An APD sensor with extended UV response for readout of BaF_2 scintillating crystals

David Hitlin

INSTR2014

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Background and motivation

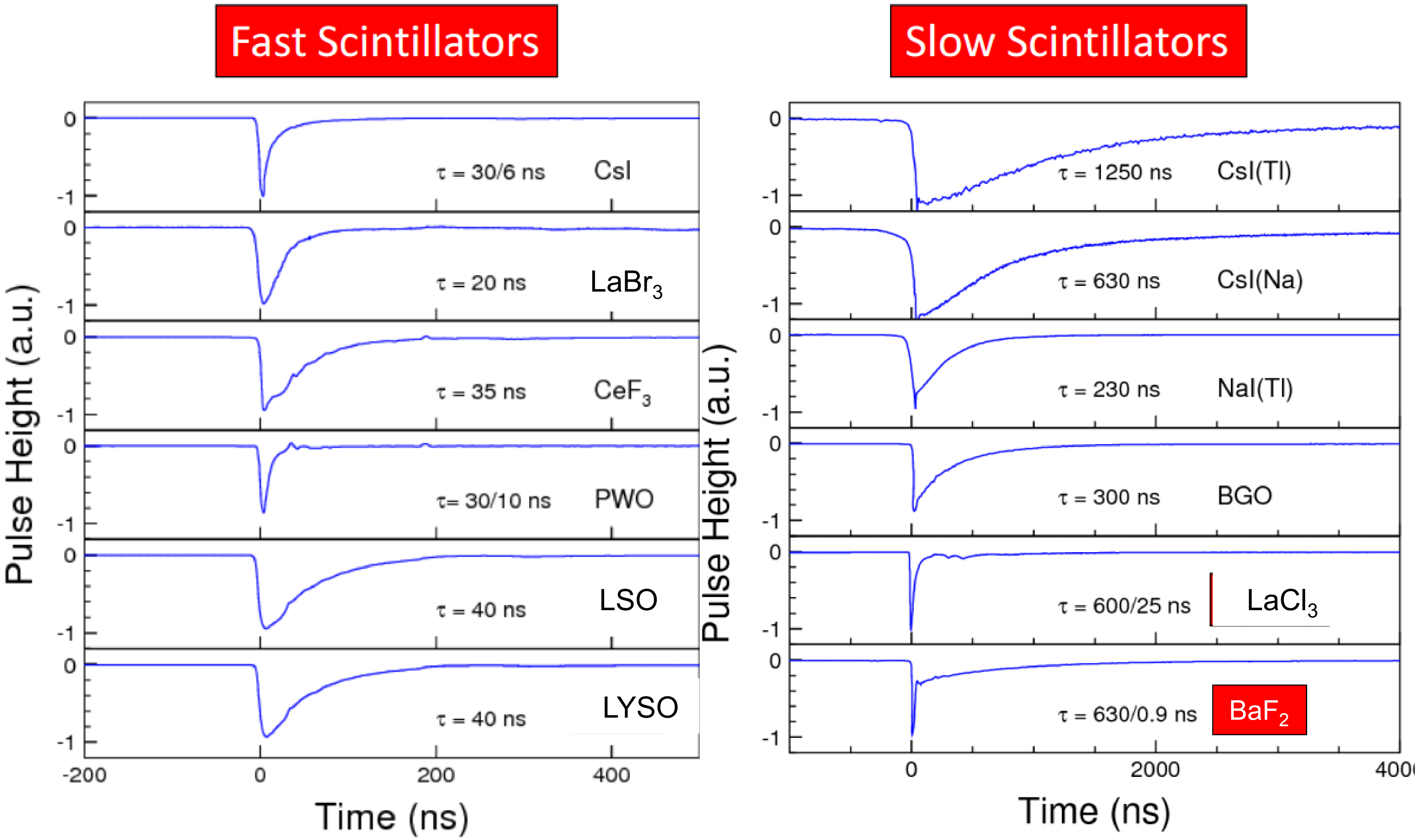
- When the cost of LYSO reached unaffordable levels, Mu2e needed a fast, radiation hard crystal with reasonable light output
- Barium fluoride is a potentially interesting candidate, but it presents unique problems
  - It has a very fast scintillation component, which is attractive, but it is accompanied by a much larger slow component
  - Both components are in the UV
- Making use of BaF_2 in a practical experiment requires a photosensor that
  - discriminates between fast and slow scintillation components
  - has a fast time response
  - works in a magnetic field
  - is stable over time
  - is radiation hard
- The development of such a sensor is the subject of this talk

Fast scintillating crystals

	LSO/LYSO	YSO	GSO	BaF_2	CsI	CeF_3	$CeBr_3$	$LaBr_3$	$LaCl_3$
Density (g/cm^3)	7.40	4.54	6.71	4.89	4.51	6.16	5.10	5.29	3.86
Radiation Length (cm)	1.14	3.04	1.38	2.03	1.86	1.70	1.96	1.88	2.81
Molière Radius (cm)	2.07	2.87	2.23	3.10	3.57	2.41	2.97	2.85	3.71
Interaction Length (cm)	20.9	27.3	22.2	30.7	39.3	23.2	31.5	30.4	37.6
Z value	64.8	33.3	57.9	51.6	54.0	50.8	45.6	45.6	47.3
dE/dX (MeV/cm)	9.55	6.70	8.88	6.52	5.56	8.42	6.65	6.90	5.27
Emission Peak[a] (nm)	420	420	430	300 220	420 310	340 300	371	356	335
Refractive Index[b]	1.82	1.80	1.85	1.50	1.95	1.62	2.3	1.9	1.9
Relative Light Yield[a,c]	100	40		42 4.8	4.2 1.3	8.6	144	153	15 49
Decay Time[a] (ns)	40	70	65	650 0.9	30 6	30	17	20	570 24
d(LY)/dT [d] (%/ºC)	-0.2	-0.3	-0.7	-1.9 0.1	-1.4	~0	-0.1	0.2	0.1

Ren-yuan Zhu

Scintillation pulse shapes



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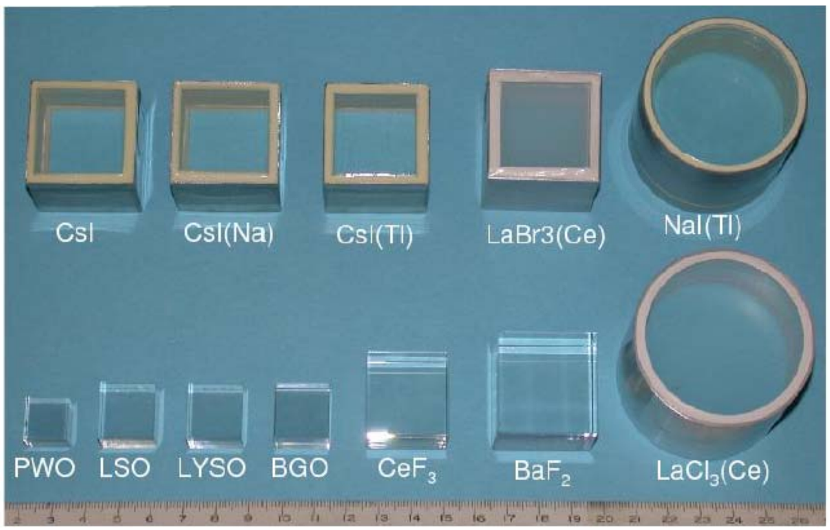
A fast crystal "figure of merit"

Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5

Motivates R&D on fast crystals and appropriate solid state readout



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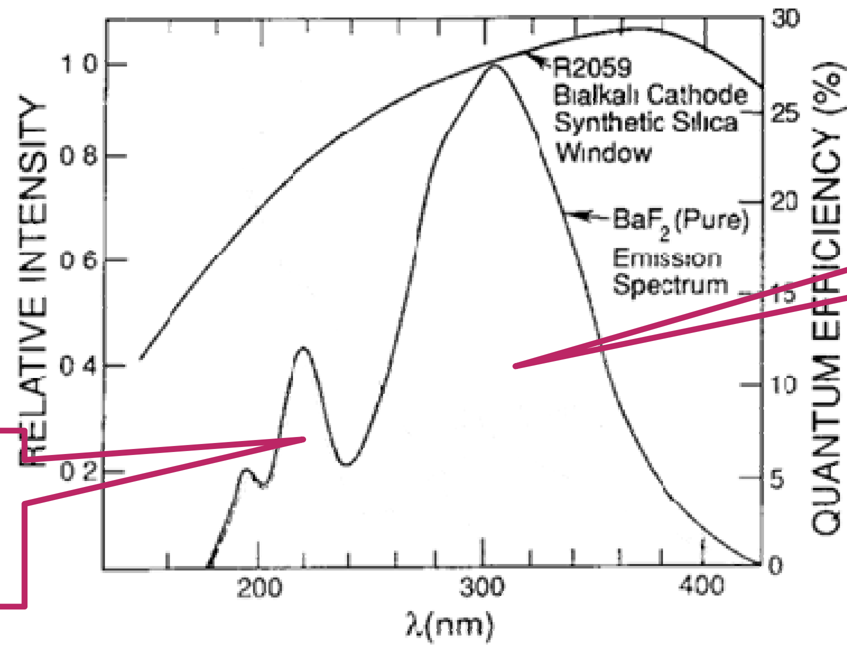
BaF_2 is a potentially attractive high rate crystal

- BaF_2 is among the fastest scintillating crystals (0.9ns), but there is a much larger, slower, component (650ns)

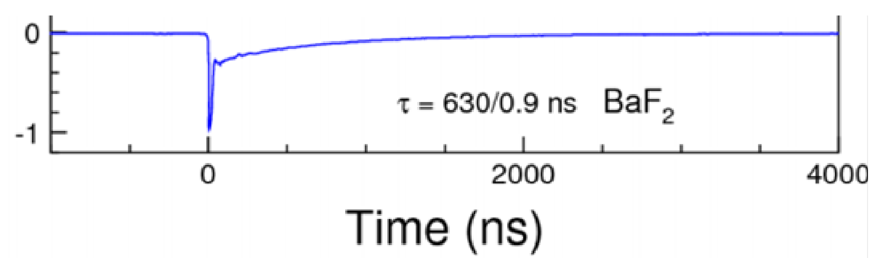


15%
900 ps

85%
650 ns

Total light output
1.2×10^4 photons/MeV

- In order to take full advantage of the fast component, it is necessary to suppress the slow component



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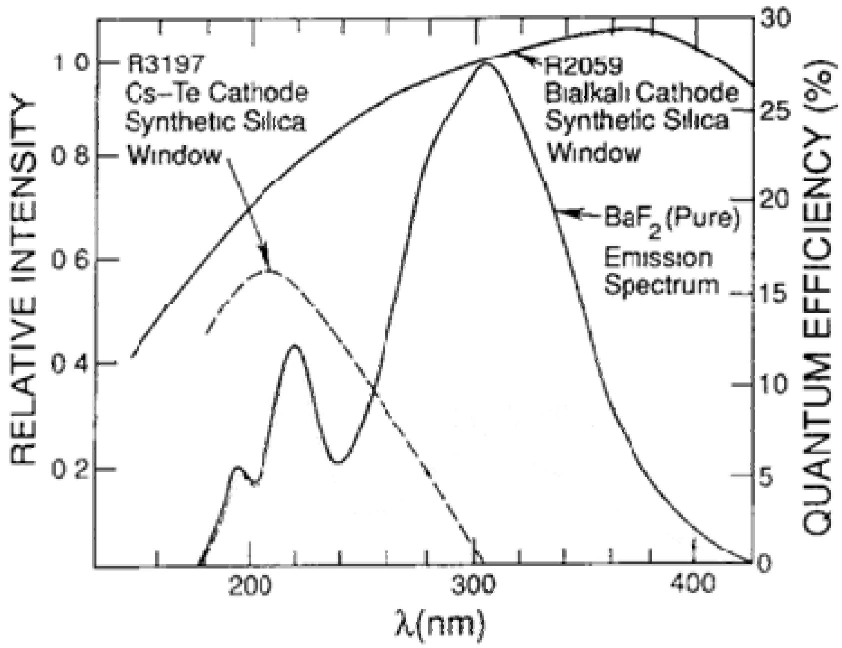

- In order to take full advantage of the fast component, it is necessary to suppress the slow component:
  - Need a "solar-blind" photosensor

BaF_2 is a potentially attractive high rate crystal

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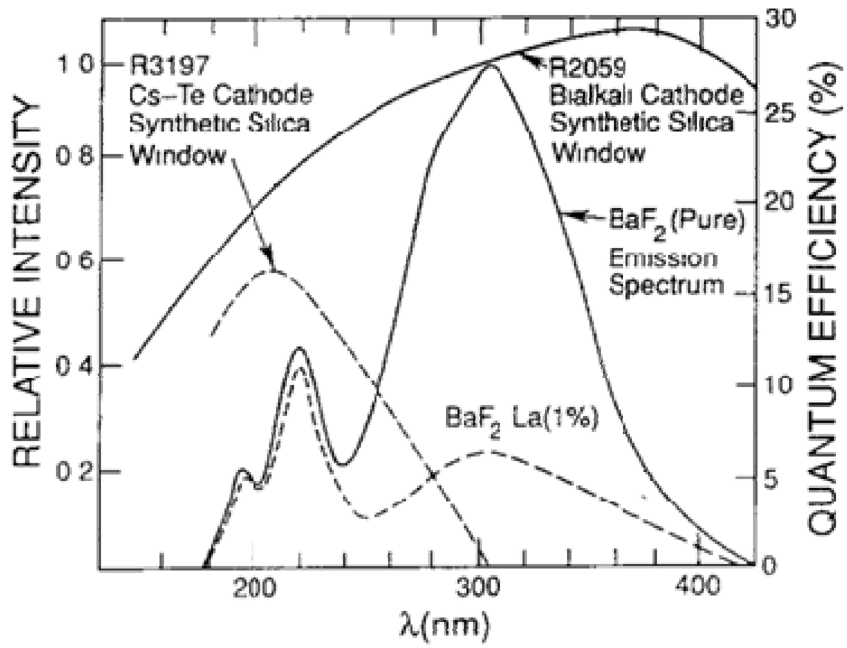


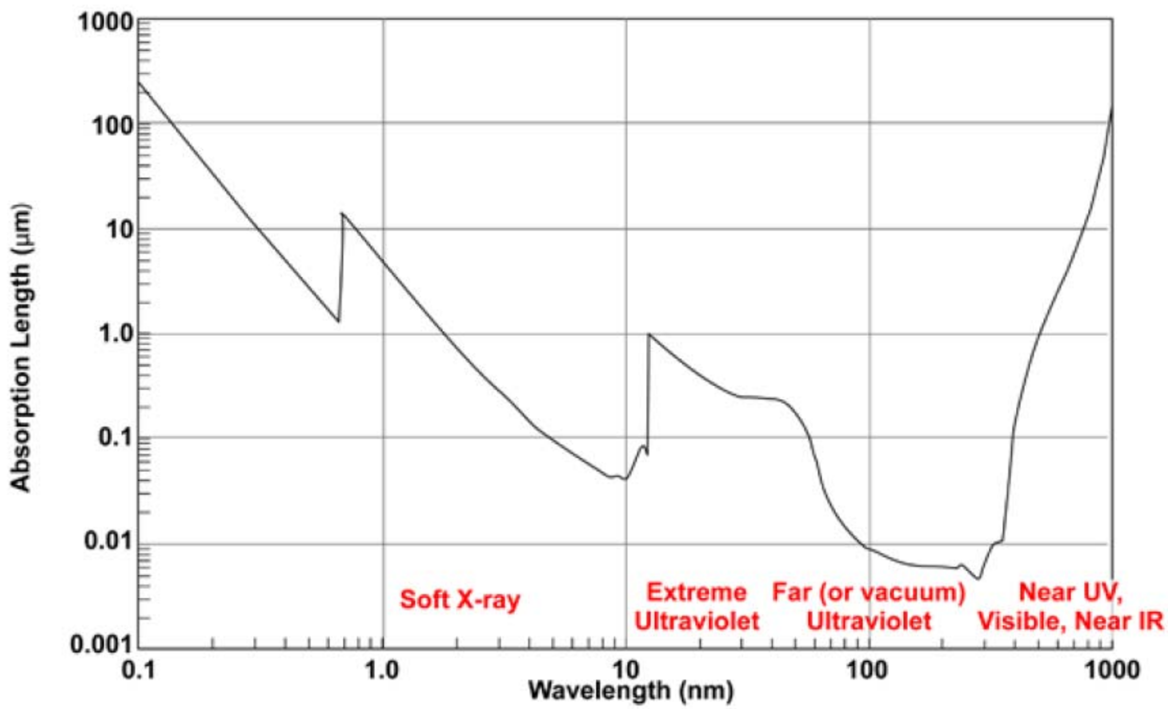
- In order to take full advantage of the fast component, it is necessary to suppress the slow component
  - La doping of pure BaF_2 suppresses the slow component by ~4
  - Other dopings can be explored

Solar-blind photosensors

- Solar-blind PMTs exist
  - Large area, fast, but expensive, and do not work in a magnetic field
- Solar-blind solid state devices also exist
  - SiC APDs (100µm diameter)
  - AlGaN APDs (< 1mm diameter)
- There are several potential approaches to fast, large area, solar-blind, magnetic field insensitive photosensors
  - A variant of the LAPPD channel plate under development by U Chicago/Argonne
  - SiPMs with or without antireflection coatings (*e.g.*, Hamamatsu)
  - Large area delta-doped APDs with AR ALD (Caltech/JPL/RMD)

How to achieve best possible QE in the 200-300 nm regime?

- Absorption length at 220 nm in silicon is less than 10 nm



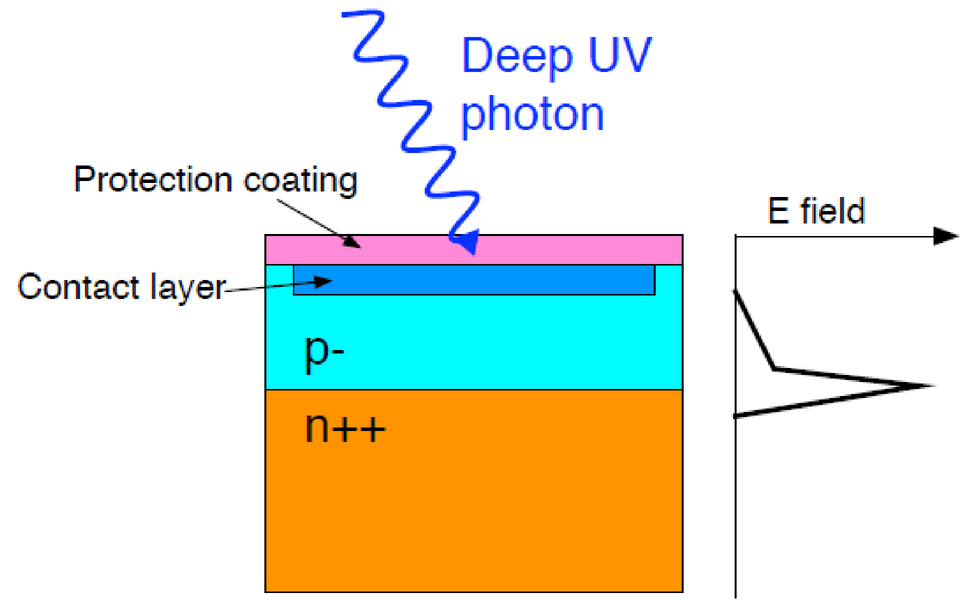
  - Protective epoxy coating on an APD or SiPM has a strong effect on QE
  - Sensitive region of device must be very close to the surface

UV sensitive MPPC

Hamamatsu Photonics/MEG

- Requirements
  - Sensitivity to liquid xenon scintillation (λ = 175 nm)
  - Large active area (12×12 mm^2)
  - Single photon counting capability
  - Moderate trailing time constant ($\tau < 50$ ns)

- In order to improve sensitivity
  - Remove protection layer
  - Match refractive index to liquid xenon
  - Apply anti-reflection coating



Cross-sectional image of MPPC

Hamamatsu UV sensitive MPPC

IEEE/NSS Seoul

[Performance of UV-Sensitive MPPC for Liquid Xenon Detector in MEG Experiment]

D. Kaneko
ICEPP, The University of Tokyo, Tokyo, Japan
On behalf of the MEG Collaboration

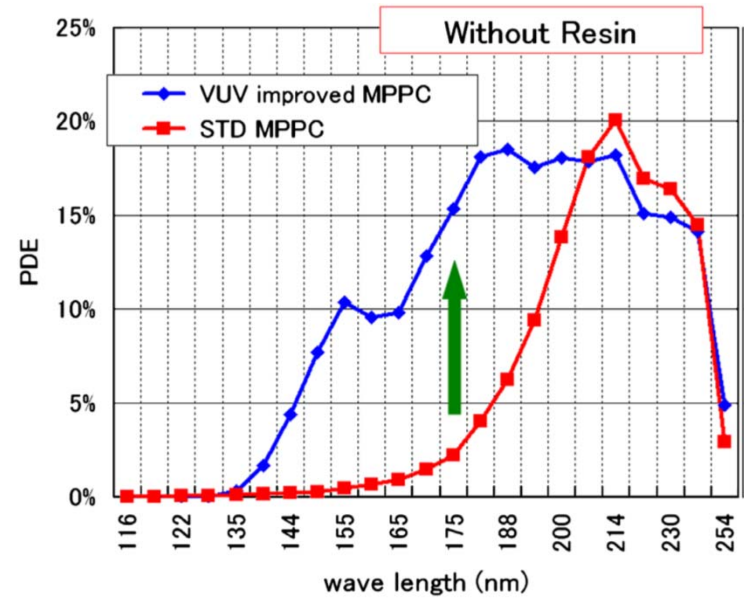
Large area MPPC sensitive to the liquid xenon scintillation light (λ = 175 nm)

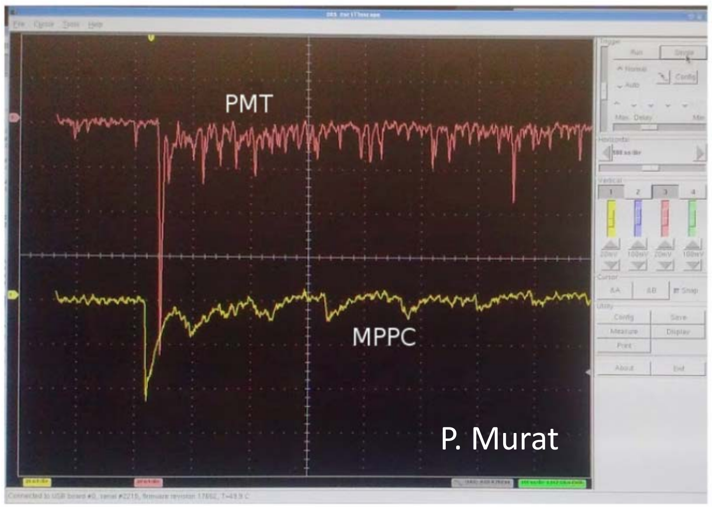
12×12 mm active area

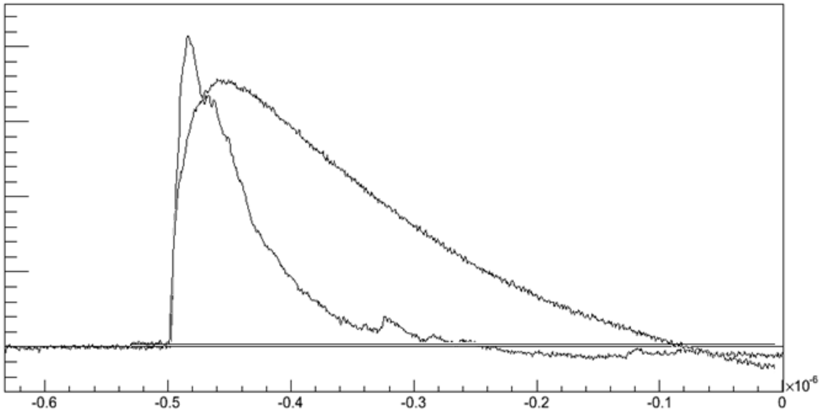
Detection efficiency (PDE) of 17%

Pixel gain around 10^6

Version with improved pixel structure is under development





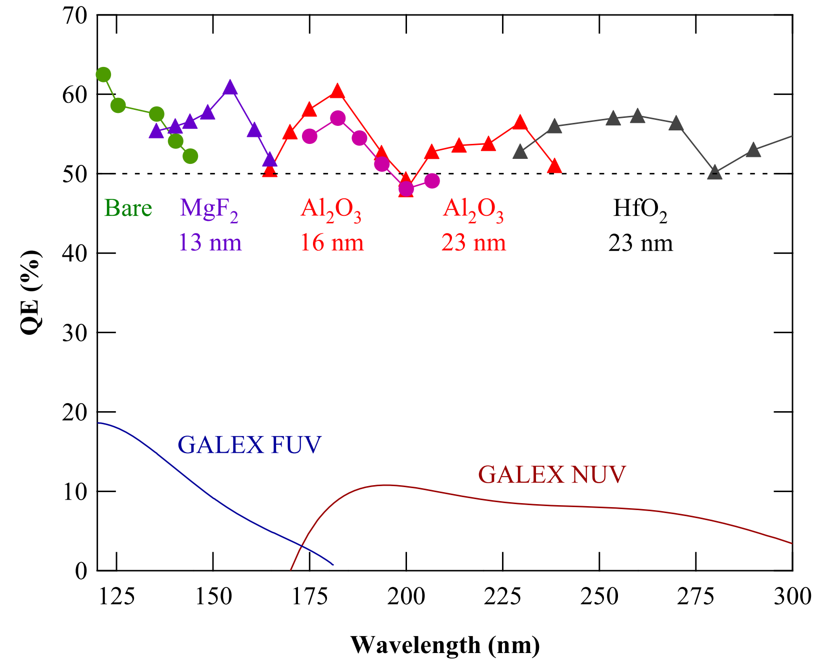


Far ultraviolet, visible-blind coatings

"Ultraviolet antireflection coatings for use in silicon detector design,"
Erika T. Hamden, Frank Greer, Michael E. Hoenk, Jordana Blacksberg, Matthew R. Dickie, Shouleh Nikzad, D. Christopher Martin, and David Schiminovich
Applied Optics, Vol. 50, Issue 21, pp. 4180-4188 (2011)

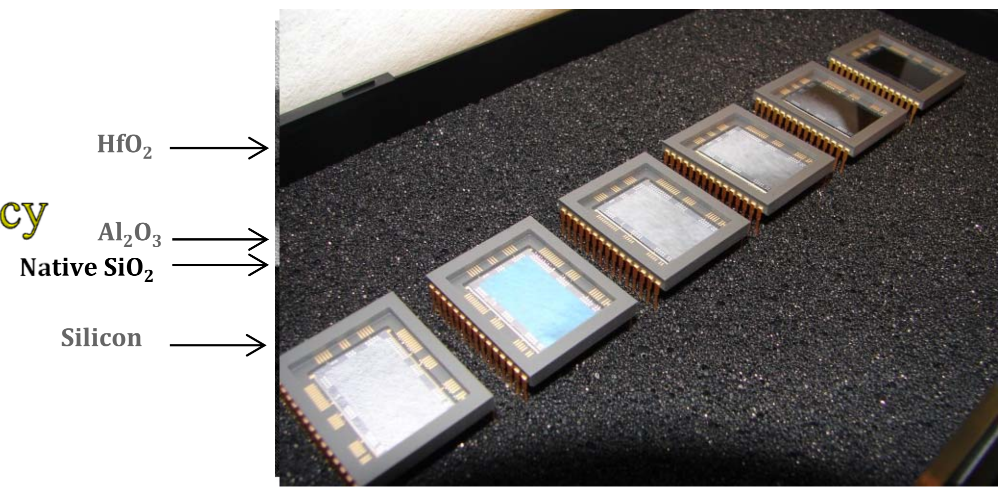
"Delta-doped electron-multiplied CCD with absolute quantum efficiency over 50% in the near to far ultraviolet range for single photon counting applications"
Shouleh Nikzad, Michael E. Hoenk, Frank Greer, Blake Jacquot, Steve Monacos, Todd J. Jones, Jordana Blacksberg, Erika Hamden, David Schiminovich, Chris Martin, and Patrick Morrissey
Applied Optics, Vol. 51, Issue 3, pp. 365-369 (2012)

"Atomically precise surface engineering of silicon CCDs for enhanced UV quantum efficiency,"
Frank Greer, Erika Hamden, Blake C. Jacquot, Michael E. Hoenk, Todd J. Jones, Matthew R. Dickie, Steve P. Monacos, Shouleh Nikzad
J. Vac. Sci. Technol., A 31, 01A103 (2013)



World record deep ultraviolet quantum efficiency

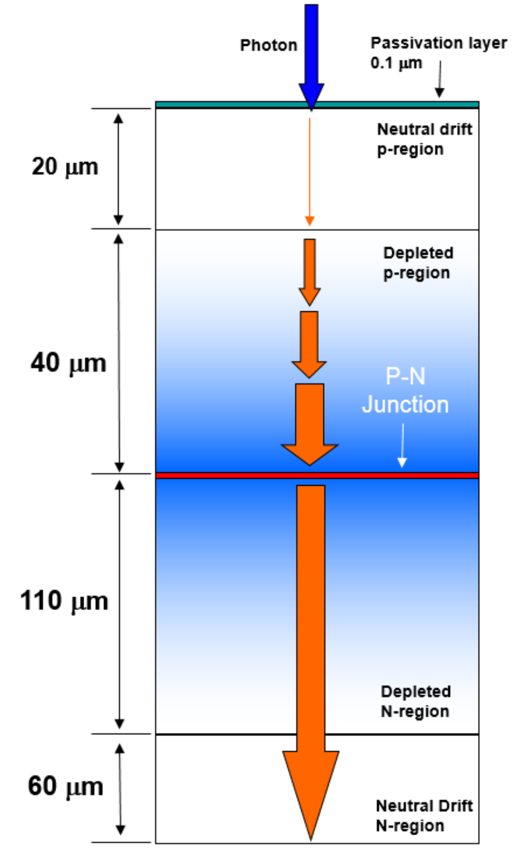
- QE > 5x Galex
- Stable
- Visible blind coatings are possible



APD structure

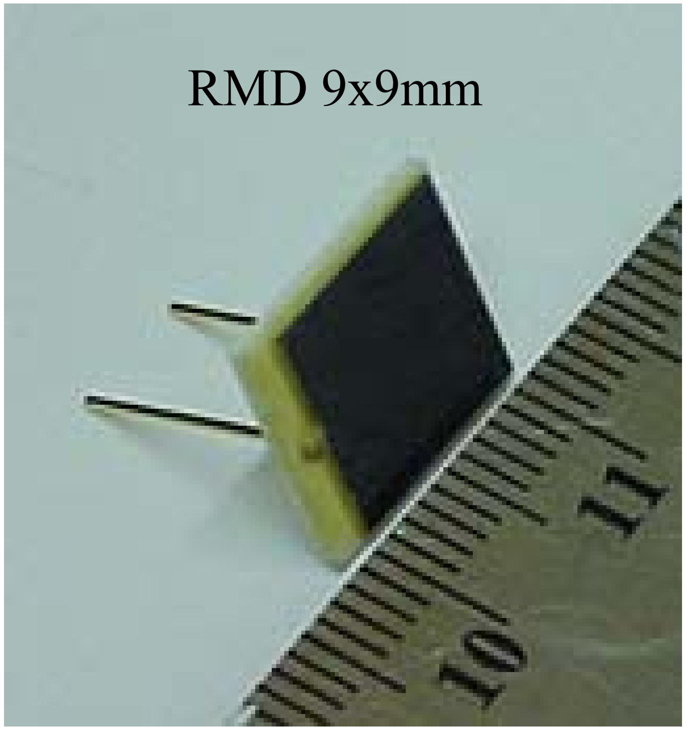
Deep-diffused architecture (RMD)

- Photoelectrons created by UV photons at the sensing surface must survive trapping at the SiO_2/Si passivation surface interface and recombination in the undepleted p-side neutral drift region (tens of μm) to reach the depletion region where the avalanche takes place
  - The thickness of the undepleted p-side region is engineered for efficient conversion of visible photons
    - This is undesirable for high UV QE
- The result is that UV QE is reduced and the device speed is determined by the ~10 ns drift time as well as by capacitance
- This structure can be modified, using proven techniques, to improve both UV quantum efficiency and device timing characteristics



Visible-blind, superlattice-doped silicon detectors

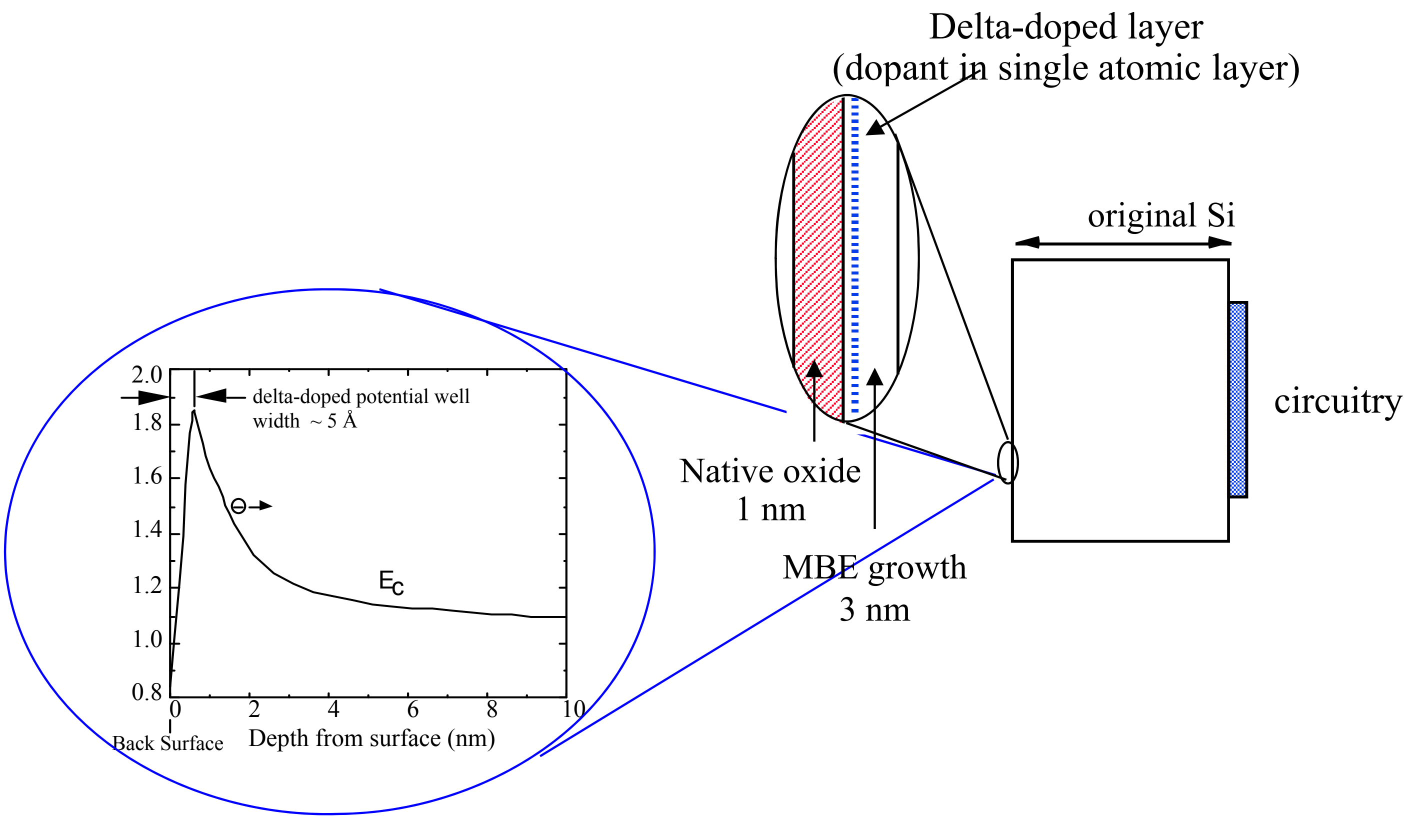
- Eliminating the potential well at the surface and reducing (or removing) the drift region improves the detector UV QE and speed
- The process is executed on modified RMD APD wafers, using an extrapolation of existing technology at Caltech's Jet Propulsion Laboratory (JPL)



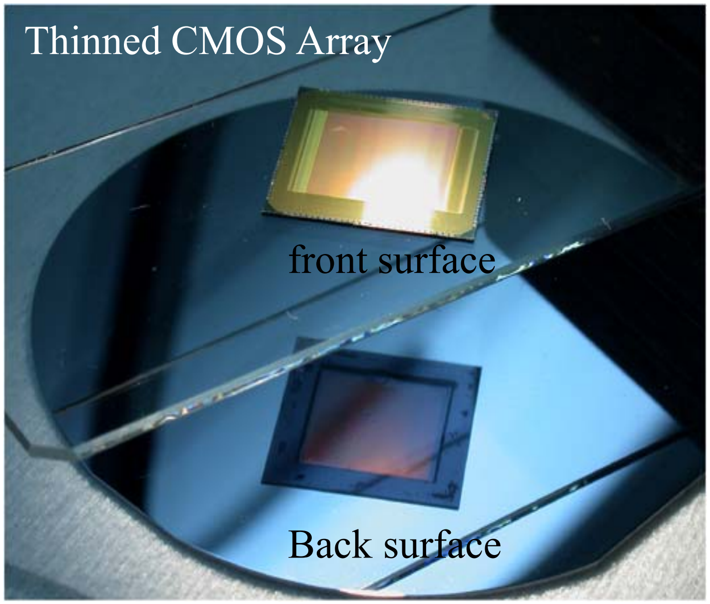
- **Molecular Beam Epitaxy**
  - > 50% QE at 220 nm
  - Low dark current
  - High conductivity
  - Radiation tolerance
- **Atomic Layer Deposition**
  - Chemically passivated interface
  - Visible-blind antireflection coatings: < 1% QE at 300 nm

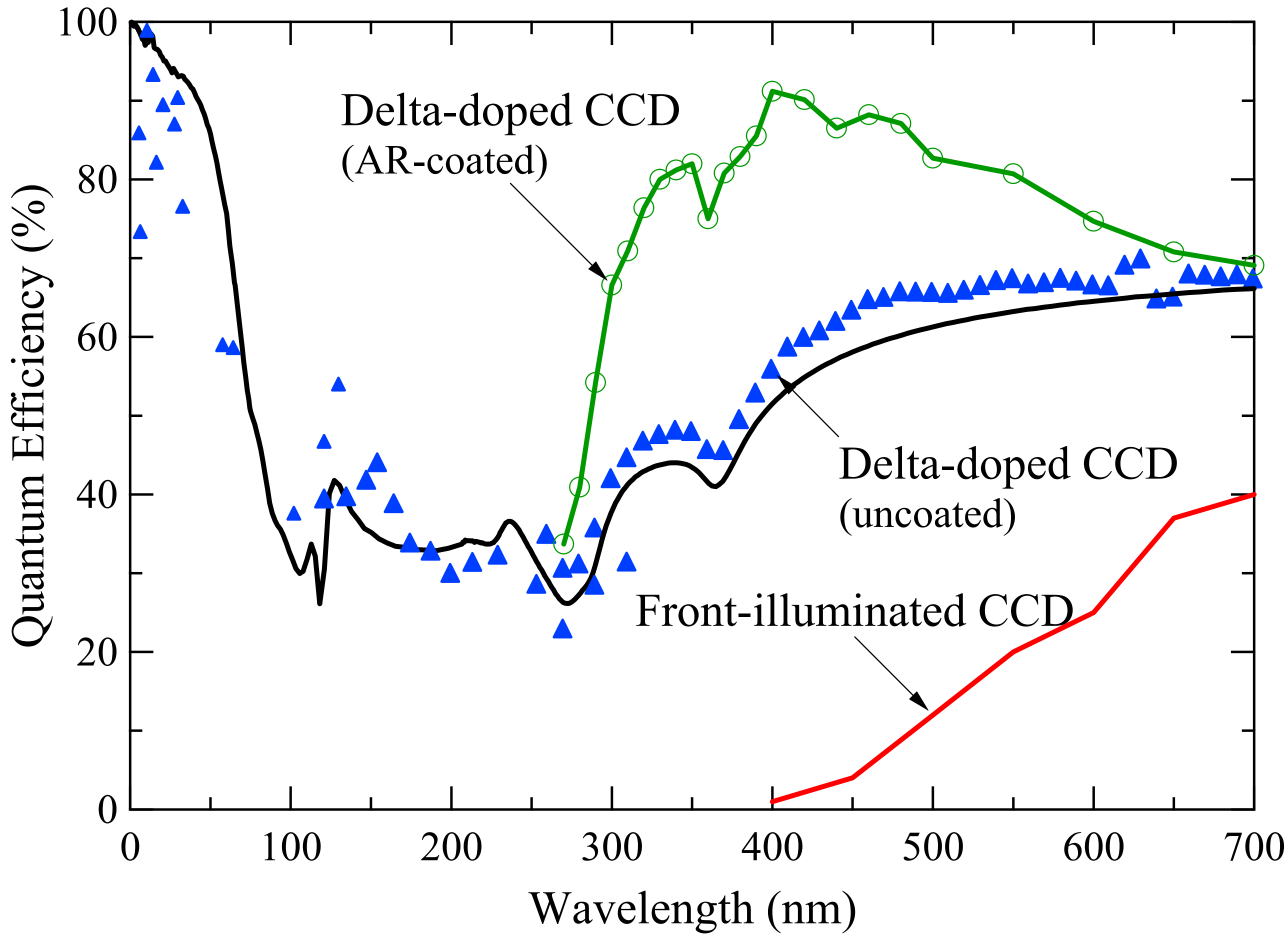
The process

- Wafers are thinned on the p-side (sensing side) to remove the undepleted region
- Drift region is replaced by 3µm vapor phase epitaxial layer
- Monolayer of boron atoms is deposited ~2.5nm below the surface, eliminating the trapping well



Delta-doping has been applied to CCD detectors

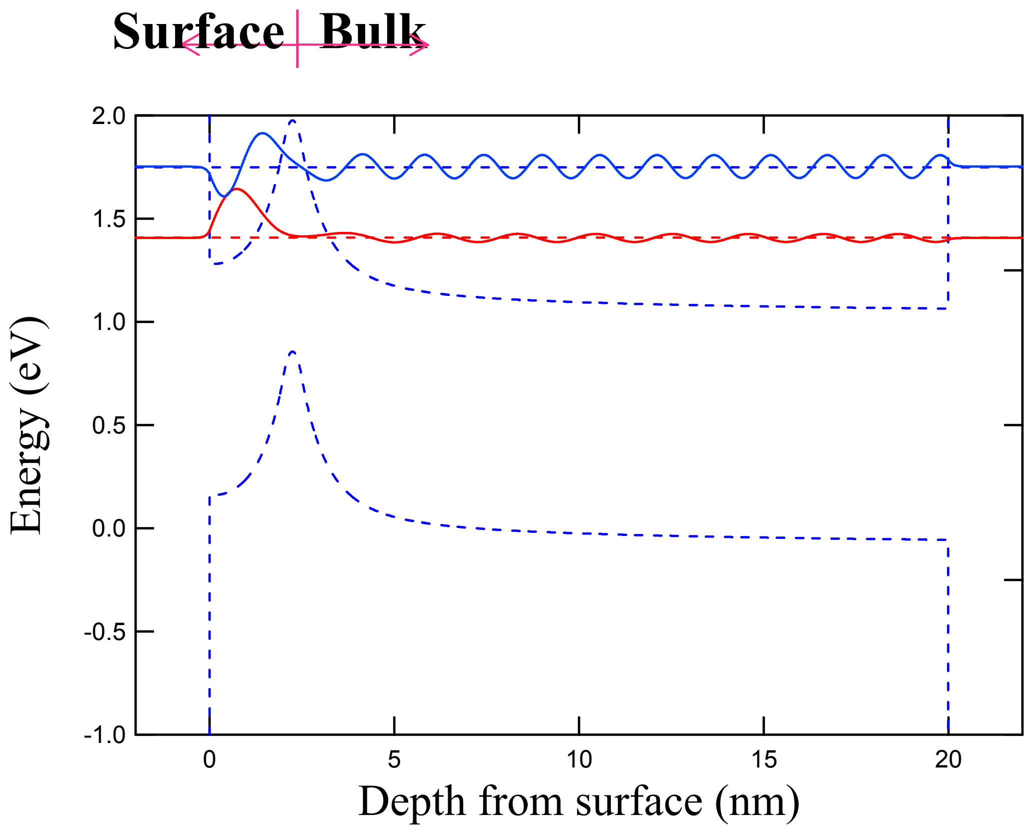




S. Nikzad, "Ultrastable and uniform EUV and UV detectors," *SPIE Proc.*, Vol. 4139, pp. 250-258 (2000).

J. Trauger (PI WF/PC2) – *No measurable hysteresis in delta-doped CCDs*

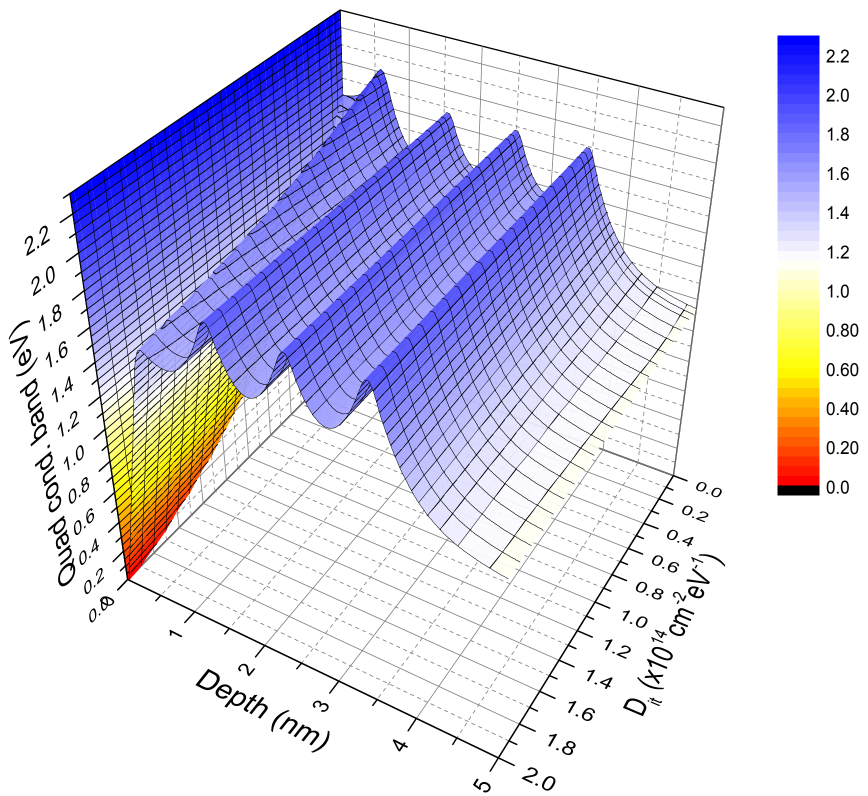
Delta doping and quantum exclusion

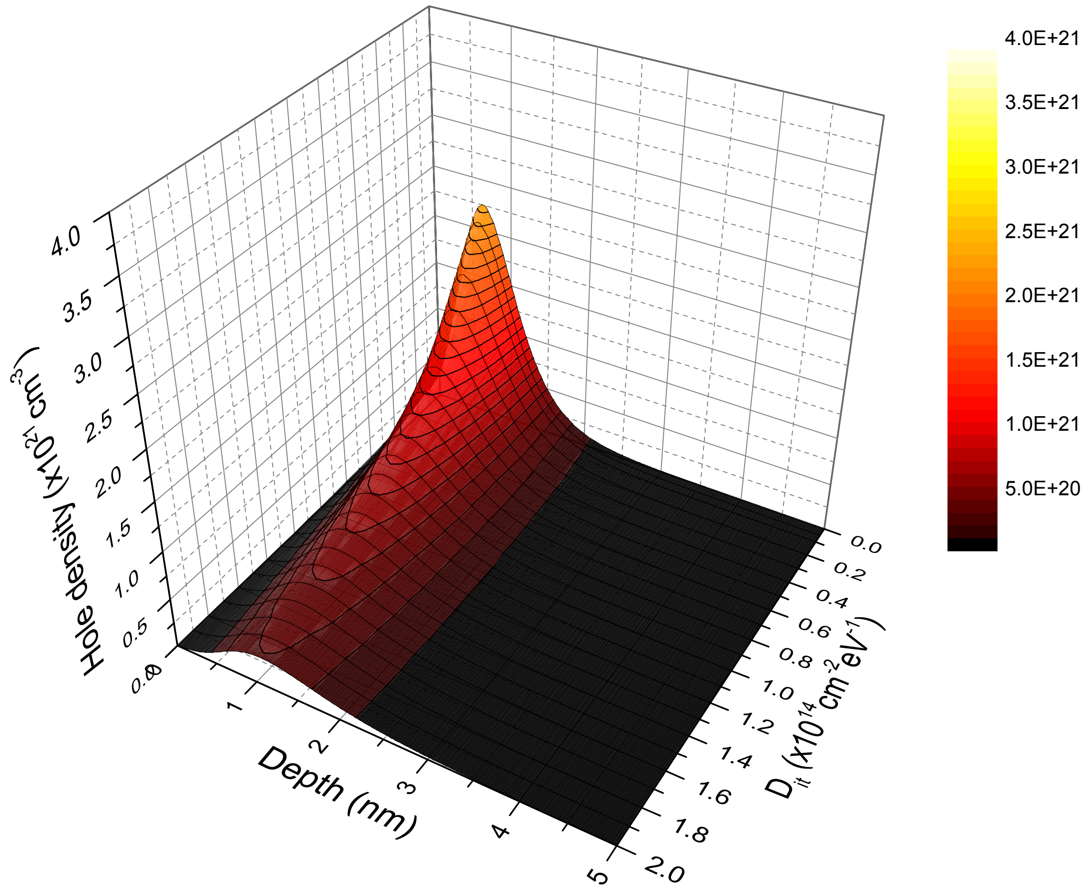


Delta-doping creates a "quantum well" in the silicon

- Majority carriers are confined to quantized subbands
- Quantum exclusion eliminates trapping
- Peak electric field is ~10^7 V/cm Positively charged surface @ 10^{13} cm^{-2}

Superlattice doped surface with delta doping



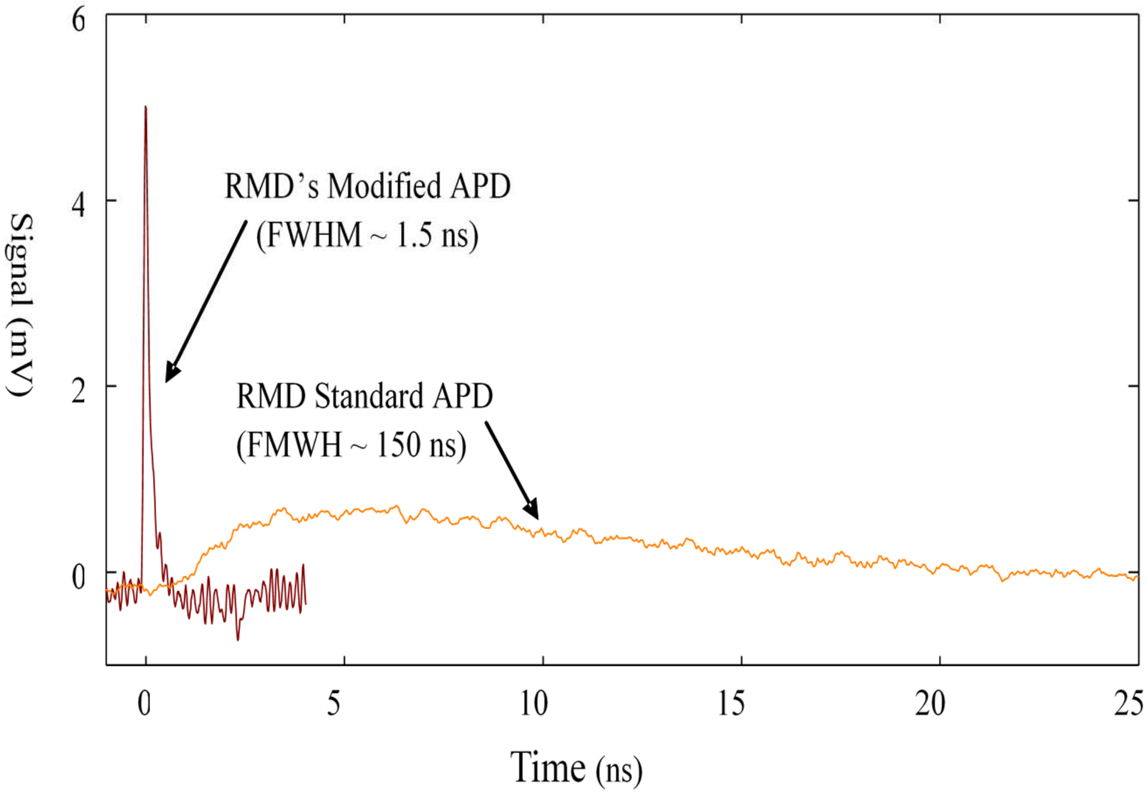


5 nm, $8x10^{14}$ cm^{-2}

2.5 nm, $2x10^{14}$ cm^{-2}

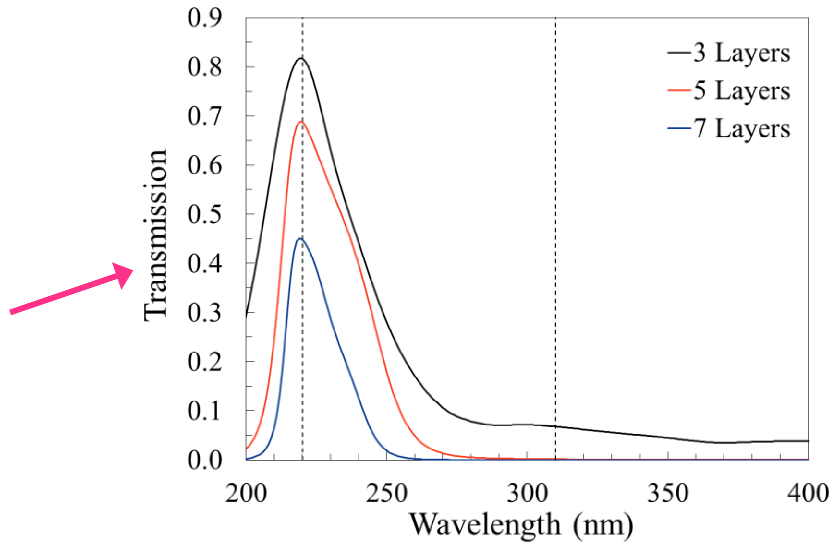
Thinning improves timing performance

- 3 μm epitaxial layer deposited on thinned RMD APD (3x3 mm^2)
- Illumination with 405 nm laser pulse



Experimental tests for Al_2O_3/Al Blocking Filters (220 nm)

- Design Approach:
  - Develop optical model for stand-alone Al_2O_3 layers (these were deposited at 200°C, Oxford ALD w/ O_2 plasma)
  - Using this model and Al reference model (Palik data) calculate for target layer thickness
  - Designs roughly based on original rejection targets for three or five layer metal/dielectric stacks (target peak @220 nm)
  - Feedback from ellipsometry data to modify thickness targets (*i.e.* due to Al layer oxidation duration processing, *etc.)*
  - Will eventually develop a refined optical model to be more predictive about the expected transmission and reflection, simple discrete layers appear insufficient especially for the five layer tests



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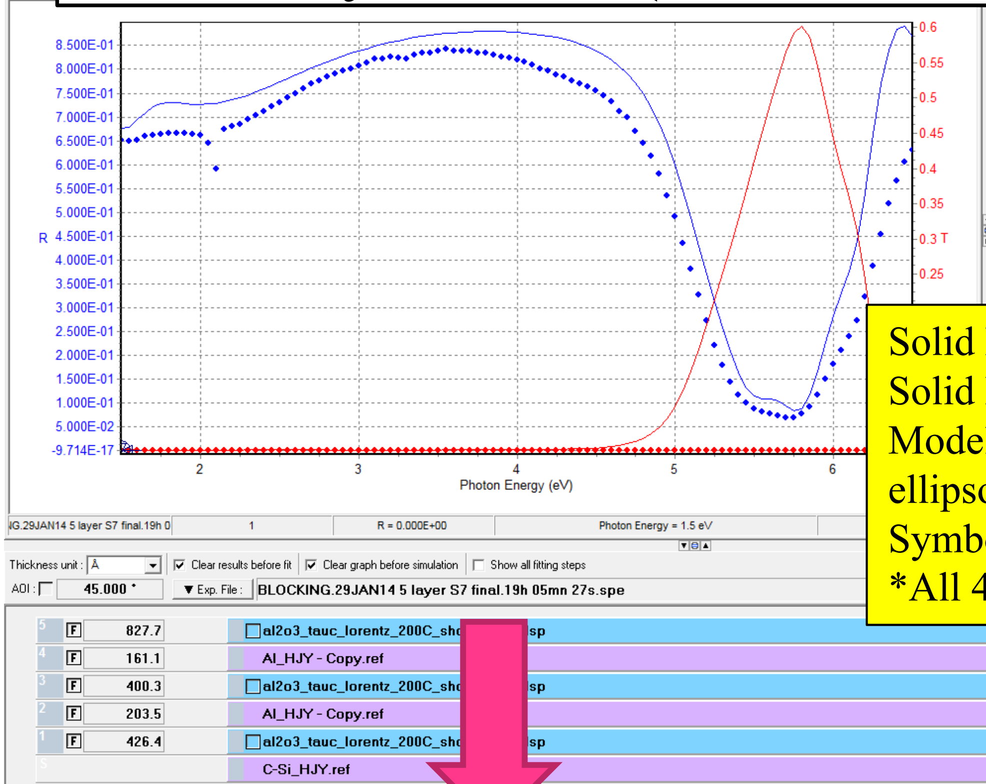
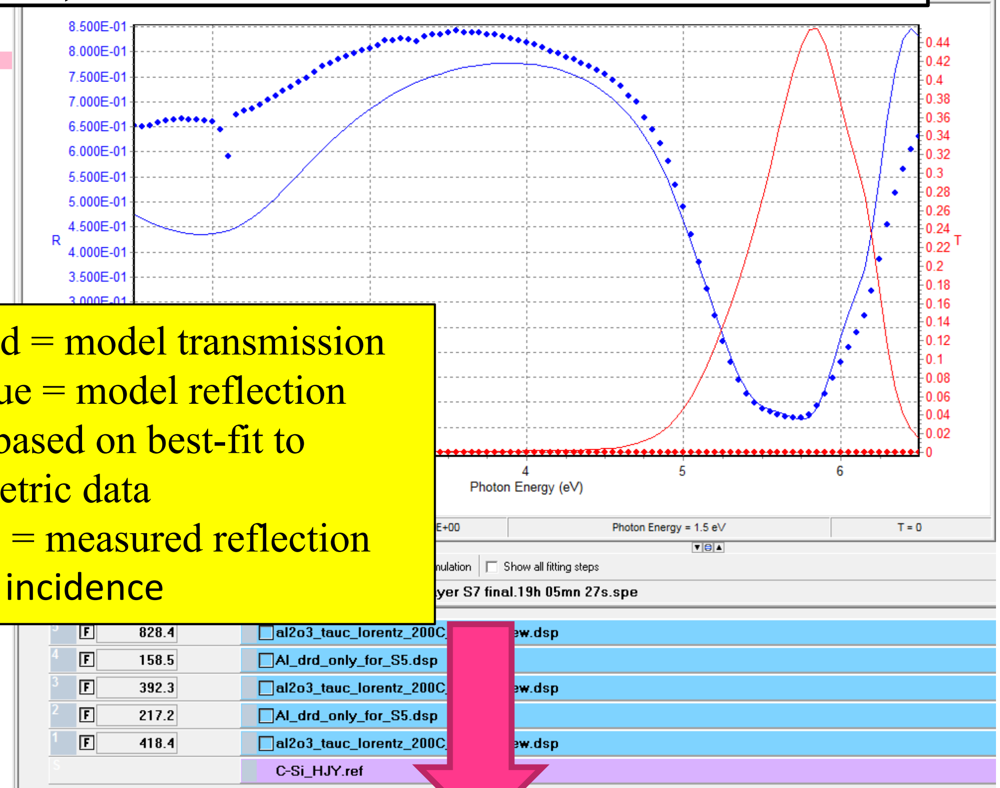
Five Layer Test (Si-DMDMD)





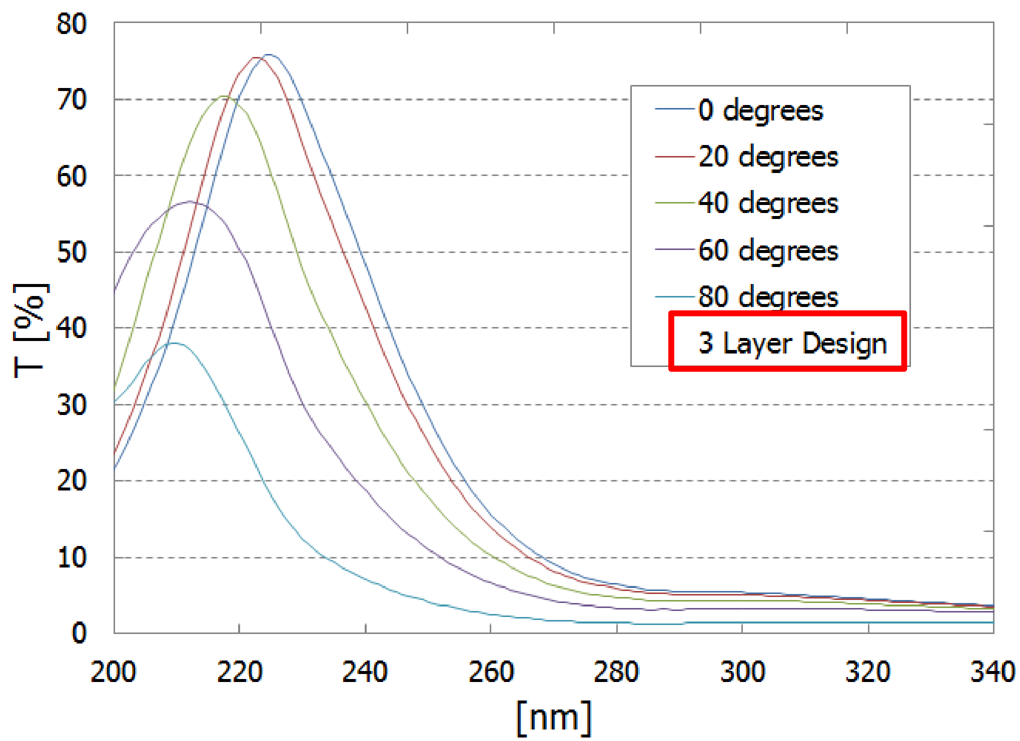
Solid Red = model transmission
Solid Blue = model reflection
Models based on best-fit to ellipsometric data
Symbols = measured reflection
*All 45° incidence

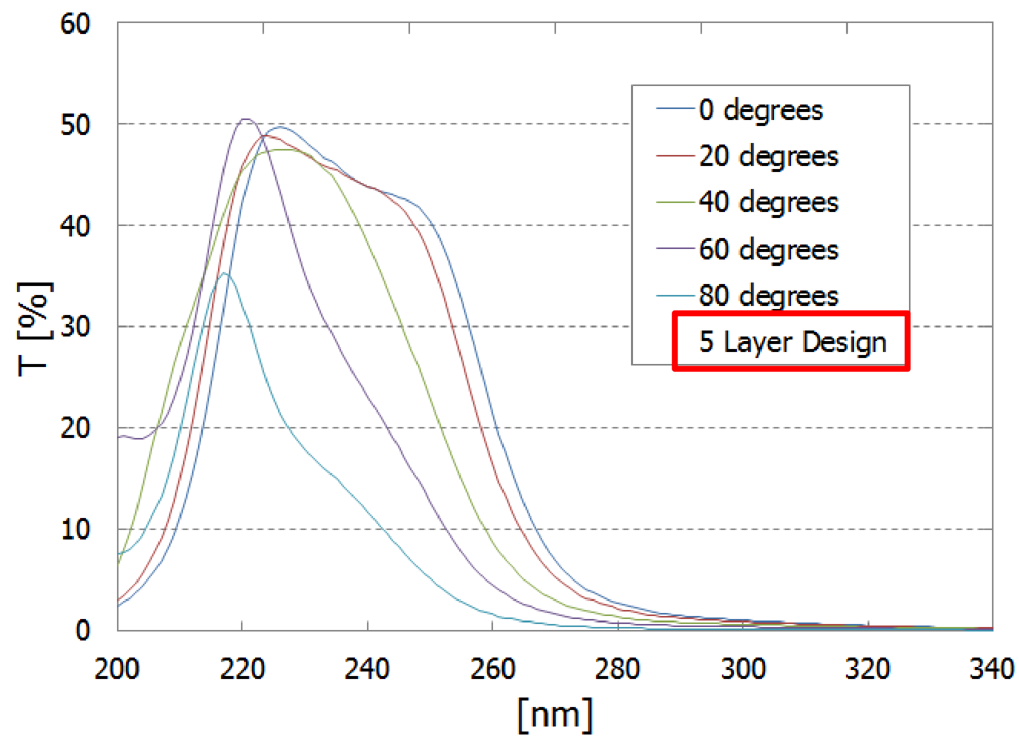
- Five layer w/ ideal Al parameters
- Best fit χ^2= 25.6 (L1 = 426Å, L2=204Å, L3=400Å, L4=161Å, L5=828Å)
- Model T @220nm = 53% (45°) , 68% (normal)
- Model T @310nm = 0.13% (45°) , 0.16% (normal)
- Predicted T_{peak} (normal) = 69% @ 218 nm

- Five layer w/ new Al parameters
- Best fit χ^2 = 9.61 (L1 = 418Å, L2=217Å, L3=392Å, L4=158Å, L5=828 Å)
- Model T @220nm = 38% (45°) , 53% (normal)
- Model T @310nm = 0.16% (45°) , 0.20% (normal)
- Predicted T_{peak} (normal) = 55% @ 218 nm

J. Hennessy

Angular dependence of integrated interference filter





J. Hennessy

Current status

- RMD has furnished six thinned APD wafers to JPL for processing
    - Two stage development plan

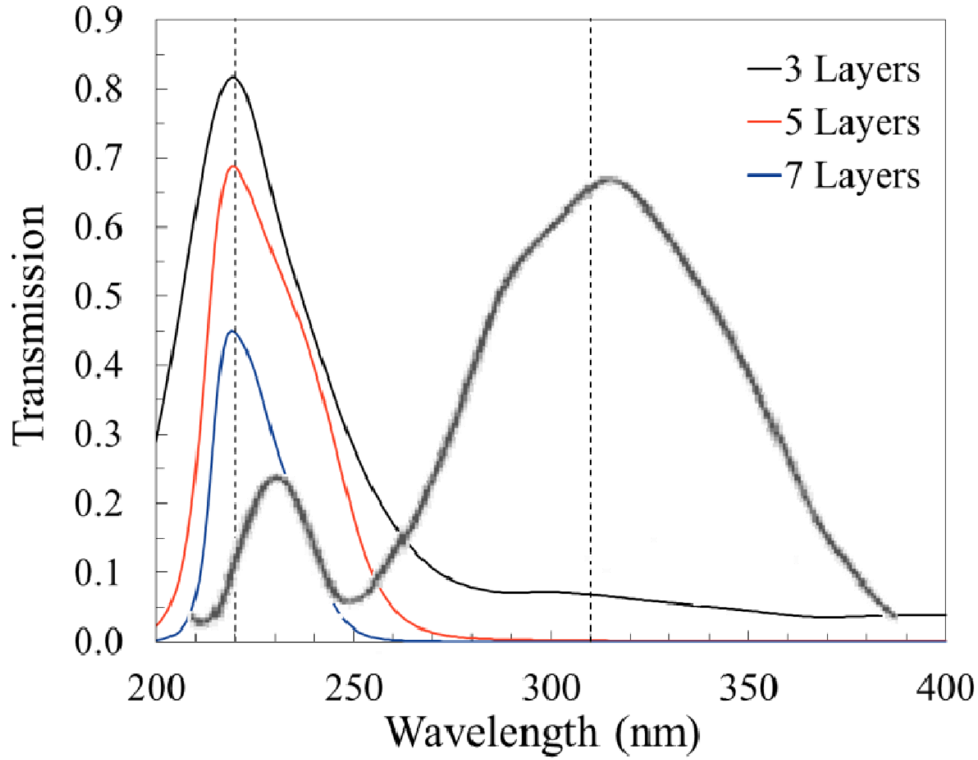
      I: Extended UV response

      II: Integrate AR interference filter
- Processed wafers have been probed and diced at RMD
    - Devices work as APDs, with somewhat increased noise but fast pulse response
        - Noise has been traced to a contaminated epitaxial vapor deposition source at JPL, which is being disassembled and cleaned
    - JPL will process and AR coat several unpackaged chips and return both coated and uncoated chips to RMD for packaging
    - Chips will undergo full characterization and then tests with BaF_2
- A second batch of wafers is being readied
    - Will explore different depths and density of the superlattice MBE and delta doping
- Goal is to have full size prototype devices for a beam test at MAMI in the fall

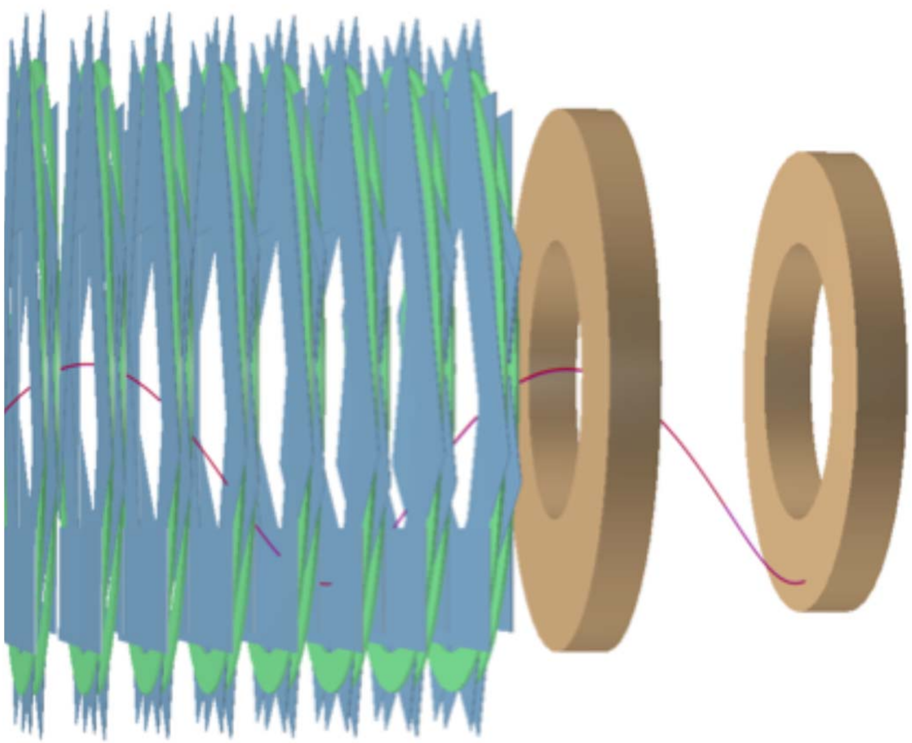
Conclusions

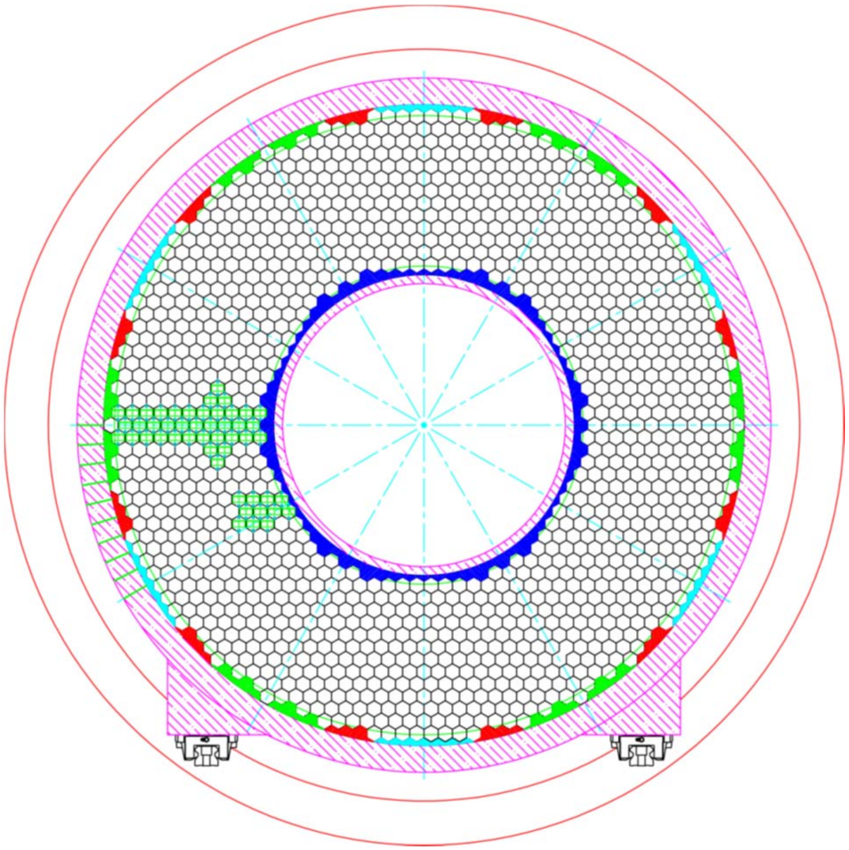
- Full utilization on the fast component of BaF_2 requires development of an appropriate sensor
- Existing large area UV sensitive APDs or SiPMs have ~20% quantum efficiency, slow time response and offer no discrimination between the BaF_2 fast and slow scintillation components
- The Caltech/JPL/RMD collaboration is developing a 9x9mm superlattice thinned, delta-doped APD with integrated AR coating and filter
  - This device promises to have >50% quantum efficiency at 220 nm, strong discrimination of the 300 nm slow component, and excellent timing characteristics

The proverbial bottom line

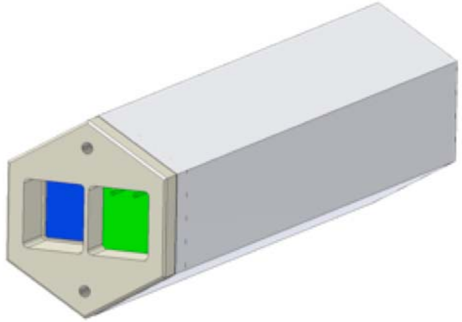


Scintillating crystal calorimeter for mu2e





- Two disk geometry
- Hexagonal BaF_2 crystals; APD or SiPM readout
- Provides precise timing, PID, background rejection, alternate track seed and possible calibration trigger.



Calorimeter crystal history

- Initial choice PbWO4: small X_0, low light yield, low temperature operation, temperature and rate dependence of light output
- CDR choice LYSO: small X_0, high light yield, expensive (→very expensive)
- TDR choice: BaF_2: larger X_0, lower light yield (in the UV), very fast component at 220 nm, readout R&D required, cheaper,

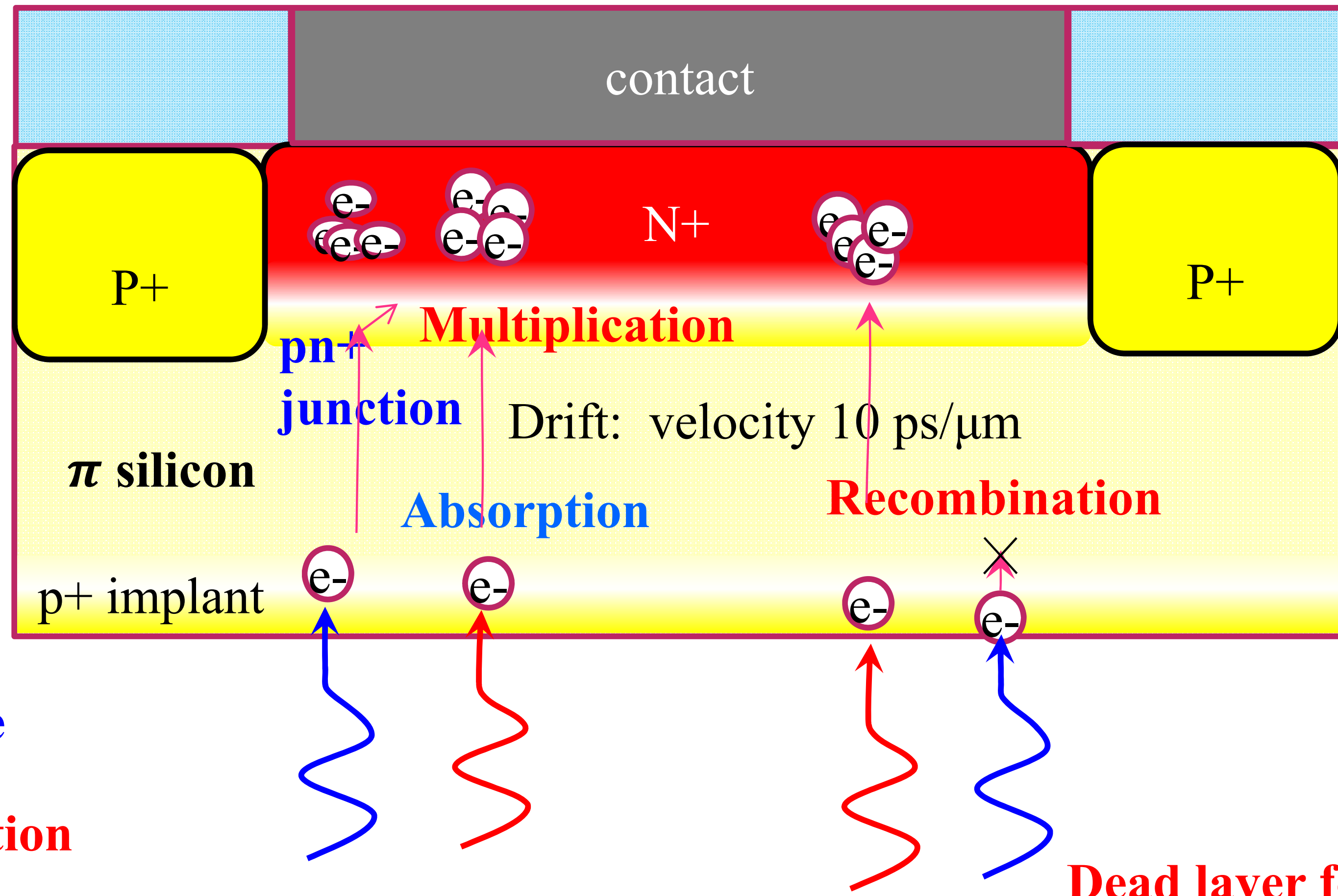
Crystal	**BaF_2**	**LYSO**	**$PbWO_4$**
Density (g/cm^3)	4.89	7.28	8.28
Radiation length (cm) X_0	2.03	1.14	0.9
Molière radius (cm) Rm	3.10	2.07	2.0
Interaction length (cm)	30.7	20.9	20.7
dE/dx (MeV/cm)	6.5	10.0	13.0
Refractive Index at λ_{max}	1.50	1.82	2.20
Peak luminescence (nm)	220, 300	402	420
Decay time τ (ns)	0.9, 650	40	30, 10
Light yield (compared to NaI(Tl)) (%)	4.1, 36	85	0.3, 0.1
Light yield variation with temperature(% / °C)	0.1, -1.9	-0.2	-2.5
Hygroscopicity	None	None	None

Reach-Through Avalanche Photodiode (RTAPD)

Reverse biased photodiode with $p^+\pi pn^+$ structure

Avalanche gain in pn+ junction

Electric field drives electrons toward junction



Deep implant

UV QE Low, unstable

No background rejection

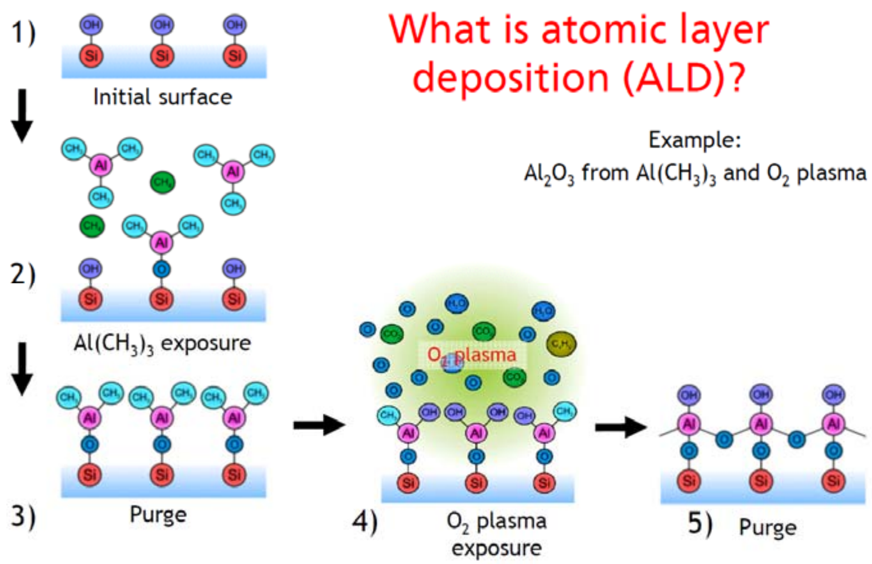
Signal
220 nm

Background
330 nm

Dead layer formed by p+ implant

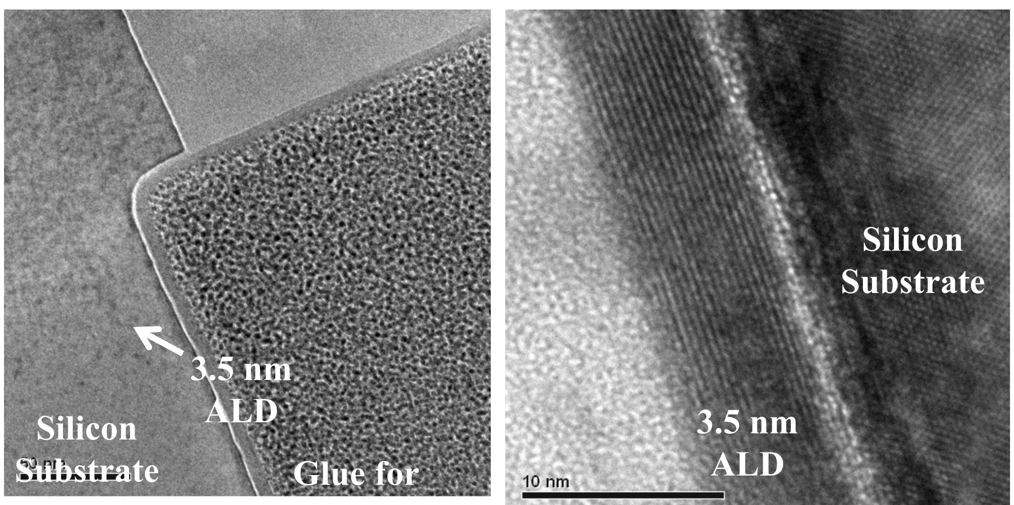
Ultraviolet light is absorbed near the surface

Atomic Layer Deposition (ALD)



- Achieves layer-by-layer growth of films with ***Angstrom***-level control over arbitrarily large surface areas
- Wide suite of materials metals, oxides, and nitrides with excellent film properties
- Can be directly integrated into existing detectors/instruments to vastly improve performance

TEM images of ultra-thin (3.5nm), conformal ALD film



Key advantages of ALD

- Fully complements the surface engineering capabilities of Si MBE with atomic control of ALD
- Thickness can be specified with Angstrom resolution
  - -Enables precise, repeatable targeting of bands *e.g.* 16.5 nm vs. 23 nm of Al_2O_3
- Process is completely independent of device size