A Large Area APD for the Readout of the Fast Scintillation Component of Barium Fluoride

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Caltech

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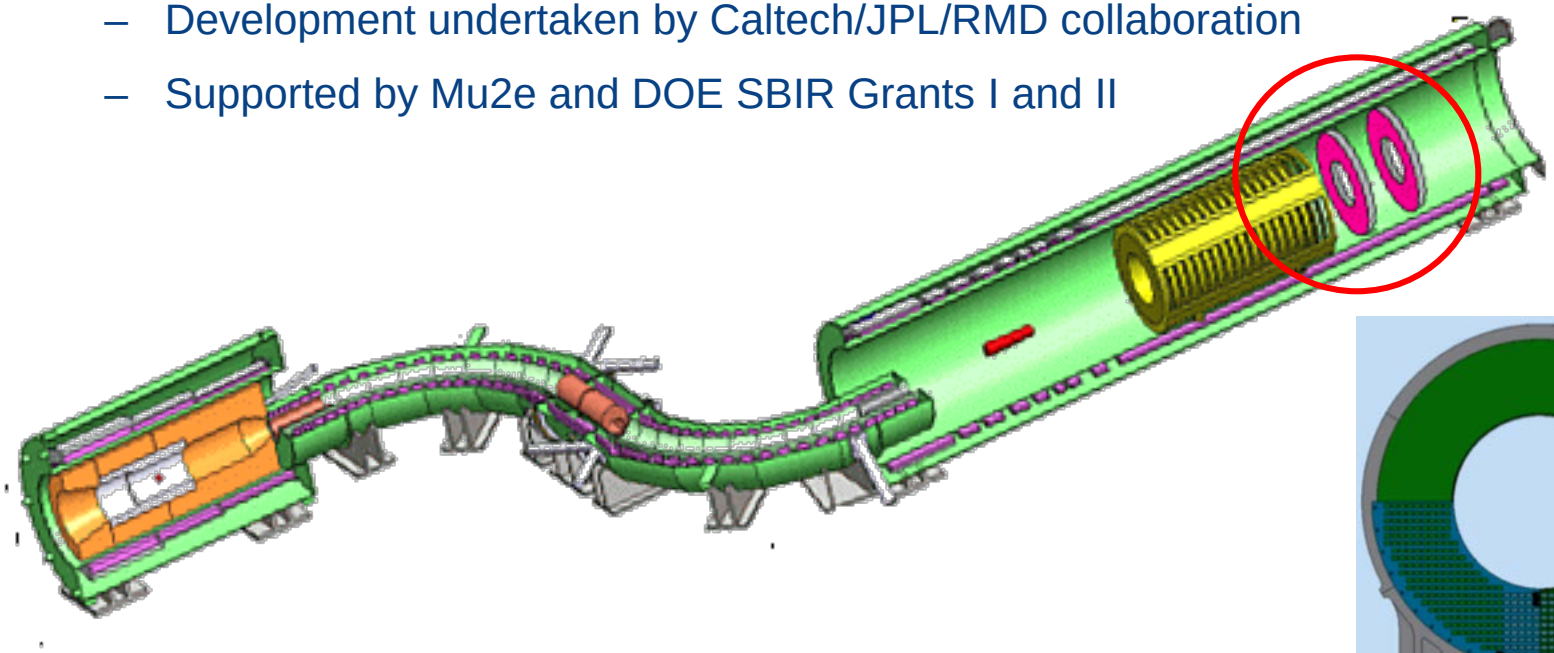
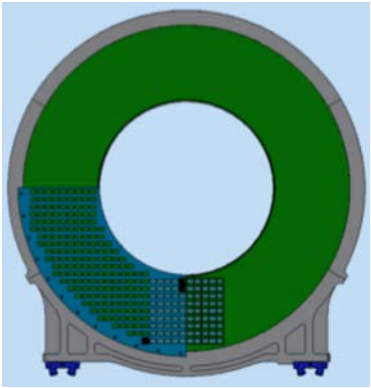
Motivation: the Mu2e calorimeter

- The baseline uses barium fluoride crystals:
  - Fast decay time ➡ short integration time, high rate capability
  - Good energy and time resolution
  - Radiation hardness
  - Suitability for a possible Mu2e upgrade
- Requires a new photosensor
  - Development undertaken by Caltech/JPL/RMD collaboration
  - Supported by Mu2e and DOE SBIR Grants I and II





Summary of calorimeter requirements

- Provide high electron reconstruction efficiency for muon rejection of 200
- Provide online trigger capability (HLT)
- Provide cluster-based track seeds for track finding
- In order to do so it should:

  → provide energy resolution $\sigma(E)/E = \mathcal{O}(5\%)$ monitored at a level of <0.5%

  → provide timing resolution $\sigma(t) < 0.5$ ns

  → provide position resolution < 1 cm

These requirements should be met in the radiation environment:

Total exposure of the inner ring of the disks

- front face of the inner ring of crystals:

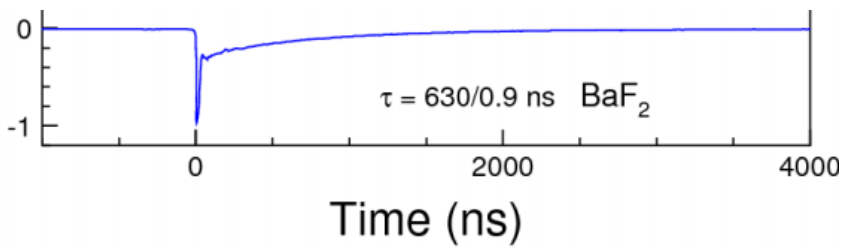
  gammas: 100 krad/crystal

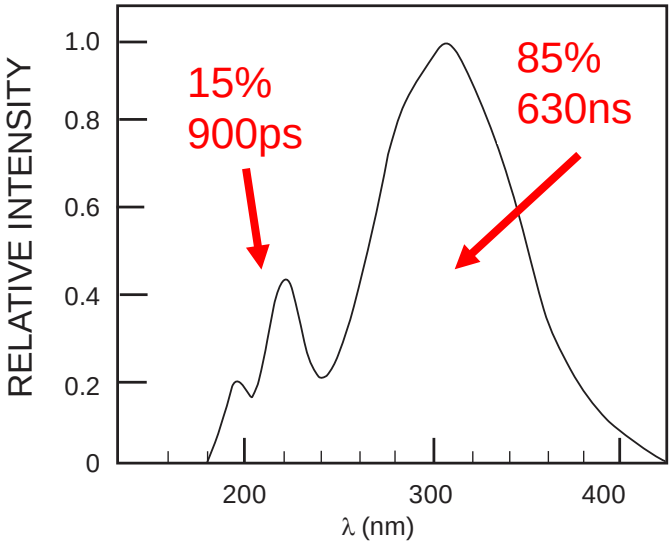
  neutrons: 10^{12} n_1 MeV/cm^2
- Inner ring of photosensors

  neutrons: 3×10^{11} n_1 MeV/cm^2

Barium fluoride scintillation light

- BaF_2 has a 220nm scintillation component with 900ps decay time, but with a much larger 300nm component having a 630ns decay time
- For the Mu2e calorimeter, we utilize the fast component to provide excellent time resolution for discrimination against background, as well as for high rate capability
  - Doing so requires either suppression of the emission of the slow component or a “solar blind” photosensor





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

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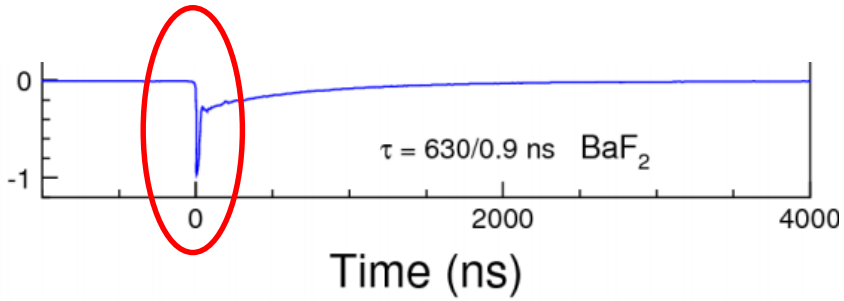

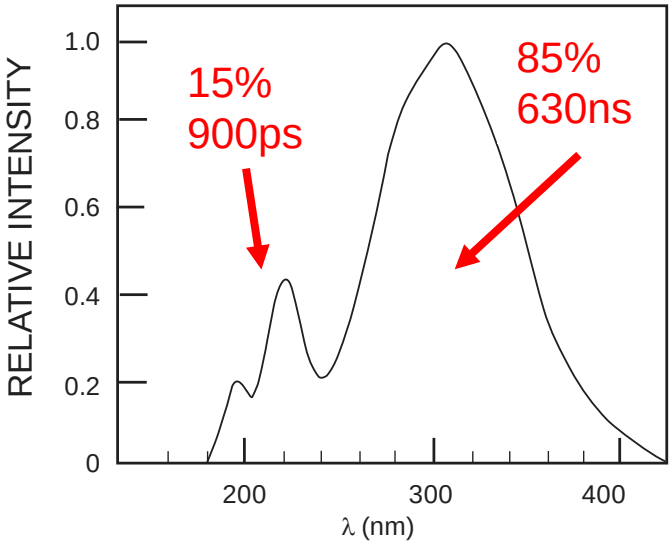

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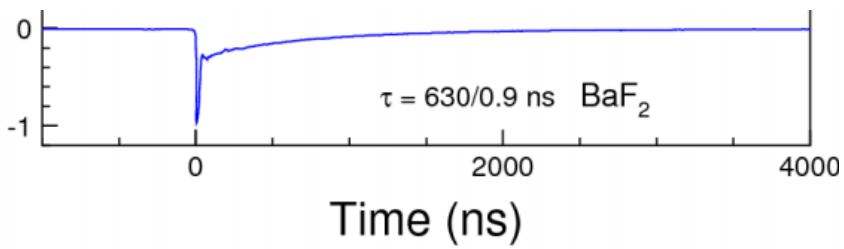
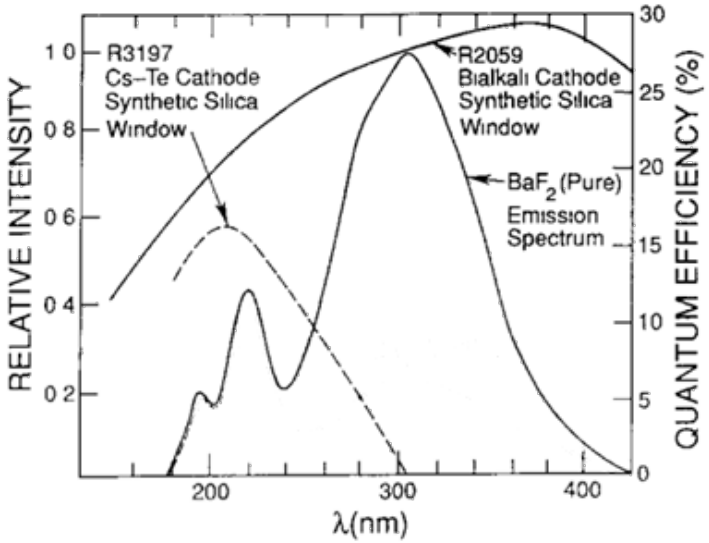
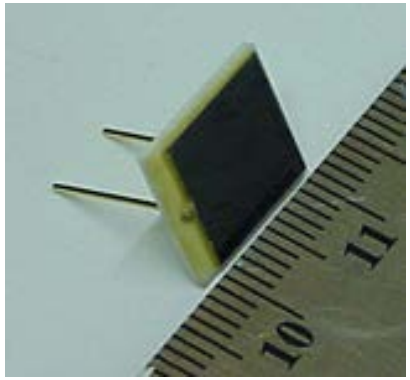




Photosensor options

We have developed an avalanche photodiode, based on an existing large area (9x9mm) RMD device, to produce a sensor that has the needed characteristics

- High gain (500 @ ~1800V) (2000 is possible)
- High quantum efficiency at 220nm
- Suppression of response at 300nm
- Improved time response characteristics
- Radiation hardness



The modifications consist of:

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

We have also begun work on SiPMs having an ALD filter, and, potentially, superlattice doping, with two manufacturers

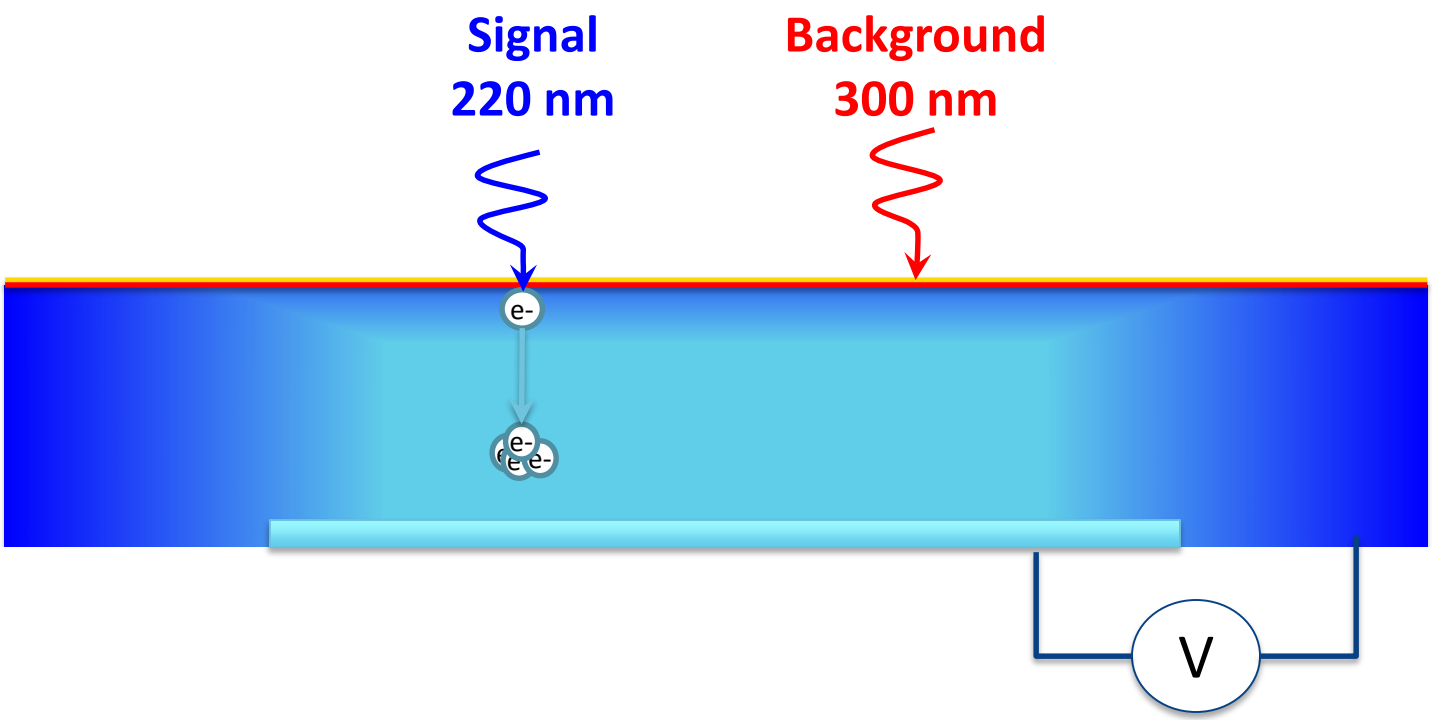
The R&D Collaboration

- JPL
  - The JPL Microdevices Laboratory invented delta-doping (3D) (M. Hoenk *et al*., APL **61** 1084 (1992)) and superlattice (2D) techniques to improve UV sensitivity and robustness of space-qualified CCD sensors
  - JPL also pioneered atomic layer deposition of antireflection and bandwidth-limiting filters
- RMD
  - RMD APDs have higher gain than others and good radiation hardness
  - RMD has a history of collaborative R&D with experimentalists

– The R&D Collaboration

H.O. Gesstson, D.G. Hitlin, K.Flood, J.H. Kim, J. Trevor, *Caltech*
M. Hoenk, J. Hennessey, A. Jewell, NASA *Jet Propulsion Laboratory, Caltech*
R. Farrell, M. McClish, *RMD Inc.*

The structure of a superlattice-doped solar-blind avalanche photodiode



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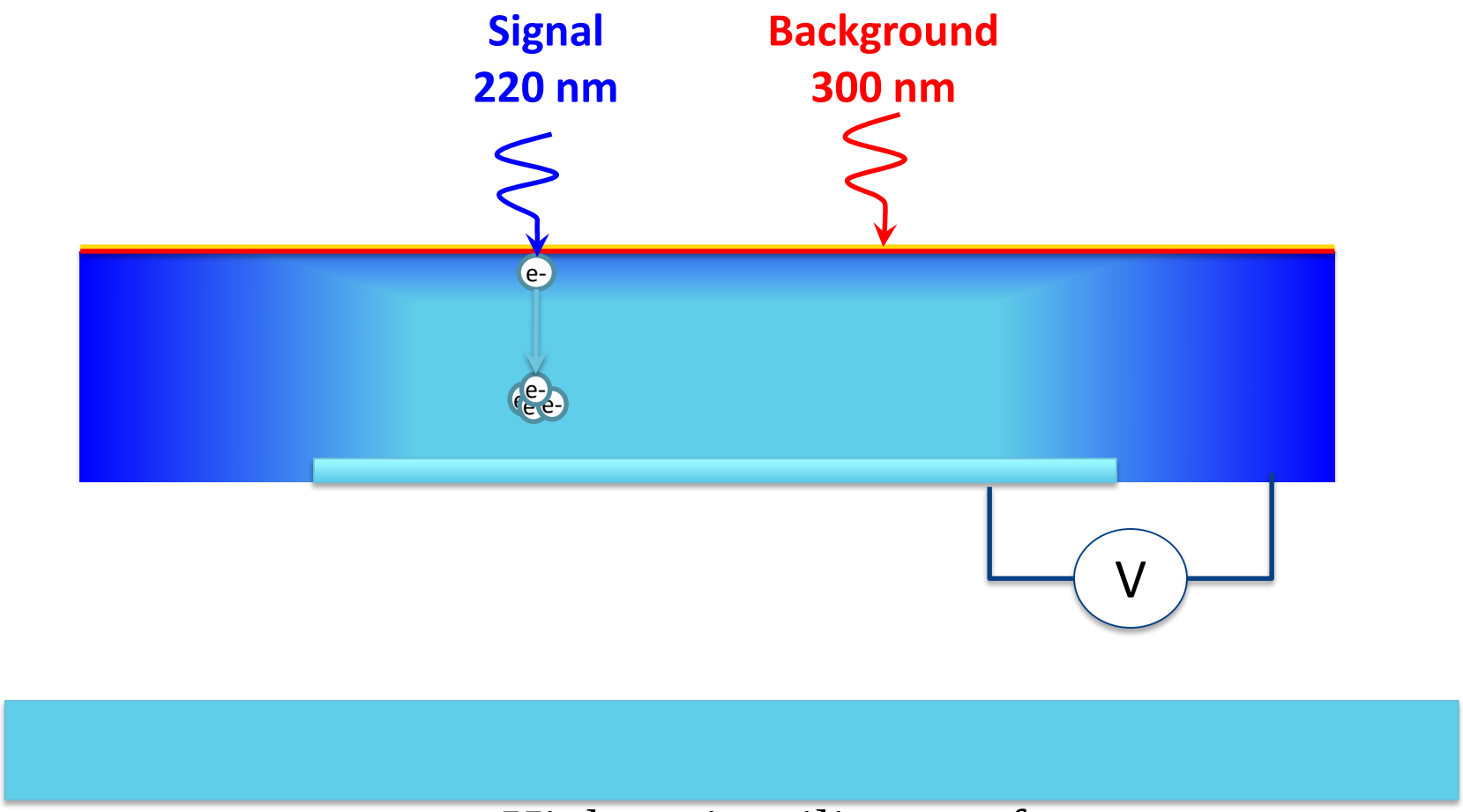

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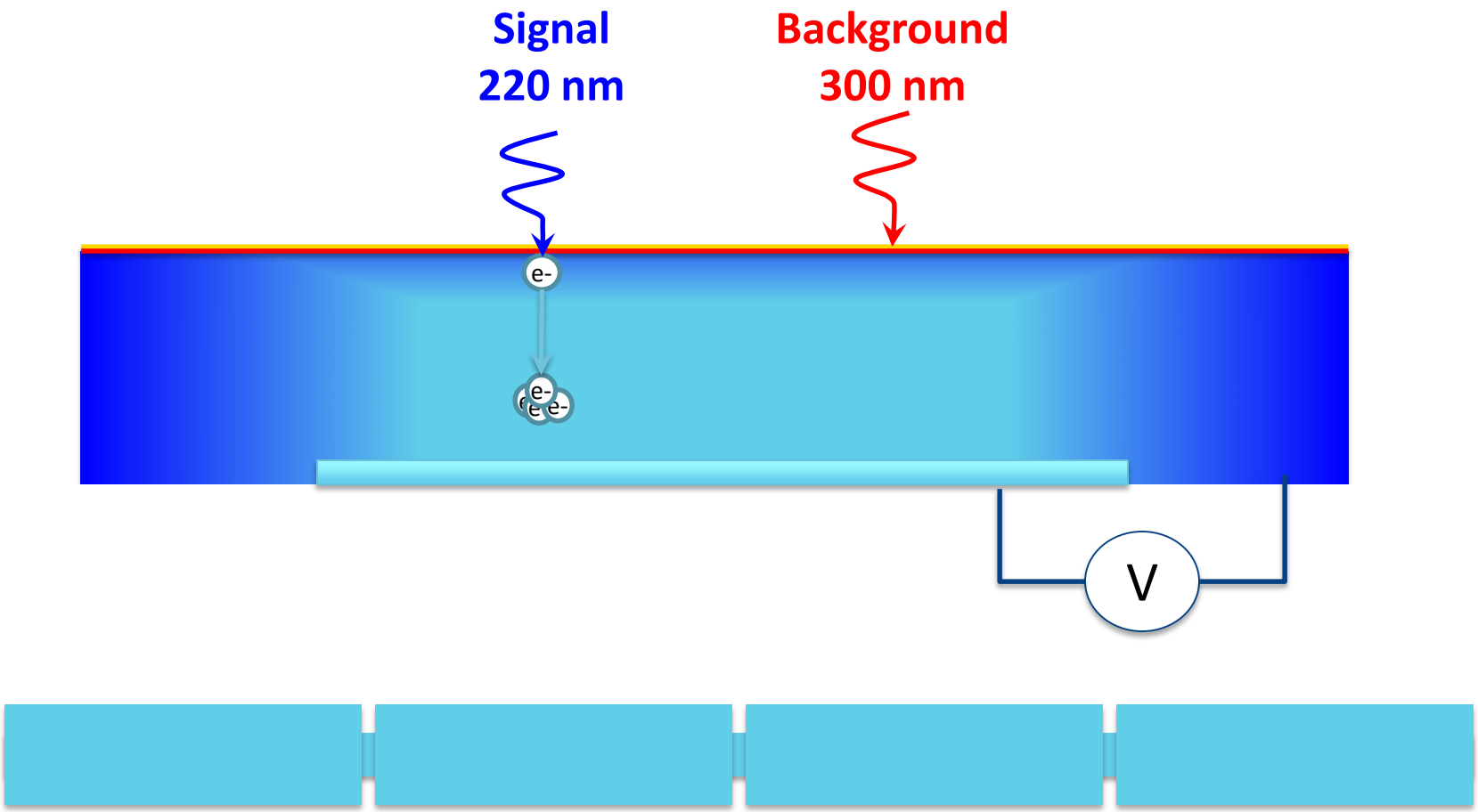

Form grooves for sidewall diffusion

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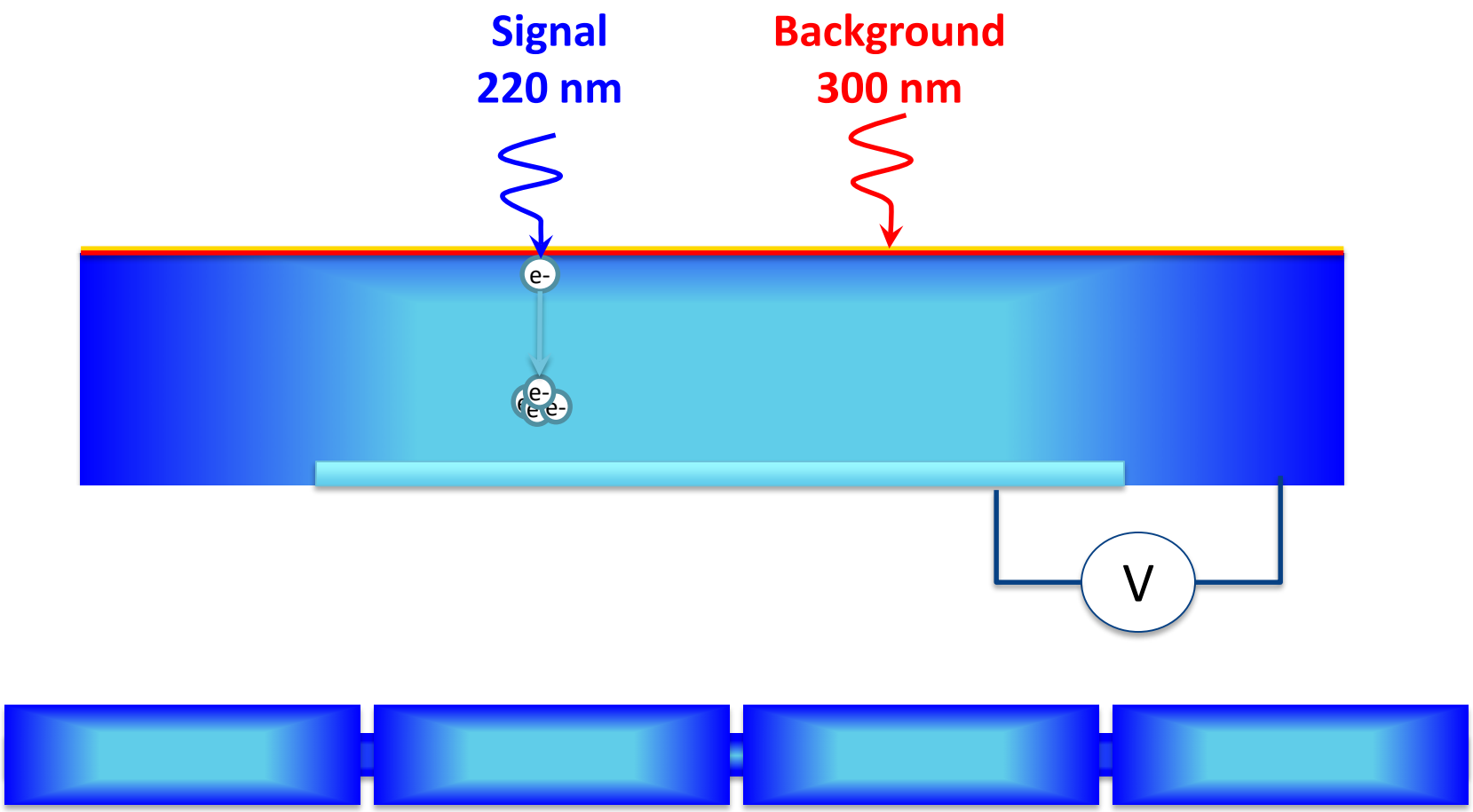

Boron diffusion

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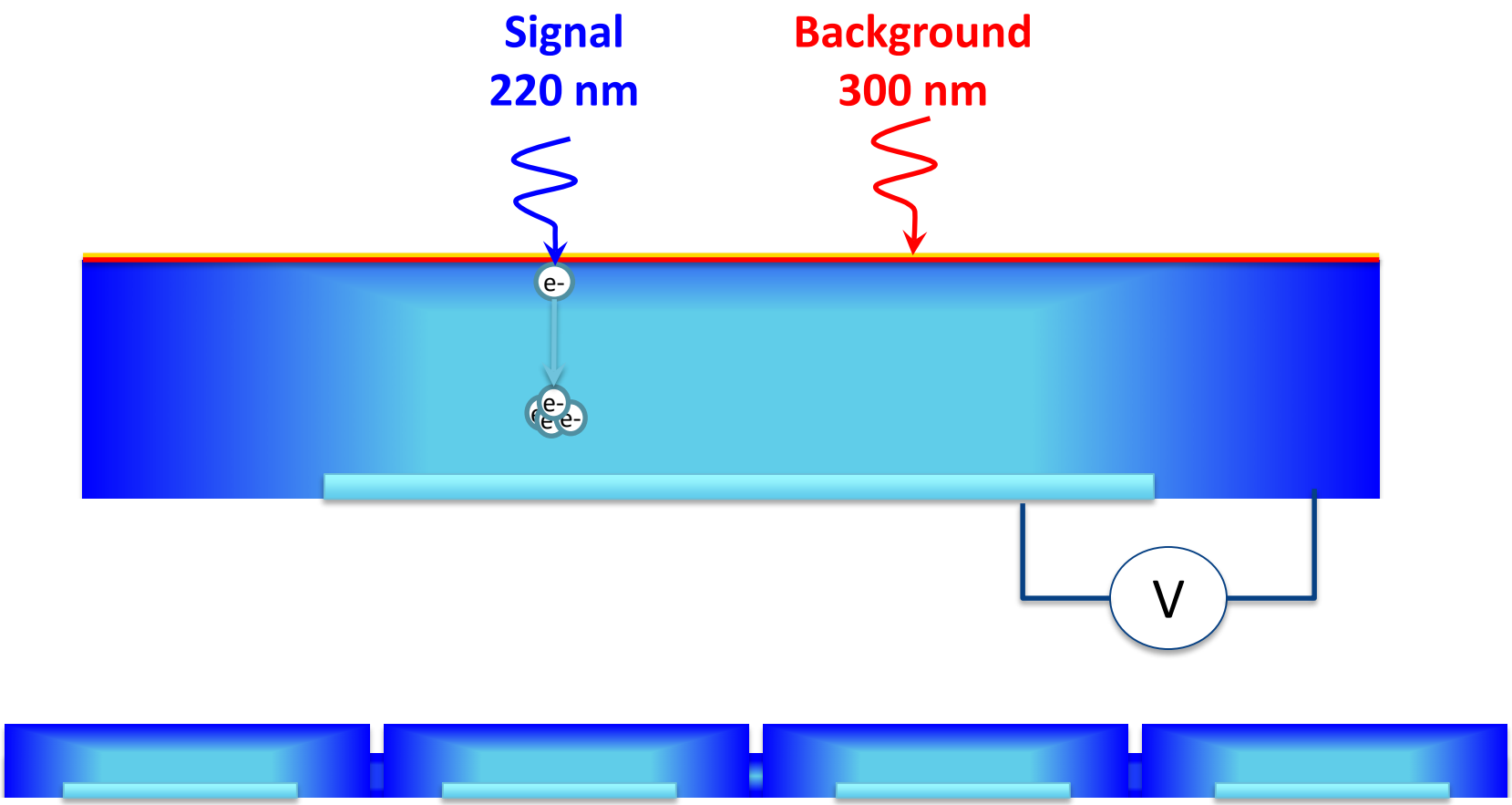
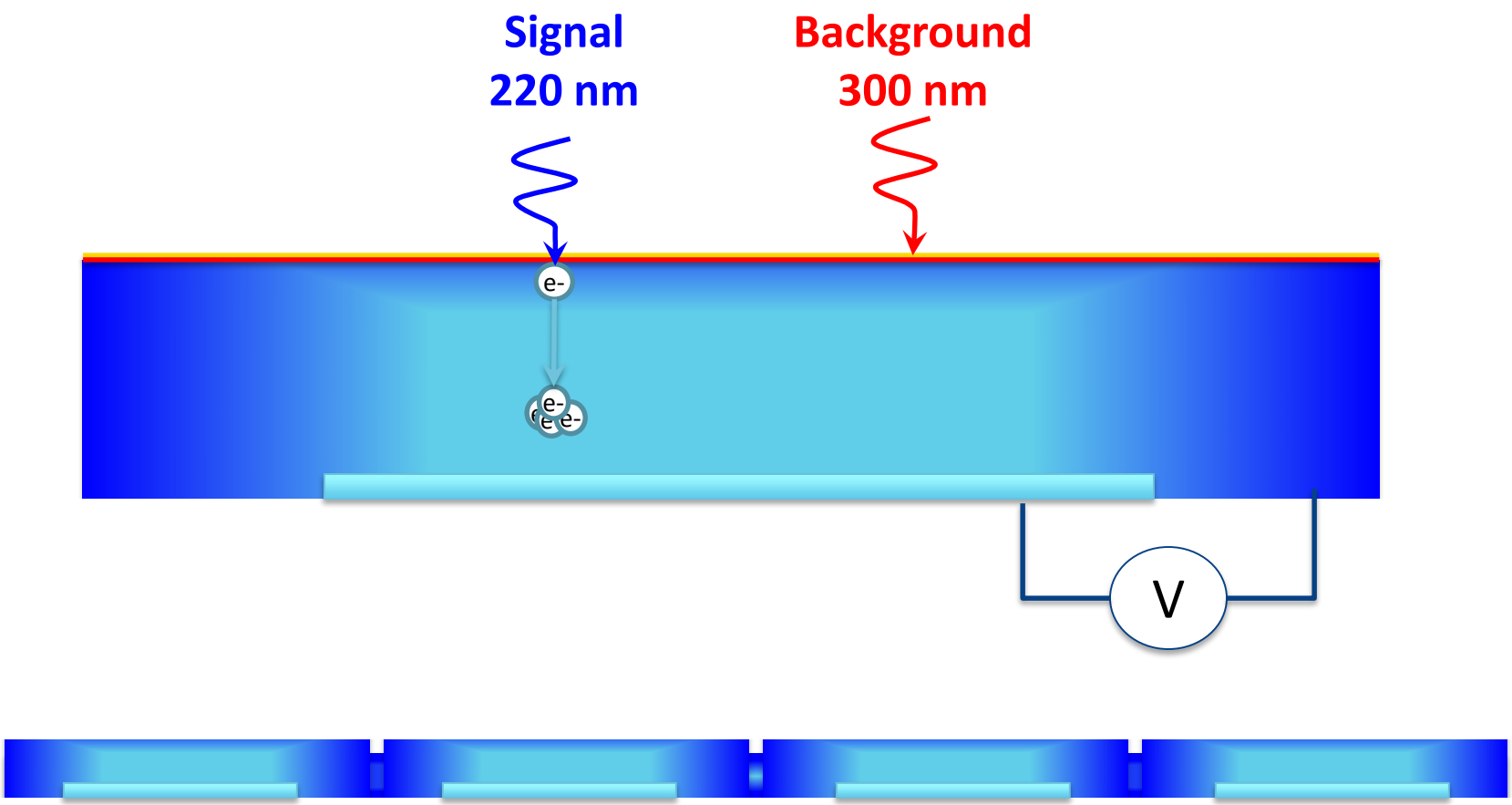


Form N+ contacts

The structure of a superlattice-doped solar-blind avalanche photodiode



Polish p-side

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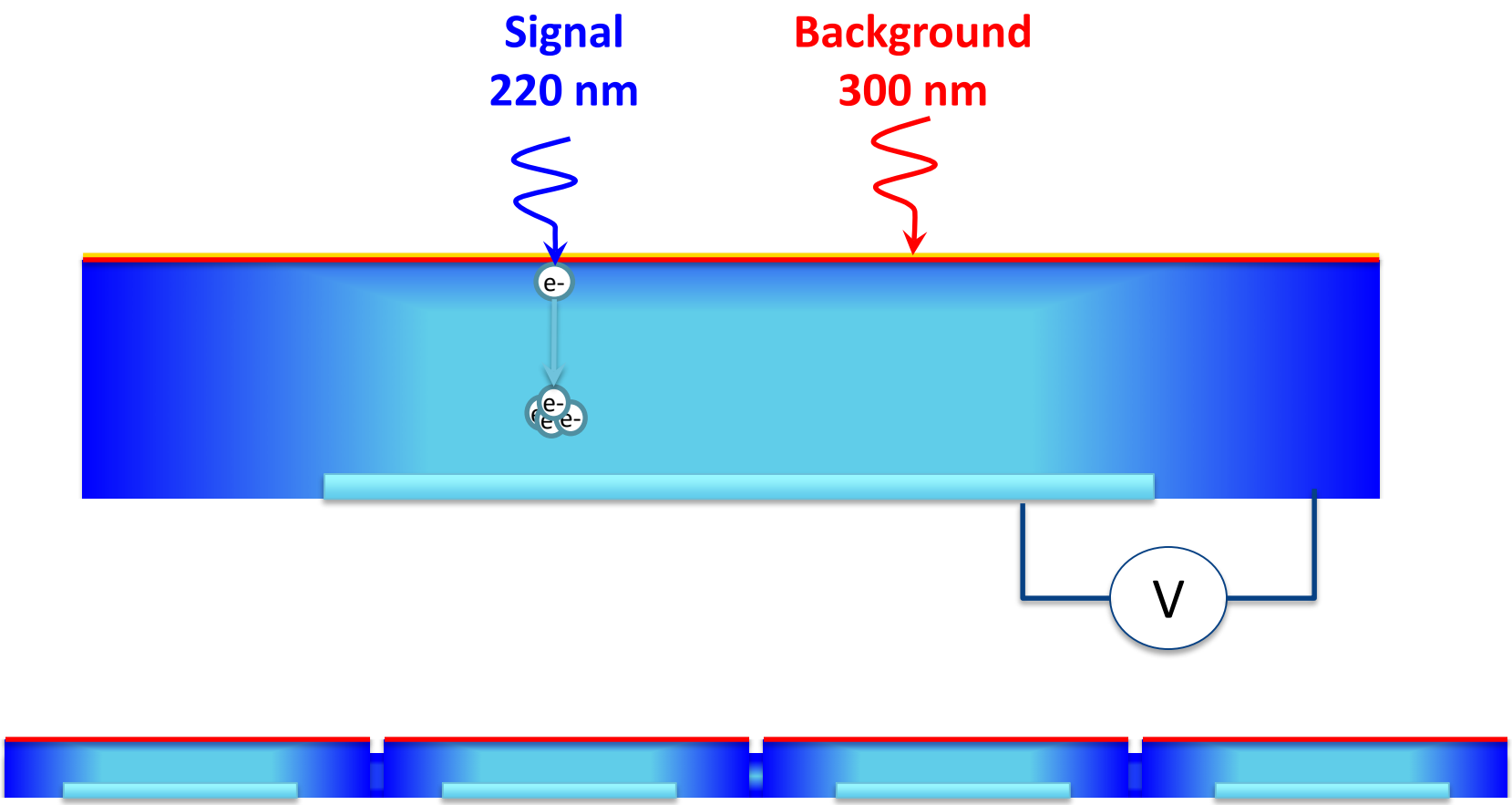

Superlattice doping by MBE

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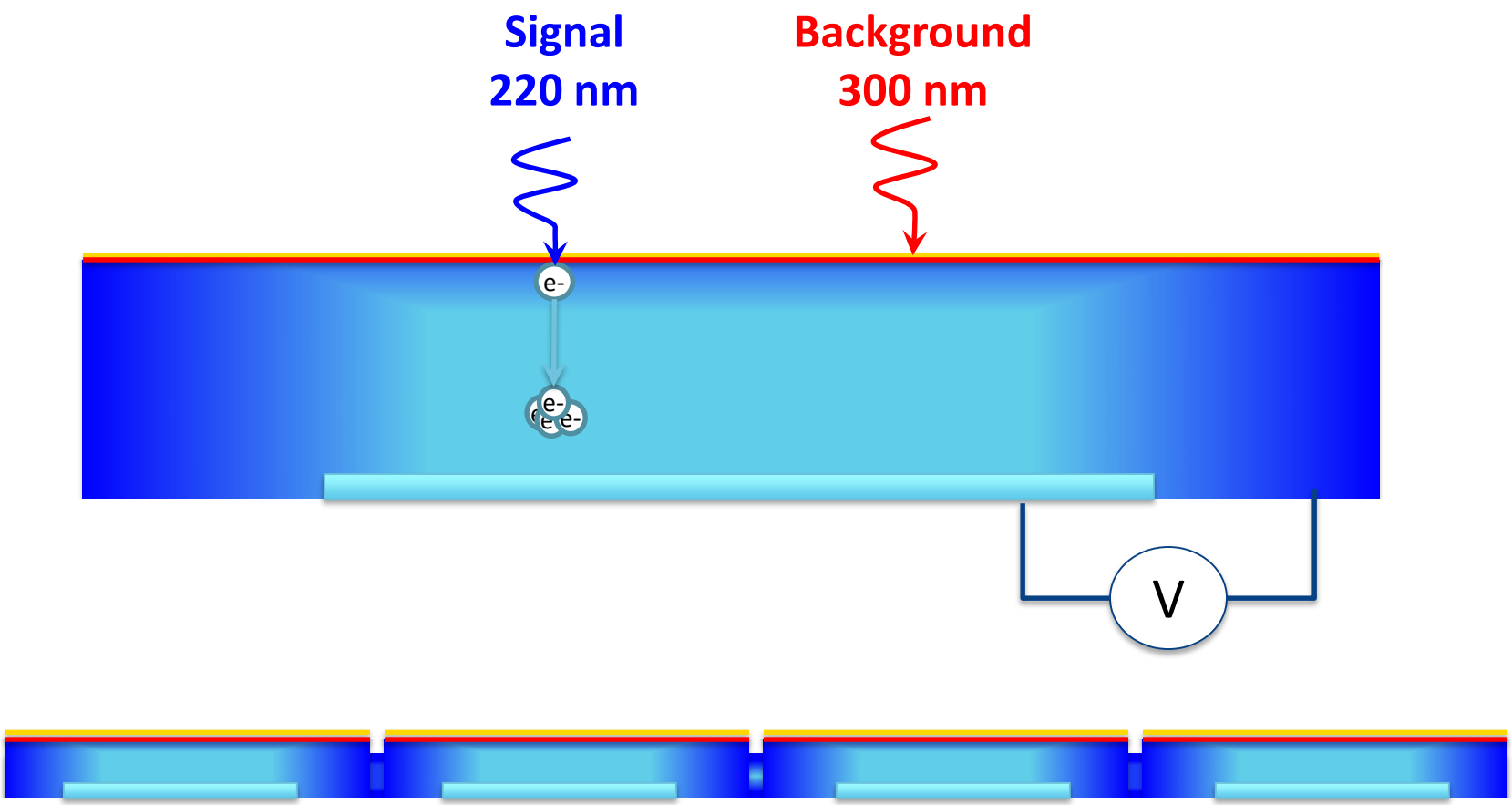


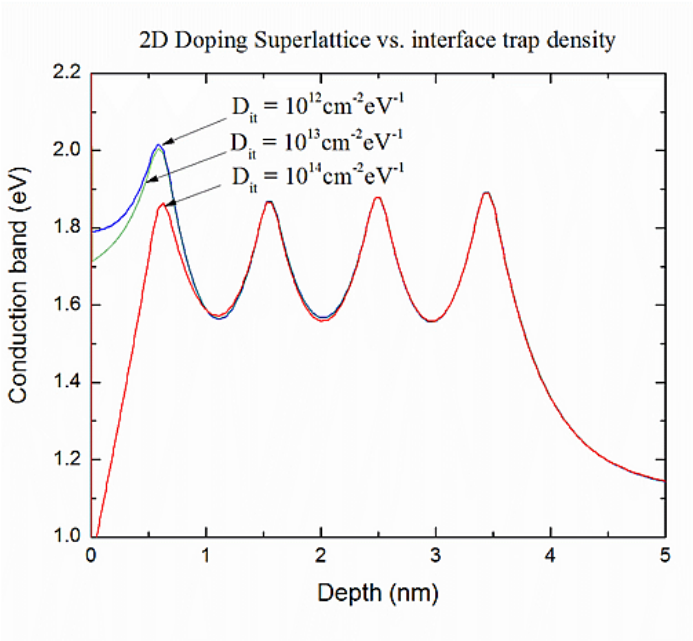
Solar blind coating by ALD

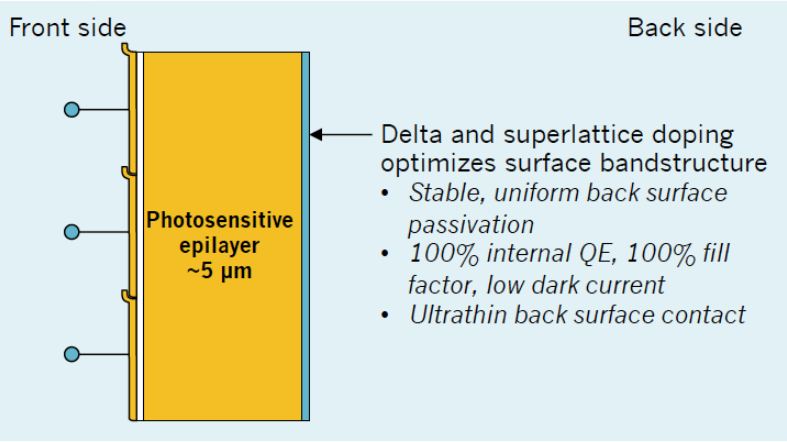
R&D chronology

- We have fabricated and tested a variety of superlattice/ALD filter sensors based on RMD APDs:
  - Chip sizes: 3x3mm^2, 9x9mm^2, 14x14mm^2
  - Superlattice process variations, *e.g.*, depth of residual undepleted region, density of doping
  - Filters: three and five layer ALD filters of various designs
  - Masking of die edge region
  - Details of bias contact region
- We have demonstrated
  - Improvement of time response due to the superlattice and removal of undepleted material
  - Improvement of QE at 220 nm due to the superlattice and antireflection filter
  - Suppression of BaF_2 slow component at 300 nm
- Remaining items
  - Superlattice devices have higher noise than standard APDs
    - Operation at reduced temperature adequately reduces noise
    - Ongoing work is making progress in further reducing the dark current
  - There have been some device failures at full bias
    - This depends in detail on bias contact geometry; it is believed to be understood
    - Long-term reliability tests will be done prior to production for 2016 beam test
  - Radiation hardness with gammas and neutrons to be demonstrated

Superlattice modifications

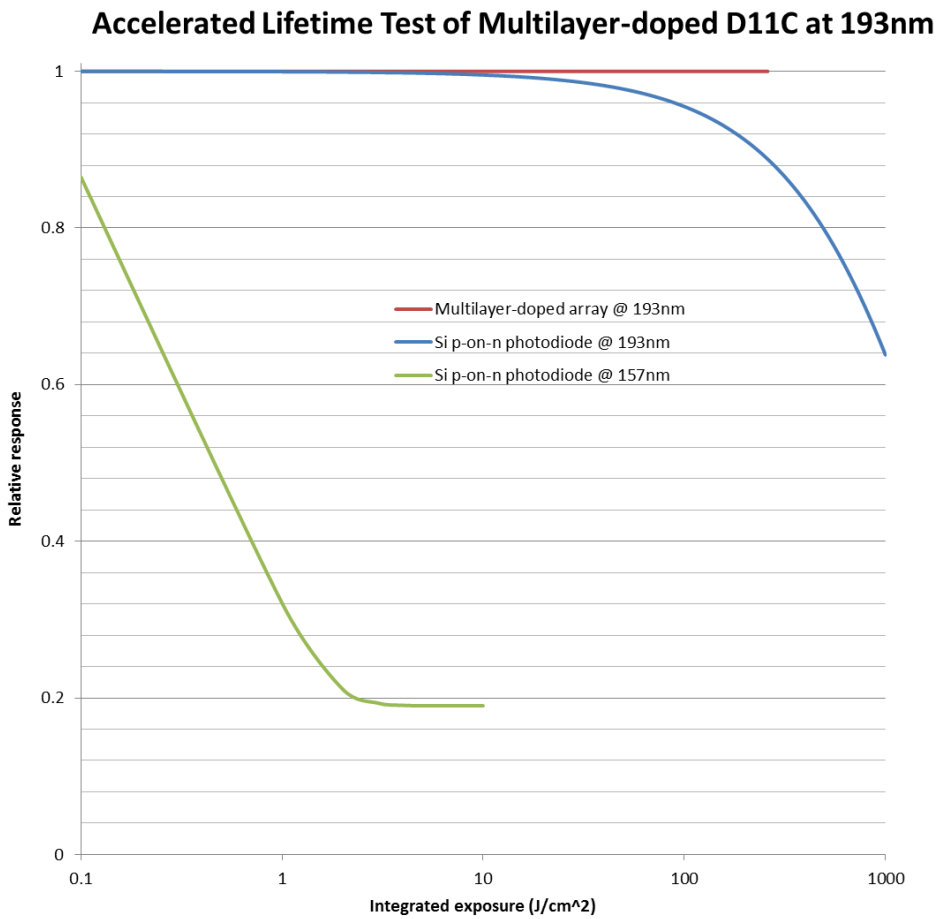
- JPL has developed superlattice structures that provide greatly enhanced quantum efficiency and improved time response
  - Delta-doping and superlattices have been successfully employed for many years to enhance the UV performance of CCDs and APDs used in UV astronomy in satellites and balloons
- Monoatomic 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





UV stability

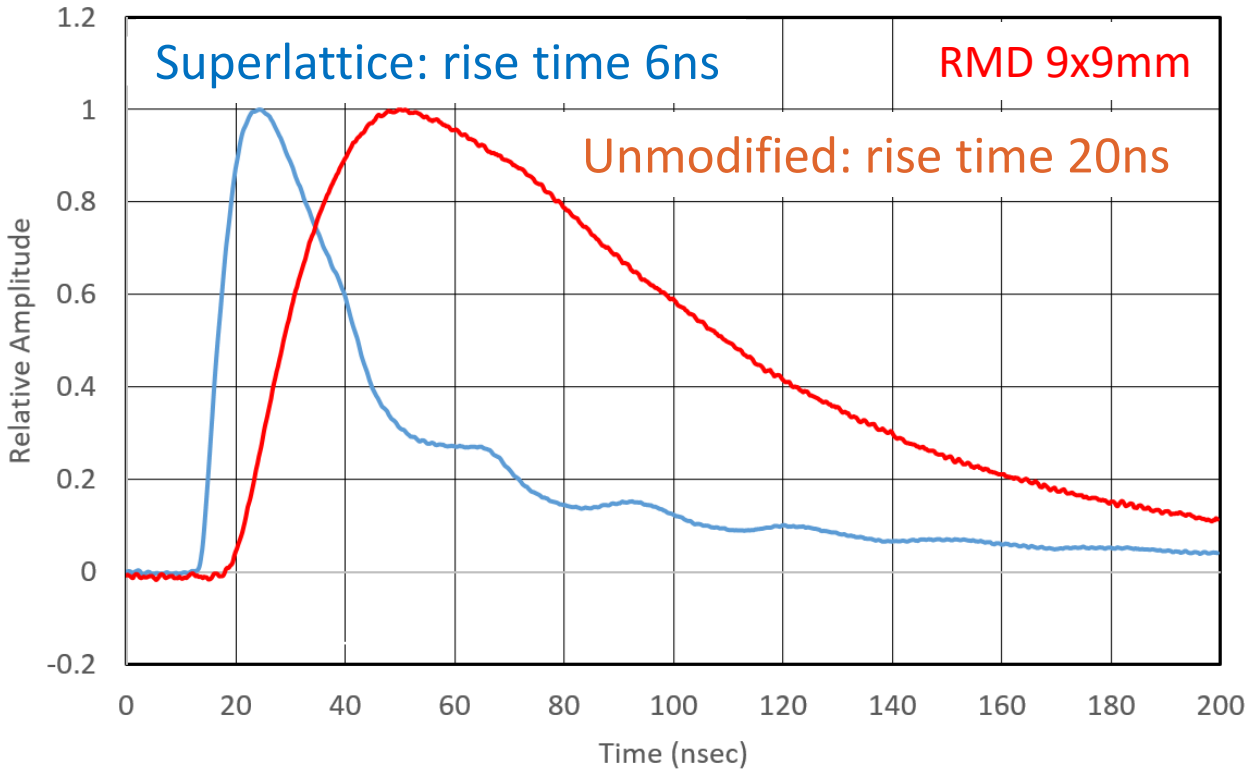
- Superlattice provides stability under intense UV illumination



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

Improved time response

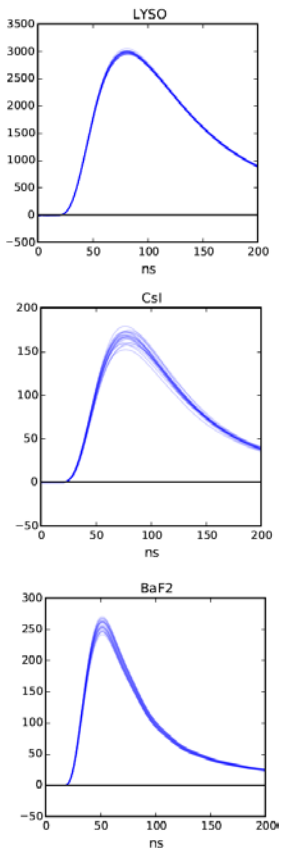
- Elimination of the undepleted region before the avalanche structure substantially improves APD time performance over normal 9mm RMD device
  - Both rise time and decay time are improved

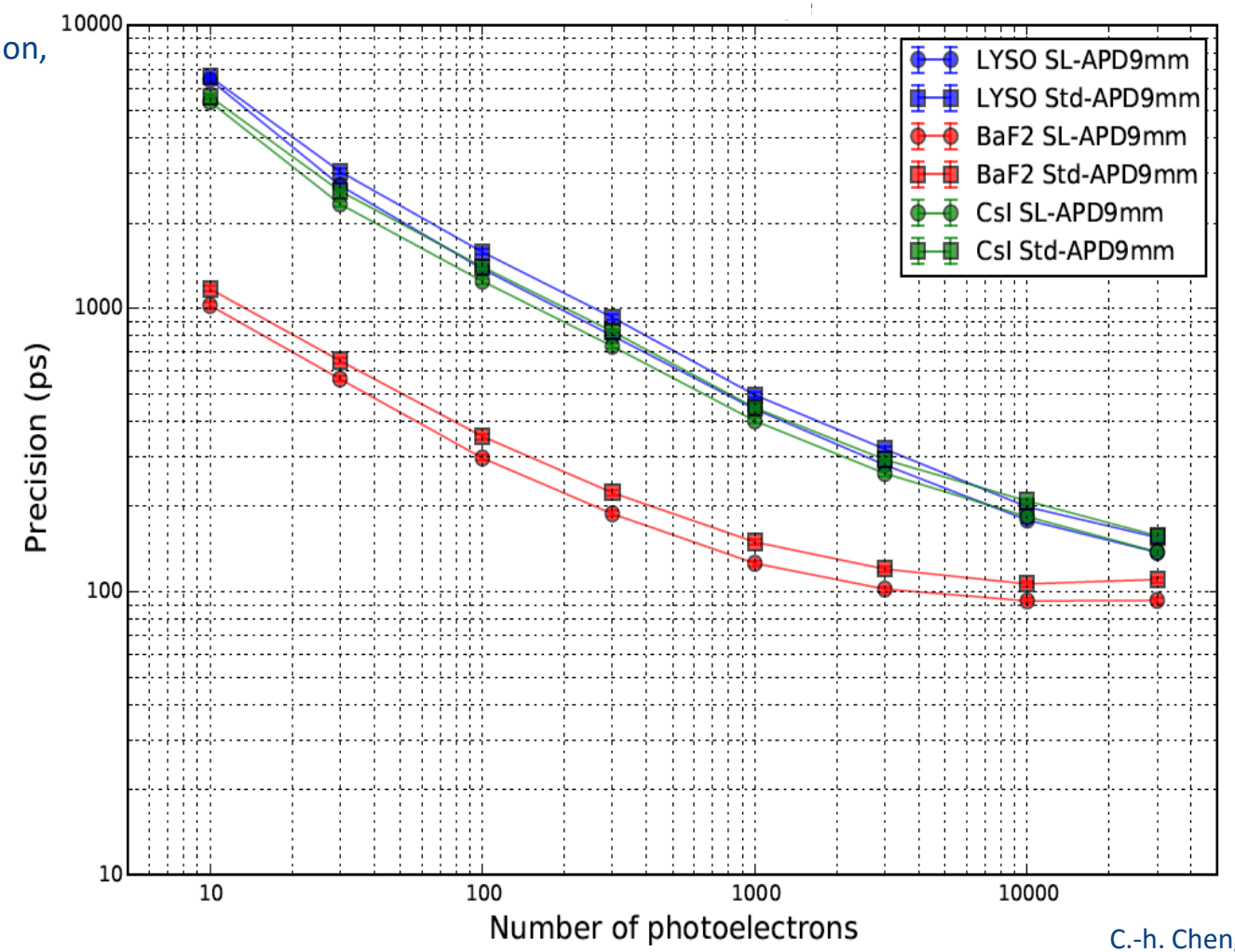


M. McClish

Simulation of the time resolution for 105 MeV/*c* electron showers, as in Mu2e

Twenty events, including shower, scintillation pulse, light propagation, APD and preamp responses

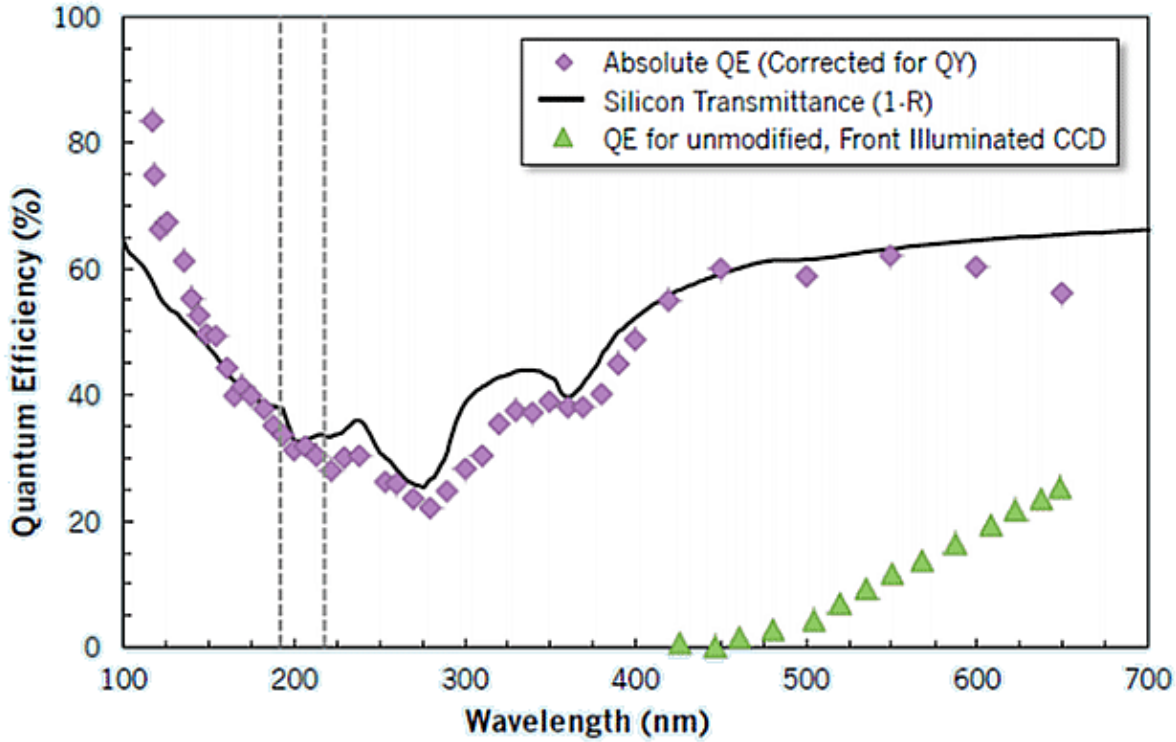




C.-h. Cheng

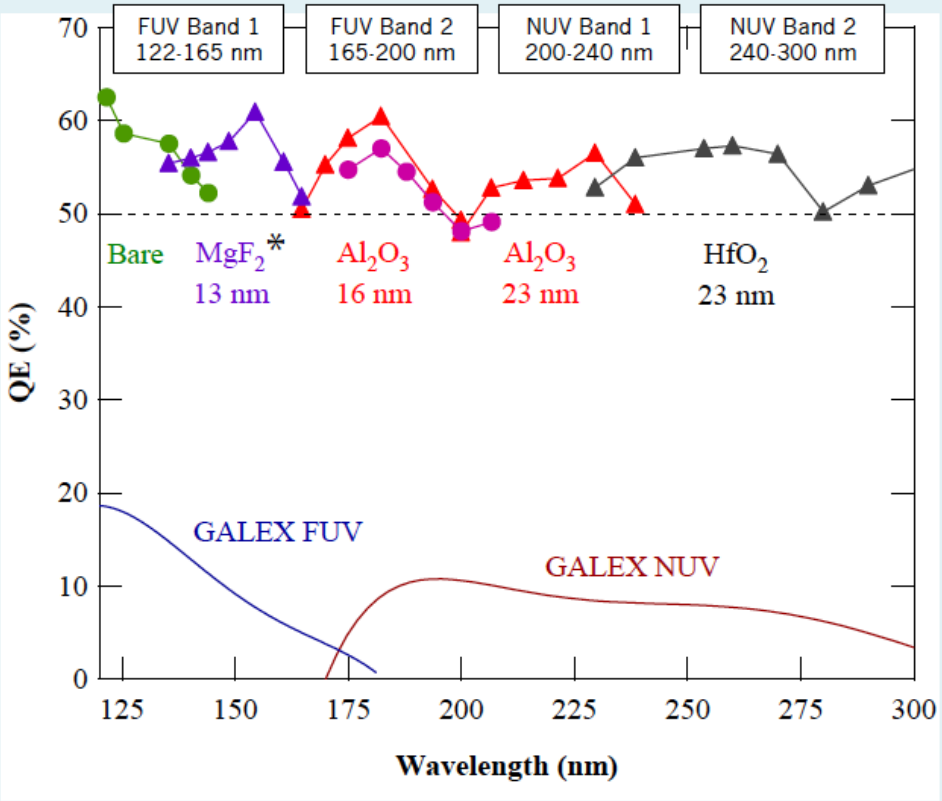
Superlattice modifications

- Recombination of photoelectrons is suppressed by quantum exclusion, resulting in close to 100% internal QE
  - Quantum efficiency in the 200-300 nm region approaches Si transmittance (1-R) limit



ALD antireflection filters improve QE

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

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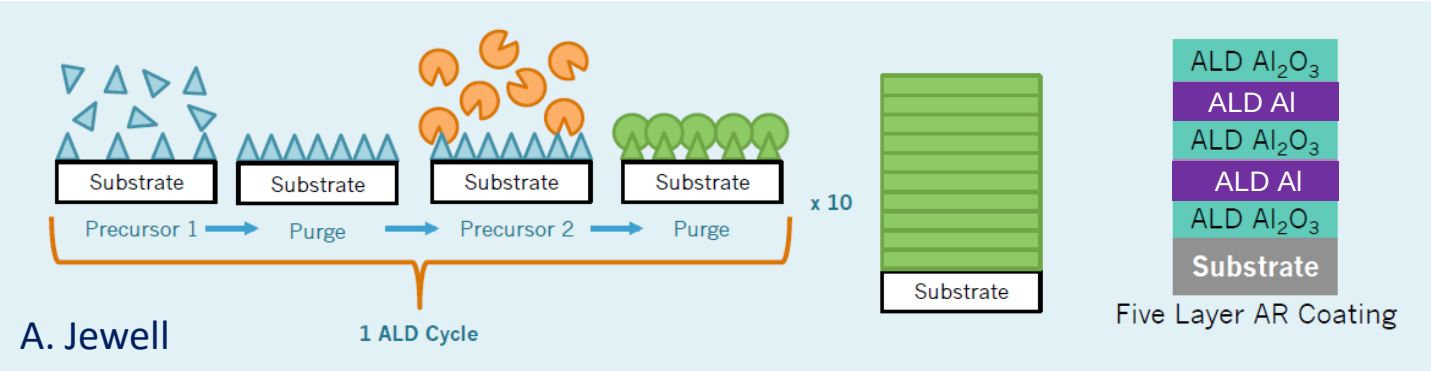
Nikzad, *et al.*, *Applied Optics*, **51**, (2012) 365.

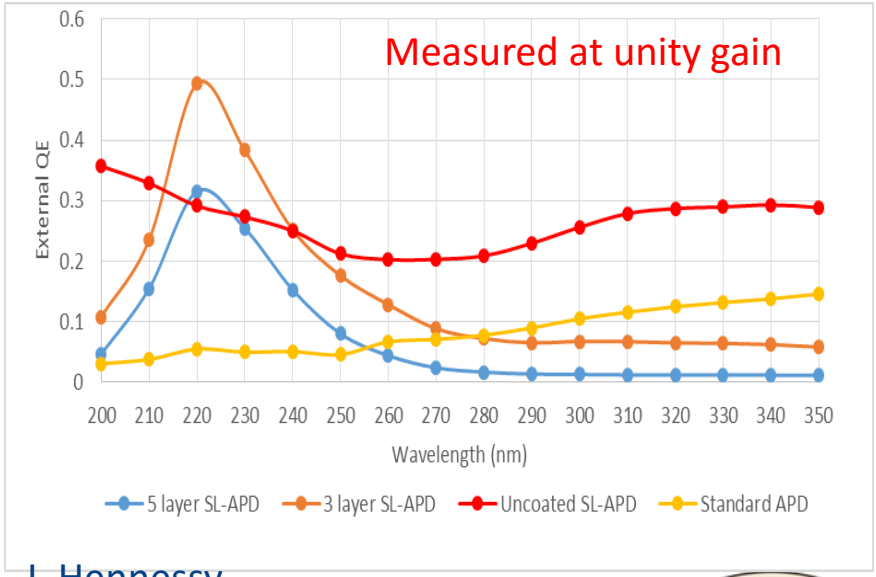
ALD antireflection filter

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



A. Jewell

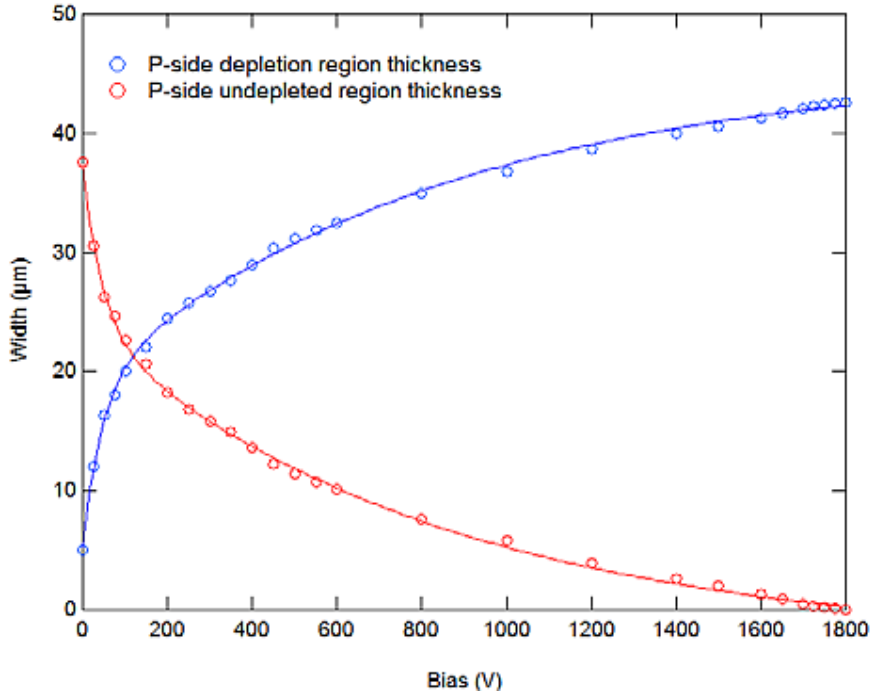
- The ALD filter has been designed to be efficient at 220 nm and provide strong extinction at 300nm
- ALD filter characteristics can be adjusted to trade QE at 220nm for 300nm extinction

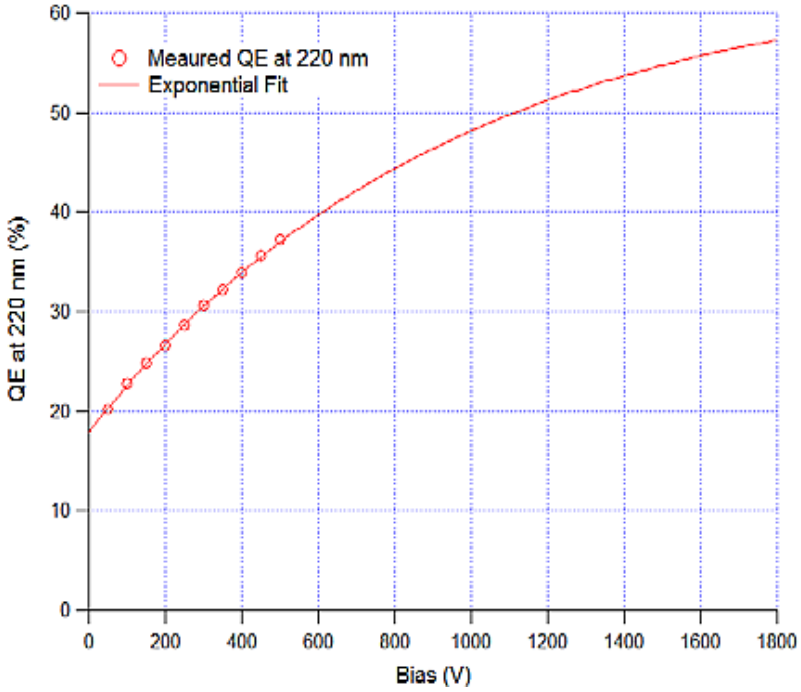


J. Hennessy

Effective QE increases with gain

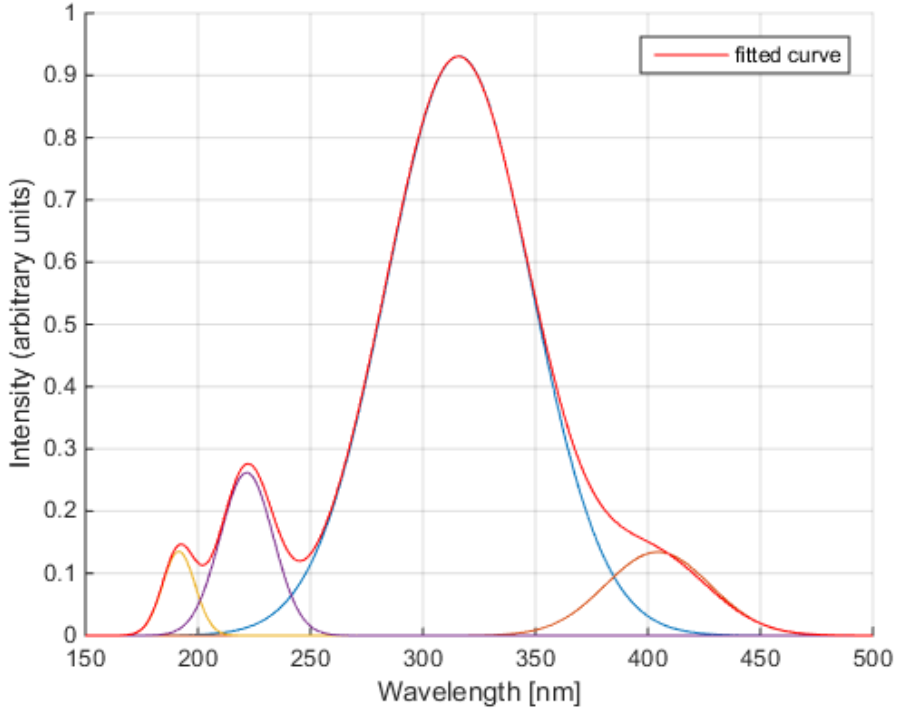
- Full quantum efficiency is reached as bias is increased, as full depletion is reached at high bias voltage





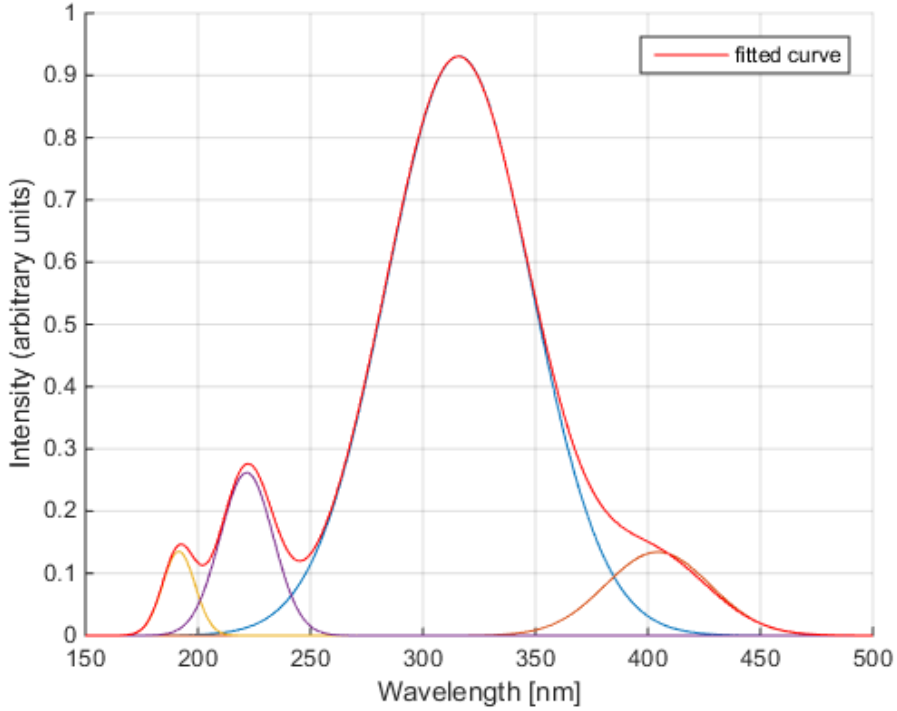
Optimizing the filter

- There are actually two fast scintillation components: 195 and 220 nm, and two slow components: 320 and 400 nm



Optimizing the filter

- The “Standard” five layer filter is centered centered on the 220 nm peak



Filter characteristics vary with angle of incidence

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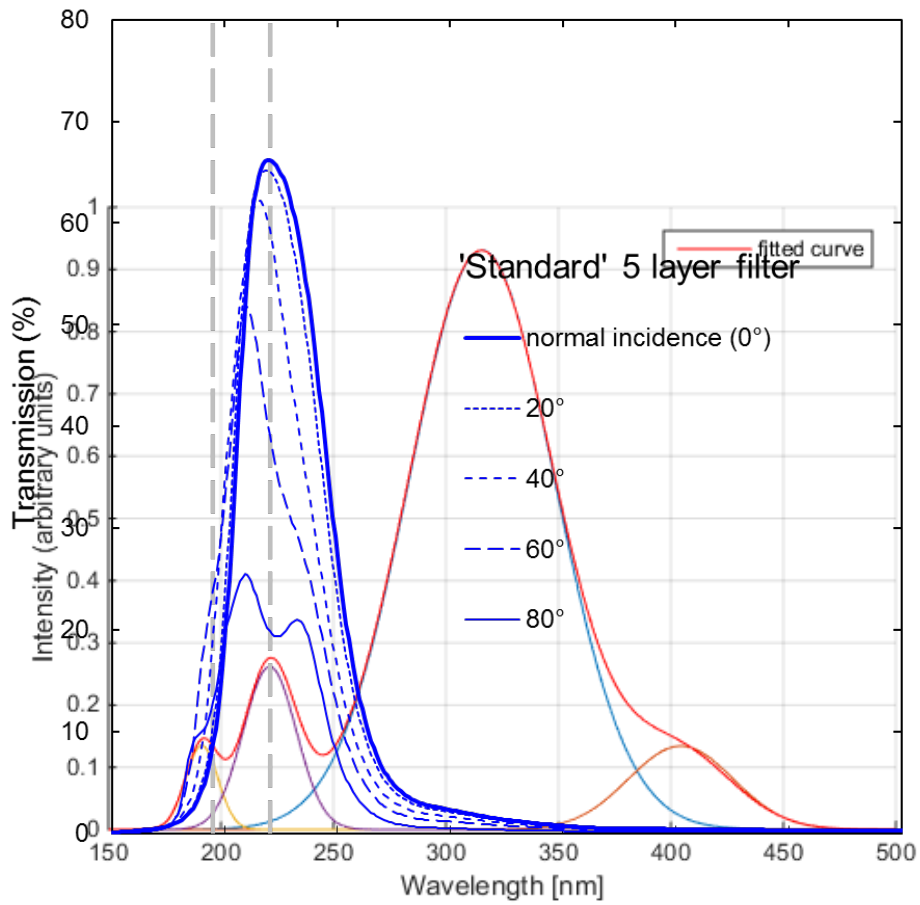

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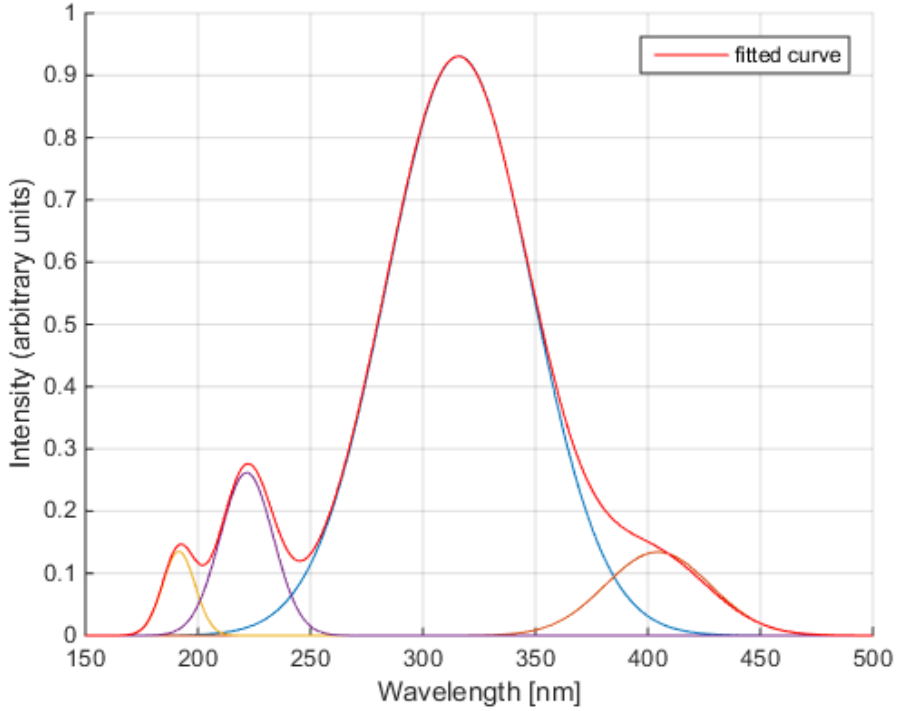
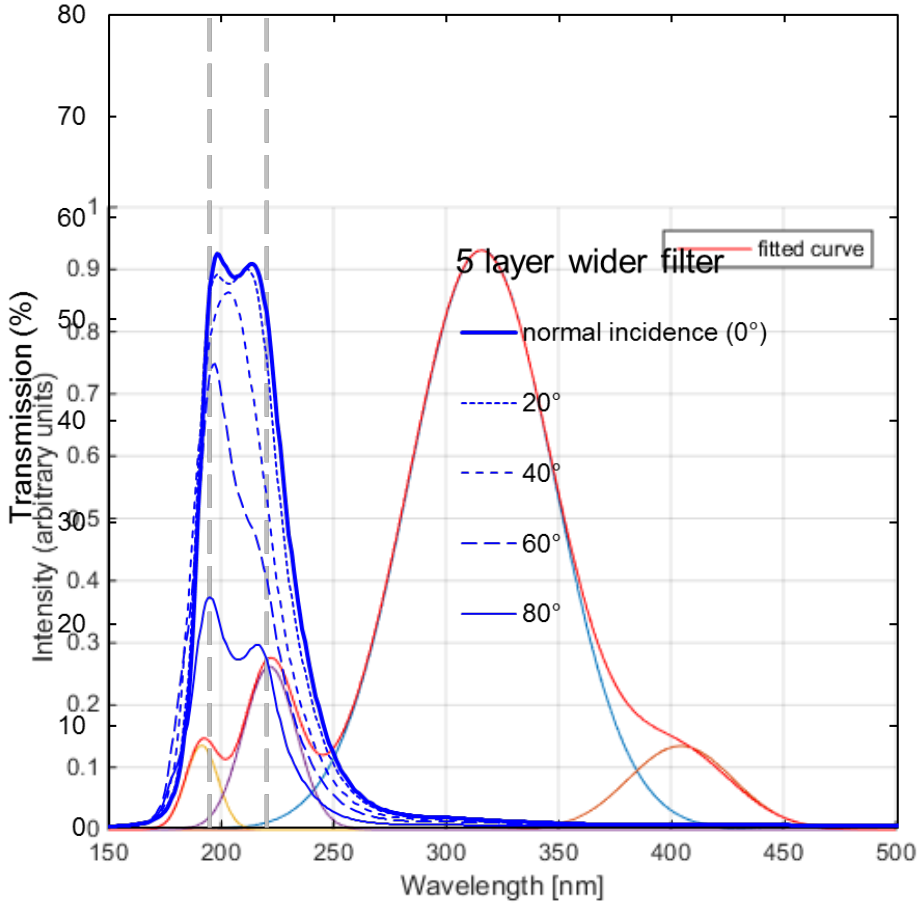


Filter characteristics vary with angle of incidence

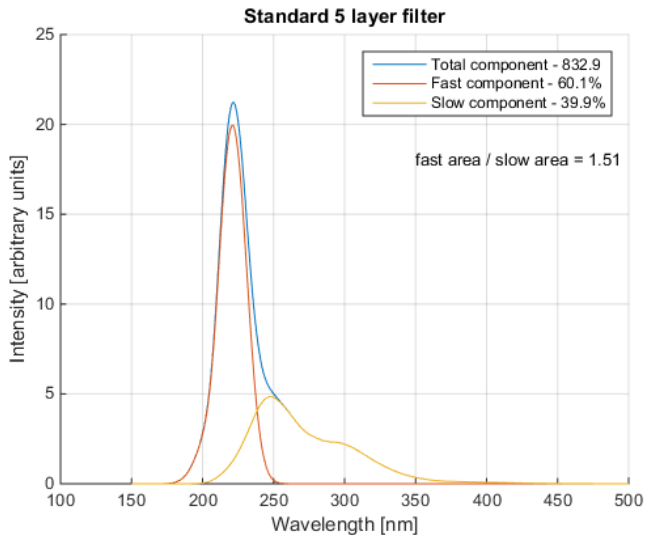
Optimizing the filter

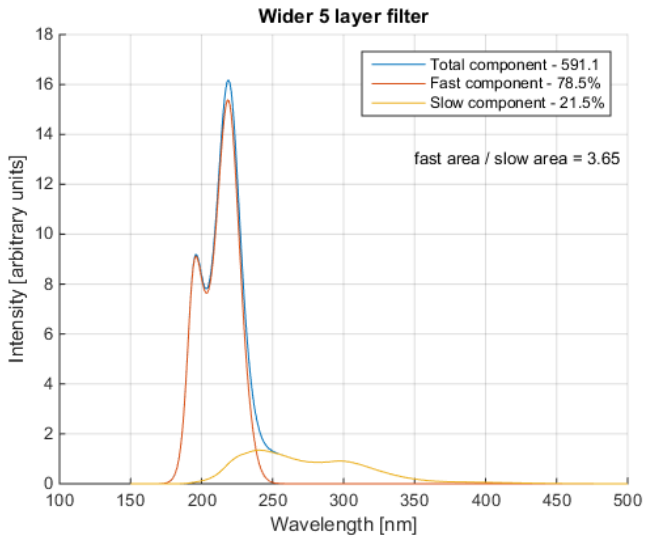
- The new "wider" five layer filter encompasses more of the 195 nm peak and provides improved slow component suppression

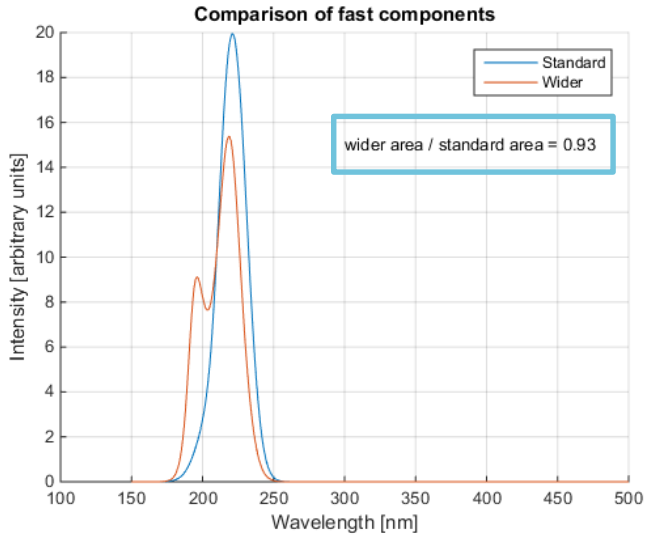


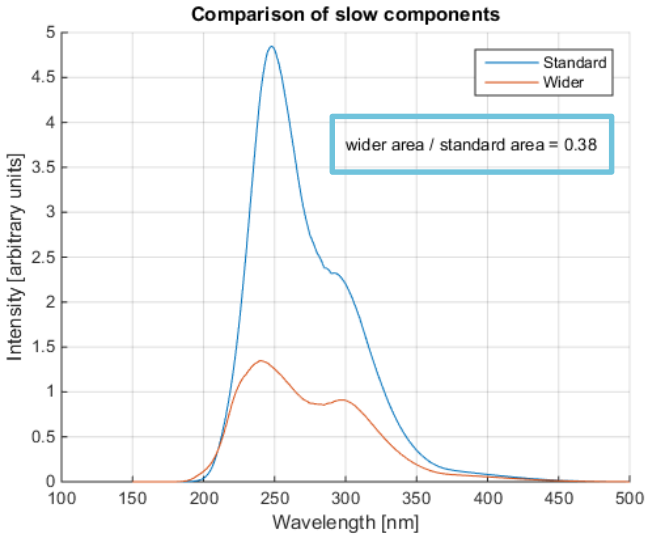
Filter characteristics vary with angle of incidence

Fast/slow component comparison



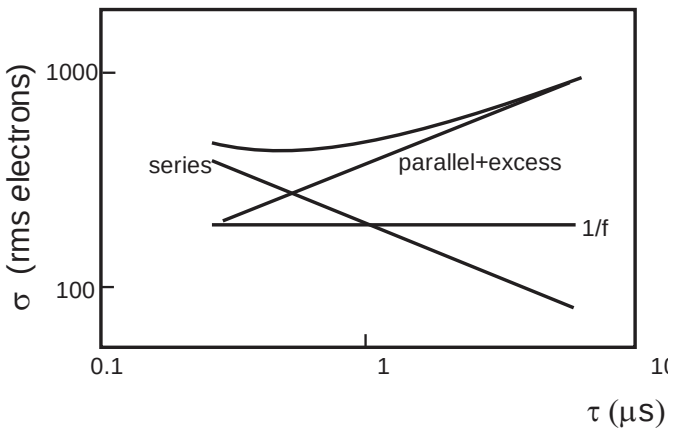






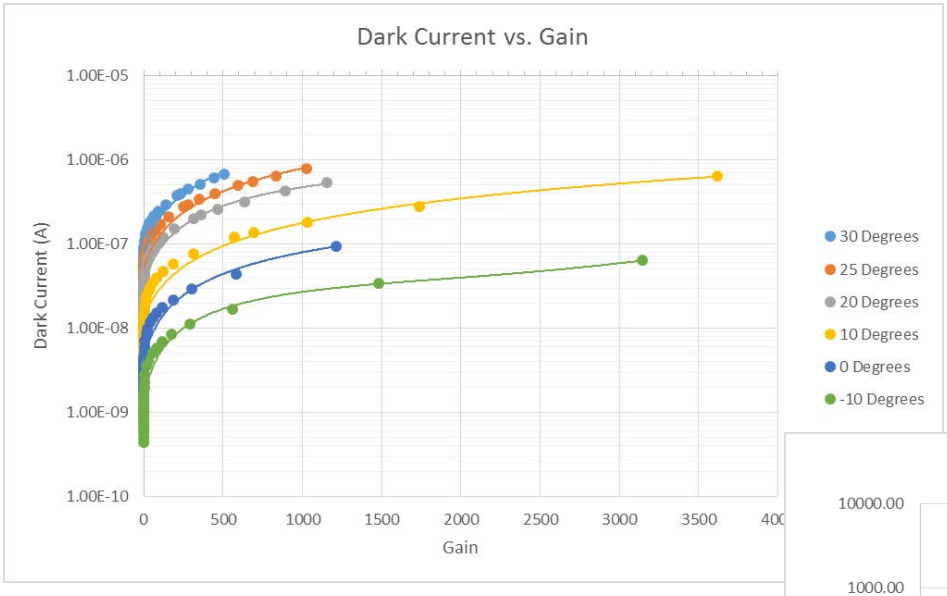
Dark current, noise, temperature and all that

- Noise in APDs is dominated by parallel noise
- For a high rate experiment such as Mu2e, we want a short gate time
- Our current superlattice APDs have higher dark current and thus higher electronic noise than the standard RMD versions
- $$electronic\,noise \propto \sqrt{I_{\mathrm{dark}} \times \tau_{\mathrm{int}}}$$
- We have been making measurements with a charge sensitive preamp and a waveform sampler with an effective integration time ~10μs
- Measured noise at a given I_{dark} thus has to be scaled to shorter gates
- Noise measurements are now being repeated with the FEE and a narrow gate
- Time resolution measurements with DRS4 will follow

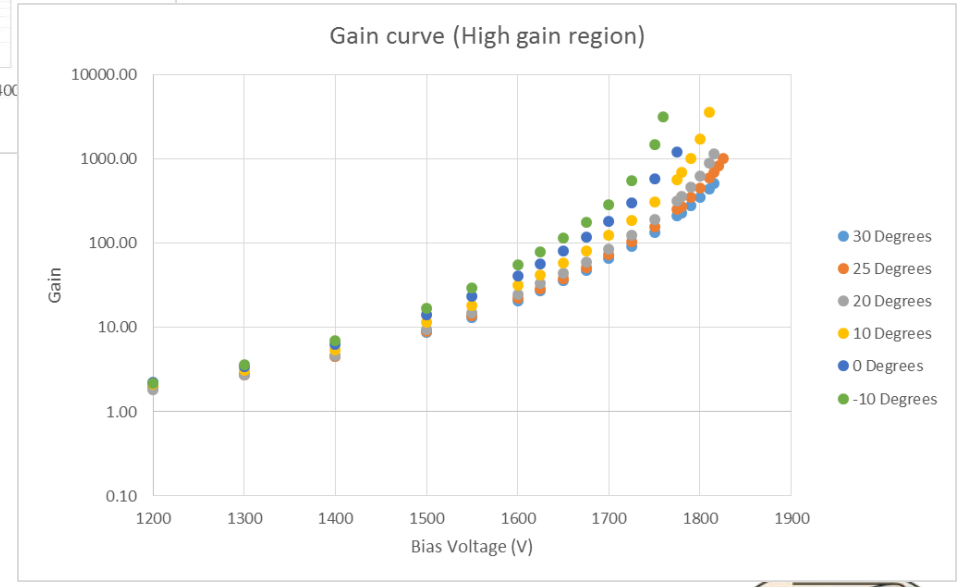


Dark current vs. temperature

- Gain at a given bias and resulting dark current are a function of temperature



Standard RMD 9x9mm APD



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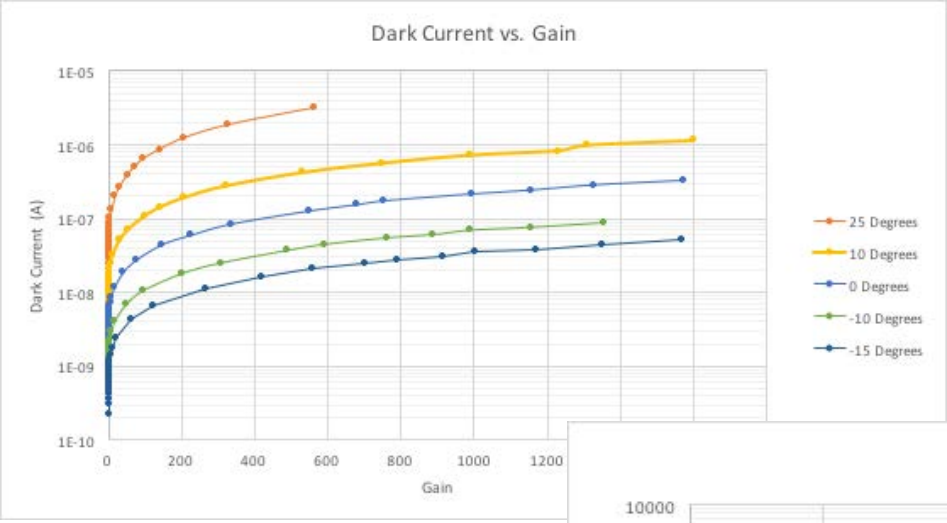
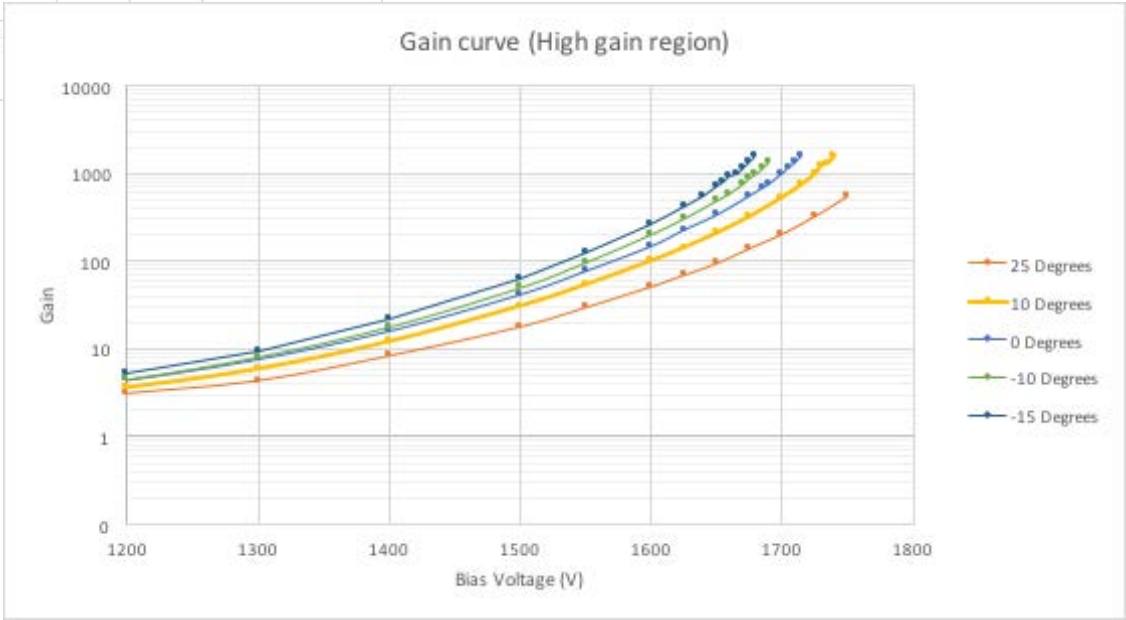




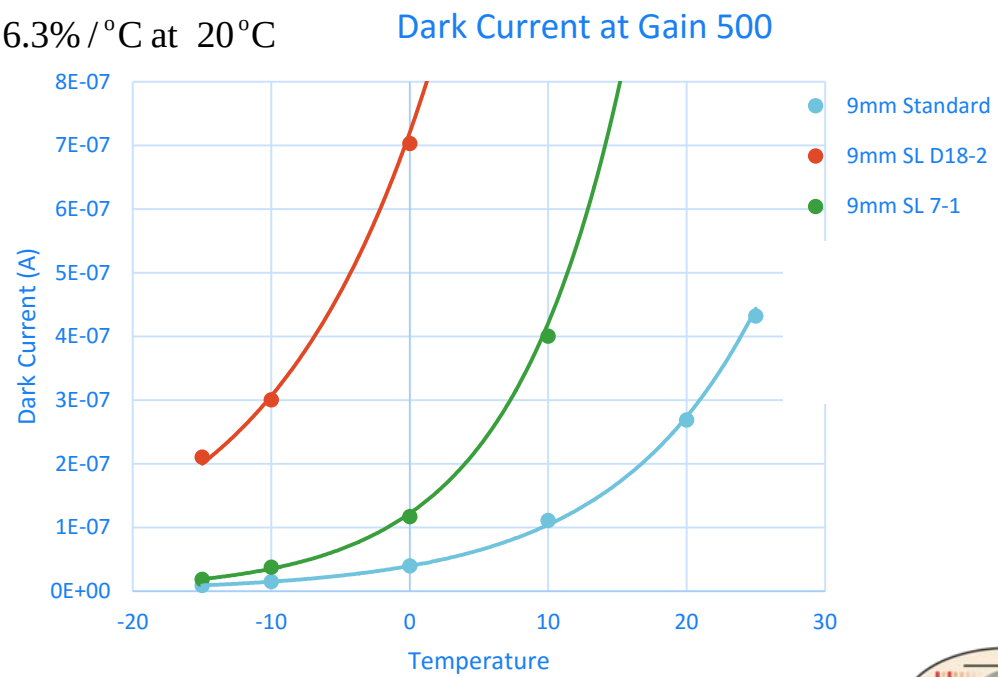
Superlattice/5 layer ALD
9x9mm APD (SL 7-1)

Comparison of dark current vs. temperature

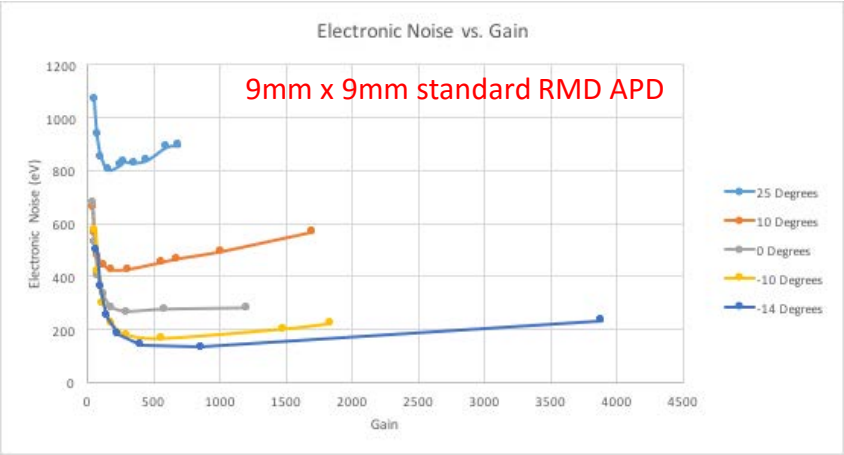
- The SL/Filter APD (D18-2) at -10°C has the same dark current as the standard APD at room temperature
- The latest SL/filter APD (SL 7-1) shows substantial improvement in dark current
- The calorimeter photosensors (APD or SiPM) and FEE/digitizers require active temperature management, *i.e.,* the capability to maintain a known temperature to a given precision

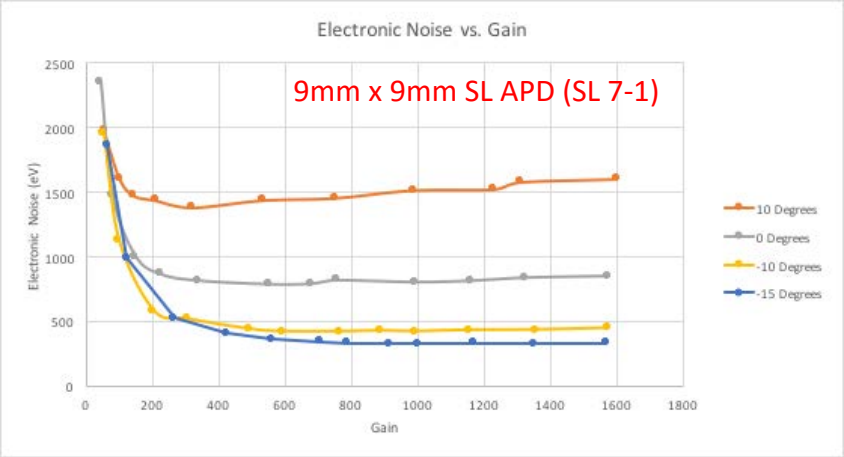
RMD APD $\Delta G/\Delta T \approx -6\%/^{\circ}C$ at -10°C

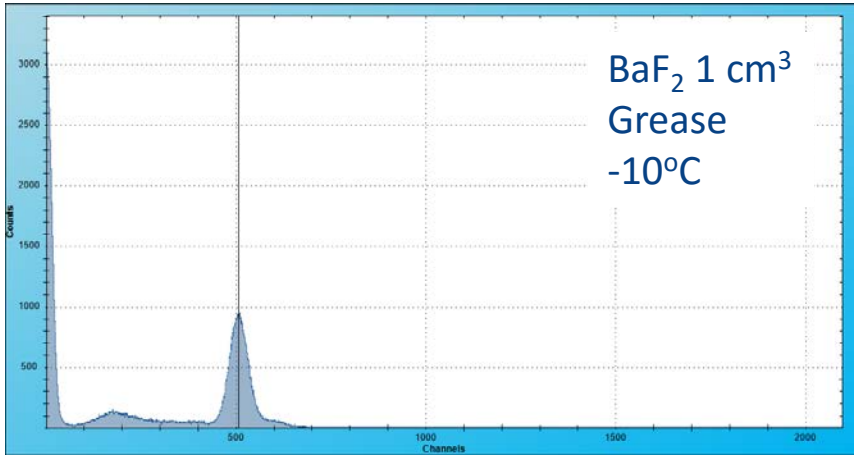
Hamamatsu MPPC $\Delta G/\Delta T \approx 6.3\%/^{\circ}C$ at 20°C

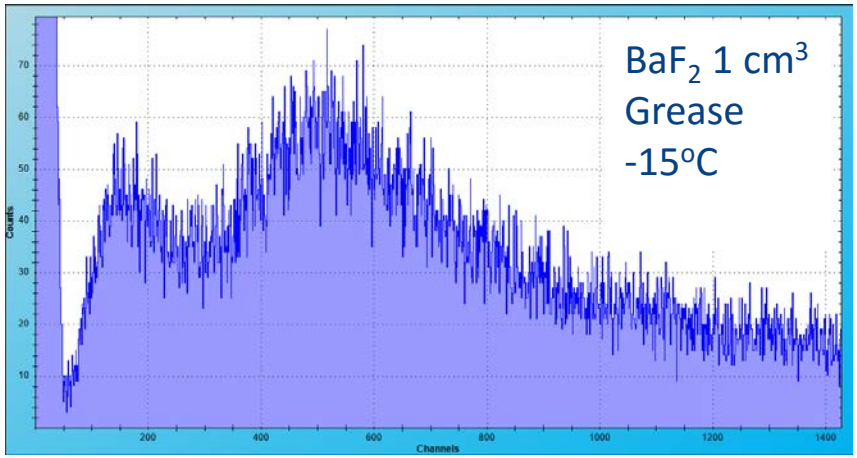


Photosensor gain, noise, ^{137}Cs spectra









- Efforts to further reduce the noise are ongoing
- Operation at of SL/ALD APDs at reduced temperature provides adequate noise performance

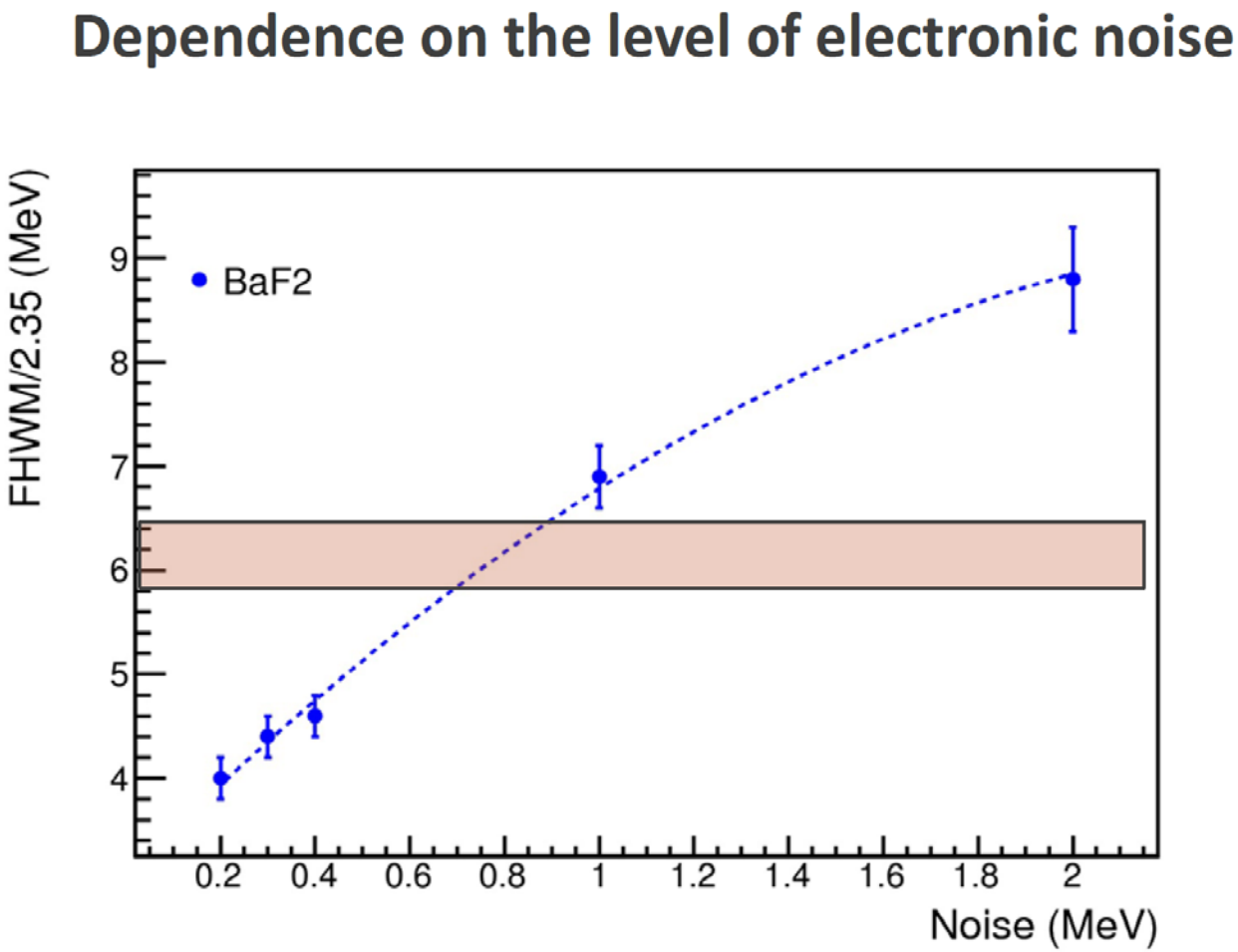
Electronic noise at reduced temperature

APD #	Temp	Bias Voltage	Gain	Dark Current	Noise (calculated) ev(Si)	Noise (measured) eV(Si)	Noise (calculated) ev(Si)	Noise (calculated) p.e.
					10 μs gate		60ns gate	
465-5-3	25	1800	449	3.99E-07	848	769	66	18.3
465-5-3	10	1775	559	1.21E-07	419	443	32	9.0
465-5-3	0	1750	578	4.41E-08	249	264	19	5.3
465-5-3	-10	1725	559	1.66E-08	155	158	12	3.3
465-5-3	-15	1700	401	7.90E-09	126	140	10	2.7
465-5-4	25	1815	526	4.87E-07	866	846	67	18.6
465-5-4	10	1780	525	1.28E-07	444	501	34	9.6
465-5-4	0	1750	436	4.77E-08	298	263	23	6.4
465-5-4	-10	1725	425	2.05E-08	198	199	15	4.3
465-5-4	-15	1725	572	1.52E-08	147	139	11	3.2
D18-2	0	1700	606	8.17E-07	1045	828	81	22.5
D18-2	-10	1660	455	2.87E-07	715	548	55	15.4
D18-2	-15	1650	468	2.04E-07	594	370	46	12.8
SL 7-1	10	1700	531	4.22E-07	802	1440	62	17.3
SL 7-1	0	1675	550	1.27E-07	432	791	33	9.3
SL 7-1	-10	1650	490	3.72E-08	248	440	19	5.3
SL 7-1	-15	1640	558	2.10E-08	175	361	14	3.8

Scale : BaF_2 23 p.e./MeV/APD(9x9) @ 60 ns τ_{int} (glue coupling, no dose)

We will presently make direct measurements with a 60 ns gate

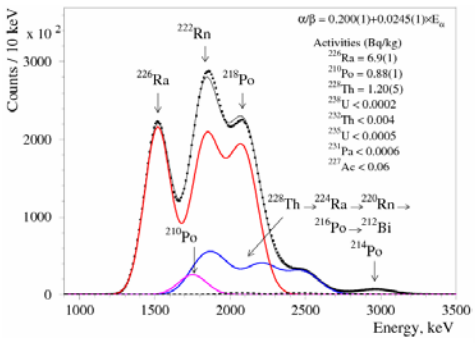
Required noise performance

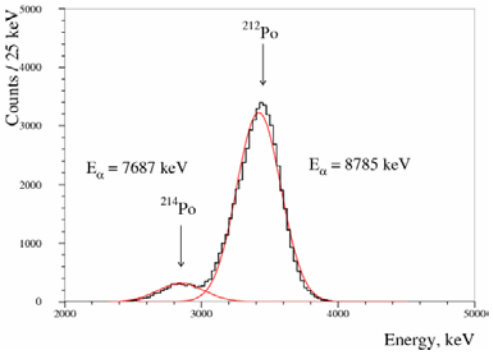


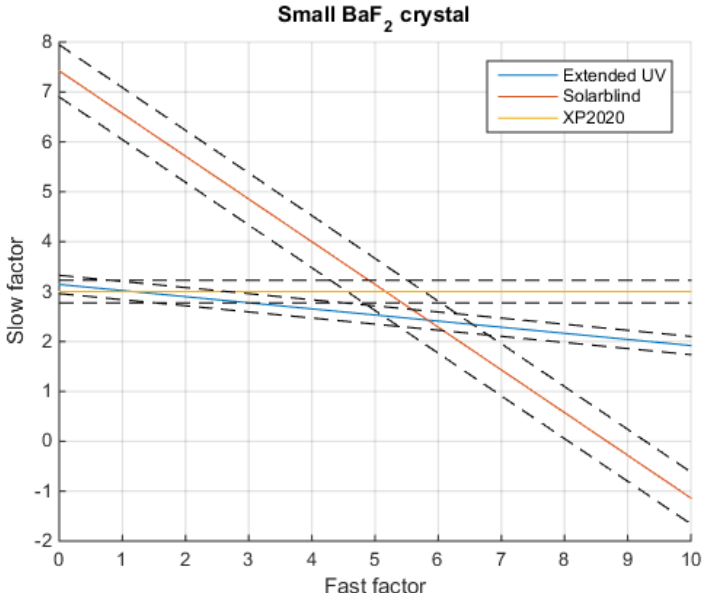
- 1X background, LRU 5%, 23 pe/MeV, glue coupling

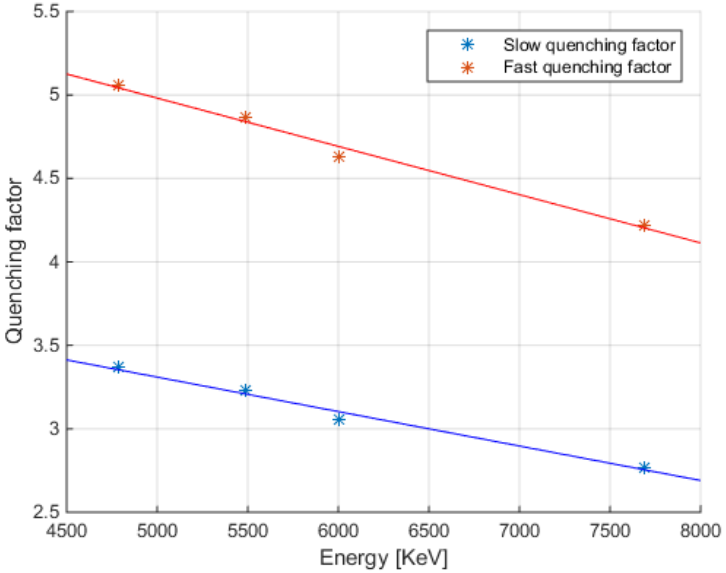
Birk's law: application to BaF_2

- Some of the barium fluoride crystal samples have traces of radioactivity, producing α lines
- The Birk's law constant for BaF_2 is quoted in the literature as 3.7
- We have found, however, that the Birk's law constant is different for the fast and slow scintillation components
- This has implications in Mu2e for the scale of the neutron-induced background







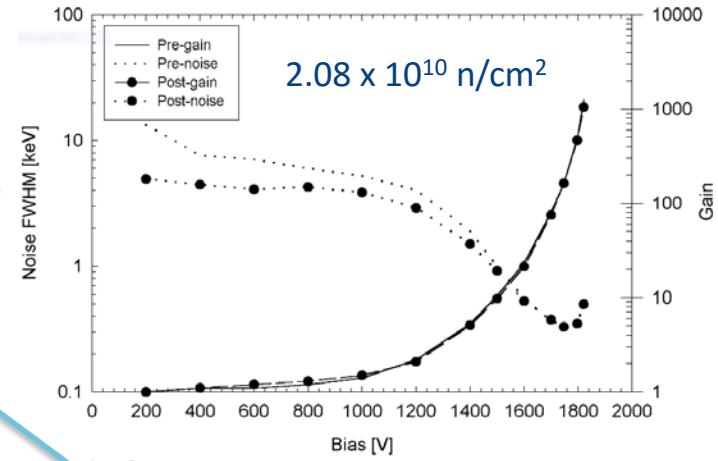


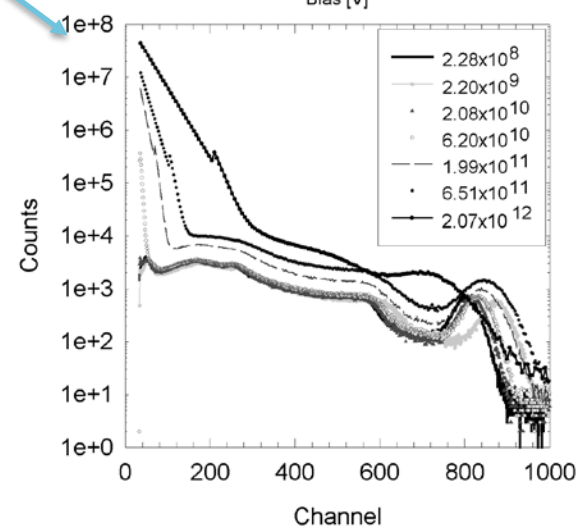
Radiation hardness

- Conventional RMD APDs (2x2 mm) were tested for radiation hardness for CMS at PSI using 72 MeV protons (up to 5 x 10^{12} n/cm^2 equivalent)

  Radiation Hardness of Avalanche Photodiodes, R. Grazioso et al. IEEE NSS Conference Record, 1, 240 (2001).

- A total dose of 2.08 x 10^{10} n/cm^2 produced little or no change in gain or noise
- ^{137}Cs spectra taken at various integrated radiation doses shows little change in quantum efficiency at Mu2e 3 year dose
- The increase in noise seen at the highest doses is reduced at lower temperatures
- Annealing at 100°C partially restores noise performance



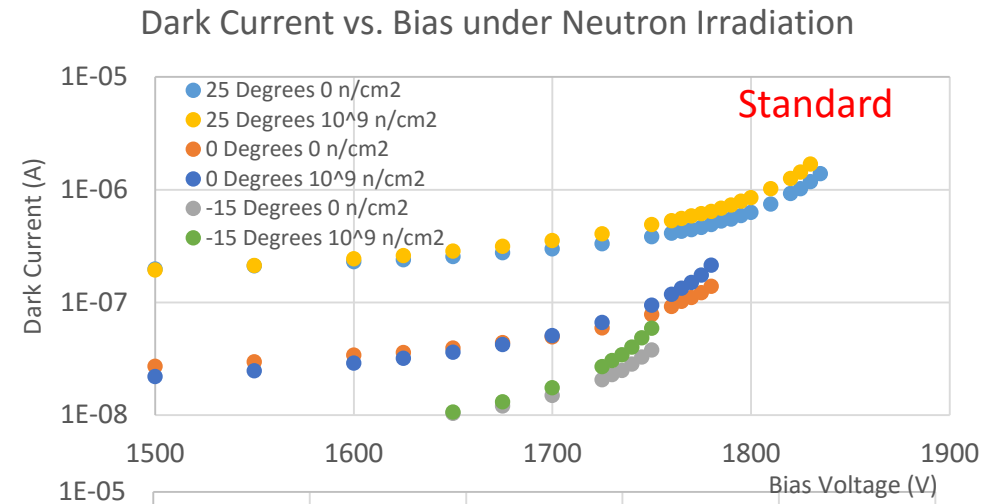


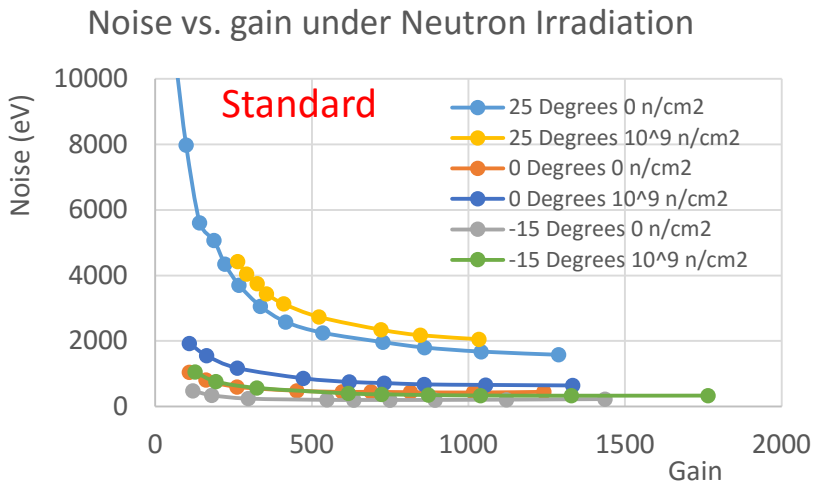
- We have begun a series of neutron and γ irradiation tests with our strong ^{252}Cf and ^{137}Cs sources, using SL/ALD APDs as well as conventional devices

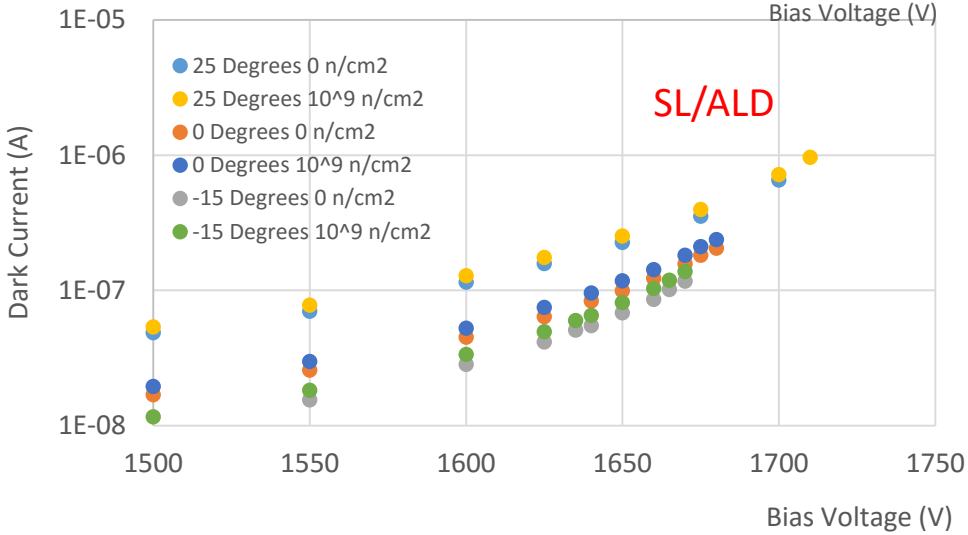
First results on neutron irradiation

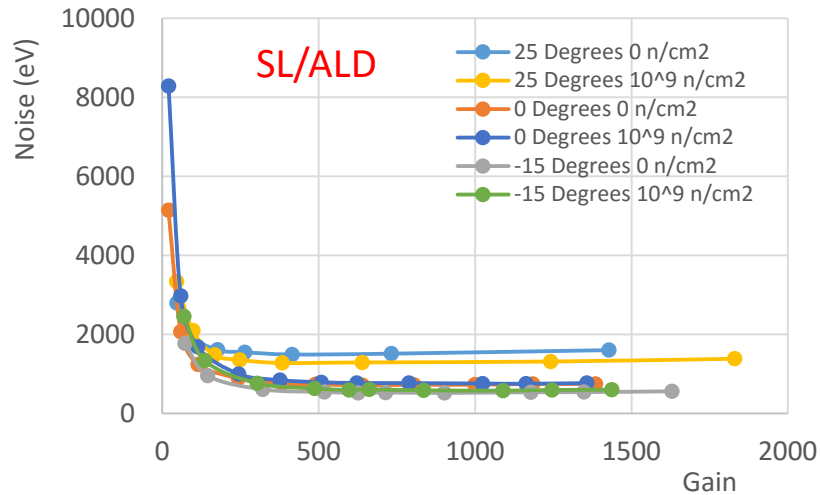
- First exposure (at room temperature) with ^{252}Cf: 10^9 n/cm^2

14x14mm^2 APDs









10^{10} exposure (60 hours) under analysis, 10^{11} underway

Conclusions

- Barium fluoride can be used to construct a very fast crystal calorimeter, provided the fast scintillation component can be exploited for its excellent time resolution and high rate capability
- We have developed the required photosensor, a superlattice-modified avalanche photodiode with a narrow band antireflection filter, by modifying a standard RMD device
- 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 APDs have been shown to be radiation hard
    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 reduced temperature provides noise performance similar to that of standard RMD APDs at room temperature
    - There is a clear R&D path, consistent with the project schedule, to further reduce the noise