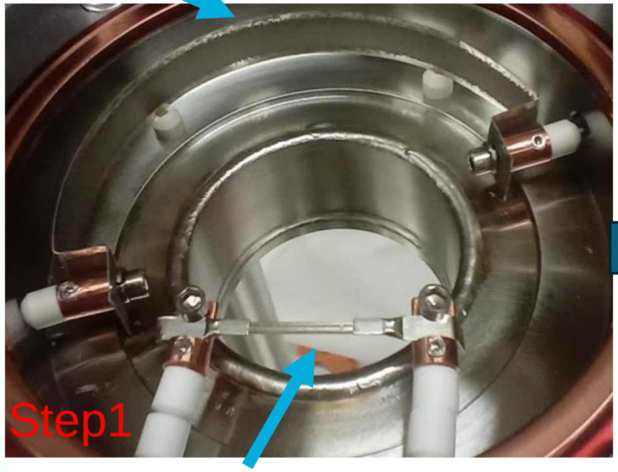
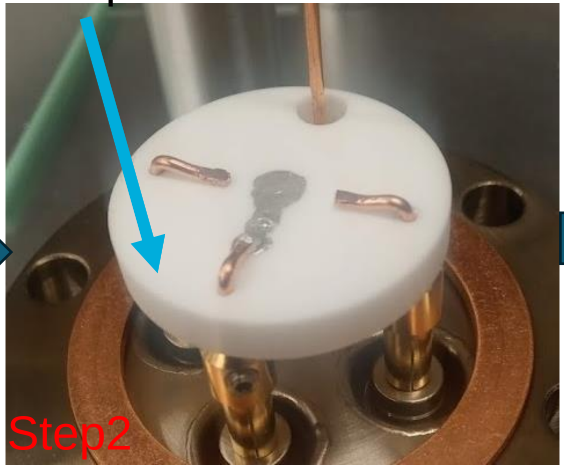
# Air- Assembly of the HPD

NEG



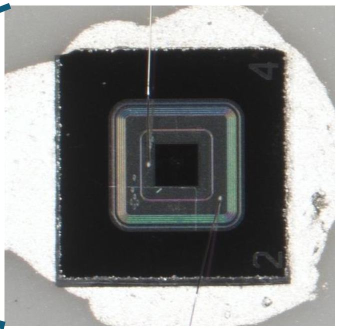

Cs dispenser

Macor plate



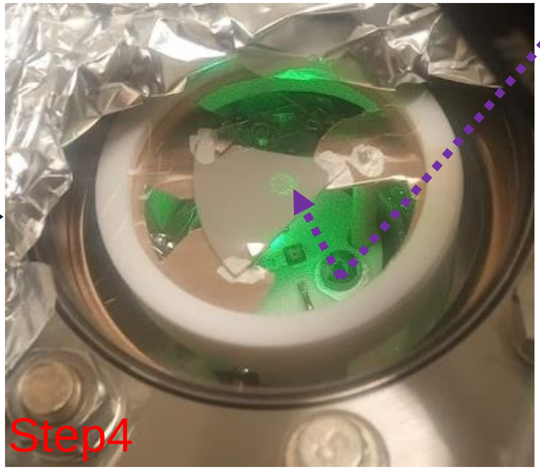


LGAD



0.65x0.65 mm$^2$

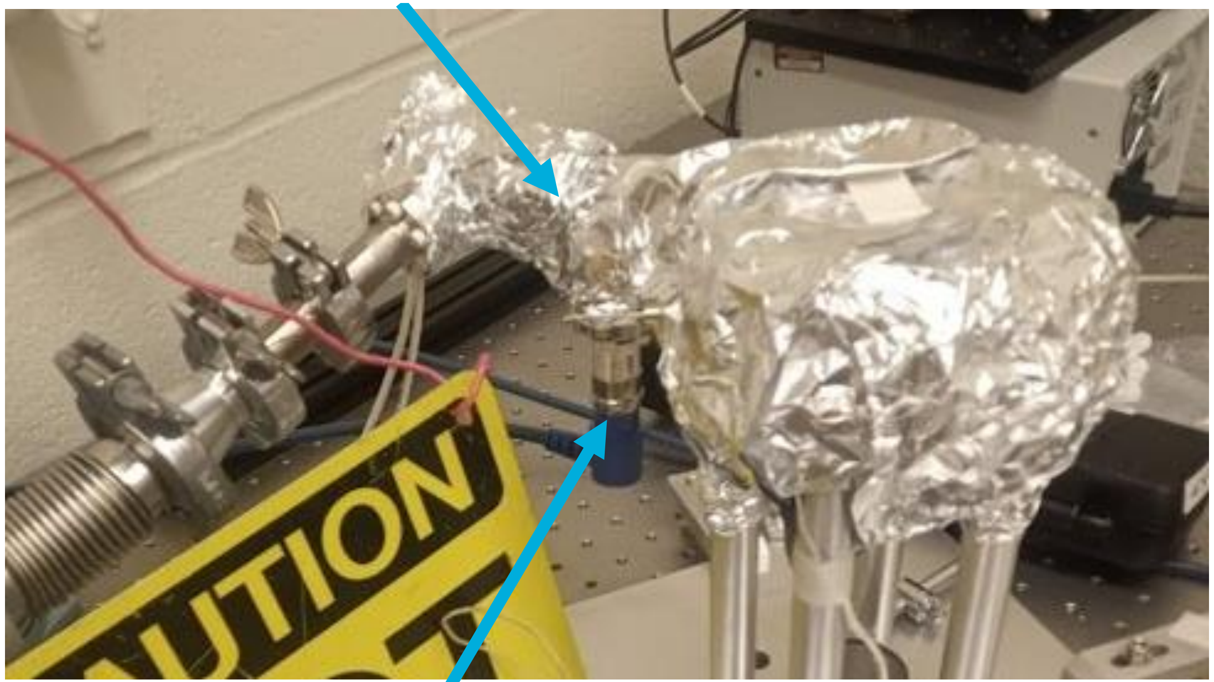
***Laser light***




- No UHV assembly requirements
- Cost effective commercial materials
- Simplified assembly process

# HPD under UHV vacuum and GaN activation

Turbo angle valve seal




UHV-Gauge

- Bake out ~150C for 1 week
- @ $10^{-9}$ Torr HPD sealed from the turbo-pump but lower close to the LGAD

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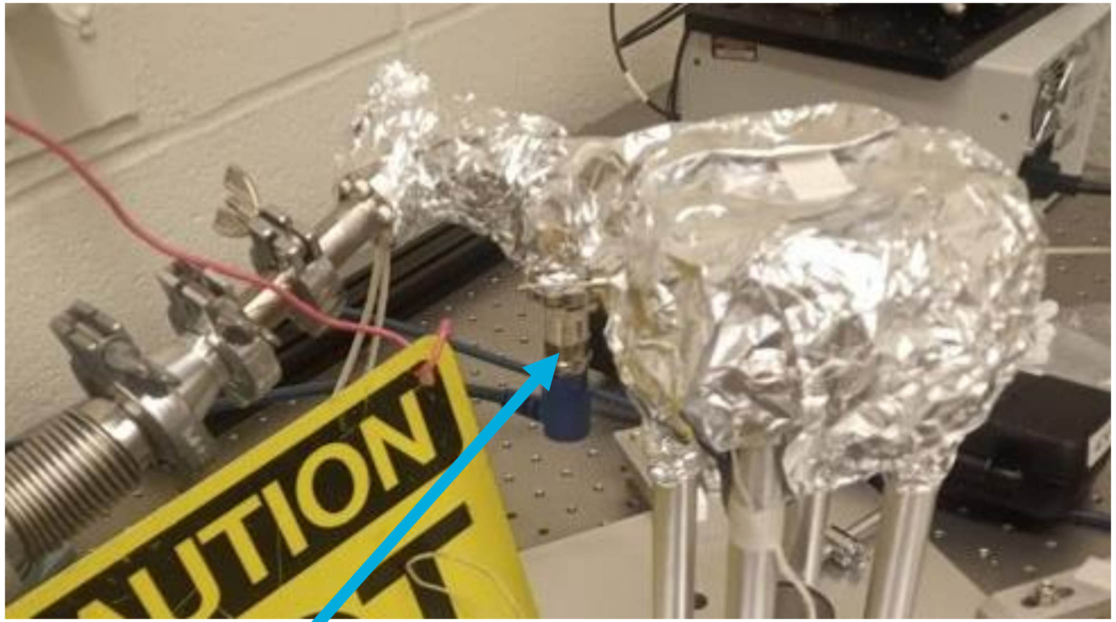
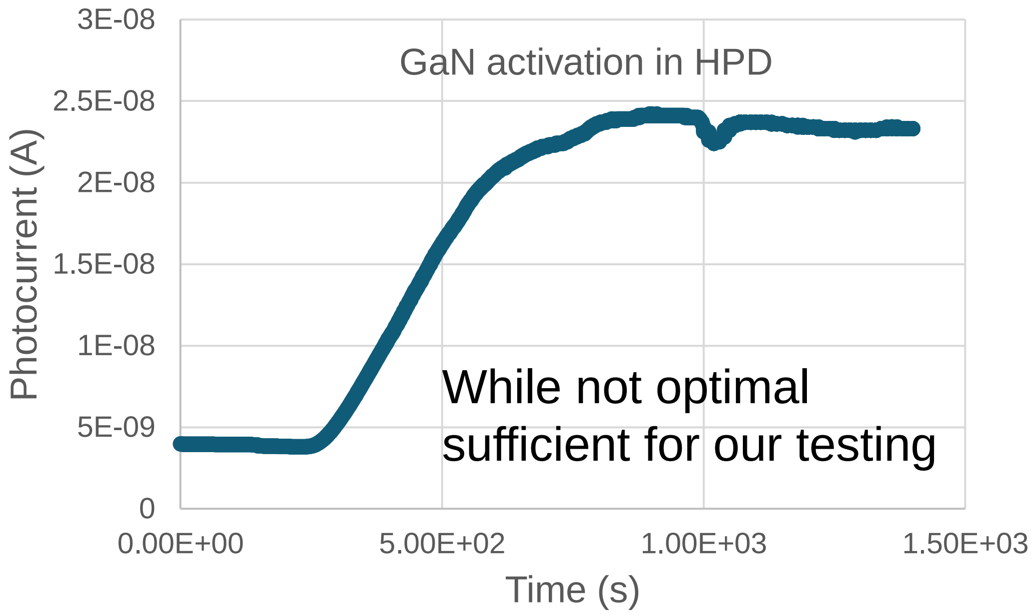
# HPD under UHV vacuum and GaN activation




Hot filament UHV-Gauge generates some gas load

- Bake out ~150 C for 1 week
- $1x10^{-9}$ Torr measured after sealed from the turbo-pump expected to be lower in vessel
- QE~0.11% measured using 280nm LED (relatively low compared to typical ~20%)




While not optimal sufficient for our testing

**Cs-dispenser overheated by mistake during the degassing procedure**

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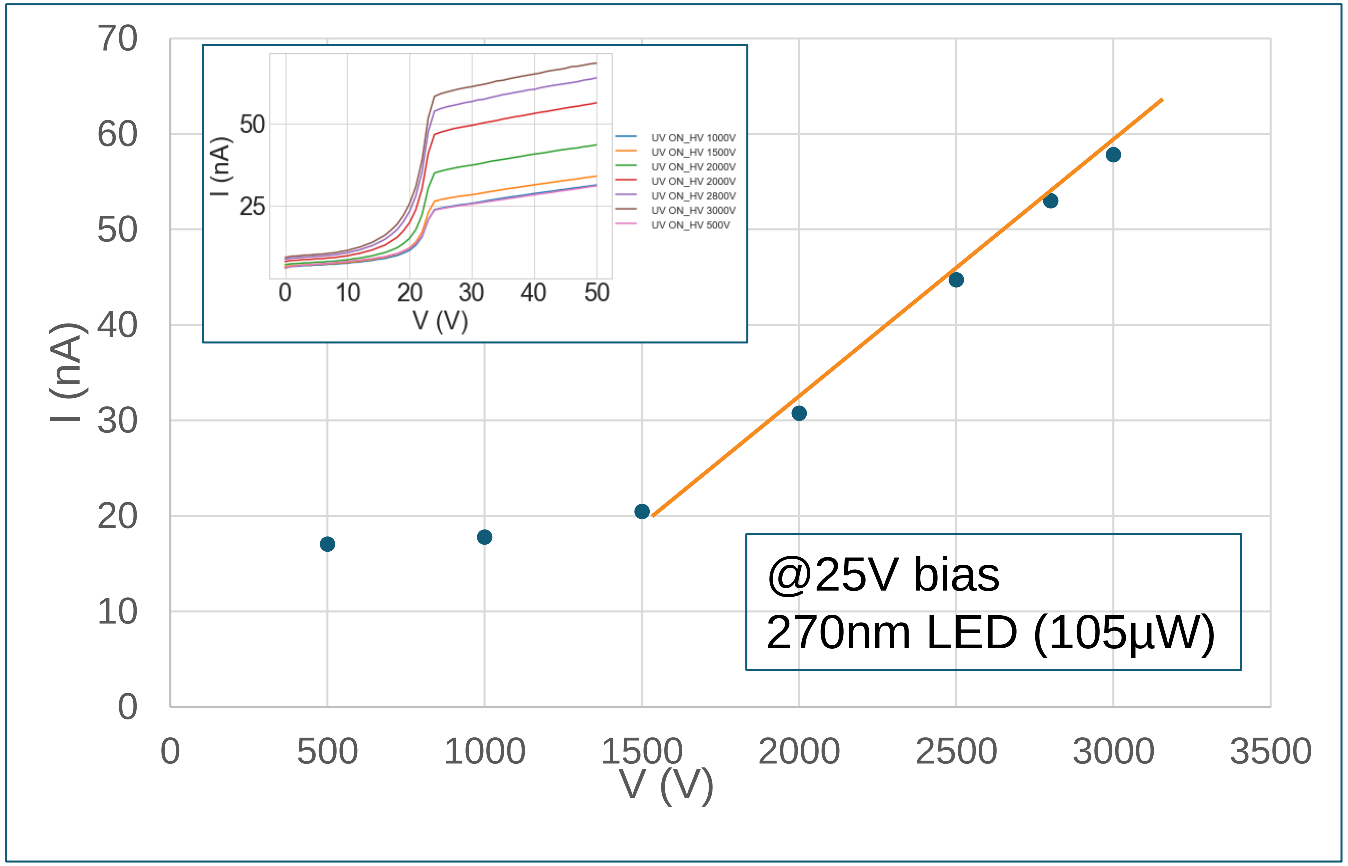
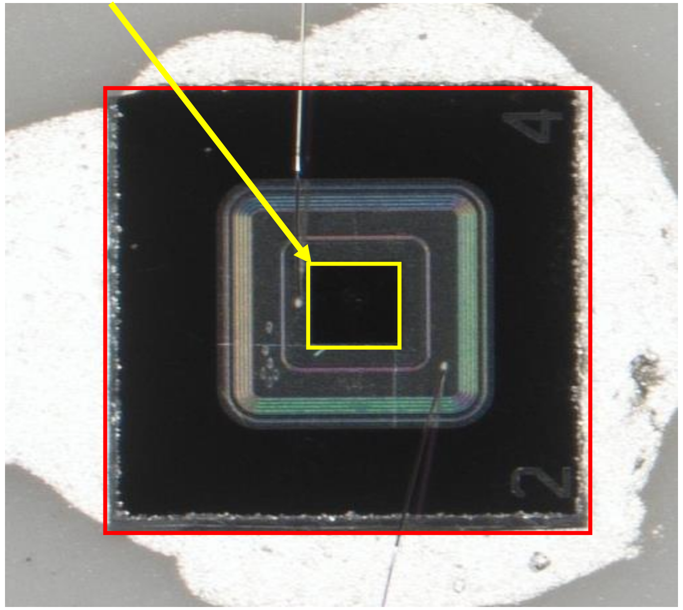
# Linear response vs electron energy




- ~1.5kV threshold acceleration voltage
- ~Linear amplification behavior >1.5kV
- Geometrical factor to be accounted for !!

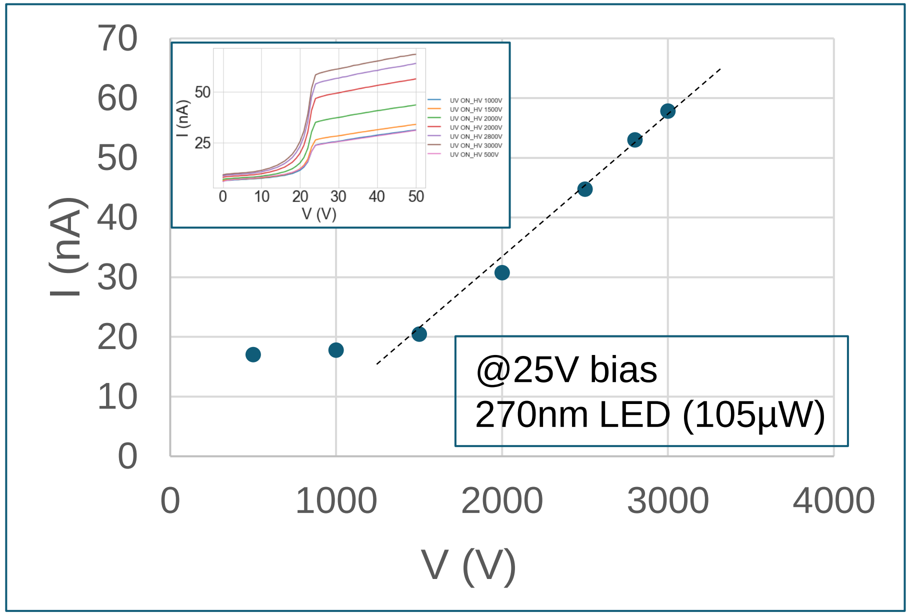
Active area is about 1/30th of the device area

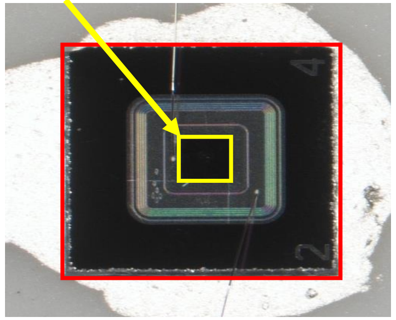


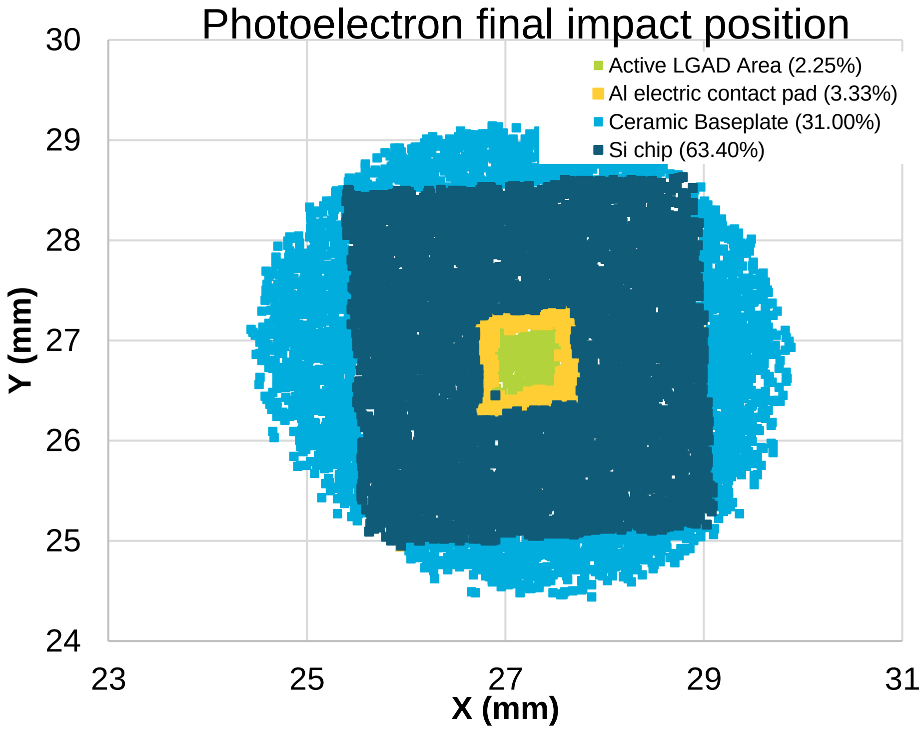
0.65x0.65 $mm^2$

# Electron tracking simulation

- **How many electrons are truly reaching the LGAD amplification area?**






Electron tracking simulations performed with SIMION, using the real HPD geometry, indicate **only ~2.25% of photoelectrons extracted from the 5 mm diameter illuminated spot on GaN are reaching LGAD active area.**

***Electron collection efficiency could be improved by considering a larger LGAD area**

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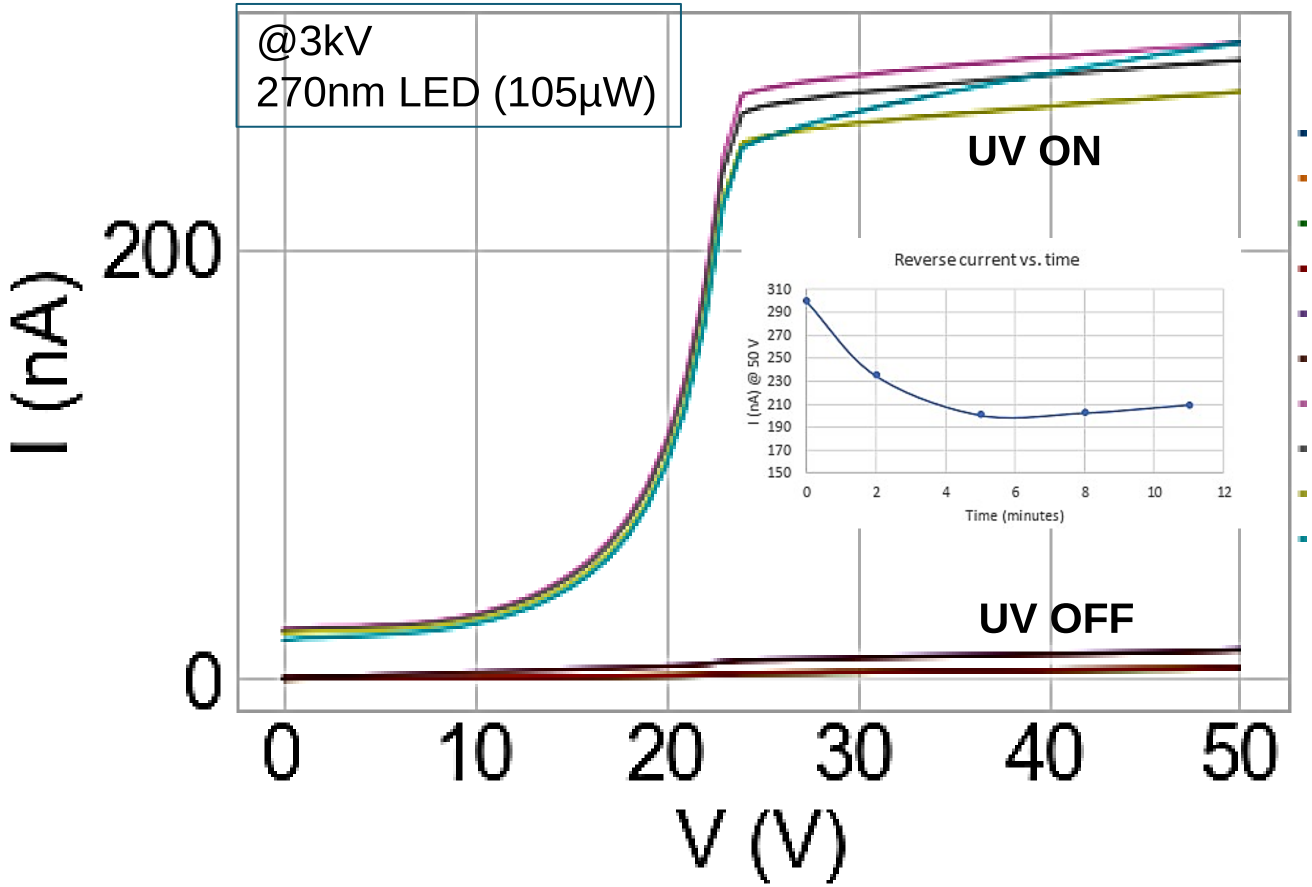
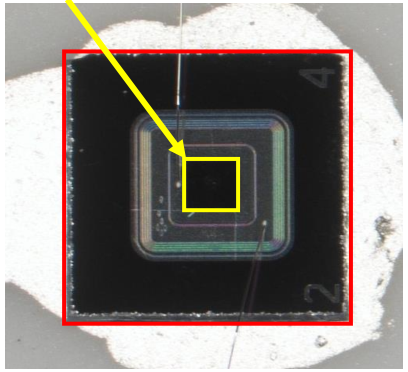
# HPD combined gain




Active area is about 1/30th of the device area



0.65x0.65 mm$^2$

We define HPD Gain @3keV by considering the measured amplified LGAD current vs the estimated photocurrent reaching the LGAD at 0 bias:

$I_{LGAD}$ (0V bias) = 9nA x 0.02 ~180pA

$I_{LGAD}$(50V bias) = 285 nA

**Gain ~1580 for single 3keV electron**

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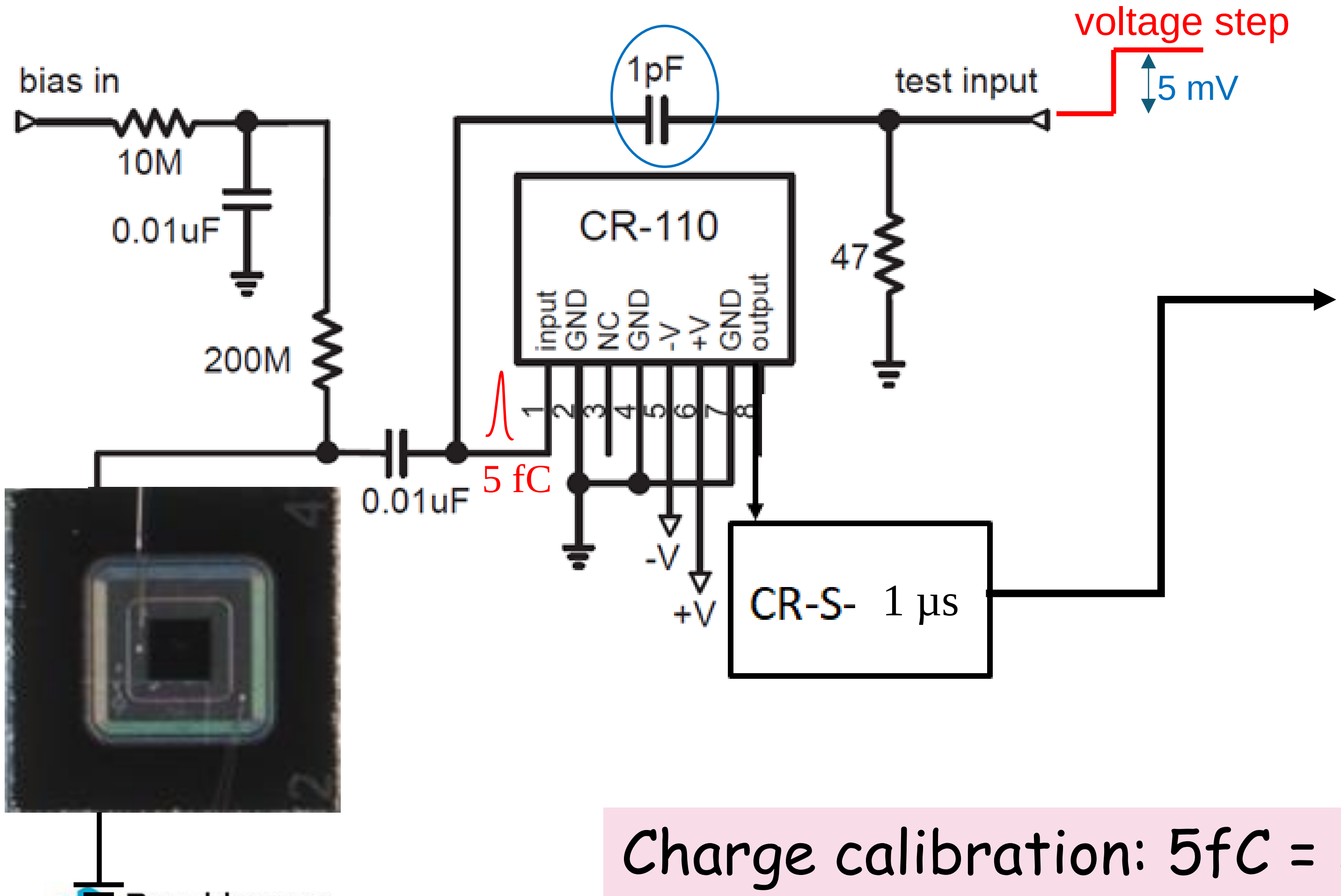
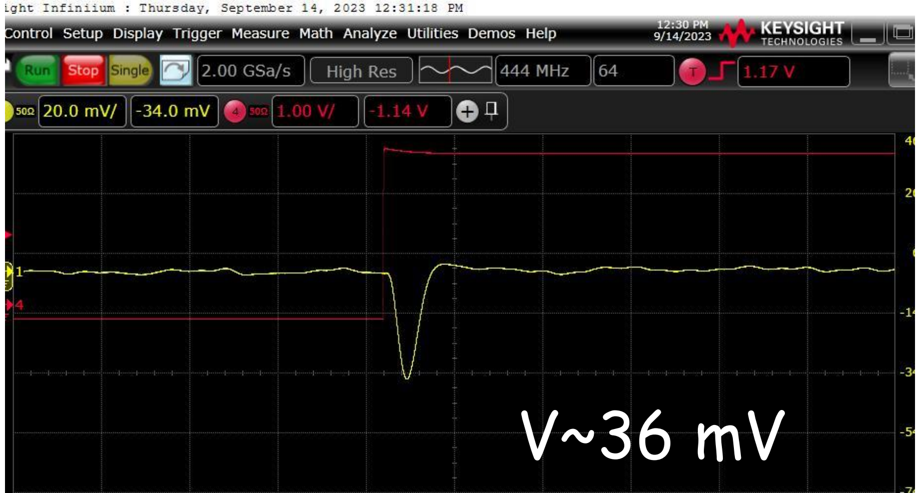
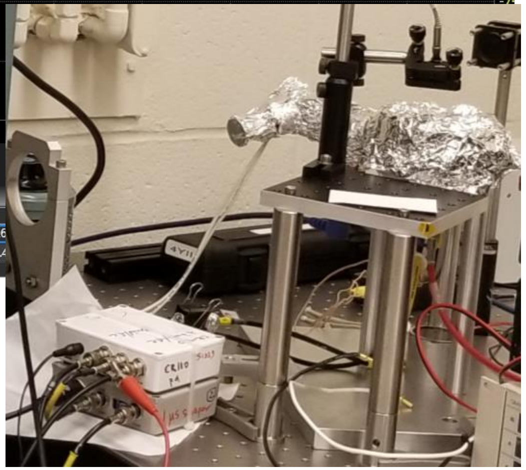
# Electronics: charge calibration

Inject known amount of charge to calibrate preamplifier




5 fC calibrated photoelectron pulse

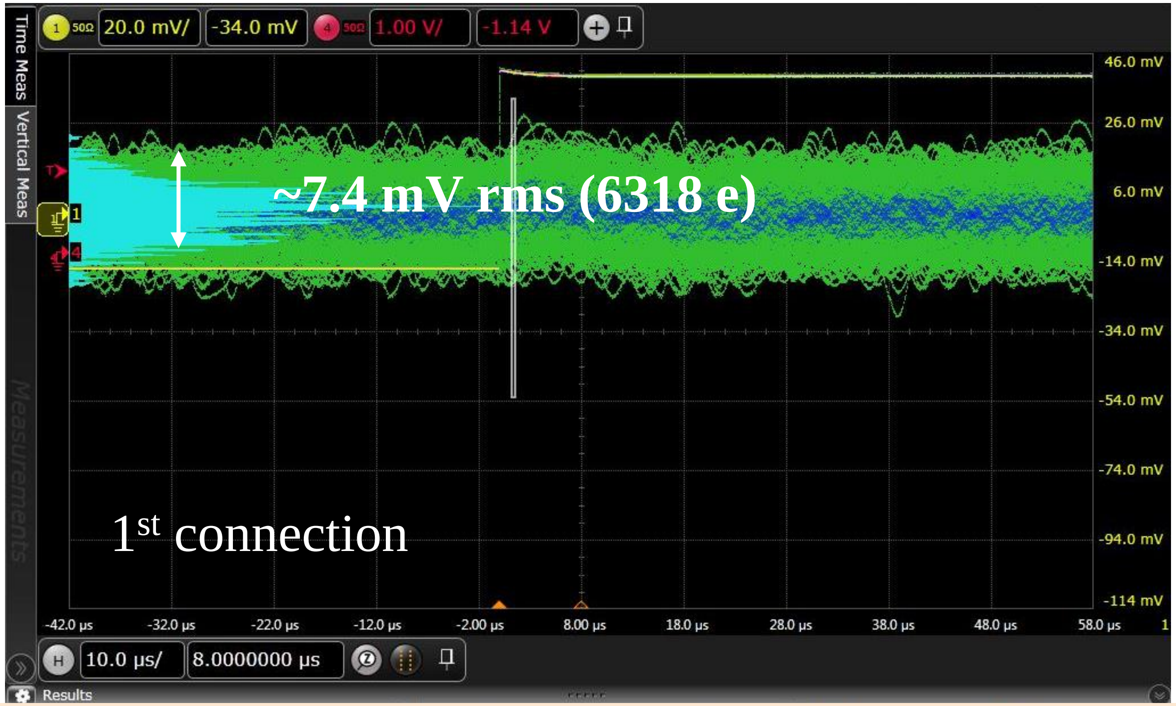


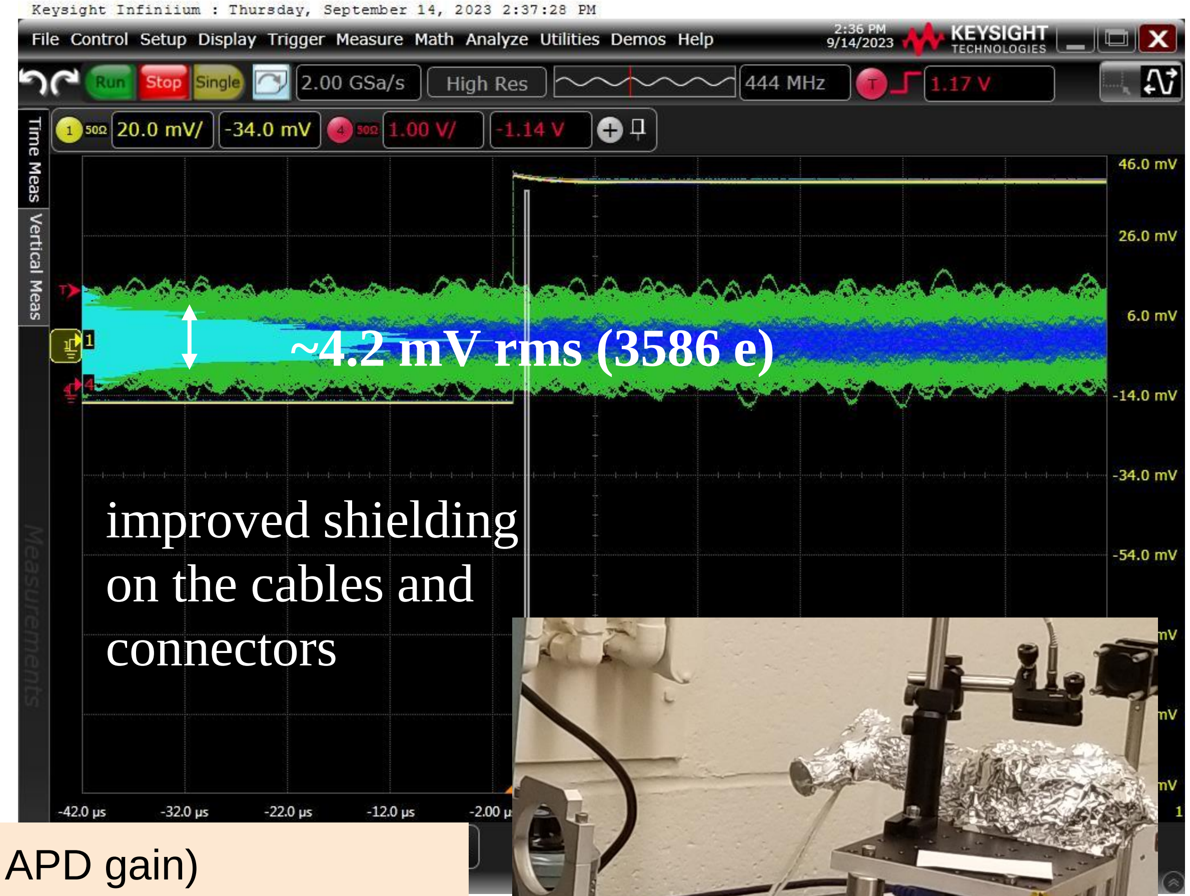



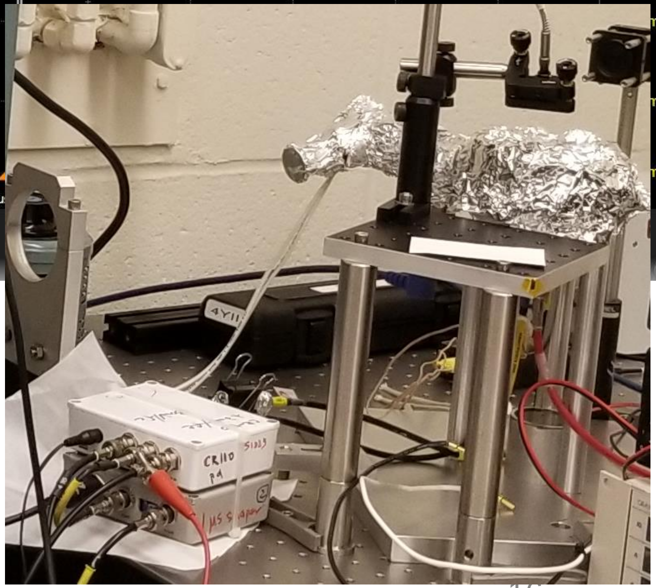
1 fC = 6250 electrons

Charge calibration: 5fC = 36 mV
1 mV signal = 0.139 fC = 868 $e^-$

# What is the noise level of the system: with LGAD attached (w/o APD gain)



system electronic noise $\sigma_{rms}$ ~ ***3500 to 6300 electrons*** (w/o APD gain)
recall: 3 keV $e^-$ → **833 electrons**
w/o charge gain LGAD will not see single 3 keV electron above background noise.

It should be possible to further reduce the noise level (in other systems the same amplifier had a factor ~10 lower noise level)

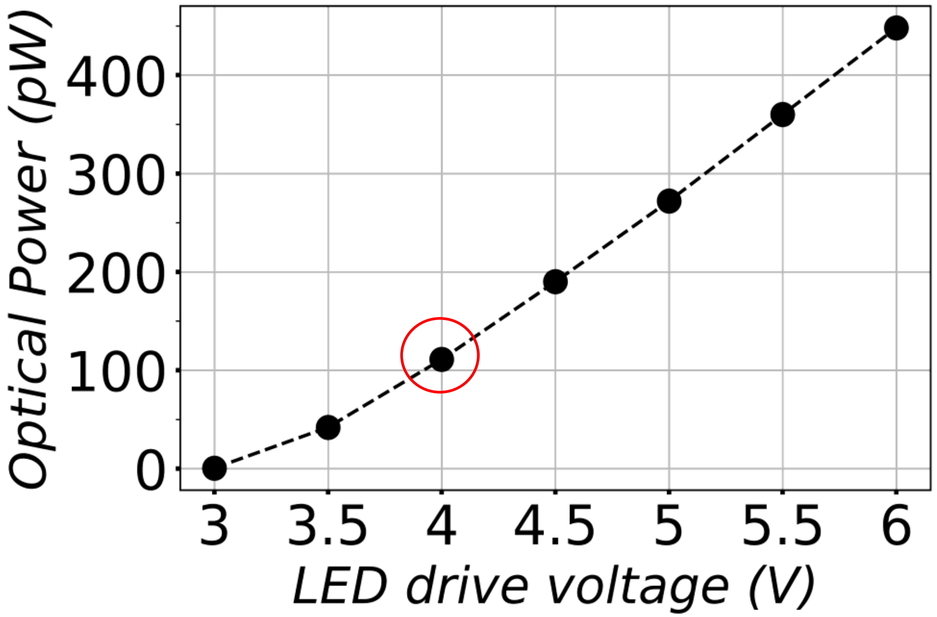
# UV LED Pulse Characteristics

- At 4V bias, 100 Hz and 20 ns pulse width the UV LED produced an average power of ~110 pW

- Every light pulse has in average ~1.54 x $10^6$ photons

Taking into account:
- The fused silica collimating lens (~90% at 280 nm)
- The UHV fused silica transmission (~90% at 280 nm)
- The UHV mirror reflectivity (~90% at 280 nm)

- Every light pulse produces **~1.12 x $10^6$ photons** on the GaN photocathode over a ~5 mm diameter circular spot

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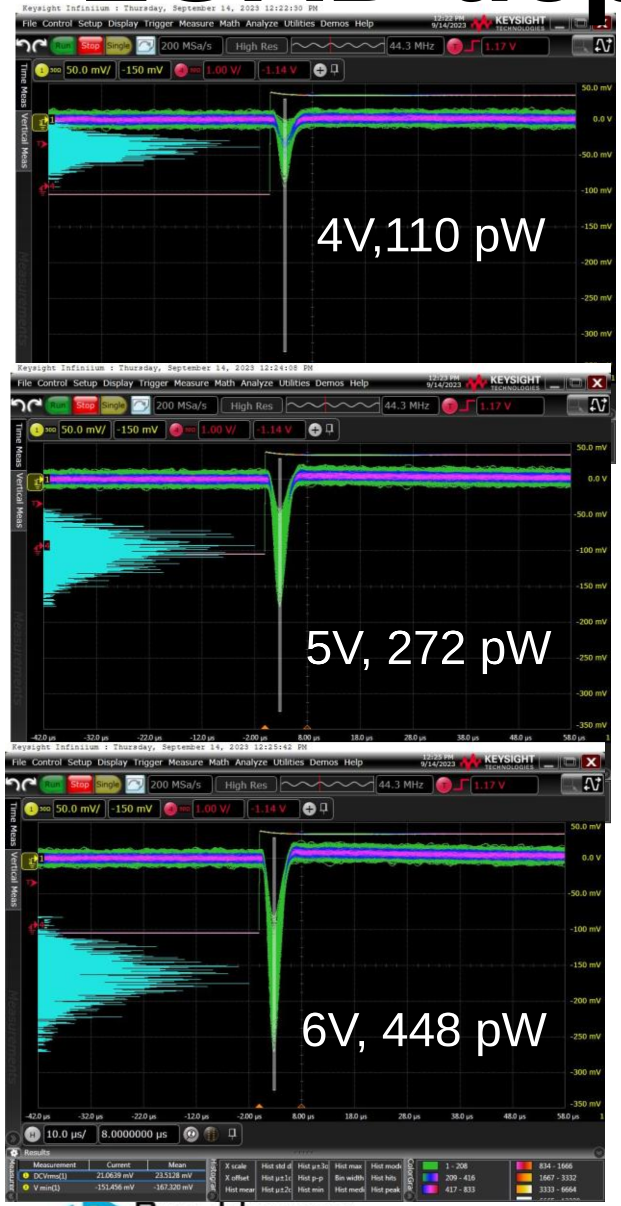
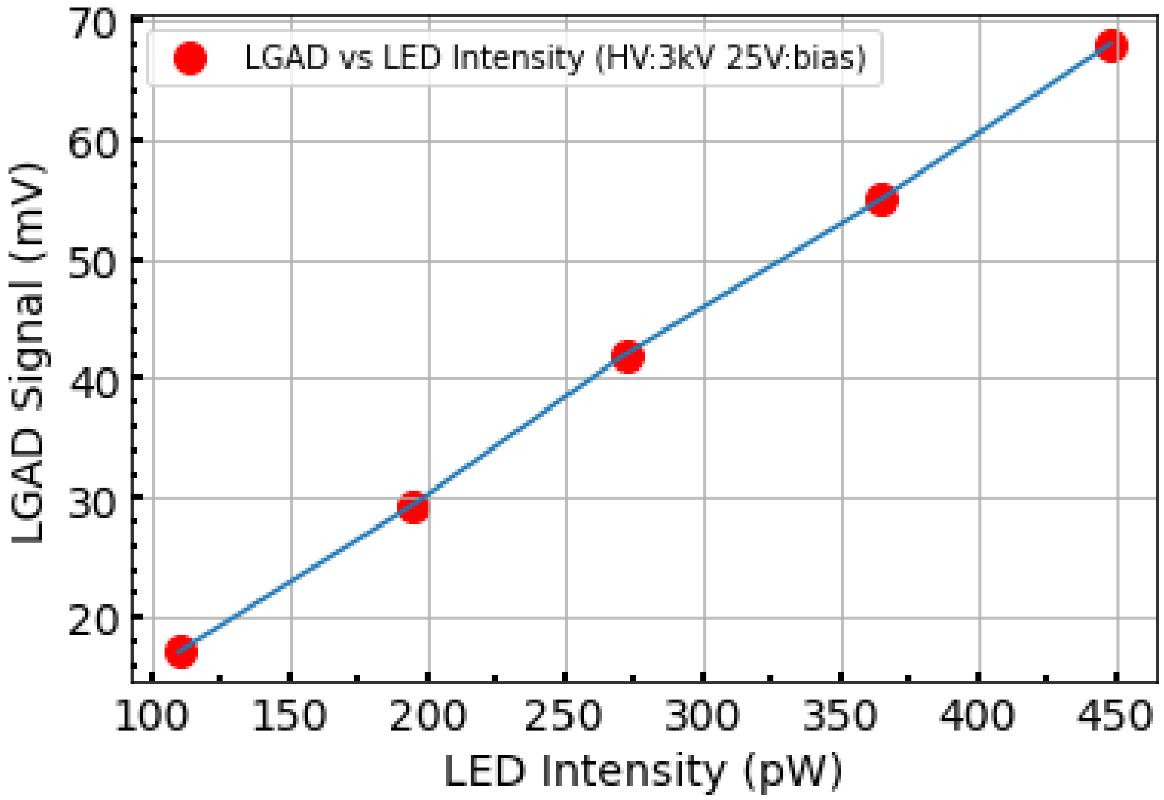
# LGAD dependence on UV LED intensity



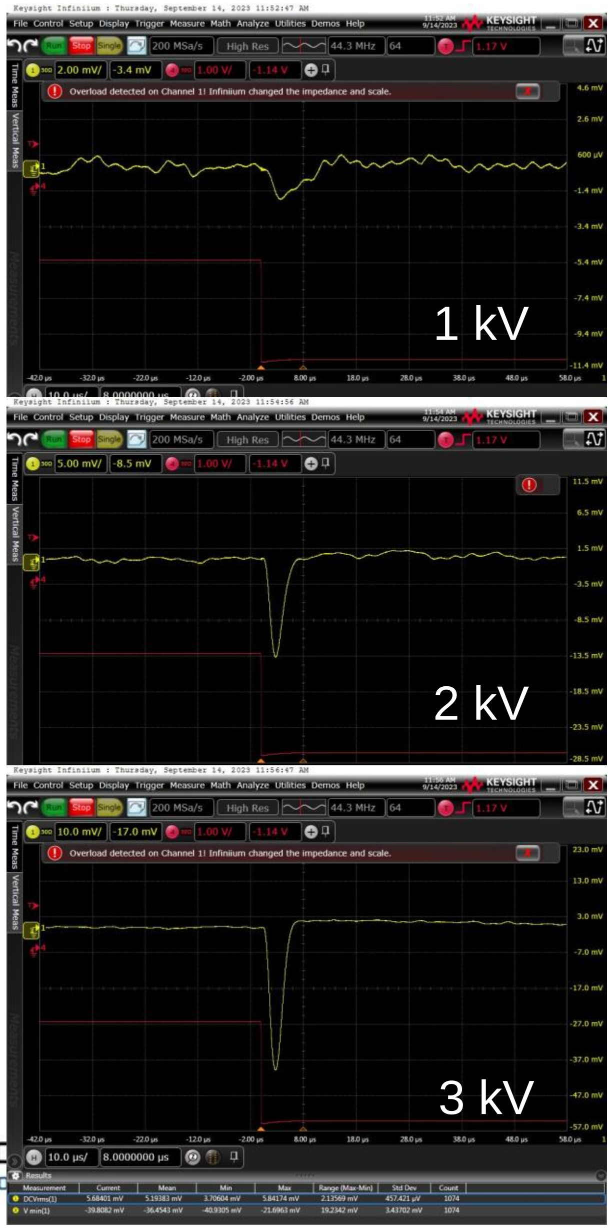



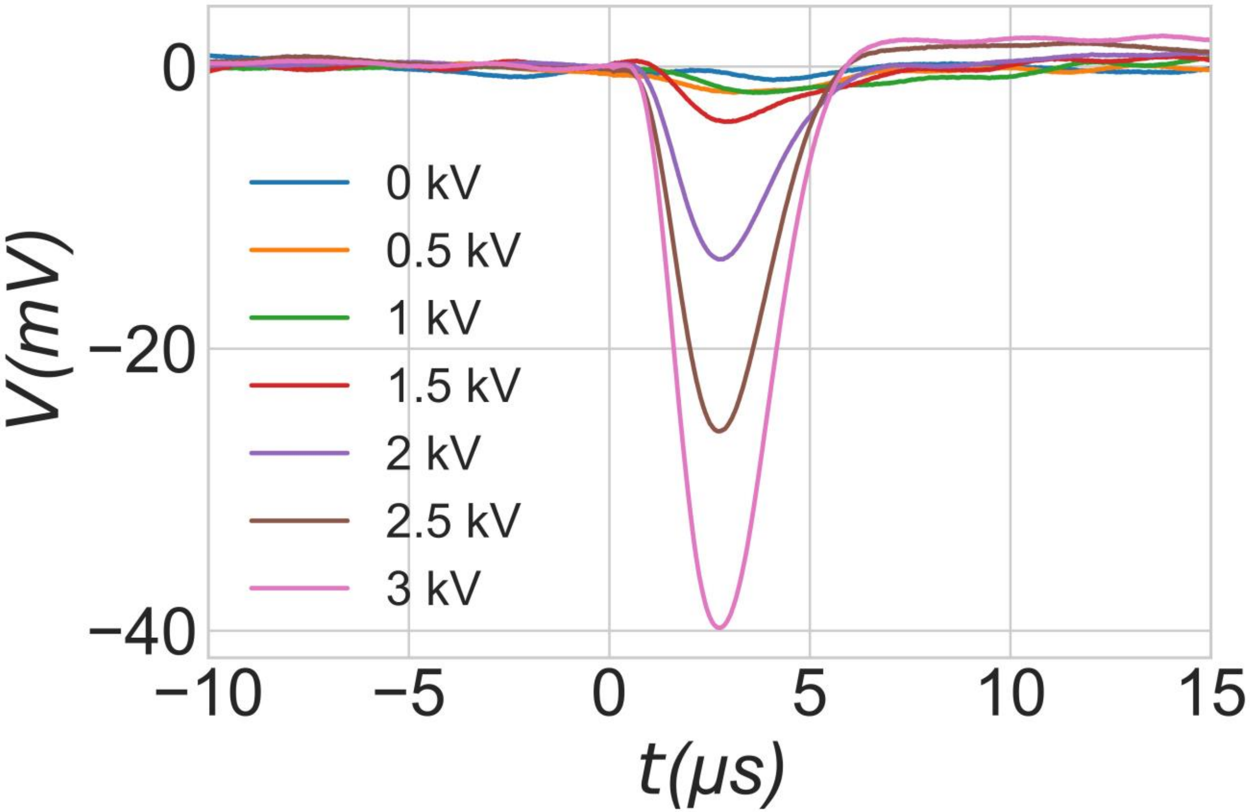

**LGAD signal increase linearly with UV LED intensity**

# Are we seeing single 3 keV $e^-$ response?

QE degraded from 0.11% to 0.066% and so ~**818 photoelectrons per UV pulse** are extracted from the GaN photocathode. Only ~2.25% of these electrons (~**18 photoelectrons**) are reaching the active area . So how many femto-coulomb did we measure ??

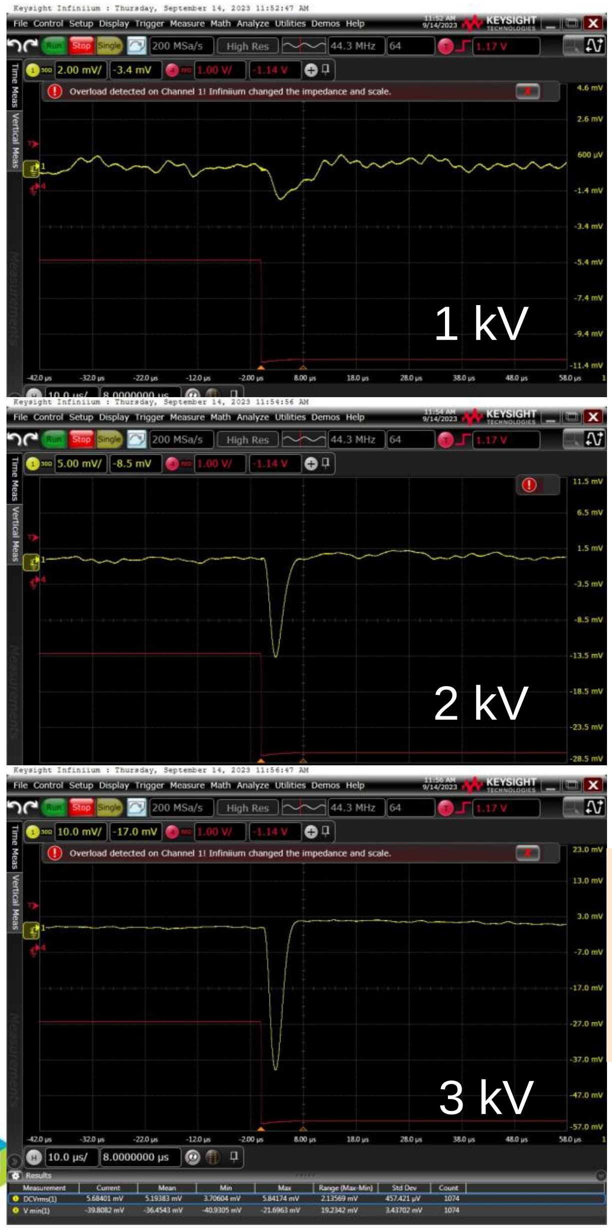
# LGAD signal dependence on HV bias on GaN

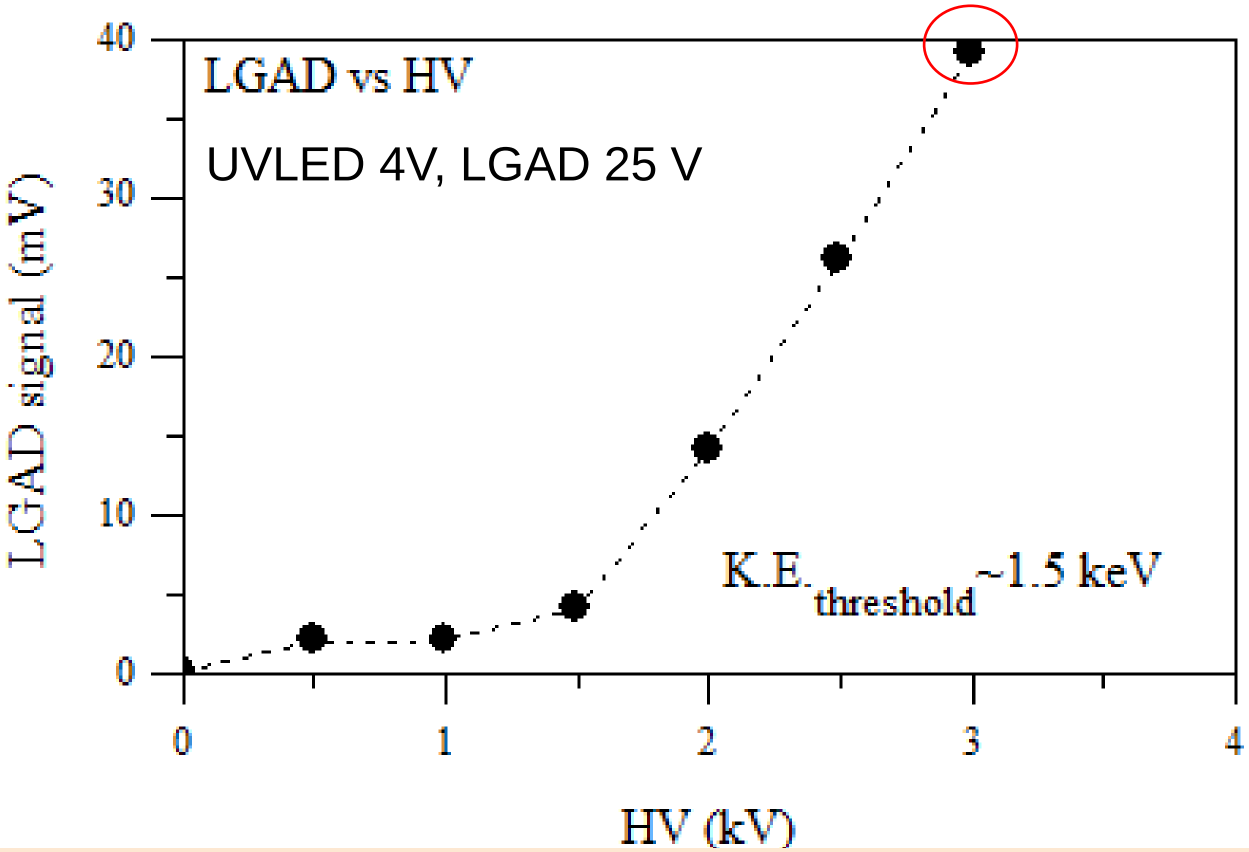



- Charge calibration: 5fC = 36 mV
- @3kV 40 mV LGAD signal =5.5 fC = **34720 e⁻**
- S/N ratio of **~9.5** and total charge gain ~ **2000**

# LGAD signal dependence on HV bias on GaN

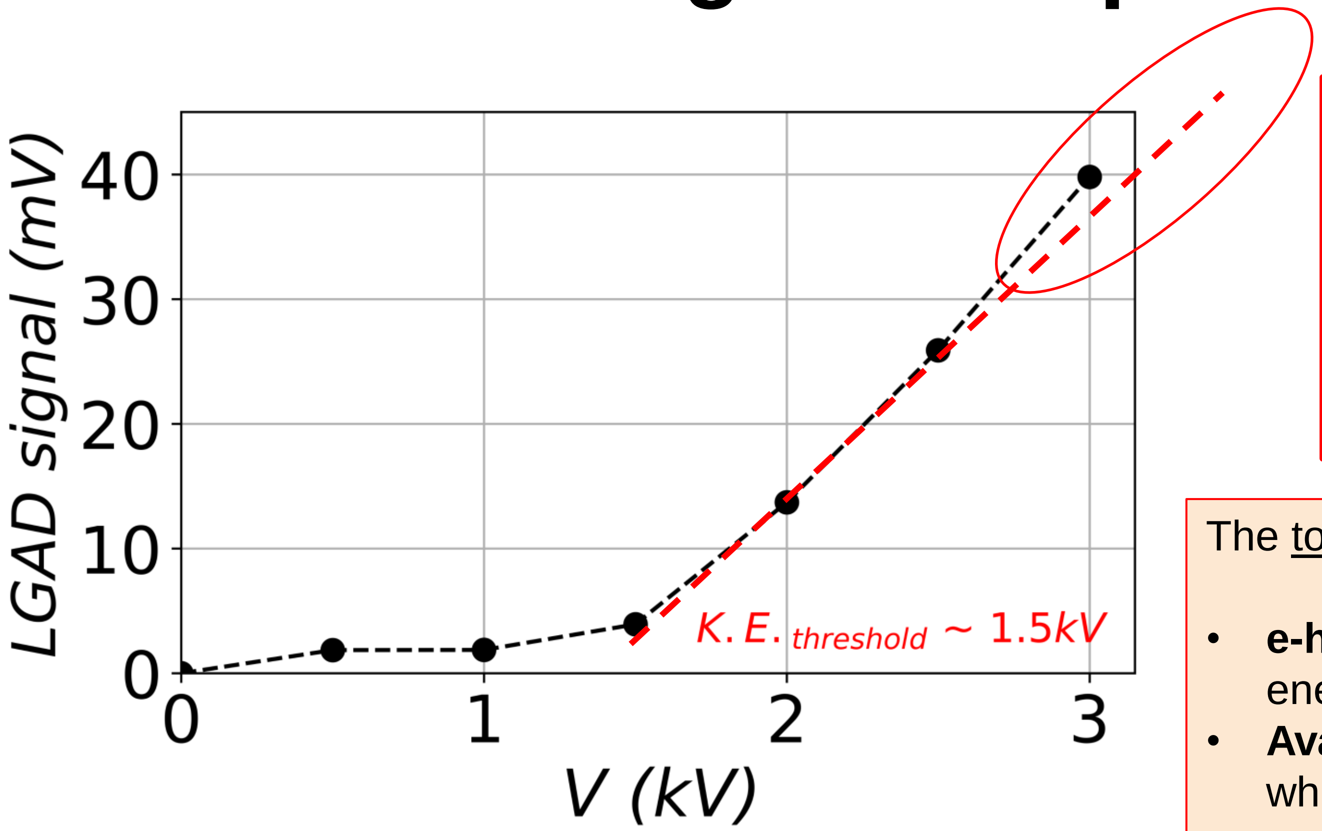



**A single 3keV photoelectron would produce a 2.5 mV signal**
**Lower than attained noise level in the amplifier (4.2mV)**
**Assuming a S/N~9 the current HPD can detect ~5 photoelectrons**

*we are NOT seeing single 3 keV $e^-$ response, yet.*

# Can we see single 3keV photoelectron in the future?




Linear(?) increase with energy of the gain

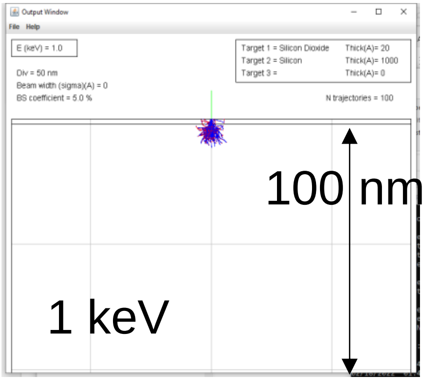
At 5kV signal would be >90 mV and the single photoelectron will produce a 5.6 mV signal which is larger than the noise level at 4.2 mV.

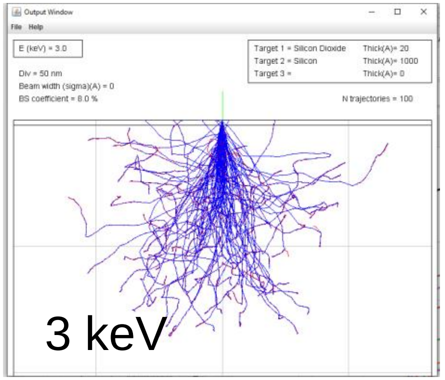
Reducing the noise level with improved set-up

The total gain of the device is the product of two factors:

- **e-h pairs production** – scales linearly with photoelectron energy
- **Avalanche gain** – which may be affected by the depth at which e-h pairs are generated

We are confident the prototype device can measure a single 5keV photoelectron



# Perspectives

- Reduce the distance a photoelectron has to travel.
- Increase the HV >5kV
- Reduce electronic noise :
  - -Incorporate the amplification electronic inside the UHV vessel
  - -Improve shielding
- Large detection area and segmented LGAD configuration

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- Thanks to Instrumentation Department's technicians and engineers




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Qrona Technologies

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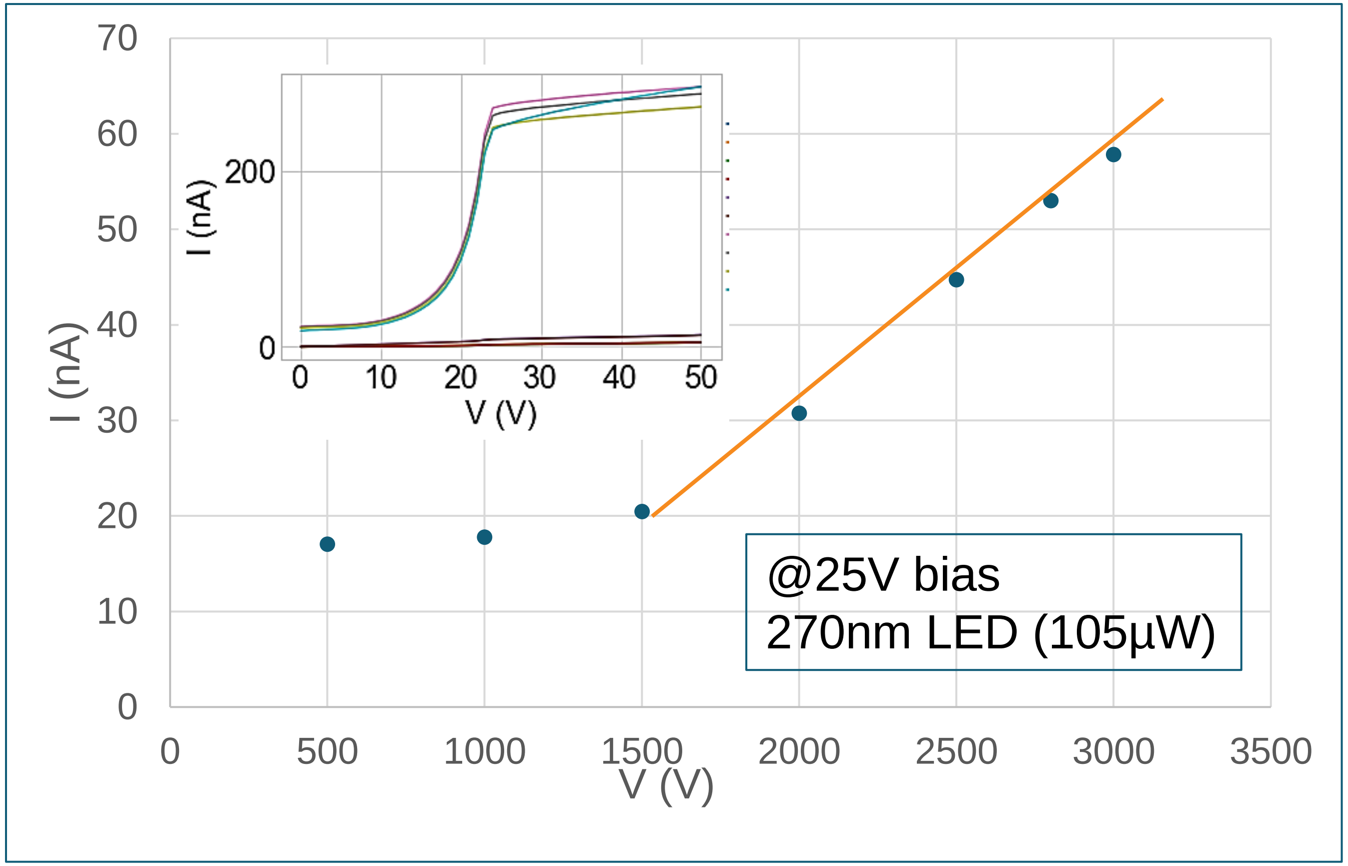
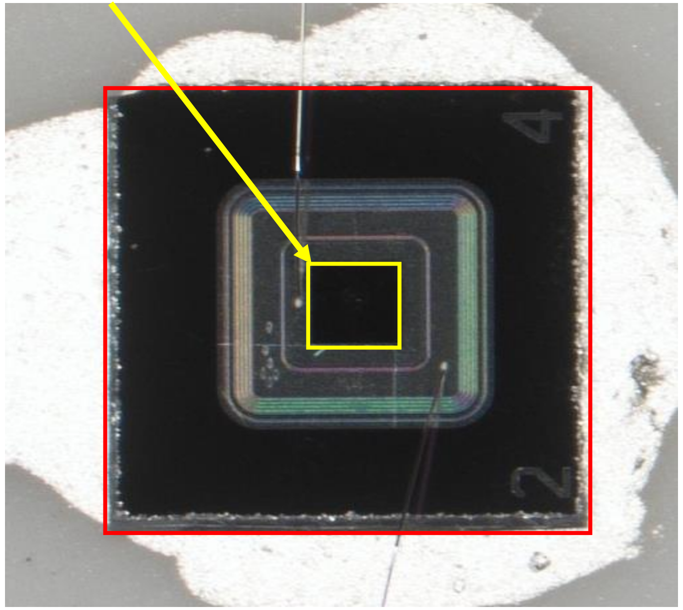
# Linear response vs electron energy



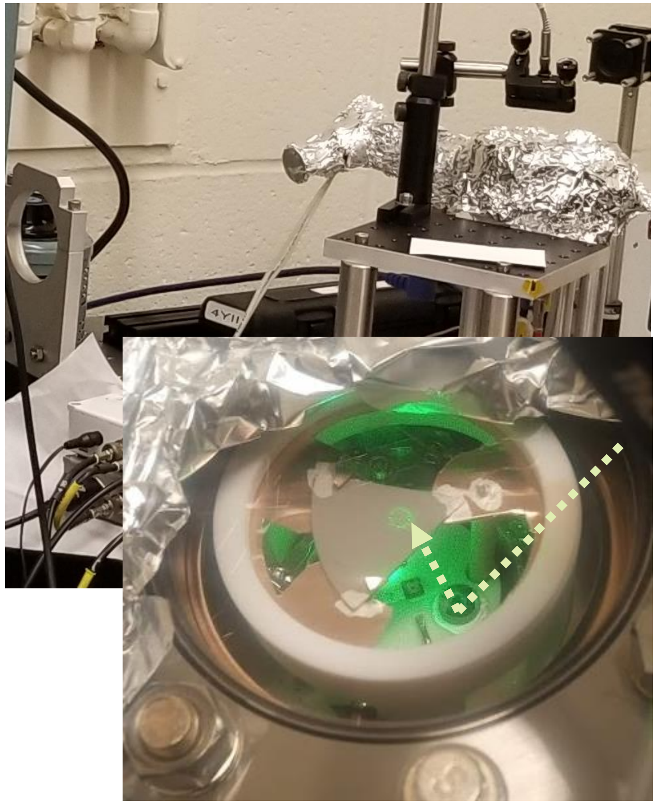

- ~1.5kV threshold acceleration voltage
- ~Linear amplification behavior >1.5kV
- Geometrical factor to be accounted for !!

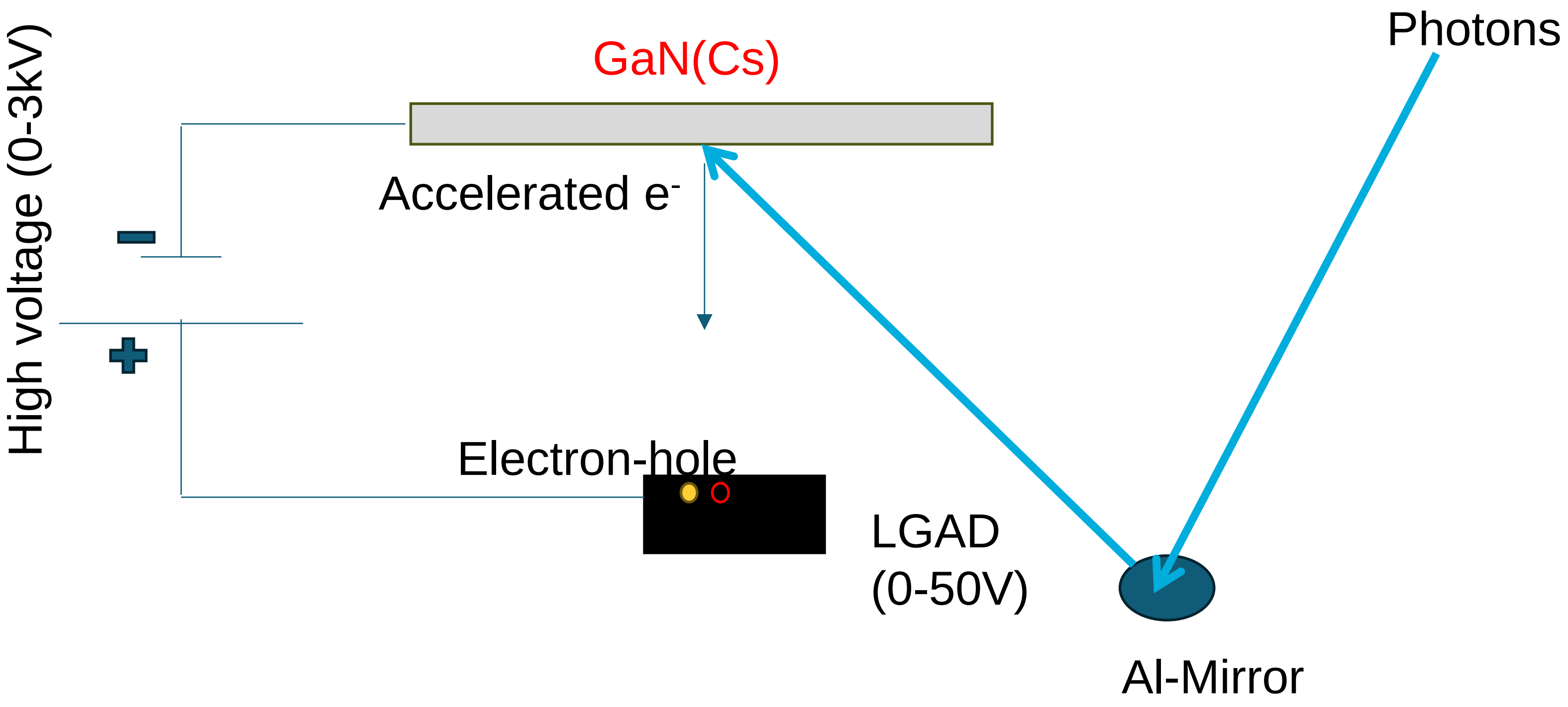
Active area is about 1/30th of the device area




$0.65 \times 0.65\ mm^2$

# CW-Laser alignment and LGAD response






- Beam waist ~5mm on the GaN
- Fiber coupled beam alignment for maximum LGAD photoelectric response
- Visible laser used for alignment only

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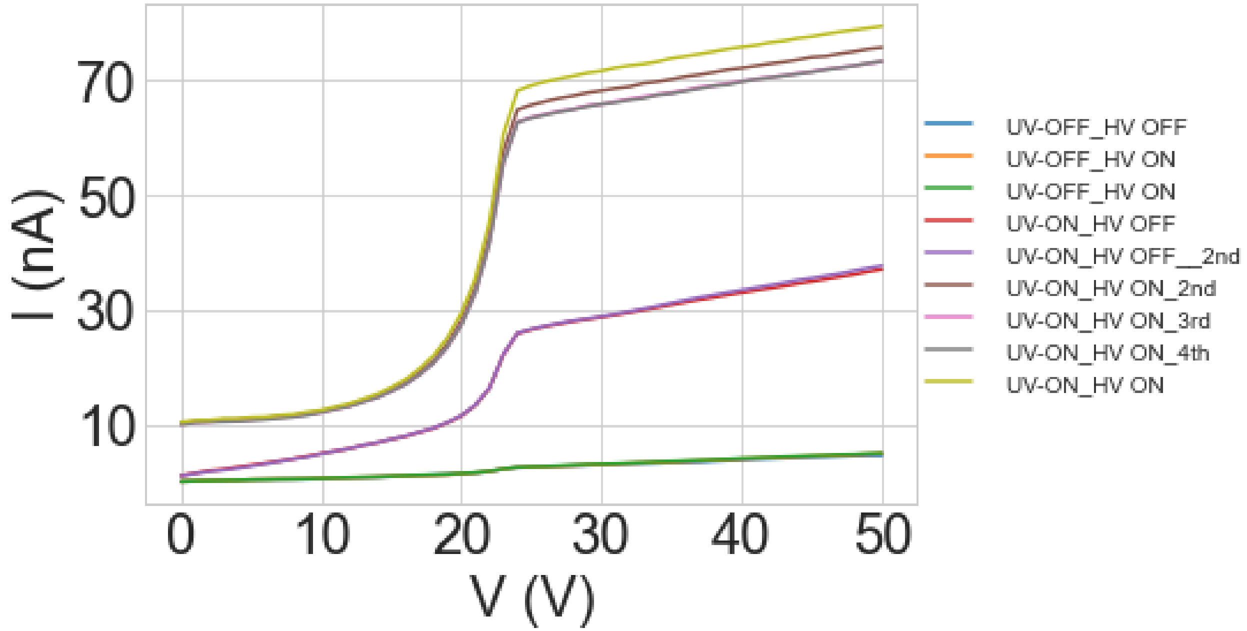
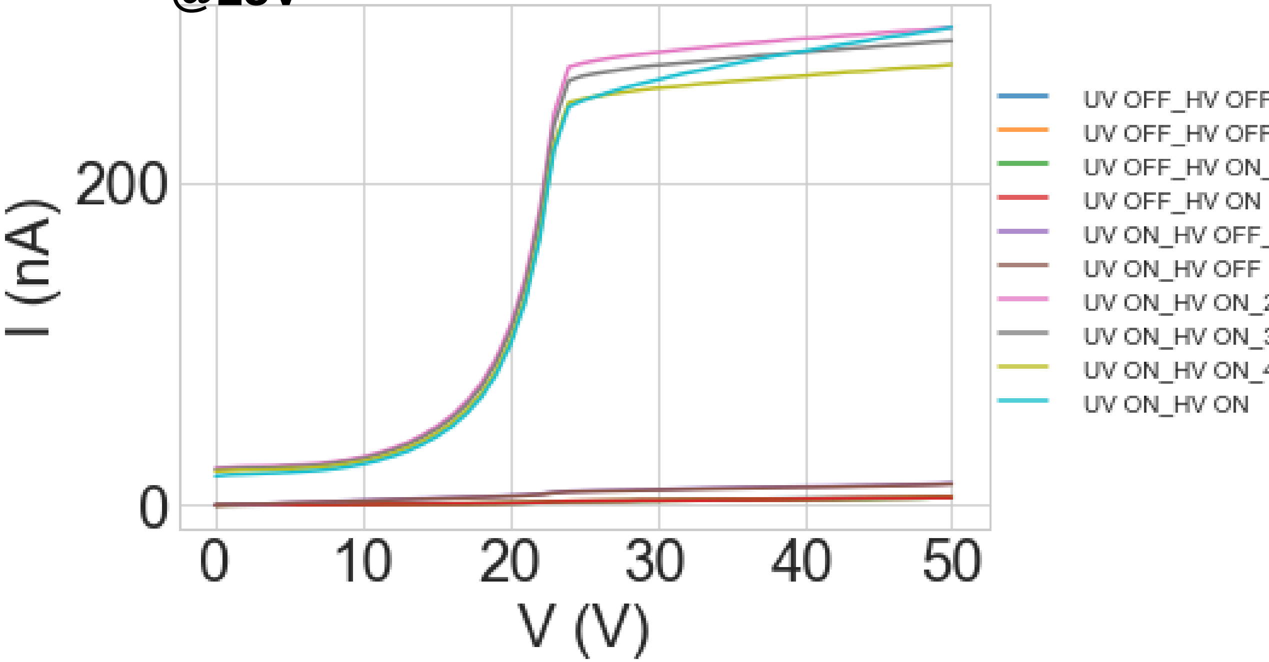
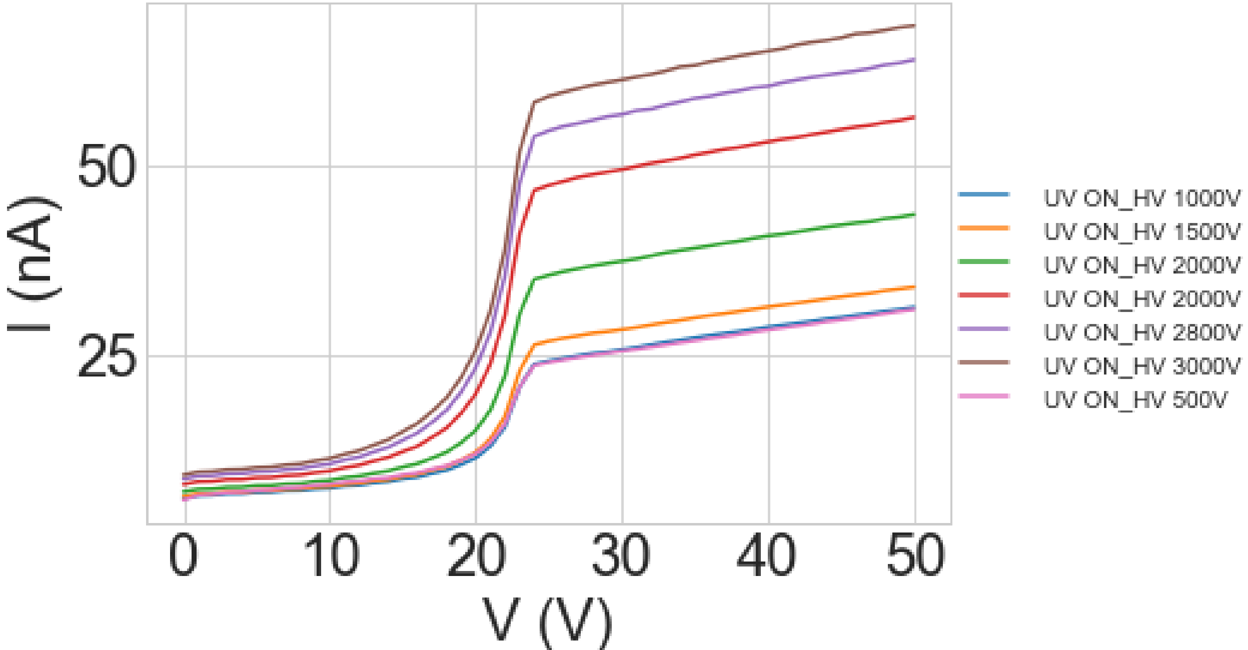
## Repeating the previous measurements:



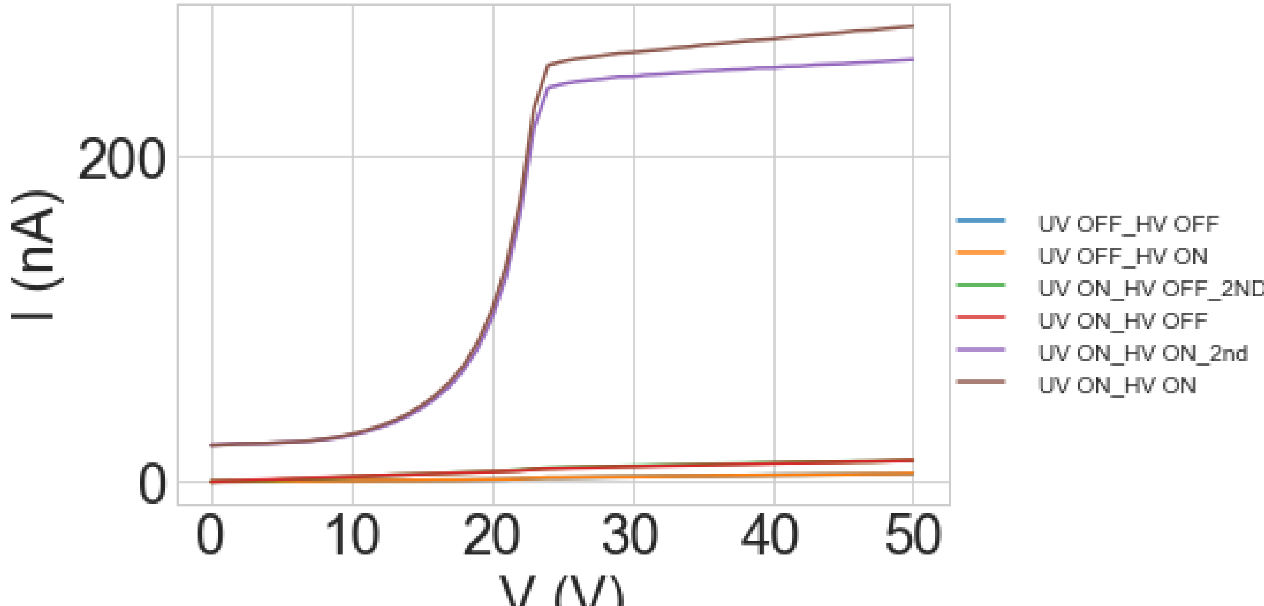

## Post_Maximizing LGAD response @25V




## HV sweep

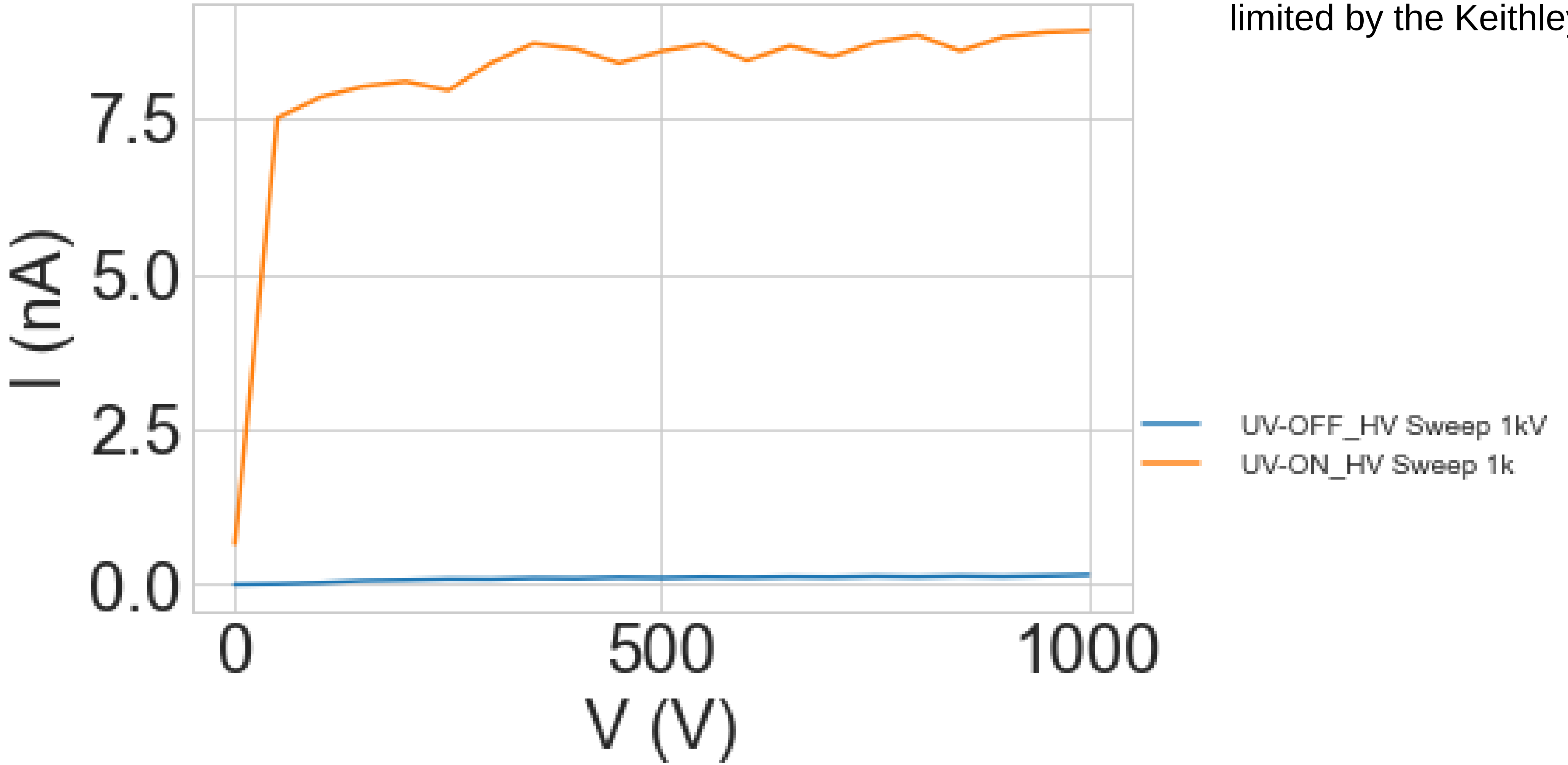



## Post_Maximizing beam reflection

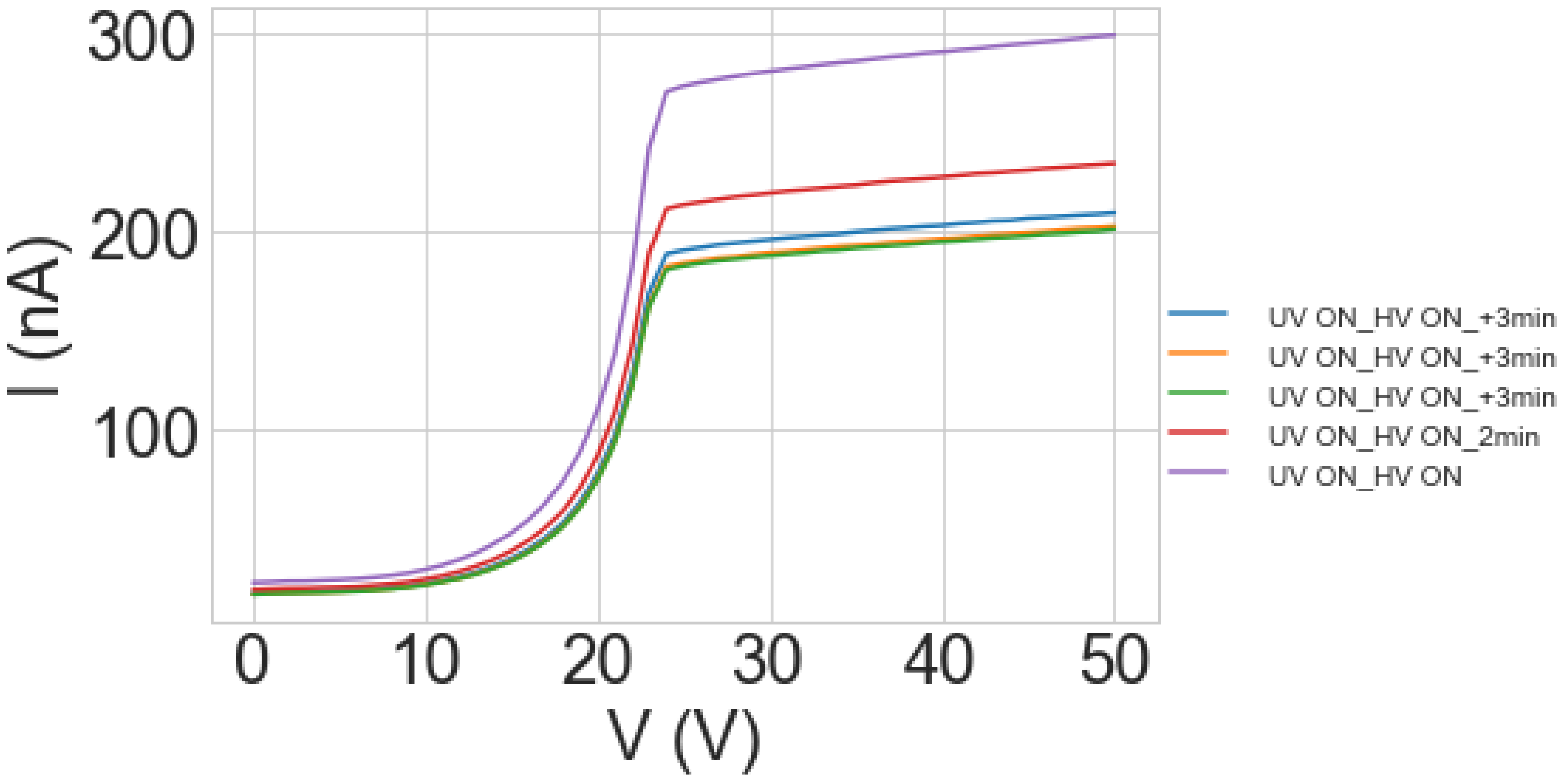


# Photocathode IV (Current output is ~7,5nA up to 1.5keV)

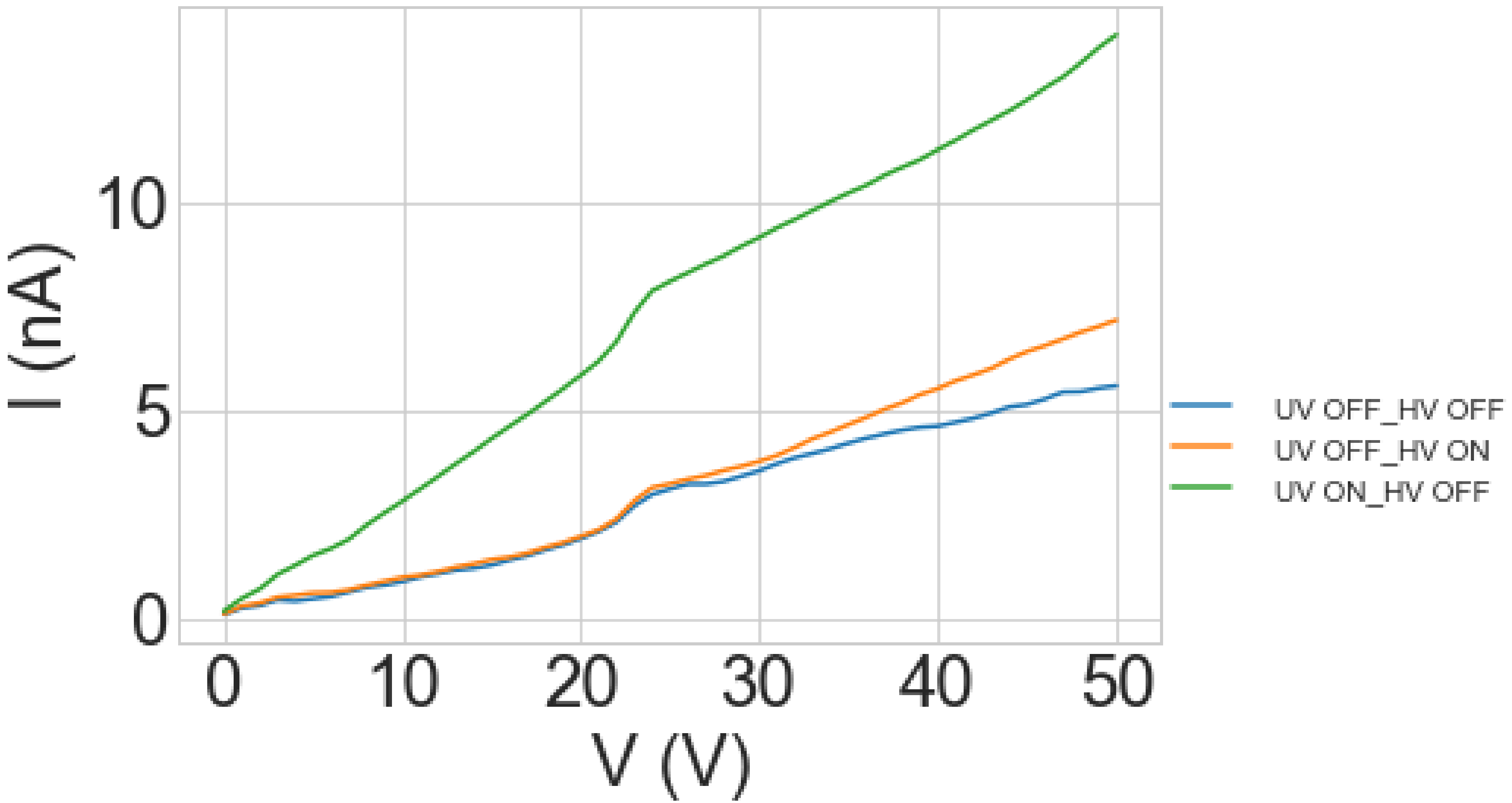
We couldn't measure the output current above 2kV, limited by the Keithley.



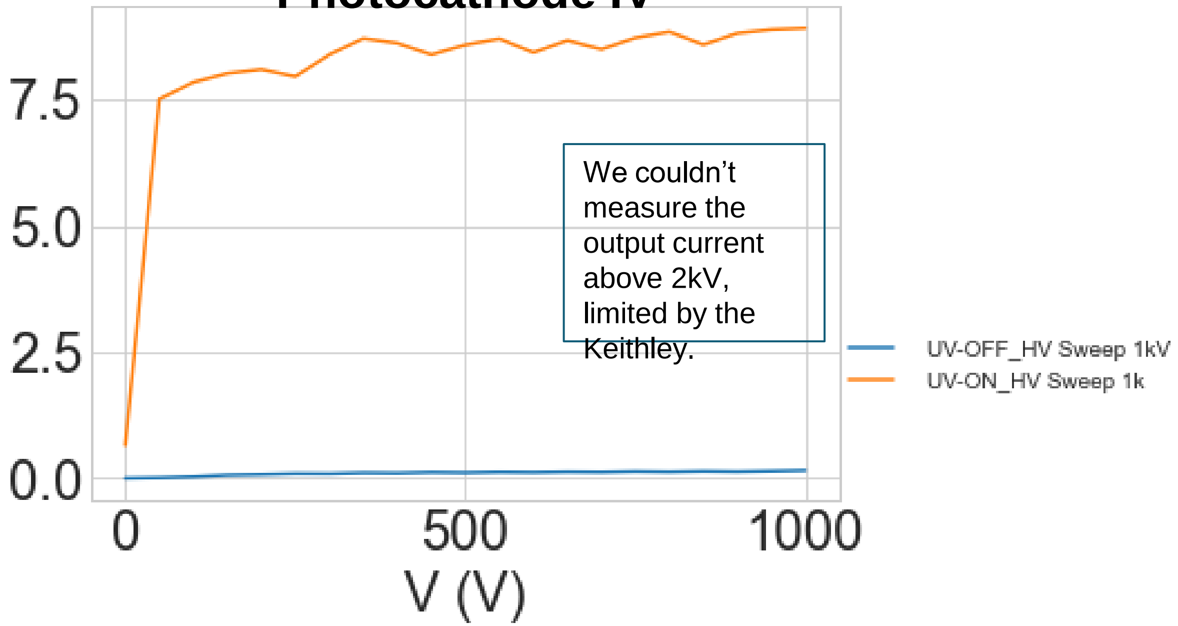
# LGAD photocurrent response decreasing in time



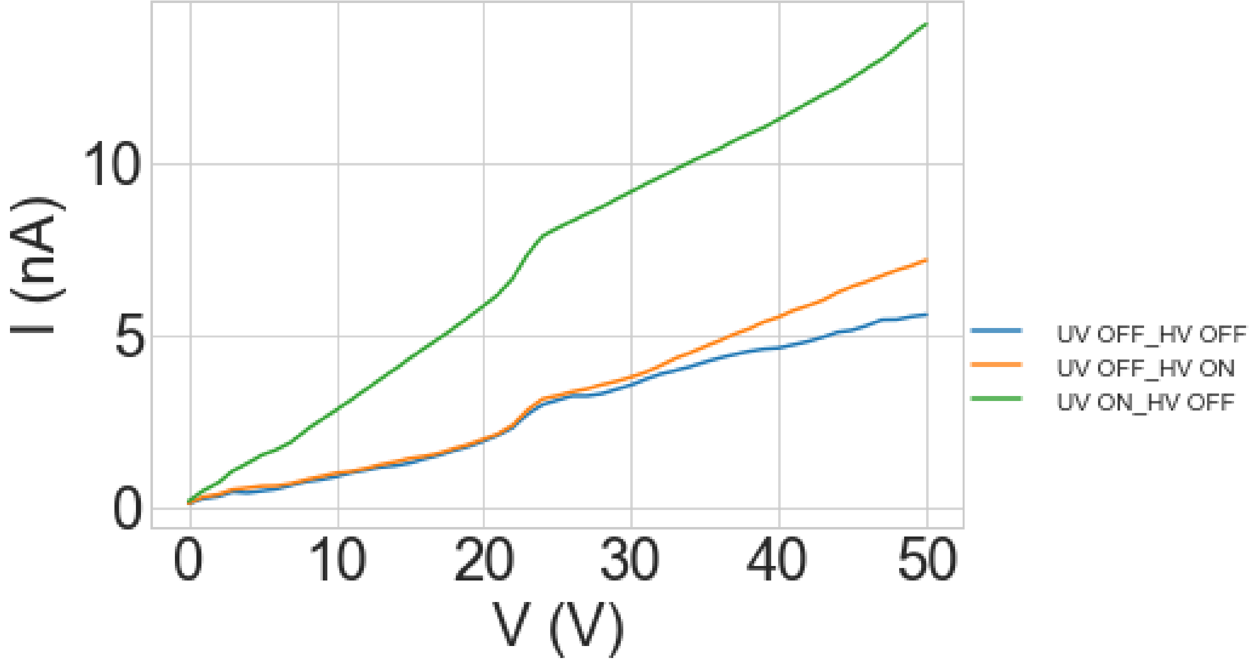
# Background measurement



## Photocathode IV




## Background measurement




## LGAD photocurrent response decreasing in tin