Photovoltaics and Power to Support NASA's Moon to Mars Objectives

Jeremiah S. McNatt
NASA Glenn Research Center, Cleveland, OH, 44135, USA

Power drives exploration. From low Earth orbit to the lunar surface to Mars and beyond, power system capabilities will dictate the capacity and lifetime of the mission. NASA's Space Technology Mission Directorate's (STMD) goal is to develop, demonstrate, and transfer new space technologies that enable reliability and performance for mission success. This talk will discuss the upcoming reorganization of STMD, highlighting where power and photovoltaic technologies will support meeting the needs of our envisioned future power systems for missions on the surfaces of the moon and Mars along with their challenges and constraints. Power system and component priorities will be shared along with updates on what STMD is currently doing to address shortfalls and how future investments will be prioritized.

Technical Point of Contact:
Jeremiah McNatt
Space Technology Mission Directorate
NASA Glenn Research Center
216-920-7929
jmcnatt@nasa.gov

Annealing of Radiation Damage in Solestial Ultra-Thin Silicon Solar Cells at 65°C and Maximum Power Point and Open Circuit Conditions under Light

A. Fedoseyev, S. Herasimenka, S. Bowden, H. Abate, Y. Gurimskaya, D. Aponte, and M. Reginevich,
Solestial Inc, Tempe, AZ, USA

The demand for a low-cost, radiation-hard photovoltaic (PV) technological solution has been escalating with the continuous exploration of space. This work reports on a distinctive aspect of a novel ultra-thin SHJ silicon solar cell, integrating *Solestial* proprietary defect-engineered technology. This innovation enables self-curing of radiation damage, leading to a minimal efficiency loss throughout the operational lifetime of the cell in space missions. Annealing campaign, addressing 1 MeV electron damage, both at Open Circuit (OC) and Maximum Power Point (MPP) operation conditions showed that the annealing rate at MPP is 8-10 times lower than that at OP. However, the experiments confirmed that the annealing rate at MPP and at 65℃ is 30 times faster than the defect formation rate. Complimentary simulations were done for a typical orbit. Remarkably, *Solestial* cells achieved complete recovery of one year's worth of radiation damage (1E+14 e/cm^2 fluence) at the MPP and under light exposure in less than 2 days - at 100°C, 4 days - at 80°C and 9 days - at 65°C. The presentation contains recovery results of *Solestial* solar cells at OC and MPP over time at different temperatures.

Technical Point of Contact:
Alex Fedoseyev
Solestial Inc
af@solestial.com

Recent Flight Heritage, Radiation Recovery and New System Development Results at mPower Technology

Murat Okandan, Kaveh Rouhani, Kevin Hell, mPower Technology, Inc.
Valentin Mihailetchi, ISC Konstanz
Astrid Gutjahr, TNO

To meet the rapidly expanding need for high volume production capable and cost effective solar power systems, we have been developing and further customizing high efficiency silicon based DragonSCALES™ modules for large constellations and other space power systems. Specifically, our DragonSCALES based solar arrays have been flying on several satellites, with the longest one with just over two years of on orbit duration and several others with one year and 6 month operation.

We have also been conducting extensive studies on the radiation recovery behavior of our current and advanced cells for next generation DragonSCALES modules with encouraging results.

During this presentation, we will cover the ongoing technology development, radiation recovery results, flight heritage and highlight new system capabilities enabled by a flexible, resilient and multi-MW/year production ready solar module and array integration approach.

Technical Point of Contact:
Murat Okandan
mPower Technology, Inc.
(505) 463-1190
mokandan@mpowertech.com

Laser power beaming spacecrafts lunar constellation

G.Blanchette, Volta space technologies
Tibor Pacher, Puli Space
P.Pino, Volta space technologies

Exploration of lunar craters presents significant challenges due to their rugged terrain and limited sunlight, which restricts the operational time rovers. This paper proposes a novel concept: a rover capable of extended missions within lunar craters, empowered by wireless laser power beamed from a satellite's constellation in orbit. This innovative approach aims to overcome the limitations of solar-powered systems by providing a quasi-continuous and reliable source of energy. The system can also support additional functions like a communication relay and positioning system.

The rover is equipped with an advanced photovoltaic cells panel optimized to efficiently convert laser energy into electrical power and thermal power. This technology allows the rover to operate for extended periods within the crater, where direct sunlight is scarce or absent altogether. By harnessing power from a satellite, the rover can explore larger regions with significant scientific interest, such as permanently shadowed craters that may contain water ice or other valuable resources. The battery mass can be reduced and additional utilizable payload mass is added.

Key technical challenges include designing the rover to effectively receive and utilize laser power, ensuring robust communication between the rover and the satellite and creating a communication relay, and also enhancing autonomous navigation capabilities suited for the crater environment. These challenges are addressed through rigorous engineering and simulation studies to optimize the satellites pointing acquisition and tracking capabilities. By enabling prolonged missions, this technology enhances our understanding of lunar resources, geology, and potential for future human exploration and habitation.

Moreover, the deployment of a satellite-based power system demonstrates a scalable approach for sustaining operations across various lunar environments, also paving the way for future missions to other celestial bodies where solar power may be impractical.

In conclusion, this paper outlines a pioneering concept for a satellite constellation based wireless laser power transfer system that can extend rover missions within lunar craters and support communications positioning functions. This innovation not only extends the operational range and duration of lunar exploration missions but also represents a significant advancement in space exploration technology, positioning humanity closer to sustained exploration and utilization of extraterrestrial resources.

Technical Point of Contact:
Guillaume Blanchette
Director Technology development at Volta Space technologies
514-338-3320
guillaume@voltaspace.co

Progress in the Development of Laser Power Beaming Systems for Aerial and Space Applications

Drew Cardwell, PowerLight Technologies
Jon Gort, PowerLight Technologies
Tom Nugent, PowerLight Technologies

Laser power beaming is increasingly considered an important technology for marine, land, stratospheric, and space power distribution applications. PowerLight has a history of designing, building, and fielding end-to-end free-space and power-over-fiber laser power beaming systems, covering a variety of use cases. In addition, PowerLight is participating in the 10-year DARPA Lunar Architecture Capability Study (LunA-10) for design and development of lunar laser power beaming systems. An overview will be given of recent laser power beaming prototype and product development at PowerLight, with an emphasis on free-space, high specific power, kilowatt-class laser power beaming receivers relevant to low altitude drones, stratospheric aircraft, and space applications. Trade-offs between receiver characteristics including form factor, thermal design, and specific power will be discussed for different applications and operating environments.

Technical Point of Contact:
Drew Cardwell
PowerLight Technologies
360-790-8679
drew.cardwell@powerlighttech.com

Improving 2J III-V Laser Power Converters at 1064 nm for Lunar Exploration

Katelynn Fleming, Rochester Institute of Technology
Steve Polly, Rochester Institute of Technology
Seth Hubbard, Rochester Institute of Technology

Laser power beaming (LPB) is a promising way to transmit power on demand for lunar exploration and colonization missions and other applications. One approach to reach high power levels and useful voltages is to use multijunction (MJ) laser power converters (LPC). We discuss our development of 2J laser power converters at for 1064 nm infared laser light. Our devices were grown via MOVPE, fabricated, and characterized at Rochester Institute of Technology. The devices were customized to convert 1064 nm laser light because high power, high coherency lasers already exist at this wavelength. A single junction device peaked about 40% efficiency under laser irradiation. Tunnel junctions were devised and tested. After inferring that zinc p-type doping resulted in compensation of the junction under annealing while the laser power converter was being grown, an annealing study was devised which showed the severity of this effect on the next iteration of the device, doped with carbon instead. The peak tunneling current dropped by almost a factor of 2 in an annealed device versus an unannealed one. A dual junction device reached 30% efficiency. This underperforms the expected efficiency based on drift-diffusion modeling, leading to the hypothesis that the tunneling junction and the current matching within the device may be at fault. Future work focuses on deconvolving those variables and ameliorating the performance. To inspect the current matching within the device, we are working with light-biased quantum efficiency measurements, which is more difficult than in solar cells because in an LPC, both subcells are made of the same material. To inspect thermal handling of the device we are using a transient Voc measurement upon incident laser irradiation. Strategies to improve the tunneling junction include working with different materials and dopants. When achieved, LPB promises to be an enabling technology at home and in space, revolutionizing extraterrestrial missions, in-flight drone charging, internet of things, implantable medical technology, emergency power delivery, and more.

Technical Point of Contact:
Seth Hubbard
Rochester Institute of Technology
585-475-4214
smhsps@rit.edu

Engineering Design Study of Laser Power Beaming for Applications on the Moon

Geoffrey A. Landis, S.R. Oleson, A. Colozza, B. Faller, J. Fittje, M. Gasper, T. Gray, J. Gyekenyesi, T. Packard, O. Sands, L. Shalkhauser, D. Squires, and N. Weckesser; NASA Glenn Research Center

Using a laser to send power to a photovoltaic receiver has been proposed to transmit electrical power on the moon, particularly for applications such as powering a rover in near-polar permanently-shadowed regions (PSR) where solar power is not available, however detailed engineering design studies of the spacecraft for such applications has not previously been undertaken. In this work, we did an engineering design study of two applications of laser power beaming for near-term lunar applications. In the first application studied, an application was studied to provide power during the lunar night for a global network of small landers spread across the lunar surface, at latitudes ranging from equatorial to near polar landing sites. We analyze a proposal to power such small landers from orbit, using a laser to beam power from an orbital power station to photovoltaic arrays on the landers that are tuned to the laser wavelength. A commercially-available high-power 1.07-µ diode-pumped fiber laser was chosen as the source. To minimize beam spread of the a spot at the required distance, a 1.5 meter optical element was provided, using a design based on the Kepler telescope. To provide power to landers at any location, three orbital stations ("beamcraft) are required, each carrying a 3-kW laser. (If the surface science platforms requiring power are only in polar locations, or conversely, only in near equatorial locations, only one orbital platform is needed.) The approach is seen to be feasible, and a systems analysis was completed, the concept of operations for the system outlined and a design for the beamcraft put together. The second design study looked at surface-to-surface power beaming using the VSAT as the laser platform, for an application to provide power to the interior of a permanently shadowed lunar crater from a surface platform. To maximize the distance of beaming, taking into account possible surface irregularities and the short distance to the horizon of the moon, it is desirable to emplace the laser at an elevation above the surface. The Vertical Solar Array Technology (VSAT) is a NASA program developing a solar array mounted vertically on a 10-m tall mast, designed for emplacement on a Commercial Lunar Payload Services (CLPS) lander to provide 10-kW (BOL) power near the south polar region of the moon, with a target readiness date of 2028. We used this design as the starting platform and the power source for a laser power beaming station. By mounting the laser beam director at the top of the solar array mast, 18.2 m above the surface, a viewing distance to power receivers up to 10 km is possible.

Requirements for the system were to be able to provide 300 W of continuous usable power to users including CLPS landers, VIPER class rovers, or the proposed Lunar Terrain Vehicle. The specified requirement was to be able to transmit power to a distance of up to 10 km, over a design lifetime of 5 years; fitting within a total system landed mass under 625 kg, and to be powered by a 7-kW VSAT array. Again, a 1.07-µ fiber laser is mounted on the deck of the lander, with laser output sent to the laser beam director by a fiber-optic cable. A 7 square meter deployable radiator keeps the laser within operating temperature limits. The beam director, based on the design of a prototype unit developed by the University of California Santa Barbara, is shown in green at the top of the mast. The system beams power for 57% of the time, with 44% of the time idle (accounting for the time when the VSAT array is itself in shadow). 1595 Watts of optical power are output in the beam. Accounting for receiver efficiency and beam losses, this results in an output onto the 1.5-meter receiving photovoltaic array of 542 watts. Of this, 300 watts is directly available to the user, while 242 watts is directed to the batteries for use while the beam is not available.

Technical Point of Contact:
Geoffrey A. Landis,
NASA Glenn Research Center
(216) 308-0822, geoffrey.landis@nasa.gov

Solar Array Performance Modeling for NASA's Artemis Missions

Spencer Furin, NASA Glenn Research Center
Hector Hernandez, NASA Johnson Space Center
Brandon Klefman, NASA Glenn Research Center

NASA's Artemis exploration campaign includes multiple elements that utilize photovoltaic power generation. Artemis mission profiles feature a variety of events that can limit solar array generation and be stressing to electrical power system (EPS) performance, including eclipses, propulsive or navigational maneuvers which constrain the positioning of the solar arrays, and spiral trajectories with significant radiation degradation. These features make predicting the performance of the power system particularly important and requires accurate modeling of power generation by the solar arrays under a variety of conditions.

One of the tools used to predict spacecraft EPS performance is the System Power Analysis for Capability Evaluation (SPACE) model developed at NASA Glenn Research Center. SPACE is used by NASA to model EPS performance for the Orion crew transport vehicle and the Power and Propulsion Element (PPE) of the Gateway space station. This presentation will provide an overview of how SPACE calculates solar array performance, including degradation factors considered and environmental conditions that drive the solar array designs. Additionally, Orion array performance predictions generated by SPACE will be compared to flight data collected during the Artemis I mission.

Technical Point of Contact:
Spencer Furin
NASA Glenn Research Center
216-433-5074
spencer.c.furin@nasa.gov

“Development and On-orbit Operation of Solar Panels for JAXA’s Lunar Lander SLIM”

Shusaku Kanaya #1, JAXA
Yu Miyazawa #2, JAXA
Hiroyuki Toyota #3, JAXA
Akio Kukita #4, JAXA
Tetsuya Nakamura #5, JAXA
Taishi Sumita #6, JAXA
Seisuke Fukuda #7, JAXA
Shujiro Sawai #8, JAXA
Shinichiro Sakai #9, JAXA

Smart Lander for Investigating Moon (SLIM) is JAXA's spacecraft designed for pinpoint landing on the moon. This pinpoint landing technology is necessary for future lunar exploration using small landers. SLIM was launched on September 7, 2023, from the Tanegashima Space Center by H2A Rocket No. 47, and achieved a pinpoint landing on the moon on January 19, 2024.
Extensive weight reduction was required to demonstrate lunar landing with a small lander. Consequently, a lightweight solar array panel (SAP) was developed. We incorporated newly developed inverted metamorphic InGaP/GaAs/InGaAs triple-junction (IMM3J) solar cells for SLIM. These IMM3J cells feature a flexible thin-film structure of only 13 μm with an initial efficiency exceeding 32%, offering over five times the power-to-mass ratio compared to conventional InGaP/GaAs/Ge triple-junction solar cells, thus contributing to SLIM's mass reduction.
SLIM's solar panels consist of three sizes of solar array sheets: 25 sheets of 6-series-3-parallel cells, 1 sheet of 6-series-2-parallel cells, and 1 sheet of 6-series-1-parallel cells. A portion of these solar array sheets was mounted on a CFRP panel, which conforms to the fuel tank's curved surface. The solar array panel generates a total of approximately 540 W of power at the beginning of life (BOL). The total mass is extremely light at about 1.07 kg, achieving a level of weight reduction that would be impossible with conventional solar panels.
The primary evaluation tests during development included thermal cycling tests and acoustic tests. For the thermal cycling test, a coupon panel consisting of a film-type array sheet attached to a curved CFRP panel using Velcro was subjected to 150 temperature cycles ranging from -146°C to +142°C. No issues were observed during this testing.
On the lunar surface, despite the low cycle count, the solar panels have endured thermal cycles from -180°C to +130°C without significant degradation in electrical output characteristics. As of the end of April, SLIM has successfully survived three lunar nights, and it is expected that the telemetry data will provide valuable insights for future lunar exploration.

Technical Point of Contact:
Shusaku Kanaya
JAXA
+81-70-1170-3302
kanaya.shuusaku@jaxa.jp

Results of the Caltech SSPP Alba Mission

Michael D. Kelzenberg, Phillip Jahelka, Richard G. Madonna, and Harry A. Atwater
California Institute of Technology, Pasadena, CA 91125

Caltech's Space Solar Power Project (SSPP) seeks to develop technologies to enable cost-effective space-based solar power, a technologically viable approach to satisfy global electricity demands with renewable, dispatchable baseload power. Our first flight experiment, the SSPD-1 mission, was launched into low-earth orbit in early 2023 to demonstrate emerging technologies related to space-based solar power: compact self-deploying space structures, scalable phased-array wireless power transmitters, and low-cost radiation-tolerant ultralight solar cells. The experiments flew as hosted payloads on a commercial vehicle. SSPD-1 was successful, operating for approximately 9 months prior to being decommissioned.

One of the experiments, *Alba*, sought to study the on-orbit performance of emerging photovoltaic technologies, many of which have had little or no reported flight heritage, including perovskites, nanostructured III-Vs, luminescent solar concentrators, and nonepitaxial GaAs, as well as shielded and unshielded Si, commercial CIGS, and commercial multijunction control cells. (32) research-scale solar cells (up to 2 x 2 cm) were flown, each employing the Aerospace Measurement Unit circuit architecture (developed by Colin Mann at Aerospace Corp) to perform *I–V* sweeps and measure cell temperature.

The mission produced over 3 million I_{SC}/V_{OC} measurements and 200k *I–V* sweeps. An unanticipated lack of sun-pointing attitude control on the host vehicle complicated the analysis of the solar cell results, but methods were developed to correct for varying insolation angle and albedo effects to allow the performance trends of the solar cells to be studied. Efforts are now underway to analyze the flight results in terms of the radiation environment and resulting degradation. Our presentation will summarize the design and execution of the experiment, the key results for each cell type flown, and lessons learned.

Technical Point of Contact:
Michael Kelzenberg
Senior Staff Scientist
Atwater Research Group
California Institute of Technology
mdk@caltech.edu
319 621 2365

Dynovas’ Motorless Deployable Array Technologies

Dr. Quinn McAllister, Dynovas Inc.
Brynn Hall, Dynovas Inc.
Ian Holm, Dynovas Inc.

NASA’s Vertical Solar Array Technology (VSAT) program is focused on the development of solar array technologies required for power generation in support of establishing a sustained presence at the lunar south pole. Dynovas’ work through the SBIR program, focusing on development of “motorless” actuation methods, augments the current state-of-the-art solar array technologies, supporting the VSAT mission and enabling scalability to 50kW+. Dynovas is developing motorless deployment methods as a potential solution to mitigate impact of lunar dust on motive systems. Dynovas’ deployable array architectures utilize bi-stable composite booms capable of array deployment and retraction for >10 cycles for 10kW arrays, and up to the 50kW scale. The composite booms are deployed and retracted via actuators such as piezoelectrics, robust inflatable structures, or shape memory alloys, eliminating the need for traditional electromagnetic motors. These actuators can be integrated directly with the composite deployment boom for a tightly packaged, conformal actuation solution, or be configured to drive the mandrel directly. Dynovas’ “motorless” actuators can also be utilized to deliver the motive extension, rotation, and tilt leveling requirements for lunar deployment of solar array systems, enabling power solutions from CubeSats to 10+kW power stations. Dynovas is well positioned for mission infusion of these technologies post-Phase II, through alignment with industry partners for requirements definition and identification of flight opportunities.

Technical Point of Contact:
Brynn Hall
Dynovas Inc.
916-690-6352
Brynn.hall@dynovas.com

The Next Chapter for GEO: ROSA's Transformative Technology

Shen Meinhold, Redwire
Jeff Manson, Redwire
Ken Steele, Redwire
Michael Stinson, Redwire
Matt LaPointe, Redwire

Redwire's Roll Out Solar Array (ROSA) technology has recently achieved significant milestones in GEO applications, marking a new era in space solar power capabilities. Key accomplishments include the successful deployment of ROSA on Maxar's Ovzon-3 spacecraft in January, a dynamic partnership with Blue Origin for their innovative GEO tug project, and the award of a multi-year contract with Thales Alenia for their next-generation GEO communication satellite platform. Despite the industry's growing focus on Low Earth Orbit (LEO) constellations, the importance of GEO spacecraft remains paramount. ROSA stands out in this domain, offering unparalleled efficiency and power capabilities for large-scale applications. These recent GEO developments underscore ROSA's adaptability across various mission profiles, from LEO to Cislunar and Lunar Surface missions, highlighting its potential to revolutionize future space endeavors. This progress in ROSA technology demonstrates Redwire's commitment to advancing space infrastructure and exploration.

Technical Point of Contact:
Matt LaPointe
Redwire
805-845-0036
matt.lapointe@redwirespace.com

Isolating the Root Cause of Solar Array Anomalies using PSIM – A SPICE and Python Physics Based Circuit Simulation Tool

Colin Mann, The Aerospace Corporation
Don Walker, The Aerospace Corporation
Yao Yue, The Aerospace Corporation
Jann Grovogui, The Aerospace Corporation
Pilar Espinet Gonzalez, The Aerospace Corporation

Anomalies in spacecraft solar arrays can significantly impact power generation and mission operations. This work leveraged a physics-based solar array simulation model (PSIM) and on-orbit telemetry data to precisely identify the specific cells within a solar array string that had shorted to the chassis. The analysis required only basic telemetry inputs, including bus voltage, array temperature, array configuration, and chassis current, to determine the exact location of the shorted cells.

PSIM is a Python library that utilizes the Ngspice circuit simulator to create a full solar array model down to the subjunction component level. Each cell on the array is individually included in the model, along with the usual blocking diodes and wire harnesses. Additional SPICE netlists can be inserted into the model at any point on the array to simulate anomalies or for more detailed analysis including peak power trackers and bus switching circuitry.

The Python module and API are available to the public as a Python distribution or can be accessed via REST API calls using the Aerospace web services. This open-source tool enables more widespread adoption of rigorous, physics-based solar array analysis to enhance spacecraft operational resilience and mission assurance.

Technical Point of Contact:
Colin Mann
The Aerospace Corporation
(310) 336-0914
Colin.J.Mann@aero.org

Re-examining the rear junction when used for micro-concentrator photovoltaics

Alex J. Grede, NRC Postdoc residing at the Naval Research Laboratory, Washington, DC, 20375 USA
Thomas C. Mood, formerly Jacobs, Hanover, MD, 21076 USA
Matthew P. Lumb, Polaris Semiconductor, Alexandria, VA, 22314 USA
Margaret A. Stevens, US Naval Research Laboratory, Washington, DC, 20375 USA
Jill A. Nolde, US Naval Research Laboratory, Washington, DC, 20375 USA
Bradley D. Weaver, US Naval Research Laboratory, Washington, DC, 20375 USA
Kenneth J. Schmieder, formerly US Naval Research Laboratory, Washington, DC, 20375 USA

Micro-concentrator photovoltaic (μCPV) systems reduce the optics and individual cells in size and weight to serve as near drop-in replacements for standard coverglass interconnected cells. The significantly less solar material (30 to 100× reduction) required for μCPV could boost manufacturing capability and the addition of concentration optics opens up photovoltaic power generation in low light conditions as far away as Saturn. That these same optics may also serve as better radiation protection prompted us to re-examine the rear-junction GaAs cell for μCPV in space.

The most efficient GaAs cell to date used a rear-junction architecture where the light is absorbed in a thick and lightly doped n-type region, which is followed by a thin and heavily doped p-type region to form the junction. This is opposed to the traditional shallow-junction where light largely passes through a thin and heavily doped n-type region to be absorbed after the junction in a thick and lightly doped p-type region. The rear-junction is compelling for μCPV, because the n-type absorber is expected to suffer less from perimeter recombination, which becomes more problematic as cell size decreases. However, the requirement of exceptional crystal quality and suppression of top surface recombination for the rear-junction architecture limited it to terrestrial use as radiation will quickly negate the high crystal quality.

The lenslet glass required for μCPV in order focus light on the cells has the side benefit of acting as a thicker radiation shield. Here we present results of both rear- and shallow-junction GaAs cells irradiated with 1 MeV electrons at fluences up to 10^{15} cm^{-2}. Three shielding conditions were used: unshielded, 200 μm coverglass, and a ~1.5 mm thick lenslet array. When protected by the lenslet array, we saw negligible degradation in performance for all devices up to the highest fluences. Separately, we show a 20-fold improvement in perimeter recombination of rear-junction devices over shallow-junction devices. While limited to electron-radiation, this study shows that, for μCPV, a rear-junction architecture is potentially suitable for space while also reducing perimeter recombination.

Technical Point of Contact
Alex J. Grede
NRC Postdoc residing at the US Naval Research Laboratory
alex.j.grede.ctr@us.navy.mil

Demonstration of photovoltaics on acoustically spalled surfaces grown by metal organic vapor phase epitaxy

Seth Hubbard, Elijah Sacchitella, Steve Polly, Rochester Institute of Technology
Mariana Bertoni, Arizona State University
Pablo Coll, Crystal Sonic

III-V solar cells exhibit exceptional conversion efficiencies, particularly for the growing space power market. Their high-power density and radiation resistance makes them extremely desirable for space-related uses, yet their cost, still exceeding \$100/W, can hamper widespread adoption in future large mega constellations (e.g. StarLink) not to mention terrestrial applications (e.g. power on UAV). The primary cost contributor is the substrate, accounting for 30-50% of the total. One cost reduction method being explored is acoustically controlled spalling to remove and reuse the substrate. Traditional spalling methods induce a crack that propagates along the natural crystallographic planes of the GaAs substrate resulting in a rough surface that may need further chemical and mechanical polishing before regrowth. An alternative spalling process using sonic lift-off to control crack propagation uses ultrasonic waves, effectively reducing the magnitude of the surface facets that arise from traditional spalling techniques.

This study demonstrates the progress in the application of sonic lift-off technology for substrate reuse in GaAs based photovoltaics. GaAs solar cells were grown at RIT on both 50 and 75mm (100) orientation GaAs substrates, with a 2° offcut towards the <100> plane, using our 3x2” Aixtron close coupled shower head metalorganic vapor phase epitaxy (MOVPE) system. Acoustic spalling was then performed by Crystal Sonic. We have investigated device performance at various states of this process using both ex-situ and in-situ methods to reduce surface roughness. In our study, the surface of a spalled substrate (substrate with thin film removed by spalling) had residual surface roughness in the range of 1 um. This was reduced using a combination of in-situ and ex-situ methods. The spalled thin films with devices were mounted to silicon wafers as handles using a nonconductive epoxy.

In our initial study, four devices were studied, a control device directly grown on an epi-ready substrate (control), a thin film device spalled from an epi-ready substrate (1st film), a device grown on a substrate that had been spalled once (1st substrate) and a thin film device grown on the substrate that had been spalled and then removed using spalling (2nd film). Encouraging results were seen for the control, 1st film and 1st substrate devices, with average results from these wafers showing almost identical solar cell metrics (Jsc=26.2 mA/cm2, Voc=1001 mV, fill factor =84%, efficiency=22%). In addition, the device yield across the control and 1st film were comparable, while the standard deviation in Voc increased for the 1st substrate (from 5mV to 20 mV), indicative of a correlation between roughness and dark current. More details of the analysis of these devices including quantum efficiency, electroluminescence and further electrical characterization will be presented during our talk. We are currently investigating growth conditions that can improve this roughness as well as spalling parameters that produce a more consistent film and device metrics.

Technical Point of Contact:
Seth Hubbard
Rochester Institute of Technology
585-475-4214
smhsps@rit.edu

Advanced metallization and processing for high efficiency III-V space solar cells

Myles Steiner,[1] Jennifer Selvidge,[1] Theresa Saenz,[1] Thien Truong,[1] Sarah Collins,[1] Mirzo Mirzokarimov,[1] Sneh Sinha,[2] Mitchell Smith,[2] Yuan Gu,[2] Chandan Howlader,[2] Melbs Lemieux,[2] Brett Walker,[2] Daniel Curry,[3] AJ Gray,[1] Thales Borrely,[1] Jacob Cordell,[1] Bill McMahon,[1] David Young[1]

1 National Renewable Energy Laboratory, Golden, CO
2 Electroninks, Austin, TX
3 University of Dayton Research Institute, Dayton, OH

III-V space cells are expensive to manufacture, due in part to a combination of the cost of epitaxy; the cost of the GaAs or Ge substrate; and the cost of post-growth processing that includes metallization, device isolation and deposition of an anti-reflection coating. Replacing photolithographic processes is a key pathway to reducing some of the post-growth processing costs. We will describe our recent efforts to print metals on the front and back of GaAs- and Ge-based cells, and to isolate individual devices with a femtosecond pulsed laser.

Screen-printing and spray-coating of silver-based complex metal inks are fast and scalable processes for metallization. GaAs- and Ge-based cells with planar back contacts show photovoltaic performance comparable to baseline electron beam-metallized cells. Printed inks are more challenging for front grids where the line resolution affects the generated photocurrent and the density of the printed metal affects the resistive power loss. We have demonstrated screen-printed lines with ≤100 µm resolution, inkjet-printed lines with ~50 µm resolution, and aerosol-printed lines with ~25 µm resolution.

We are working to improve the print resolution as well as the contact resistance and film density of all these prints. We have also developed the ability to isolate III-V devices with a high-power femtosecond pulsed laser, as an alternative to contact photolithography and wet-chemical etching. The laser ablation process is augmented by a mild and selective alkaline etch to remove ablation residue. We have demonstrated GaAs and GaInP cells with photovoltaic performance approaching the baseline performance, showing only a small loss in Voc and with a pathway to improvement, and are working toward demonstrating ablation of tandem cells.

Technical Point of Contact:
Myles Steiner
National Renewable Energy Laboratory
303-384-7675
myles.steiner@nrel.gov

Thermoradiative Power Cells for Deep Space and Lunar Applications

Stephen Polly, Rochester Institute of Technology
Andrew Schaefer, Rochester Institute of Technology
Crystal Qu, Rochester Institute of Technology
Geoffrey Landis, NASA Glenn Research Center
Seth Hubbard, Rochester Institute of Technology

The thermoradiative cell (TRC) is a new concept for thermal-to-electrical power conversion, working like a thermophotovoltaic (TPV) cell in reverse. In a conventional photovoltaic or TPV device, photons from the Sun or other black body radiator are absorbed and excite charge carriers which are separated at a p/n junction diode, rejecting waste energy as heat. Using similar materials and architecture, the TRC directly absorbs heat, providing energy to charge carriers through direct thermal excitation. These recombine at a p/n junction and emit infrared photons into a cold environment, such as deep space or a permanently shadowed lunar crater, from which a negligible number of photons are returned to the TRC. This recombination generates power from a positive internal current density and a negative voltage, opposite in sign to conventional (T)PV, with operation in the second quadrant of the current-voltage curve. In this work, supported by a Phase II NASA Innovative Advanced Concepts (NIAC) program, the TRC is theoretically and experimentally investigated as a power source where the use of photovoltaic power is impractical. Using a 50 K environment as a heat sink, a range of TRC bandgaps and operating temperatures are modeled representing heat from a radioisotope source. For a representative material of $InAs_{0.91}Sb_{0.09}$ (0.28 eV), power conversion efficiencies of greater than 12% are predicted, a significant increase over conventional thermoelectric generators, with a power density of more than 5 mW/cm^2. An experimental setup was developed to test TRC performance in vacuum on a heated stage facing a liquid nitrogen cooled surface, as an analog of a radioisotope heated device operating in deep space. Device performance of InGaAs photodetector diodes, as well as the development of metalorganic vapor phase epitaxy (MOVPE) grown InAsSb devices will be shown.

Technical Point of Contact:
Stephen Polly
Rochester Institute of Technology
585-475-6811
sjpvpr@rit.edu

Electroluminescence Imaging: A Quantitative Characterization Technique to Measure Dust Occlusion of Solar Cells

Meghan Bush, NASA Glenn Research Center
Timothy J. Peshek, NASA Glenn Research Center
Roselin Campos, Maxar Space Systems
Harry Yates, Maxar Space Systems
Bran Tranter, Maxar Space Systems

Electroluminescence (EL) imaging is a qualitative characterization technique that is typically used to identify cracks, corrosion, and other defects in solar cells. It consists of imaging a cell under forward bias, where the solar cell emits photons due to radiative electron-hole pair recombination. Over the past few years, our team has expanded this into a quantitative technique with the help of image processing. We have primarily used this method to investigate lunar dust occlusion on solar cells and arrays. Lunar dust occlusion of solar cells is a major concern because it directly limits light accessible to the cell, decreasing power output. Many teams are working to develop dust mitigation technology to protect these arrays on the surface of the Moon, but thoroughly characterizing their efficacy is important to ensure their success prior to launch. Here, we present EL as a quantitative characterization technique to observe dust coverage on solar arrays that, when coupled with IV performance measurements, can offer unique insights into how dust coverage impacts power output.

Quantitative electroluminescence imaging works by running EL images through an image processing script that first grayscales the image then plots a histogram of the brightness of each pixel. On its own, it does not offer much insight into a solar cell's performance. However, when comparing images to a baseline pristine, undamaged, or uncoated solar cell, it can quickly provide information about the impacts of surface contaminants or damage to the cell. Here, we present a case study where quantitative EL is used to measure the efficacy of dust mitigation technology for flexible solar arrays and discuss the lessons learned about dust mitigation, testing with lunar simulant, and this characterization technique.

Technical Point of Contact:
Meghan Bush
NASA Glenn Research Center
meghan.bush@nasa.gov

Evaluation of Large Area Ultra-Light Environmental Protection for Space Solar Arrays

Pilar Espinet-Gonzalez, Jann A. Grovogui, Abigail R. Meyer, Yao Y. Lao, Colin Mann, Don Walker
Energy Technology Department, The Aerospace Corporation, El Segundo CA, 90245, USA

The vast majority of conventional solar cells in space are protected with a thin sheet of coverglass adhered on the front side with space grade epoxy adhesive. Coverglass serves multiple roles in protecting solar arrays in space, including but not limited to: 1) shielding against high energy particle radiation, 2) protection against atomic oxygen in low earth orbits, 3) improvement of radiative cooling of the solar array due to its higher emissivity in the IR wavelengths, 4) bleeding off accumulated electrical charge when conductive coatings are also deposited.

While there are many benefits to incorporating coverglass in the solar array design, there are also limitations and challenges introduced to the design and fabrication process. The step of precisely adhering the coverglass onto the solar cell is time consuming, negatively impacting the production output and the cost of the solar array assembly. Further, typically the minimum thickness of coverglass used is ≈ 75 um, adding unnecessary weight to the solar array beyond radiation shielding needs. The rigidity of coverglass also limits opportunities to explore truly flexible solar cell and array architectures and is unable to take advantage of lower cost manufacturing approaches such as roll-to-roll or spray coating in short lifetime missions in low radiation environments.

As the cost of launch services continues to decrease, new satellite constellation designs have become increasingly prominent, focusing on short lifetimes and low-cost assembly processes to meet rapidly growing demand. Additionally, advancements in flexible and/or retractable solar blankets can also reduce stowed volume and make possible lighter deployment mechanisms reducing even further the cost. This has renewed the interest in lower cost flexible solar cell architectures which will require a thin film flexible shield to fully exploit their benefits. However, while there are strategies being explored for flexible solar cells and array substrates, there are currently no alternatives to traditional coverglass.

In this study the specific radiation protection requirement against the space environment encountered in different orbits and mission lifetimes have been evaluated. In particular, the potential of several transparent films and adhesives as alternatives to the current space grade coverglass/silicone encapsulation approach have been evaluated for a representative short lifetime (5 years) mission in LEO. The optical degradation of the films and adhesives under vacuum UV, plasma, high energy particles radiation and atomic oxygen (AO) have been characterized to determine their potential and limitations.

Technical Point of Contact:
Pilar Espinet Gonzalez
The Aerospace Corporation
pilar.espinetgonzalez@aero.org

UV Stress Testing of Perovskite Devices Packaged with Different UV-blocking Materials

Nancy D. Trejo, Giles E. Eperon
Swift Solar, 981 Bing St., San Carlos, CA, 94070

Perovskite solar cells have reached impressive efficiencies and show promise as a low-cost PV technology for terrestrial and space applications. However, their sensitivity to moisture, heat, and UV light necessitates proper encapsulation and rigorous stress testing to ensure device efficacy and longevity. This is particularly important for space applications where UV light illumination is stronger than that on earth. This study focuses on testing perovskite devices encapsulated with UV protecting layers with varying UV cutoffs. UV protection is provided either through the encapsulant with UV absorbers or with a UV-blocking coating on the front sheet. The encapsulated devices are stress tested by exposing them to UVA-340 fluorescent lamps. While perovskite devices of different compositions may require different UV light protection, this study shows that varying the UV cutoff range can be a good way to find the optimum value to increase stability while minimizing efficiency loss.

Technical Point of Contact:
Nancy Trejo
Swift Solar
707-775-9222
Nancy.trejo@swiftsolar.com

Space Based Solar Power – Enabling Lunar Night Survival and Beyond

Christopher G. McKinney – Advanced Systems Formulation Manager, NASA MSFC
Les Johnson – Chief Technologist, NASA MSFC
Randall Hopkins – Advanced Concepts Office, NASA MSFC
Tim Peshek – Chief, Photovoltaics and Electrochemical Systems, Glenn Research Center
Jeff McNabb – Research Engineer, Georgia Tech Research Institute

The current power state of the art for lunar surface operation involves the use of photovoltaic (PV) arrays to receive sun energy and/or radioisotope thermoelectric generators (RTGs). Without power from one of these sources, a lander, rover, or human habitat has a very low likelihood surviving the lunar night when the temperature drops to below -150C.

The NASA George C. Marshall Space Flight Center (MSFC) and Glenn Research Center (GRC) are evaluating the use of laser beamcraft in low lunar orbit to enable lunar night survival, with stretch goals of enabling continued science, exploration, and manufacturing during the lunar night, within permanently shadowed regions (PSRs), or outside of settled areas with permanent power generators. These satellite designs utilize a photovoltaic (PV) array to provide charging power to the craft's batteries, which are then used to power the laser. Power is received on the ground via dual-use PV receiver. Heat generation on the craft is mitigated by radiators sized by measuring the power conversion efficiencies of the PV, battery, and laser. Conceptually, no additional heat mitigation is required for the surface asset, as the power density (defined as irradiance in W/m^2) delivered in most cases is no more than the power/heat delivered by the sun.

With just 3 satellites in low lunar orbit (LLO), complete lunar surface coverage is possible. An orbital period of 2 hours allows approximately 15 minutes of power transmission per lunar asset and up to 1 hour and 45 minutes of battery recharge, dependent on the moon's relation to the sun. Assuming a relatively small surface asset requires 5W continuous to operate its heaters, the satellite should be capable of delivering approximately 10W per 15-minute pass and requires around 120Whr per day, delivered evenly across 12 passes (or 3 hours of transmission).

MSFC and GRC intend to continue investigating the viability of SBSP for the lunar surface not as a replacement for typical ground-based power generation systems but as a supplement enabling the rapid industrial development of the surface of the moon via the flexible delivery of power. The satellites discussed herein would be able to bridge the gap between the current state of the moon – lifeless and harsh – and the desired future state – lively and robust – and allow NASA to achieve its M2M goals with an added level of safety and efficiency.

Technical Point of Contact
Christopher G. McKinney
NASA Marshall Spaceflight Center
christopher.g.mckinney@nasa.gov

Advanced Solar cells with Thermal, Radiation, And Light management (ASTRAL) for Space Based Solar Power

Louise C. Hirst[1,2], Eduardo Camarillo Abad[1], Jiayi Li[2], Tyler Colenbrander[2], Armin Barthel[1], Oliver Trojak[3], Nina Vaidya[4], Kai Sun[3], Otto Muskens[3]

1. Department of Materials Science and Metallurgy, University of Cambridge, Cambridge CB3 0FS, United Kingdom
2. Department of Physics, University of Cambridge, Cambridge CB3 0HE, United Kingdom
3. Department of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom
4. Faculty of Engineering and Physical Sciences, University of Southampton, Southampton, SO16 7QF, UK

The solar cell element of a space based solar power (SBSP) system has a unique set of design requirements including: (i) extended lifetime in high radiation environments such as high altitude orbits, required to deliver superior coverage of the Earth's surface, with lifetimes for several decades targeted to achieve required levelized cost of energy; (ii) high efficiency with low mass for practically feasible and lower cost launch, as well as pathways to affordable and large scale production. These requirements cannot be achieved with currently available commercial systems, necessitating development in this area. This presentation will cover PV system challenges for SBSP as well as our development of Advanced Solar cells with Thermal, Radiation, And Light management (ASTRAL) which is a photovoltaic concept designed to address the specific requirements of SBSP. In this design an novel ultra-thin III-V dual junction architecture is employed for intrinsic radiation resilience enabling decades of on orbit solar energy conversion as well as substantial reduction in radiation shielding requirements, reducing mass and corresponding launch costs. This is integrated with a light management system, comprising a rear surface engineered scattering structure with a quasi-random texture and a front surface multilayer thermal management coating which acts as an anti-reflection coating in the visible region of the spectrum while being highly emissive in the infra-red to enable passive radiative cooling and prevent runaway heating under solar concentration. Furthermore, the front surface coating is designed to block low energy protons and reduce surface charging. This system is holistically developed to target lower levelized cost of energy for SBSP systems. Device and optical simulations of the complete optimized architecture, along with projected radiation damage for target mission profiles will be presented, as well as our latest experimental progress showing promising performance of ultra-thin subcells with integrated light management and radiation test data.

Technical Point of Contact:
Prof. Louise Hirst
University of Cambridge
Tel: (Materials office) +44 (0)1223 331538, (Physics office) +44 (0)1223 760078
lh619@cam.ac.uk

Mapping Spectroscopic Ellipsometry of CdS/CdSe/CdTe Photovoltaics

Mohammed A. Alaani , Prakash Koirala, Puja Pradhan, Adam B. Phillips, Nikolas J. Podraza, Michael J. Heben, Robert W. Collins
Department of Physics & Astronomy and Wright Center for Photovoltaics Innovation & Commercialization, University of Toledo, Toledo, Ohio 43606 USA

Thin film CdS/CdSe/CdTe solar cells devices have been fabricated by RF magnetron sputtering starting from CdS/CdSe front layers deposited on TEC-15M glass. The performance of these devices exhibit sensitivity to the fabrication conditions that control the process of CdSe/CdTe intermixing, which leads to formation of CdSexTe1-x graded absorber. In this work, both CdSe and CdS layers have been measured by mapping spectroscopic ellipsometry (M-SE) for process calibration which involves determining the spatial variations across the sample area (15 cm x 15 cm). The ultimate goal is to improve the device performance by correlating the solar cell performance parameters (open-circuit voltage, short circuit current density, fill factor) with the effective CdS and CdSe layer thicknesses. Coarse and fine-scale optimization are enabled by intentional thickness variations and unintentional spatial non-uniformities. Following this method, the highest performance device was obtained with 13 nm CdS and 100 nm CdSe. Increasing the CdS thickness above 13 nm reduces the open-circuit voltage and fill factor due to the formation of CdSe1-zSz with z approaching 0.5, where this region negatively impacts the electronic properties of the alloy. The results show that for a complex solar cell structure, M-SE demonstrates sensitivity to device performance from subtle thickness variations and serves as feasible approach for device structure optimization when combined with deposition non-uniformities.

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Technical Point of Contact:
Mohammed Razooqi Alaani, PhD
Department of Physics & Astronomy, University of Toledo
+1 (269) 271 6576
Mohammed.razooqi@utoledo.edu

Limitations of Dark IV Testing for Space Solar Arrays

Bao Hoang, Maxar Technologies
Jeremiah McNatt, NASA Glenn Research Center
Casey Hare, Angstrom Designs, Inc.

There is constant pressure on ground test capabilities to keep up with the advances in space solar array technology. Existing solar simulators for light IV testing can be incapable of accurate testing of new solar arrays because of increased array size, new solar cell technologies, or novel deployment methods, which can make ground deployment and offloading challenging. An example is the legacy Spectrolab LAPSS, which cannot accurately test solar cells with more than 3 junctions. In these cases, there is a temptation to substitute non-illuminated "dark" IV testing for illuminated "light" IV.

This talk discusses the dark IV and light IV methods, the challenges in both IV methods, the types of failures that can be detected by both methods and the risks of substituting dark IV for light IV without careful consideration.

Technical Point of Contact:
Casey Hare
Angstrom Designs, Inc.
(805) 448-4138
Casey.Hare@AngstromDesigns.com

Solar Cell IV Testing on the Lunar Surface

Scott Ireton, Angstrom Designs, Inc.
Casey Hare, Angstrom Designs, Inc.
Eric Jordan, Aegis Aerospace, Inc.
Charles Parrish, Aegis Aerospace, Inc.

Active characterization of solar cells, including current-voltage (IV) curves and temperature measurement, is critical for determining photovoltaic performance. Flight data for understanding combined effects on cell performance is incredibly valuable and can be difficult and expensive to obtain. Through NASAs STMD Tipping Point Contract, Aegis Aerospace subcontracted Angstrom Designs to develop a solar cell characterization platform for the lunar surface that leverages the Aerospace Measurement Unit (AMU). The payload, carrying Perovskite and Silicon solar cells, is scheduled for launch after the conference, so the focus of the talk is on capability, technology development, and testing. We will also discuss requirements, capabilities, and opportunities from a new partnership between Angstrom Designs and Aegis Aerospace to bring active solar cell characterization, with sample return, to the LEO environment.

Technical Point of Contact:
Scott Ireton
Angstrom Designs, Inc.
(415) 450-0372
Scott.Ireton@AngstromDesigns.com

Ion Beam Irradiation and Micro-Analysis of Photovoltaic and Microelectronics Samples Utilizing a Versatile Ion Beam Facility at the University of North Texas

Bibhudutta Rout
Department of Physics, Ion Beam Laboratory, University of North Texas, Denton, Texas 76203, USA
bibhu@unt.edu

Energetic ion beams have been used for materials analysis, modifications, and synthesis in various fields involving semiconductors, photovoltaics, and biomaterials. At the University of North Texas, Ion Beam Laboratory, we have two dedicated ion accelerator facilities providing proton and other heavy ion beams of energies from a few tens of kilo electron-volts (keV) to several Mega electron-volts (MeV) enabling targeted irradiation of various layers of the materials and electronic devices. We also have a novel and powerful scanning ion microprobe (~ 500 nm spot sizes) for elemental concentration and compositional characterization in various stacks of PV devices along with simultaneous irradiation of targeted layers of the devices. In this presentation, we will highlight using proton microprobe for quantitative elemental micro-analysis of a wide range of elements in PV devices and electronic materials utilizing several complementary ion beam analysis techniques. These techniques are relatively non-destructive and require minimal sample preparations providing quantitative information about elemental diffusion due to the aging of the PV devices. A review of some of our works on ion irradiation-induced effects in various photovoltaic devices will be described.

Technical Point of Contact:
Bibhudutta Rout
Professor and Associate Director of Ion Beam Laboratory
Department of Physics, Ion Beam Laboratory, University of North Texas, Denton, Texas 76203, USA
940-369-8127
bibhu@unt.edu

Enhancing durability and performance in photovoltaic cells through guanidinium-based quasi-2D halide perovskites.

Matthew Bamidele, Oklahoma State University
Tai Nguyen, Oklahoma State University
Do Young Kim, Oklahoma State University

In the realm of photovoltaic technologies, halide perovskite solar cells (PSCs) have emerged as frontrunners owing to their outstanding performance and progress within few years of research. The solution-based processability of these hybrid semiconductors makes them particularly appealing for cost-effective and scalable production. Although solar cells based on halide perovskites have achieve power conversion efficiencies over 25%, their commercial adoption is limited due to their poor stability under typical environmental conditions such as heat, humidity, and light exposure. Among other approaches, the use of layered two-dimensional (2D) perovskites has been thoroughly explored to enhance the stability of perovskite solar cells, often at the expense of their efficiency. In this investigation, we developed methods to enhance the stability of perovskite solar cells while preserving their efficiency by incorporating a quasi-2D perovskite layer. Specifically, we utilized quasi-2D guanidinium-based perovskites synthesized with lead acetate (PbAc), achieving notably higher efficiency than cells fabricated with traditional lead iodide (PbI). This improvement is primarily due to the unique perpendicular orientation of the quasi-2D perovskite crystal structure, which significantly enhances charge extraction. Perovskite solar cells fabricated using PbAc precursor exhibited power conversion efficiencies roughly twice that of PbI-based cells. Furthermore, the efficiency of these cells continuously improved over several weeks, a phenomenon attributed to age-induced recrystallization, highlighting their potential for prolonged stability and delayed device degradation. After 3,000 hours, these cells maintained nearly unchanged performance. Additionally, we introduced a hybrid approach that layers a 3D $MAPbI_3$ film atop a quasi-2D $GA_2MA_4Pb_5I_{16}$ layer, increasing the efficiency by approximately 20% compared to traditional 3D perovskite solar cells. This configuration not only achieved superior crystallinity and excellent film quality but also demonstrated significant durability, maintaining about 98% of its initial performance even after 1,900 hours. This research underscores the benefits of layered perovskite structures in boosting the performance and lifespan of solar cells.

Technical Point of Contact:
Do Young Kim
School of Materials Science and Engineering, Oklahoma State University
352-562-2660.
doyoung.kim@okstate.edu

Radiation Tolerance of Metal-Halide Perovskites: Fact or Fiction?

Ahmad R. Kirmani[1], Bibhudutta Rout[2], Ian R. Sellers[3]
[1]School of Chemistry and Materials Science, Rochester Institute of Technology (RIT), NY 14625
[2]Department of Physics, University of North Texas (UNT), TX 76203
[3]Department of Electrical Engineering, University of Buffalo (UB), NY 14260

Metal-halide perovskites (MHPs) are a new class of easily manufacturable minerals, almost 10x cheaper than silicon, with remarkable optoelectronic properties and potential for photovoltaic applications. Recent findings of radiation tolerance and self-healing in MHPs have spurred interest in their potential as a scalable and low-cost space power technology. In this talk, we will challenge the prevailing narrative, suggesting that MHPs *might not be* as radiation tolerant as currently perceived. Considering the latest experimental evidence presented across the community – further supported by theoretical insights – it appears likely that perovskites undergo radiation induced damage easier than previously thought, notably due to the smaller threshold displacement energies than typically considered in – for example – SRIM analysis. This inevitably results in facile defect generation and degradation of MHPs at levels far in excess of that typically considered necessary for high performance solar cells. However, here, we propose that unlike traditional PV systems such as silicon and III-V's, the soft structure inherent in MHPs, often considered their Achilles heel, may in fact represent an advantage over traditional systems, with the dynamic nature of the lattice in these materials facilitating defect healing and materials recovery driven by the strong electron-phonon coupling inherent in these highly polar systems. Furthermore, the subtle nature of defect formation and propagation in MHPs coupled with their highly complex out-of-equilibrium structural dynamics appears to result in nearly simultaneous displacement damage and defect generation, followed by local healing that induces defect annihilation. The result is the observation of high and often unchanged remaining factors observed experimentally in MHP solar cells upon proton irradiation. While their ability to self-heal places MHPs in a unique class of materials that offer the potential to undergo in-orbit recovery in space, we suggest such conclusions should also be considered with care calling to attention the need to develop a new set of space-testing protocols for this unique set of materials that moves past current AIAA protocols traditionally used for PV materials. To this end, here, we discuss several outstanding questions in the field of MHPs for space PV and the need for developing consistent global testing protocols that truly enable the assessment of MHPs in the young and emerging field of space PV. We will highlight the necessity to develop theoretical models specific to these materials that can predict in-orbit behavior of the MHPs, and the importance of testing these materials under coupled or simultaneous stressors that mimic extreme environments, where radiation, thermal cycling, vacuum, AM0 photoexcitation, atomic oxygen, and ultraviolet radiation (amongst others) combine to cause nonlinear effects and accelerated degradation not easily reproduced under terrestrial testing conditions.

Technical Point of Contact:
Ahmad R. Kirmani
School of Chemistry and Materials Science, Rochester Institute of Technology
arksch@rit.edu

Metal Halide Perovskite Solar Panels for Space Applications

Joseph M. Luther
National Renewable Energy Laboratory, Golden, CO, United States

Metal Halide Perovskites are a hybrid semiconductor class only first applied toward photovoltaic applications in 2009. In the ensuing 15 years, there has been tremendous progress in efficiency now with this technology being developed by many industrial players and on the brink of commercialization. The efficiency of perovskite cells in single junction and multijunction configurations continues to increase at unprecedented rates, but it has never been the efficiency (specifically) that is holding this technology back. It is the durability of the panels which is sensitive to many factors.

Perovskites also have a variety of noteworthy features that make them exceptionally promising for space applications. The space market might also be an easier first target for perovskite companies, and they could provide a complementary product in relation to existing space PV options.

In this talk, I will discuss the most promising aspects along with the most challenging aspects of adapting these cells toward space applications, showing results from numerous ground testing experiments as well as space flights. The "goods" and "bads" of aspects such as efficiency, radiation tolerance, packaging, thermal cycling fatigue, etc. will be discussed in a compare-and-contrast format.

Technical Point of Contact:
Joseph M. Luther
National Renewable Energy Laboratory
Joey.Luther@nrel.gov

Thermal Performance of Perovskite-Based Photovoltaics for Operation in Low Earth Orbit

Timothy S. Krause[1], Kaitlyn T. VanSant[2,3], Andrew Lininger[4], Kyle Crowley[2], Timothy J. Peshek[2], and Lyndsey McMillon-Brown[2]
[1]University Space Research Association, NASA Glenn Research Center, Cleveland, OH, 44135, USA
[2]NASA Glenn Research Center, Cleveland, OH, 44135, USA
[3]National Renewable Energy Laboratory, Golden, CO, 80401, USA
[4]Department of Physics, Case Western Reserve University, Cleveland, OH, 44106, USA

Perovskite-based photovoltaics are attractive for applications in space. The space environment is harsh with extreme temperatures, atomic oxygen, ionizing radiation, UV radiation, and thermal cycling. Here, we evaluate the thermal performance of a perovskite active layer and perovskite photovoltaic devices in low earth orbit. We determine that a 1 μm layer of silicon oxide coupled with a 500 nm zirconia thin film aid in cell thermal management. We model the residual stresses between various layers in the device and prove that thermally induced mechanical failure of the perovskite ($t > 460$ years) is unlikely during the operating lifetime of a space mission. We identify target power conversion efficiencies to manage operating temperature of a perovskite-based photovoltaic.

Technical Point of Contact:
Lyndsey McMillon-Brown
NASA Glenn Research Center
216-433-5197
Lyndsey.McMillon-Brown@nasa.gov

Metal Halide Perovskite Solar Cells for Emerging Space Applications

Megh N. Khanal,[1] Hadi Afshari,[1] Vincent R. Whiteside,[1] Ahmad R. Kirmani,[2] Giles E. Eperon,[3] Joseph M. Luther,[4] Bibhudutta Rout,[5] and **Ian R. Sellers[1]**

[1]Department of Electrical Engineering, University at Buffalo, Buffalo, NY 14260, USA
[2] School of Chemistry & Materials Science, Rochester Institute of Technology, Rochester, NY 14623, USA
[3] Swift Solar, San Carlos, CA 94070 USA
[4] National Renewable Energy Laboratory, Golden, CO 80401, USA
[5] Department of Physics, University of North Texas, Denton, TX 76203, USA

In this presentation the potential of metal halide perovskite solar cells for space power applications will be presented. This presentation will focus on our recent work on the feasibility of metal halide perovskites for space, which includes the assessment of the systems in low-intensity-low-temperature (LILT) conditions for outer planetary missions, in addition to exposure to high temperatures and variable radiation conditions that directly and independently impact the absorber and transporting layers of the devices. Here, the discussion will include a number of perovskite systems such as solution processed mixed Pb-Sn systems and the FAMACs family of metal halide perovskites, as well as blade-coated architectures. It will be shown that perovskites display remarkable tolerance to high radiation exposure and that while measurements *do* suggest high energy radiation negatively affects the transporting layers and interfaces in the devices: the perovskite absorber *is not affected* in any significant way. Moreover, these systems are observed to self-heal under ambient conditions in the dark demonstrating the unique behavior of perovskite solar cells and their potential for future space applications. This is further substantiated by high temperature measurements that indicate specific triple cation perovskites displays no appreciable or permanent degradation up to 500 K, supporting in particular their potential as candidate systems for future lunar missions.

Technical Point of Contact:
Ian R. Sellers
Department of Electrical Engineering
SUNY Buffalo, Buffalo, NY 14260. USA
isellers@buffalo.edu
716-645-1152

Proton Radiation Hardness of Antimony Chalcogenide Solar Cells

Alisha Adhikari,[1] Joel Blodgett,[1] Vijay Karade,[1] Randy J. Ellingson,[1] Zhaoning Song,[1] and Yanfa Yan[1]

[1]Wright Center for Photovoltaics Innovation and Commercialization, Department of Physics and Astronomy, The University of Toledo, OH 43606, USA

Antimony chalcogenide-based thin-film solar cells have received immense attention for terrestrial and space photovoltaic (PV) applications due to their excellent optoelectronic properties, ease of synthesis, and material robustness. To utilize solar cells for space power applications, the study of their proton radiation hardness is pivotal. In this work, the effect of proton irradiation on the PV performance of antimony chalcogenide-based solar cells was studied. Devices were exposed to protons with different energies (150, 650, and 1000 keV) for three fluences (1.00E+10, 1.00E+11, and 1.00E+12 protons/cm^2), and their current density-voltage characteristics and external quantum efficiency (EQE) before and after radiation were compared. Our results indicate that antimony selenide (Sb_2Se_3) solar cells exhibited high remaining factors in PV performance after being exposed to lower fluences of protons and showed a decreased performance with increasing fluences. However, antimony sulfoselenide ($Sb_2(S,Se)_3$) solar cells suffered from significantly reduced device performance after proton irradiation, regardless of fluences and proton energies. This result suggests that sulfur anions are susceptible to proton radiation, causing overall degradation in the device performance of $Sb_2(S,Se)_3$ solar cells.

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Technical Point of Contact:
Dr. Zhaoning Song
Department of Physics and Astronomy
Wright Center for Photovoltaics Innovation and Commercialization
The University of Toledo, Toledo, OH, 43606, USA
419-297-5455
Zhaoning.Song@utoledo.edu

This is a **Student Poster**

High Efficiency, Light weight, and Flexible CdTe Based Solar Cells

Manoj K. Jamarkattel[1], Sabin Neupane[1], Nadeesha Katakumbura[1], Sanjeev Budhathoki[1], Prabodika N. Kalurachchi[1], Ebin Bastola[1], Adam B. Phillips[1], Yanfa Yan[1], Randy J. Ellingson[1], and Michael J. Heben[1].
[1]Wright Center for Photovoltaics Innovation and Commercialization, Department of Physics and Astronomy, University of Toledo, Toledo, OH, 43606, USA

Cadmium telluride (CdTe) has a 1.5 eV optical band gap with high absorption coefficient, making it an excellent material for solar cells. CdTe-based thin-film solar cells are well-established and commercialized photovoltaic (PV) for terrestrial use, with a record efficiency of 22.6% under AM1.5 illumination. In addition, it has demonstrated radiation hardness in space deployment[1] and efforts have been made to develop lightweight and flexible CdTe-based solar cells, aiming for high specific power and flexible installation capability.

Here, we will discuss efforts to prepare high efficiency CdTe PV devices on lightweight substrates. We compare and contrast the performance of CTO/$(In_xGa_{1-x})_2O_3$)/CdSe/CdTe solar cells fabricated on 3YSZ ceramic substrates (20 microns thick) obtained from ENrG Inc. and on Corning® Willow® glass (100 microns thick) substrates. Efficiency parameters and J-V curves will be reported under AM0 and AM1.5 conditions. Our preliminary results show that specific power density of ~ 700 W/kg (without packaging) can be achieved for flexible and lightweight CdTe solar cells fabricated on Corning® Willow® glass with device efficiency of 17.2 % and 14.6 % were measured under AM1.5G and AM0 irradiances. We will discuss the limiting factors for device performance and potential pathways to eliminate them.

This material is based on research sponsored by the U.S. DOE's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement DE-EE0008974, through the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy, under Award Number 37989, and Air Force Research Laboratory under agreement number FA9453-19-C-1002 and FA9453-21-C-0056. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The views expressed are those of the authors and do not reflect the official guidance or position of the United States Government, the Department of Defense or of the United States Air Force. The appearance of external hyperlinks does not constitute endorsement by the United States Department of Defense (DoD) of the linked websites, or the information, products, or services contained therein. The DoD does not exercise any editorial, security, or other control over the information you may find at these locations. Approved for public release; distribution is unlimited. Public Affairs release approval # 2024-3092.

Technical Point of Contact:
Michael J. Heben
Department of Physics and Astronomy
Wright Center for Photovoltaics Innovation and Commercialization, University of Toledo
4195303870
Michael.heben@utoledo.edu
This is a **Student Poster**

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Analysis of Glint During the Artemis I Mission

Alex Jurcago, John Carroll University
Spencer Furin, NASA Glenn Research Center
Ed Lewandowski, NASA Glenn Research Center

Glint occurs when light reflects off a specular (mirror-like) surface. In the context of spacecraft, glinted light can land in places that may cause unintended negative effects. During the Artemis I mission in November and December of 2022, the vehicle was configured intentionally to cause glint to occur in order to study its effect on the Orion electrical power system (EPS). With the vehicle in a nose-to-sun attitude, light was reflected off the crew module's reflective skin and onto forward-pointed solar array wings (SAWs), producing more current than would result from direct solar flux alone. Along with this flight test, glint was unexpectedly observed several other times during the mission, primarily due to light reflecting from one SAW to another. The planned glint events helped to anchor the models previously used to study this phenomenon and to understand what parameters have the most significant impact on glinted current generation. With refined models, the SAW-to-SAW glint occurrences were studied with the goal of characterizing its potential impact on vehicle operation.

In this presentation, the two models used for estimating glinted current generation will be discussed, as well as a worst-case study that was performed before the Artemis I mission. In-flight telemetry data will be compared to values of SAW section current produced by the models for both planned and unplanned glint occurrences. Material optical properties and other parameters studied will be outlined and their significance on the impact of glint will be discussed. Finally, the implications of glint to future space missions are discussed. These include implications to proximity operations and the configuration of large space structures such as Gateway.

Technical Point of Contact:
Alex Jurcago
John Carroll University
330-741-0373
ajurcago25@jcu.edu

This is a **Student Poster**

Trap Analysis of Zn- vs. C-doped 2.1eV AlGaInP irradiated by 3MeV Protons

Tal Kasher[1], Hemant Ghadi[2], John T. Hart[2], Zachary S. Bittner[2], Andrew Espenlaub[2], Daniel Derkacs[2], Nate Miller[2], Tyler J. Grassman[1], Steven A. Ringel[1]
[1] The Ohio State University
[2] SolAero by Rocket Lab

AlGaInP is often used in the uppermost sub cell for advanced III-V multijunction space solar cells for accessing wider and more ideal bandgaps while remaining lattice-matched to Ge substrates. However, the increased Al in a III-V compound can create deep level defects, leading to reduction in key material properties like diffusion length. While there have been advances in suppression of grown-in defects, there is comparatively little work characterizing the defects resulting from space radiation, especially protons. This work presents a systematic study of defect evolution with proton radiation using a combination of deep level transient (thermal and optical) spectroscopies (DLTS/DLOS) to complete probe the entire bandgap. 2.1 eV *p*-type AlGaInP layers, doped with either zinc or carbon ($N_A \approx 10^{17}$ cm^{-3}), were grown via metal organic chemical vapor deposition (MOCVD) on GaAs substrates in order to compare the two common dopants used in the base layer of AlGaInP solar cells. Mesa-isolated Schottky diodes were fabricated using standard lithographic techniques and sample irradiation consisted of 3 MeV protons to a total fluence of 4×10^{12} cm^{2}, with an intermediate step at 2×10^{12} cm^{-2}.

The as-grown DLTS trap spectra revealed a trap state at E_V + 0.7 eV, with DLOS revealing two additional states at E_V + 1.0 eV and E_V + 1.9 eV. After irradiation, a new state at E_V + 0.4 eV was detected. The close Arrhenius behavior of each individual defect state implies that all states were the same for both Zn- and C-doping. All defect states were found to be sensitive to proton-irradiation and increase in concentration with each additional dose of radiation, a behavior exhibited by defects with some intrinsic (i.e. not impurity) characteristic. After irradiation, a net reduction in acceptor concentration was observed due to the introduction of donor-like defect states. Interestingly, the carrier removal rate for Zn at $4.1 \pm 0.6 \times 10^{3}$ cm^{-1} was found to be lower than that of C at $5.7 \pm 0.6 \times 10^{3}$ cm^{-1}. To further study this observed difference in carrier removal, each individual trap state was characterized via DLTS/DLOS.

In general, all defect states had similar trap concentrations between Zn- and C-doping. However, the E_V + 1.9 eV state showed much higher trap concentration by an order of magnitude as compared to all other states. The trap introduction rate, a measure of the net increase in trap concentration divided by the fluence, was extracted for all trap states. The trap introduction rate for all states was ~600-700 cm^{-1}, except for the E_V + 1.9 eV state which had a 2× trap introduction rate at ~1100-1300 cm^{-1}. The higher trap concentration coupled with the higher trap introduction rate emphasizes the dominance of the E_V + 1.9 eV state. The total trap concentration for both Zn and C was then summed and found to be equal to each other. Furthermore, the total summed trap concentration matched the carrier removal of Zn but not that of C, for all fluences. There are many possible reasons for this interesting difference, and work is currently underway to understand this discrepancy including a final dose of radiation to a total fluence of 6×10^{12} cm^{2} followed by a systematic annealing study which will be presented at the conference.

Technical Point of Contact:
Tal Kasher
Ohio State University
(704)-649-6923, kasher.4@osu.edu

This is a **Student Poster**

Encapsulation Study of Metal Halide Perovskites for Space Applications

Megh.N. Khanal[1], Mritunjaya Parashar[2], Tamara Merckx[3], Vincent R. Whiteside[1], Giles E. Eperon[4], Mohin Sharma[2], Bibhudutta Rout[2], Yinghuan Kuang[3], Bart Vermang[3], Ian R. Sellers[1].
[1]Department of Electrical Engineering, University at Buffalo, Buffalo, NY 14260, USA
[2] Department of Physics, University of North Texas, Denton TX 76203, USA
[3] Imec, imo-imomec, Thin Film PV - partner in Solliance, Thor Park 8320, 3600 Genk, Belgium.
[4]Swift Solar, San Carlos, CA 94070 USA

The Metal Halide Perovskites (MHP) solar cells, considered for space applications, are influence by several factors including launch-induced degradation, radiation exposure, and temperature cycles. Studies show that unencapsulated MHP devices are affected by environmental conditions like high temperature and humidity experienced during pre-launch. Interestingly, these exposed devices exhibited self-healing properties and performance improvement after proton irradiation [1]. Additionally, Polymer-based encapsulants, tested for their suitability in space conditions, proved to be unsuitable due to their susceptibility to decomposition and excessive heating under high-energy proton exposure [2]. The space graded glass prevents protons directly impacting the structure but shows a low device performance due to low thermal conductivity (local heat buildup). This suggests the potential for optimizing the MHP solar cell for space applications by developing suitable encapsulation strategies.

Technical Point of Contact:
Megh N. Khanal
PhD Student
University at Buffalo
meghkhan@buffalo.edu

This is a **Student Poster**

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Effects of Proton Bombardment on Sunnyside Device Performance of Industry-grade Bifacial CdTe:Cu- and CdTe:As-based Solar Cells

Scott Lambright[1], Aesha P. Patel[1], Sabin Neupane[1], Zachary W. Zawisza[1], Molly Smith[1], James Becker[2], Manoj K. Jamarkattel[1], Adam B. Phillips[1], Abasi Abudulimu[1], Richard Irving[1],Zhaoning Song[1], Michael J. Heben[1], Yanfa Yan[1], Randy J. Ellingson[1]

1 Wright Center for Photovoltaics Innovation and Commercialization (PVIC), Department of Physics and Astronomy, University of Toledo, Ohio, 43606, USA

2 First Solar, Inc., Advanced Research, 28101 Cedar Park Blvd, Perrysburg, Ohio, 43551

Industry-grade CdTe-based photovoltaic devices have been characterized using current density-voltage characteristic curves both before and after exposure to 150+ kV proton bombardment (full factorial skew with proton acceleration voltage levels of 0.15, 0.65, and 1.0 MV proton fluence levels of $1*10^{11}$, $1*10^{12}$, or $1*10^{13}$ cm^{-1}.) Proton fluence strongly influences post-exposure performance, with median photon conversion efficiency (PCE) performance for samples exposed to the lowest fluence within 13% of controls while median PCE for samples exposed to the highest fluence degrading between 20-100%. Post-exposure device performance does not strongly correlate with proton acceleration voltage in low-fluence conditions; however, we find a strong negative correlation between PCE and proton acceleration voltage at high proton fluence. CdTe absorber p-type dopant also affects post-exposure performance, with Cu-doped CdTe solar cells experiencing ~ ½ the performance degradation that As-doped devices experience for a given high-fluence proton bombardment exposure condition.

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Additionally, the base material used for the CdSeTe-based PV devices was provided by First Solar, Inc.

Technical Pont of Contact:
Scott Lambright
University of Toledo Physics Department
(419) 307-6795
scott.lambright@rockets.utoledo.edu

This is a **Student Poster**

Wide spectral range optical characterization and electronic transport property determination using spectroscopic ellipsometry

[1]Madan K. Mainali, [1]Indra Subedi, [1]Prakash Uprety, [1]Dhurba R. Sapkota, [1]Prakash Koirala, [1]Zhaoning Song, [1]Yanfa Yan, [2]Seth M. Hubbard, [1]Robert W. Collins, and [1]Nikolas J. Podraza
[1]Wright Center for Photovoltaic Innovation and Commercialization, University of Toledo, Toledo, OH, USA
[2]NanoPower Research Laboratory, Rochester Institute of Technology, Rochester NY, USA

Spectroscopic ellipsometry is a non-invasive, contactless optical characterization tool sensitive to structural, optical, and electrical properties of materials in bulk form, thin films, and complicated device structure stacks such as thin film solar cells. When applied over a wide spectral range spanning the millimeter (THz), infrared (IR), visible (Vis), to vacuum ultraviolet (VUV), information on electronic transitions including the band gap, phonon modes related to chemical bonding, and free carrier absorption can be obtained from the optical response. Enhanced sensitivity to electronic transport properties (carrier mobility, concentration, and effective mass) are obtained from optical Hall effect using THz range spectroscopic ellipsometry measurements performed under different applied magnetic fields. Examples of these approaches will be discussed for III-V compounds in multilayer stacks, complete perovskite solar cells, and characterization of other materials of interest for solar cell devices. The optical properties in the form of the complex dielectric function spectra of epitaxial InGaAs and InAlAs lattice matched to InP in the multilayer yield sensitivity the direct band gaps of InGaAs (0.73 eV) and InAlAs (1.44 eV) layers affected by strain, phonon modes (252 cm-1 for InGaAs, 351 cm-1 for InAlAs), and carrier mobility and carrier concentration (9444 cm2/Vs and 1.7 × 1017 cm-3 for InGaAs, 5713 cm2/Vs and 2.5 × 1016 cm-3 for InAlAs). Free carrier concentration in the ITO, PEDOT:PSS, and (FASnI3)0.6(MAPbI3)0.4 perovskite absorber layers within a complete thin film solar cell are determined.

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Technical Point of Contact:
Madan K. Mainali
Wright Center for Photovoltaic Innovation and Commercialization
University of Toledo
Madan.Mainali@rockets.utoledo.edu

This is a **Student Poster**.

Optimization of InGaAs quantum wells for two-Junction Solar Cells

Anthony Mazur, Rochester Institute of Technology
Steve Polly, Rochester Institute of Technology
Seth Hubbard, Rochester Institute of Technology

III-V materials are an attractive option for space photovoltaics for their high efficiency, allowing for a significantly reduced cost-per-kg ratio when compared to other materials. The efficiencies of these materials can be pushed even further with care given to the design of the photovoltaic structure. Introducing multiple junctions of different bandgaps can help to reduce thermalization losses from higher energy photons. The inclusion of strain-balance quantum wells (SBQWs) allows for bandgap engineering for a better match to the solar spectrum. RIT has recently reported excellent results using 50 SBQWs in the GaAs junction of an InGaP/GaAs two-junction solar cell, demonstrating 27.5% AM0 and 30.3% AM1.5G efficiencies.This work presents an extension on these results, investigating the impact of increasing optical thickness through the inclusion of more QWs, and enhancing per well performance using thinner strain balancing barriers. Devices are grown epitaxially in an Aixtron close-coupled showerhead 3x2" metalorganic vapor phase epitaxy (MOVPE) research reactor, monitored in-situ via a LayTec EpiCurve TT telemetry system providing emissivity corrected surface temperature, growth rate, and substrate curvature measurements. High-resolution x-ray diffraction (HRXRD) characterizes the epitaxial quality of grown quantum wells. Devices are characterized using external quantum efficiency, then tested under AM0.

Technical Point of Contact:
Anthony Mazur
Growth Engineer, Rochester Institute of Technology
856-364-0474
aamnprl@rit.edu

This is a **Student Poster**

Identifying Suitable Front Contacts for Cd(Se, Te) Solar Cells on Space-Qualified Cover Glass

Aesha P. Patel[1, 2], Joel N. Duenow[2], Deborah L. McGott[2], Joshua A. Brown[2], Prabodika N. Kaluarachchi[1], Adam B. Phillips[1], Michael J. Heben[1], Matthew O. Reese[2] and Randy J. Ellingson[1]

[1]Wright Center for Photovoltaic Innovation and Commercialization, Department of Physics and Astronomy, The University of Toledo, Toledo, Ohio
[2]National Renewable Energy Laboratory, Golden, Colorado

To employ solar cells in space, achieving high specific power (W/kg) and radiation hardness is crucial. CdTe thin-film solar cells are expected to demonstrate the capability of achieving high specific power and radiation hardness comparable to Si and III-V solar technologies, which currently dominate in space applications. Although CdS/CdTe solar cells have been studied extensively for performance degradation, and somewhat for radiation tolerance, the more modern, higher efficiency architecture based on Cd(Se, Te) (CST) remains relatively unexplored for space application. The maximum efficiency achieved by CdTe under terrestrial STC is 22.4% at the laboratory scale. However, for terrestrial applications, CdTe is generally deposited on commercially available fluorine-doped tin oxide (FTO)-coated ~3 mm thick glass substrates. Whereas, ultrathin and lightweight glass substrates do not come with a transparent conducting oxide (TCO) layer, hence TCO, as well as emitter choice becomes crucial.

Here, we report the fabrication of CST solar cells, based on multi-source evaporation, on space-qualified cover glass, with a matrix of different front TCOs and emitters to determine the optimum working combination for high-efficiency superstrate-configured CST solar cells on thin glass substrates. The aim is to monitor the effects on UV transmission, while balancing it with the sheet resistance, determine their stability to high temperatures and reactive ambients in the processing, and then calculate the figure of merit to assess the quality of TCOs. The device structure will then be optimized to achieve maximum device performance under AM0 atmospheric conditions with minimal losses compared to that under the AM1.5G condition.

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Technical Point of Contact:
Randy J. Ellingson
Wright Center for Photovoltaic Innovation and Commercialization, Department of Physics and Astronomy (PVIC), The University of Toledo
Phone number: 419.530.3874
randy.ellingson@utoledo.edu

This is a **Student Poster**.

Photoluminescence Mapping as an Indicator of External Radiative Efficiency in Quantum Wells

Crystal Qu, Rochester Institute of Technology
Rivka Stasavage, Rochester Institute of Technology
Steve Polly, Rochester Institute of Technology
Seth Hubbard, Rochester Institute of Technology

Rochester Institute of Technology has recently reported excellent performance of photovoltaics 50-pairs of strain balanced quantum well (QW) in a GaAs 2-junction design with 27.5% AM0 efficiency and an open-circuit voltage (V_{oc}) loss of only 11 mV compared to a control GaAs device without QWs. However, developing high-quality QW structures is time consuming, costly, and typically necessitates complete fabrication to understand the effect of QWs on V_{oc}. External radiative efficiency (ERE) is a non-contact method to measure an implied open circuit voltage (iV_{oc}), which would expedite this process to be used with test structures which do not require fabrication. This method will be used to investigate a range of QW device performances and will be compared with photoluminescence (PL) mapping to correlate the quantitative ERE measurement to the qualitative PL system. The relationship between PL maps and EQE can be a useful tool when evaluating both fundamental performance of a device, but also in comparison to processing metrics and overall wafer yield. This presentation will discuss the correlation between the ERE system to the PL mapper, using this newly developed combination method to evaluate GaAs test structures and photovoltaic devices with InGaAs QWs.

Technical Point of Contact:
Seth Hubbard
Rochester Institute of Technology
585-475-4214
smhsps@rit.edu

This is a **Student Poster**.

Development of III-V solar cells using inverted growth and acoustic spalling on GaAs wafers

Elijah Sacchitella, RIT
Stephen Polly, RIT
Seth Hubbard, RIT
Pablo Guimera Coll, Crystal Sonic Inc.
Mariana Bertoni, ASU

III-V solar cells exhibit exceptional conversion efficiencies for space applications. Their high power density and radiation resistance makes them desirable for space related uses. The primary cost contributor of a III-V device is the substrate, account for over 30% of total cost. One cost reduction method being explored is acoustically controlled spalling or sonic lift off. Current spalling methods induce a crack that propagates along the natural crystallographic planes of the GaAs substrate. This results in a rough surface that needs further chemical and mechanical polishing before regrowth. Sonic lift off is an alternative process that uses sound waves to control crack propagation through the substrate, effectively reducing the magnitude of the surface facets that arise from traditional spalling techniques. This work showcases progress in substrate reuse utilizing acoustic spalling, or sonic lift off. 3” wafers were grown at RIT by metal organic chemical vapor deposition (MOCVD). Fabrication of wafers that underwent acoustic spalling have shown that 2 substrate reuses are possible with little to no device degradation under the AM1.5g spectrum. These devices will be retested under AM0 to determine performance in pLEO. Additionally, the scale up to 3” wafers required new fabrication techniques and a reformatted device structure to avoid excess handling of the spalled thin films. The differences in device structures as well the necessary steps to scale to 3” wafers will be highlighted and discussed in this poster. Overall, this study shows the promise of substrate reuse for GaAs based photovoltaics for both terrestrial and AM0 applications on 3” GaAs wafers.

Technical Point of Contact:
Elijah Sacchitella
PhD Candidate
Rochester Institute of Technology
Ejs5943@rit.edu

This is a **Student Poster**

Development of External Radiative Efficiency Technique as a Predictor of Material Quality for InGaP

Rivka Stasavage, Rochester Institute of Technology
Steve Polly, Rochester Institute of Technology
Seth Hubbard, Rochester Institute of Technology

Lattice-matched InGaP is an important material often used as the top cell in state of the art space photovoltaics. However, its quality and bandgap are highly sensitive to the epitaxial growth conditions. In determining the optimal growth conditions many devices need to be fabricated, which is a costly and often time-consuming process in the development of photovoltaic materials. A non-contact method of determining the quality of bulk material can expedite research by cutting down on intermediate fabrication runs. In order to quantify the quality of material we developed an optical setup which allows us to measure external radiative efficiency (ERE). With ERE as well as photoluminescence (PL) we calculate an implied open circuit voltage (iV_{oc}), a predictor of device performance. In this work, we present the details of our ERE optical setup, as well as the theory behind it. To validate the system, ERE measurements using InGaP materials, and fabricated photovoltaic devices, will be presented as grown under various conditions via metal organic vapor phase epitaxy (MOVPE) at Rochester Institute of Technology. This work includes a study to compare the ERE extracted iV_{oc} and measured V_{oc} under AM0 as a function of temperature. LIV, EQE and ERE results will be compared and presented to validate the efficacy of the ERE technique.

Technical Point of Contact:
Seth Hubbard
Rochester Institute of Technology
585-475-4214
smhsps@rit.edu

This is a **Student Poster**

The 4G32-Advanced four-junction solar cell adapted to spectral conditions on Mars

Felix Gerstenberger, Philipp Schroth, and Matthias Meusel
AZUR SPACE Solar Power GmbH Gerald Siefer, Fraunhofer Institute for Solar Energy Systems ISE

To explore the technical options for future missions on Mars, the project OptimisM (ESA Contract No. 4000138511) pursues the goal to identify a solar cell for Mars applications with 10 % more power than the state-of-the-art triple-junction solar cells. For this, AZUR`s four-junction 4G32-Advanced solar cell has been adapted for the proposed spectrum for the Mars surface “Exomars nominal worst case”, which is more red-rich compared to the AM0 spectrum and lower in intensity (see Figure 1). To achieve current-matching of the upper three subcells on Mars, the bandgap and absorption edge, respectively, have been shifted. Additionally, the grid spacing has been adapted to the lower sun intensity on Mars of less than 200 W/m².

The cells have been measured at AZUR SPACE and Fraunhofer ISE. The solar simulator spectrum was in both cases adjusted with existing reference cells but using calibration values calculated from the absolute quantum efficiency and the spectrum on Mars. Efficiencies up to 32.0 % have been measured for the “Exomars nominal worst case” spectrum and 28 °C. It is worth mentioning, that additional spectral and temperature conditions have been investigated by Fraunhofer ISE, which will be part of the presentation.
Compared to an efficiency of 27.3 % of the 3G30-Advanced cell under the same conditions, this result corresponds to a power increase over 14 % by the adapted 4G32 Advanced structure, significantly exceeding the initial goals. It can be concluded that the 4G32-Advanced can easily be adapted for Mars conditions presenting a promising solution to power future explorations on Mars.

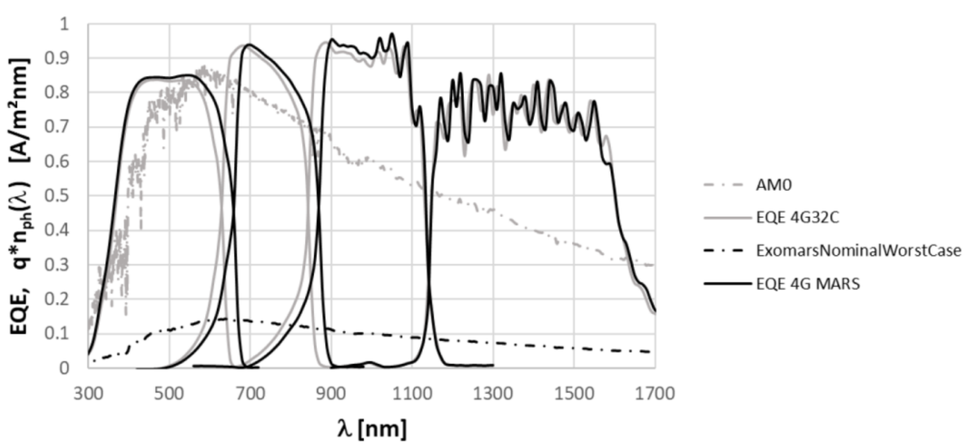

Figure 1: Spectral distribution of the AM0 and the Mars spectrum plotted together with the external quantum efficiency (EQE) of the AZUR´s 4G32-Advanced solar cell. To adapt the four-junction cell to the more red-rich Mars spectrum, the absorption edge of the upper two subcells was shifted by about 30 nm.

Technical Point of Contact:
Felix Gerstenberger
AZUR SPACE Solar Power GmbH
+49 7131 67 - 2695
felix.gerstenberger@azurspace.com

Technology and Manufacturing Advancements to Address Increasing Space Solar Power Demands

Daniel C. Law
Spectrolab Inc., a wholly-owned subsidiary of The Boeing Company, Sylmar CA

Spectrolab has adapted to a rapidly changing space solar power market. Spectrolab's latest state-of-the-art solar cell product is the XTJ Targeted Environment (XTE) family of cells specifically optimized for different mission environments. XTE-SF, XTE-HF and XTE-LILT are qualified to the AIAA-S111-2014 standard and optimized for LEO, GEO, MEO, and LILT environments respectively. XTE production cells fabricated were averaging over 32% efficiency (AM0, corrected to 28 °C, 135.3 mW/cm^2).

Spectrolab's next Ge-based, lattice-matched solar cell product called XTE Plus, which consists of both GEO and LEO variants tailored to those mission orbits. The XTE Plus GEO product has a BOL efficiency of 32.6% (AM0, corrected to 28 °C, 135.3 mW/cm^2) with radiation retention factors optimized for equivalent fluences of ≥1e15 1 MeV e-/cm^2 1-MeV electron. The XTE Plus LEO product has a BOL efficiency of 32.4% and is optimized for low cost, low radiation exposure missions (5% EOL $/W reduction relative to XTE), and high factory throughput. Both XTE Plus variants are currently undergoing AIAA S-111 qualification. The qualification will focus on key electrical characterization of the solar cell including BOL/EOL efficiencies, temperature coefficients and standard GEO atmospheric thermal cycle test coupons.

Spectrolab will also present its initiatives to meet the increased demand for space solar power. For example, we have increased our bare cell capacity by ~25% with targeted tool purchases and process optimization of two gating wafer processes: photolithography and metal liftoff. Moreover, Spectrolab is on track for a similar ~25% increase in capacity in the CIC area with a key process equipment acquisition.

Technical Point of Contact:
Dr. Daniel C Law
Spectrolab – a wholly-owned subsidiary of The Boeing Company
818-838-7496
daniel.c.law@boeing.com

Advancements in SolAero's III-V solar cells for space

Albert Perry III, Alireza Abrand, Dan Aiken, Zac Bittner, Tobias Burger, Ben Cho, Daniel Derkacs, Andrew Espenlaub, Frank Fencl, Ryan Hool, Mische Hubbard, Nicole Marroquin, Nate Miller, Bradley Nordell, Pravin Patel, Janine Walker.
All authors: SolAero by Rockelab, Albuquerque, NM

SolAero by Rocket Lab, a space-systems division of Rocket Lab, is the world's only fully vertically integrated merchant supplier of space solar array panels to the global aerospace market. SolAero manufactures high-efficiency III-V multijunction solar cells and related power conversion devices for a variety of applications including orbital spacecraft, landers, rovers, and for power beaming. SolAero has powered over 1000 spacecraft over the last 20+ years including recent missions of interest to the NASA community such as the James Webb Space Telescope (L2), the Ingenuity Mars Helicopter, the NASA Gateway Power and Propulsion Element (Lunar), NASA DART (near-earth), Lucy (Trojan), Psyche (Trojan), the Parker Solar Probe, and the Mars Insight Lander.

Although the specific constraints and environments of these missions vary, nearly all benefit from the continued improvements such as increased efficiency, reduced mass, and reduced cost. These metrics drive key performance indicators, such as W/kg, W/cm^2, \$/W, that affect spacecraft capability and sometimes become enabling factors for missions. SolAero manufactures cells within two main technology families 1) upright architectures on Ge (ZTJ, ZTJ-Ω, Z4J, etc.), and 2) inverted metamorphic multijunction architectures (IMM4J, IMM-α, etc.). The 32% (AM0 1353 W/m^2) IMM-α, 30% (AM0 1353 W/m^2) Z4J, and the 31.3% Z4J+ cells have been in volume manufacturing for the last several years. We have completed development of the next generation of IMM technologies (33.3% IMM-b) and currently are in the qualification stages. An update on this development and the performance of these newest cells will be provided. The IMM4J cell, used on the Ingenuity Mars Helicopter, has been extensively characterized in Jupiter and Saturn LILT (low intensity low temperature) conditions. IMM 3J and 4J variants are very well suited for LILT environments and also work well in certain unique spectral environments, such as the clouds of Venus. Discussion of how the latest advances in IMM technology can be applied to IMM4J and how this cell performs in some extreme environments will also be provided. Our next generation of technologies (Z4J+) have also been evaluated for performance under LIRT conditions as well as Venus flyby high intensity conditions, in the lab, and will be provided in this presentation.

Technical Point of Contact:
Albert Perry III
SolAero by RocketLab
albert.perry@rocketlabusa.com

Flexible and lightweight solar power modules for LEO satellites and next-generation arrays

Chris Youtsey, MicroLink Devices, Inc.

MicroLink Devices has developed advanced thin-film solar cells based on inverted metamorphic multi-junction (IMM) designs and epitaxial lift-off (ELO) over the past fifteen years. The IMM design replaces the conventional Ge bottom cell for a thin InGaAs junction grown using a metamorphic buffer and an optimal bandgap for high efficiency. The ELO process enables the transfer of the solar cell epitaxial material to a flexible metal support structure. The ELO process is nondestructive and allows multiple reuses of the GaAs substrate for epitaxial growth for cost reduction. The layer-transferred solar cells combine high efficiency (>30% AM0) with low mass (<20 mg/cm2) for exceptional specific power as high as 3000W/kg. MicroLink has commercialized this technology to power high-altitude long-endurance (HALE) aircraft that can fly continuously for months in the stratosphere. The low mass and high efficiency of the ELO IMM solar cells are critically enabling for the lightweight HALE aircraft platforms.

This presentation will discuss recent work at MicroLink to develop solar power modules for space that offer many of the unique advantages and approaches that have been successful for HALE aircraft. This includes the use of flexible, space-grade polymer encapsulations applied at the module level that, in combination with the thin-film ELO solar cells, provide high flexibility and robustness as well as low mass (areal mass density < 400 g/m^2 and specific power up to 1000W/m^2). New interconnects as well as low-profile ELO GaAs bypass diodes are under development that are compatible with the module-level encapsulation approach. The product development status as well as qualification timeline will be discussed. The new space power module technology is well suited for LEO constellation satellite applications as well as next-generation folding or rollable arrays that would benefit from low mass, high robustness and flexibility.

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Technical Point of Contact:
Chris Youtsey
MicroLink Devices, Inc.
(847) 588-3001
cyoutsey@mldevices.com

Dimensionally Modified Halide Perovskites and Chalcogenides for Thin-Film Tandem Solar Cells

Karthika Haridas[1], Alexander F. Kratzer[1], Huilong Liu[2], Rubaiya Murshed[3], Shubhra Bansal[1,2,3,*]
[1]School of Materials Engineering,
[2]School of Mechanical Engineering, Purdue University, West Lafayette, IN 47906
[3]Department of Mechanical Engineering, University of Nevada Las Vegas, Las Vegas, NV 89154

Thin-film photovoltaic (PV) technologies such as CdTe and CIGS are limited by an efficiency plateau due to limiting factors such as small minority carrier lifetimes, high surface recombination rates and low dopability resulting in large VOC-deficits compared to ideal values based on detailed-balance approach. Although many approaches are being taken to improve power conversion efficiency (PCE) of single-junction devices including novel buffer layers, dopants, bandgap grading, post-deposition treatments, etc. the improvements in performance have been limited. Here, we will present thin-film tandem PV approach for superstrate CdTe and substrates CIGS technologies using 0D-halide perovskite and 2D-transition metal dichalcogenide (TMD) materials.

Cs2SnI6 has a direct bandgap of 1.6 eV, and the closed-packed halide framework results in dispersed conduction and valence bands leading to low electron effective masses of 0.48m0 for electrons and 1.32m0 for holes. Cs2SnI6 exhibits electron and hole mobilities of 310 cm2V-1s-1 and 42 cm2V-1s-1, respectively, and is believed to be an ambipolar material due to formation of n-type iodide vacancies/tin interstitials or p-type cesium vacancies. Devices up to 5% PCE have been demonstrated with enhancements such as Cl, F, Rb, Ag, In doping; ZnO nanorod electron transport layer (ETL); ethylene diamine post-deposition treatments. Our recent results have shown Cs2SnI6 superstrate *n-i-p* planar devices with Zn(O,S) ETL and ethylene diamine (EDA) post-deposition treatment with PCE of 5.18%; making it a promising candidate as top-cell for CIGS tandem devices.

Although wide-bandgap halide perovskites offer promising solutions for substrate thin-film PV technologies like CIGS, novel low-bandgap stable materials are needed for a superstrate PV technology like CdTe. Here, we present a novel device design with CdTe/2D-MoTe2 tandem devices, wherein 2D-MoTe2 exhibits a bandgap of 1.1 eV and excellent electron and hole mobilities of 110 cm2V-1s-1 and 426 cm2V-1s-1, respectively.

Here, we will present our recent analysis on Cs2SnI6/CIGS and CdTe/2D-MoTe2 thin-film tandem solar cells with 2-terminal and 4-terminal architectures. Recent experimental results towards demonstration of 4-T tandem devices will also be discussed.

Technical Point of Contact:
Shubhra Bansal
Purdue University
(765)-201-0369
bansal91@purdue.edu

Advancements in Thin-Film Solar Cells for Space Applications

Amit H. Munshi, Colorado State University, Fort Collins, CO

The pursuit of high-efficiency, lightweight, and cost-effective solar cells is essential for space exploration and satellite technology. Recent research published in ACS Energy Letters highlights the development of a 4-terminal (4-T) tandem solar cell utilizing Cadmium Telluride (CdTe) and perovskite materials, achieving a record efficiency of over 24%. This breakthrough leverages the well-established efficiency of CdTe photovoltaics and the tunable bandgap properties of perovskites, resulting in a highly efficient, low-cost solution suitable for space applications.

The presentation will delve into the innovative design and fabrication process of the 4-T CdTe/perovskite tandem solar cells. Near-infrared-transparent perovskite solar cells (NIR-TPSCs) were developed with an efficiency of 18.3% and an average transmission of 24.76% in the 300-900 nm range. These NIR-TPSCs were integrated with 19.56% efficient opaque CdTe solar cells, resulting in a tandem configuration with a power conversion efficiency (PCE) of 23.42%. By employing a refractive index matching liquid, the PCE was further increased to 24.2%.

The distinct advantages of thin-film solar cells, such as their flexibility, lightweight nature, and high efficiency, make them particularly suitable for space applications. The findings will be explored in the context of improving the power systems of satellites and spacecraft, addressing critical challenges such as limited space, weight constraints, and the demand for high power output. Additionally, the safety concerns related to the use of cadmium in CdTe cells will be addressed, emphasizing the stringent safety protocols and recycling measures that mitigate these risks.

Furthermore, the presentation will cover the potential for these advanced thin-film solar cells to operate efficiently under the unique conditions of space, including radiation exposure and temperature extremes. The adaptability of thin-film technology for deployment on various space missions, from satellites to deep-space probes, will be highlighted, showcasing its transformative impact on the efficiency and sustainability of space exploration.

By uncovering the complexities and innovations beneath the surface of solar technology, this presentation aims to provide a comprehensive understanding of how advanced thin-film solar cells can revolutionize space missions, paving the way for more efficient and sustainable space exploration.

Technical Point of Contact:

Amit Harenkumar Munshi
Assistant Research Professor
Colorado State University, Department of Mechanical Engineering
+1 970 215 4116
Amit.Munshi@colostate.edu

Perovskite Tandem Solar Cells for Space Power Applications

Zhaoning Song, Yanfa Yan
Department of Physics and Astronomy and Wright Center for Photovoltaic Innovation and Commercialization, University of Toledo, Toledo, Ohio 4360

Outstanding photoelectrical properties, bandgap tunability, and low-temperature processing make metal halide perovskites excellent candidates for achieving efficient and cost-effective tandem solar cells for space power applications. Here, we report our progress on fabricating perovskite-based multi-junction tandem cells consisting of one or more solution-processed perovskite subcells. Perovskite-based tandem solar cells are fabricated by integrating a wide-bandgap (1.7 – 2.1 eV) Pb-based mixed-halide (Br-I) perovskite top subcell with a narrower-bandgap (1.1 – 1.4 eV) bottom subcell based on crystalline silicon, CdSeTe, or divalent metal alloyed (Pb-Sn) iodide perovskites. An intermediate bandgap (1.5 – 1.6 eV) perovskite middle subcell is also incorporated for triple-junction tandems. Varying the halide perovskite composition and thickness for each subcell enables us to tailor the photovoltaic performance of the tandem devices with respect to the terrestrial (AM1.5G) and space (AM0) solar spectra. We will discuss some key challenges facing perovskite-based tandem solar cells, including the intrinsic stability issues of various perovskites, the manufacturing of perovskite tandem devices, and the assessments of their space radiation hardness. Finally, an outlook is given on the research directions that are needed to realize the full potential of perovskite tandem devices for reliable and efficient space power sources.

Technical Point of Contact:
Zhaoning Song
University of Toledo
419-530-3785
zhaoning.song@utoledo.edu

Modeling Candidate Metal Halide Perovskites for Highly Efficient Tandem Solar Cells

Zhigang Wu,[1] Kevin Ly,[2] John W. Lawson[1] and Lyndsey McMillon-Brown[3]
[1]NASA Ames Research Center, Moffett Field, California 94035, USA
[2]KBR Inc., NASA Ames Research Center, Moffett Field, California 94035, USA
[3]NASA Glenn Research Center, Cleveland, Ohio 44135, USA

Highly efficient tandem solar cells based on metal halide perovskites have been proposed to be coated on electric aircraft wings and fuselage to greatly reduce the mass of batteries used to power the motors, because metal halide perovskites have many relevant excellent properties including strong optical absorption and appropriate band gaps, while tandem cells have the potential of exceeding the Shockley-Queisser limit of energy conversion efficiency (33%) for a single-junction solar cell. To achieve a higher efficiency than that of perovskites-based single-junction solar cells previously manufactured in NASA Glenn Research Center, perovskites with a suitable band-gap range of 1.7–1.9 eV need to be found and characterized for the top layer. There are numerous possible compositions, and it is not efficient to manufacture and test new compositions without the guidance from reliable modeling.

Highly accurate first-principles calculations can help select the most promising candidate perovskites with strong optical absorption and matching band gaps. However, for perovskites with complex compositions, large unit cells prevent the highly accurate many-body perturbation method of GW from being carried out, while the density functional theory (DFT) based on LDA/GGA is efficient but not sufficiently accurate for band-gap calculations. In this talk we will summarize current theoretical advances in accurately and efficiently band-gap calculations for metal halide perovskites. Then we will present our calculations using these newly developed computational methods, comparing the computed band gaps of a few prototypical perovskite compositions obtained by a variety of methods, in order to find out which is the best approach to determine the band gaps of novel and complex perovskites.

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Technical Point of Contact:
Zhigang Wu
NASA Ames Research Center
Moffett Field, CA 94035
510-5654251
zhigang.wu@nasa.gov