An APD for the efficient detection of the fast scintillation component of BaF₂

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Abstract

Barium fluoride crystals are the baseline choice for the calorimeter of the Mu2e experiment at Fermilab. By the fast (decay time 0.9 ns) 220 nm scintillation component and discriminating against the larger slow (decay time 630ns) 300 nm component, it is possible to build a radiation-hard calorimeter with good energy and time resolution and high rate capability. This requires a solid state photosensor with high quantum efficiency at 220 nm, discrimination against the 300 nm component and good rise and decay times. Progress on the development of such a sensor is presented.

Keywords: barium fluoride, photosensors, APD, solar blind, superlattice, atomic layer deposition

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1. Introduction

The Mu2e experiment at Fermilab[1] employs a crystal calorimeter for the identification of 105 MeV electrons produced in the rare process of muon-to-electron conversion on an aluminium nucleus. The calorimeter must operate in a high rate, high radiation, environment, in the presence of substantial background from muon decay and muon capture. Several crystals have been considered for the calorimeter. The initial concept employed PbWO₄. Problems of low light output and the variation of light output with instantaneous rate motivated the design of a calorimeter based on LYSO[2], which is an excellent match to the problem, having high light output, fast scintillation decay time and good radiation hardness. However, the price of LYSO has increased substantially[3] in the last few years, making it too expensive for the Mu2e application. An interesting alternative is barium fluoride, BaF₂, which has two scintillation components, one at 220 nm has a decay time of 0.9 ns, while the larger component at 300 nm has a decay time of 630 ns[4]. Figure 1 shows the BaF₂ scintillation time distribution.

Figure 1: The fast and slow scintillation components of BaF₂

The existence of the very fast scintillation component in BaF₂ makes this crystal an attractive candidate for high rate ap-

plications such as the Mu2e calorimeter, in both its initial and possible upgrade phases. The BaF₂ scintillation spectrum is shown in Figure 2. BaF₂ was thoroughly investigated as a candidate for the calorimeter of the GEM detector at the SSC[5] more than two decades ago, and has, in fact, been employed in the TAPS experiment[6] at Mainz, which does not have a magnetic field. For Mu2e to make full use of the high rate capability afforded by the fast decay time component at 220 nm, however, requires a means of rejecting the much more intense slow component at 300 nm with a readout device that can operate in a 1T magnetic field. Solar blind photomultipliers have adequate quantum efficiency at 220 nm, and some rejection at 300 nm, but are not suitable for use in a magnetic field.

Figure 2: The BaF₂ fast scintillation component at 220 nm comprises ~15% of the light, the slow component at 300nm, ~ 85%

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There are approaches to making use of the fast 220 nm component of BaF₂: reducing the size of the 300 nm component

through doping and/or finding a suitable readout device that is insensitive to the slow component while retaining adequate quantum efficiency for the fast component. It is possible to reduce the 300 nm emission component without too much effect on the 220 nm component by doping with rare earths such as lanthanum[7], but this is not a large enough reduction to solve the problem at hand. We have begun a study of this type of doping, mainly aimed at understanding the radiation hardness of doped BaF₂ crystals.

Our main focus has been on developing UV sensitive solid state photosensors. There are commercial devices with extended UV response, but no large area devices that can discriminate between the wavelengths of the fast and slow components of BaF₂ emission. We have thus formed a Caltech/JPL/RMD collaboration to develop such a device.

2. Superlattice deposition

Typical large area APDs have poor quantum efficiency in the BaF₂ spectral region. However, APDs and SiPMs/MPPCs from Hamamatsu and RMD made without the normal protective epoxy coating, and therefore somewhat fragile, have quantum efficiencies in the 200 nm region of 17% [8]. These devices cannot, however, discriminate between the 220 nm fast component and 300 nm slow components of BaF₂. The presence of the slow component limits the rate capability of the calorimeter, and can therefore be an issue in high background conditions.

Our approach is to transform a large-area (9×9 mm²) RMD APD [9], which has high gain (up to 2000) and low capacitance 0.7pf/mm², into a superlattice-doped APD [10] and to incorporate an atomic layer deposition (ALD) antireflection filter [11] that provides 60% quantum efficiency at 220 nm and 0.1% efficiency at 300 nm, thereby enabling us to obtain a larger number of photoelectrons/MeV, and also to take full advantage of the fast decay time component of BaF₂.

Superlattice (2D) doping, a JPL-developed surface passivation technique, produces stable surfaces on silicon photosensors. These techniques were developed to overcome surface damage due to ultraviolet radiation in satellite instrumentation. The subsurface structures are formed using a combination of molecular beam epitaxy and controlled crystalline silicon growth. After growing a thin layer of undoped silicon, a monolayer of boron is deposited, then another silicon layer is grown, and the process is repeated up to four times. The resulting subsurface structure, with high quality self-organized layers of boron atoms at densities of $\sim 2 \times 10^{14}/\text{cm}^2$ (see Figure 3),

The reason for the low QE achieved by most solid state devices in the UV region is two-fold: in typical devices there is an undepleted region of tens of microns between the Si/SiO₂ passivation region on the absorbing surface and the depletion region that is in close proximity to the avalanche region. Due to quantum exclusion, the superlattice structure suppresses recombination of charge at the surface, thereby improving the QE in the 220 nm region to close to the theoretical maximum. The greatly reduced undepleted region of the superlattice-doped device also produces substantially improved timing characteristics (see Figure 4). Second, most devices have a protective resin

Figure 3: A four-layer superlattice grown by MBE, in which four 2D-doped layers are separated by 1 nm. This 2D doping creates a maximum field of 10^7 V/cm. The 2D doping superlattice forms a surface depletion layer with a fixed width of less than 1 nm, which is stable against interface trap densities in excess of 10^{14} cm^{-3} , enabling the detector to remain stable even when the surface is severely damaged by irradiation by DUV radiation.

Figure 4: Response of unmodified and superlattice-doped 9×9 mm² RMD APDs.

layer that lowers the net quantum efficiency. This layer is not required in our device, which is passivated and protected by the creation of an atomic layer deposition filter described below.

3. Atomic layer deposition filter

It then remains to apply a multilayered atomic layer deposition (ALD) coating to serve as a bandwidth-reducing interference and antireflection filter. These films, in our case alternating layers of aluminum and aluminum oxide, are created by forming a series of single atomic layers through self-limiting chemical reactions with the substrate. This process produces uniform pinhole-free layers of precise thickness. Figure 5 shows the calculated transmission of any early version of such a filter as a function of wavelength. For a five-layer ALD

coating, the QE at normal incidence for the fast component of BaF₂ is close to 70%, and the extinction at the slow component wavelength is nearly complete. The transmission of the filter is a function of the incident angle; this response is shown in Figure 3 for the current version of the five-layer interference filter, which has response extended to below 200 nm.

Figure 5: Quantum efficiency (QE) as a function of wavelength for the original three, five seven layer ALD filter design.

Figure 6: Response of an improved five layer ALD filter as a function of angle of incidence and wavelength.

4. Electrical performance

We have produced several versions of superlattice/ALD-modified RMD APDs thus far. The anticipated filter response and quantum efficiency improvements have been experimentally demonstrated. The devices, however, have somewhat elevated dark current and noise, as seen in Figure 6. Operation

at somewhat reduced temperatures improves the noise performance substantially: at $\sim 25^\circ$ below ambient, the noise of the superlattice/ALD-modified devices is equivalent to that of standard devices at room temperature.

Several process variations are being investigated to reduce the dark current and associated noise. These include variation of the parameters of the superlattice deposition layers, modification of the first dielectric layer of the ALD filter and changes to the electrical contact geometry. The current devices are nonetheless suitable for deployment in the Mu2e calorimeter.

Figure 7: Noise in rms electrons of a standard and a superlattice-doped RMD APD as a function of gain.

5. Conclusion

We have described the development of a solar-blind avalanche photodiode suitable for the readout of the fast scintillation component of barium fluoride. The device, a modified RMD APD with a superlattice-doped region and an integrated atomic layer deposition filter, has high quantum efficiency for the 220 nm fast component, strong extinction for the 300 nm slow component and excellent timing performance.

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