Wednesday Afternoon, November 8, 2023

Thin Film Division
Room A105 - Session TF+QS-WeA
Thin Films for Space and Electronic Applications

Moderators: John Hennessy, Jet Propulsion Laboratory, **Richard Vanfleet**, Brigham Young University

2:20pm **TF+QS-WeA-1 From Space Thrusters to Exoplanets Research***, **Christine Charles**, R. Boswell, M. Davoodianidalik, J. Machacek, D. Tsifakis, M. Shadwell, H. Punzmann,* Australian National University, Australia*; K. Takahashi,* Tohoku University, Japan*; J. Lecomte, N. Suas-David, L. Rutkowski, E. Dudas, A. Benidar,* Université de Rennes, France*; S. Kassi,* Université de Grenoble-Alpes, France*; R. Georges,* Université de Rennes, France*; N. Smith, P. Tesch,* Oregon Physics **INVITED**

Thousands of nano and micro-satellites are expected to be launched over the next decade, many in constellations, and rideshare opportunities are increasing. The Space Plasma, Power and Propulsion (SP3) laboratory works on a range of projects dealing with fundamental physics in astrophysical plasmas (infrared spectroscopy of exoplanet atmosphere) as well as physics and engineering challenges related to space propulsion systems (geometric and plasma nozzles, the “Bogong” Naphthalene cold gas thrusters). The scalability in geometry and power of radiofrequency plasma devices has allowed the development of a range of electrodeless thrusters such as the low pressure (~1 mTorr) Helicon thruster and the higher pressure (~1 Torr) Pocket Rocket thruster. These have yet to be flown but have surprisingly been wonderful training platforms and opened doors to new areas of research. Expanding nearly collisionless plasmas (i.e. Helicon thrusters) can be used to investigate out-of-equilibrium thermodynamics via polytropic index studies both in the laboratory and in space. Expanding collisional plasmas (i.e. Pocket Rocket thruster) can be used to investigate plasma fluid flows in nozzle. As an example, the development of the Pocket Rocket thruster into a laminar nozzle capable of producing high vibrational temperatures for molecular gases, “Platypus”, was carried out for implementation onto the SMAUG exoplanet research apparatus (Spectroscopy of Molecules Accelerated in Uniform Gas flows) which produces non-LTE (Local Thermodynamic Equilibrium) spectra of various molecules characterised using cavity ringdown spectroscopy yielding successful acquisition of absorption spectra in the infrared using naphthalene/argon plasmas. Naphthalene is also our propellant of choice for the cost-effective green and safe “Bogong” thruster, co-developed by Boswell Technologies and SP3, fully space qualified and deployed in Low Earth Orbit on the 4th of January 2023 by a Space X Falcon 9 rocket (Transporter-6 Mission, 300 kg Skykraft satellite stack).Similar radiofrequency plasma technologies are used for our various thruster concepts and for our focused ion beam (FIB) studies using the Hyperion source developed by Oregon Physics. The use of such FIB applies to materials characterisation, forensic studies and bio-medical applications. SP3 is collaborating with Oregon Physics to develop an O_3^- negative ion source. It is interesting that the mature ion gridded thruster technology (in operation on many commercial satellites including the deep space Bepi Colombo spacecraft on its way to Mercury) share technical similarities with focused ion beam sources.

3:00pm **TF+QS-WeA-3 Photodegradation of Self-Immolating Polymers as a Potential Solution to Optical Scattering***, **Alexandra Stapley**, S. McFarland, J. Vawdrey, K. Mitchell, W. Paxton, D. Allred,* Brigham Young University

Starshades and other optical devices that are sensitive to scattered light require dust mitigation techniques to provide low-scatter surfaces and edges. Poly(olefine) sulfones have been shown to photodegrade with the assistance of a photobase generator when exposed to deep UV light (254 nm) and heat (120°C). These may be applicable in minimizing dust on optical surfaces for space applications. Their behavior in vacuum was not investigated, however. We synthesized Poly(2-methyl 1-pentene) sulfone (PMPS) and Poly(1-hexene) sulfone (PHS) with and without a photobase generator. We studied the photodegradation (172 nm or 254 nm) of thin films in vacuum. Spectroscopic ellipsometry was used to quantify film thickness over time. The PMPS film with photobase generator fully degraded when exposed to 172 nm light in vacuum. A significant finding was that heat was not required to produce this result. PMPS film degradation without the photobase generator was slower and incomplete. The results of our PHS studies are also promising. This study shows that a PMPS film could potentially be used to protect optical surfaces until their deployment in space.

3:20pm **TF+QS-WeA-4 Enhancement of the Bifacial Absorber of Silver Antimony Sulfur Selenide Photovoltaic Devices***, **Sanghyun Lee**,* University of Kentucky*; M. McInerney,* Rose-Hulman Institute of Technology

Silver Antimony Sulfur Selenide, $AgSb(S_xSe_{1-x})_3$ thin-film solar cells have promising properties such as tunable bandgap (0.7 - 1.9 eV), good doping concentration (10^{16} cm^{-3}), and high absorption coefficient ($>10^4$ cm^{-1}). The efficiency of $AgSb(S_xSe_{1-x})_3$ thin-films with x=0.53, 0.58, and 0.61 has been studied with >2.77 %. Since Antimony Sulfur Selenide, $Sb(S_xSe_{1-x})_3$thin-films have shown good optical and electronic properties as an absorber layer, further optimization of thin-film absorber layers could be achieved by utilizing both $Sb(S_xSe_{1-x})_3$ and $AgSb(S_xSe_{1-x})_3$ thin-films for bifacial devices. Furthermore, substituting Ag in $Sb(S_xSe_{1-x})_3$ thin-films tends to increase the bandgap of the absorber layer by lowering the valence band based on studies of other thin-film absorber layers (CIGS, CZTSSe).

In this contribution, we have theoretically studied bifacial photovoltaic devices by combining thin-film absorbers of $AgSb(S_xSe_{1-x})_3$, $Sb(S_xSe_{1-x})_3$, and the combination of $AgSb(S_xSe_{1-x})_3$ and $Sb(S_xSe_{1-x})_3$ thin-films from the electronic band structure perspective. To fully utilize the promising properties of both $Sb_2(S_xSe_{1-x})_3$ and $AgSb(S_xSe_{1-x})_3$ films, we investigated different compositions and concentrations of Sulfur and Selenium with proposed empirical equations for electron affinity and bandgap energy through modeling and simulations.

Four different structures of thin-film absorbers have been studied above Molybdenum metal thin-films. For both $AgSb(S_xSe_{1-x})_3$ and $Sb(S_xSe_{1-x})_3$ thin-films, the electron affinity and bandgap energy increase as Sulfur (x) composition increases. However, the increased bandgap is not directly translated into improved solar cells efficiency due to the alignment of thin-film electronic structures. The best efficiency was achieved with 2 um $AgSb(S_{0.4}Se_{0.6})_3$ thin-film devices(18.4 %) at sulfur concentration, x = 0.4. However, once we combine two $AgSb(S_xSe_{1-x})_3$ and $Sb(S_xSe_{1-x})_3$ thin-films while keeping a total thickness, 2 um (1 um/1 um), an interface between $AgSb(S_{0.4}Se_{0.6})_3$/ $Sb_2(S_{0.4}Se_{0.6})_3$ and Molybdenum metal thin-films is preferably formed due to reduced effective Schottky hole barrier. If we assume the same amount of defect states at the interface, the improved effective Schottky hole barrier is 128 mV due to the favorable band alignment, which is approximate 4.3 times better than a $AgSb(S_{0.4}Se_{0.6})_3$ thin-film structure. With a bi-layer $AgSb(S_{0.4}Se_{0.6})_3/Sb_2(S_{0.4}Se_{0.6})_3$ thin-film absorber, we studied various doping concentrations impact on device efficiency based on the modified electronic band structure of each thin-film. The doping concentration of $AgSb(S_{0.4}Se_{0.6})_3$ thin-film mainly increases the photogenerated current while $Sb_2(S_{0.4}Se_{0.6})_3$ thin-film improves open circuit voltage.

4:20pm **TF+QS-WeA-7 Atomic Scale Processing and Surface Engineering to Maximize Microdevice Performance for Remote Sensing and Imaging Applications***, **Frank Greer**,* Jet Propulsion Laboratory (NASA/JPL) **INVITED**

Future UV, X-ray, infrared, and sub-millimeter telescopes and spectrometers have the potential to revolutionize our understanding of the formation and habitability of the modern universe, Earth, and other planetary bodies.[1-4] Star formation, dark energy, and the composition of the intergalactic medium are only some of the key scientific topics that can be addressed by UV astronomy and astrophysics. Sub-millimeter astronomy can probe the fine structure of the cosmic microwave background, giving glimpses into the early universe immediately following the Big Bang.[5] Remote observation in the infrared is critically important for the understanding of many aspects of Earth Science and Exoplanet atmospheres.

Unfortunately, harnessing the full potential of these missions is often constrained by performance of the available detectors and optical elements (the eyes of the instruments) that make the measurements and take the images. The limitations of these key components are frequently due to non-idealities in the materials and interfaces that are imbedded in or form these devices. Thus, the state-of-the art in materials science, thin films, and semiconductor processing can limit what we can know and learn because it constrains what we can "see". To improve our ability to "see" (by making new types of observations or observations with greater sensitivity), effort is required to improve the specialized materials that impact space-based instruments.

While bulk materials are important, many of the critical challenges in materials science for space applications occur at the nanoscale. Nanoscale coatings deposited by techniques such as atomic layer deposition (ALD) can be used in a variety of ways, including, but not limited to: anti-reflective coatings for UV detectors, passivation layers for infrared detectors, wiring layers in superconducting circuits, or superconducting sensing elements.Nanoscale surface engineering through atomic scale processes can substantially improve the optoelectronic properties of III-V sensors and optical elements such waveguides, especially in shorter wavelength ranges where surface roughness is particularly important.

This presentation will detail the fundamental materials science, surface engineering, and ALD/ALE approaches we have used in the fabrication of a variety of devices in multiple different wavelength ranges, demonstrating the boost in performance that is obtained with atomic level precision at key steps in the fabrication process.

[1]Barth, C. A. *Appl. Optics* 8, 1295, (1969).

[2]Hendrix, A. R., et al. *Icarus* 206, 608-617, (2010).

[3]Nicastro, F., et al. *Science* 319, 55-57, (2008).

[4]Martin, D. C. et al. *Nature* 448, 780-783, (2007).

[5]de Bernardis, P. et al. *Nature* 404, 955-959, (2000).

5:00pm **TF+QS-WeA-9 Advances in Plasma-Based Atomic Layer Processing of AlF_3 for the Passivation of FUV Mirrors***, **Virginia Wheeler**, D. Boris,* US Naval Research Laboratory*; L. Rodriguez de Marcos, J. del Hoyo,* NASA Goddard Space Flight Center*; N. Nepal, A. Lang, M. Sales, S. Walton,* US Naval Research Laboratory*; E. Wollack, M. Quijada,* NASA Goddard Space Flight Center

Efficient ultraviolet mirrors are essential components for UV astronomy. While aluminum mirrors with fluoride-based passivation layers are commonly used in this application space due to their proven stability and reliability, the optical performance is still insufficient for systems where several reflections are required. In previous work, we demonstrated the feasibility of a new, room temperature plasma process based on electron beam-generated plasma in a benign SF_6 environment to simultaneously remove the native oxide and form an AlF3 layer with tunable thickness [1]. This process has been used to demonstrate Al-mirrors with high FUV reflectivity (R≈90% at λ=121nm), large area uniformity of the fluoride coating layer, low coating-induced polarization aberration, and improved durability. Plasma-enhanced atomic layer deposition (PEALD) is a known low temperature, highly conformal coating process which has previously been shown to produce AlF3 films [2], though little has been reported on their performance in FUV applications. In this work, we focus on optimizing PEALD AlF3 films and compare both the materials properties as well as the FUV performance with those produced through self-fluorination electron beam generated plasma process.

PEALD AlF3 films were deposited using trimethylaluminum and SF_6 plasma precursors in a Veeco Fiji G2 reactor equipped with a turbo pump and substrate biasing. This reactor has also been customized to include a similar planar electron beam generated plasma if required to etch the native oxide from substrates prior to deposition of AlF3 films. ALD windows were optimized using an *in situ* ellipsometer to monitor the growth rate directly on Al substrates and supplemented with post-deposition x-ray photoelectron spectroscopy and atomic force microscopy to elucidate process-structure-property relationships. Plasma diagnostics, including optical emission spectroscopy and Langmuir probe measurements, were also conducted on the reactor to correlate plasma properties, such as fluence and ion energy, to resulting film properties. Initial plasma characterization showed that there was high atomic fluorine present at the substrate surface using a 1:1 Ar/SF6 plasma at 10mTorr but that this concentration was slightly reduced from that measured within the remote ICP plasma. Additionally, it was found that the fluorine density within the plasma increases linearly with SF6 flow fraction and RF power but only subtle differences were seen with increasing pressure. The influence of these parameters on the AlF3/Al interface and FUV performance will also be discussed.

[1] L.V. Rodriguez de Marcos, et al. Opt. Mater. Express 11, 740-756 (2021)

[2] M.F.J. Vos, Appl. Phys. Lett. 111, 113105 (2017)

5:20pm **TF+QS-WeA-10 Thin Film Processes for UV Detector Technologies for Next Generation NASA Missions***, **Robin Rodríguez**, A. Jewell, J. Hennessy, M. Hoenk, T. Jones, S. Nikzad,* Jet Propulsion Laboratory (NASA/JPL)

Galileo was the first deep space mission to fly a silicon charge-coupled device (CCD) for imaging; since then, silicon-based photodetectors have been used for imaging and/or spectroscopy on nearly every NASA mission. JPL's Advanced Detectors and Nanomaterials Group utilizes thin-film processing and nanoscale interface engineering methods to fabricate advanced detector technologies with improved stability and sensitivity. Our research is largely focused on the use of molecular beam epitaxy (MBE) for band structure engineering and passivation of silicon-based photodetectors. Developments in recent years has been geared toward wafer-scale processing as well as improving the space worthiness of MBE-passivated detectors. We also use atomic layer deposition (ALD) processes to engineer new coatings for advanced optics or detectors, including the customization of detector response over a broad wavelength range. The performance objectives for our technologies are defined to meet the objectives of a variety of NASA research programs with the ultimate goal of flight instrument and mission infusion. This presentation will provide an overview of recent advances in detector optimization for ultraviolet (UV) imaging and spectroscopy applications. Copyright 2023. All Rights Reserved.

5:40pm **TF+QS-WeA-11 Commercializing Nanowire LEDs***, **David Laleyan**, B. Le, G. Frolov,* NS Nanotech Canada*; M. Stevenson, S. Coe-Sullivan,* NS Nanotech

MicroLED display technology consists of many carefully arranged microscopic light-emitting diodes (LEDs) to directly create color pixels. MicroLED displays thus have the potential brightness, efficiency, and response time of inorganic LEDs, but suffer from the high cost of epitaxy, as well as the challenges of creating red, green, and blue emitters on a single material and substrate. Furthermore, conventional approaches of growing planar LEDs and then etching them into micron-scale devices cause a fundamental loss of efficiency, especially for the smallest devices. In this regard, nanowire-based LEDs for microLED applications have been of great interest and a topic of extensive research for over a decade. This is due to their unique ability to maintain high efficiencies as the LED size becomes quite small, even into the sub-micron regime, contrary to conventional thin-film LEDs. Another valuable benefit is the ability to form photonic crystal arrangements, such that the formation of a photonic bandgap leads to highly directional and narrow bandwidth emission. Most recently, reports have shown nanowire LEDs in the green with >25% external quantum efficiency (EQE) and red with >8% EQE, competitive with the best direct green and InGaN red LEDs ever fabricated – despite being sub-micron in size.

These structures were obtained by molecular beam epitaxy (MBE) using a selective area epitaxy (SAE) technique, where nanostructures can be controllably grown on a thin-film template. Novel development and engineering efforts are required for such nanowire LEDs to become commercially viable. This work presents a pathway towards the wafer-scale production of nanowire LEDs for displays. This talk will explain how breakthrough academic research can be made manufacturable by studying run-to-run variability, understanding the process windows, targeting yield-limiting steps, and ensuring process scalability. Focusing on the reproducibility and uniformity of nanowire growth by SAE is the first critical step toward the large-scale deployment of these highly efficient LED that are perfectly suited for the next generation of microLED displays.

Author Index

Bold page numbers indicate presenter

— A —
Allred, D.: TF+QS-WeA-3, 1
— B —
Benidar, A.: TF+QS-WeA-1, 1
Boris, D.: TF+QS-WeA-9, 2
Boswell, R.: TF+QS-WeA-1, 1
— C —
Charles, C.: TF+QS-WeA-1, **1**
Coe-Sullivan, S.: TF+QS-WeA-11, 2
— D —
Davoodianidalik, M.: TF+QS-WeA-1, 1
del Hoyo, J.: TF+QS-WeA-9, 2
Dudas, E.: TF+QS-WeA-1, 1
— F —
Frolov, G.: TF+QS-WeA-11, 2
— G —
Georges, R.: TF+QS-WeA-1, 1
Greer, F.: TF+QS-WeA-7, **1**
— H —
Hennessy, J.: TF+QS-WeA-10, 2
Hoenk, M.: TF+QS-WeA-10, 2
— J —
Jewell, A.: TF+QS-WeA-10, 2
Jones, T.: TF+QS-WeA-10, 2
— K —
Kassi, S.: TF+QS-WeA-1, 1
— L —
Laleyan, D.: TF+QS-WeA-11, **2**
Lang, A.: TF+QS-WeA-9, 2
Le, B.: TF+QS-WeA-11, 2
Lecomte, J.: TF+QS-WeA-1, 1
Lee, S.: TF+QS-WeA-4, **1**
— M —
Machacek, J.: TF+QS-WeA-1, 1
McFarland, S.: TF+QS-WeA-3, 1
McInerney, M.: TF+QS-WeA-4, 1
Mitchell, K.: TF+QS-WeA-3, 1
— N —
Nepal, N.: TF+QS-WeA-9, 2
Nikzad, S.: TF+QS-WeA-10, 2
— P —
Paxton, W.: TF+QS-WeA-3, 1
Punzmann, H.: TF+QS-WeA-1, 1
— Q —
Quijada, M.: TF+QS-WeA-9, 2
— R —
Rodriguez de Marcos, L.: TF+QS-WeA-9, 2
Rodríguez, R.: TF+QS-WeA-10, **2**
Rutkowski, L.: TF+QS-WeA-1, 1
— S —
Sales, M.: TF+QS-WeA-9, 2
Shadwell, M.: TF+QS-WeA-1, 1
Smith, N.: TF+QS-WeA-1, 1
Stapley, A.: TF+QS-WeA-3, **1**
Stevenson, M.: TF+QS-WeA-11, 2
Suas-David, N.: TF+QS-WeA-1, 1
— T —
Takahashi, K.: TF+QS-WeA-1, 1
Tesch, P.: TF+QS-WeA-1, 1
Tsifakis, D.: TF+QS-WeA-1, 1
— V —
Vawdrey, J.: TF+QS-WeA-3, 1
— W —
Walton, S.: TF+QS-WeA-9, 2
Wheeler, V.: TF+QS-WeA-9, **2**
Wollack, E.: TF+QS-WeA-9, 2