Instrument Research & Development

The Properties of Cryogenic CMOS Avalanche Photodiodes

SSPM Detector for Polarized Target Scintillator Readout

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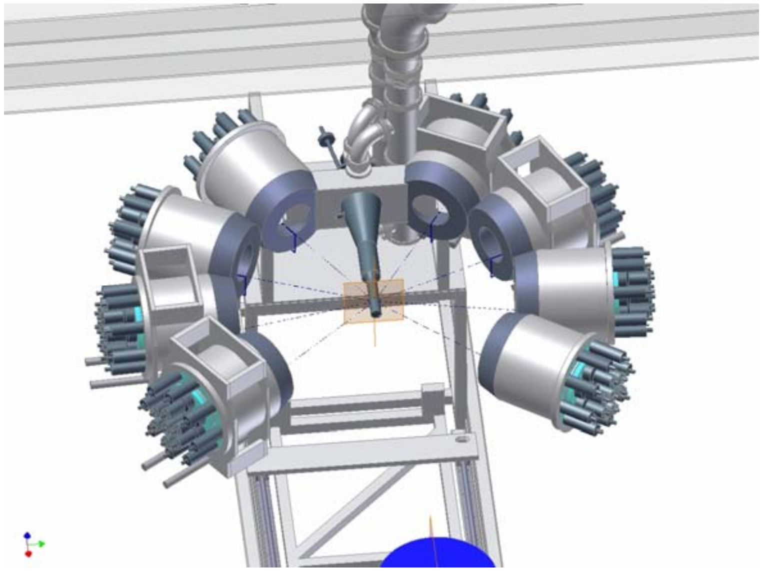
Extreme Environments and the Polarizability of Protons

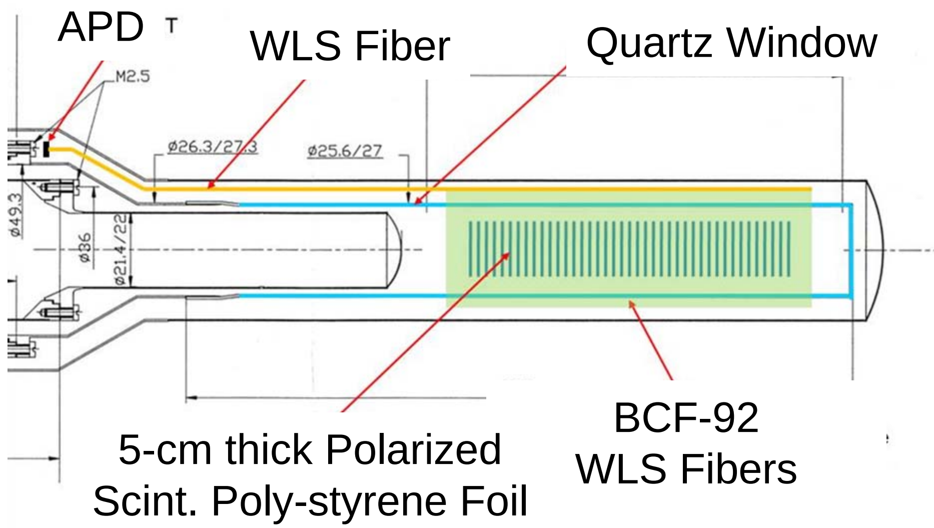
- **Goal: Develop photodetectors with gain that operate in extreme environments:**
  - **Temperatures around a few Kelvin**
  - **High magnetic fields of several Tesla**
  - **High-helium environments.**
  - **Small physical spaces of less than 1 cm x 1 cm**
- **PMTs will fail if exposed to these types of environments, where a solid-state photodetector may not.**
- **New class of nuclear physics experiments:**
  - **Look at spin polarizability of nucleons**
  - **Spin polarizabilities characterize how circularly polarized photons interact with a polarized nucleon.**
  - **Little is known how circularly polarized fields influence polarized protons.**
- **Scatter circularly polarized photons off of polarized protons.**
- **HIFROST:**
  - **Polarized proton target**
  - **NaI detectors are used to measure scattering kinematics**
  - **Few Tesla**
  - **Target at a few milliKelvin**



- **Background Rejection**
  - **Target is a hydrocarbon scintillator with embedded polarized protons**
  - **Rejection of backgrounds is done using a coincidence signal**
    - **NaI signal**
    - **Scintillator signal**
    - **Beam signal**
  - **Scintillator will be readout with a photodetector**

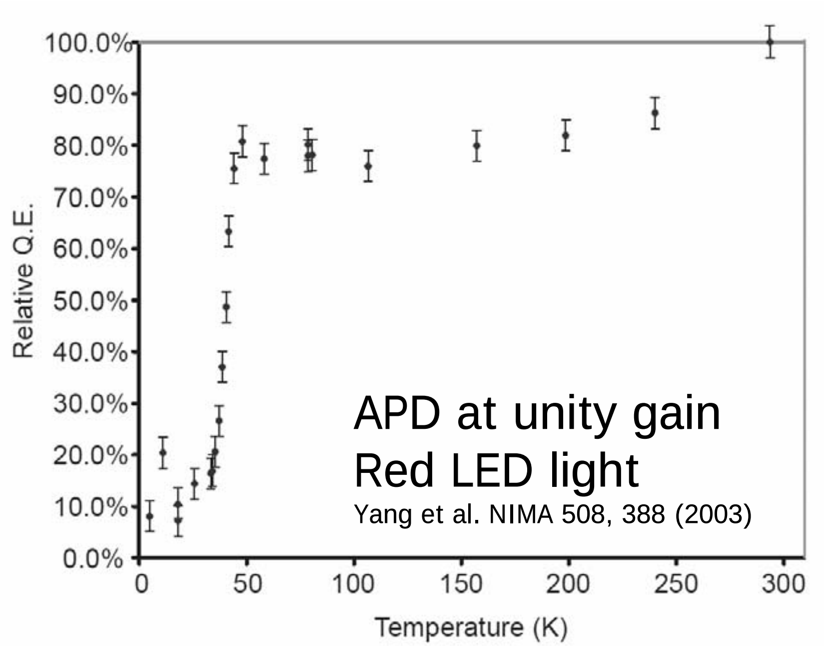
Polarized Proton Target

Light capture with wavelength shifters

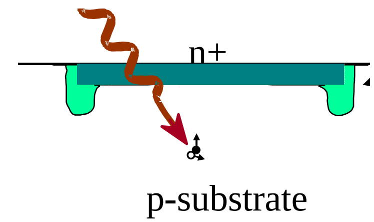


- **A PMT can not be used for the existing target cryostat: A complete redesign of the system would be required.**
- **Mount photodetectors outside the dilution refrigerator: Temperature ~ 3-4 K**
- **Scintillation rests within a transparent vessel**
- **Wave-length shifting fibers (Saint Gobain BCF-92, max. emission 480nm) are use to collect the light and transport it to the photodetector.**
- **The design goal is to obtain photon collection efficiencies of approximately 10% with an energy resolution of 10%.**
- **This resolution is necessary to reject backscattered protons freed from ^{12}C atoms in comparison to the scatter of free polarized protons.**

GPD Operation at Low Temperatures

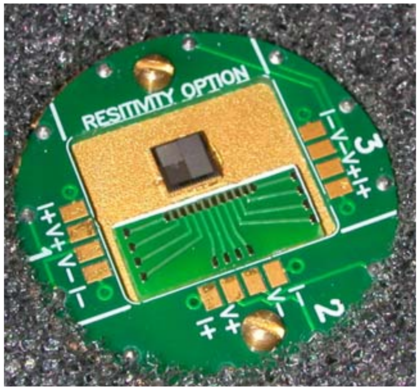


- Typical APD structure is doped to reduce excess noise at room temperature.
- Large gains are achieved at high biases (~1000 V).
- Carrier loss is a viable explanation for loss of QE below 40 K.

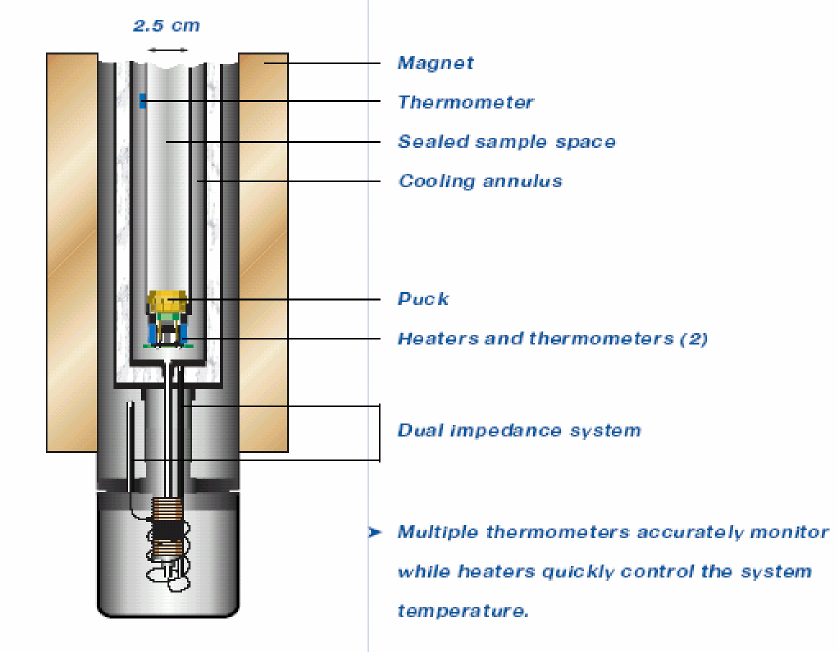


- Geiger Photodiode (GPD) is an avalanche photodiode operated beyond the breakdown voltage.
- The GPD is the basic building block for a solid-state photomultiplier.
- Doping leads to a low voltage breakdown.
- Carrier loss should be less of an issue.

Setup for GPD Evalution

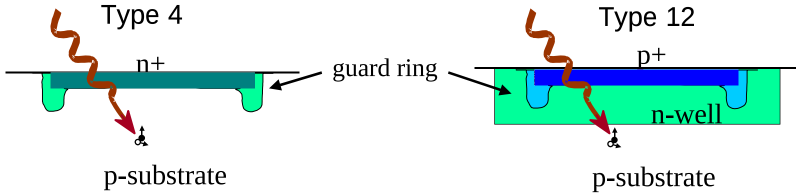


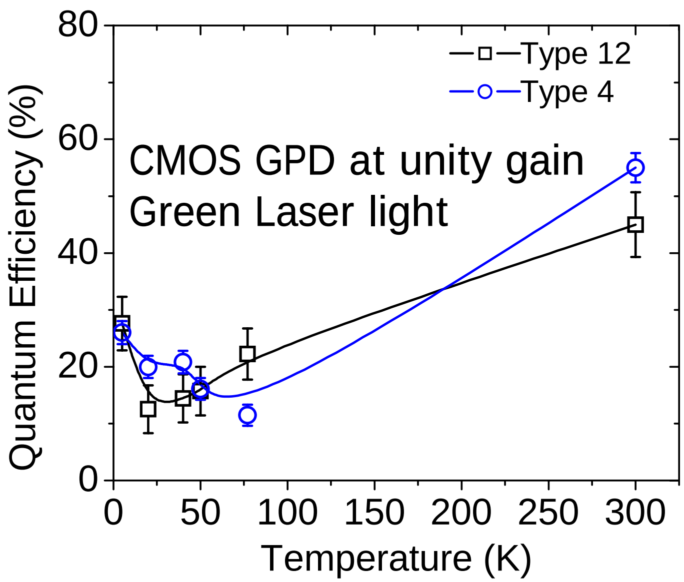
Puck with
SSPM and GPD

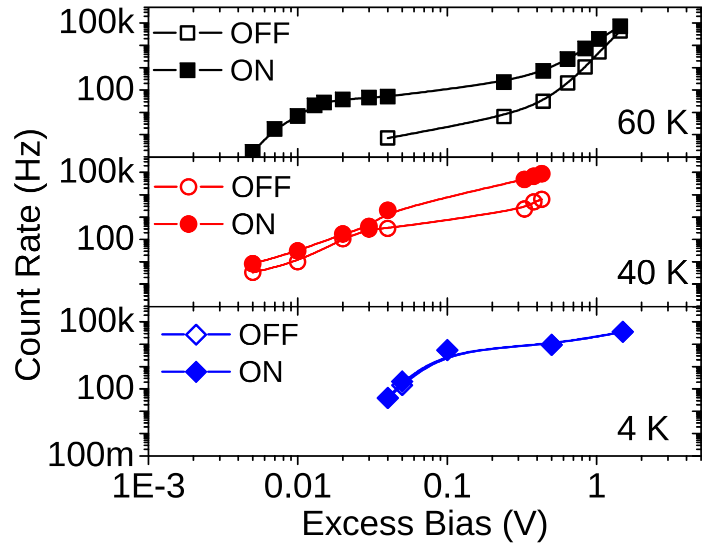


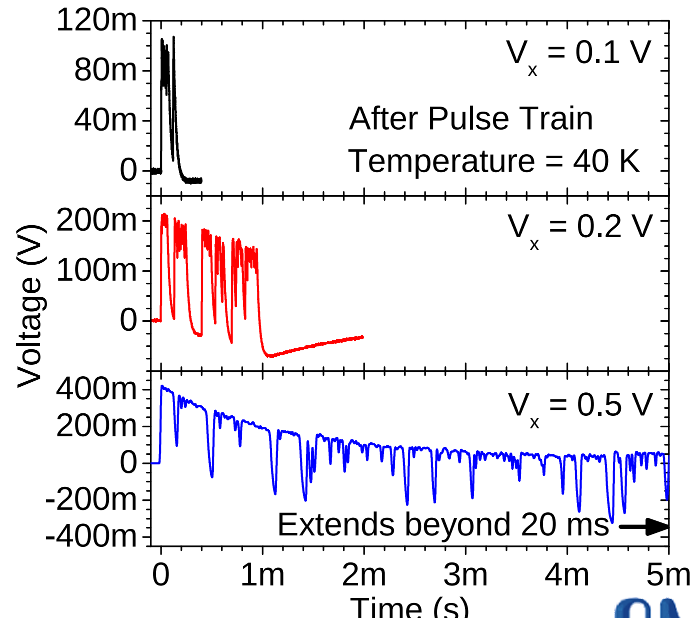
- **Mounted GPD and SSPM to puck for insertion into cryostat at the University of Massachusetts.**
- **Mounted LED and Laser to a viewport on the cryostat to inject light into the system.**

GPD Results



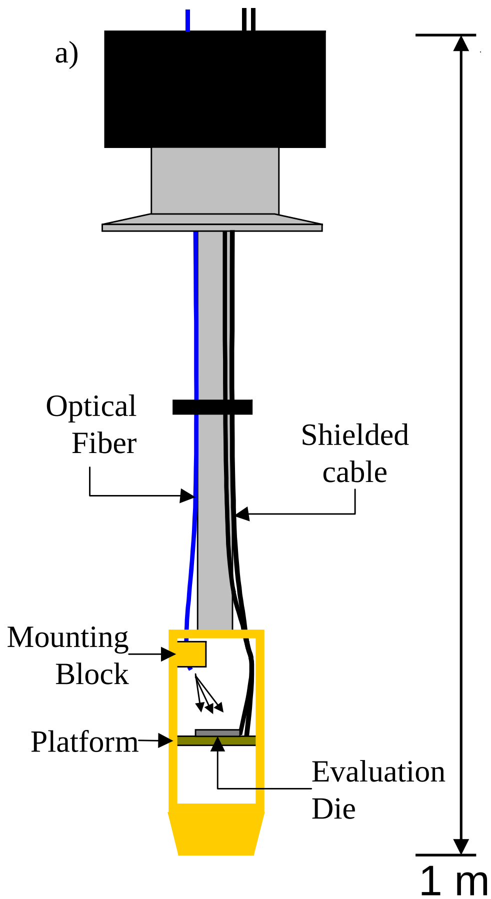


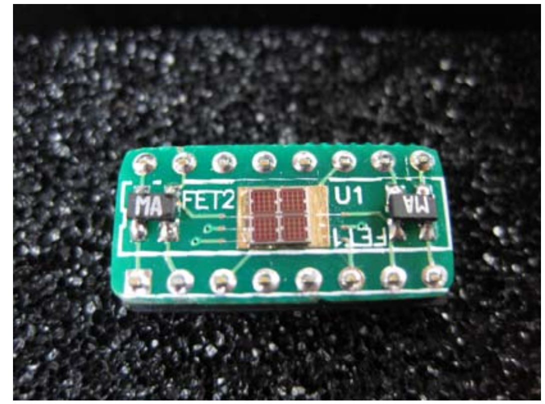


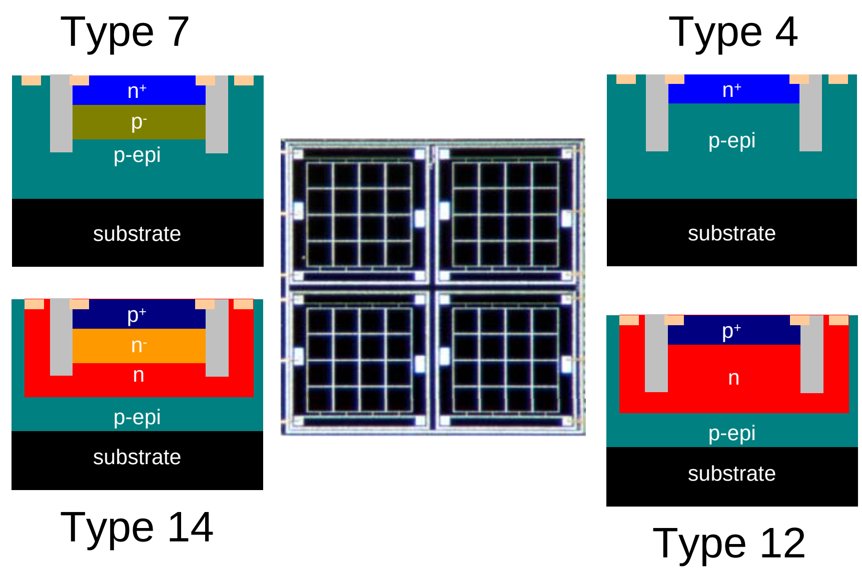


- ➢ **Excess noise at low temperatures.**
- ➢ **After pulsing effect.**

APD Setup

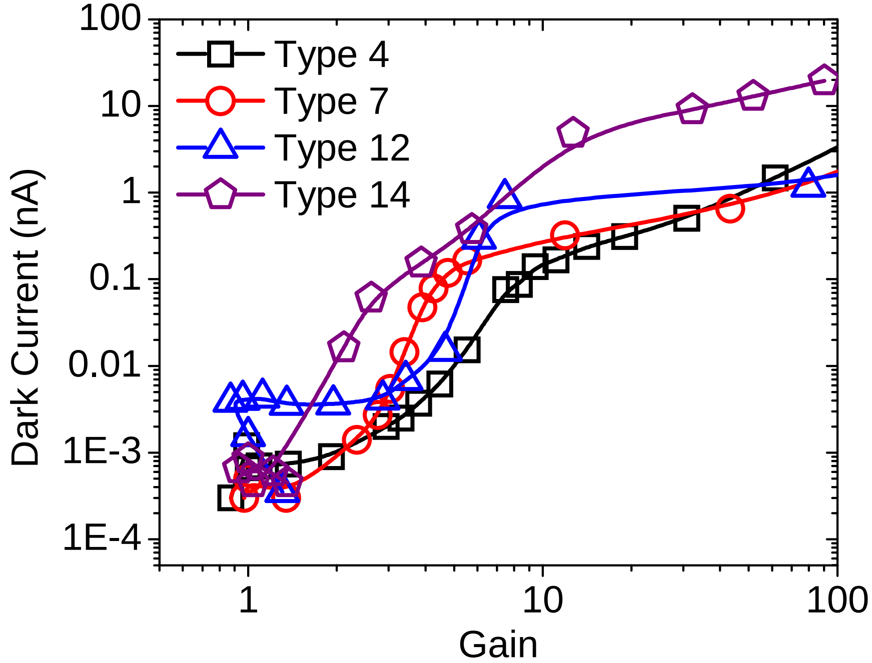

a)
Optical Fiber
Shielded cable
Mounting Block
Platform
Evaluation Die
1 m

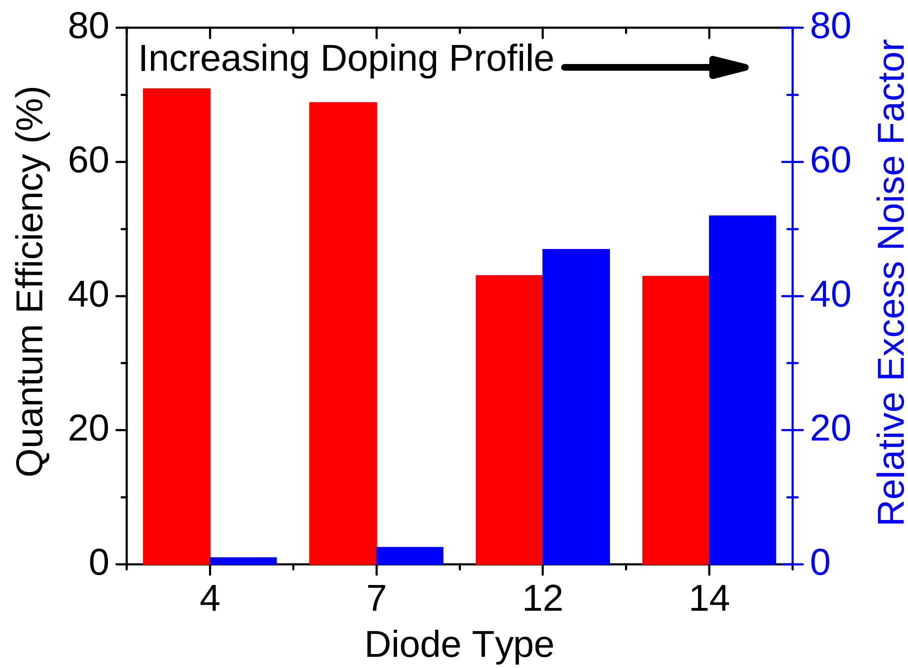

FET2
U1


Type 7
n+
p-
p-epi
substrate
Type 4
n+
p-epi
substrate
p+
n-
n
p-epi
substrate
Type 14
p+
n
p-epi
substrate
Type 12

Determining Best Diode

- **Determine the QE, gain, dark noise and excess noise at 4 Kelvin.**



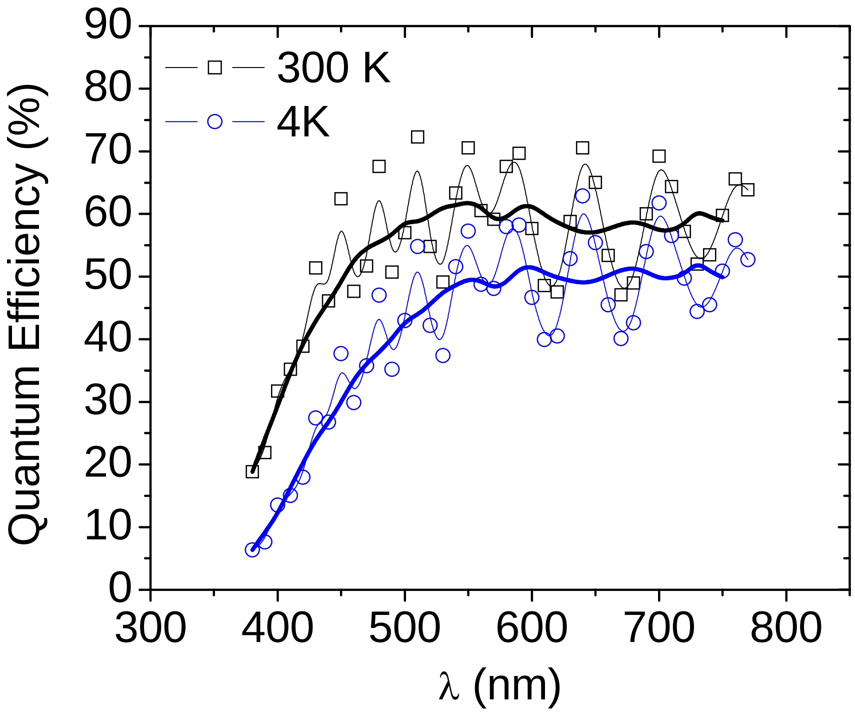


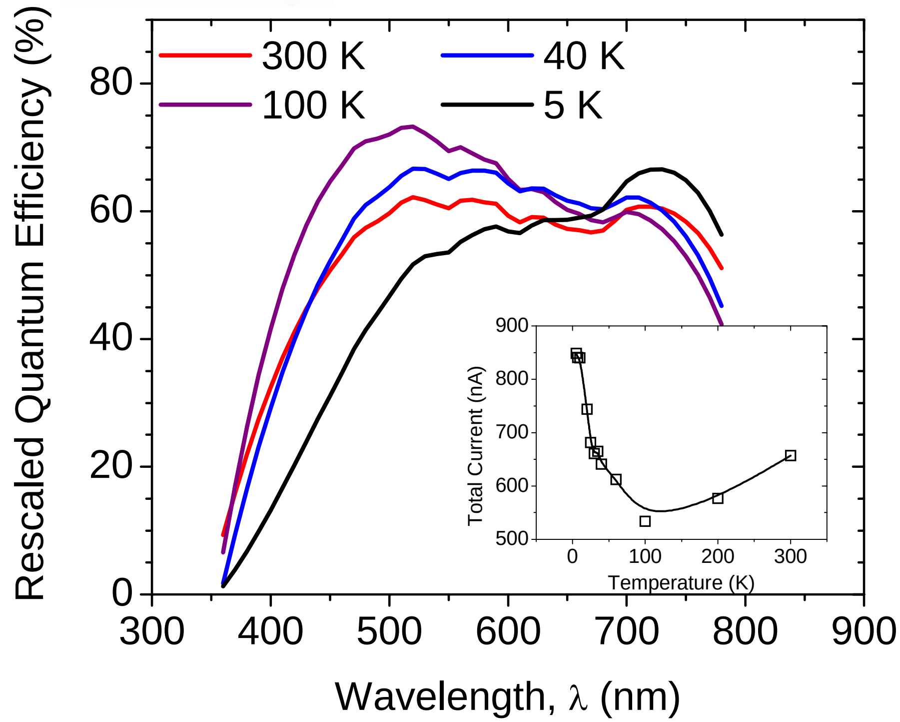
- **QE and Gain measured with a 532 nm LED.**
- **Excess noise is determined by pulsing the LED to collect a pulse height distribution.**
- **Best Diode: Type 4.**

Quantum Efficiency

Open window to cryostat

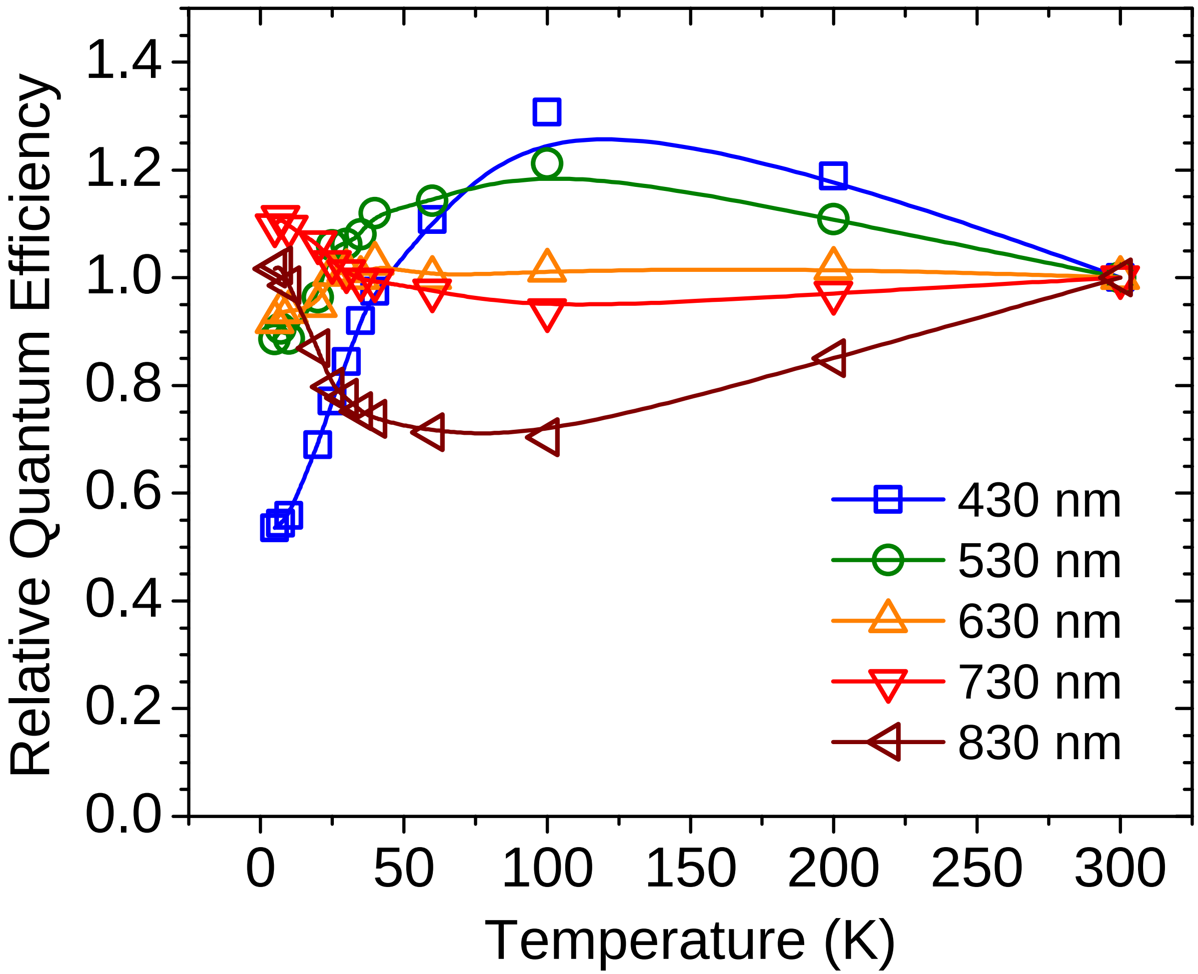
Piped in light using fiber



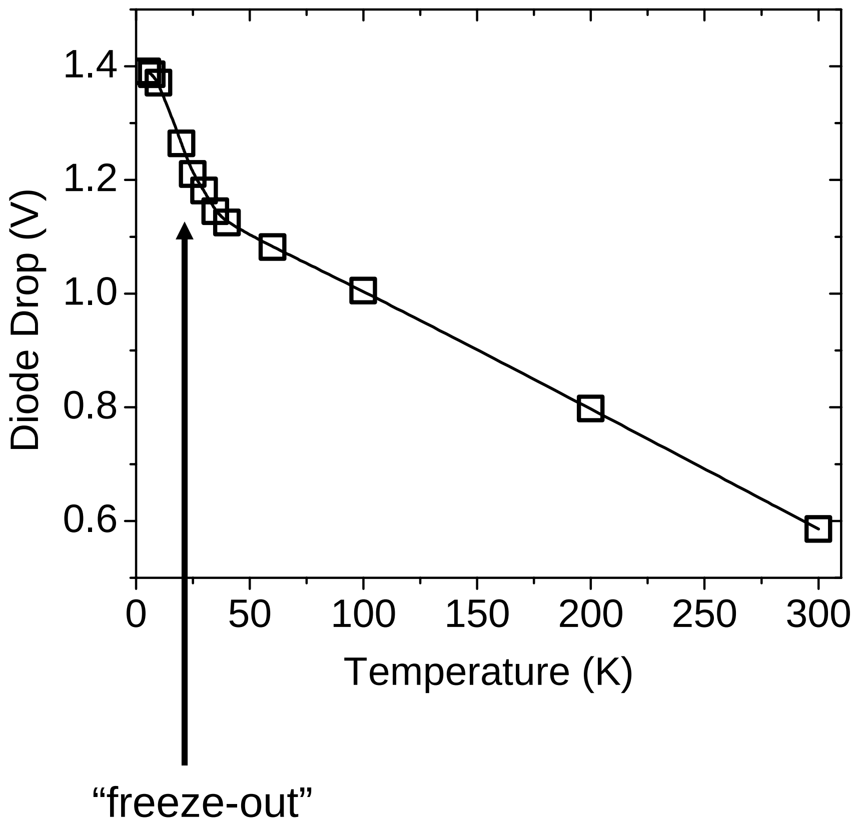


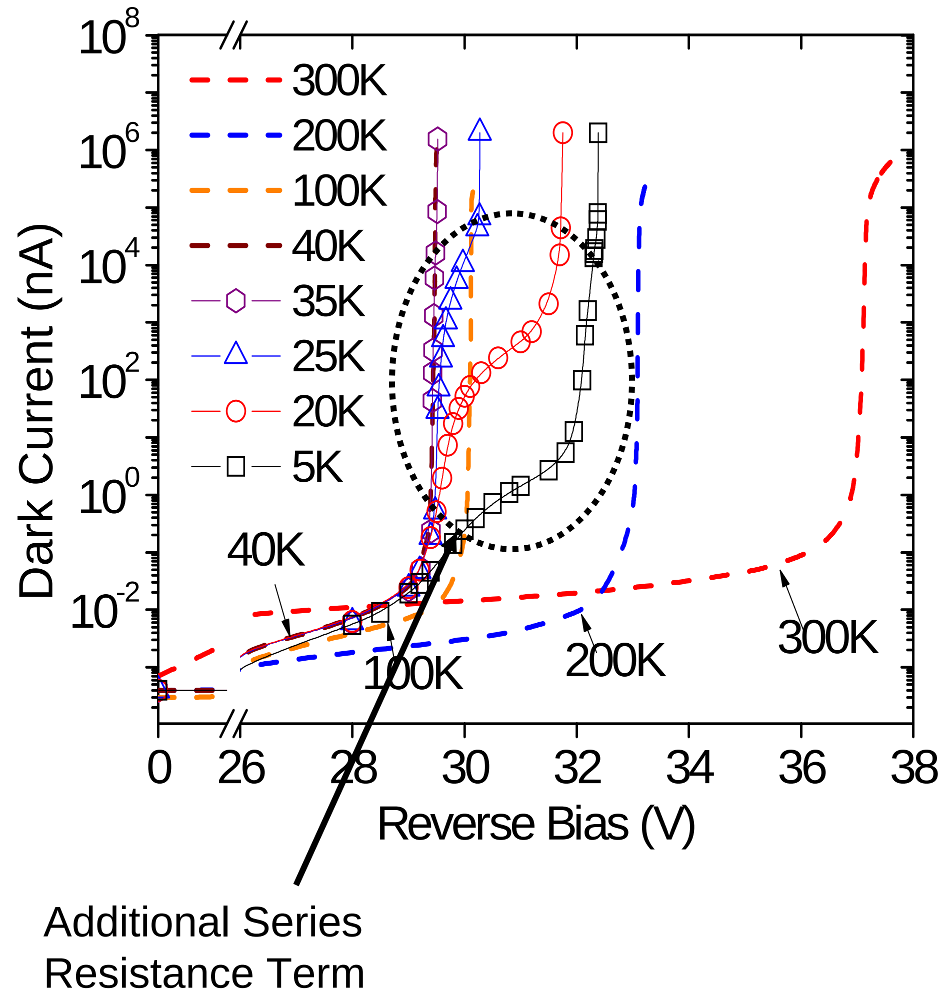
- **Device is at 0V**
- **To measure QE at low temperature, the current at low temperatures is compared to the RT currents.**
- **Rescaled QE to account for possible changes in light transmission.**

Relative Quantum Efficiency

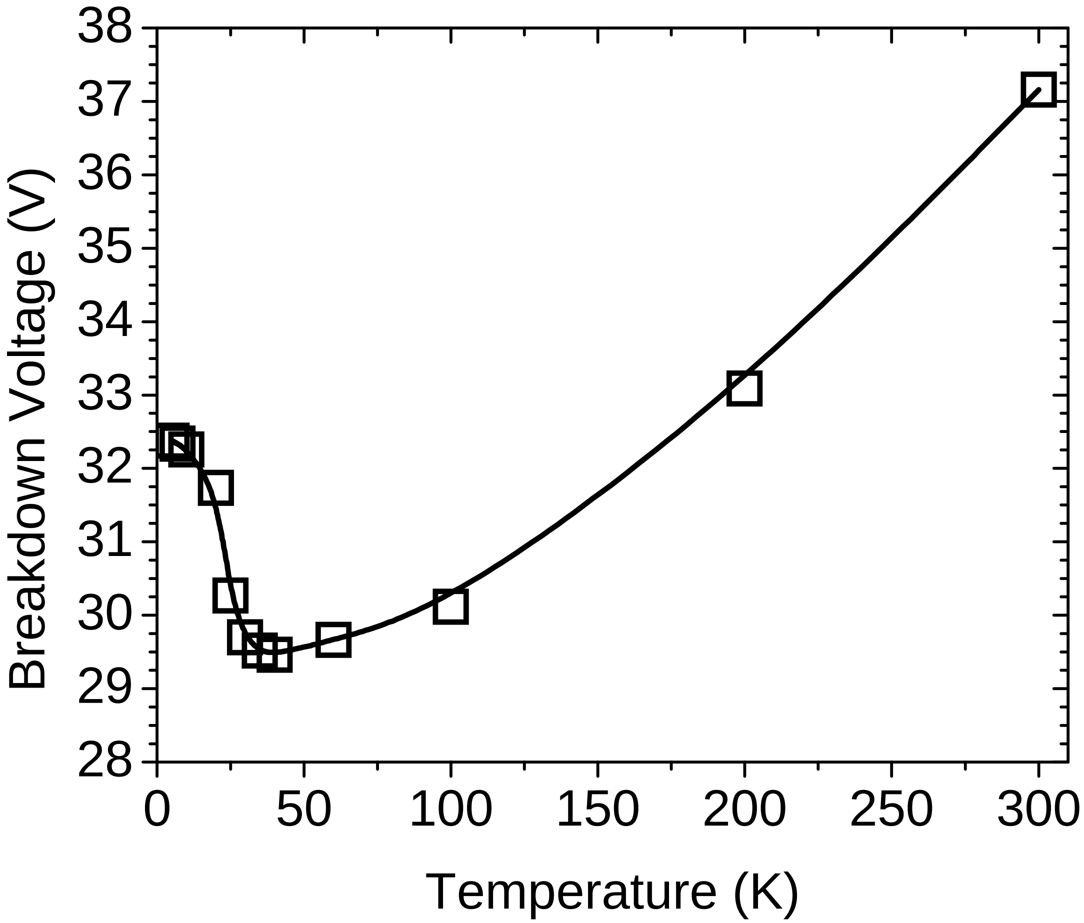


IV Curves and Diode Drop





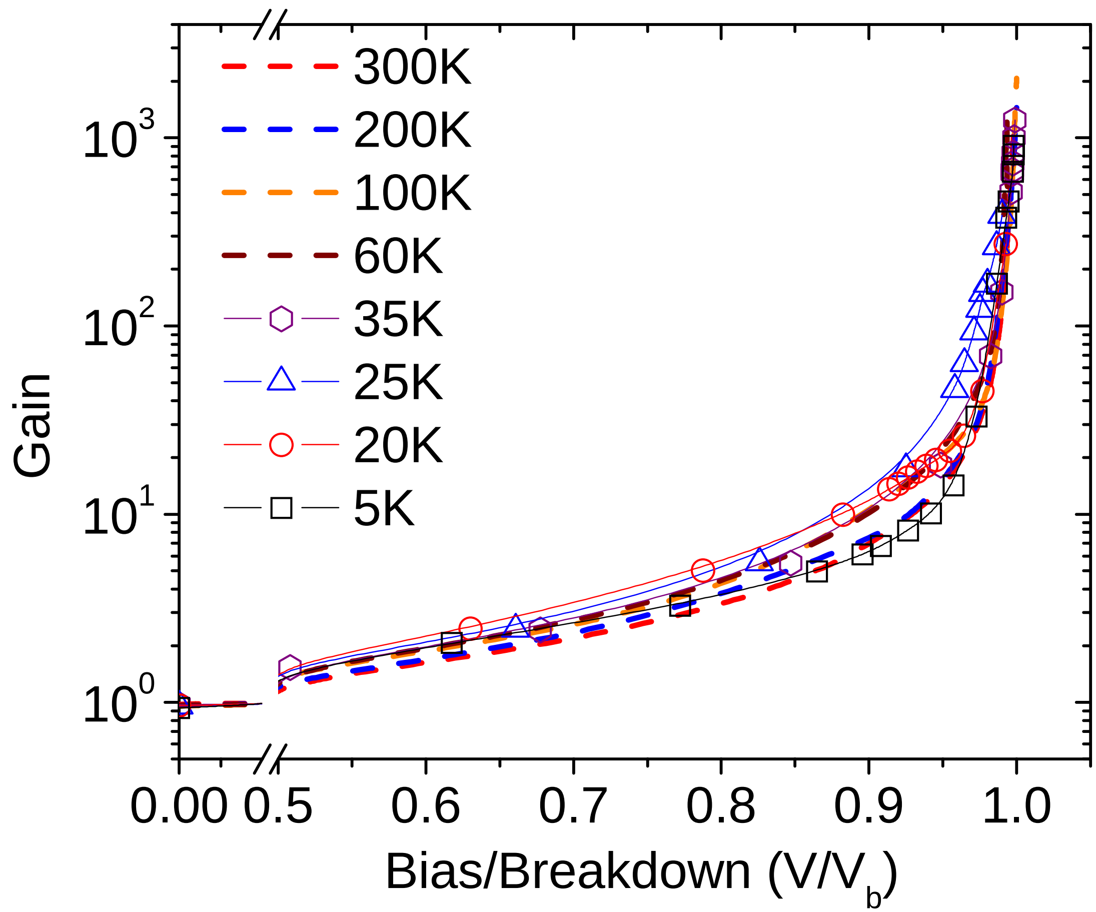
Breakdown



- **Strong dependence on temperature.**

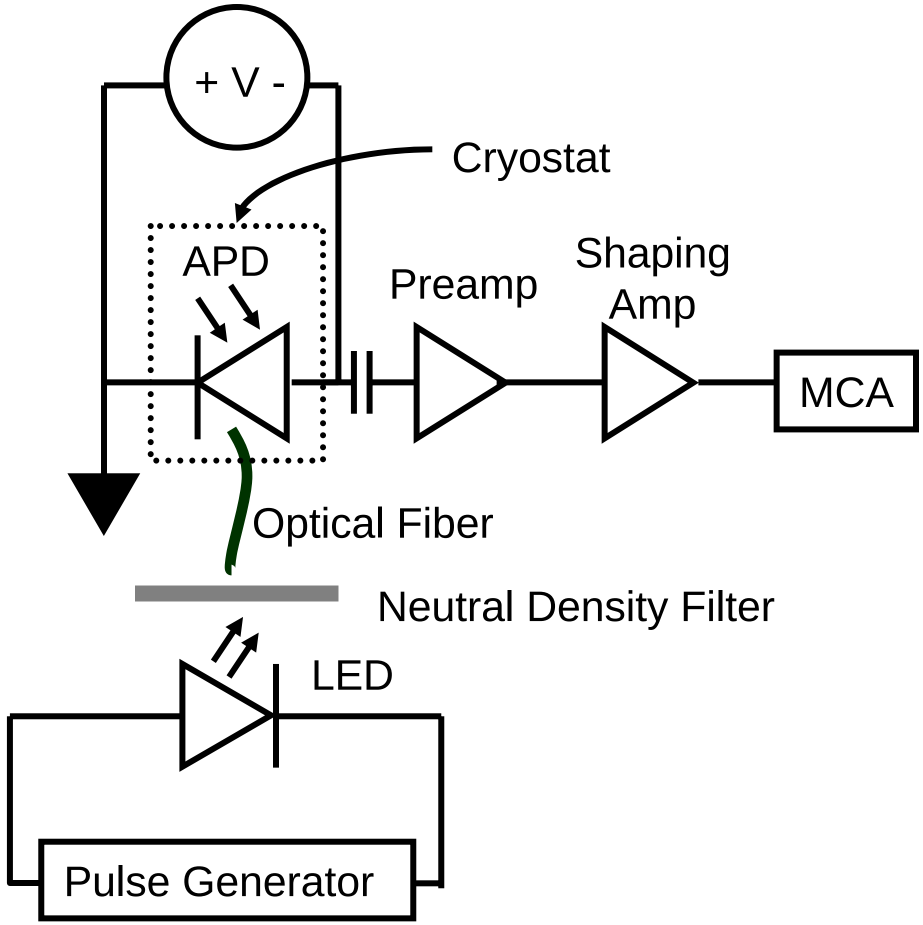
Gain

$$Gain \propto \frac{1}{1-\left(\frac{V}{V_b}\right)^n}$$



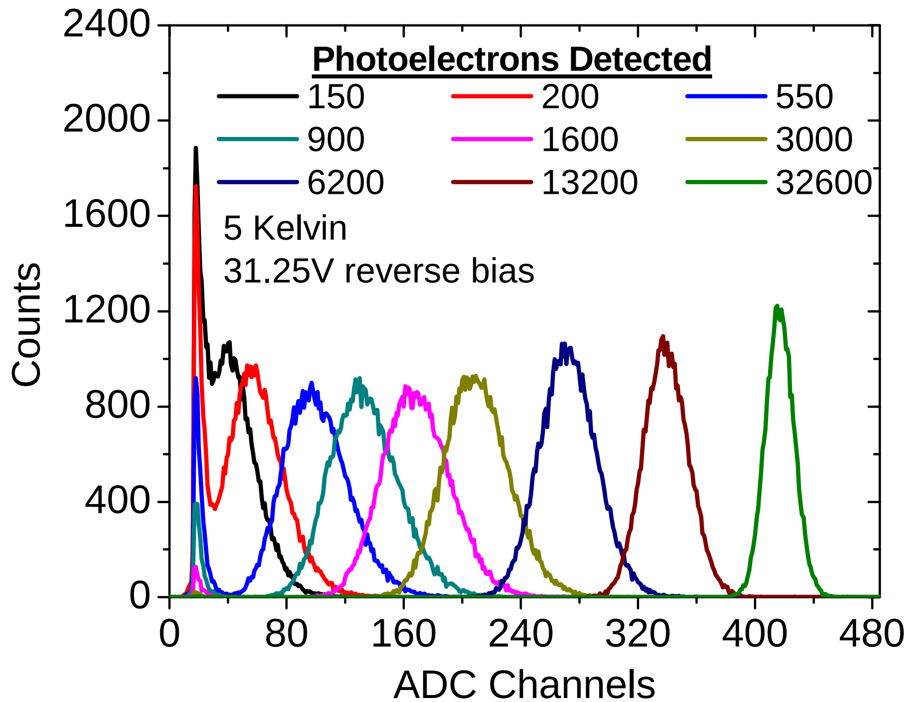
- **Measured using 532-nm LED light**
- **Weak dependence on temperature.**

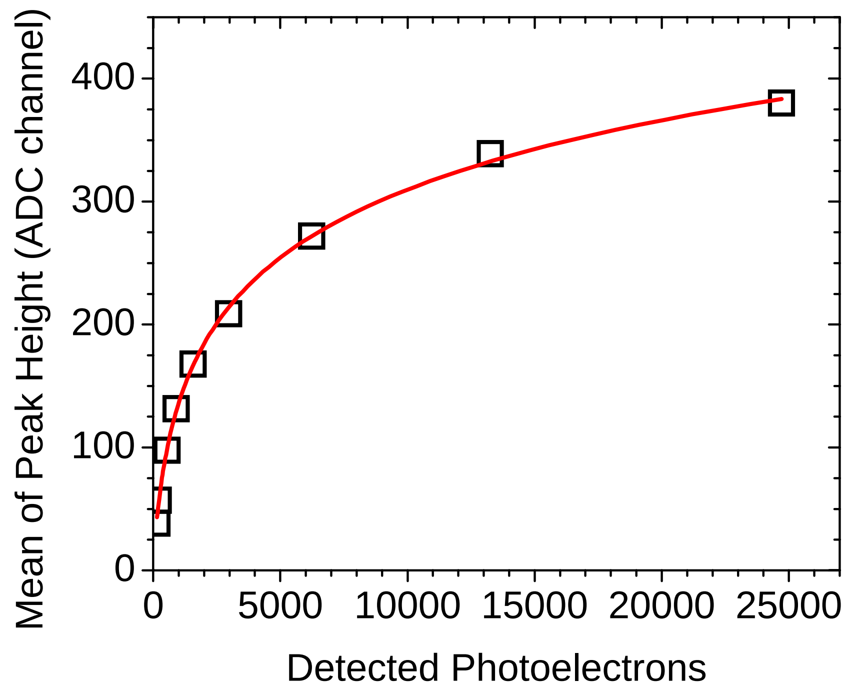
Pulsed Light



- **532-nm LED is driven with a 20-ns pulse.**
- **Neutral density filters are used to attenuate light intensity.**
- **Signal coupled to the Amptek CoolFET charge-sensitive preamplifier.**
- **Used a 20-ns shaping time.**
- **Fed signal into a Amptek Pocket MCA.**

Response

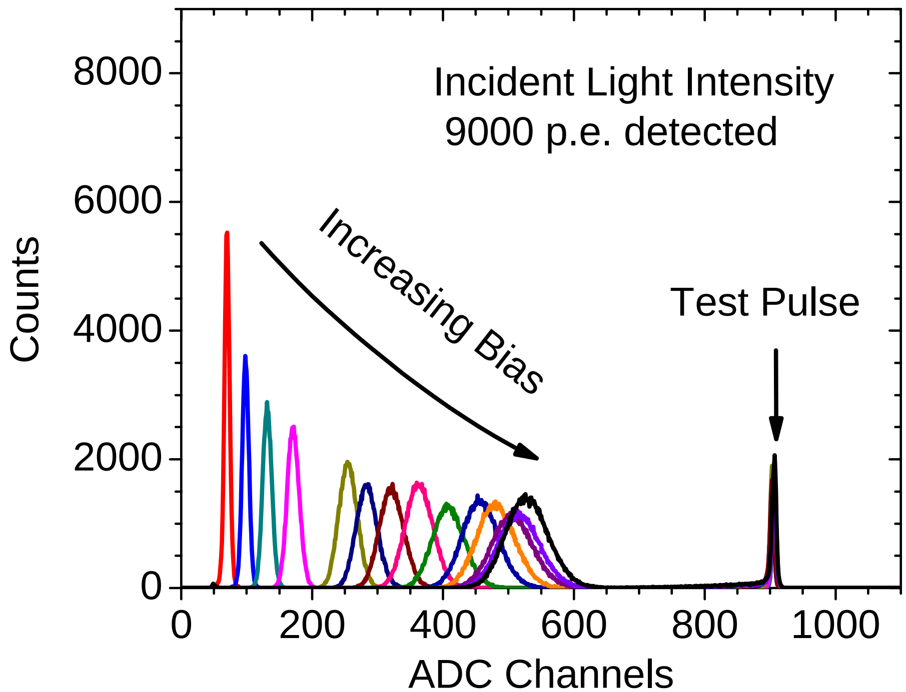


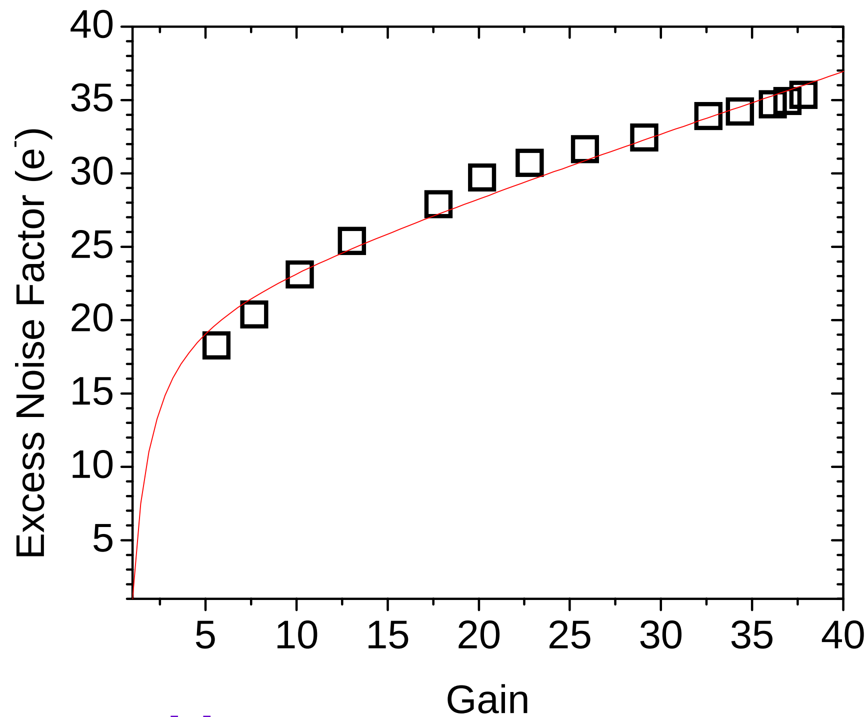


- Temperature = 5 K
- Bias = 31.25 V: Gain ~20
- Changed NDF to vary light intensity.

Excess Noise

$$F = \frac{\sigma_{total}^2}{\sigma_{photons}^2 + \sigma_{dark}^2}$$

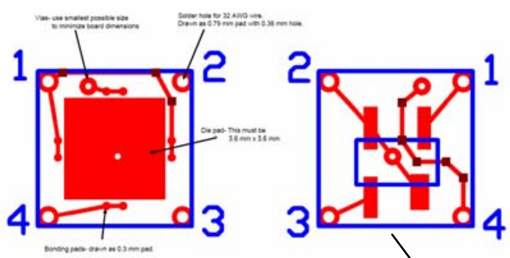


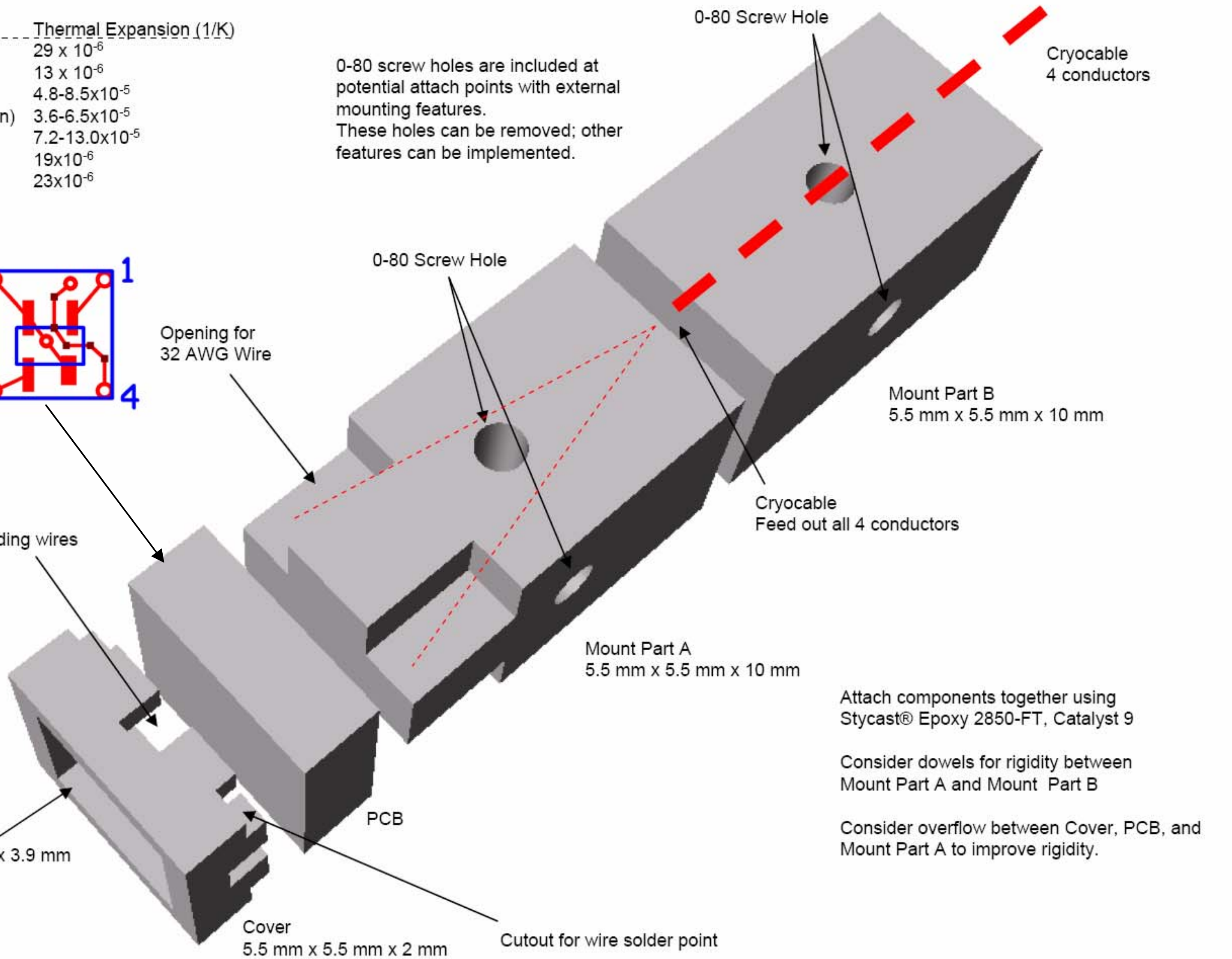


- **Set a constant light intensity but vary bias.**
- **Room temperature excess noise can be explained in terms of the hole to electron ionization ratio, κ, and the gain.**
- **The dependence shown here has an addition term or an offset.**

Readout & Packaging

Materials	Thermal Expansion (1/K)
Stycast Epoxy	29×10^{-6}
FR4	13×10^{-6}
Acetal (Delrin)	$4.8\text{-}8.5 \times 10^{-5}$
Polycarbonate (Lexan)	$3.6\text{-}6.5 \times 10^{-5}$
Polyethylene	$7.2\text{-}13.0 \times 10^{-5}$
Brass	19×10^{-6}
Aluminum	23×10^{-6}





Attach components together using Stycast® Epoxy 2850-FT, Catalyst 9

Consider dowels for rigidity between Mount Part A and Mount Part B

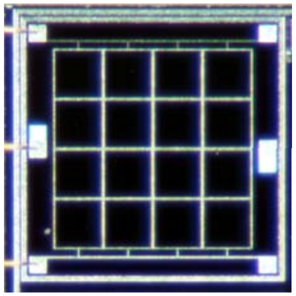
Consider overflow between Cover, PCB, and Mount Part A to improve rigidity.

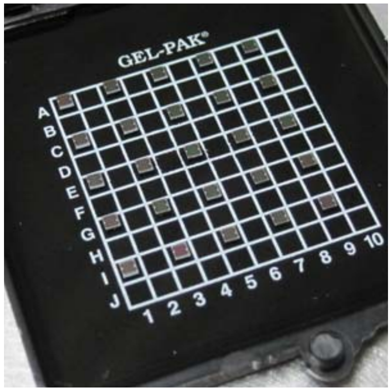
Schedule

Task	Percent Complete	To Be Completed
Design Proportional Mode Photodetector Elements	100%	
Simulate Heat Constraints for Target Area	100%	
Develop Ancillary Readout Electronics	100%	
Fabricate CMOS Test Array for Cryogenic Evaluation	100%	
Construct Test Apparatus for Evaluation at Low Temperatures	100%	
Measure Characteristics of Prototype Detectors	100%	
Evaluate Photodetector and Select Optimal Design	100%	
Layout and Design Photodetector System	100%	
Fabricate CMOS Photodetector	100%	
Develop Package for Low Temperature and High B-Field Operation	20%	Dec. 2010
Develop Setup for Testing in the HIFROST Environment	0%	Jan. 2011
Create Robust Coupling Between Target and Photodetector.	20%	Mar. 2011
Evaluate Performance in the HIFROST Environment	0%	May 2011
Provide Complete Instrument with Optimized Readout.	10%	Aug. 2011

End of No-Cost Extension August 2011

Final Remarks





- CMOS Geiger Photodiodes are limited at low temperatures.
- CMOS APDs are a viable photodetector at low temperatures.
- Negligible effects from magnetic fields
  - No drift region
  - avalanche process within the depletion width ~10 um
- Exploring the implementation of a FET coupled directly to the APD for signal to noise improvement.
- Potential low-cost device for scientific experimentation within a operation regime of
  - Temperatures (<100 Kelvin)
  - High Magnetic Fields (>50 Gauss)
  - Compact (Die size of 1.5 mm x 1.5 mm)
  - Low Voltage (<50 V)
  - Solid-state: No vacuum tubes- less sensitive to environment.
  - Can be exposed to ambient light while biased for short periods without adverse effects.
- We have been solicited by scientists regarding this instrument for other low temperature nuclear experiments.