A fast avalanche photodiode for the readout of the fast 220nm component of barium fluoride scintillation light

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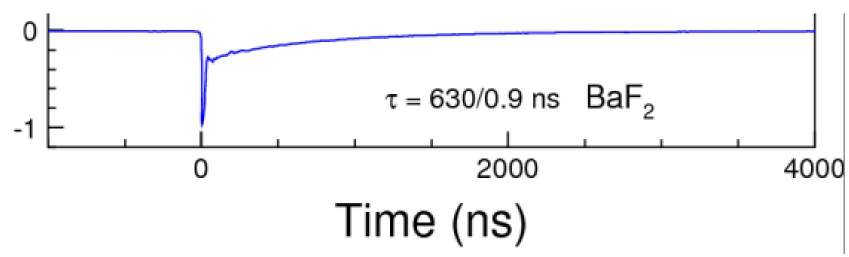
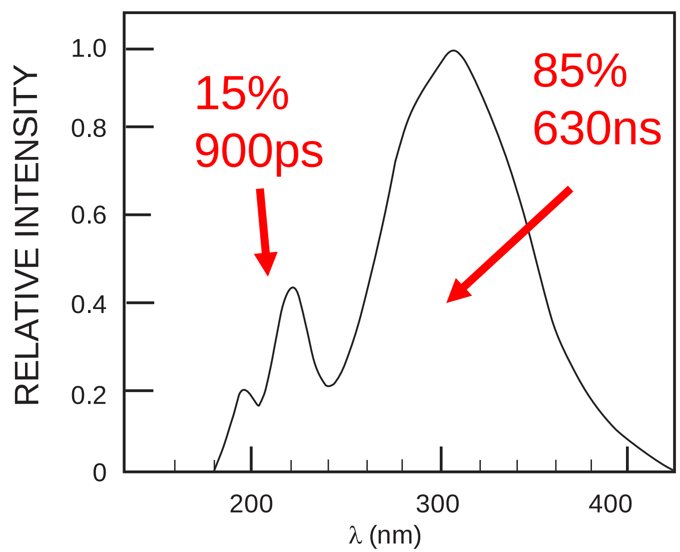
Outline

- Barium fluoride scintillation properties
- UV sensitive avalanche photodiode
- Adding an ALD filter to the APD
- Adding a superlattice
- Measurements
- Conclusion

Barium fluoride scintillation light

- BaF_2 has a 220nm scintillation component with 900ps decay time, but also has a much larger 300nm component which has a 630ns decay time
- The fast component can provide excellent time resolution, for discrimination against background, as well as high rate capability
  - This requires either suppression of the emission of the slow component or use of a “solar blind” photosensor





Fast (cross-luminescence) 1,800 photons/MeV
Slow (self-trapped exciton) 10,000 photons/MeV

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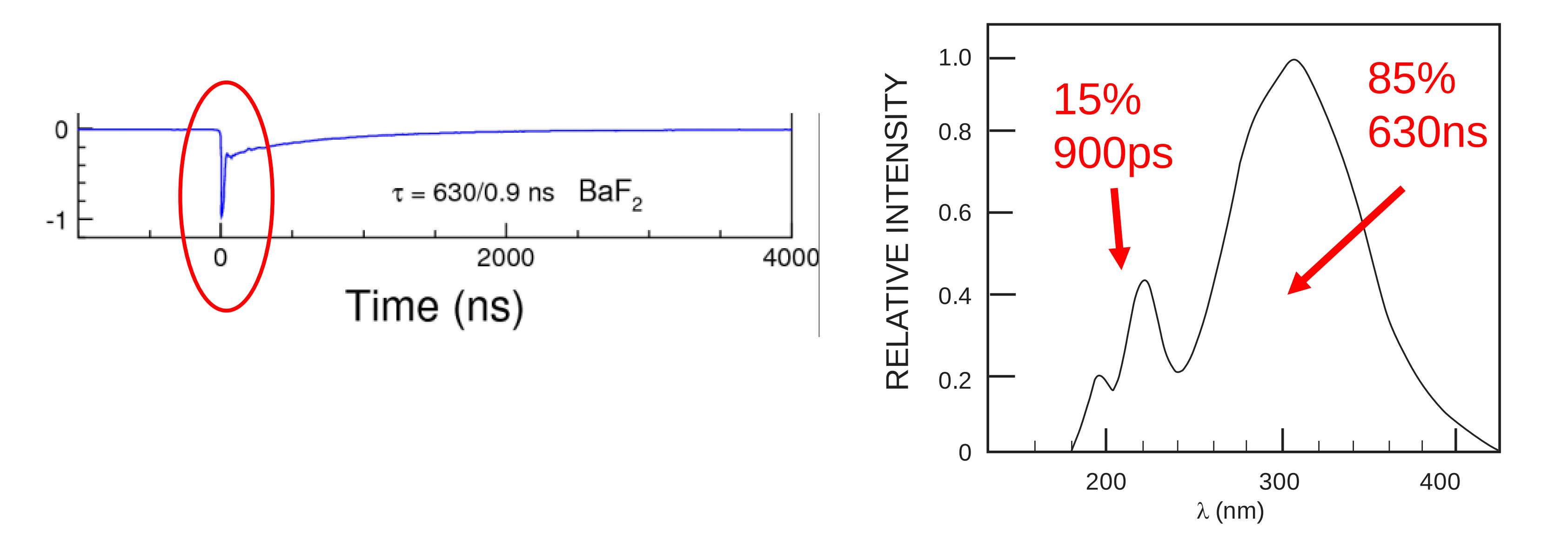

BaF_2 properties

Photosensor options

ALD filter

Superlattice

Gain, noise

Radiation hardness

Conclusion

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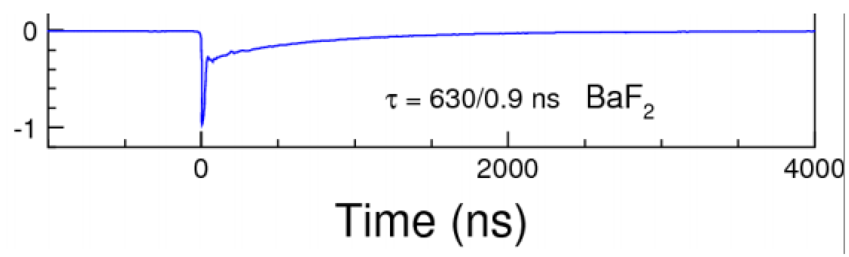
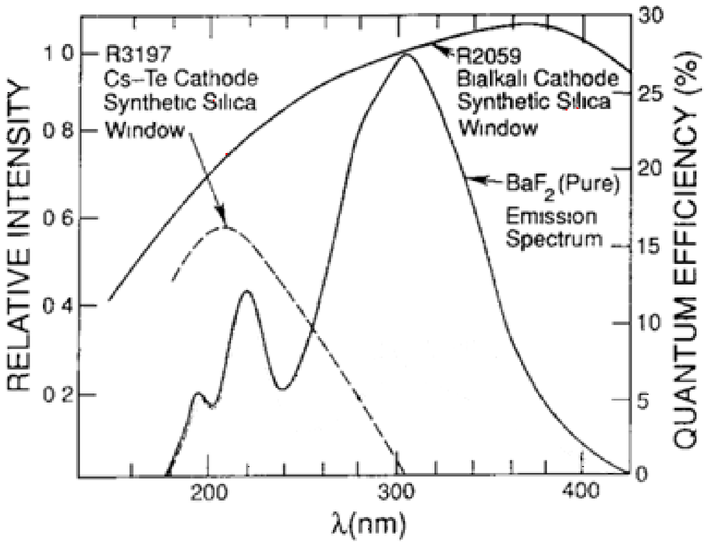
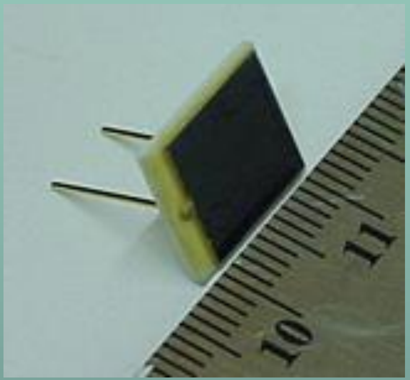




Photosensor R&D

Under a DOE SBIR Phase II grant, we* are developing an avalanche photodiode, based on an existing large area (9x9mm) RMD device, to produce a sensor that has



- High gain (500 @ ~1800V)
- High quantum efficiency at 220nm
- Suppression of response at 300nm
- Improved time response characteristics

The modifications consist of:

- Removal of undepleted silicon in front of avalanche region
- Using molecular beam epitaxy (MBE) to produce a superlattice region beneath the SiO_2 surface
- Producing an antireflection bandwidth filter using atomic layer deposition (ALD)

Work is also beginning on UV sensitive SiPMs

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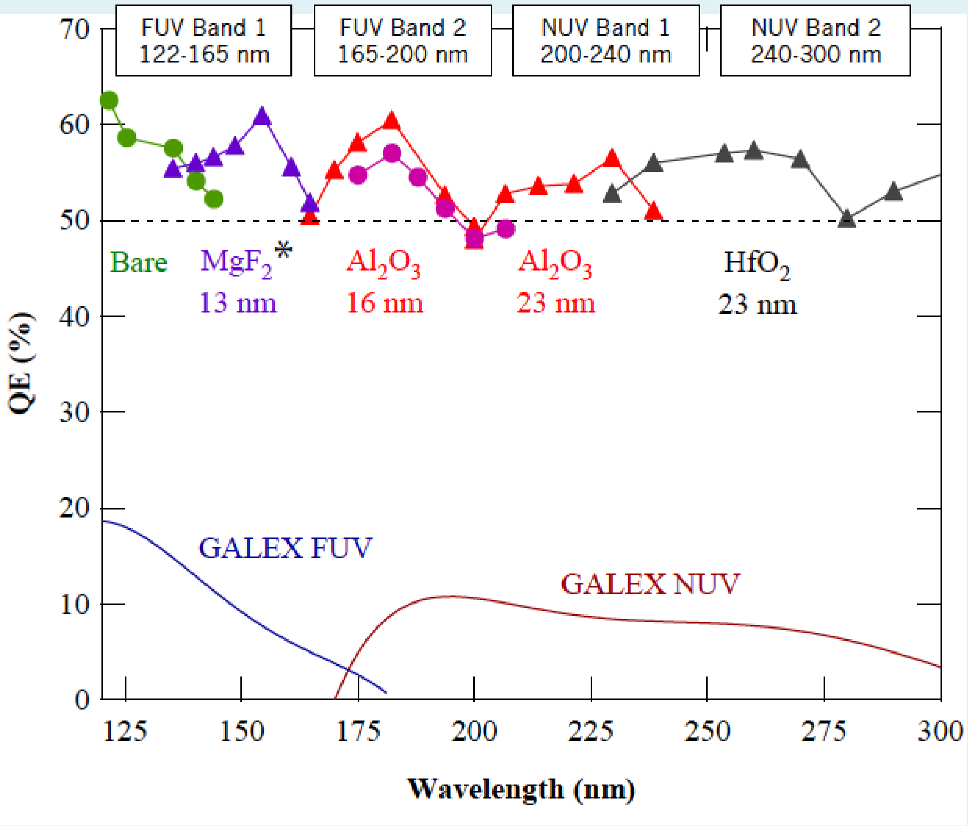
M. Hoenk, J. Hennessey, A. Jewell, *Jet Propulsion Laboratory, Caltech*
R. Farrell, M. McClish, *RMD Inc.*

ALD antireflection filter

- BaF_2 properties
- Photosensor options
- ALD filter
- Superlattice
- Gain, noise
- Radiation hardness
- Conclusion

AR Coatings for UV Detectors



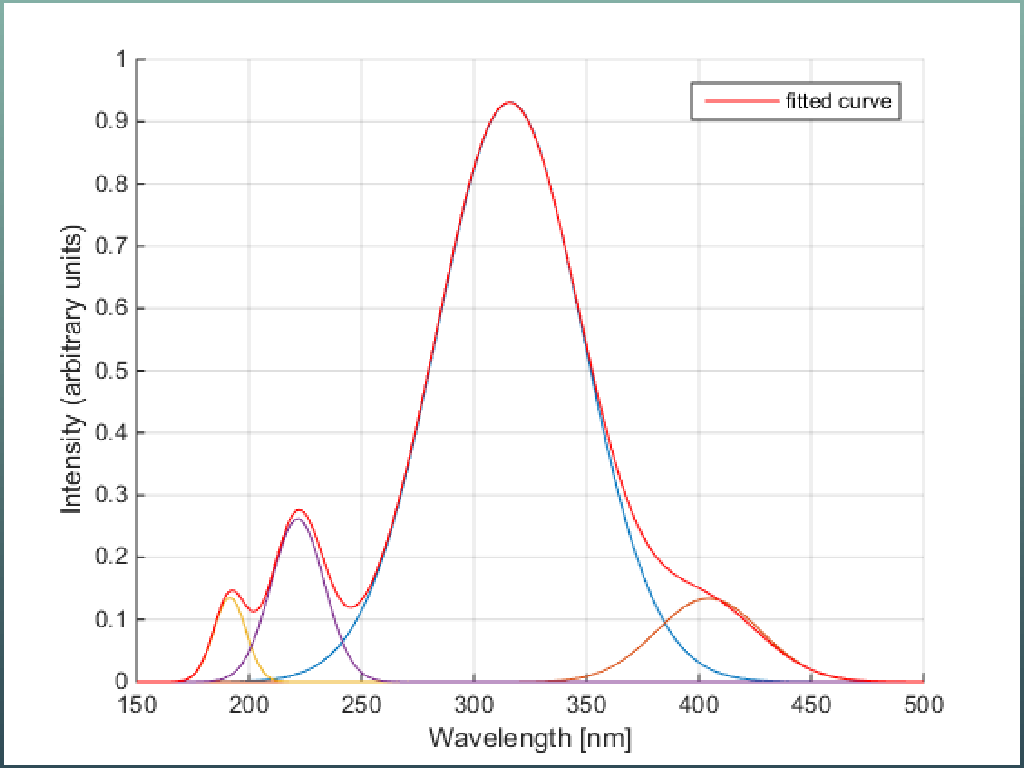
*MgF_2 result for thermally evaporated film

ALD-AR coatings provide up to **2X improvement** over uncoated baseline and a **5x-50x improvement** over incumbent UV detector technology

Nikzad, *et al.*, *Applied Optics*, **51**, (2012) 365.

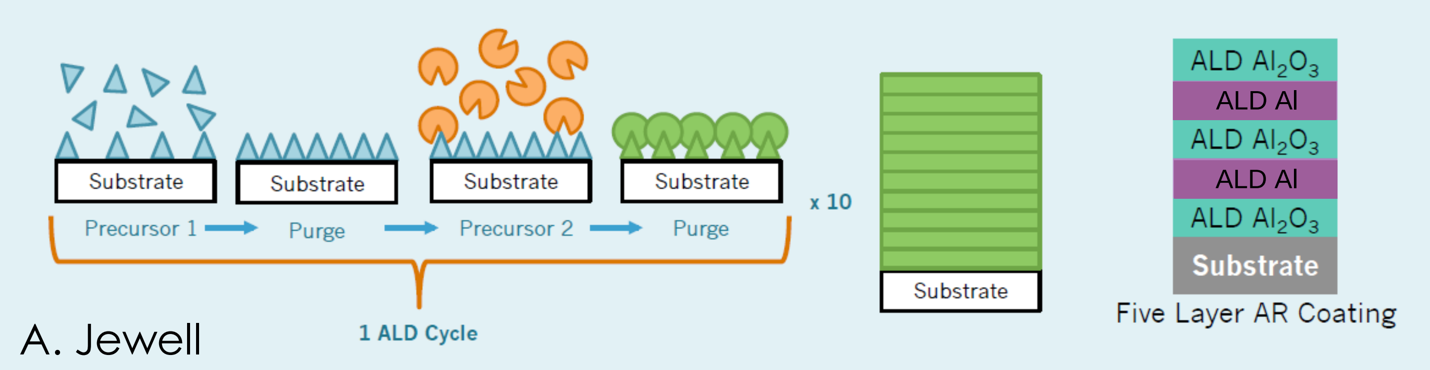
Bandpass filter

- The BaF_2 scintillation spectrum is well-fit by four Gaussians
- We have studied 3, 5 and 7 layer filters
  The best choice is a five layer filter that encompasses the 195 nm and 220 nm fast decay time peaks and provides excellent suppression of the slow components

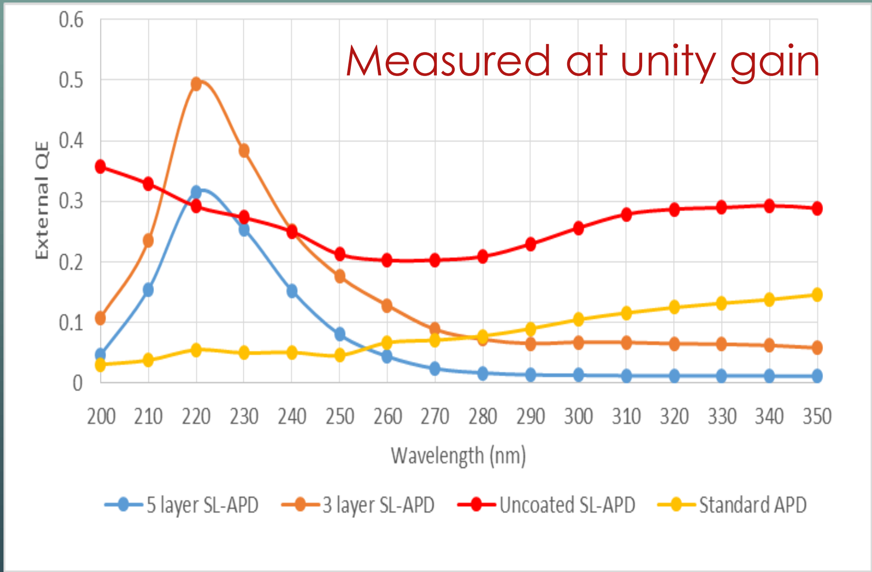


ALD antireflection filter

- Atomic layer deposition of multiple groups of single atomic layers produces integrated antireflection filters



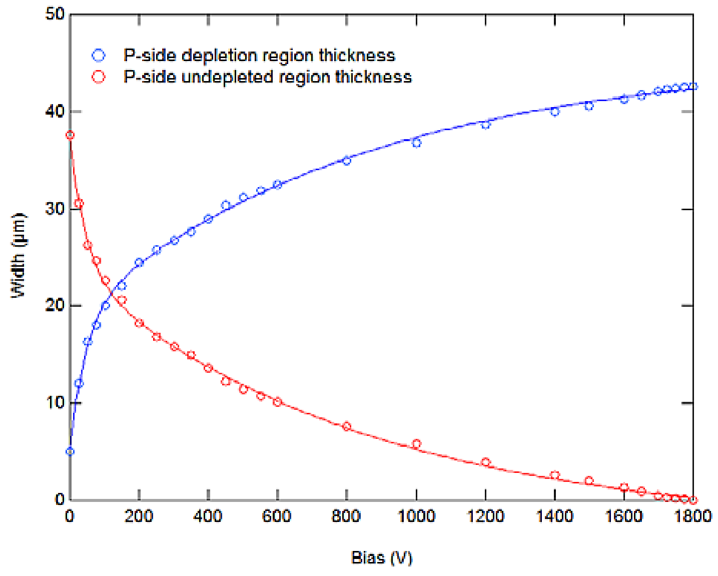
- ALD filter has been designed to be efficient at 220 nm and provide strong extinction at 300 nm
- ALD filter characteristics can be adjusted to trade QE at 220nm for 300 nm extinction

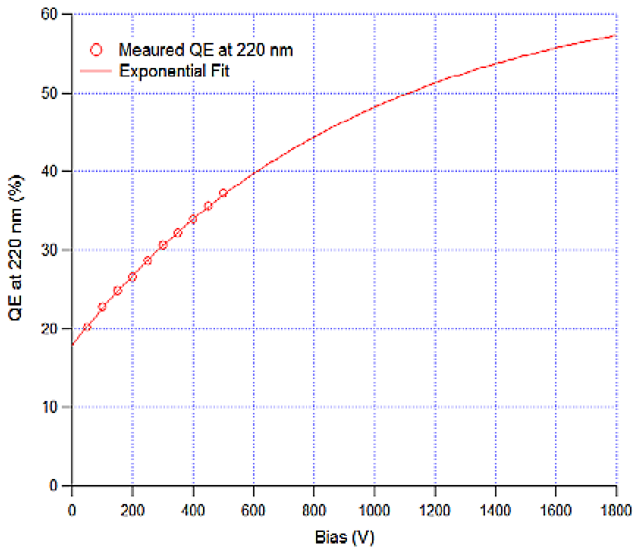


J. Hennessy

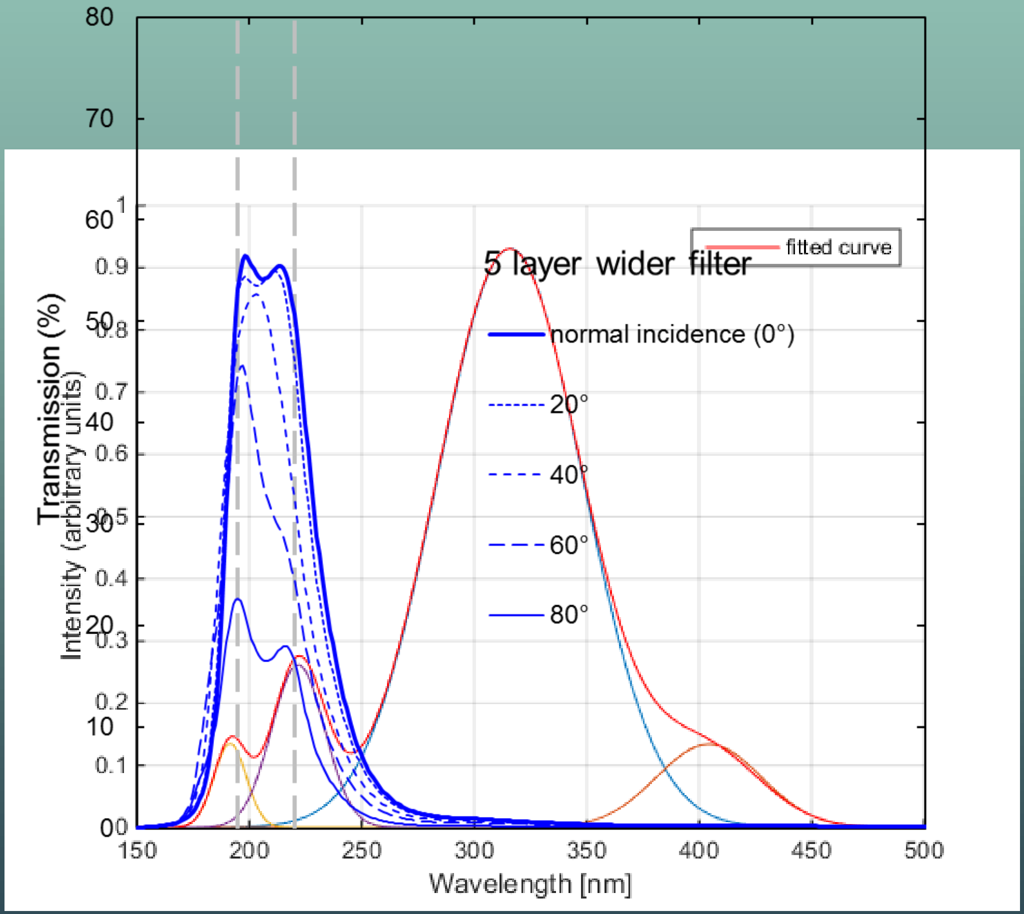
Effective QE increases with gain

- As full depletion is reached at high bias voltage, net quantum efficiency increases



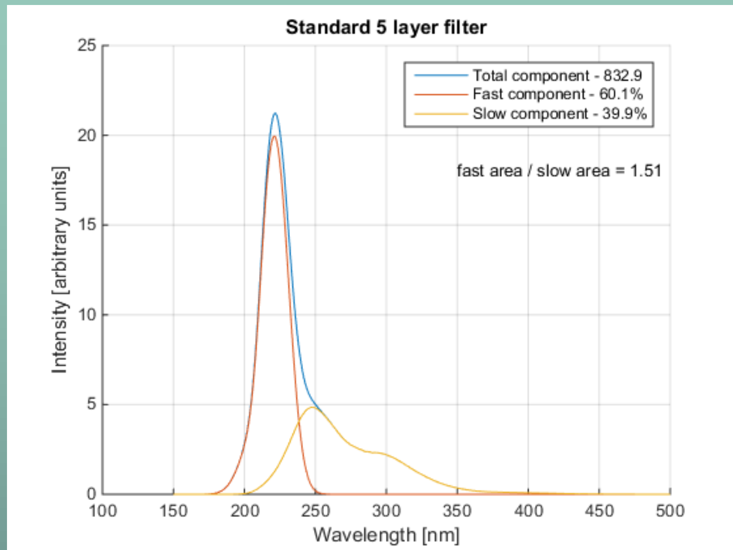


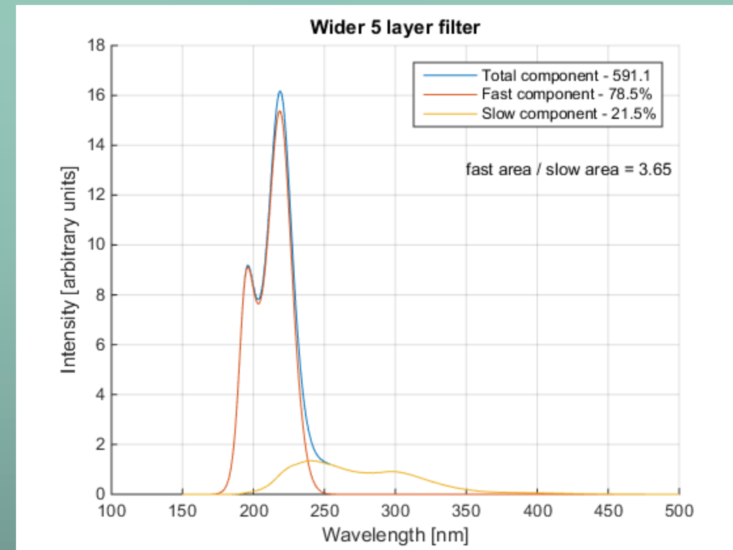
Bandpass filter

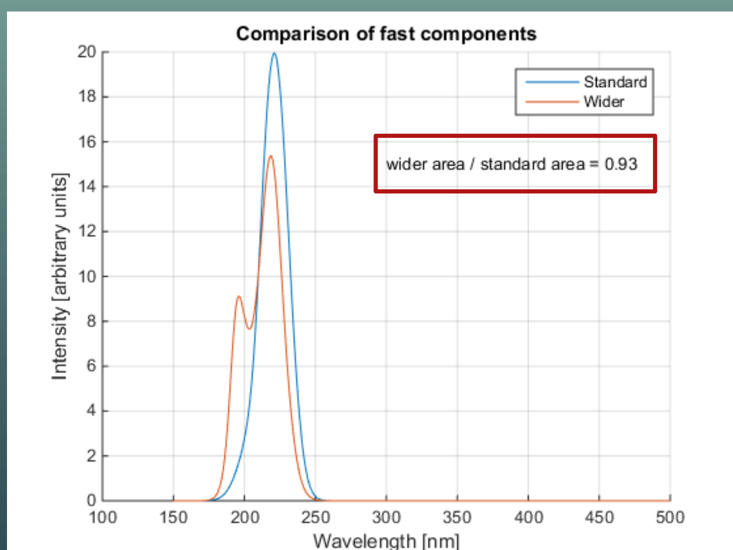


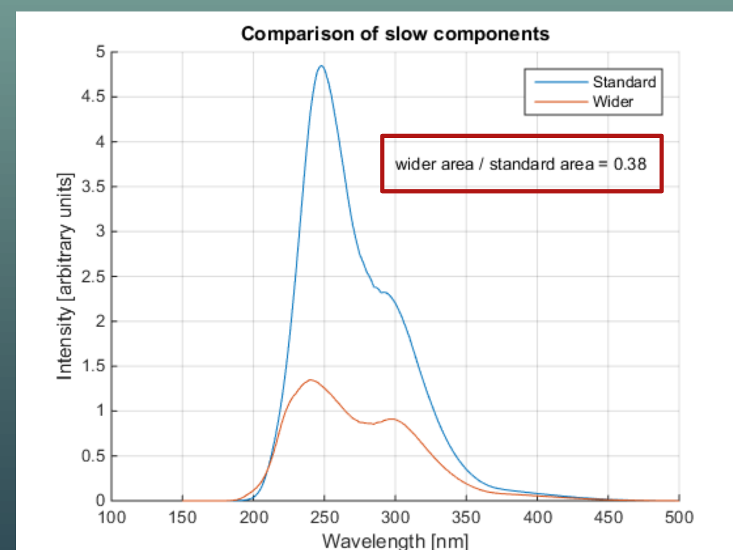
Filter characteristics vary with angle of incidence

Net fast/slow component comparison









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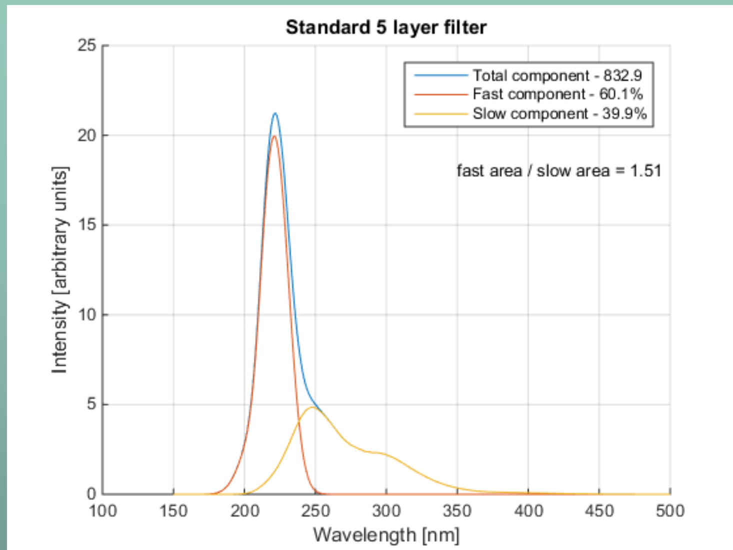
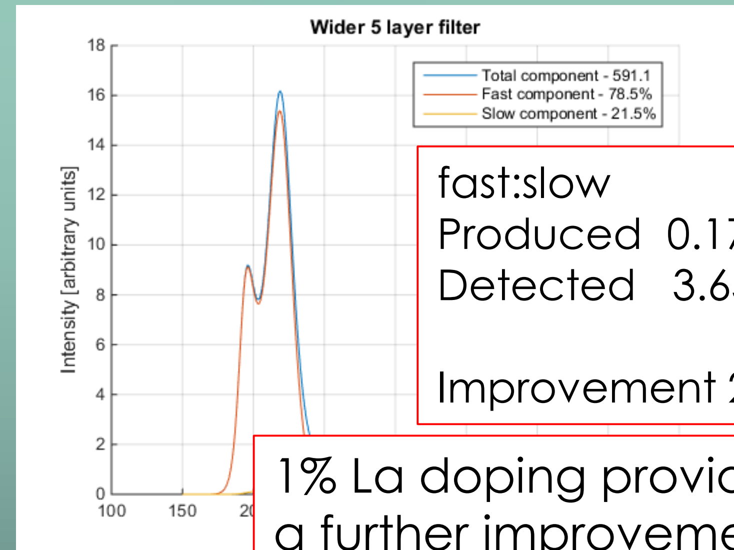
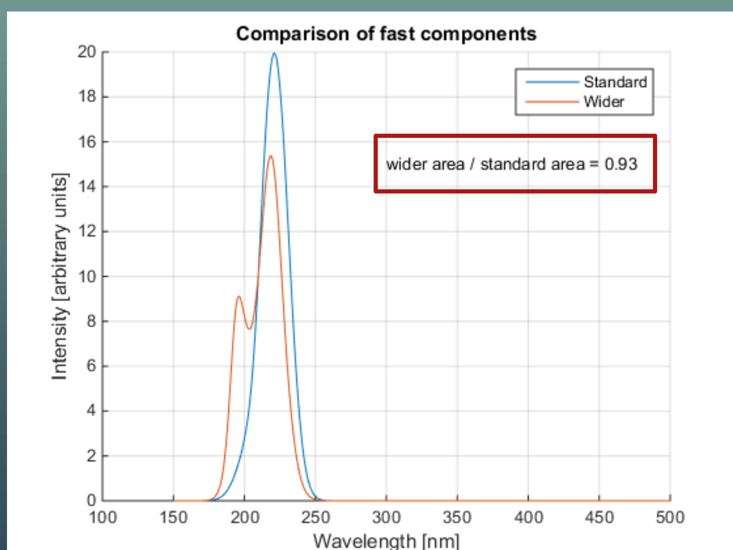
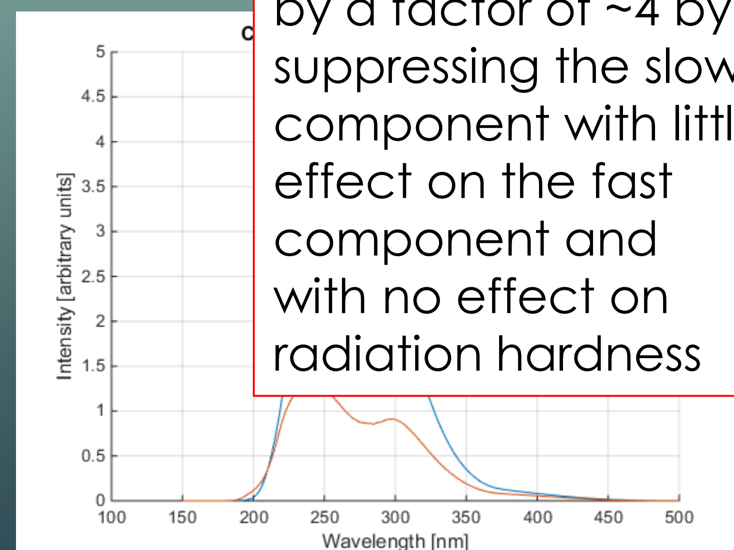




fast:slow
Produced 0.176
Detected 3.65

Improvement 20.7

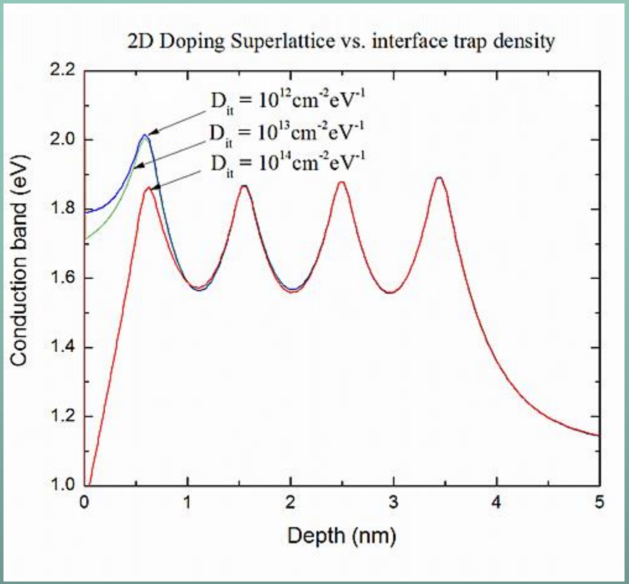


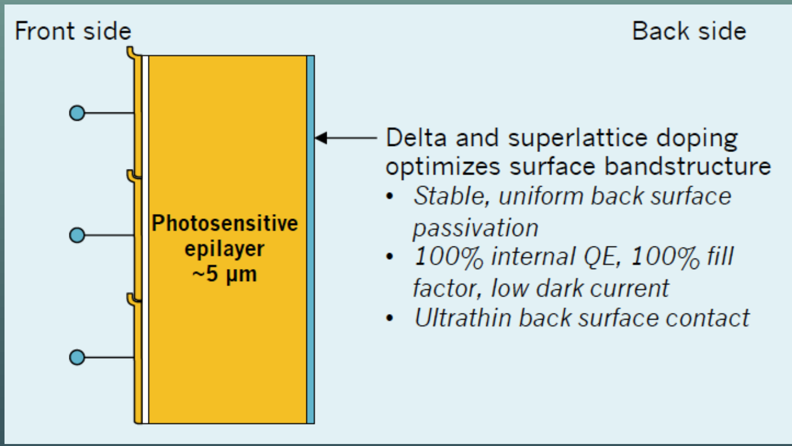


1% La doping provides a further improvement, by a factor of ~4 by suppressing the slow component with little effect on the fast component and with no effect on radiation hardness

Superlattice modifications

- JPL has developed superlattice structures that provide greatly enhanced quantum efficiency and improved time response
  - Delta-doping and superlattices have been successfully employed for many years to enhance the UV performance of CCDs and APDs used in UV astronomy in satellites and balloons
- Monoatomic layers of boron are implanted beneath the (thinned) photosensitive surface of the Si device using molecular beam epitaxy (MBE) (2D doping)
- The MBE layers allow the conduction band to remain stable with varying surface charge

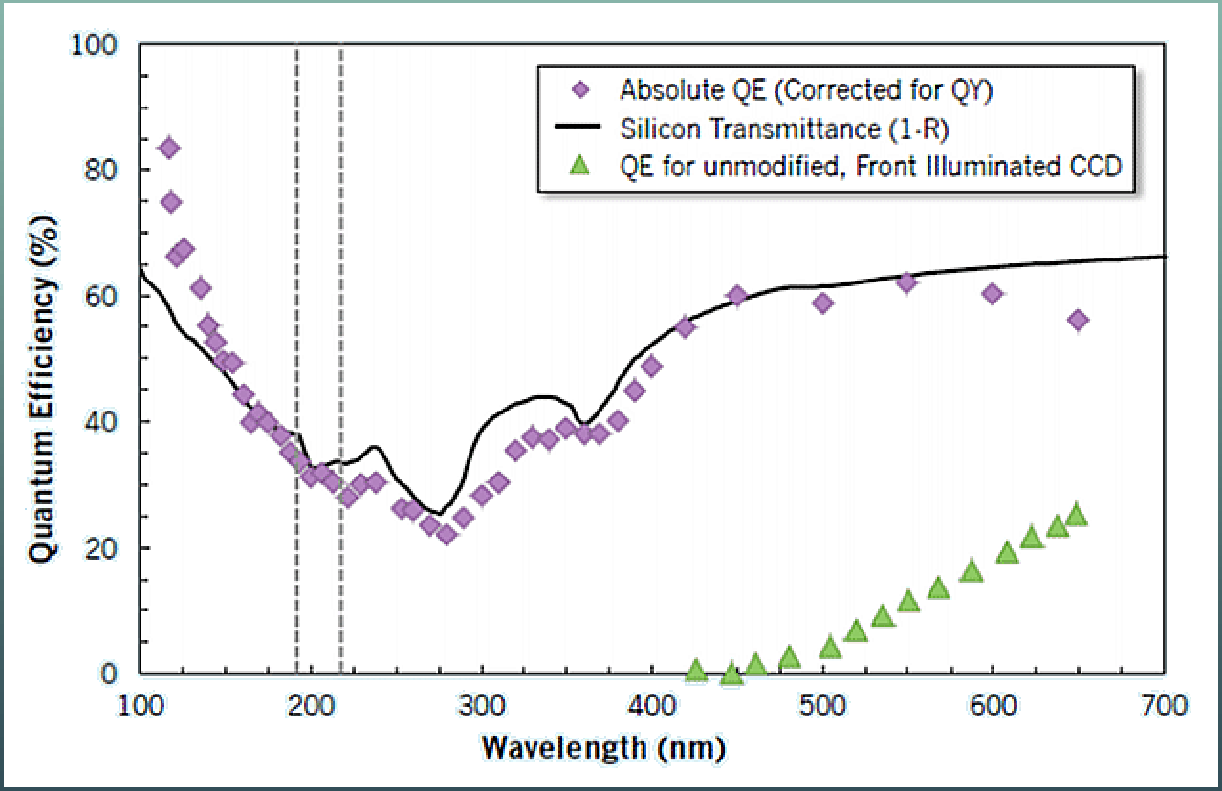




M. Hoenk *et al.*, APL **61** 1084 (1992)

Superlattice modifications

- The superlattice suppresses recombination by quantum exclusion, producing close to 100% internal QE
- Quantum efficiency in the 200-300 nm region approaches Si transmittance limit



UV stability

- Superlattice provides stability under intense UV illumination

BaF_2 properties

Photosensor options

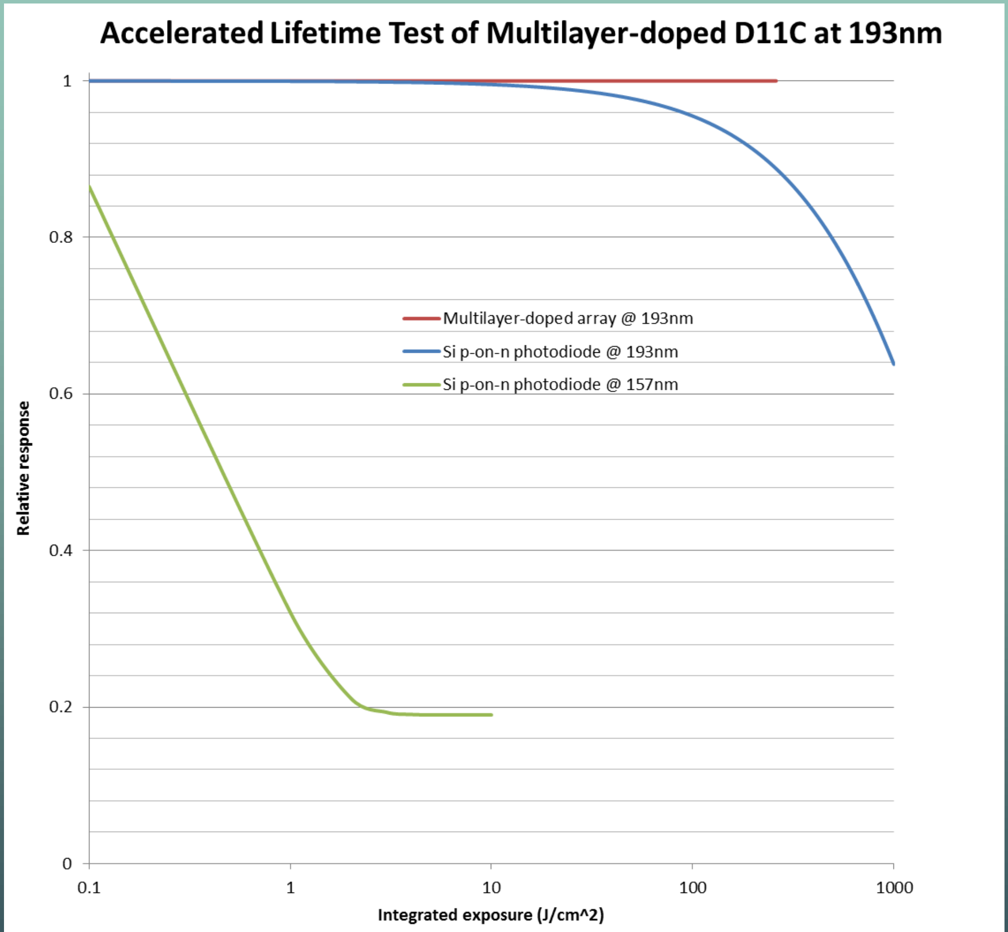
ALD filter

Superlattice

Gain, noise

Radiation hardness

Conclusion



U. Arp *et al.*, J. Elect. Spect. and Related Phenomena, **144**, 1039 (2005)

BaF$_2$ properties

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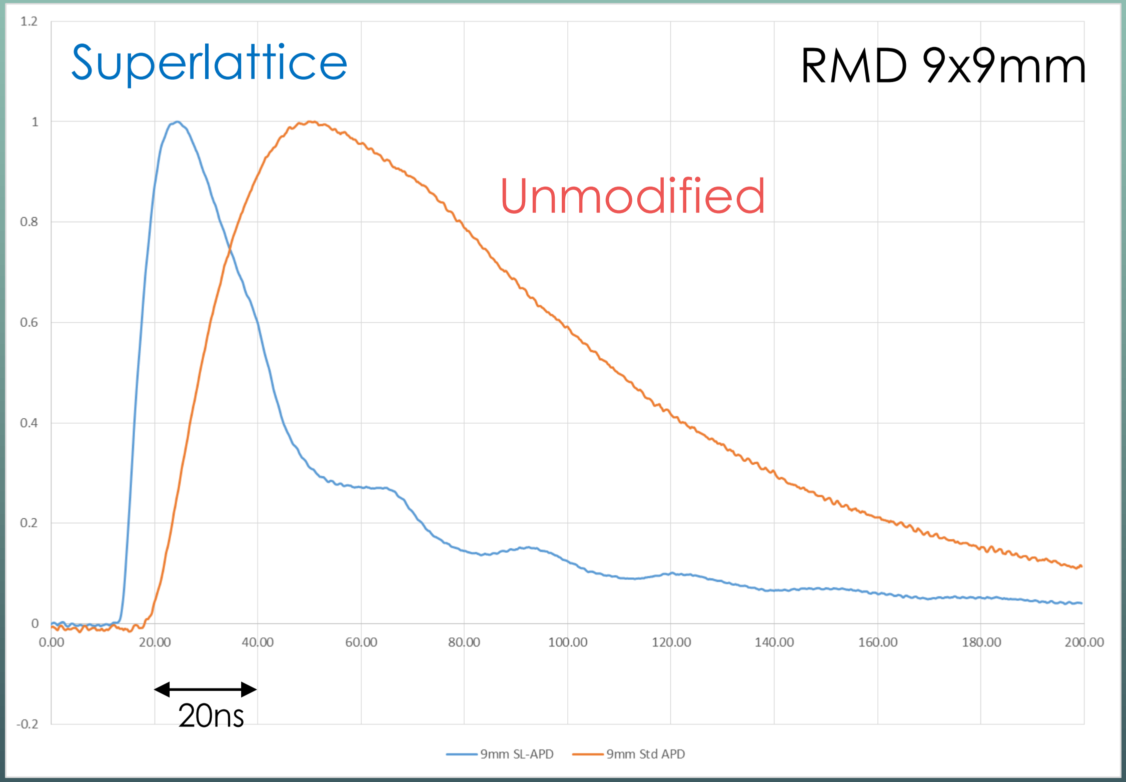
Conclusion

Improved time response

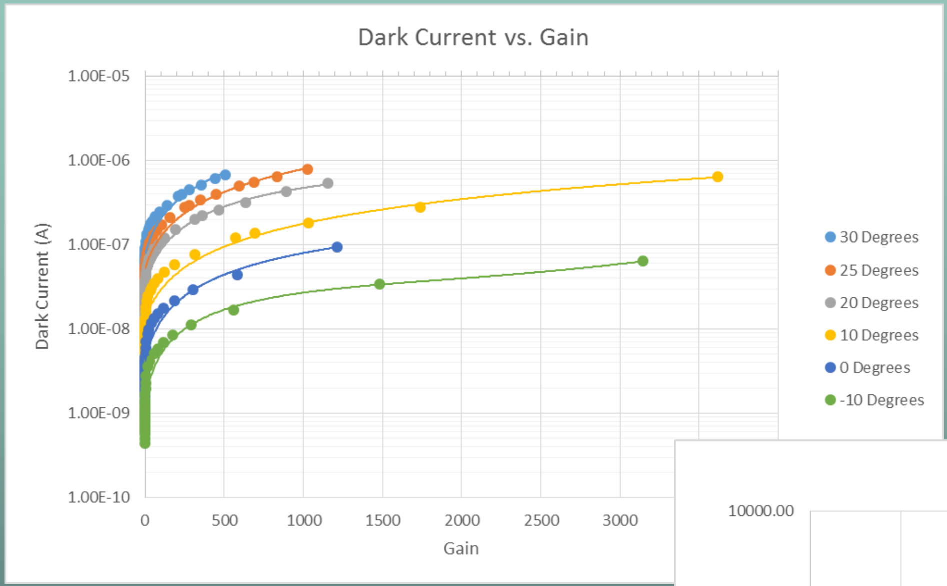
- Elimination of the undepleted region before the avalanche structure improves APD time performance

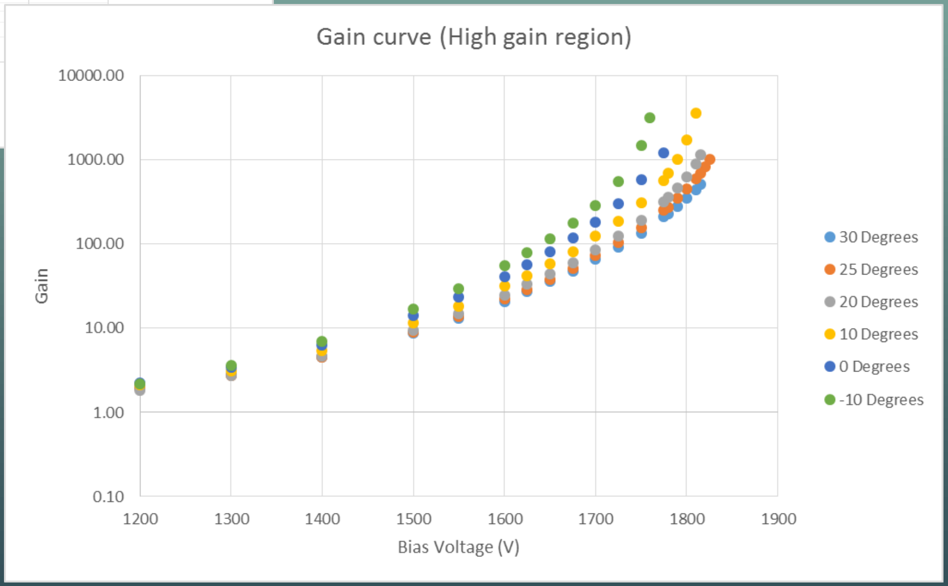


M. McClish

Dark current vs. temperature

Standard RMD 9x9mm APD





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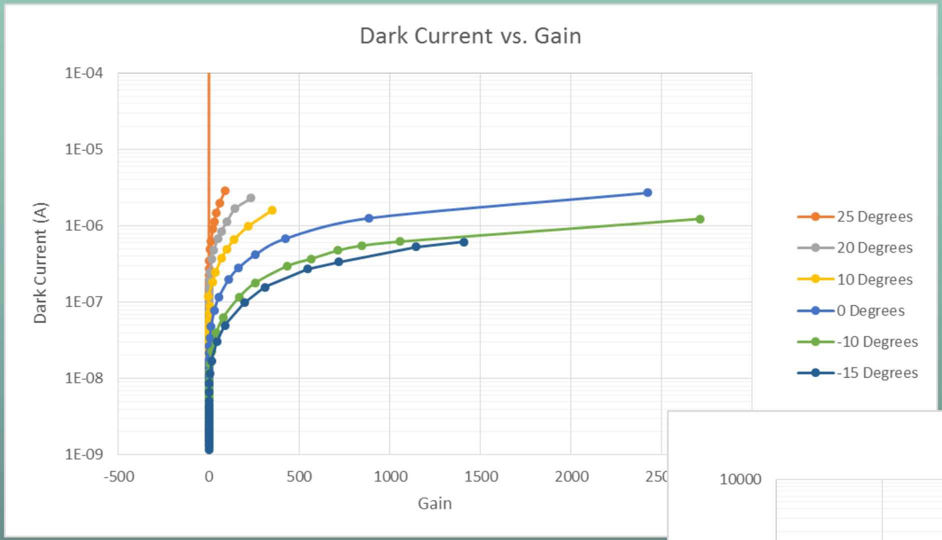
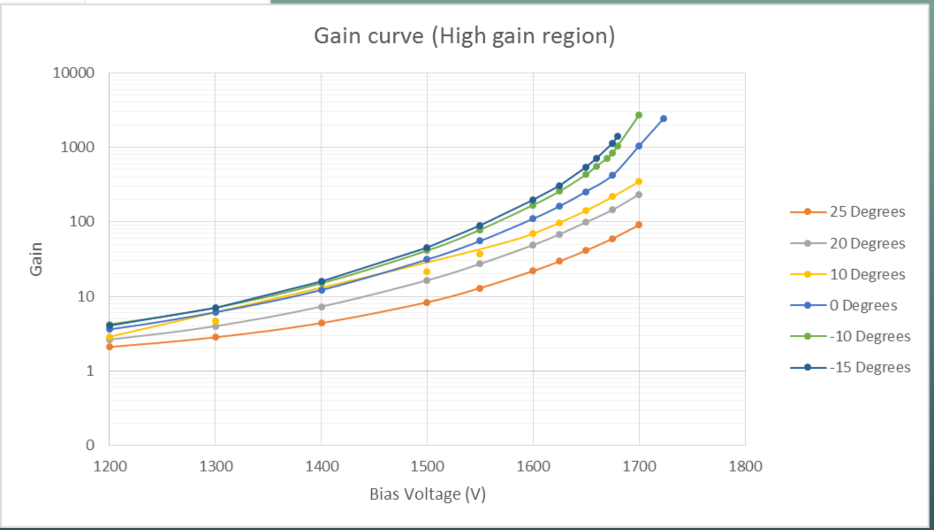
Dark current vs. temperature

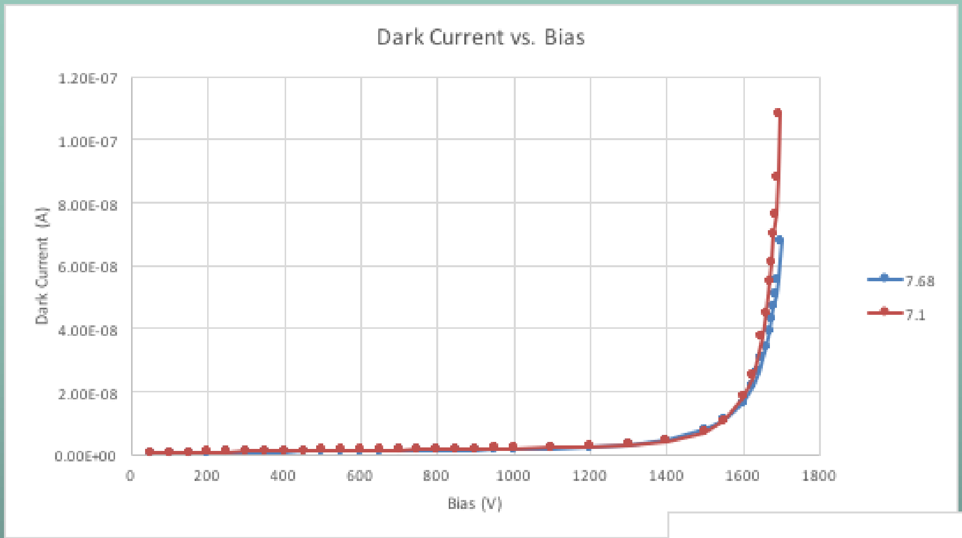
Superlattice/5 layer ALD 9x9mm APD

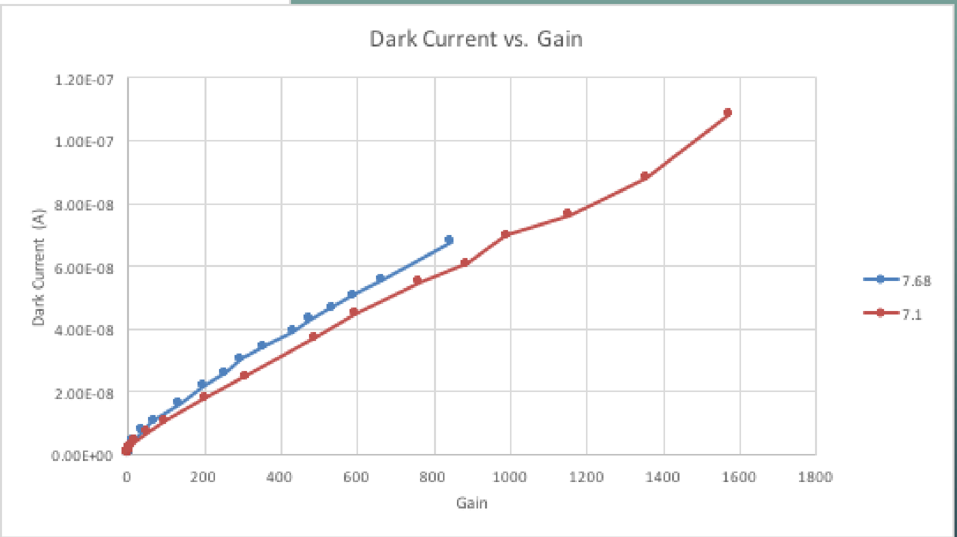




Gain/dark current at -10C

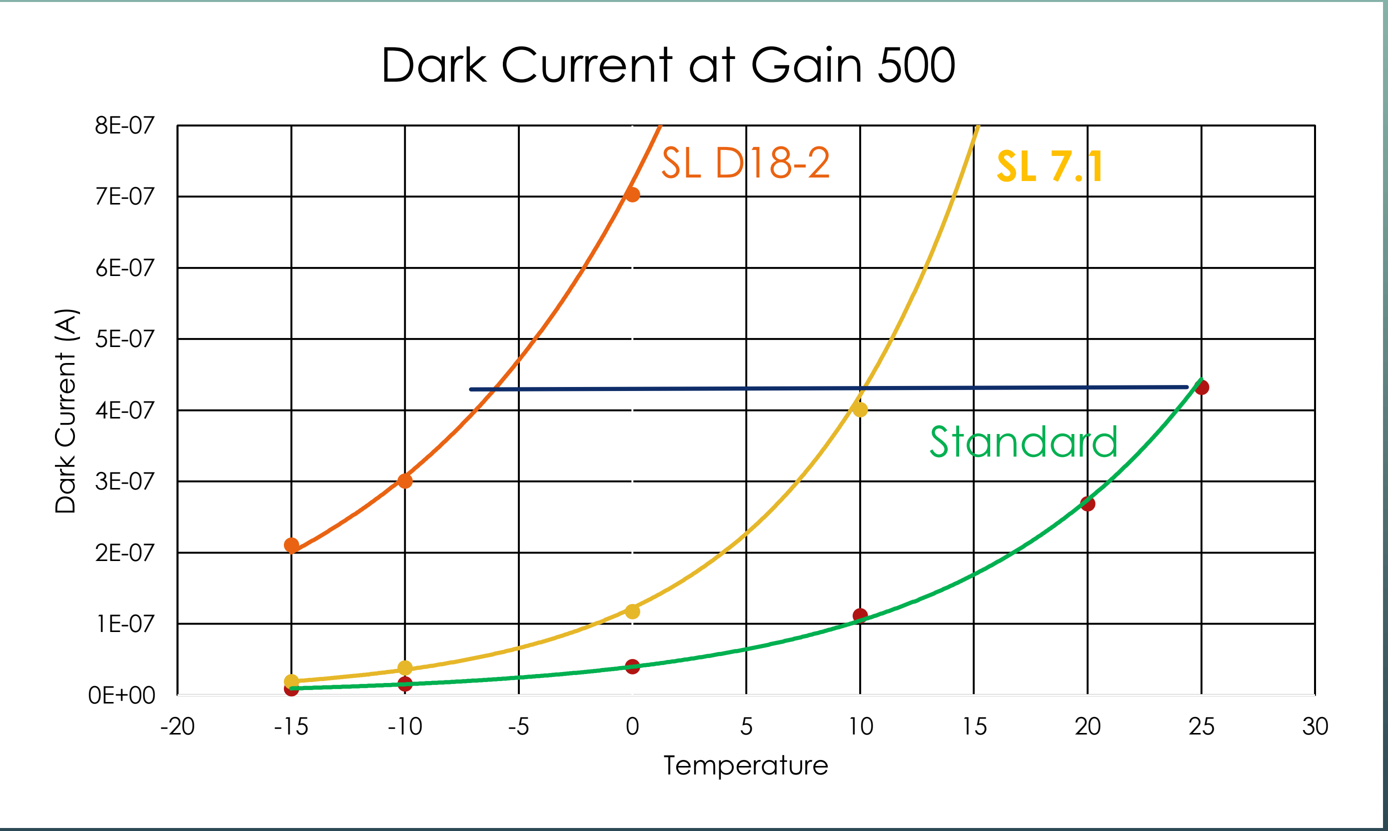
- BaF_2 properties
- Photosensor options
- ALD filter
- Superlattice
- Gain, noise
- Radiation hardness
- Conclusion





Dark current vs. temperature

- Early SL/Filter APD (D18-2) has the same dark current at -10°C as the standard device APD at room temperature
- Latest SL/filter APDs (SL 7-1 and 7.68) show substantial improvement in dark current over earlier wafers with only modest cooling: same dark current as standard device at +10 °C



BaF$_2$ properties

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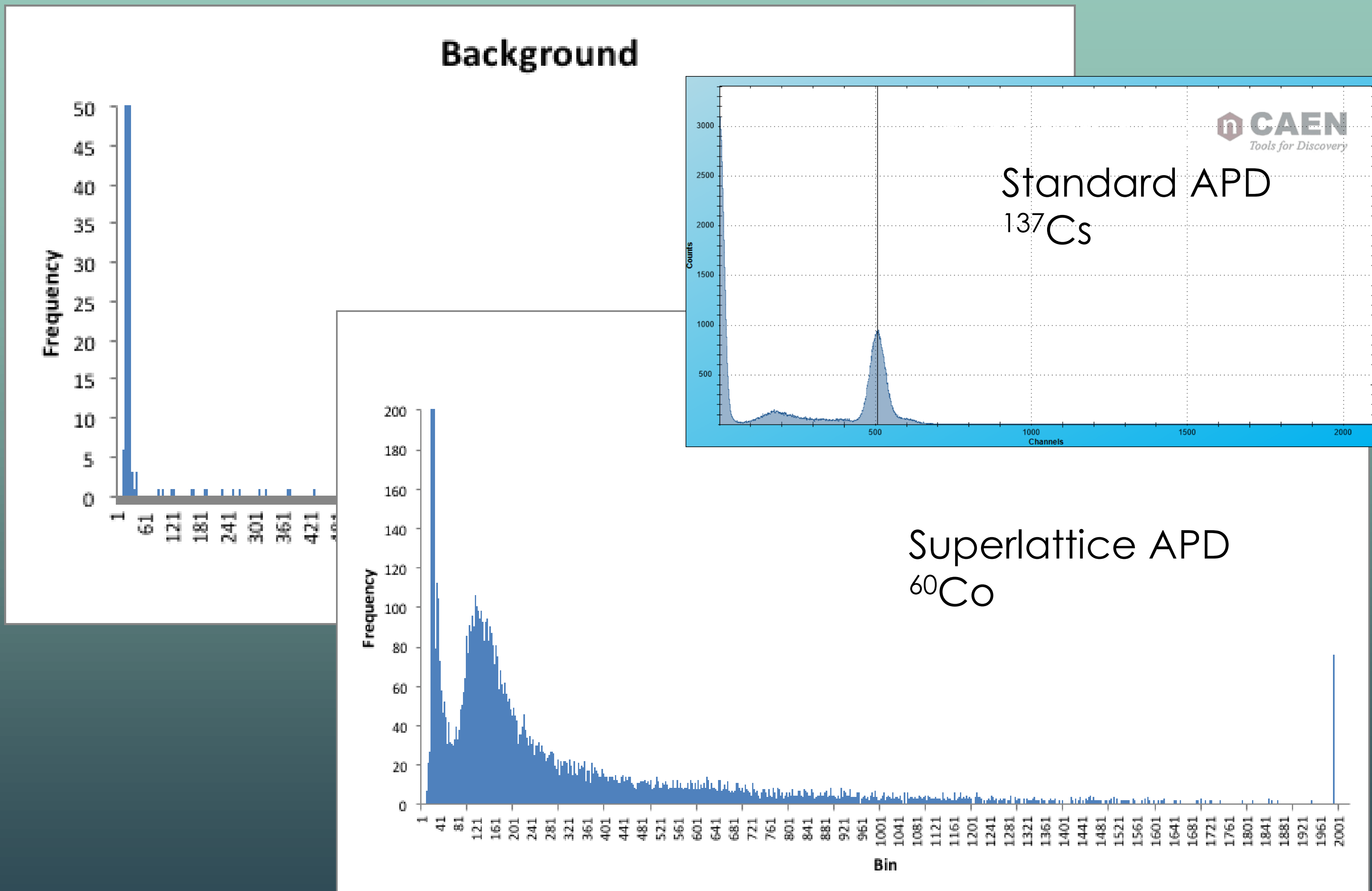
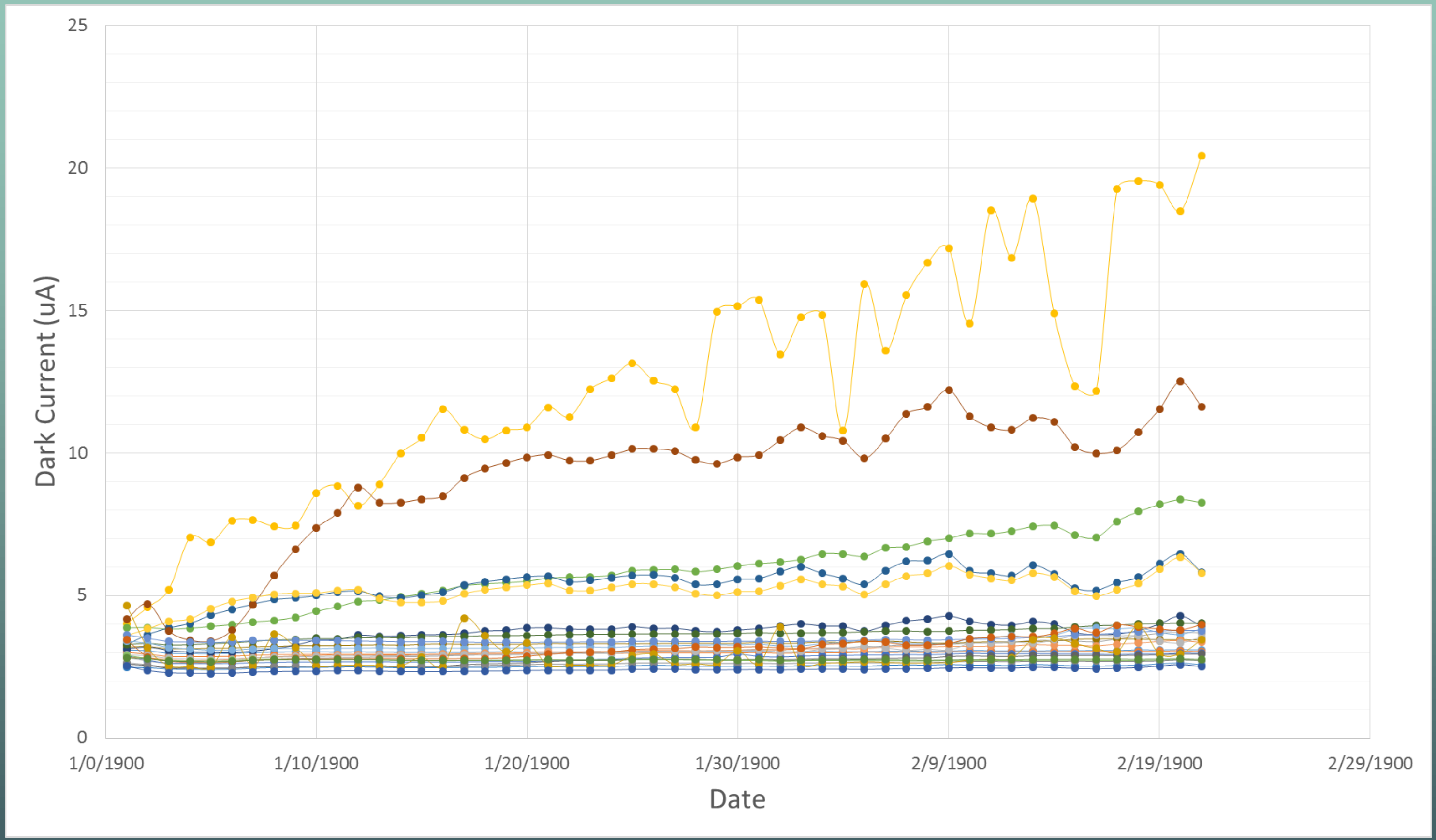
Spectra

- Taken with a small BaF_2 (1 cm^3) & 9 mm SL APD



Reliability test – 80 days

- Biased at ~1600v at 50C



- Infant mortality: 5 of 24
- 19 devices with 0 failures implies MTTF > 10^6 hours

γ irradiation of standard and SL APDs

- BaF_2 properties
- Photosensor options
- ALD filter
- Superlattice
- Gain, noise
- Radiation hardness
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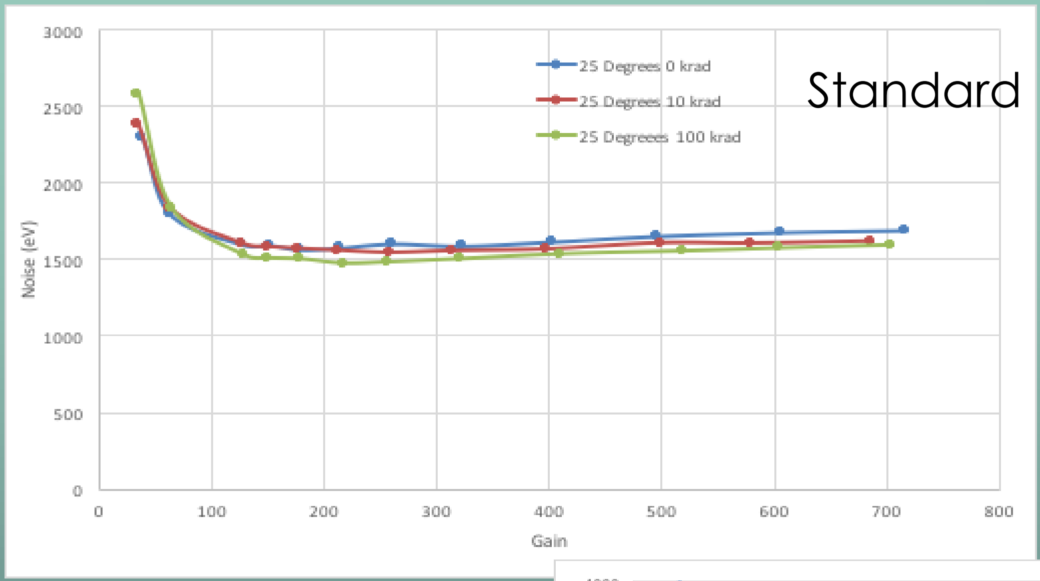
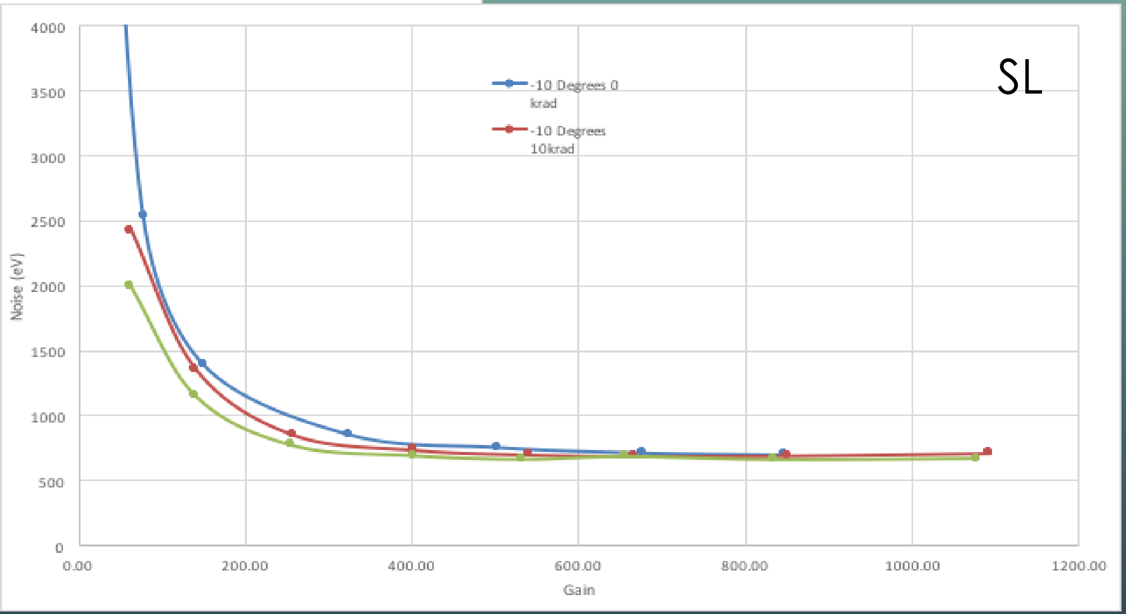
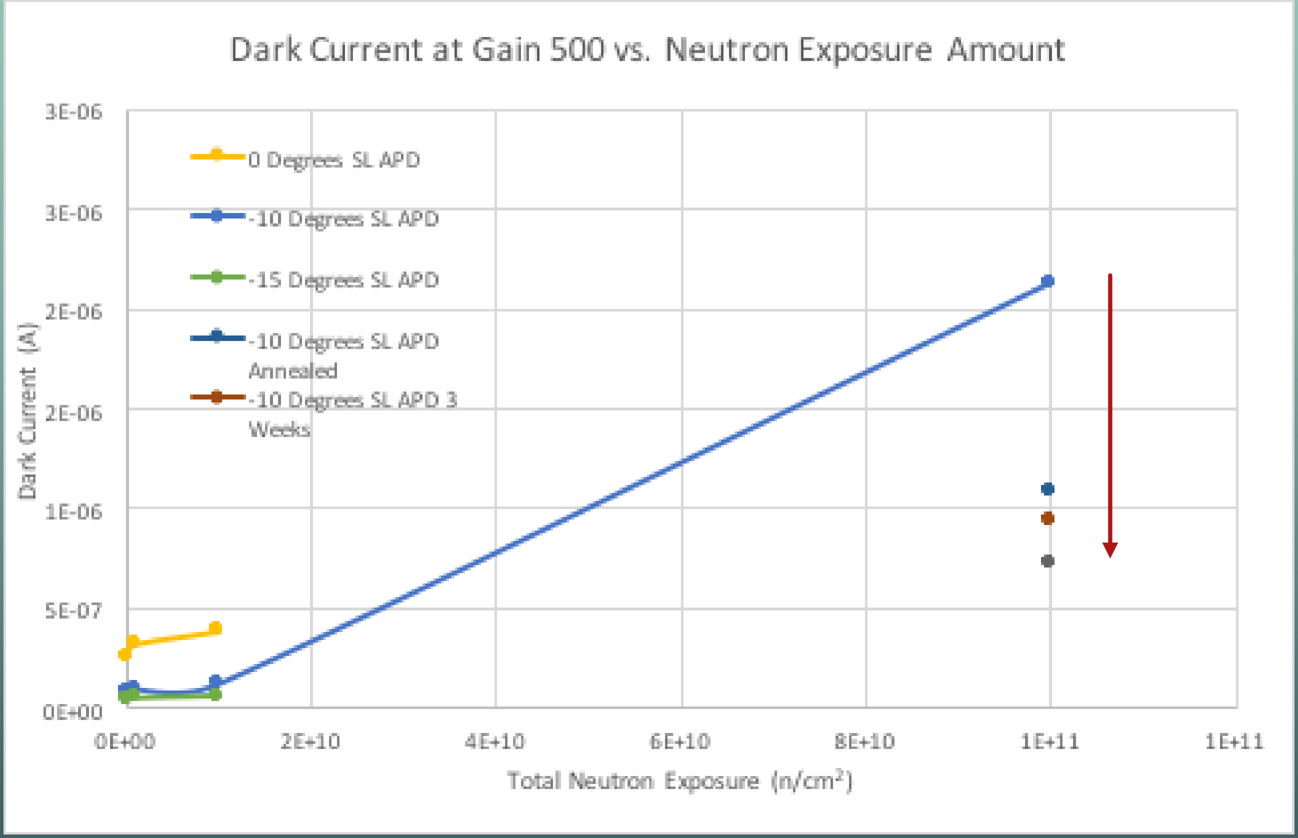




Irradiation done without bias, as we feared that unrealistic high rates could damage APDs

Neutron irradiation

- 14 mm superlattice APD
  - Exposure rate is 1.4 x 10^5 n/cm^2/s (8.2 days to 1x10^{11})



Dark current decreases after exposure due roannealing of damage

BaF$_2$ properties

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Conclusion

- We have developed an avalanche photodiode suitable for the readout of the fast component of barium fluoride scintillation light by modifying a standard RMD APD using superlattice and atomic layer deposition techniques
- Device characteristics
  - High gain (>500)
  - High QE for the 220nm BaF_2 fast component
  - Insensitive to the 300nm BaF_2 slow component
  - Excellent time performance
  - Can withstand high integrated flux of UV
  - Standard RMD APD has been shown to be radiation hard with gammas and protons
    - Irradiation tests of the SL APDs with gammas and neutrons are underway
  - Noise of initial devices is higher than that of standard devices
    - Operation at 10°C provides noise performance similar to that of standard RMD APD at room temperature