Progress on a photosensor for the readout of the fast scintillation light component of BaF$_2$
Photosensor options for BaF$_2$ readout

- BaF$_2$ 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$_2$ 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$_2$

- 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 BaF$_2$ forward calorimeter, reading out both fast and slow components with HR2059-01 PMTs
  - They use an integration time of 2µs; they are thus limited to a single crystal rate of ~100kHz
- An upgrade must cope with increased rates, so they eliminate the slow component using a bandpass filter centered at 214 nm with a transmission at $\lambda_{\text{max}}$ that varies from 36 to 42%
- Elimination of the slow component allows a gate of 20ns, with a resulting single crystal rate capability up to ~2 MHz

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 BaF$_2$ (1cm$^3$)

PMT 9813

Hamamatsu S13372
1000 ns gate

PMT 9813
200W2D filter

PMT 9813
25 ns gate
Integrated approaches

- 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 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 Cs$_2$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_{opaque} \sim 30\% at 220 nm
- Wide-band semiconductors such as AlGaN are radiation-hard

- Could be used as photocathodes for MCP devices
- An interference filter could be incorporated

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]).

Integrated approaches

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- 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 \( \sim 1\text{-}10 \text{ J/cm}^2 \)

ALD antireflection filters improve QE

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

AR Coatings for UV Detectors

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

*NfF₂ result for thermally evaporated film

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.

J. Hennessey JPL

David Hitlin  CPAD Madison WI  Dec. 8, 2019
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
BaF$_2$ fast/slow component comparison

**Dec. 8, 2019**

David Hitlin      CPAD Madison WI 15
Fast/slow component comparison

**Produced**: 0.176

**Detected**: 3.65

**Improvement**: ~20
ALD filter with Y-doped BaF$_2$ provides further suppression

![Graphs showing the filter response for pure BaF$_2$ and Y-doped BaF$_2$ with and without a 5-layer filter.](https://example.com/graphs.png)
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 processed have been explored to remove or thin the usual 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 SiN_x
  - This limits filter design optimization due to strong UV absorption
- We have therefore also made wafers with alternative passivation using SiO_2
  - allows a better match to the 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

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<th>FBK meas.</th>
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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 (35µm pixels) with a several process variations
  – Ion implantation after SiN_x passivation
  – SiN_x passivation as sacrificial layer before ion implantation, then removed and replaced
  – SiO_2 passivation
  – Several SiN_x and SiO_2 thicknesses
  – Standard and with metal/poly guard ring structures

• Six wafers have been processed at JPL
  – SiN_x passivation - apply filter
  – SiO_2 passivation – apply filter
  – SiO_2 passivation, no filter – delta-doped to improve QE and rise time
Wafer level production and processing

Wafer Layout

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<td>Test Structure</td>
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Test Structures

Mask alignment markers
(Filter etching as post-processing step)

origin

Dec. 8, 2019
Filter options with updated optical models

- Three layer and five layer structures in which the first layer is either SiO₂ or SiNₓ
- All layers are thin enough that there is little advantage in moving to the higher order filters
  - The increased loss in the SiNₓ makes it difficult to have significant throughput below 200 nm

Examples:

- 3 layer on SiNₓ
- 5 layer on SiNₓ
- 3 layer on SiO₂
- 5 layer on SiO₂

2nd order version:

First order on SiNₓ
- Al₂O₃ – 12 nm
- Al – 10 nm
- Al₂O₃ – 28 nm
- Al – 13 nm
- SiNₓ – 25 nm

Second order on SiO₂
- Al₂O₃ – 20 nm
- Al – 11 nm
- Al₂O₃ – 30 nm
- Al – 19 nm
- Al₂O₃ – 60 nm
- SiO₂ – 37 nm

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

- 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$_2$ 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 $<1$ns 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$_2$ fast component
    - Insensitive to the 320nm BaF$_2$ 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.