UV/Optical Photon Counting and Large Format Imaging Detectors from CubeSats, SmallSats to Large Aperture Space Telescopes & Imaging Spectrometers

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Abstract

Future large aperture space astrophysics and cosmology missions require high performance and single photon counting detectors. At the same time, some planetary missions place stringent environmental requirements on photon counting detectors. These requirements pose challenges in efficiency, spectral response, noise, and durability for detectors in space. We discuss our technology and instrument development efforts toward meeting these challenges. We present an example of the development of superlattice-doped silicon detectors and their performance verification through system integration, deployment in suborbital missions and ground-based observations. We discuss initial results from using these detectors in far UV and near UV Offner-based ultraviolet imaging spectrometers (UVS) that are under development at JPL.

Introduction

After the great successes of the Hubble Space Telescope (HST) and Galaxy Evolution Explorer (GALEX), the astrophysics and cosmology community is planning for ultraviolet (UV) and optical telescopes with very large apertures for discoveries beyond these missions. NASA is supporting four flagship mission concept studies in preparation for the next decadal plan for cosmology and astrophysics to be conducted by the National Research Council. Two of these mission concepts, Large UV Optical Infrared Survey Telescope (LUVOIR) and the Habitable Exoplanet Mission (HabEx), would require ultralow noise detectors in the ultraviolet to short wavelength infrared spectral range for potential instruments such as starshades, coronagraphs, and spectrographs.

The ultraviolet spectral region is rich with diagnostic spectral lines that are essential for probing exoplanet atmospheres, detecting surface reflectance, studying proto-planets, and understanding the intergalactic and circumgalactic medium. In planetary science, data from the UVIS instrument on Cassini and the HST instrument STIS have shown ultraviolet signatures of potential plumes of water on moons of Jupiter and Saturn. These findings have spurred the planetary community into taking a closer look with a planned NASA flagship mission to Europa. Discovery and New Frontier class missions to other planetary bodies have also been initiated. These missions require low noise, high-efficiency ultraviolet/visible detectors and UV-only detectors that could be reliably produced at low cost. Additionally, several instruments under study would require photon counting detectors.

For future space missions, high efficiency and tailored spectral response will be essential. LUVOIR, is considering a fifteen-meter aperture telescope with some instruments in the 100-2000 nm spectral range. To achieve the exciting central goal of detecting and characterizing habitable exoplanets, HabEx is performing trade studies for instruments in the 200-1800 nm range that require ultralow noise detectors. Innovative detector and instrument technologies that address these requirements must be validated and verified at system level and in relevant environments to reduce the risks for deployment in space. Lower cost platforms such as CubeSats, sounding rockets and high-altitude balloons offer opportunities for technology maturation, deployment and validation at minimal cost.

Single Photon Counting Detector Development

The field of UV instrumentation, especially in space, has been dominated by image-tube technologies such as photomultiplier tubes (PMTs) and microchannel plates (MCPs). These detectors have the advantages of photon-counting and visible-blind capabilities, but suffer from low quantum efficiency (QE) as well as durability and stability issues associated with high voltages. Although the UV spectral range poses challenges for solid-state detectors, great progress has been made with wide bandgap materials and high-performance silicon imaging detectors [Nikzad 2015, Nikzad 2016b, Pad-

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manabham 2017]. Avalanche photodiode arrays (APDs) and electron multiplying charge coupled devices (EMCCDs) use avalanche multiplication to achieve single photon counting capability for imaging and spectroscopy applications that require detection of faint objects [Hynecek 2001, Jerram 2001]. We focus this paper on superlattice-doped EMCCDs (Figures 1 and 2).

Figure 1: Several superlattice-doped CCD201 EMCCDs with different AR coatings, distinguished by their respective hues. See Figure 2 for more details.

Surface passivation of back-illuminated silicon detectors, especially in the science-rich far- to extreme- ultraviolet regions of the spectrum, has long been a problem for silicon detectors in space, where radiation-induced surface damage can degrade detector performance [Defise 1998]. At JPL, we have developed radiation-hard surface passivation technologies for high UV QE and exceptional stability and durability [Hoenk 2013, Hoenk 2014, Nikzad 2016a,b]. Accelerated lifetime tests of JPL's superlattice-doped CMOS detectors with pulsed deep UV lasers (193 nm and 263 nm) have demonstrated that these detectors are uniquely immune to radiation-induced surface damage [Hoenk 2013].

JPL's surface passivation processes comprise wafer-scale bonding, thinning, superlattice doping, and antireflection (AR) coatings. By using molecular beam epitaxy (MBE) to grow highly-doped, nanometer-scale layers of single crystalline silicon on the back surface of fully-fabricated silicon imaging arrays, we have demonstrated detector QE near the reflection limit (100% internal QE) and extended their spectral range from soft x ray to visible and near infrared [Hoenk 1992, Nikzad 1994, Blacksberg 2008, Hoenk 2013]. Within these ultrathin layers of single crystal silicon, we embed multiple 2D sheets of dopant atoms that passivate and stabilize the surface [Hoenk 2013]. These superlattice-doped detectors can then be tailored and optimized by using atomic layer deposition (ALD) to form custom, multilayer antireflection (AR) coatings [Hamden 2011, Nikzad 2012]. Recently we extended this capability to deposit visible-rejection, UV bandpass filters directly on back-illuminated silicon detectors [Hennessy 2015]. We have used these processes to develop high-performance CCD and CMOS imaging detectors with tailorable spectral response, as well as fully-depleted photodiodes and linear-mode APDs [Nikzad 2016].

Validation through Suborbital Platforms

We have developed superlattice-doped EMCCDs for the Faint Intergalactic Red-shifted Emission Balloon experiment (FIREBall-2). Superlattice-doped e2v CCD201 detectors were optimized for high QE in a narrow atmospheric window centered at ~205 nm. Figure 1 shows superlattice-doped EMCCDs with various AR coating designs for FIREBall-2 optimization, as evidenced by the different hue of the device surfaces. Figure 2 shows the measured and modeled response of three different AR coating designs, depicting the increase in peak QE while narrowing the response as the number of dielectric layers increase in the design. A three-layer AR-coated device was selected for flight as it rendered the best overall response and easier instrument optical alignment. While CCD201 detectors are generally operated in frame transfer mode with 1-megapixel resolution, here we thin the entire device without any shielding, allowing us to take advantage of the entire 2-megapixel array for sensing and imaging. Compared to FIREBall-1 detector that was a spare GALEX MCP detector, the FIREBall-2 detector has a factor of five improvement in the QE. FIREBall-2 detector is cooled to suppress dark current and the CCD201 gain register reduces the read noise to negligible values. Several FIREBall-2 candidate detectors were used for observation at the Palomar's Cosmic Web Imager to

verify detector performance [Kyne 2016, Hamden 2015]. The FIREBall-2 detector has been delivered and integrated in the flight spectrograph and its performance has been verified. Launch is planned for September 2017.

Ultraviolet Imaging Spectrometer: System Integration and Performance Verification of Single Photon Counting UV Detectors

Aboard nearly every planetary mission, as well as on the HST, there is an ultraviolet spectrometer. This is in part due to the richness of information that exists in this part of the spectrum as many species have diagnostic atomic or molecular signatures in the 90 nm to 300 nm region of the spectrum.

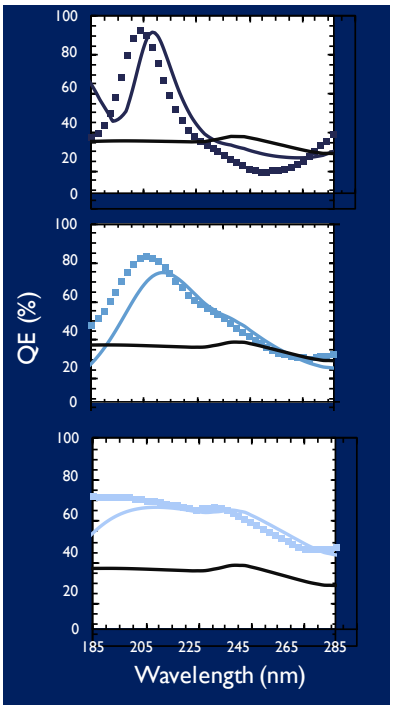

Figure 2: Measured and modelled design of the FIREBall detector AR coatings. FIREBall balloon experiment requires optimization for the narrow ultraviolet atmospheric window which is centered at 205 nm. The designs are based on five-layer (top), three-layer (middle), and single layer (bottom) dielectrics. The higher number of layers create a higher peak QE but narrower response.

While the previous UV spectrometers have produced invaluable information, there is room for improvement, especially in the detector technology. Much as in astrophysics missions, the workhorse of UV detection in planetary instruments has been the image-tube-based MCPs that suffer from low QE and require high voltage. Our goal is to develop a compact, high throughput ultraviolet instrument that can be used for planetary atmospheric and surface studies. We are developing Offner-based [Mouroulis 1998] ultraviolet and UV/visible spectrometers (UVS) with one of the key components being the solid-state UV photon counting detectors, i.e., the superlattice-doped EMCCDs with tailored response. Figure 3 shows photographs of the laboratory prototype of JPL's compact ultraviolet imaging spectrometer and its key components. The electron-beam fabricated convex grating and the mirror shown in Figure 3 are coated using ALD to optimize their reflectivity and response, using techniques similar to the AR coatings that we developed to tailor the response of detectors.

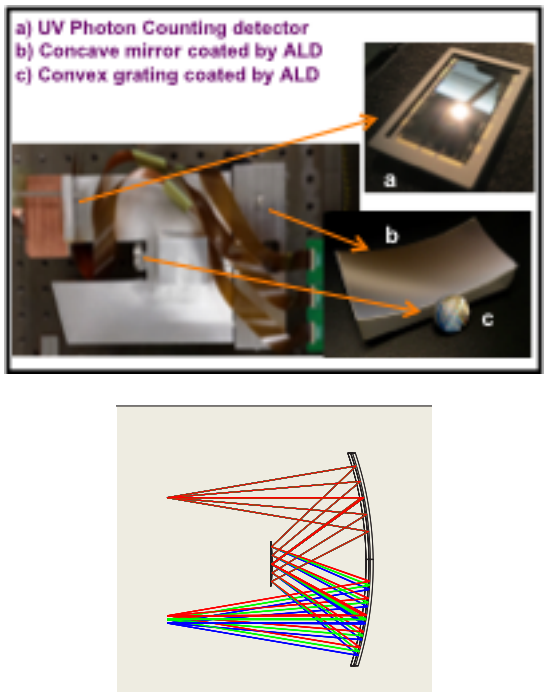

Figure 3: Benchtop prototype of the NUV/Visible channel of JPL's UVS in the UV testbed at JPL and some of the key elements of the instrument: the high efficiency, low operating voltage ultraviolet photon counting detector, optical elements including an electron-beam fabricated grating enhanced with advanced coatings produced by atomic layer deposition. A typical compact Offner schematic design with convex grating is shown on the bottom.

Figure 4 shows images from the bare (i.e., no AR coating) superlattice-doped EMCCD that is in the focal plane of the near ultraviolet channel of the JPL's UVS. Sharp, well-delineated lines even at Lyman alpha (121.6 nm) have been observed. The QE of this detector with coatings is nearly x5 higher than the typical MCP QE [Nikzad2012, Nikzad 2016].

Visible-blind filters have been designed and demonstrated on single element detectors. Work is underway for integration of these filters, designed for the far ultraviolet channel of the Offner UVS, into superlattice-doped EMCCDs.

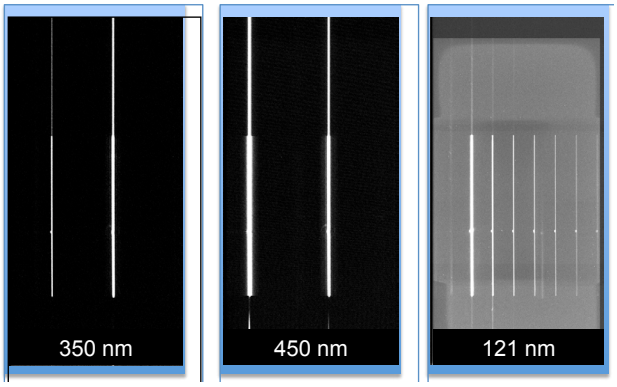

Figure 4: Images of spectral lines recorded by a superlattice-doped EMCCD in JPL's Offner-based, near ultraviolet/visible imaging spectrometer.

Summary

We presented an overview of photon counting detector development in our laboratory directed toward future astronomy missions such as LUVOIR and HabEx, and planetary missions being considered in Discovery and New Frontier programs. We discussed achieving high ultraviolet QE and photon counting by superlattice doping and ALD-custom coating 2-megapixel EMCCDs. We achieve out-of-band rejection in silicon detectors by developing integrated visible-rejection filters. Superlattice-doped and custom-coated EMCCDs were optimized and delivered to FIREBall-2, a balloon-borne spectrograph that is planned for launch in September 2017. Additionally, system-level validation is underway by integrating the same type of device with different spectral optimizations in Offner-based UV imaging spectrometers that we are developing at JPL for planetary applications.

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