Progress on a photosensor for the readout of the fast scintillation light component of BaF$_2$
BaF$_2$ scintillator and photosensors

- BaF$_2$ is an excellent candidate for a fast, high rate, radiation-hard crystal for the Mu2e-II calorimeter, provided that one has a way of utilizing the 220 nm cross-luminescence fast component (1500 photons/MeV) without undue interference from the larger 320 nm slow component
  - There are actually two fast components ($\tau = 0.6$ ns) at 195 and 220 nm and two slow components ($\tau = 630$ ns) at 320 and 400 nm
- Our approach to BaF$_2$ calorimetry
  1. Suppress the BaF$_2$ slow component by Y doping, as developed by Zhu et al.: a major advance, although much R&D remains to be done
  2. Develop a photosensor that is sensitive only to the fast component, is rad-hard and works in a magnetic field – our solution is a large area SiPM

The photosensor is being developed by a Caltech/JPL/FBK collaboration:

- JPL: J. Hennessy, M. Hoenk, A. Jewell
- FBK: A. Ficorella, A. Gola, G. Paternoster
Pure and Y-doped BaF$_2$

Fast (220nm) and slow (320 nm) scintillation components

Y doping can suppress slow scintillation component

Radiation hardness (pure BaF$_2$)

BaF$_2$ with a VUV SiPM readout has the best experimental coincidence time resolution (CTR) achieved with PET-sized crystals

Building on our experience with a large area APD developed with RMD, we have adopted a phased SiPM development approach:

1. Incorporate a three-layer ALD filter on a 6x6 mm NUV SiPM structure, exploring different SiNx passivation layers, guard ring structures, …
2. Fabricate 2x3 arrays of the 6x6 mm chips, biased in series parallel configuration à la MEG and Mu2e to read out larger crystals
3. Improve slow component rejection with more sophisticated filters
4. Use delta doping and backside illumination to improve PDE, the effectiveness of the filter, and timing performance

I will show results from the first 6x6mm chip arrays:
- I/V curves
- Excess noise measurements
- PDE as a function of wavelength, demonstrating filter performance
- Radioactive decay and cosmic ray spectra with small BaF₂ crystals

We have detailed plans for the next rounds of R&D, which will provide an improved filter, better UV tolerance and improved time response.
ALD antireflection filters improve QE

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.

This ALD technique can be used to make a sophisticated bandpass filter.

ALD bandpass interference filters

- A five-layer filter encompasses both the 195 nm and 220 nm peaks and provides improved slow component suppression
- Upper side performance has been measured on an APD at zero bias

Transmission of an interference filter is dependent on angle of incidence

The passivation layer on which the filter is constructed is SiO₂
ALD bandpass interference filters

- A five-layer filter encompasses both the 195 nm and 220 nm peaks and provides improved slow component suppression.
- Upper side performance has been measured on an APD at zero bias.

Fabricated RMD APDs worked well, but were fragile and noisy at room temperature.

Measurement is scaled using a model to obtain the QE at nominal gain/bias.
SiPM fabrication and test

- FBK has fabricated wafers based on current NUV designs, with various modifications, including guard ring structures
- FBK thins or removes SINx passivation layer
- ALD filters are deposited at JPL
- The wafers are returned to FBK for probing and dicing into chips
- 6x6mm devices with three-layer filters have been fabricated and tested at Caltech
  - Filter performance and PDE as a function of wavelength have been measured with a spectrophotometer down to 200nm
  - We have characterized excess noise performance
  - We have then taken radioactive decay and cosmic ray spectra with pure BaF$_2$ crystals, measuring the fast/slow scintillation yield
Wafer level production and processing

Wafer Layout

<table>
<thead>
<tr>
<th>Structure</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>35(\mu)m_std</td>
<td>231</td>
</tr>
<tr>
<td>35(\mu)m_RqM</td>
<td>231</td>
</tr>
<tr>
<td>Test Structure</td>
<td>22</td>
</tr>
</tbody>
</table>

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

Test Structures
Recognizing the greater complexity of the SiPM structure, we began with a simpler three-layer filter designed to incorporate a thinned SiNx passivation layer.

The bandpass of this filter is broader than that of a five-layer filter and has less suppression of the slow component.
FBK SiPM I-V Curves

W11

- Voltage (V)
- Current (µA)
- Curves for 611, 612, 613

NUV

- Voltage (V)
- Current (µA)
- Curves for 614, 615, 616

March 18, 2021

David Hitlin  CPAD Instrumentation Frontier Workshop
Excess Noise Factor: FBK #611

\[ \sigma^2_{\text{observed}} = \sigma^2_{\text{Poisson}} + \sigma^2_{\text{SiPM}} + \sigma^2_{\text{Electronics}} + \sigma^2_{\text{LED}} \]

\[ = N_{\text{pe (Poisson)}} + N_{\text{pe}} \times \sigma^2_{\text{pe}} + \sigma^2_{\text{Pedstal}} + \sigma^2_{\text{LED}} \]

\[ = N_{\text{pe (Poisson)}} \times \left(1 + \sigma^2_{\text{pe}} + \sigma^2_{\text{Pedstal}}/N_{\text{pe}} + \sigma^2_{\text{LED}}/N_{\text{pe}} \right) \]

\[ \text{ENF} = \frac{\sigma^2_{\text{observed}}}{N_{\text{pe (Poisson)}}} = \frac{N_{\text{pe (Poisson)}}}{(\mu_{\text{observed}}/\sigma_{\text{observed}})^2} \]

\[ \therefore \mu_{\text{observed}} = N_{\text{pe (Poisson)}} \]
FBK SiPM measured performance

PDE scanned vs. wavelength at several bias voltages, with gain measured

Calibrated with pulsed LED @ 465 nm for SiPM bias at 29 V

Excess noise factor determined at each bias

L. Zhang, J. Oyang

Filtered SiPM PDE (%) with pure and 6% Y doped BaF₂ spectra (AU)
BaF$_2$ + AmBe: PMT and SiPM readout

- An AmBe neutron source emits copious 4.4 MeV gammas
- FBK SiPM #611 operated at 29.5V
- BaF$_2$ dimension 9 x 9 x 9 mm, wrapped with teflon with an opening of 6x6 mm
- $3400 \text{ (adc)} / 29.1 \text{(pe/adc)} = 117 \text{ pe}$
- $117 \text{ pe} / 4.4 \text{ MeV} = 27 \text{ pe/MeV}$

J. Oyang

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FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
BaF$_2$ dimension 1” x 1” x 1”, wrapped with teflon with an opening of 6x6 (mm)
Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2 MeV
(26631 - 68) adc / 148 pe/adc = 180 pe
180 pe / 16.2 MeV = 11 pe/MeV   With 2x3 array, expect 60-70 pe/MeV
Use of 200 and 2000 ns gates allows extraction of ratio of slow-to-fast scintillation components seen by filtered SiPM: ~4
SiPM 611 BaF$_2$ with AmBe source (4.4 MeV)

Use of 200 and 2000 ns gates allows extraction of ratio of slow to fast scintillation components seen by filtered SiPM: ~4

March 18, 2021
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CPAD Instrumentation Frontier Workshop
Rise/fall time measurement: FBK #611

- Measured with a picosecond laser
  - $\lambda = 373$ nm
  - Pulse width 21 ps

Laser: -10dB
FBK#611 @29.5 V
Pulse Height: 10 mV
Rise time: $1317 \pm 156$ psec
20/80

decay time: 150 nsec
The bandpass of the five-layer filter (this design assumes complete removal of SiNx passivation) is narrower, encompasses the small 195nm fast component and has superior suppression of the slow component.
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The bandpass of the five-layer filter (this design assumes complete removal of SiNx passivation) is narrower, encompasses the small 195nm fast component and has superior suppression of the slow component.
Further improvement of fast/slow performance

- A system comprising
  - 6% Y-doped BaF$_2$ crystals
  - five-layer filtered SiPMs

provides a ratio of fast-to-slow scintillation components that enables high quality electromagnetic calorimetry in high-rate applications such as Mu2e-II.
Current status and plans

• Next steps in the program
  – Measure spectra with Y-doped BaF$_2$ crystals to verify the fast/slow scintillation yield
  – Employ 3 x 2 chip array of 6x6mm chips in series/parallel configuration to read out larger crystals
    – we have samples in hand
  – Measure radiation hardness with γ’s and neutrons
  – Burn-in studies for MTF
  – Fab more sophisticated five-layer filters on remaining wafers – this is getting underway as JPL reopens
  – Produce delta-doped superlattice, back-illuminated versions that will have improved QE and timing characteristics
Superlattice structures

- JPL has developed superlattice (delta-doped) structures that provide enhanced quantum efficiency and improved time response for photosensors
  - Delta-doped 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 photosensitive surface of the SiPM using molecular beam epitaxy (MBE) (2D doping)
- The MBE layers allow the conduction band to remain stable with varying surface charge
What does the superlattice do?

- 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 improved time performance** over a normal 9mm RMD APD
  - This should work with SiPM structure as well
    - Both rise time and decay time were improved

- The superlattice structure provides **stability under intense UV illumination**
  - Relevant regime for Mu2e-II is ~ .1-10 J/cm² of 200 -300 nm UV (~ 4-6 eV)

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Next steps in the program

1. Optimization of the MBE superlattice layer parameters
   - In order to decouple the details of fabricating surface structures from the avalanche structures, this will first be done on a photodiode (i.e., no gain)
   - A superlattice will be added to diode structures with SiPM-like layouts of different area, in order to evaluate the relative contribution of surface and volume leakage currents

![Diode structures with different areas](image)

2. More complex filters will be incorporated

![Layer structure diagram](image)

Process variation study

*10% thickness variation in deposited Al layers only*
Next steps – the ultimate goal

3. Backside illuminated SiPM with optimized superlattice
   - Decouples the illumination/collection region and the high field avalanche region
   - Provides a higher fill factor
   - Provides robust protection against damage from UV scintillation light
   - Allows for more options for the filter design
   - Requires wafer thinning and bonding

   - Design will incorporate what we learn from MBE on the photodiode structures
Conclusions

- A barium fluoride crystal calorimeter that exploits the fast scintillation component for its high-rate capability and excellent time resolution is an important component of high-rate experiments such as Mu2e-II and could improve volumetric resolution in PET as well
  - 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 0.6ns decay time of the fast component for improved rate capability and time resolution, a UV sensitive filtered SiPM is required and is under development

- Desired device characteristics
  - High gain ✓
  - Good PDE for the 220nm BaF$_2$ fast component ✓
  - Rejection of the 320nm BaF$_2$ slow component ✓
  - Excellent rate performance
  - UV stability
  - Radiation hard to gammas, neutrons and UV photons

- We are building on the initial success towards a fully capable device
MCP PMTs for BaF$_2$ – an aside

- Microchannel PMTs at first glance seem like an attractive photosensor for BaF$_2$ readout
  - Large area
  - High gain
  - Work in a magnetic field
  - Capable of 30ps timing
  - With ALD coating, there is a factor of two gain reduction at 5 C/cm$^2$ collected at the anode
- Barium fluoride scintillation emits 12,000 optical photons/MeV (fast+slow component)
  - A 10 krad exposure (100J/kG) to a 3x3x30 cm$^3$ crystal produces 75 x 10$^{18}$ photons, or 23 x 10$^{16}$ pe at 10% geometric and 30% photocathode efficiency. With a 9 cm$^2$ cross section and a gain of 10$^6$, this is $\sim$1.7 x 10$^4$ C/cm$^2$ collected at the anode
  - Thus, MCPs are not suitable for readout of scintillating crystals in a high-rate environment