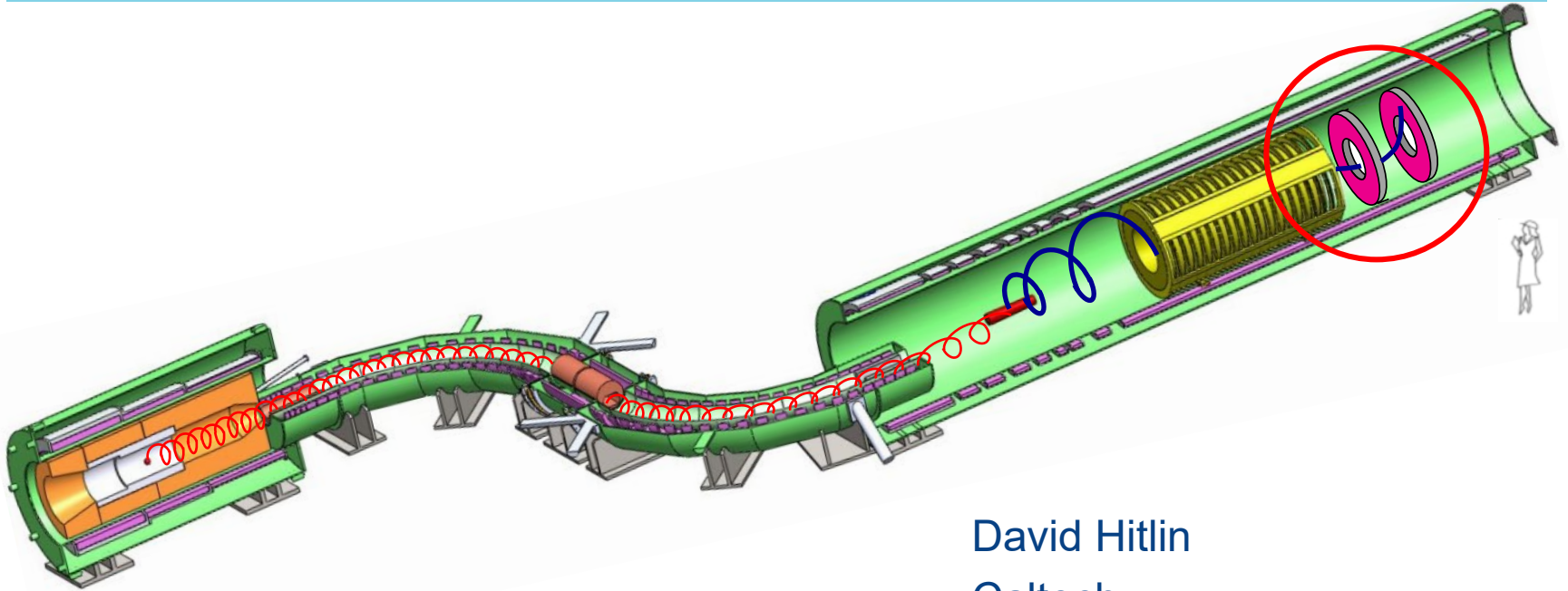


# Progress on a photosensor for the readout of the fast scintillation light component of $\text{BaF}_2$

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David Hitlin

Caltech

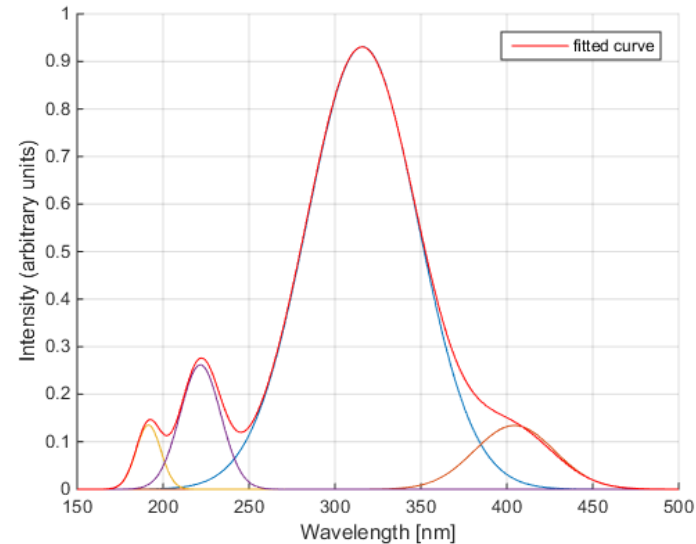
CPAD. Madison WI

December 8, 2019



# Photosensor options for BaF<sub>2</sub> readout

- BaF<sub>2</sub> has long been identified as an excellent choice for a Mu2e (II) calorimeter, provided that one has a way of utilizing the 220 nm fast component without undue interference from the 320 nm slow component
- There are actually two fast components ( $\tau < 1$  ns) at 195 and 220 nm and two slow components ( $\tau = 630$  ns) at 320 and 400 nm
- Viable approaches:
  - Directly suppress the slow scintillation component
  - Interpose an external filter
  - Use a photosensor that is sensitive only to the fast component
- Suppression of the BaF<sub>2</sub> slow component by Y doping, as developed by Zhu *et al.*, is a major advance, although quite a bit of R&D remains
  - Is the resulting fast-to-slow component amplitude ratio already sufficient to meet the rate and time resolution requirements of Mu2e-II?
  - If the consensus is “Yes”, I can perhaps conclude my presentation here



# Photosensor options for Y-doped BaF<sub>2</sub>

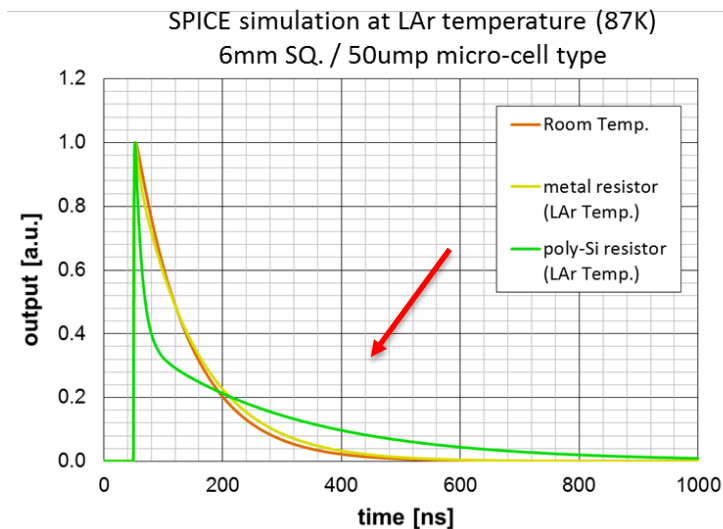
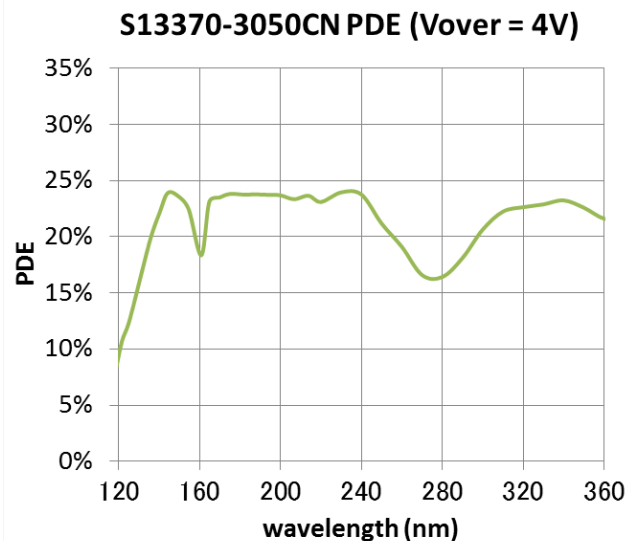
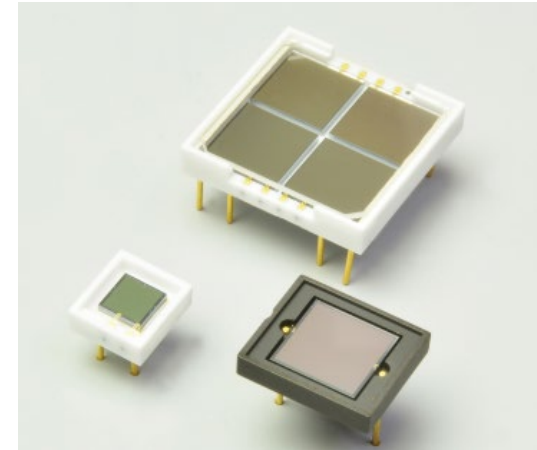
- I believe we still lack an ideal photosensor for the rates of Mu2e-II
- What is required of an appropriate photosensor?
  - **Spectral sensitivity** in the 200 nm region for best energy and time resolution
  - **Fast/slow component discrimination** for high rate capability
  - Improved **rise/fall time** characteristics to fully capitalize on the fast component native time resolution and rate capability
  - **Radiation hardness** (photons/neutrons)
- Photosensor candidates
  - Large area SiPMs developed for the MEG upgrade, DUNE, ... having ~25% PDE at 220nm (these already exist – e.g., Hamamatsu, FBK,,)
  - Large area delta-doped APDs with an integrated filter, having 50% PDE at 220nm and strong suppression at 320nm developed at Caltech/JPL/RMD
    - These have larger dark current and more noise than standard RMD devices, but can be run at reduced temperatures
  - Large area SiPMs with an integrated filter and potentially improved time response are currently under development at Caltech/JPL/FBK
  - Affordable MCPs, *i.e.*, LAPPDs



# Hamamatsu VUV MPPC

## S13370 series

- High PDE in VUV wavelength range
  - No slow/fast component discrimination
- Low optical crosstalk through trench structure
- Typical decay time of a large area device, dictated by RC
- 4@ 6x6mm
- Work at cryogenic temperatures

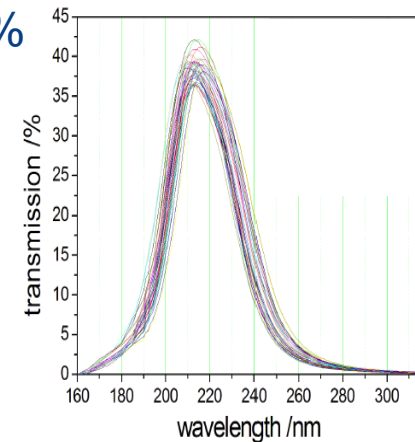
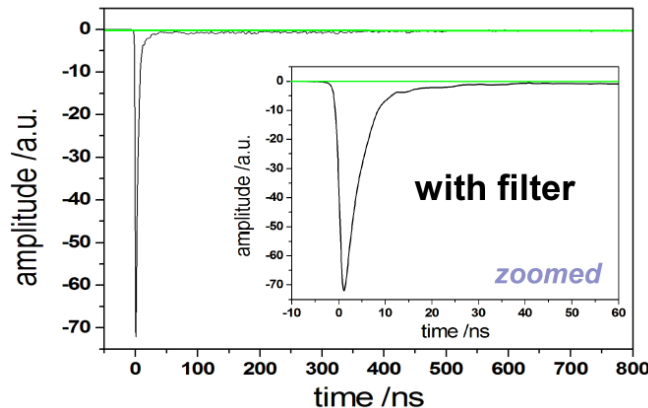
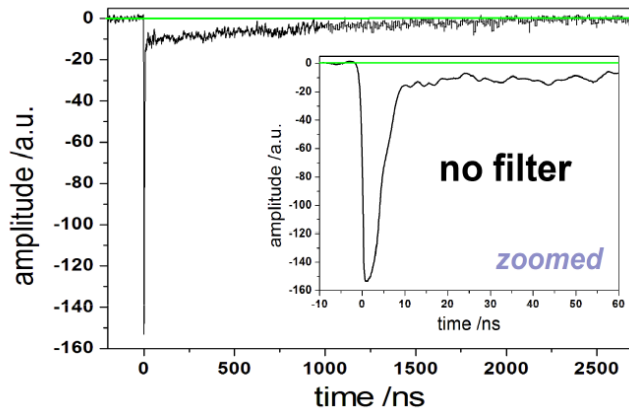
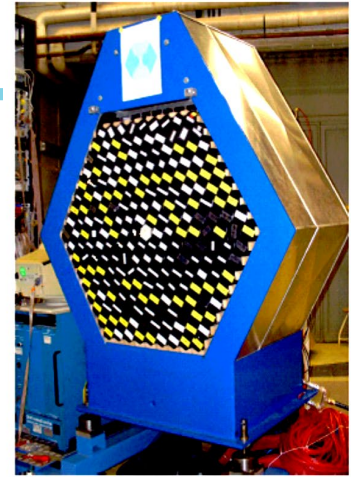


Series/parallel connection of 6x6 mm SiPMs, as in the current Mu2e calorimeter, improves decay time characteristics



# PMT + external filter

- The TAPS experiment at ELSA at Mainz (no B field) has for many years had a  $\text{BaF}_2$  forward calorimeter, reading out both fast and slow components with HR2059-01 PMTs
  - They use an integration time of  $2\mu\text{s}$ ; they are thus limited to a single crystal rate of  $\sim 100\text{kHz}$
- An upgrade must cope with increased rates, so they eliminate the slow component using a bandpass filter centered at  $214\text{ nm}$  with a transmission at  $\lambda_{\text{max}}$  that varies from 36 to 42%
- Elimination of the slow component allows a gate of  $20\text{ns}$ , with a resulting single crystal rate capability up to  $\sim 2\text{ MHz}$

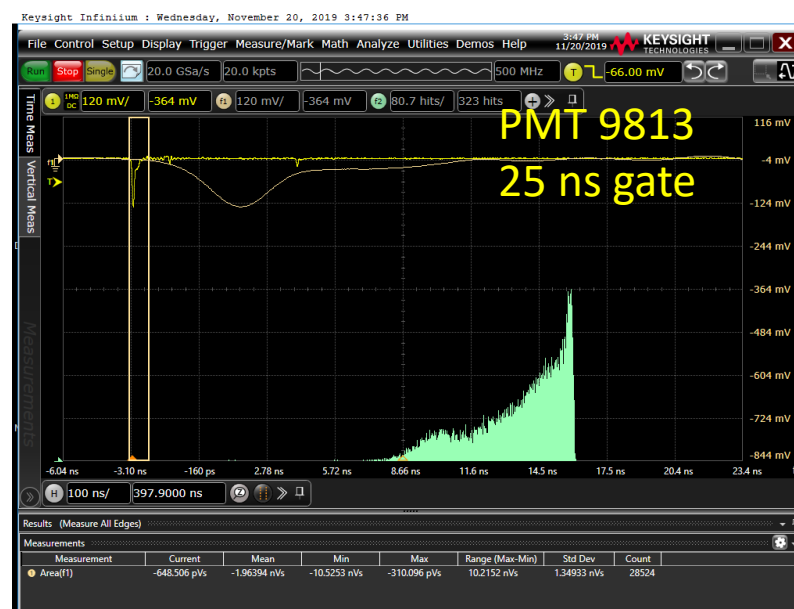
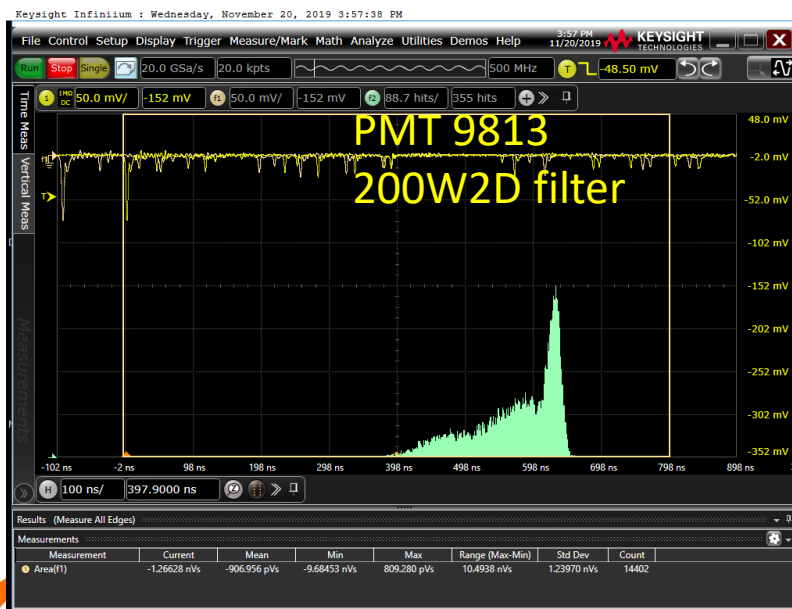
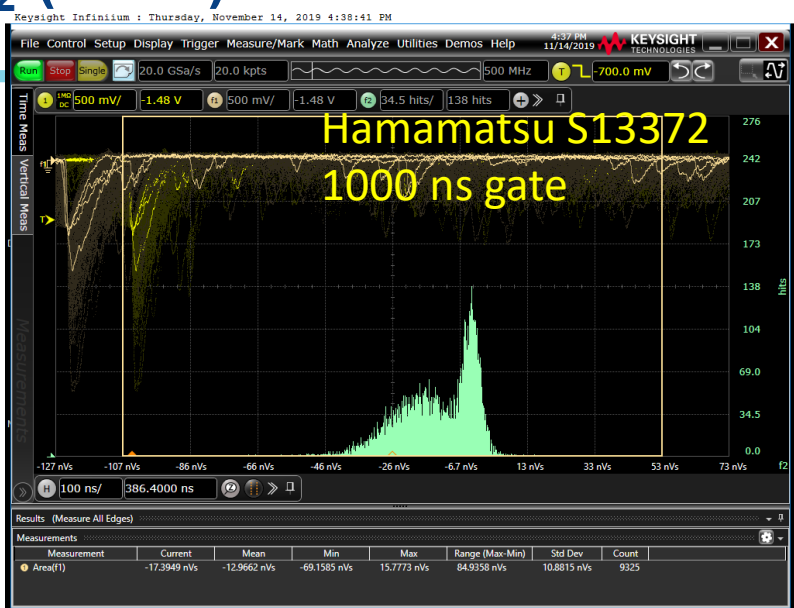
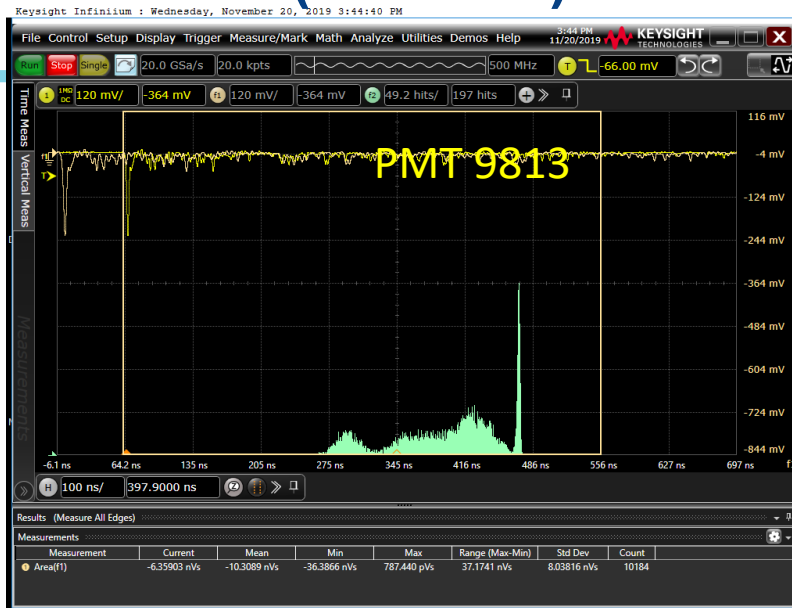


S. Diehl, R.W. Novotny,  
B. Wohlfahrt and R. Beck,  
CALOR 2014

An external filter can also be used with an appropriate solid state photosensor  
However, an filter integrated with the silicon sensor can achieve greater efficiency



# $^{137}\text{Cs}$ line (662 keV) on $\text{BaF}_2$ (1cm<sup>3</sup>)





# Integrated approaches

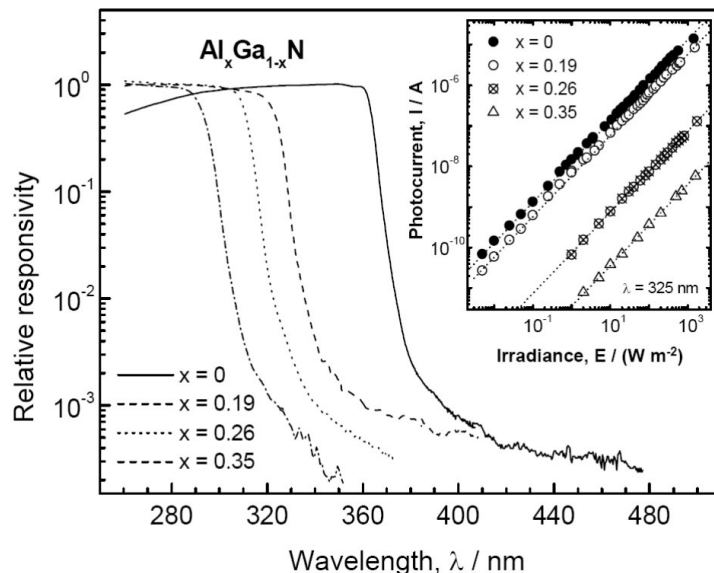
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- The **LAPPD**, a channel plate PMT that works in a magnetic field, is very fast and potentially very attractive, but a great deal of R&D remains before we have practical device for use with  $\text{BaF}_2$ 
  - Need either a photocathode with an extended UV response and a quartz entrance window (*i.e.*, no filter), or
  - An efficient filter and/or wavelength-shifting coating on the window
  - A size appropriate to the scintillating crystal Molière radius
  - An affordable price
- DH and RYZ had initiated an effort with ANL to develop an 8x8 cm LAAPD with a  $\text{Cs}_2\text{Te}$  UV-extended solar-blind photocathode
  - After preliminary discussions, this effort has been suspended



# AlGaN photocathodes for an MCP

- AlGaN photocathodes have UV sensitivity and are solar-blind
- Have been used in astrophysics for years,  $QE_{\text{opaque}} \sim 30\%$  at 220 nm
- Wide-band semiconductors such as AlGaN are radiation-hard



U.Schühle, J.-F.Hochedez, "Solar-Blind UV detectors", ISSI Scientific Report SR-009, ISBN: 978-92-9221-938-3

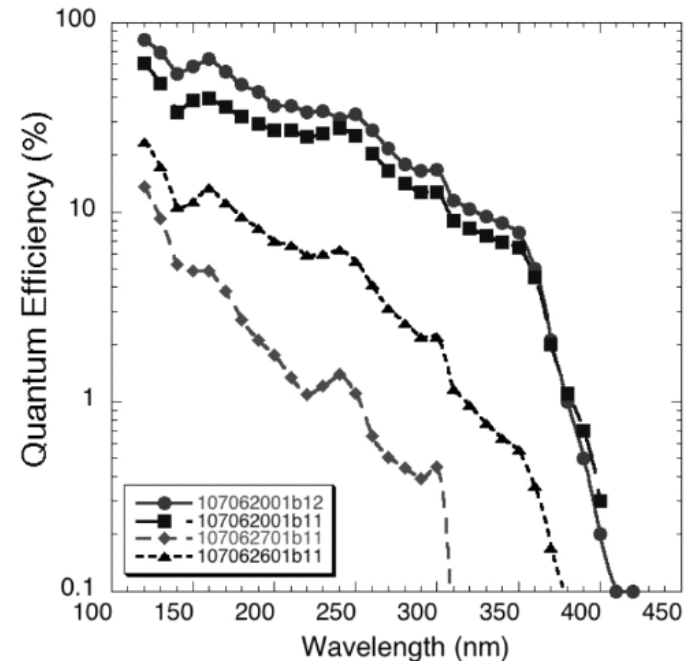


Figure 9. Opaque QE vs. wavelength for 500nm GaN on Alumina substrates (107062701 solid alumina substrate, 107062601 – substrate with 25 $\mu$ m holes) compared with 150nm GaN (107062001 [two thermal procedures]).

O.Siegmund *et al*, Proc.SPIE 7021,70211B, 2008, doi:10.1117/12.790076





# Integrated approaches

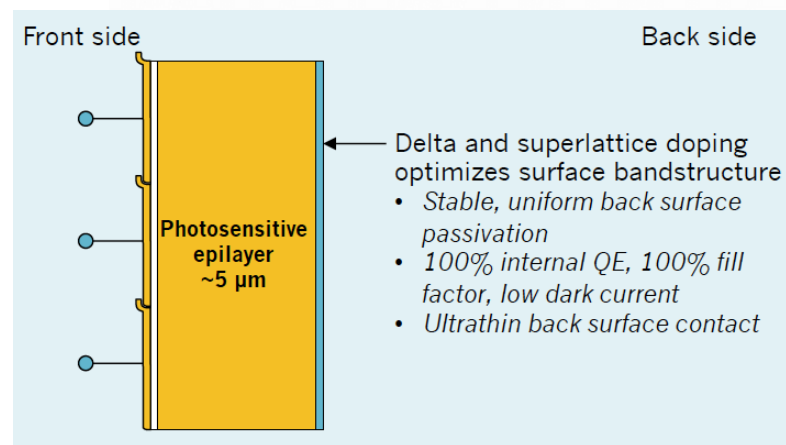
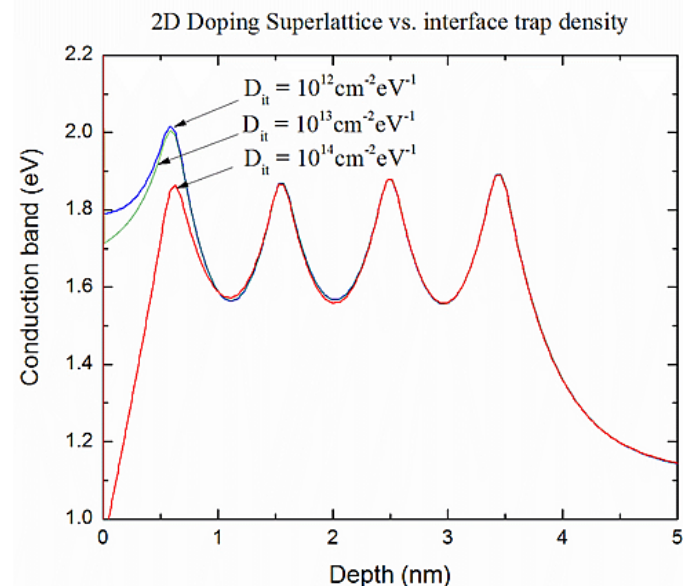
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  - Need either a photocathode with an extended UV response and a quartz entrance window (*i.e.*, no filter), or
  - An efficient filter and/or wavelength-shifting coating on the window
  - A size appropriate to the scintillating crystal Molière radius
  - An affordable price
- A large area **APD**, with delta-doping for improved speed and QE, and an integrated ALD-applied interference filter
  - Devices have been produced, but noise is large at room temperature
- A large area **SiPM**, with **delta-doping** (a super-lattice) for improved speed and QE, and an **integrated ALD-applied interference filter**
  - Development is underway
    - We made an abortive attempt with Hamamatsu
    - We have an ongoing effort with JPL/FBK
- Note that delta-doping and ALD filter application are independent processes



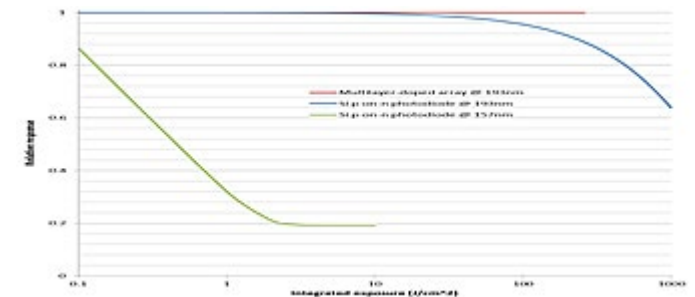
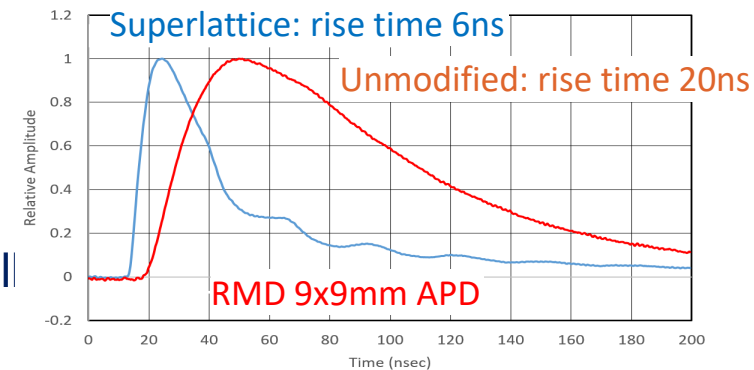
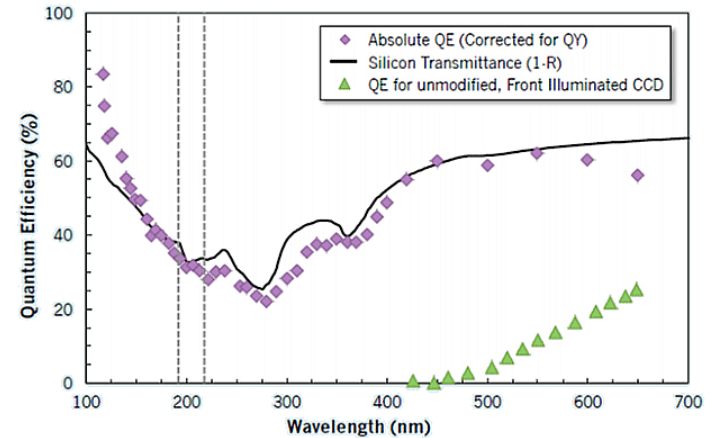
# Superlattice structures

- JPL has developed superlattice structures that provide greatly enhanced quantum efficiency and improved time response for photosensors
  - 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



# Superlattice performance improvements

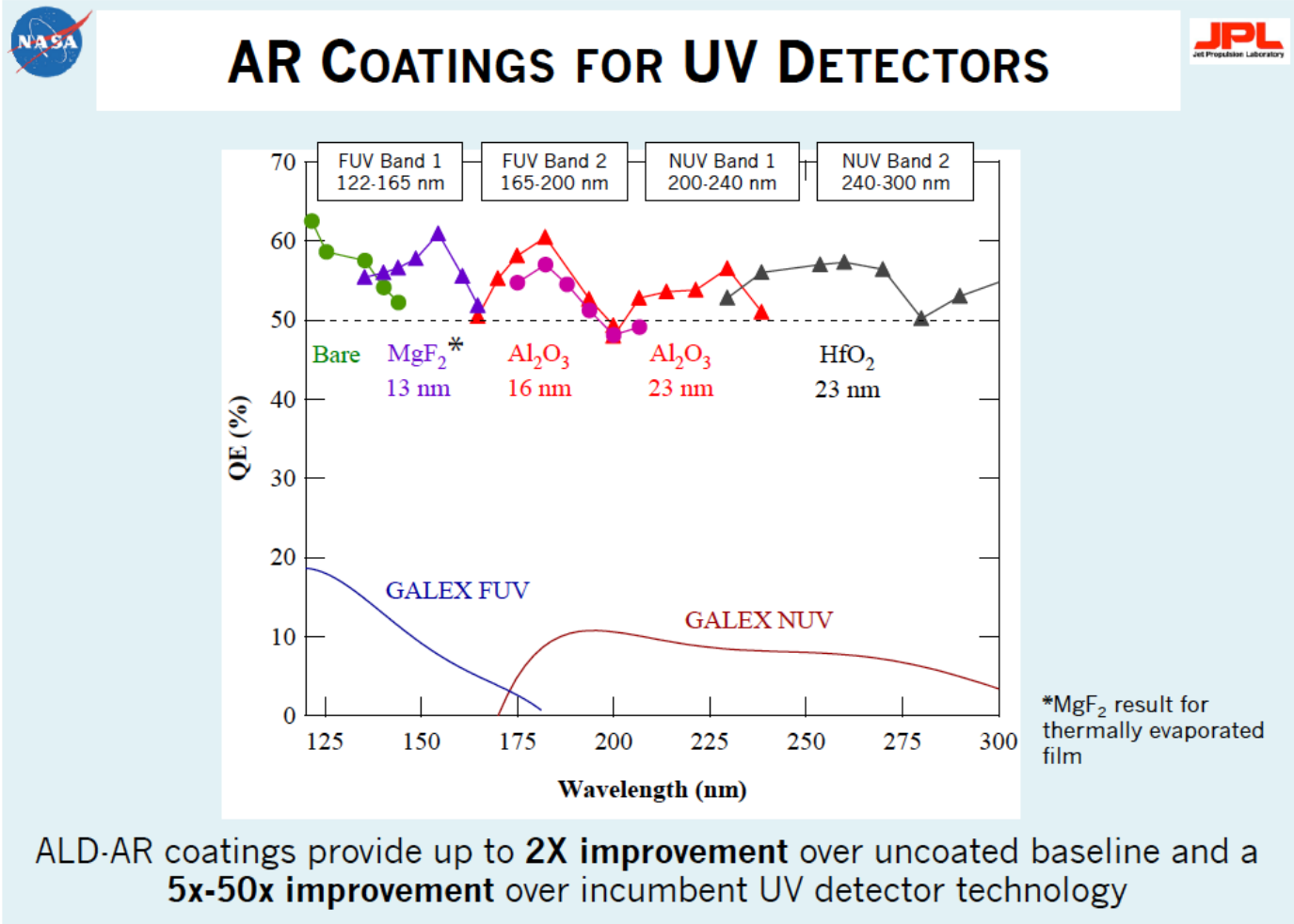
- Recombination of photoelectrons is suppressed by quantum exclusion, resulting in close to 100% internal QE
  - Quantum efficiency in the 200-300 nm region approaches the silicon transmittance (1-R) limit
- Elimination of the undepleted region before the avalanche structure substantially improves APD time performance over normal 9mm RMD device
  - This should work with SiPM structure as well
  - Both rise time and decay time are improved
- The superlattice structure provides stability under intense UV illumination
  - Relevant regime is  $\sim 1\text{-}10 \text{ J/cm}^2$



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



# ALD antireflection filters improve QE



© 2015 California Institute of Technology. Government sponsorship acknowledged

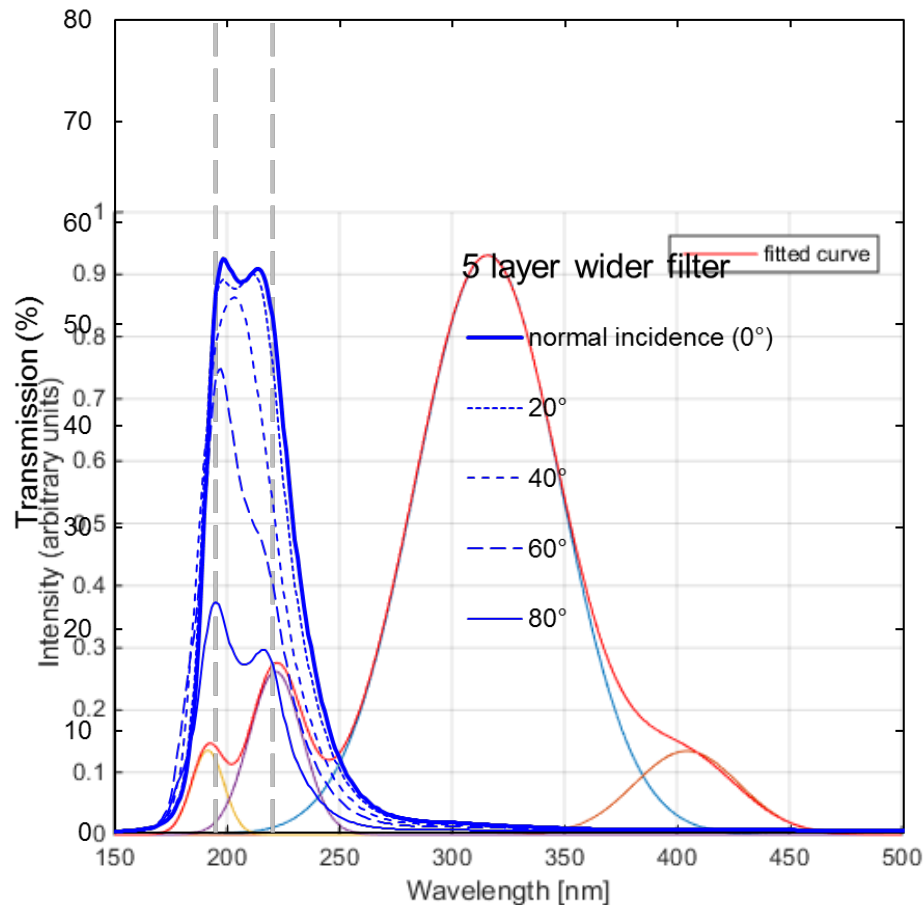
Nikzad, et al., *Applied Optics*, **51**, (2012) 365.



The ALD technique can also be used to make a bandpass filter

# ALD bandpass interference filters

- Three and five layer filters have been investigated
- The “wider” five layer filter encompasses more of the 195 nm peak and provides improved slow component suppression

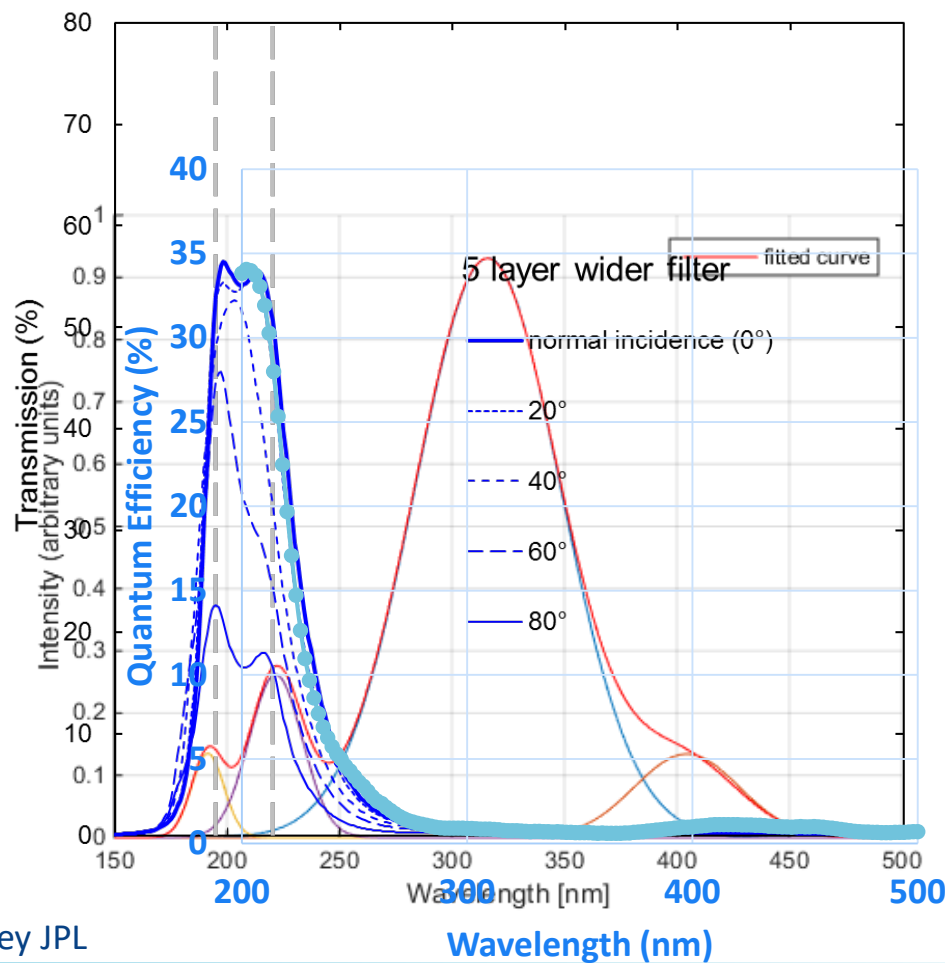


Filter characteristics vary with angle of incidence



# ALD bandpass interference filters

- Three and five layer filters have been investigated
- The “wider” five layer filter encompasses more of the 195 nm peak and provides improved slow component suppression



Measured QE on APD  
at zero bias  
QE ~ doubles at nominal gain



J. Hennessey JPL

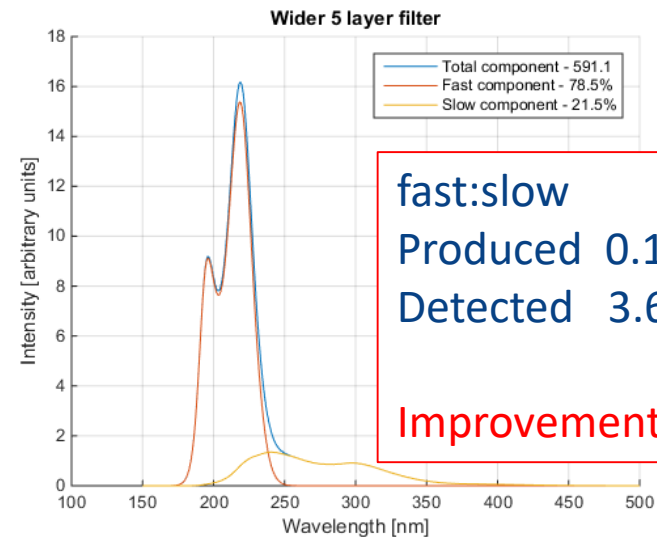
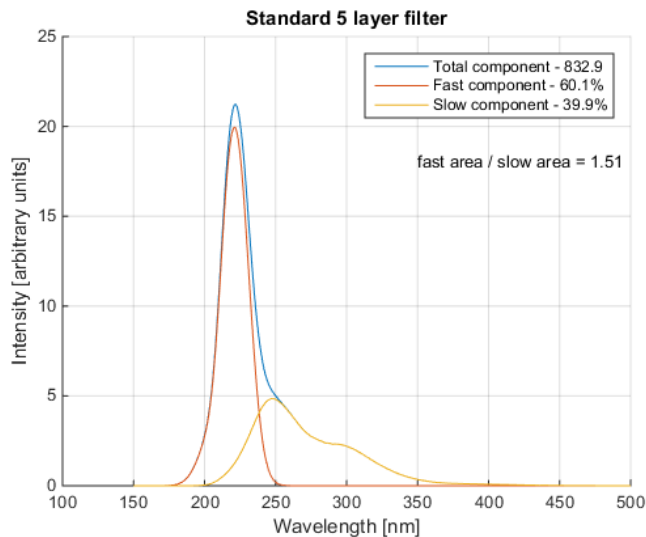
David Hitlin CPAD Madison WI

Dec. 8, 2019

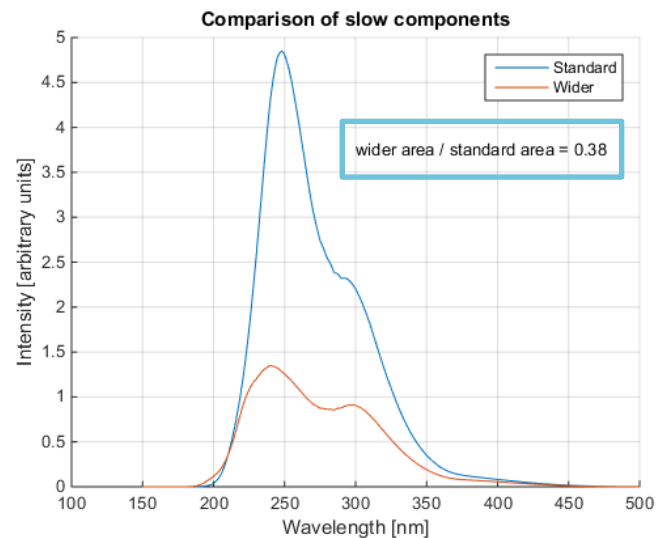
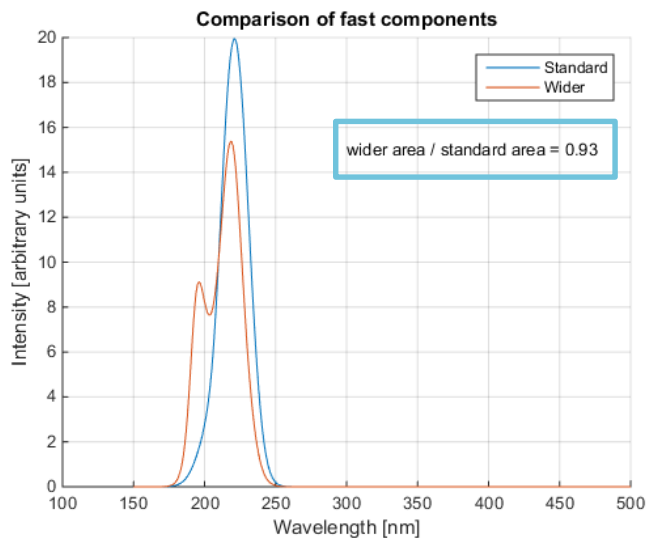
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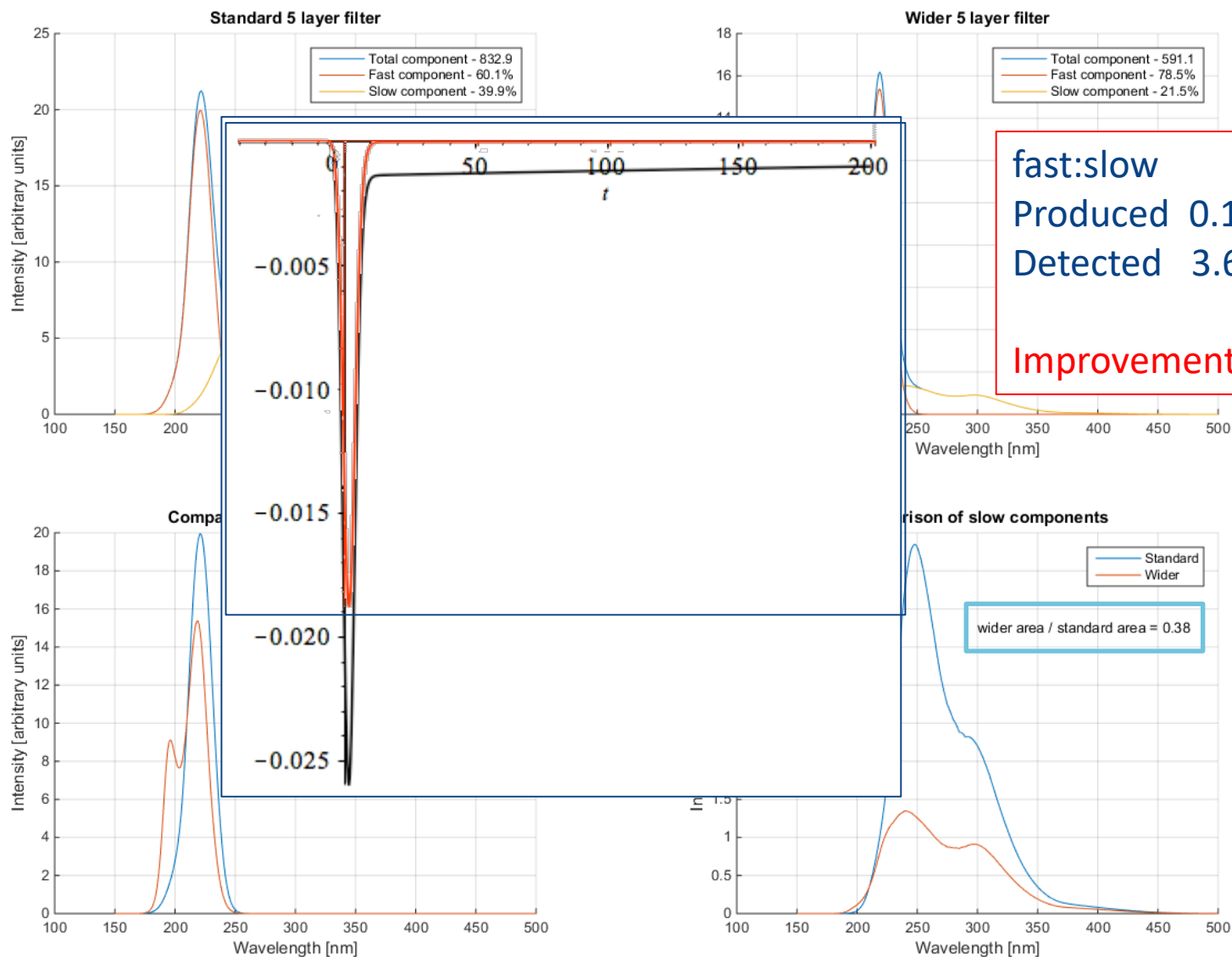
# BaF<sub>2</sub> fast/slow component comparison



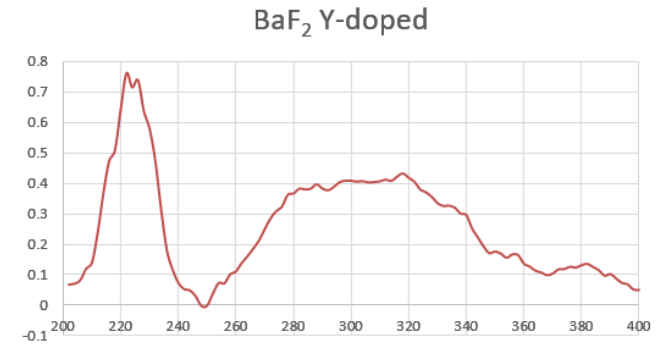
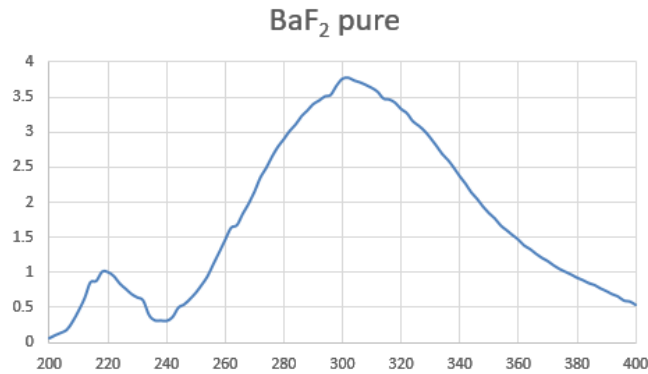
fast:slow  
Produced 0.176  
Detected 3.65  
Improvement ~20



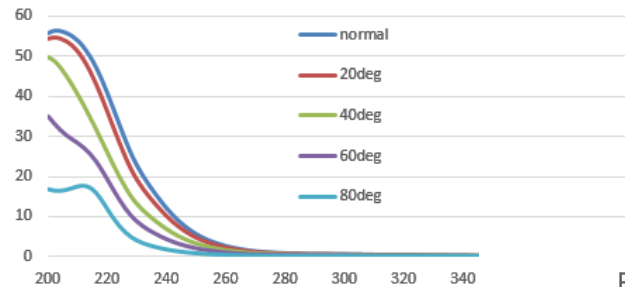
# Fast/slow component comparison



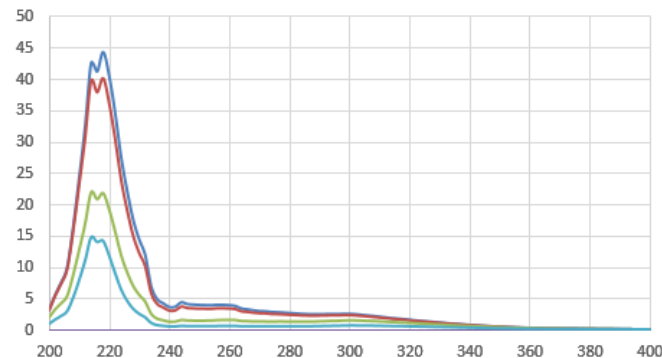
# ALD filter with Y-doped $\text{BaF}_2$ provides further suppression



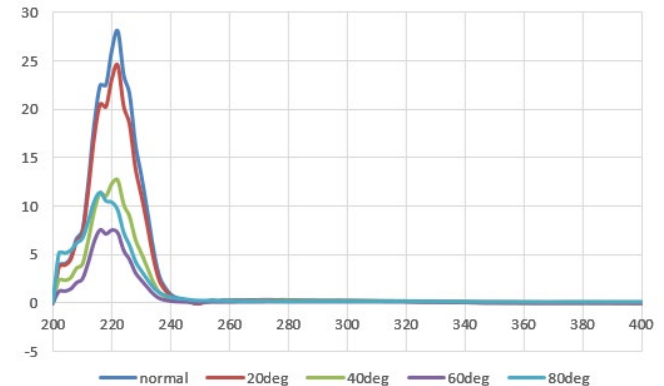
5 layer filter response



$\text{BaF}_2$  pure with 5 layer filter



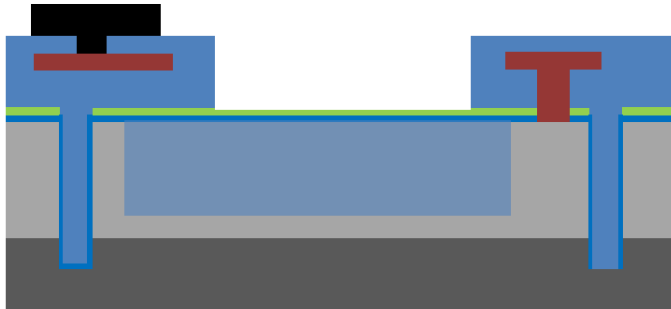
$\text{BaF}_2$  Y-doped with 5 layer filter



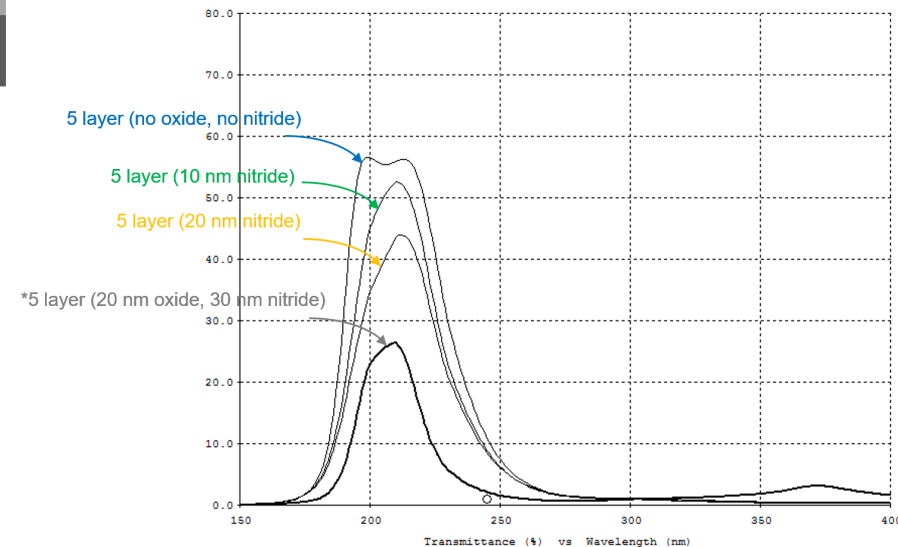
# SiPMs with ALD filter and/or delta doping

- FBK SIPM

- Caltech and JPL are working with FBK to incorporate a 220nm filter on a large area SiPM and to also incorporate a superlattice
- Many processes have been explored to remove or thin the usual  $\text{SiN}_x$  passivation from individual cells



- JPL has developed an appropriate interference filter that will be deposited at wafer level
- FBK has produced 6x6mm chips for testing at Caltech



G. Paternoster FBK    J. Hennessey JPL

# Filters built on measured passivation layer

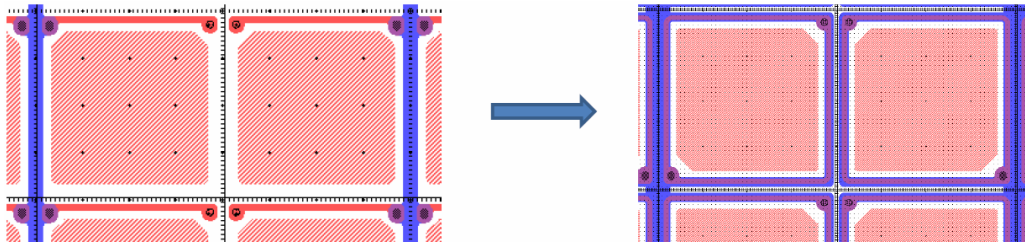
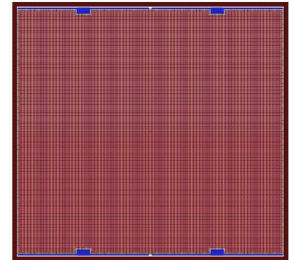
- Standard SiPM passivation is done with  $\text{SiN}_x$ 
  - This limits filter design optimization due to strong UV absorption
- We have therefore also made wafers with alternative passivation using  $\text{SiO}_2$ 
  - allows a better match to the  $\text{BaF}_2$  fast component
- Precise knowledge of the thickness of the passivation layer is required to design an optimal filter
  - Ellipsometry measurements at JPL confirm FBK thickness values
  - Nominal filter design parameters are tweaked to actual passivation layer thickness

W1 test structures		
	JPL meas.	FBK meas.
pt 1	29.25	28.78
pt 2	29.26	28.9
pt 3	29.36	29.09
pt 4	29.45	29.09
pt 5	28.58	28.29
pt 6	28.93	28.55
pt 7	29.3	28.92
pt 8	28.98	28.57
pt 9	29.48	29.16
std	0.3	0.3
avg	29.2	28.8

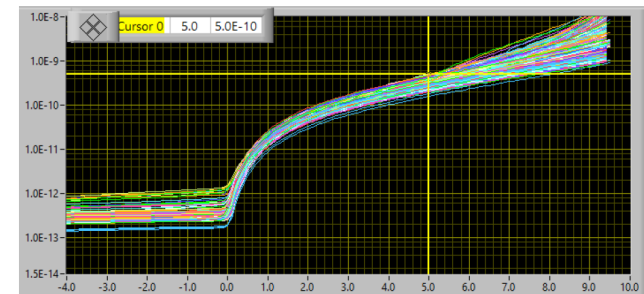


# Wafer level production and processing

- FBK has produced wafers with 6 mm x 6 mm SiPMs (actually 4 internally interconnected 3 mm x 3mm structures (35 $\mu$ m pixels) with a several process variations
  - Ion implantation after SiN<sub>x</sub> passivation
  - SiN<sub>x</sub> passivation as sacrificial layer before ion implantation, then removed and replaced
  - SiO<sub>2</sub> passivation
  - Several SiN<sub>x</sub> and SiO<sub>2</sub> thicknesses
  - Standard and with metal/poly guard ring structures



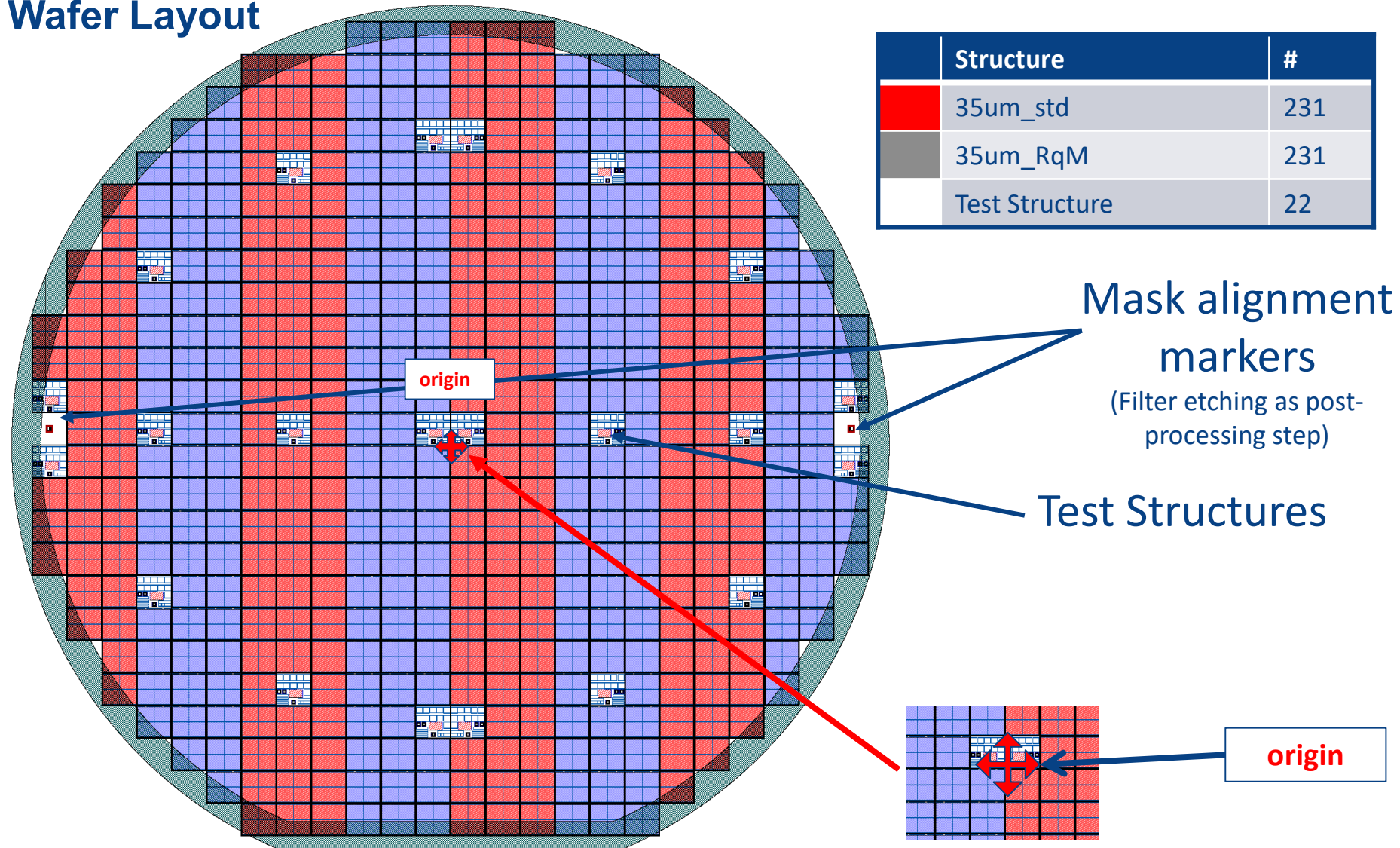
- Six wafers have been processed at JPL
  - SiN<sub>x</sub> passivation - apply filter
  - SiO<sub>2</sub> passivation – apply filter
  - SiO<sub>2</sub> passivation, no filter – delta-doped to improve QE and rise time





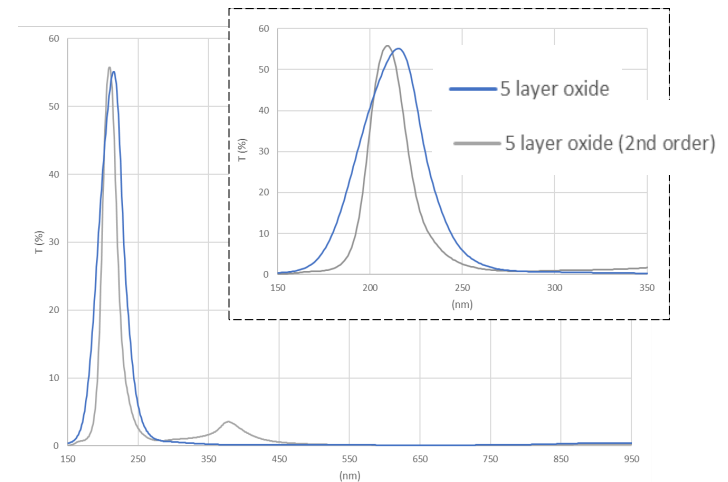
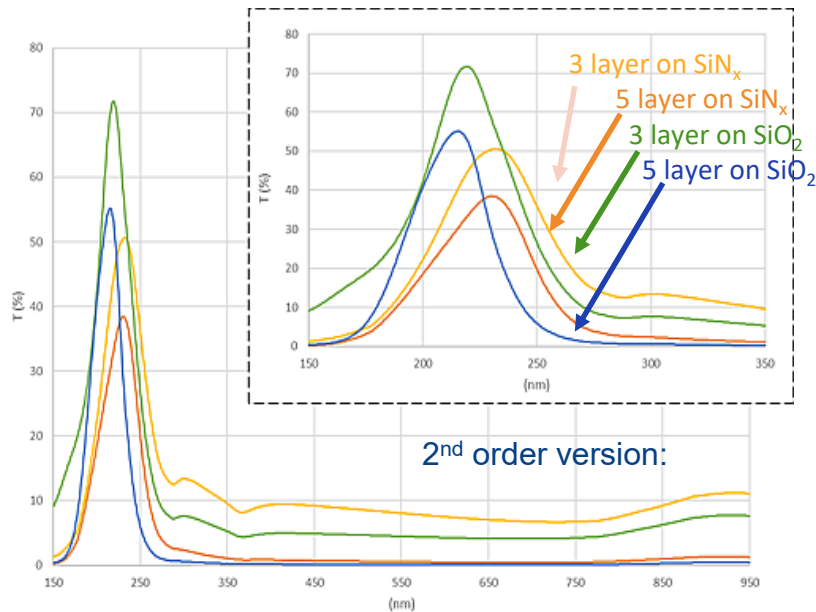
# Wafer level production and processing

## Wafer Layout

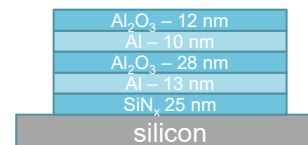


# Filter options with updated optical models

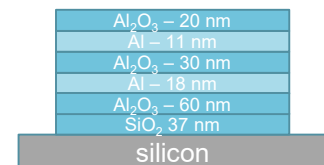
- Three layer and five layer structures in which the first layer is either  $\text{SiO}_2$  or  $\text{SiN}_x$
- All layers are thin enough that there is little advantage in moving to the higher order filters
  - The increased loss in the  $\text{SiN}_x$  makes it difficult to have significant throughput below 200 nm



First order on  $\text{SiN}_x$



Second order on  $\text{SiO}_2$



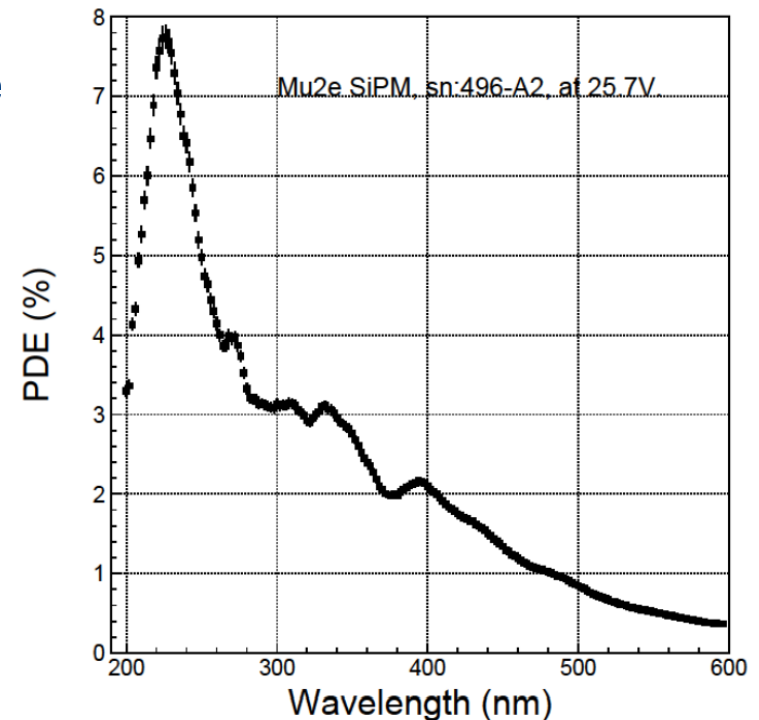
Examples:



J. Hennessey JPL

# Next steps

- After the ALD filters (and, eventually, superlattice structures) are created at JPL, the wafers are returned to FBK for probing and dicing into chips
- Chips with differing filters and with and without superlattices are being tested at Caltech for filter performance and QE and then spectra will be taken with pure and Y-doped barium fluoride crystals
  - Our existing spectrophotometer has been modified to extend response to 200 nm
- Radiation hardness studies and MTF studies will follow
- Additional wafers are available for further rounds with modified parameters
- Measured QE of a five-layer filter on a device that was not brought to full bias, resulting in surface recombination and incomplete charge collection



# Conclusions

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- A very fast barium fluoride crystal calorimeter that exploits the fast scintillation component for its high rate capability and excellent time resolution is an appropriate component of a Mu2e-II upgrade or other high rate experiments
- Y-doped BaF<sub>2</sub> provides very significant suppression of the 320 nm slow component with little effect on the 220 nm fast component
- In order to fully exploit the < 1ns decay time of the fast component for improved rate capability and time resolution, better photosensors are required and several are under development
- Desired device characteristics
  - High gain
  - High QE for the 220nm BaF<sub>2</sub> fast component
  - Insensitive to the 320nm BaF<sub>2</sub> slow component
  - Excellent rate performance
  - UV stable
  - Radiation hard to  $\gamma$ s and neutrons
- A SiPM with these performance characteristics is in development
- Other promising technologies may yet emerge

