Cryogenic CMOS Avalanche Diodes for Nuclear Physics Research

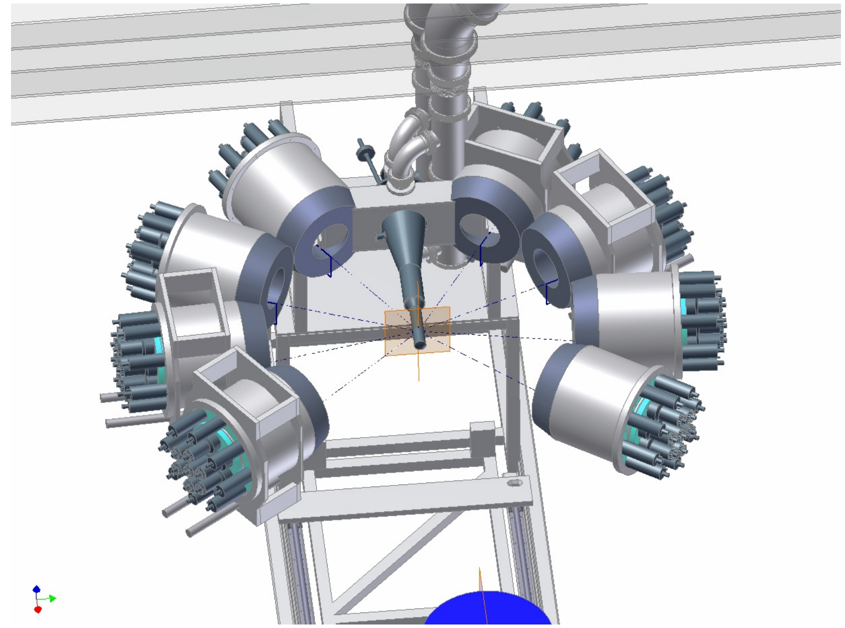
SSPM Detector for Polarized Target Scintillator Readout

Erik Johnson[1]
Jie Chen[1], Christopher Stapels[1], Chad Whitney[1], Rory Miskimen[2], Don Crabb[3], Skip Augustine[4], and James Christian[1]

[1]Radiation Monitoring Devices, Inc., Watertown, MA
[2]University of Massachusetts, Amherst, MA
[3]University of Virginia, Charlottesville, VA
[4]Augustine Engineering, Encinitas, CA

Extreme Environments and the Polarizability of Protons

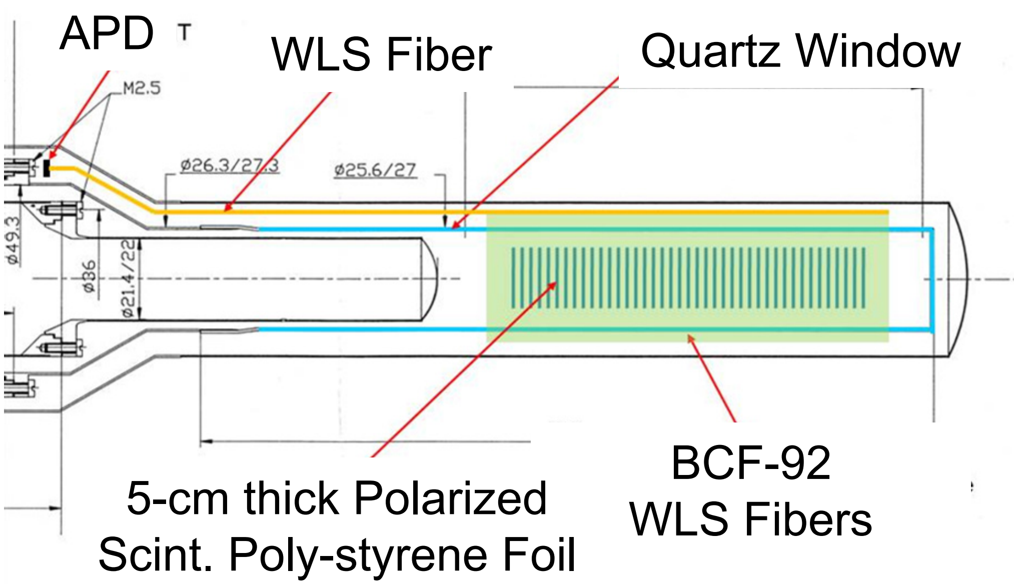
- Goal: Develop photodetectors with gain that operate in extreme environments:
  - Temperatures around a few Kelvin
  - High magnetic fields of several Tesla
  - High-helium environments.
  - Small physical spaces of less than 1 cm x 1 cm
- PMTs will fail if exposed to these types of environments, where 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

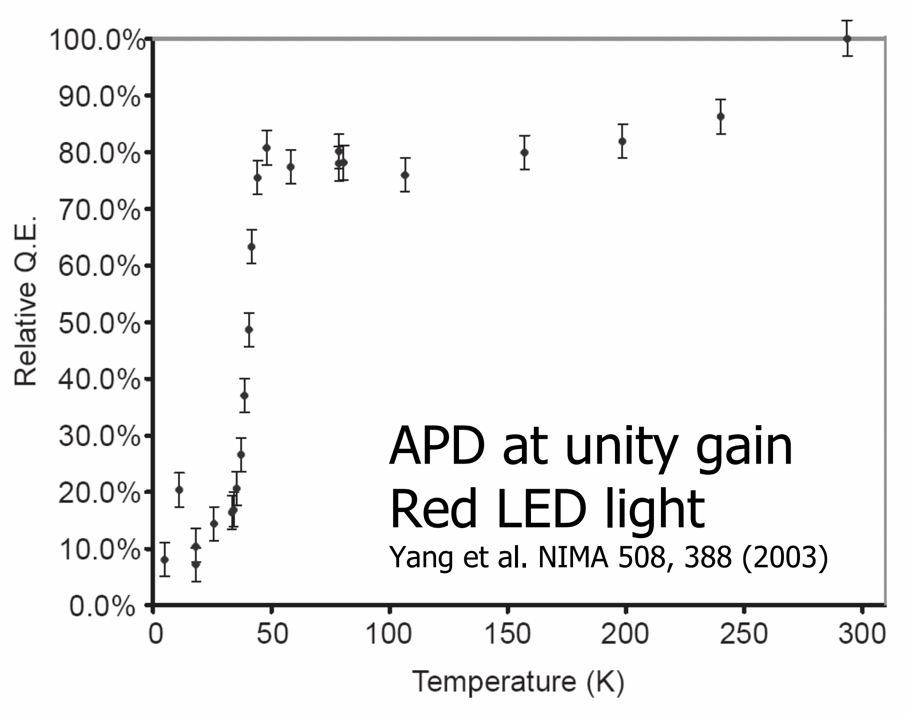
Polarized Proton Target

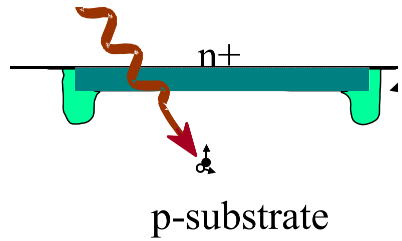
Light capture with wavelength shifters



- 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

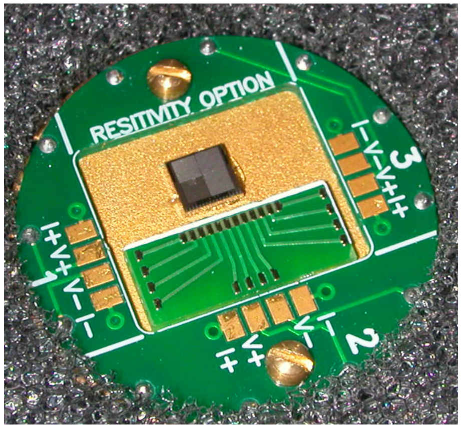




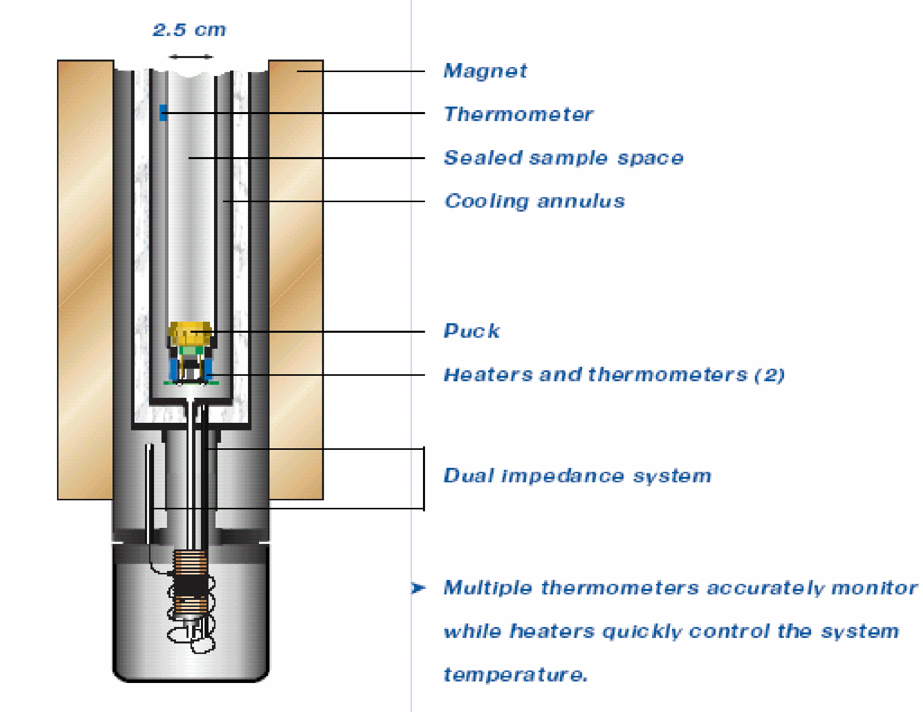
- Typical APD structure is doped to reduce excess noise at room temperature.
- Large gains are achieved at high biases (~1000 V).
- Carrier loss is a viable explanation for loss of QE below 40 K.

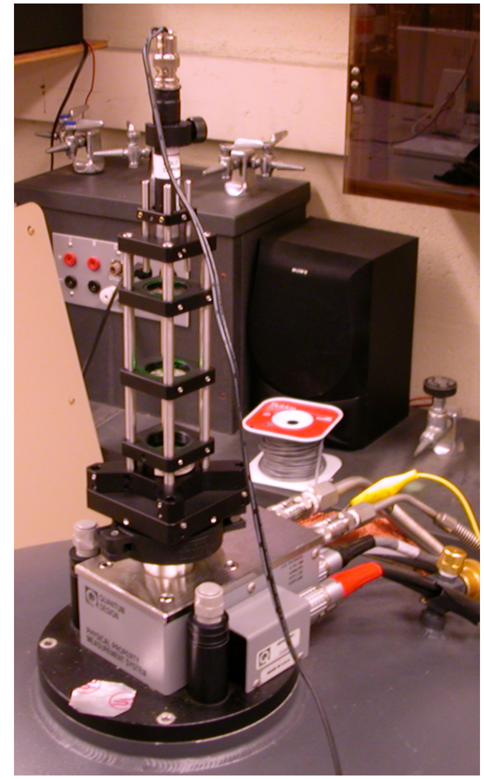
- Geiger Photodiode (GPD) is an avalanche photodiode operated beyond the breakdown voltage.
- The GPD is the basic building block for a solid-state photomultiplier.
- Doping leads to a low voltage breakdown.
- Carrier loss should be less of an issue.

Setup for GPD Evalution



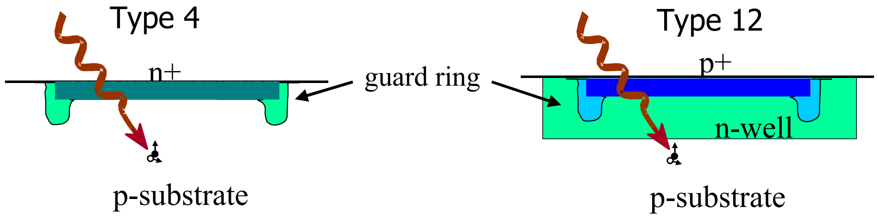
Puck with
SSPM and GPD

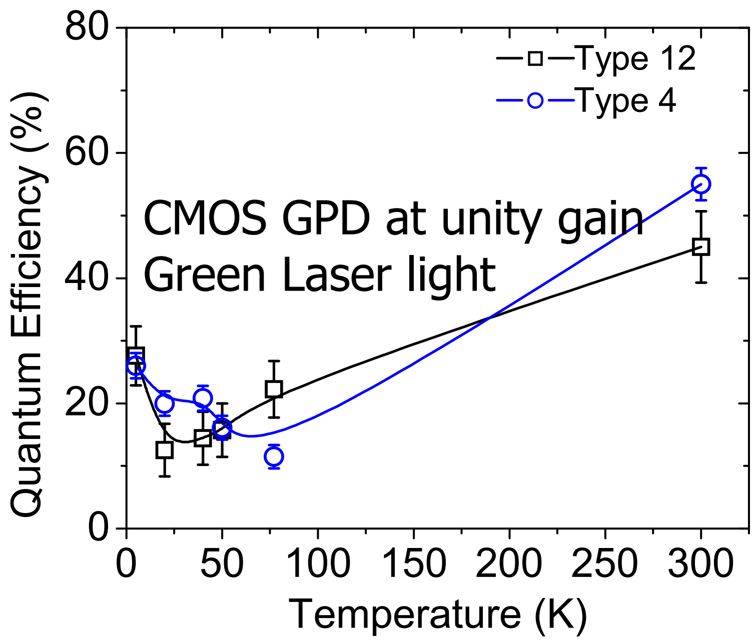


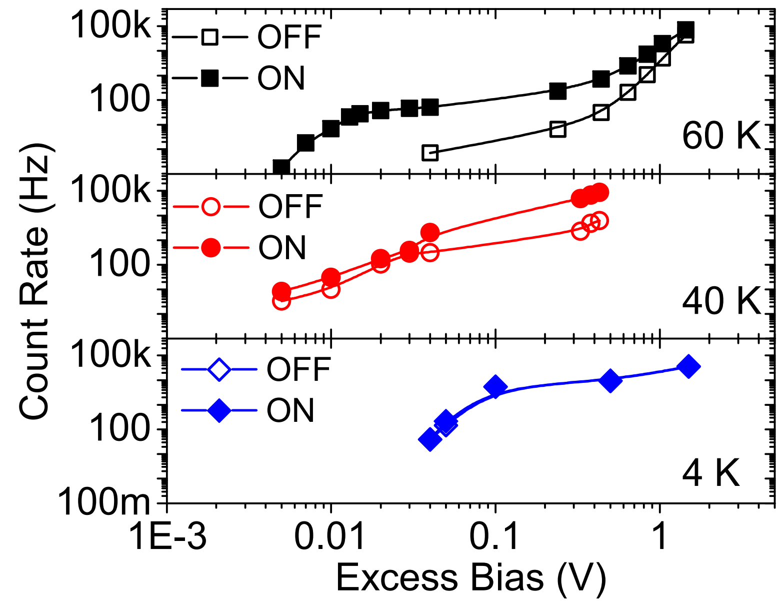


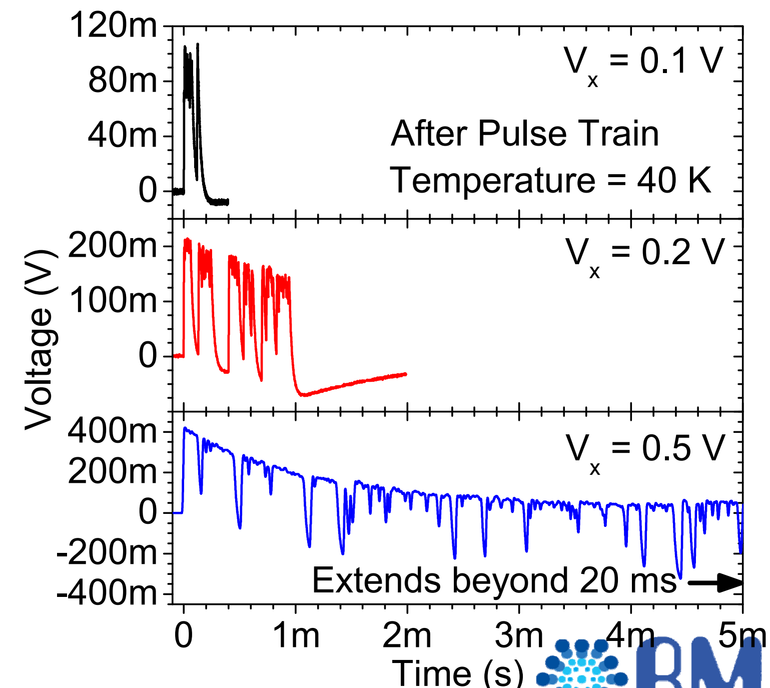
- Mounted GPD and SSPM to puck for insertion into cryostat at the University of Massachusetts.
- Mounted LED and Laser to a view port on the cryostat to inject light into the system.

GPD Results



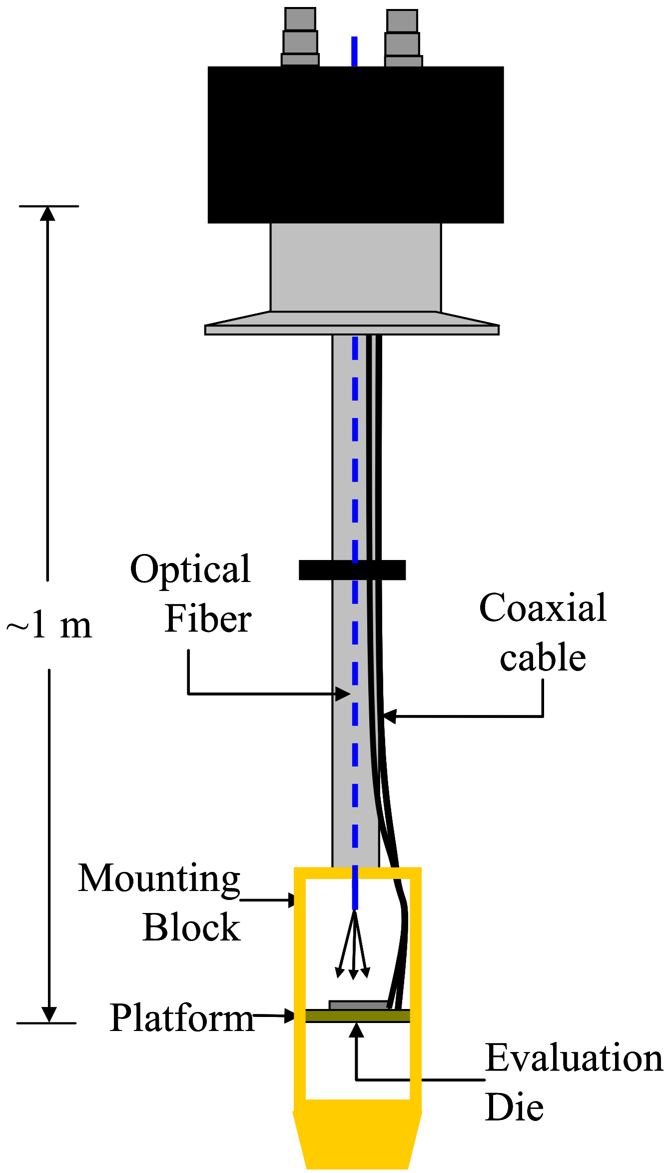


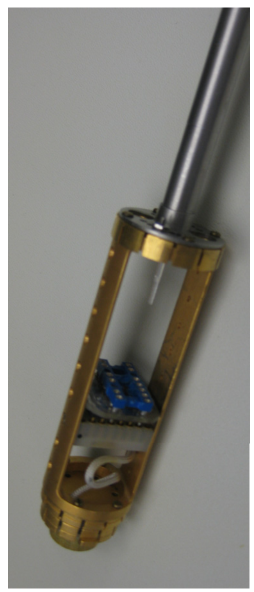


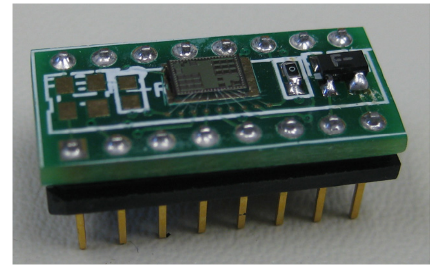


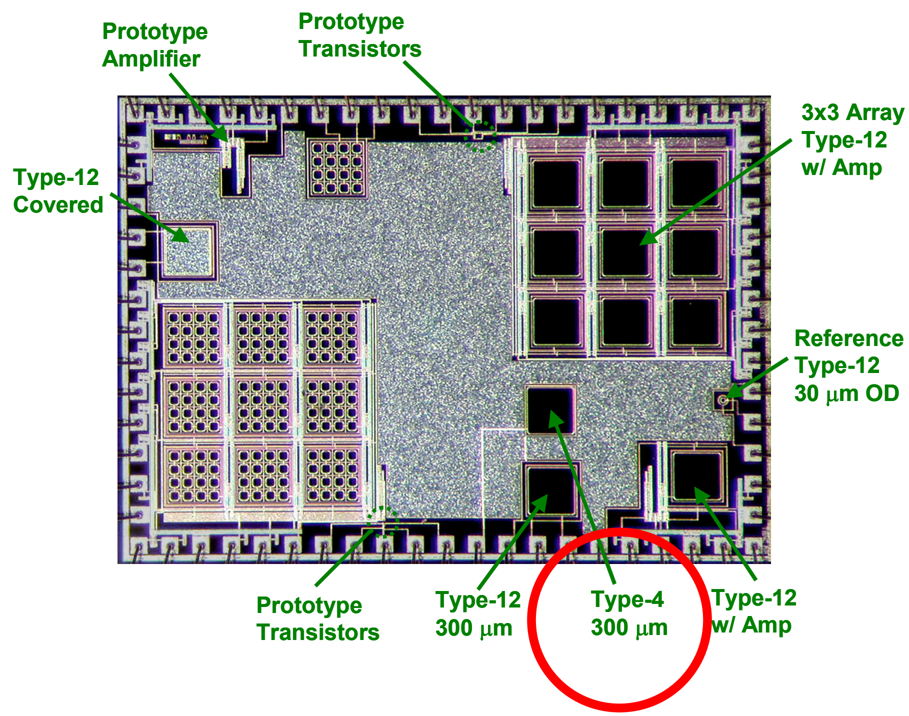
- Excess noise at low temperatures.
- After pulsing effect.
- Geiger mode operation is not viable.
- Proportional mode (below breakdown) has promise.

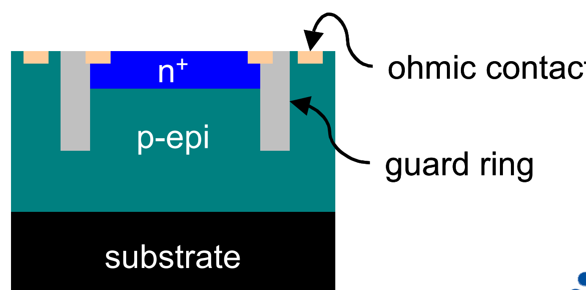
APD Setup


~1 m
Optical Fiber
Coaxial cable
Mounting Block
Platform
Evaluation Die

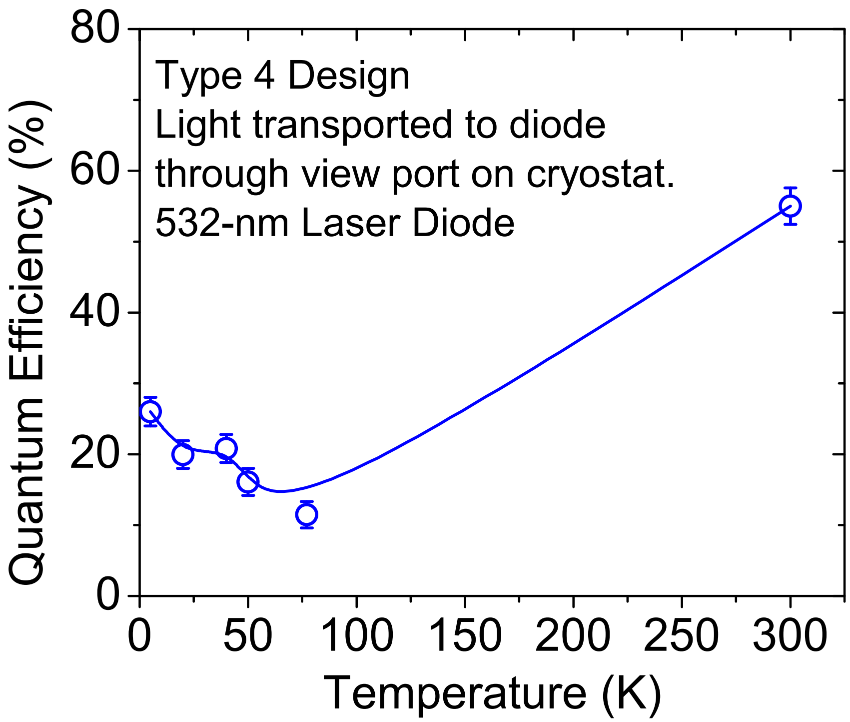


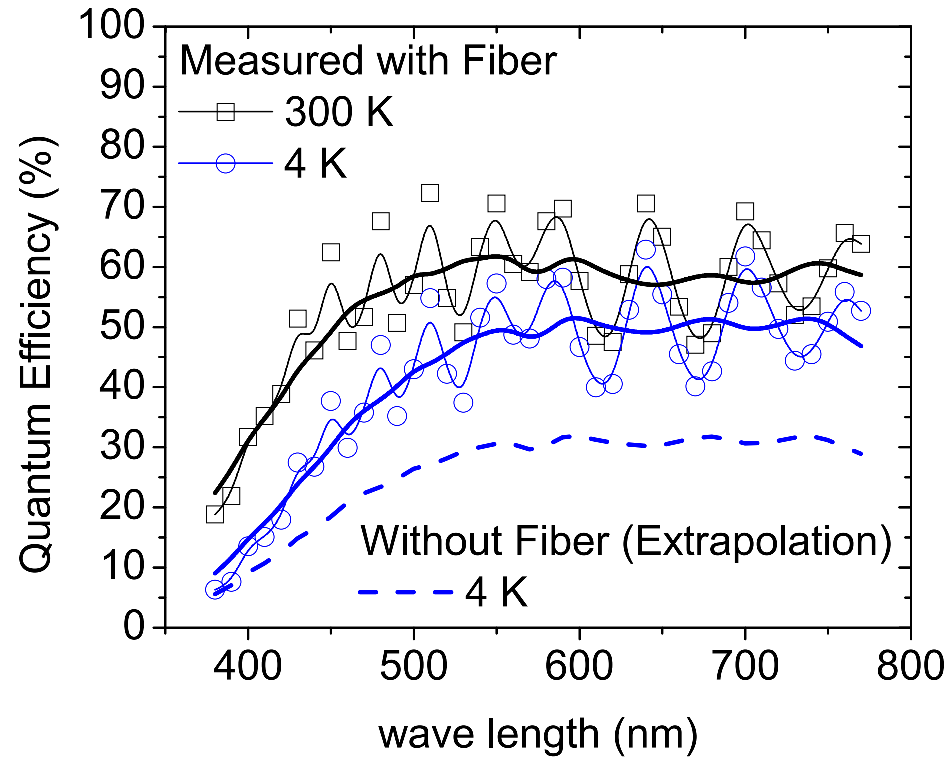



Prototype Amplifier
Prototype Transistors
3x3 Array Type-12 w/ Amp
Type-12 Covered
Reference Type-12 30 μm OD
Prototype Transistors
Type-12 300 μm
Type-4 300 μm
Type-12 w/ Amp


n+
p-epi
substrate
ohmic contact
guard ring

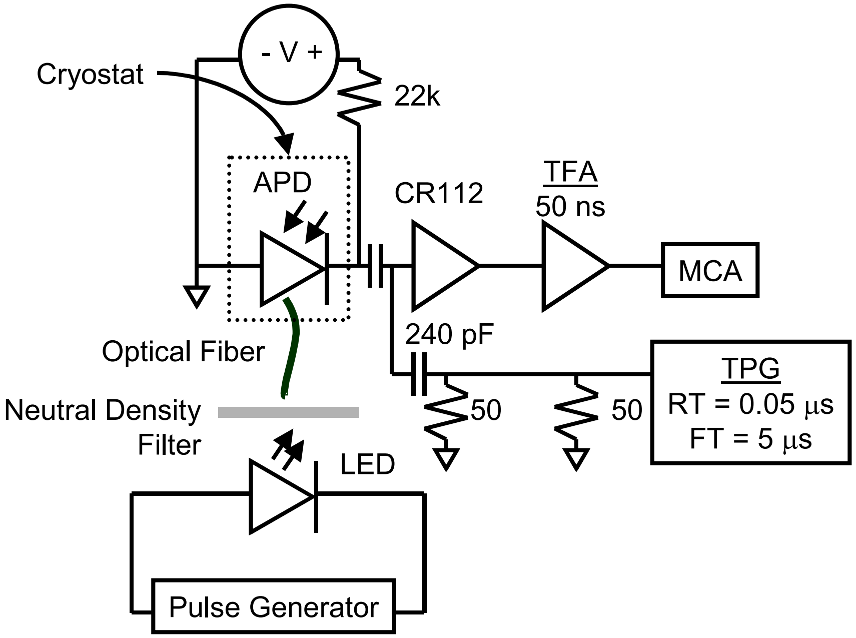
Quantum Efficiency

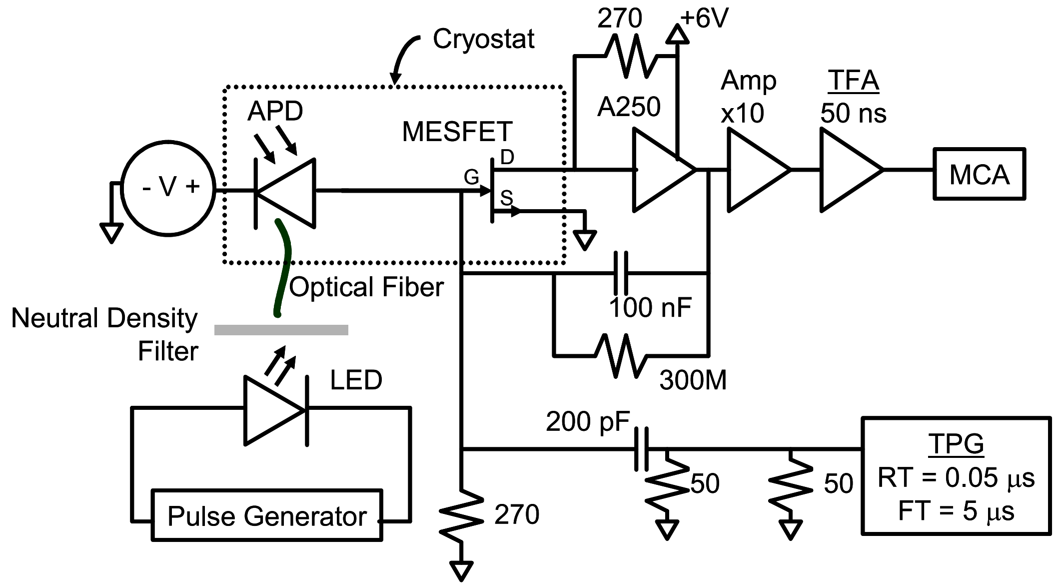


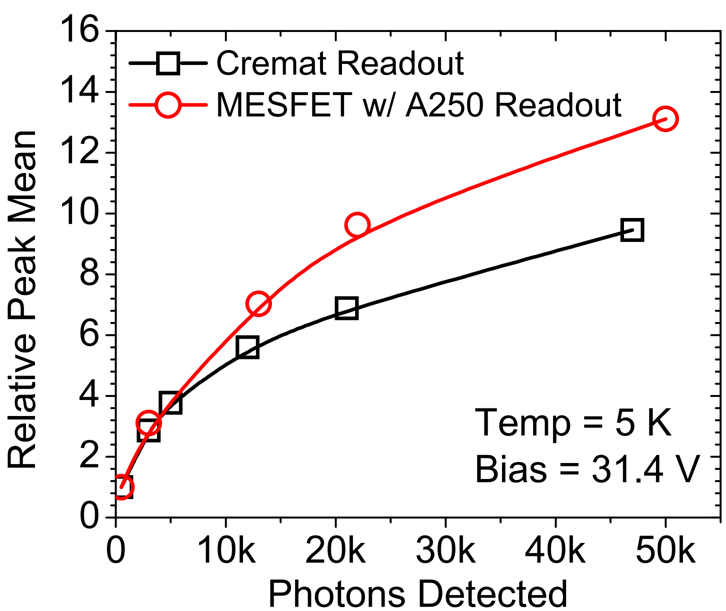


- A systematic loss in QE is observed but is still sufficiently large.
- Made relative measurements with respect to room temperature.
  - Optical view port
  - Fiber
- Light transport efficiency and emission geometry is not corrected for the fiber measurements.

Readout Schemes

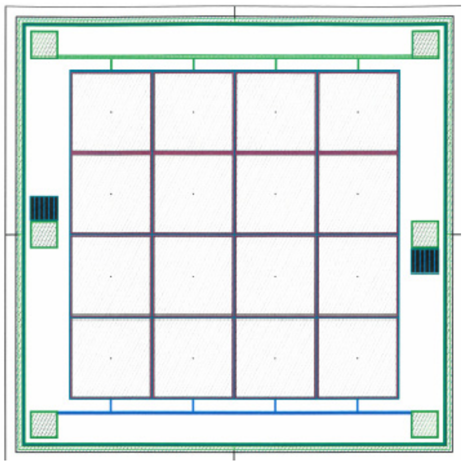


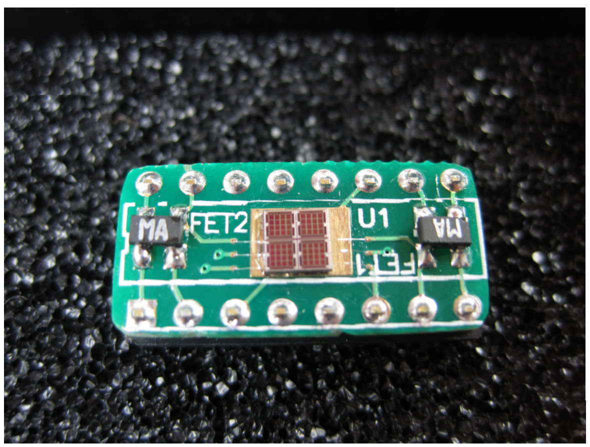


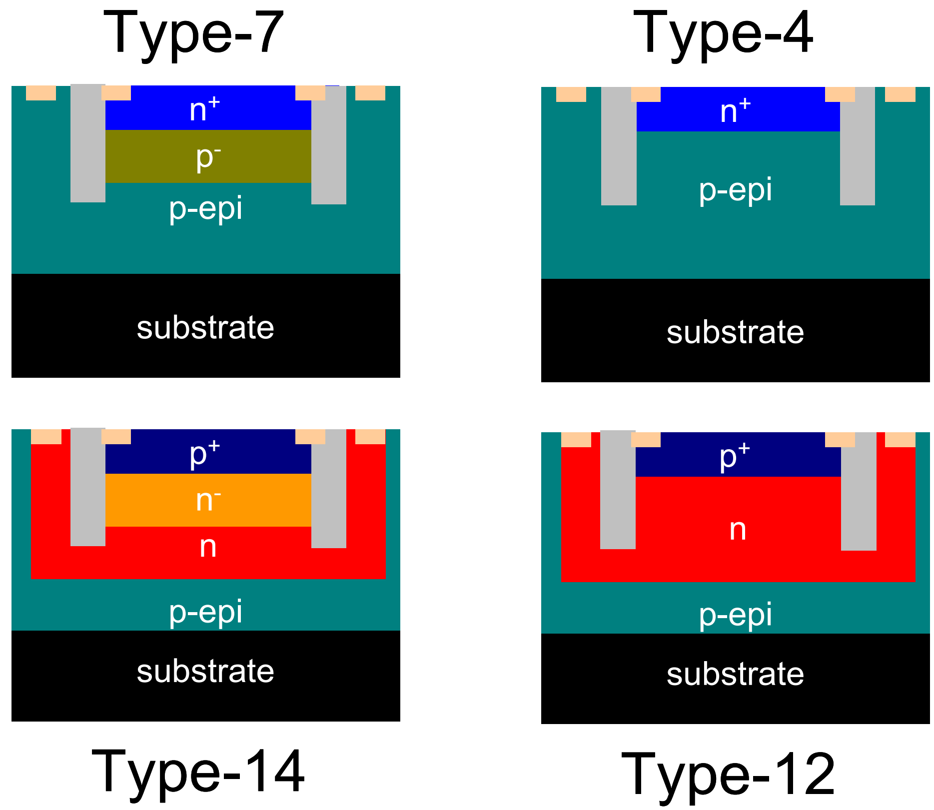


- Two readout schemes are compared:
  - External, room temperature components.
  - 1st stage transistor within the detector package- used with Amptek A250.
- Noise is comparable, not significant difference.
- Gain from A250 readout is sufficiently larger.

Prototype Devices



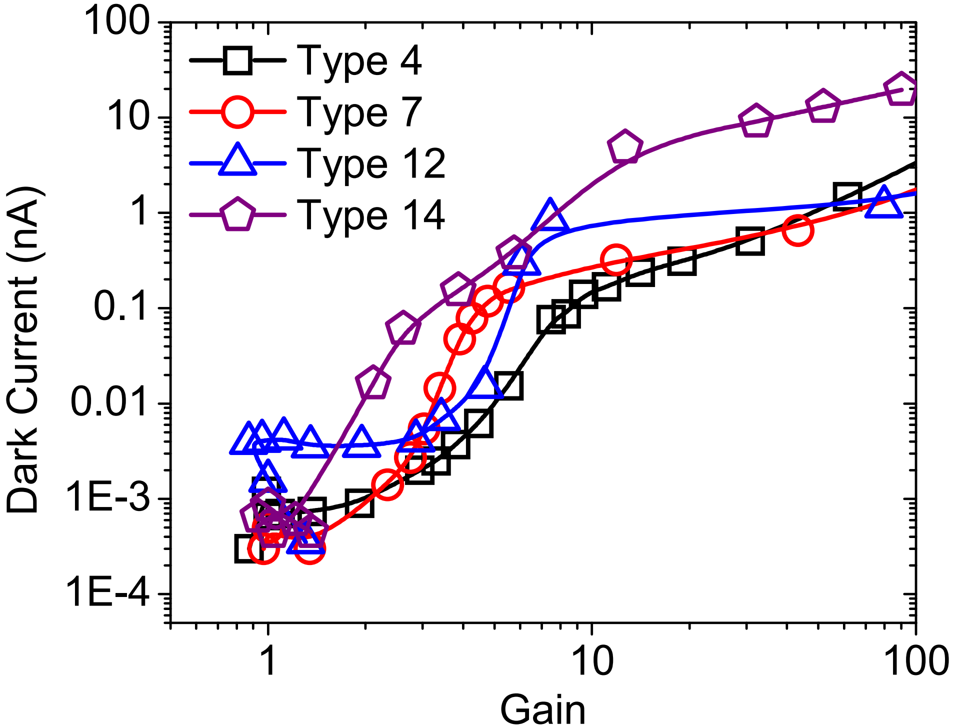


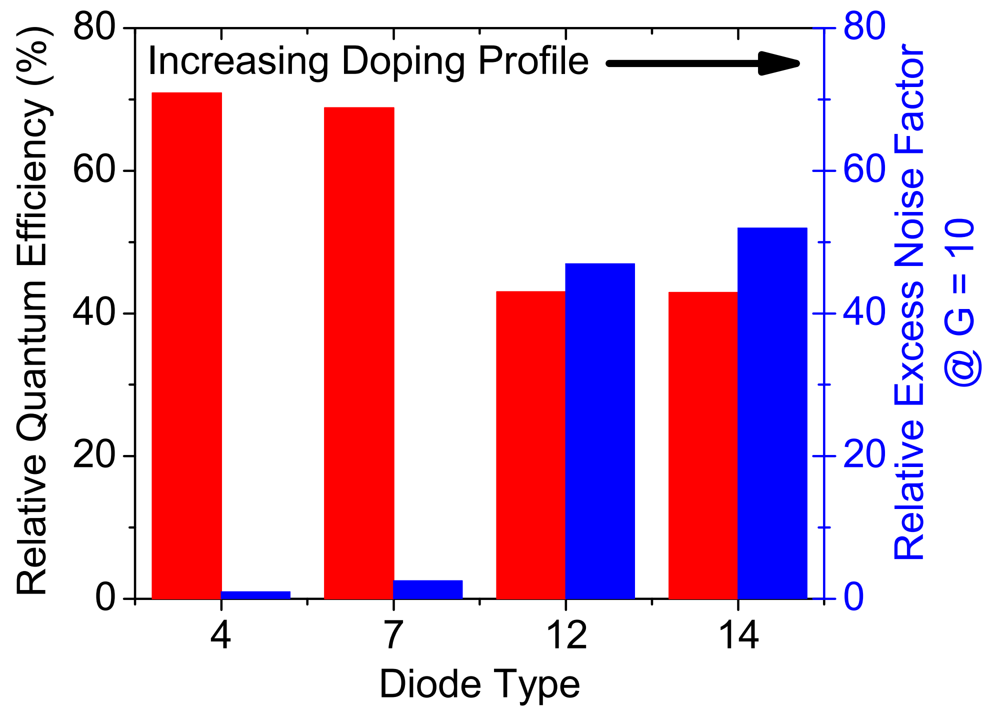


- Four test arrays were fabricated.
- Use existing probe to evaluate the prototypes.

Determining Best Diode

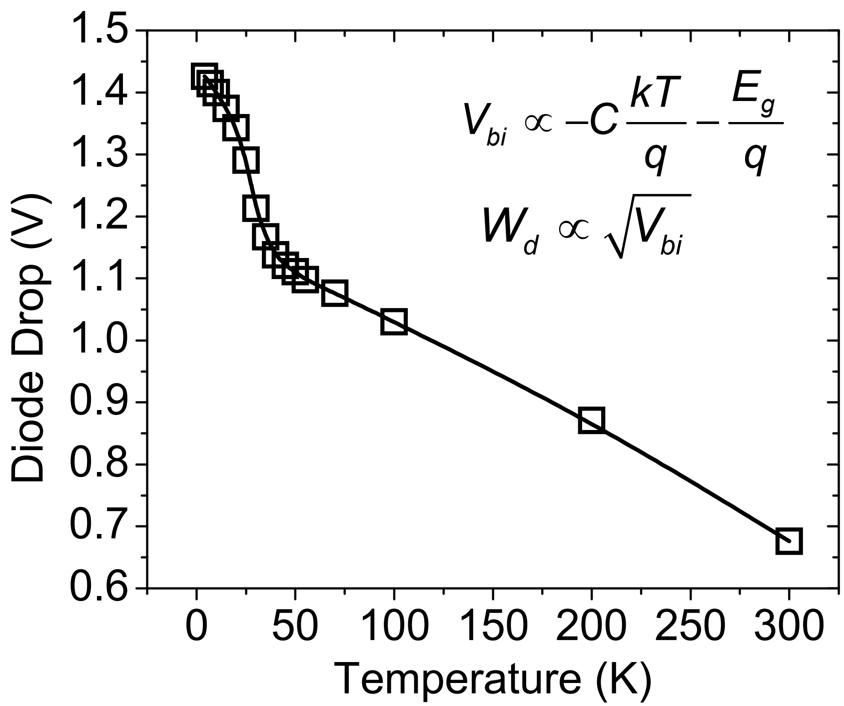
- Determine the QE, gain, dark noise and excess noise at 4 Kelvin.

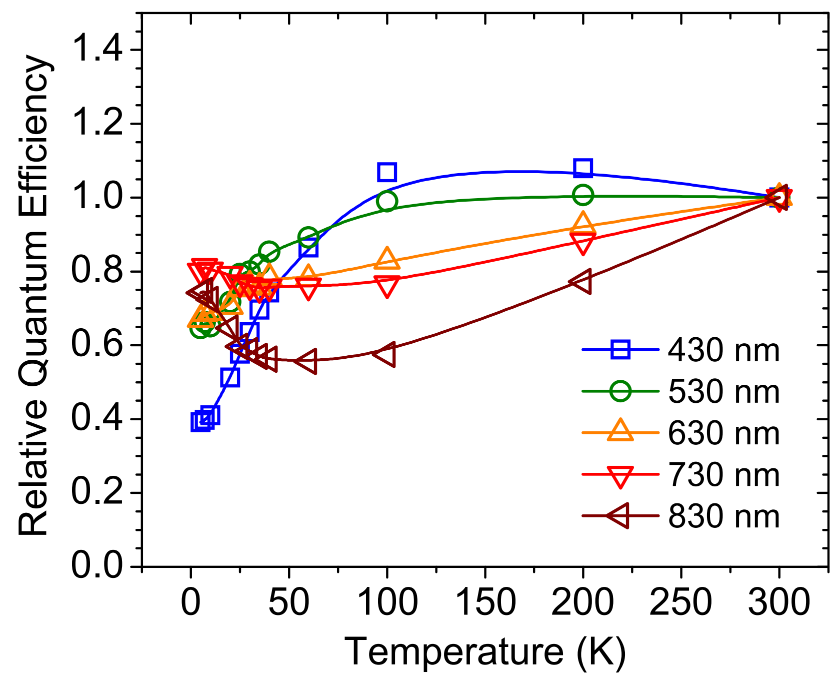




- QE and Gain measured with a 532 nm LED.
- Excess noise is determined by pulsing the LED to collect a pulse height distribution.
- Best Diode: Type 4.

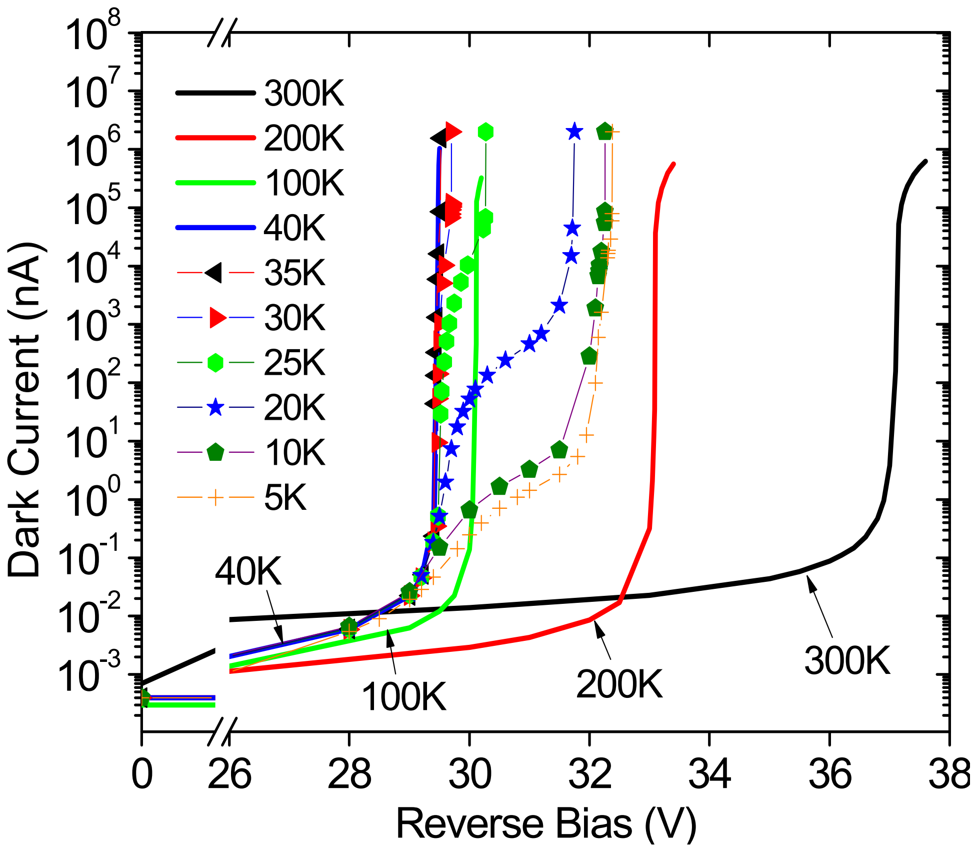
Effects on Quantum Efficiency

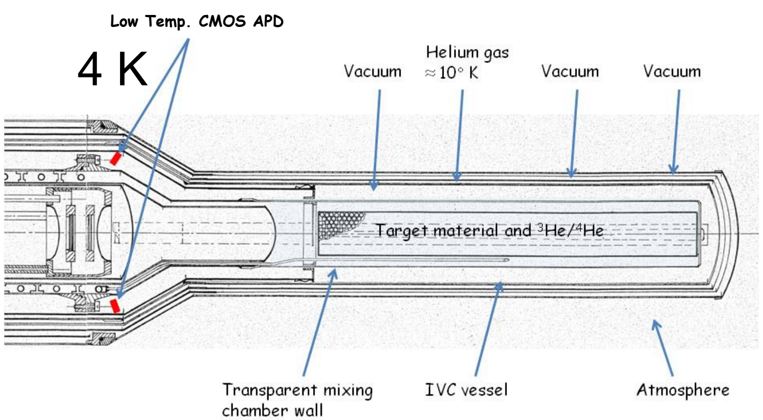




- Diode drop is direct related to the junction width.
- Wavelength dependence:
  - Systematic drop over all wavelengths: charge collection loss.
  - Near surface recombination and reflection significantly reduce the short wavelengths.
  - Rapid increase in the depletion width enhances longer wavelengths.

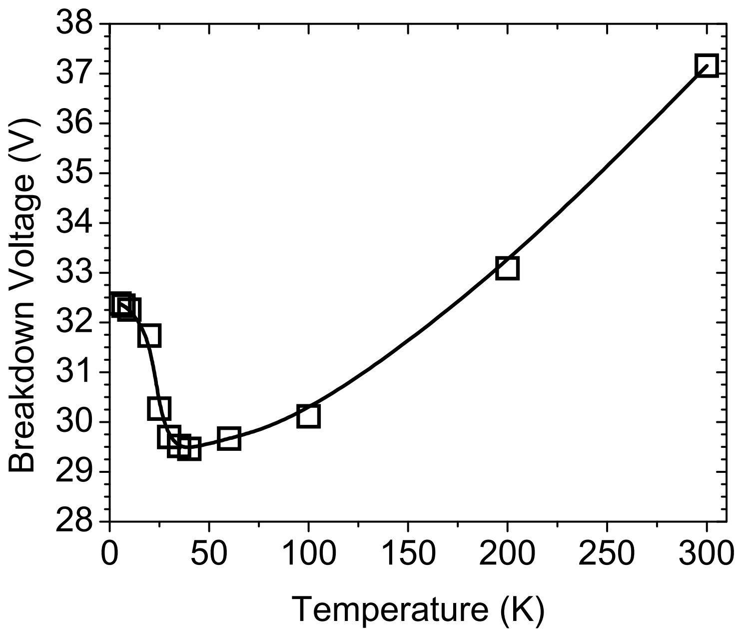
Dark Current and Heat Load

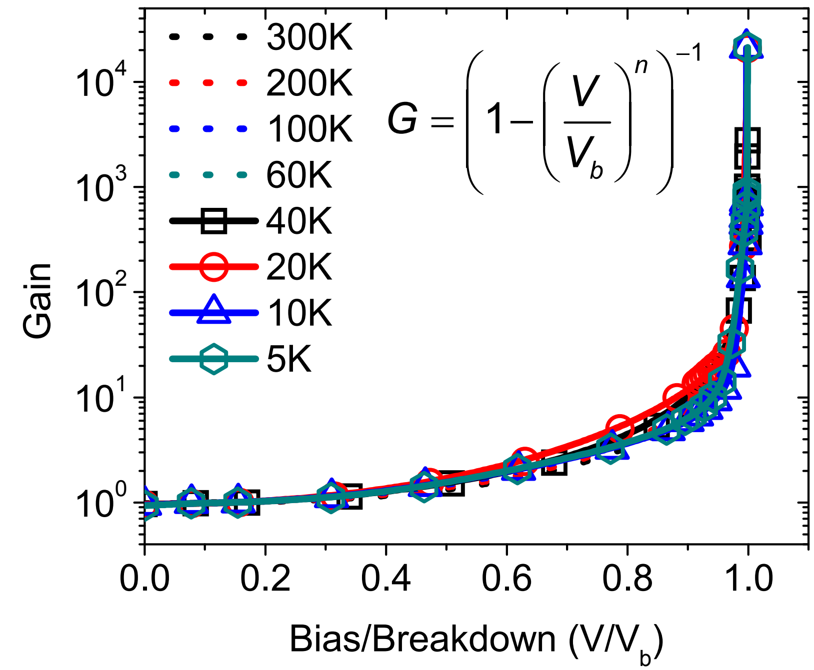


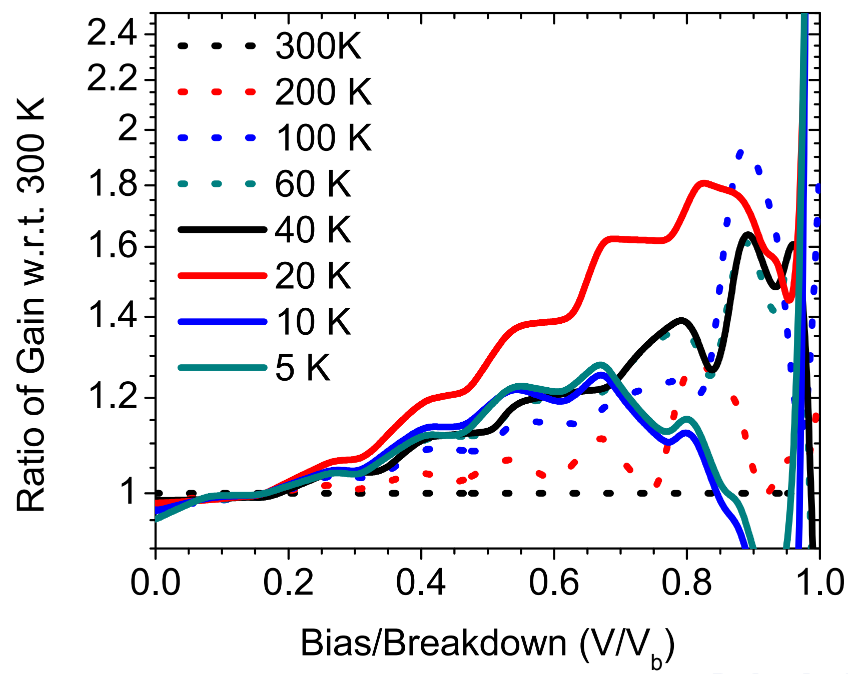


- Dark Current:
  - Reverse bias breakdown is proportional to temperature.
  - Around 40 K, onset of "freeze-out" conditions.
  - Observe a resistive term that is inversely proportional to the temperature.
- Heat Load:
  - Heat deposition in the target from the photon beam is 20 μW.
  - Radiation heating is 30 nW
  - Net cooling power of 780μW for remaining components within the cryostat.
  - 6 μW summed over all detectors from scintillation light.
  - Dark current: 10 nA at 32 V for 1 array
  - Four arrays per detector, and two detectors within the experiment.
  - 2.6 μW for low-temperature APDs.
  - No significant heat load from APDs.

Gain

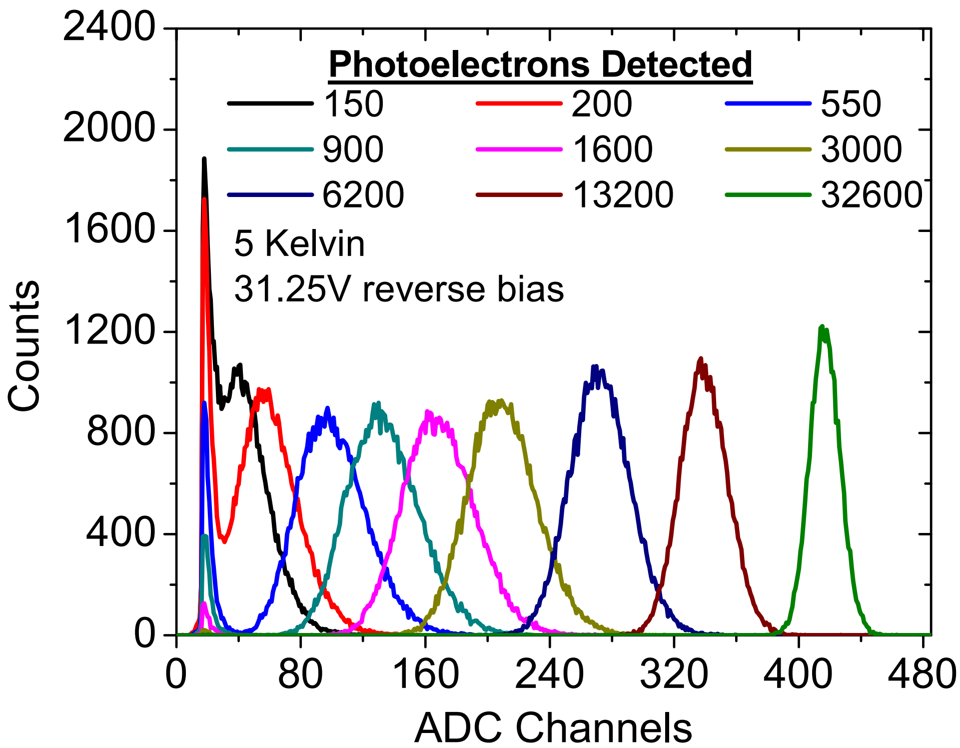


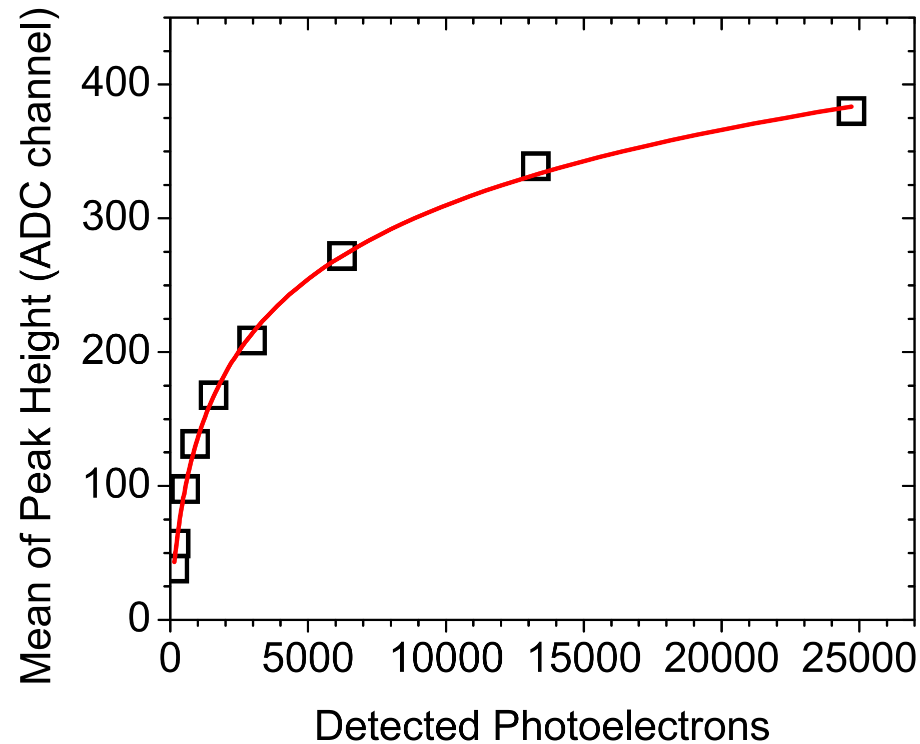




- The breakdown voltage:
  - The point where the current rapid approaches infinity– 2nd breakdown point.
  - 2nd point can be due to some Zenner or side wall breakdown.
  - This region can be attributed to the high resistive term.
  - 1st point is constant at ~29.5 V from 0 to 25 K– avalanche breakdown.
- High resistance is seen at 25 K where gain is peaked.

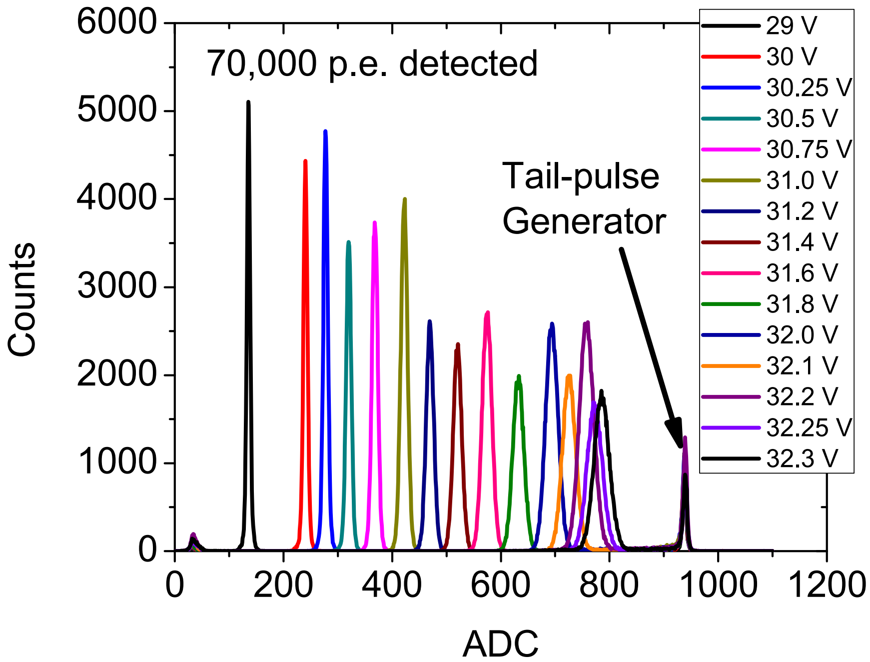
Pulsed Light Response

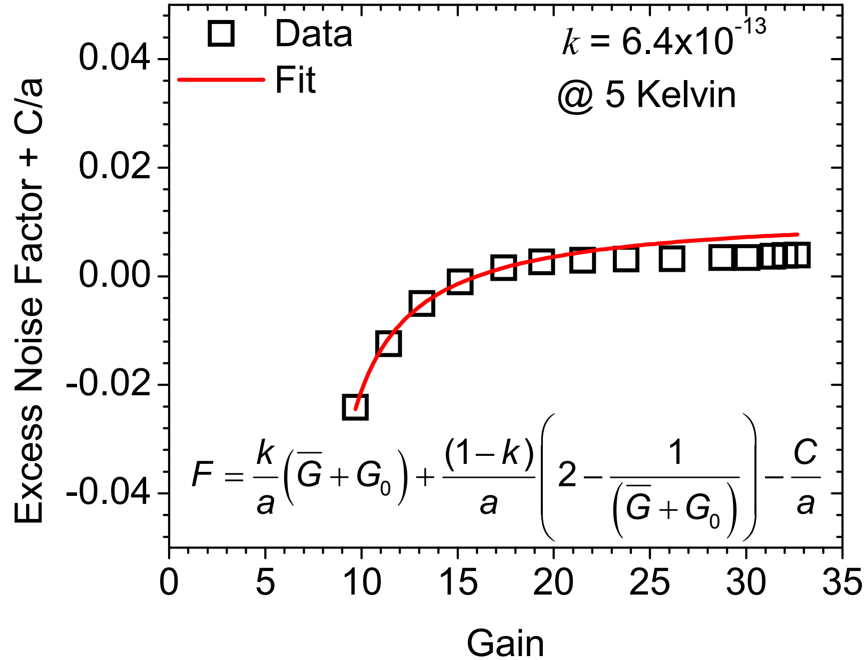


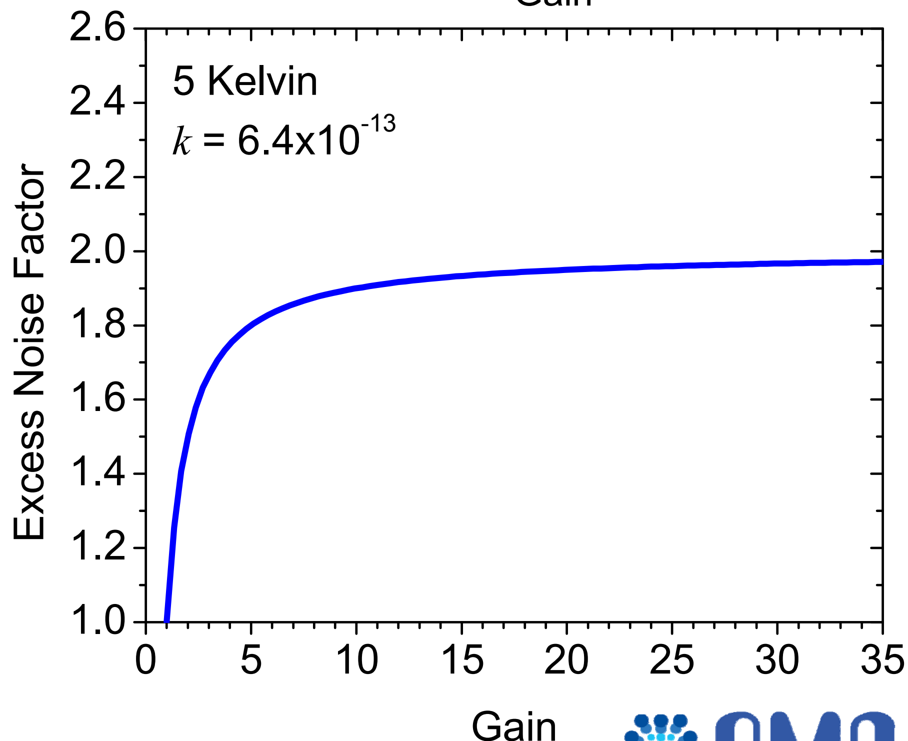


- Temperature = 5 K
- Bias = 31.25 V: Gain ~20
- Changed NDF to vary light intensity.

Excess Noise Factor







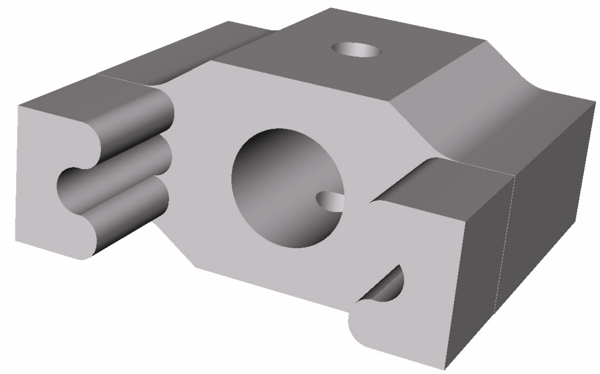
- A number of spectra were collected at various light intensities and biases.
- A number of corrections were made to remove effects due to the light source and voltage drops in the charge sensitive amplifier.
- Vary low k ratio, single carrier multiplication.

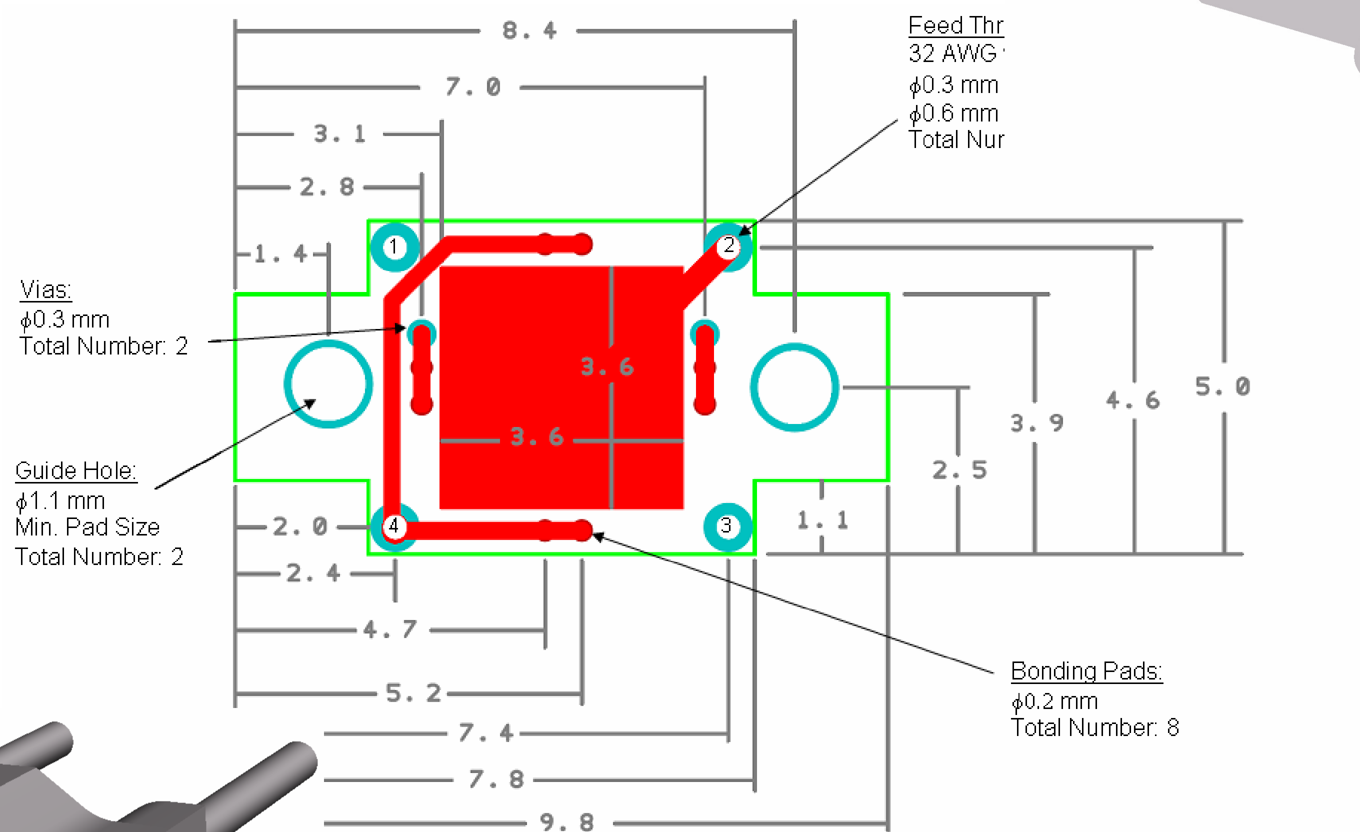
Packaging Materials

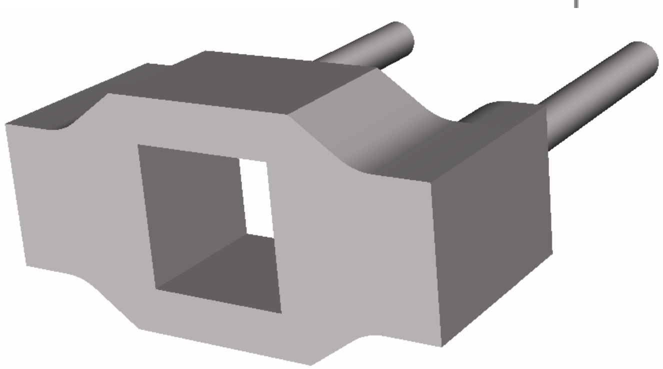
Material	Thermal Expansion Coefficient (1/K)
Stycast Epoxy	29×10^{-6}
FR4	13×10^{-6}
Silicon	2.6×10^{-6}
Acetal (Delrin)	$4.8 – 8.5 \times 10^{-5}$
Polycarbonate (Lexan)	$3.6 – 6.5 \times 10^{-5}$
Polyethylene	$7.2 – 13 \times 10^{-5}$
Brass	19×10^{-6}
Aluminum	23×10^{-6}
Stainless Steel	17×10^{-6}

- Space constraints limit the use of screws.
- Cryogenic epoxy will be used to bond parts.
- Coefficient of expansion is matched for a few materials.
- Continue to use glycol phthalate for die attach.

Package Design

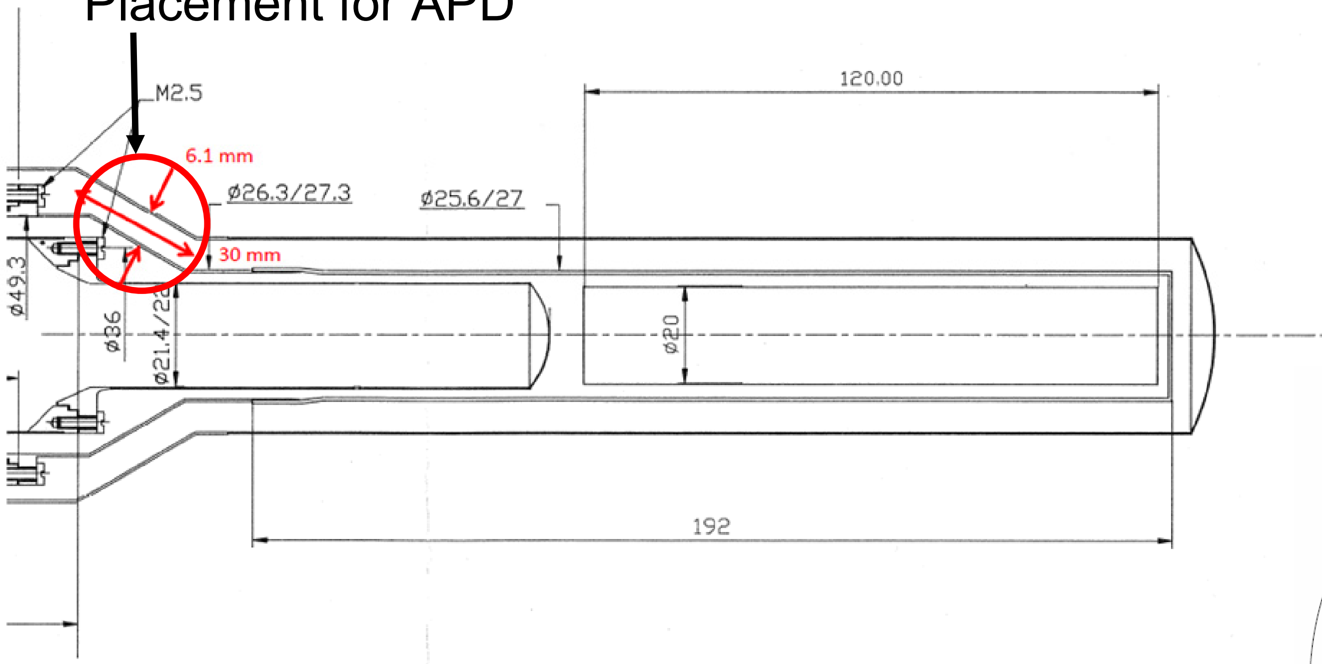


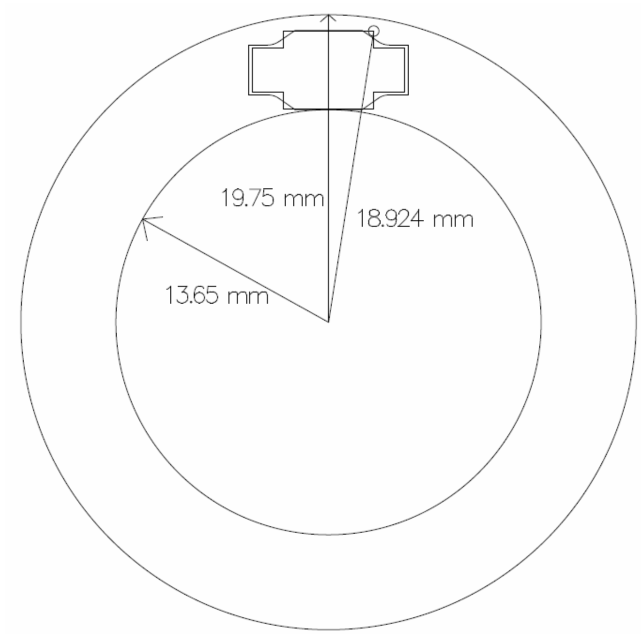




Geometry for HIFROST Target Cryostat

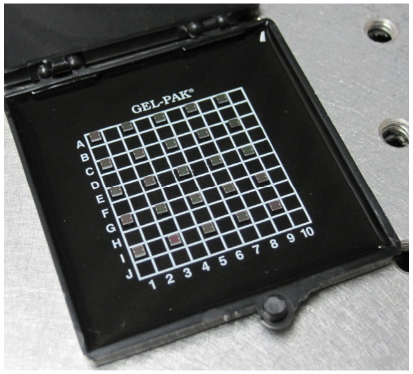
Placement for APD

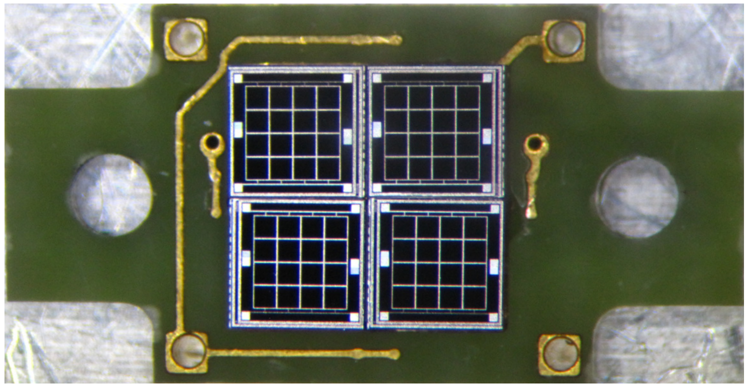


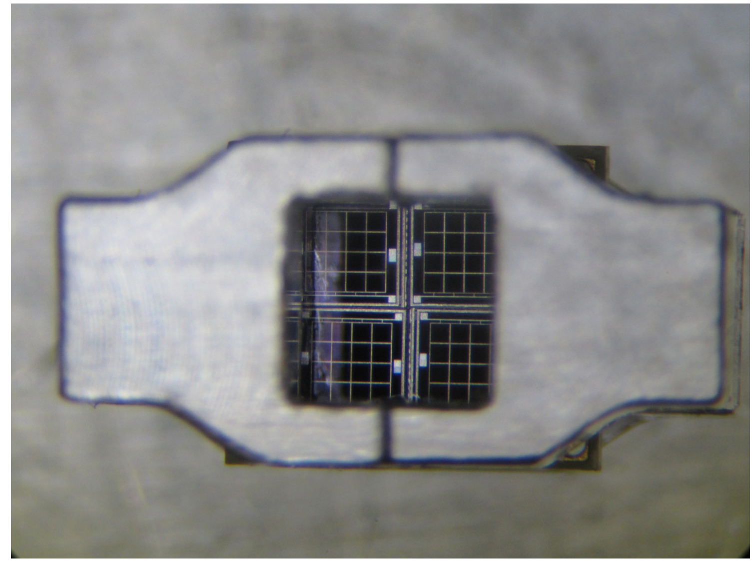


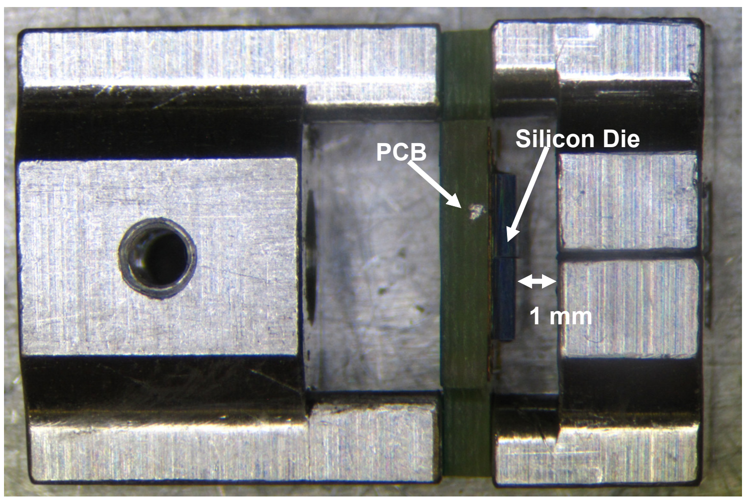
- Specified at smallest radius of curvature for placement region.
- There is roughly 0.826 mm clearance for package design.

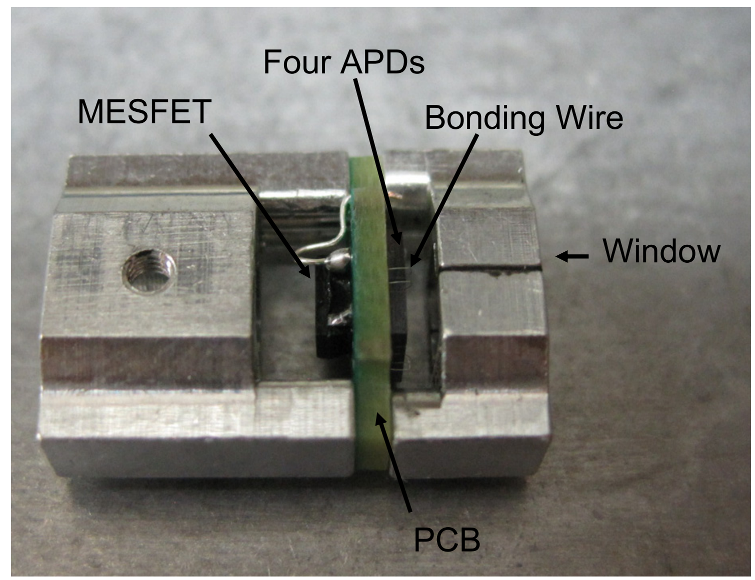
Assembly


GEL-PAK®

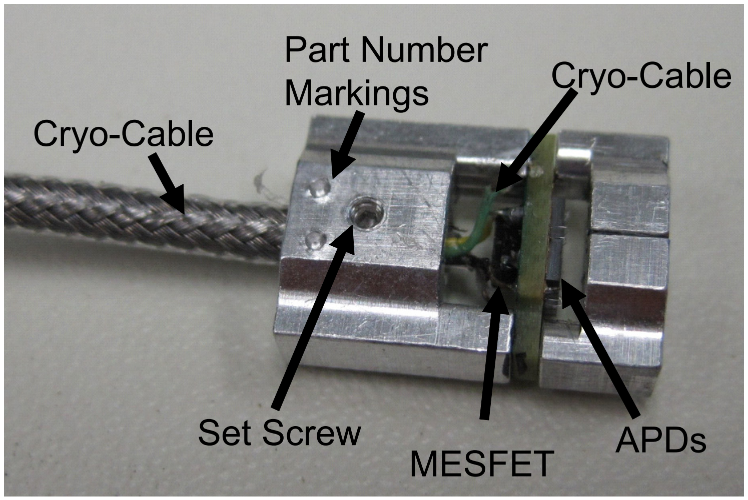





PCB
Silicon Die
1 mm


Four APDs
MESFET
Bonding Wire
Window
PCB

Quality Control



- Six detectors where made.
- QC done at room temperature.
- No shorts.
- Each response to room light.
- Capacitance at 0 V: ~ 2.5 nF.
- Diode Drop: 0.55 V
- Each device showed gain.
- MESFET Drain to source current:
  - Drain set to +5V
  - Source set to ground.
  - Gate at 0V: ~20 mA
  - Gate at -0.6 V: ~10 mA
- All Devices passed QC.

Final Remarks

- Fabricated in a commercial CMOS foundry.
- Non-magnetic and no effects from magnetic fields.
- Potential low-cost device for scientific experimentation within a operation regime of
  - Temperatures (<100 Kelvin)
  - Compact (Die size of 1.5 mm x 1.5 mm)
  - Low Voltage (<50 V)
  - Solid-state: No vacuum tubes- less sensitive to environment.
- Delivered four units to the University of Massachusetts.
- Commercialization:
  - Solicited for and provided quotes.
  - Presented results at various meetings with some interest.
  - Limited stock of parts.
  - Updating website and product brochure.
  - Considering using silicon area in other foundry run for future products.