UV Photon Counting Detectors for High-Altitude Balloon and Sounding Rocket Experiments

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Abstract

We report on development of ultraviolet photon counting detectors based on the 2D-doped and atomic layer deposition (ALD) custom coated electron multiplying CCD (EMCCDs) and their deployment in a high-altitude balloon experiment Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall)-2 that was launched on September 22, 2018. The detector quantum efficiency (QE) was optimized for the narrow stratospheric window of a balloon at 200 - 225 nm. We also discuss the development of high QE, 2D-doped EMCCDs for the challenging spectral range (140±20 nm) that includes the hydrogen line Lyman alpha (121.6 nm) and a required 3 orders of magnitude out of band (λ>160 nm) rejection ratio. This detector is being developed for the Spatial Heterodyne Interferometric Emission Line Spectrometer (SHIELDS) sounding rocket experiment for heliophysics and planetary science studies.

Introduction

Suborbital missions, including sounding rockets and high-altitude balloons, constitute an important part of NASA's portfolio. These missions provide relatively low-cost access to space and are used for the advancement of enabling or promising technologies for future orbital missions and they also provide the opportunity to demonstrate proof of concept science investigations. Additionally, suborbital missions provide opportunities to train people for mission-critical roles, such as principal investigator, instrument scientist, instrument system engineer, and detector scientist in lower risk platforms. Although flights are short, much of the system level validation of the technology and evaluation of their utility for space-based observations can be performed in suborbital missions. Successful suborbital flight of detectors constitutes a major step toward the readiness for future missions.

Suborbital missions are particularly important for the ultraviolet spectral range, as ground based "on-sky" observations have limited scope (down to 320 nm in observatories such as Palomar or Keck) due to atmospheric absorption of ultraviolet light. At the same time, the ultraviolet spectrum has significant diagnostic capability. UV instruments have been used in the past and are in various stages of planning, design, development, and deployment for future NASA missions. These include large flagship Earth-orbiting telescopes for potential flight in 2030s, such as Large UV Optical Infrared survey mission (LUVOIR) and Habitable Exoplanet characterization mission (HabEx), that have been conceived to study the early universe, the life cycle of stars, and examine habitability of exoplanets through the study of biomarkers. In pushing the boundaries of discovery beyond previous missions, new detector technologies are needed. For example, the astrophysics Earth-orbiting large telescope missions would block the light from the star internally using a coronagraph or externally using a starshade in order to directly image exo-solar planets and to detect and characterize the light from the planetary surface or planetary atmosphere. The instruments planned for these missions would require low noise, high-efficiency, ultraviolet/visible and solar blind UV detectors—in many cases photon counting detectors.

It should be noted that while EMCCDs have been baselined for several instruments, the development and maturation of other promising detector technologies will be monitored by missions in planning or under study. The back-illumination processes including 2D doping and ALD processes are universally-applicable to silicon detectors.

Ultraviolet Single Photon Counting Detector for FIREBall-2

FIREBall-2 (FB-2) is a balloon-borne experiment that is designed to discover and map faint emission

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from the circumgalactic medium (CGM) of low redshift galaxies using a spectrograph. FB-2 is a continuation and modification of FIREBall-1 (FB-1), a pathfinding mission that used a spare GALEX microchannel plate (MCP) detector in its 2006 and 2009 flights. FB-1 validated a number of engineering designs at system level for the FB instrument and the FB-1 flights established that improved detectors would be necessary to achieve the goals of the mission. FB-2 was enabled by significantly upgrading FB-1, in part through improving the detector quantum efficiency (QE) and reducing complexity by moving from image-tube-based detectors to solid state photon counting detectors.

FIREBall-2's upgraded detector camera system included a high QE, low-noise, UV 2D-doped and custom ALD-coated EMCCD, which improved instrument performance by more than an order of magnitude. 2D-doping processes resulting in stable response and reflection limited QE (100% internal QE) in a variety of silicon detectors have been described in detail previously [Hoenk 2014, Nikzad2016, Nikzad2017]. JPL's end-to-end post-fabrication, back-illumination processes comprise wafer-scale bonding, thinning, superlattice doping, and antireflection (AR) coatings, as well as out-of-band rejection filters integrated in the detectors. For the key step in this process—the surface passivation of fully-fabricated silicon detectors—we employ low temperature molecular beam epitaxy (MBE) for growth of highly-doped, nanometer-scale layers of single crystalline silicon, which achieves detector QE near the reflection limit and expands the spectral response from soft X-ray to visible and near infrared [Hoenk 1992, Nikzad 1994, Hoenk 2013]. With internal QE at near 100%, these 2D-doped detectors' external QE can then be tailored and optimized by designing custom antireflection coatings and filters. We use atomic layer deposition (ALD) to deposit custom coatings for tailoring the external QE of silicon detectors including antireflection (AR) coatings [Hamden 2011, Nikzad 2012] as well as out of band rejection filters using metal dielectric stacks that are directly deposited on the 2D-doped detector surface [Hennessy 2015]. Previous publications detail the demonstration of high-performance CCD and CMOS imaging sensors [Nikzad 2016, Nikzad 2017].

EMCCDs were invented nearly two decades ago. They overcome the conventional CCD's read noise by amplifying the signal through a special serial multiplication register [Hynecek 2001, Jerram 2001]. EMCCDs have been baselined for NASA's astrophysics flagship mission, Wide Field Infrared Survey Telescope (WFIRST). Furthermore, they have been used have been used in LUVOIR and HabEx designs as baseline detectors for a number of instruments.

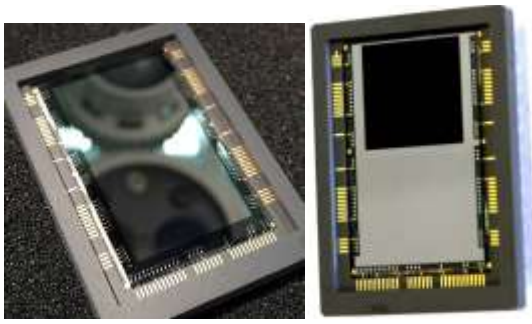

Figure 1: Photo of the 2D-doped and custom coated UV version of the EMCCD (left). Unlike standard commercially available versions, where fast readout in frame transfer mode is used to delineate the one-versus-two photon hit per pixel, the FIREBall-2 detector was expected to detect extremely low fluxes with low probability for two-photon hit per pixel per exposure time. In contrast, SHIELDS, a heliophysics sounding rocket mission, will have higher signal levels and will fly a version of the 2D-doped EMCCD with storage shield for operation in the frame transfer mode (right).

We developed 2D-doped EMCCDs for FIREBall-2 flight. These 2D-doped e2v CCD201 detectors were optimized for high QE in a narrow stratospheric window centered at ~205 nm. These CCDs have a 2kx1k, 13-μm^2 format and are typically operated in the frame transfer mode with an aluminum coating shielding the storage area. Unlike the commercial version, these devices were thinned such that the entire 2kx1k area was available for light sensing (Figure 1). 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 its slightly wider band allowed for easier instrument optical alignment. The FIREBall-2 detector has a factor of five improvement in the QE over the FB-1 MCP detector. FIREBall-2 detector was cooled to less than -100°C to suppress dark current, while the CCD201 gain register reduces the read noise to negligible values [Kyne 2016, Hamden 2015].

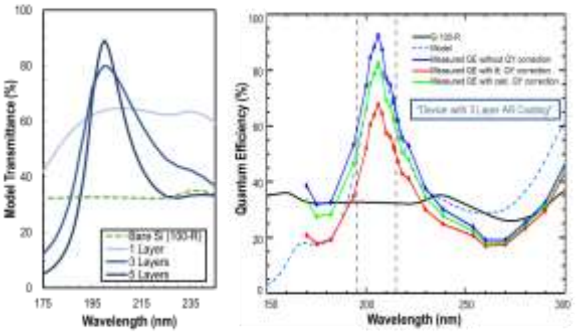

Figure 2: Multilayer dielectric coatings were used to increase the QE in the narrow band of the stratospheric UV window of the FB-2 balloon. LHS: model of three one, three, and five-layer coatings demonstrate increasing peak QE and narrowing the band with increasing layers. RHS: Measured QE of EMCCDs enhanced by these layers confirms the model. The 3-layer coated 2D-doped EMCCD was selected for flight [after Hamden 2016].

FB2 used a second generation (V2) controller for counting photons (CCCP) from NüVü cameras. This controller is unique to this instrument given the low noise requirements of FB-2. One of these requirements is extremely low clock-induced-charge (0.001 e/pix/fr), which has been achieved using this controller through wave shaping with reduced and staggered clock swings. The NüVü controller gives us full control over all CCD clocking and serial readout, with the exception of the high voltage (HV) clock, which is a sinusoidal resonance clock and is locked to 10 MHz. The NüVü controller allows us to operate a Teledyne e2v CCD201-20 EMCCD in photon counting mode, a process that uses impact ionization to amplify signal electrons to well above the read noise. FB2 uses sinusoid clock shapes for parallel clocking and an arbitrary shape (sinusoid like) for serial clock readout. The parallel clock amplitude ranges from 10-12 V and serial clocks are 10 V. During exposure and readout, the EMCCD is operating in non-inverted mode (NIMO), where less CIC can be generated but more thermal noise can build up, particularly during long exposures. FB2 cools the detector to at least -100°C to keep the dark current low. For the 2018flight the detector temperature was kept at ~ -115°C. Keeping the EMCCD temperature stable is important as this is highly linked to HV clock stability. It is recommended to keep the temperature within 0.01°C of required operating temperature to prevent gain instability. Prior to flight, the superlattice-doped, AR-coated EMCCD was integrated in the flight spectrograph and its performance was verified in the laboratory and as well at the balloon facility in September 2017. Due to a number of facility regulations and inclement weather, only one balloon flight was allowed during September 2017 and FB-2 did not fly until the following year. The FB-2 payload remained at Fort Sumner, NM for nearly one year for the next flight opportunity. For two months leading to the September 2018 launch window, the FB-2 went through regular pre-flight checkout and system recalibration. The FB-2 detector continued to perform well and did not need any major recalibration. Figure 3 shows the FB-2 gondola at the Fort Sumner balloon facility in the lead up to the launch. On September 22, 2018, FB-2 was launched and all payload systems worked nearly flawlessly.

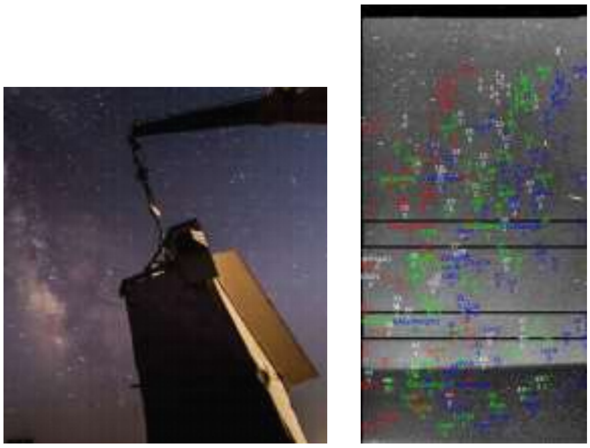

Figure 3: Left FIREBall-2 gondola outside the Fort Sumner, NM balloon flight facilities (credit P. Balard). One the right, a typical data obtained during the FB-2 September 2018 flight where many of the UV signal from GALEX were detected. This is despite the balloon defect that prevented FB-2 reaching full altitude and flight duration. FIREBall-2 instrument otherwise performed as expected. Science publications are in preparation.

Far Ultraviolet Detector Development for SHIELDS Sounding Rocket

SHIELDS is a suborbital sounding rocket that employs an all-reflective spatial heterodyne spectrometer (SHS) to measure the interplanetary hydrogen (IPH) velocity at higher precision and to map the deflection of the upstream IPH flow direction with multiple line of sight measurements during a single rocket flight (April 2020). SHIELDS requires a high efficiency photon counting UV detector optimized for the hydrogen line and its redshifted signal. During the 10-minute flight, every photon literally must be counted in order to collect enough signal in the

UV band in order to resolve discrepancies resulting from previous measurements from two satellite missions.

In SHIELDS, faint UV signal has to be detected during ~10-minute rocket flight, in the presence of visible light, which places different requirements on the detector and camera development. In-band QE of better than 25% (representing a factor 3 over the MCP detector used in the same flight) and an out of band rejection of ~3 orders of magnitude. This was achieved by 2D doping of the same base EMCCD as used for FB-2 mission but instead of a multilayer dielectric coating, a metal-dielectric stack using aluminum and aluminum fluoride is used. Relative QE measurements demonstrated out of band rejection was successfully achieved. More quantitative measurements are underway. To reduce mass and volume, a custom set of electronics is under development comprising a sensor board, an FPGA board, and a power board (Fig. 4). Boards have been fabricated and are in the process of testing. The SHIELDS detector is operated in the frame transfer mode.

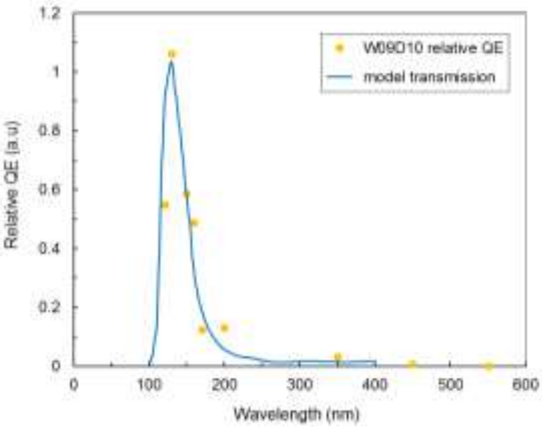

Figure 3: SHIELDS requires detection of Ly α hydrogen signal in presence of high background. This required metal dielectric stacks to be incorporated directly on the back surface of the 2D-doped EMCCD for out of band rejction. The relative QE measurements here have resulted in better than 3 orders of magnitude out of band rejection.

Summary

We presented an overview of photon counting detector development in our laboratory focused on two ultraviolet missions. First a balloon-borne experiment FIREBall-2 for detection CGM and IGM emission in a narrowband of UV, i.e., 205 ± 20 nm accessible by a high-altitude balloon. We discussed achieving high UV QE and photon counting by 2D doping and ALD-custom coating of a 2-megapixel EMCCDs, operated in full frame mode. We discussed the first flight of FB-2 in September 2018 and the in-flight performance of the detector. Work is underway in preparation for the next two flights in 2020 & 2022 by design and incorporation of detector-integrated filters centered at 205 nm. We described the development of a photon counting UV camera which is currently underway in preparation for the sounding rocket SHIELDS. 2D-doped, custom-coated EMCCDs are optimized for 140 ± 20 nm.

Figure 4: 2D-doped EMCCDs packaged for testing with the SHIELDS camera electronics.

Acknowledgements

We gratefully acknowledge the collaborative effort with Teledyne-e2v Inc. and helpful discussions with P. Jerram, P. Turner, D. Morris, K. Lawrie, D. Mehmet. This work was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

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