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25th Space Photovoltaic Research and Technology Conference

Jeremiah S. McNatt, Compiler
Glenn Research Center, Cleveland, Ohio

February 2019

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Brook Park, Ohio
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National Aeronautics and
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Cleveland, Ohio 44135

February 2019

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Contents

Welcome to the 25th Space Photovoltaic Research and Technology Conference

Greetings and Welcome to the 25th SPRAT Conference!

It's a great pleasure to welcome you to the NASA Glenn Research Center, the Ohio Aerospace Institute, and Cleveland, Ohio for the silver anniversary of the conference. Held generally every 1.5 to 2 years, the SPRAT conference has been here in Cleveland for over 44 years.

In reflecting on the welcoming words of the first SPRAT conference, we are reminded of the goals and paths forward that still resonate today and push us to continue this meeting. The emphasis on research in that first greeting spurned the following questions: "Where do we want to be? Why haven't we been able to get there? What is it we don't understand about the cell?" In many ways we are continuing to address these questions today.

We would like to say thank you to everyone who is contributing to the excellent technical content of this conference. We have many great presentations and workshop discussions dedicated to advances in space photovoltaics on the agenda, in addition to the social functions that will give us time to catch up with friends and colleagues.

Although technology changes over time, the core mission of the conference remains the same:
To address the issues and advancements made in space photovoltaic cell and solar array technology. We look forward to continuing the tradition.

Thank you

SPRAT Conference Committee

SPRAT
Space Photovoltaic Research and Technology Conference

"We want to focus specifically on where we are now, how far we have come, how far we can expect to go, and where want to go." – Daniel Bernatowicz, Chair *High Efficiency Silicon Solar Cell Review, 1974*

The Irving Weinberg Award

The Irving Weinberg Award is dedicated to the memory of Dr. Irving Weinberg (1919–1995), a leading contributor to the field of space photovoltaic research and development. He spent most of his professional career at the NASA Glenn Research Center (GRC) working on advanced solar cell designs and their performance within the radiation environment of space. A recognized leader in his field, Dr. Weinberg was a brilliant, dedicated individual who worked tirelessly up to the time of his passing on understanding the underlying mechanisms of radiation damage within solar cells and the application of this knowledge toward the improvement of space photovoltaic devices. This award honors his accomplishments as a researcher, leader, and mentor to a new generation of space photovoltaic scientists and engineers.

The Irving Weinberg Award was established in 1995 and first presented at the 14th Space Photovoltaic Research and Technology Conference. The award is presented at every SPRAT conference to an individual who has made significant contributions to the field of space photovoltaics and represents the dedication, diligence, and leadership qualities exhibited by Dr. Weinberg during his career.

This year the Irving Weinberg Award is presented to Mr. David M. Wilt. Mr. Wilt has worked in space photovoltaics research for 34 years, starting out as the Advanced III-V Photovoltaic Group Lead at the NASA GRC (23 years) and more recently as the Acting Technical Advisor for the Spacecraft Component Technology Branch at the Air Force Research Laboratory's (AFRL), Space Vehicles Directorate. Mr. Wilt's research at NASA focused on fundamental compound semiconductor materials deposition and device development for solar, thermal, laser and radioisotope energy conversion technologies. He was also active in developing technologies for space experiments (International Space Station, Mars Pathfinder, etc.) and served as the power systems design lead for the GRC concurrent engineering team.

At AFRL, Mr. Wilt's research activities have broadened to include development of ancillary solar cell and array technologies including alternative cover-glass materials and solar cell metallization, as well as novel array technologies to enhance power system resilience. He also directs and manages contracted research activities of over $15M. Mr. Wilt holds a Bachelor of Science in physics, a Master of Science in industrial engineering (engineering management), has authored over 200 technical publications and holds 10 patents in a variety of photovoltaic device technologies. Mr. Wilt considers his greatest career achievements to be the friends and colleagues that he's made over his career.

In recognition of his leadership and valuable contributions to the space photovoltaic community, we are honored to announce Mr. David M. Wilt as this year's recipient of the Irving Weinberg Award.

Irving Weinberg Award Recipients

Dr. Chandra Goradia	14th SPRAT	Oct. 24-26, 1995
Dr. Masafumi Yamaguchi	15th SPRAT	Jun. 10-12, 1997
Dr. Dennis Flood	16th SPRAT	Aug. 31-Sept. 2, 1999
Mr. Henry Curtis	17th SPRAT	Sept. 11-13, 2001
Dr. Bruce Anspaugh	18th SPRAT	Sept. 16-18, 2003
Dr. Geoffrey Summers	19th SPRAT	Sept. 20-22, 2005
Dr. Dean Marvin	20th SPRAT	Sept. 25-27, 2007
Dr. Edward Gaddy	21st SPRAT	Oct. 6-8, 2009
Dr. Robert Francis	22nd SPRAT	Sept. 20-22, 2011
Dr. Paul Sharps	23rd SPRAT	Oct. 28-30, 2014
Dr. Mark Stan	24th SPRAT	Sept. 20-22, 2016
Mr. David Wilt	25th SPRAT	Sept. 19-21, 2018

AGENDA

25th Space Photovoltaic Research and Technology Conference

Wednesday, September 19, 2018

7:30 Breakfast

8:00 – 9:00 Registration

9:00 – 9:30 Introductory and Welcome Remarks
(NASA Glenn Research Center/TBD)

Session I
Agency Overviews

9:30 Overview of Current Research and Development Efforts in the Photovoltaic and Electrochemical Systems Branch at NASA GRC
(NASA Glenn Research Center/Eric Clark)

10:00 Space Power Generation Technology Developments at the Air Force Research Laboratory (Air Force Research Laboratory/Kyle Montgomery)

10:30 – 10:45 Break

Session II
Advances to Commercial Cells

10:45 Progress in the Development and Production of Inverted Metamorphic Epitaxial Liftoff (ELO) Solar Cells for Space and Near Space Applications
(MicroLink Devices/D.W. Cardwell)

11:05 XTJ Targeted Environment (XTE) Solar Cells for Earth Orbits and Outer Space Missions
(Specrolab Inc./Daniel Law)

11:25 SolAero Solar Cell Development and Characterization in Extreme Environments
(SolAero Technologies/Nate Miller)

11:45 Space-Compatible Solar Cells for Emerging Space Applications
(Alta Devices/Andy Ritenour)

12:05 – 1:05 Lunch

1:05 – 1:20 Group Photo

Session III
Thin Film Technologies

1:20 An Investigation of Flexible Cu (In, Ga) Se^2 Solar Cells Under Low Intensity Low Temperature for Potential Applications for Outer Planetary Missions
(University of Oklahoma/Collin Brown)

1:40 Metal Halide Perovskite Thin Films for Space Photovoltaics
(University of Virginia/Joshua Choi)

2:00 Development of Perovskite Solar Cells for Space Applications
(California Institute of Technology/Michael Kelzenberg)

2:20 The Mechanisms of Stabilizing CIGS Using Nanoscale Self-Assembled Interlayers of Organofunctional Silanes (NASA Glenn Research Center/Timothy Peshek)

2:40 Organic-Inorganic Perovskite Thin Film Solar Cells for Space Applications
(Toledo University/Yanfa Yan)

3:00 – 3:15 Break

Session IV
Technologies for Unique Mission Locations

3:15 4X Line-Focus and 25X Point-Focus Space Photovoltaic Concentrators Using Flat Fresnel Lenses, Multi-Junction Cells, and Graphene-Based Radiators
(Mark O’Neill LLC/Mark O’Neill)

3:35 Lightweight Monolithic Microcell CPV for Space
(Pennsylvania State University/Christian Ruud)

3:55 Extreme Environments Solar Power Project
(NASA Glenn Research Center/Jeremiah McNatt)

4:15 5 Watt Per Kilogram Tritium Betavoltaic (City Labs/P. Cabauy)

4:35 Lightweight Flexible CdTe Modules on Ceramic Substrate for UAVs and Other Aerospace Applications (Lucintech/Victor Plotnikov)

4:55 High Temperature Silicone Adhesive for Photovoltaics on the Venus Surface
(Central State University/Ibrahim Katampe)

5:45 **Picnic** (NASA GRC Picnic Grounds)

Thursday, September 20, 2018

7:30 Breakfast

8:30 Irving Weinberg Award Presentation

Session V
Cell Performance Enhancements Using Novel Materials

8:50 Self-Assembled Nano-Scale Masks for Fabricating Light Trapping Structures on III-V Solar Cells (Naval Research Lab/Erin Cleveland)

9:10 Light Management in Single-Junction GaAs/InAs Quantum Dot Solar Cells Using Back Surface Reflectors (Rochester Institute of Technology/Julia D'Rozario)

9:30 Flexible and Light Weight GaAs Solar Cells with Micro-Pattern and Back Reflectors (MicroLink Devices/Kamran Forghani)

9:50 Development of Light Management Strategies for Improved Performance and Radiation Hardness of 3J Photovoltaics (Rochester Institute of Technology/Stephen Polly)

10:10 Enhancing Spectral Conversion in Rare-Earth Doped Nano Materials Using Plasmonic Meta-Surfaces (South Dakota School of Mines and Technology/Steve Smith)

10:30 – 10:45 Break

Session VI
CubeSat/SmallSat Systems and Technologies

10:45 Thin-Film Solar Arrays for Small Spacecraft (NASA Marshall Space Flight Center/John Carr)

11:05 Nano-Enhanced Power System Components for an Advanced Technology Testbed CubeSat (Rochester Institute of Technology/Chris Schauerman)

11:25 Quantum-Dot Enhanced Tandem Solar Cells for CubeSat Nano-Enabled Space Power System (Rochester Institute of Technology/Anastasiia Fedorenko)

11:45–12:45 Lunch

Session VII
Advances in III-V Research

12:45 Space-Relevant Characterization of III-V/Si Multijunction Solar Cells (Ohio State University/Jacob Boyer)

1:05 Integration of Quantum Dots and Quantum Wells into InGaAs and GaAs Metamorphic Sub-cells for Radiation Hard 3-J ELO IMM Photovoltaics (Rochester Institute of Technology/Seth Hubbard)

1:25 Resilient, Affordable GaInP/GaAs Solar Cells Grown by Dynamic-Hydride Vapor Phase Epitaxy (National Renewable Energy Laboratory/Aaron Ptak)

1:45 Arcing on Space Solar Cells – Contamination and Damage to Interconnects and Coverslides (Air Force Research Laboratory/Dale Ferguson)

2:05 – 3:30 **Workshops**

The River Styx: Getting Low TRL Tech Over the Valley of Death:
Chairs: Timothy J. Peshek & Sheila G. Bailey

Solar Cell/Panel Qualification and Performance Testing
Chairs: Matthew G. Myers & Phillip P. Jenkins

6:30 – 8:30 **Banquet**

Friday, September 21, 2018

7:30 Breakfast

Session VIII
Measurements and Calibration

8:30 Reconstituting the U.S. National Solar Cell Balloon Flight Program
(United States Air Force, Space and Missile Systems Center, Advanced Developments/Justin Baker)

8:50 Low-Temperature Characterization of Multijunction Solar Cells Using a Combined Characterization Approach (The Aerospace Corp/Don Walker)

9:10 Calibration and Standards with Near-Field Solar Simulation
(Angstrom Designs/Casey Hare)

9:30 Intelligent Solar Cell Carrier (iSC^2) for Solar Cell Calibration Standards
(The Aerospace Corp/Colin Mann)

Session IX
Next Generation Array Concepts

9:50 Multi-Mission Modular Array: Mission Adaptability
(Lockheed Martin/Scott Billets & John Gibb)

10:10 Qualification and Insertion of Roll-Out Solar Array (ROSA) for Multiple SSL Spacecraft Platforms and Their Synergy for Future NASA Missions (SSL/Boa Hoang)

10:30 Mars Surface Solar Array Structures: Recent SBIR Contracts
(NASA Langley Research Center/Richard Pappa)

10:50 International Space Station (ISS) Roll-Out Solar Array (ROSA) Spaceflight Demonstration Mission, Key Results, and Forward Plans
(Deployable Space Systems/Matthew LaPointe)

11:05 – 11:20 Break

11:20 – 11: 50 Workshop Summaries

Session X
Silicon Technologies

11:50 Ultrathin Silicon Solar Cells for Powering Future Space Economy
(Regher Solar LLC/Stanislau Herasimenka)

12:10 Numerical Modeling of Radiation Effects in Si Solar Cell for Space
(Regher Solar LLC/Alex Fedoseyev)

12:30 Reserved for Late News

12:50 Reserved for Late News

1:10 Closing Statements, Conference Ends

Session I
Agency Overviews

Overview of Current Research and Development Efforts in the Photovoltaic and Electrochemical Systems Branch at NASA GRC

Eric Clark
NASA Glenn Research Center

The Photovoltaic and Electrochemical Systems Branch at the NASA Glenn Research Center serves as the focal point for development of advanced photovoltaic, fuel cell, and battery technology development to meet NASA's space and aeronautic mission needs. This presentation will summarize current development efforts, as well as, highlight some future mission needs.

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Space Power Generation Technology Developments at the Air Force Research Laboratory

Kyle H. Montgomery, Jessica L. Buckner, Zachary S. Levin,
Lt. Jacqueline H. Cromer, and David M. Wilt
Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, NM 87117

The Advanced Space Power program at the Air Force Research Laboratory maintains a robust portfolio of technology development for heritage military systems, such as GPS, AEHF, and SBIRS, as well as novel constellation concepts to support advanced military systems. The portfolio of technology development includes high efficiency solar cells, novel solar arrays, and advanced energy storage. Solar energy conversion using photovoltaics remains the dominant means of providing electric power to spacecraft on earth-orbital and other near-Sun missions. This presentation will highlight some recent developments in space solar cell and solar array technologies developed through the Advanced Space Power program. In addition, future needs will be discussed in terms of enabling a new space architecture that the U.S. Air Force is pursuing. Topics of discussions will include IMM solar cell developments, advanced light trapping in multijunction solar cells, the compact telescoping array (CTA), and concentrators in space.

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Session II

Advances to Commercial Cells

Progress in the Development and Production of Inverted Metamorphic Epitaxial Liftoff (ELO) Solar Cells for Space and Near Space Applications

D. W. Cardwell, A. P. Kirk, J. D. Wood, D. Rowell, M. Drees, G. Hillier, R. Chan, C. Stender, F. Tuminello, K. Forghani, A. Wibowo, M. Osowski, and N. Pan
MicroLink Devices, Inc.

Relative to state-of-the-art 3J Ge wafer based III-V solar cells, inverted metamorphic multi-junction (IMM) III-V solar cells offer higher BOL and EOL efficiencies, greater specific power, and greater flexibility. The ELO process enables cost saving through the recovery of the crystalline growth substrate. These characteristics make IMM-ELO solar cells especially attractive for space and near space applications. MicroLink has developed and is currently producing high specific power IMM-ELO solar cells and solar sheet products that have been incorporated into a variety of solar powered UAVs. MicroLink's solar sheets are now being used to power Airbus's Zephyr S high-altitude solar powered UAVs, which have 80-foot wingspans. A Zephyr S recently (July 25, 2018) set the world record for flight endurance, exceeding the previous record of 14 days, 22 minutes, and 8 seconds*. MicroLink is also developing IMM-ELO solar cells and solar sheets designed for a variety of space mission conditions.
* https://www.airbus.com/newsroom/press-releases/en/2018/07/Zephyr-S-set-to-break-aircraft-world-endurance-record.html

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XTJ Targeted Environment (XTE) Solar Cells for Earth Orbits and Outer Space Missions

Daniel C. Law, Philip T. Chiu, James H. Ermer, Chris M. Fetzer, Moran Haddad, Shoghig Mesropian, Rob Cravens, Xing-Quan Liu, Pete H. Hebert, and Jeffrey P. Krogen

SPECTROLAB INC., A WHOLLY-OWNED SUBSIDIARY OF THE BOEING COMPANY,

Spectrolab introduced XTJ Prime in 2016 with an average beginning-of-life (BOL) production efficiency of 30.7% (135.3 mW/cm^2 AM0 at 28°C) primarily optimized for geosynchronous orbit (GEO) missions. However, the current profile and future outlook of space missions have evolved to include diverse earth orbits other than GEO, including low radiation, high thermal cycle lifetime low earth orbit (LEO) missions; high proton radiation middle earth orbits (MEO); high proton radiation, orbit raising segments added to classical GEO missions; and extremely low-intensity, low temperature (LILT) missions to the outer planets of our solar system. Spectrolab is pursuing a new family of space solar cells called XTJ Targeted-Environment (XTE) to optimally address the unique challenges associated with the varying mission environments. Building upon the heritage of the AIAA S-111 and S-112 qualified XTJ and XTJ Prime solar cells, the XTE cell maintains similar cell structure with only small modifications to achieve higher efficiency at the target mission environments. The XTE cells consist of four product variants: (1) standard radiation fluence (SF) designed specifically for GEO-type missions with a typical cumulative 1×10^{15} e$^-$/cm^2 fluence of equivalent 1-MeV electrons, (2) low radiation fluence (LF) variant for LEO-type missions with up to 1×10^{14} e$^-$/cm^2 fluence of equivalent 1-MeV electrons, (3) high radiation fluence (HF) variant for MEO-type missions or missions with orbit transfer through the Van Allen radiation belt with a cumulative 1×10^{16} e$_-$/cm^2 fluence of equivalent 1-MeV electrons, and (4) XTE LILT designed specifically for low solar-intensity, low temperature missions to outer planetary environments.

Three (SF, LF, and LILT) of the four XTE cell variants completed engineering confidence test. The XTE SF and XTE LF variants have demonstrated an average AM0 efficiencies of 32.2% and 32.6% (135.3 mW/cm^2 AM0 at 28°C) in multiple engineering confidence cell builds. The XTE LILT cells have also achieved an average BOL efficiency of 37% under AM0 5.5 AU, -140°C, 4.5 mW/cm^2 Jupiter conditions. In particular, the efficiency achieved by the XTE LILT cells demonstrates a 13% relative improvement over UTJ cells, the baseline LILT devices in NASA JUNO mission. Note that not only the efficiency of the XTE LILT cell is higher than that of UTJ cell, the XTE LILT cell efficiency also increases linearly as temperature decreases towards -140°C. AIAA-S111-2014 qualification is underway for XTE SF, LF, and LILT variants with a completion date expected in the first quarter of 2019. Spectrolab anticipates the family of XTE cells will provide critical space solar power for various missions in *Journey to Mars* where significant solar power is needed to support crew and material from Earth to Moon and Mars and back using solar electric propulsion.

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SolAero Solar Cell Development and Characterization in Extreme Environments

Nate Miller, Claiborne McPheeters, Christopher Kerestes, Christopher Sulyma, Zachary Bittner, Benjamin Cho, Samantha Cruz, Daniel Derkacs, Alex Haas, John Hart, Pravin Patel, Michael Riley, Paul Sharps, Alex Stavrides, Jeff Steinfeldt, Claudia Struempel, and Steven Whipple

SolAero Technologies Corp., Albuquerque, NM, 87123, USA

An overview will be given of recent progress at SolAero in the development and qualification of next-generation solar cell technologies for various space applications. The IMM-α and Z4J solar cells have been optimized for highest efficiency for typical GEO end-of-life radiation and temperature environments and have beginning-of-life efficiencies of 32% and 30%, respectively (AM0, 28 °C 1353 W/m^2). Both cells are currently undergoing qualification to the AIAA-S111-2014 standard and have been selected for commercial spacecraft programs. As such, transfer of these technologies from R&D to production manufacturing environments has substantially proceeded. The ZTJ-Ω cell, which is optimized for highest efficiency under typical LEO end-of-life radiation and temperature environments, has a beginning-of-life efficiency of >30% (AM0, 28 °C 1353 W/m^2), has completed delta qualification to the AIAA-S111-2014 standard, and is in full high-volume production. These new cell technologies offer a significant value proposition over SolAero's heritage ZTJ technology for typical LEO and GEO missions, especially at the system level.

A great deal of characterization has also been done on SolAero solar cell technologies in non-traditional deep space environments where low-intensity and low-temperature (LILT) conditions exist. These extreme environmental conditions represent a significant departure from the typical LEO and GEO environments used for the optimization of space solar cell technologies, which drives shifts in cell selection and leaves room for further cell optimization. Internal SolAero R&D efforts as well as partnerships with NASA, JPL, APL, and various commercial customers have produced a good set of baseline LILT performance data for ZTJ, IMM4J, and IMM-α, as well as some initial progress in optimizing cell technologies for LILT conditions. SolAero has characterized a large set of ~200 ZTJ cells over a variety of LILT conditions up to 5.5AU and down to -140 °C. The low mass of IMM technologies is beneficial for LILT applications where very large array sizes are often needed due to the low irradiance conditions. The IMM4J cell has shown promising performance relative to IMM-α and ZTJ in many LILT environments due to its BOL performance and favorable temperature coefficients. Thus, work on various partnership programs has focused on characterization of IMM4J cells, typically under Jupiter (~5.5 AU, -140 °C) or Saturn (~10 AU, -165 °C) conditions. An overview of the depth and breadth of this LILT characterization work will be provided.

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Space-Compatible Solar Cells for Emerging Space Applications

Andy Ritenour, Paul Sims, Erhong Li, Aarohi Vijh, Brendan Kayes, and Jim Neff
Alta Devices

There is growing demand for solar cells to power CubeSats and other short-duration LEO spacecraft. We report single-junction thin-film GaAs solar cells with flexible polymer encapsulation, designed to power ~2 year missions in LEO. The simplicity of the cell design combined with established epitaxial lift-off (ELO) based manufacturing enables production in high volume with lower cost than traditional CICs. We report reliability testing results of Alta Devices matrices (4 cells in series with a bypass diode) and cells including: test flight on a CubeSat in LEO, thermal cycling, 1 MeV electron radiation testing, outgassing, absorptivity/emissivity, and UV/atomic oxygen exposure. A polymer-encapsulated 75.4mm × 52mm matrix weighs 2.2 g and can produce ~1 W of power under AM0 spectrum (~250 W/m^2, ~450 W/kg). We also discuss our roadmap to enhance performance and reliability.

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Session III

Thin Film Technologies

An Investigation of Flexible $Cu(In,Ga)Se_2$ Solar Cells Under Low Intensity Low Temperature for Potential Applications for Outer Planetary Missions

Collin R. Brown, University of Oklahoma
Vincent R. Whiteside, University of Oklahoma
Dmitry Poplavskyy, MiaSolé Hi-Tech Corp.
Khalid Hossain, Amethyst Research Inc.
Mangal S. Dhoubhadel, Amethyst Research Inc.
Ian R. Sellers, University of Oklahoma

$Cu(In,Ga)Se_2$ (CIGS) solar cells are a promising thin film solar material with record power conversion efficiencies up to 22.7% which can be produced via low cost methods on flexible substrates. Their high efficiency, lightweight nature, and the potential for high specific power make CIGS interesting for space applications; particularly, where deployable high packing volume technologies are preferred such as, in CubeSats and/or SmallSats. Moreover, CIGS has been shown to be remarkably resistant to radiation damage and exhibit self-healing behavior under certain conditions making these systems particularly interesting for missions to the harsh environment of (for example) Jupiter. Despite this potential, CIGS solar cells also exhibit metastable defect formation with a complex and dynamic structure, which is currently inhibiting their large-scale implementation for terrestrial PV applications.

Here, the performance of commercial flexible CIGS is investigated and reported with relation to potential applications for deep space. Initially, thermal cycling experiments are performed to determine their stability under intense environmental conditions. Thereafter, current-voltage and external quantum efficiency measurements are assessed for conditions (i.e. Low-Intensity Low-Temperature (LILT)) similar to the environment around Mars, Jupiter, and Saturn with the effects of material metastability specifically assessed under these conditions. Afterwards, CIGS solar cells were assessed upon irradiation by 1 MeV protons with fluences similar to the 1-year maximum fluence around Jupiter. Finally, annealing at a slightly elevated temperature was performed to observe self-healing behavior of the irradiated samples.

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Metal Halide Perovskite Thin Films for Space Photovoltaics

Joshua J. Choi, University of Virginia

Metal halide perovskites (MHPs) are revolutionizing the solar cell research field - the record power conversion efficiency of MHPs based solar cells has reached 22.7% which is on-par with solar cells based on Si and GaAs. What is particularly exciting about MHPs is that they can be manufactured into lightweight and flexible solar cell devices using simple solution processing at low-cost. Based on these attributes, MHPs have been called the "next big thing in photovoltaics" and worldwide research efforts have grown explosively. Interestingly, MHPs exhibit positive and small temperature coefficient of bandgap which provides an intriguing opportunity for development of solar cells that maintain performance at high temperature. Moreover, due to high light absorption coefficient, only about 500 nm thick film of MHPs can harvest most of the sunlight, resulting in flexible thin film with only 2 g/m^2 of weight. Successful development of MHP solar cells for space applications can result in transformative advances that enable higher specific power, lower cost and simpler operations compared to the state of the art approaches. In addition, the flexibility of MHP thin films will enable various novel concepts for re-stowable/re-deployable arrays

Here we present our recent research results on MHP solar cells for space applications. Solar cells were fabricated to test performance and stability at high temperature, with a particular focus on all inorganic metal halide perovskites[1] and two-dimensional perovskites.[2] To increase efficiency and reliability, we sought to obtain MHP thin films with improved quality. Synchrotron based *in-situ* X-ray diffraction techniques were employed to study how the MHPs nucleate and growth into thin films.[2-4] The new insights enabled us to obtain MHP thin films with controlled crystallographic orientations which were found to be critically important to achieve higher efficiency. We also demonstrated flexible and lightweight MHP solar cells through all low-temperature processing on flexible substrates.[5] Flexible solar cells with 17.1% efficiency, which is among the highest for flexible solar cells, were achieved.[6]

This work is supported by an Early Career Faculty Award grant from NASA's Space Technology Research Grants Program (NNX15AU43G).

1. *ACS Energy Letters*, 2, 1043 – 1049 (2017)
2. *Nature Communications*, 9, 1336 (2018)
3. *Journal of Materials Chemistry A*, 5, 113 - 123 (2017)
4. *Journal of Materials Chemistry A*, 5, 7796 – 7800 (2017)
5. *The Journal of Physical Chemistry Letters*, 8, 3206–3210 (2017)
6. *Manuscript in preparation*

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Development of Perovskite Solar Cells for Space Applications

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Perovskites are a promising photovoltaic technology for space applications. Although they lack the flight heritage and efficiency of established space PV technologies such as III-V multijunctions, they have the potential to be produced at dramatically lower cost, and they can in fact achieve higher specific power, exceeding 20 W/g for small research cells.[1, 2] Perovskites have recently been reported to offer remarkable radiation resistance, suggesting that unshielded, ultralight perovskite solar cells could enable a 10x or higher breakthrough in specific power of space solar panels.[3–5] Such decreases in cost and mass could have dramatic impacts on the capabilities of spacecraft, and could help enable the realization of space-based solar power.

We are evaluating the potential performance of perovskite solar cells for space applications. We have fabricated devices at the ~cm2 scale and have performed radiation studies (proton and electron), vacuum annealing, temperature cycling, and light soaking. We have investigated various cation formulations and passivation schemes for the perovskite materials, as well as various hole and electron transport layers including NiO, TiO2, CuSCN, PCBM/C60, Cr, PEDOT, and ITO. We have fabricated cells on glass slides as well as on ultrathin polymer films (2 micron thick Mylar) and Al foils, and are experimentally evaluating several critical aspects of space operation: radiation resistance, stability under sunlight in vacuum, UV resistance, and extended thermal cycling. We will report our latest results, and our progress towards realizing large-area ultralight perovskite cells for space applications.

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References

[1] M. Kaltenbrunner et al., "Flexible high power-per-weight perovskite solar cells with chromium oxide-metal contacts for improved stability in air," Nat Mater, vol. 14, pp. 1032-1039, 2015.
[2] Z. Song et al., "A technoeconomic analysis of perovskite solar module manufacturing with low-cost materials and techniques," Energy & Environmental Science, vol. 10, pp. 1297-1305, 2017.
[3] J. S. Huang et al., "Effects of Electron and Proton Radiation on Perovskite Solar Cells for Space Solar Power Application," IEEE PVSC, 2017.
[4] Y. Miyazawa et al., "Tolerance of Perovskite Solar Cell to High-Energy Particle Irradiations in Space Environment," iScience, vol. 2, pp. 148-55, 2018.
[5] I. Cardinaletti et al., "Organic and perovskite solar cells for space applications," Solar Energy Materials and Solar Cells, vol. 182, pp. 121-127, 2018.

The Mechanisms of Stabilizing CIGS Using Nanoscale Self-Assembled Interlayers of Organofunctional Silanes

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We will present work on using hydrophilic organofunctional silanes to preclude competitive moisture-related degradation (and healing) processes. The use of an amine terminated silane molecule has been shown to reduce the degradation of specific transparent conducting oxides and here we present the outcomes of device testing under high heat and humidity tests on unencapsulated CIGS thin film PV cells. These tests are derived from the IEC 61646 standard for testing terrestrial thin films solar cells, but are analogous to tests required as part of the AIAA S111 standard. These tests indicate the treated device cohort achieves a 4X reduction in the initial degradation kinetics, but also the control CIGS cohort undergoes an anomalous healing process. This healing process very clearly indicates the multimodality of the degradation process in CIGS even under single factor stressors, such as high humidity. To make a statistical statement about these data a new open source project was initiated to develop analytical models of single diode I-V curves and use those models in conjunction with machine learning to extract parameters such as series resistance, shunt resistance and reverse saturation currents. Variations in those parameters including the differing time dependencies of series and shunt resistances allow for a type of deconvolution of the modes of degradation. Using data analytics we explore these phenomena within the context of published CIGS studies and propose a hypothetical mechanism of silane protection that includes a quenching of damage initiation through surface dangling bond passivation and sodium ion migration.

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Organic-Inorganic Perovskite Thin Film Solar Cells for Space Applications

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Organic-inorganic metal halide Perovskite Solar Cells (PSCs) have progressed tremendously in the past few years. The low-temperature solution processing and high optical absorption coefficients of perovskite absorber layers provide an exceptional opportunity for fabricating light-weight flexible PSCs, holding great promise for space applications. Here, we report a process to fabricate efficient flexible PSCs. We have developed a facile water vapor treatment of SnO_2 electron selective layer which demonstrates improved open-circuit voltage (V_{OC}) and fill factor (FF) while reducing the degree of current-voltage hysteresis. With such a treatment, our best flexible PSC fabricated on a commercial poly(ethylene terephthalate) (PET) substrate shows a power conversion efficiency of 18.36 (17.12)% when measured under reverse (forward) voltage scan and a stabilized efficiency of 17.08%. Furthermore, we have also investigated the effects of electron irradiation on PSCs. We find that the electron irradiation (10^{13} to 10^{15} e/cm^2) leads to significant device degradation due to decomposition of the perovskite absorber layer. Unlike PSCs degraded in ambient conditions, the irradiated cells retained similar V_{OC} and FF values after the test, indicating that the charge selective layers and electrodes remained almost unchanged after the exposure to the electron irradiation. Additionally, we show that an indium tin oxide (ITO) back contact layer can mitigate the degradation induced by electron irradiation, likely due to the reduction of the electron bombardment on perovskites and the protection against the escape of volatile species from perovskites. These results show the PSCs have a great potential for space applications if the critical stability issues can be resolved.

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Session IV

Technologies for Unique Mission Locations

4X Line-Focus and 25X Point-Focus Space Photovoltaic Concentrators Using Flat Fresnel Lenses, Multi-Junction Cells, and Graphene-Based Radiators

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At the past two SPRAT conferences, our team described the development of robust, high-performance, ultra-light space photovoltaic concentrator arrays with greatly improved performance metrics compared to prior space arrays of either one-sun or concentrator varieties. In the last two years, much additional advancement of this new concentrator array technology has taken place, including both 4X line-focus and 25X point-focus versions, shown in Fig. 1 and Fig 2, respectively.

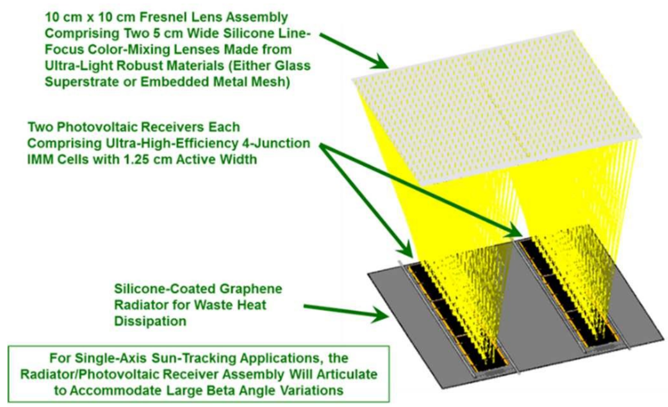

Fig. 1. 4X line-focus concentrator module.

The line-focus version requires only single-axis sun-tracking, while the point-focus version requires dual-axis sun-tracking. Both versions use ultra-light, flat, robust Fresnel lens optical concentrators, 10 cm x 10 cm in size, multi-junction solar cells, and waste heat radiators employing graphene as the primary lateral heat-spreading material. In the past two years, we have successfully developed, built, and tested fully functional concentrator modules of both the line-focus and point-focus versions. These advancements were funded under a NASA Phase II SBIR contract (including Phase IIE and CCRPP modifications) and a NASA Phase I STTR contract, and we are now beginning a new NASA Phase I SBIR contract.

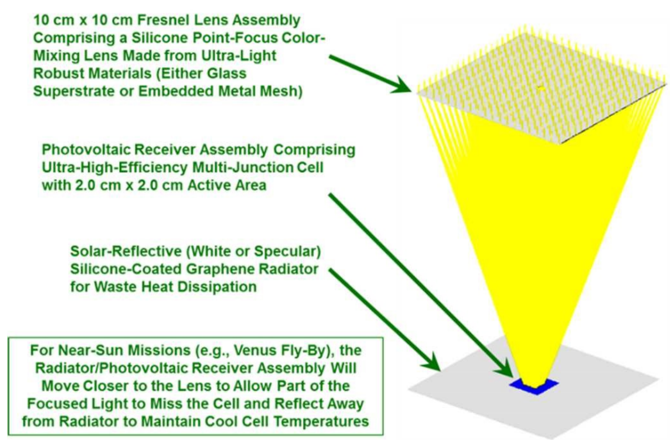

Fig. 2. 25X point-focus concentrator module.

The proposed paper will provide the latest results for the new space photovoltaic concentrator technology, including test results on new lenses, new cells, new radiators, and fully functional concentrator modules of both 4X line-focus and 25X point-focus versions.

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Lightweight Monolithic Microcell CPV for Space

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Concentrating photovoltaics (CPV) can deliver high efficiency photovoltaic power in space at reduced cost. Previous space CPV designs are limited by the size of the optical system which is governed by the PV cell size. Here, transfer-printed microcells are leveraged to create a new lightweight, ultrathin, and monolithic CPV design. The microcell array is embedded in a radiation-tolerant glass optic that delivers 83% optical efficiency, a ±7° acceptance angle at 32× geometric gain. Total thickness of the system is <1 mm, enabling specific power of 352 W/kg using state-of-the-art triple junction microcells. The concept is demonstrated experimentally with a geometric gain of 18.5× using 20×20 mm lenslet array coupled to an array of 650 × 650 μm^2 terrestrial triple junction microcells. Recent work including improvements to the design and progress towards coupon samples with space specific 200 × 200 μm^2 cells and custom optics will be shared.

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Extreme Environments Solar Power Project

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NASA missions such as DAWN and JUNO, as well as the planned Europa Clipper mission, rely on solar power despite their destination's extreme distance from the Sun and the high radiation environment typically encountered. This reliance on off-the-shelf state of the art solar cells has impacted mission design and ultimate performance, as solar cells designed for 1AU space applications suffer from low intensity, low temperature (LILT) performance effects and limited radiation tolerance has required additional shielding or overdesign in order to maintain EOL performance. While reasons for the performance degradation are reasonably well understood and solutions have been proposed, the lack of a continuous mission pull for improved performance has made a dedicated project to address these issues unpractical in the past. However, with NASA embarking on the Europa Clipper mission in the next decade and a recognition that improvements to radiation tolerance positively impact all space missions; NASA's Space Technology Mission Directorate has initiated a project to develop advanced solar cells that are more efficient under LILT conditions and solar array concepts, such as concentrator systems, that improve overall performance under both LILT and high radiation conditions.

The Extreme Environments Solar Power (EESP) project was developed to mitigate the LILT effects and the elevated radiation that would be experienced by spacecraft in Jupiter orbits. Spacecraft in this environment are subjected to intense radiation on the order of 4E15 1MeV e/cm^2 and temperatures near -125 ºC while seeing less than 10% of the solar flux relative to a mission near Earth (~50 W/m2). The LILT environment is known to cause performance degradation in the power output of some solar cells. This LILT effect has been noted and verified through ground-based testing. However, the effect is variable from cell-to-cell, affecting the reliability of accurately predicting solar array performance throughout the life of the mission. The issue becomes more pronounced when one cell with this degradation characteristic is added in a series string with well-behaved, predictable cells. The current solutions involve increasing the solar cell coverglass thickness, oversizing the solar arrays, and "cherry picking" solar cells that show high performance under LILT conditions. The EESP project aims to optimize the end of life performance (EOL) of the solar cells and the array configuration specifically for this environment and to overall reduce the cost of the power system.

An overview of the current status of the EESP project and the path to achieving the following goals will be presented:

- 35% beginning of life (BOL) cell efficiency 28% EOL at the blanket (or equivalent) level, measured at 5 AU and -125 ºC relative environment
- 8-10 W/kg measured at EOL inclusive of the array structure and deployment mechanism with all gimbals, structures, and control systems required for pointing or otherwise achieving end performance levels must be accounted for in calculations
- Packaging density of at least 60 kW/m^3
- Technology capable of operation over the range of 100 – 300 V.
- Demonstration of a reasonable path to space qualification
- Demonstration of the ability to integrate proposed technology into a solar array structure that can survive launch conditions

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5 Watt per Kilogram Tritium Betavoltaic

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Tritium has a power density of 340 W/kg and City Labs' new metal hydride film has a power density approaching 70 W/Kg and can be expanded to 100 W/kg. City Labs and Microlink will develop a direct energy conversion betavoltaic device based on a wide bandgap III-V junction with a high beta-flux metal tritide. The betavoltaic p/n junction will increase the efficiency of betavoltaic devices from 8% up to 12% based on the incident tritium beta flux. The secondary goal is to investigate the release of the III-V betavoltaic epitaxial layer. Due to the thinness of such devices, the improved betavoltaic p/n junctions can be easily stacked within conventional rectangular, cubic, or cylindrical electronic package configurations of reduced form factor and will provide cost savings of up to 90%. Such an advanced semiconductor device will produce much higher power outputs than is possible with existing state-of-the-art devices. Betavoltaic power sources are already capable of life spans in excess of 20 years with broad-range temperature-insensitivity benefits. The addition of these ultra-thin, engineered semiconductors will add a significant boost in power density. This increased power/energy density for tritium betavoltaics will open up pathways for significant advances in power solutions for diminutive form factor, low-power microelectronic devices that may be used in CubeSat and in-space power systems. Candidate applications include microwatt-to-milliwatt autonomous 20+ year sensors/microelectronics for use in structural health & ordnance monitoring, mesh networks, tagging and tracking wireless sensors, medical device implants, and even in deep space exploration platforms (where photovoltaics experience distance-related diminishing output). Tritium betavoltaics are uniquely capable of addressing this power niche for devices requiring reliable, uninterrupted power through extremes of temperature, longevity, and diminutive form factors where traditional batteries cannot operate. This work is supported by NASA Phase I SBIR NNX14CA53P, NNX16CC50P, and 80NSSC18P2067.

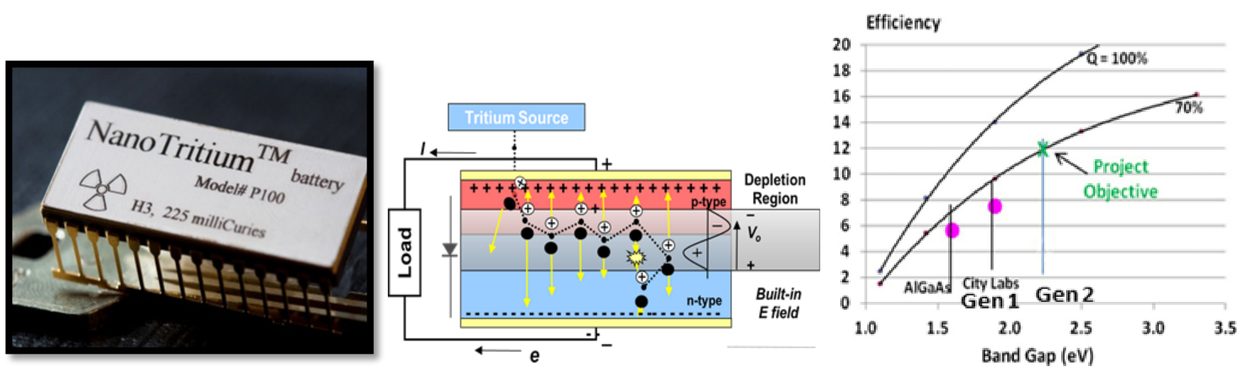

Figure 1. City Labs commercial betavoltaic battery (left), schematic showing principles of operation (middle), betavoltaic semiconductor bandgap vs efficiency chart (right).

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Lightweight Flexible CdTe Modules on Ceramic Substrate for UAVs and Other Aerospace Applications

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Kathy Olenick, ENrG Inc.

Solar energy harvesting with photovoltaics (PV) has exciting potential for providing the energy needed to power UAVs. Lucintech has recently developed an extremely lightweight and flexible PV module based on thin-film technology that is scalable to large areas. Our modules use innovative, ultra-thin, flexible translucent ceramic ribbon developed by ENrG Inc. as a superstrate that also provides a hermetic, radiation hard barrier. Because the ceramic ribbon is only 20 micrometers thick, the power-per-unit-mass rivals the best available PV technology. Furthermore, the flexibility enables conformable PV mini-modules that can be designed to give very high coverage, even for curved surfaces and can be adapted to the shape and size of different surface elements. In contrast with some other technologies, our PV is already in the form of mini-modules easily integrated with very high surface coverage without altering the aerodynamics. Due to the anticipated lower cost, the PV can be applied to the wings and fuselage. Another possibility is adding PV on the underside of the wings that would allow the craft to be powered by ground-based light beams at times when the sun is not shining.

The use of PV power for UAVs requires very high power per unit mass (P_M) and very high power per unit area (P_A). A Performance Index, $P_{UAV} = (P_M P_A)^{1/2}$ is commonly used to capture the importance of both P_M and P_A to the overall suitability of a given type of PV cell or module for power generation on-board a UAV. Realistic power to mass ratios must consider barrier films and encapsulation materials which often have a large impact on the P_M and the P_{UAV}. Our newly developed CdTe modules on thin flexible ceramic can exceed the current state-of-the-art P_M (1300W/kg) and have competitive values of P_A so that the overall performance index is close to that available with expensive epitaxial lift-off GaAs cells. We target 15% module efficiency in the near term and project that we can reach 18% efficiency considering that 22% cell efficiencies are already demonstrated by First Solar for a similar thin-film CdTe structure on rigid glass.

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High Temperature Silicone Adhesives for Photovoltaics on the Venus Surface

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The harsh environment at the surface of Venus, with a low solar intensity, red-rich solar spectrum, high temperatures, and a corrosive acid environment, makes it a challenging location to use photovoltaics. For the design of photovoltaic power generation for future missions to Venus, solar arrays that can function at high temperatures under low light intensity must be developed, and a significant difficulty in this is achieving a long lifetime without degradation under Venus conditions. One issue that must be addressed is the encapsulation to protect the solar cells from the environment, and most particularly the transparent adhesive affixing the cover-glass to the cells. In this paper the factors affecting the reliability and degradation of transparent silicone adhesives under Venus conditions are discussed.

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Session V

Cell Performance Enhancements Using Novel Materials

Self-Assembled Nano-Scale Masks for Fabricating Light Trapping Structures on III-V Solar Cells

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Recently, there has been a great deal of interest in reducing the thickness of the GaAs junction in a triple junction GaInP/GaAs/Ge architecture to improve its radiation tolerance. [1] However reducing the GaAs junction also reduces the optical path length within the GaAs cell. One way to mitigate this problem is to incorporate light trapping architectures in the middle junction of a cell in order to reduce the thickness while maintaining the photocurrent absorption within the junction. Our team has recently published a proposed architecture to accomplish this task. Simulations of this device indicated an improved end-of-life photocurrent, while maintaining strong photon absorption in the middle cell. [2] As a proof of concept, we are using natural lithography to create an optical proof-of-concept experiment. Natural photolithography is a process that relies on the formation of self-assembled and organized monolayers of colloidal nanospheres, which produces a shadow mask that can in turn, be used to pattern materials at the nanoscale. This allows us to eliminate the use of conventional lithography, which is dependent upon expensive masks sets or controlled scanning of an electron beam. In this work, we have grown a test structure, which has simulated InGaP and GaAs junctions and an InAlP layer for patterning periodic pillars. Subsequently, structures attached to a handle with a low-index epoxy were released from the underlying GaAs substrate. In this talk, we will discuss the trials and tribulations of using natural photolithography to produce periodic, 350 nm pitch, nanostructures for light trapping. Lastly, we will discuss transmission measurements, which will be the first indication of the effectiveness of this technique.

[1] L. C. Hirst, M. K. Yakes, J. H. Warner, M. F. Bennett, K. J. Schmieder, R. J. Walters and P. P. Jenkins, "Intrinsic radiation tolerance of ultra-thin GaAs solar cells", Applied Physics Letters, 109, 033908 (2016)
[2] A. Mellor, N.P. Hylton, S.A. Maier, N. Ekins-Daukes, "Interstitial light trapping design for multi-junction solar cells", Solar Energy Materials & Solar Cells, 159, 212-218 (2017)

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Light Management in Single-Junction GaAs/InAs Quantum Dot Solar Cells Using Back Surface Reflectors

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Surface texturing has been used as an effective method to enhance absorption in photovoltaic devices. For single-junction GaAs solar cells, light trapping along with nano-scale features can result in highly efficient devices as less light is lost and more of the spectrum is utilized. Texturing the backside of the solar cell along with a reflective metal can increase the optical path length (OPL) as unabsorbed photons scatter and reflect off of the back surface to reabsorb in the active region. If nano-scale features, such as quantum dots (QD), are included in the active region, the back surface reflectors (BSR) can increase the absorbed light in the extended wavelength range of the QD. Utilizing BSRs introduces the ability to grow less QD layers to produce thinner and less complex devices. This also leads to a more radiation tolerant device as the inevitable issue of radiation degradation in minority carrier diffusion length is reduced.

In this work, single-junction GaAs solar cells with InAs QDs have been grown by metal organic vapor phase epitaxy (MOVPE). The cells were grown inverted and released using a substrate removal technique. Initially, a test structure with a 5-period superlattice and surface layer of InAs QDs was grown to determine optimal growth conditions. Atomic force microscopy (AFM) images of the surface QDs were taken at three spots across the wafer. Using the Scanning Probe Imaging Software (SPIP), the QDs were measured with an average density of 9×10^{10} cm^{-2}, and an average diameter and height of 12.4 nm and 1.67 nm, respectively. The InAs QDs photoluminescent peak at 1128 nm is over 100 times more intense than the GaAs bulk peak at 873 nm, and suggests excellent material quality due to the strong QD response.

Three BSRs were developed in a 4 µm layer of $Al_{0.1}Ga_{0.9}As$ through lithography and chemical etch processes to investigate the impact on OPL and QD absorption. The first texture is a flat reflector to achieve an OPL increase of 2. The second texture is a 2-D triangular grating created from a crystallographic etch after patterning 4 µm masked with 2 µm clear spaced lines. Simulations from Synopsys RSoft FullWAVE show that this texture with a 6 µm period and aspect ratio of 0.31 can increase the OPL to approximately 7. The third texture used a maskless chemical etch in a temperature controlled $NH_4OH:H_2O_2:H_2O$ solution and resulted in a roughened surface capable of reaching the Lambertian limit as random surface geometry scatters light in more directions. Reflectance data shows this texture requires uniform temperature control since only select regions across the device resulted in less than 5% reflectance. Simulations from the commercial optical transfer matrix software, TFCalc, show that an additional 500 nm of SiO_2 between the textured surface and the reflector can result in higher reflectance for incident angles greater than 25° compared to BSR designs with no dielectric layer. Final GaAs/InAs QD solar cells with 500 nm of SiO_2 were grown with base thicknesses of 238 nm and 2000 nm to examine light trapping impacts in thin film structures. The presented work will include device characterization through light I-V and quantum efficiency to study the short circuit current as a function of BSR and base thickness.

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Flexible and Light Weight GaAs Solar Cells With Micro-Pattern and Back Reflectors

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III-V multijunction solar cells have the highest record efficiency for any type of photovoltaic devices: E.g. about 38% for AM1.5 1-sun and 33% for AM1.5 1-sun, as reported for 3 junction cells utilizing epitaxial-lift-off (ELO) [1].

Application of backside reflecting mirror for solar cells will enhance the performance by multiple photo-recycling events. The increase in optical absorption, not only helps to boost the performance but also helps to thin the cell, making them radiation-hard for space applications. We present our finding on back patterned GaAs solar cells. Single junction GaAs solar cells with two different configurations of up-right on rigid n-type substrate, as well as inverted flexible ELO cells were investigated. Several different patterns were applied and their effect on the overall cell short circuit current (Jsc) and quantum efficiency was studied. A more than 4% increase of the Jsc was observed in the backside patterned devices. The Jsc as function of light incident angle will also be presented, indicating an improved photo-response at smaller incident angles as compared to the planar control samples.

[1] Alex Kirk et al., Recent Progress in Epitaxial Lift-Off Solar Cells, IEEE PVSC Proceeding (2018)

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Development of Light Management Strategies for Improved Performance and Radiation Hardness of 3J Photovoltaics

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The management of light inside a solar cell is of paramount importance for device efficiency, and judicious light manipulation can have significant impacts on radiation tolerance of devices and on the manufacturability of highly strained nanostructured absorbers. This work will discuss RIT's progress in development of light management structures, both through numerical simulation using commercial packages RSoft and Synopsis, as well as experimentally using MOCVD-grown devices. Radiation hardness of Ge-based triple junction can be increased through thinning the GaAs sub-cell at the cost of a reduced optical path in the absorbing regions of the diode, causing a reduction in output current density at beginning of life. The optical path length (OPL) of photons able to be absorbed by the GaAs diode can be recovered through the incorporation of photonic structures independent of minority carrier lifetimes, resulting in a thin GaAs cell for improved performance at end of life, without a loss in current density at beginning of life. This methodology also works well in conjunction with the incorporation of strain-based nanostructures, such as quantum wells or dots, which alter the band structure to one more favorable to the current matched detailed balance ideal. A larger OPL reduces the number of strain layers needed to achieve the same effective absorbance, increasing the crystal quality of subsequent layers grown.

On the path to demonstrating this concept, a doped distributed Bragg reflector (DBR) was developed targeting high reflection centered near 850 nm by MOCVD. The DBR was made from 20 repeating pairs of 52 nm AlAs followed by 72 nm $Al_{0.1}Ga_{0.9}As$, which was confirmed by HRXRD and normal incidence reflectance fitting. The DBR represents a maximum factor of two enhancement in absorption in the base for the reflected wavelengths, and was used to compare an optically thick 3.6 μm GaAs solar cell to a similar design with half the GaAs absorber thickness of 1.8 μm. The reduced thickness design showed a reduction in collection efficiency, approximately 7% less than the optically thick design. Incorporating the 20x DBR restored carrier generation to nearly the same levels as the optically thick design, losing less than 0.5% of the optically thick integrated current density. In order to increase the enhancement factor beyond two, the reflected light has to be bent to an angle greater than 15° to the surface to induce total internal reflection (TIR). Progress towards developing photonic structures to achieve this, through patterning a dielectric layer on top of the DBR followed by epitaxial layer overgrowth (ELO) to bury the patterned dielectric layer, will also be presented. The buried dielectric layer should provide sufficient refractive index contrast to enable refraction and/or diffraction to bend the reflected light, while the DBR ensures the diffracted light is reflected back into the middle cell. The pattern also allows a continuous semiconductor path through the growth, allowing for electrical contact to additional sub-cells or a back contact.

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Enhancing Spectral Conversion in Rare-Earth Doped Nano Materials Using Plasmonic Meta-Surfaces

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Spectroscopic imaging is used to investigate surface plasmon polariton (SPP) enhanced energy transfer upconversion (ETU) of rare-earth doped $NaYF_4:Yb^{3+},Ln^{3+}$ upconverting nano-particles (UCNPs) on noble metal nano-structured substrates, including arrays of Au nano-pillars and nano-cavities with optical resonances coincident with rare-earth ion absorption (Yb^{3+}) or emission (Er^{3+},Tm^{3+}) energies. The mechanisms for the observed enhancement and power dependence are understood through analytical and computational models, relating the observed enhancement to kinetics of the ETU system and the photonic properties of the substrates.

While upconversion can be achieved through a variety of optical processes, such as two-photon absorption, second-harmonic generation, cooperative luminescence, two-step absorption and energy transfer upconversion, at low excitation intensity, the energy transfer upconversion process is by far the most efficient [1]. With the advent of nano-sized UC materials, the range of applications wherein such materials can be deployed has greatly increased. For instance the areas of bio-imaging, bio-labeling and photodynamic therapy benefit greatly from upconverting nano-particle (UCNP) materials due to the long penetration depth of near-infrared light in biological tissues [2,3]. There are also prospects for spectral conversion in increasing efficiency in solar energy applications [4]. However, low luminescence efficiency still limits the full potential of these materials.

In the vicinity of a metallic nanostructure, luminescence enhancement can be achieved through the amplification of the incident field, where local electromagnetic fields at the UCNP position are intensified due to plasmon resonances, and through the modification of the radiative rates of the phosphors [5-8]. By optimizing the geometry of the metallic nanostructures, and placing them within suitable proximity to the UCNPs, significant enhancement in UC efficiency should be achievable. In this work, we investigate the efficacy of specific plasmonic nanostructures towards radiative control of energy transfer upconversion processes in β-phase $NaYF_4$:Yb:Er[Tm] nanoparticles, using spectroscopic imaging to directly visualize the local enhancement associated with specific noble metal nanostructures.

Figure 1 shows a survey of the UCNPs (figure 1a) and the plasmonic nano-arrays we have investigated (figure 1b-d, and f-g), including representative spectra on and off the arrays [7-14]. Figure 1h shows the power dependence of the energy transfer upconversion enhancement of $NaYF_4$:Yb,Er UCNPs on Au nano-cavity arrays (figure 1f-g)[14]. The nano-cavity arrays support a surface plasmon (SP) resonance at 980nm, coincident with the peak absorption of the Yb^{3+} sensitizer. Spatially-resolved upconversion spectra show a 30X to 3X luminescence intensity enhancement on the nano-cavity array compared to the nearby smooth Au surface, corresponding to varying excitation intensities from 1 W/cm^2 to 300kW/cm^2, spanning the non-linear and saturation power dependence regimes. Figure 1I shows the measured and simulated power dependence of the ETU enhancement on the nano-cavity arrays, the latter obtained by simultaneous solution of a system of coupled rate equations developed by our team [13]. Our analysis shows the power dependent enhancement in upconversion luminescence can be almost entirely accounted for by a constant shift in the effective excitation intensity, which is maintained over five orders of magnitude variation in excitation intensity, limited by the kinetics of the ETU process.

In these measurements, it is shown that the amplification of the excitation field is independent of the emission wavelength, indicating the enhancement in upconversion emission is due entirely to increased absorption by the Yb^{3+} sensitizer. Analysis of the statistical distribution of emission intensities in the spectroscopic images on and off the nano-cavity arrays provides an estimate of the average enhancement factor independent of fluctuations in nano-particle density. Our most recent work in random aggregates of

Ag nanowires show evidence for collective plasmon resonances which manifest as local “hot-spots” with enhancements factors exceeding thirty times [15].

Our current focus is on assigning the kinetic constants via rate equation analysis [16], and eliminating inhomogeneous broadening using single particle spectroscopy. These results suggest significantly higher upconversion enhancement factors can be achieved under proper conditions by utilizing the surface plasmon polariton interaction with the ETU UCNPs while maintaining optimal ETU kinetics.

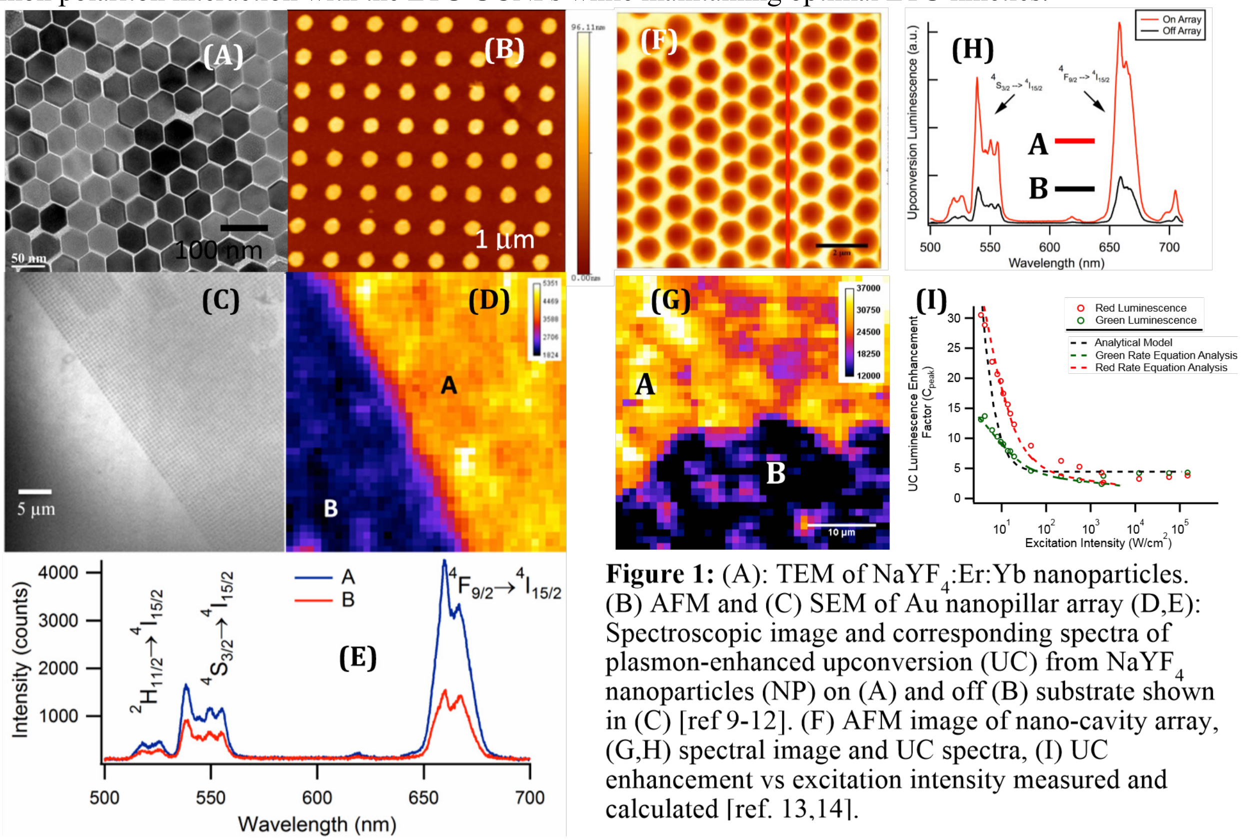

Figure 1: (A): TEM of $NaYF_4$:Er:Yb nanoparticles. (B) AFM and (C) SEM of Au nanopillar array (D,E): Spectroscopic image and corresponding spectra of plasmon-enhanced upconversion (UC) from $NaYF_4$ nanoparticles (NP) on (A) and off (B) substrate shown in (C) [ref 9-12]. (F) AFM image of nano-cavity array, (G,H) spectral image and UC spectra, (I) UC enhancement vs excitation intensity measured and calculated [ref. 13,14].

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REFERENCES

[1] Auzel, F. *Chem. Rev.* **2004**, *104*, 139–73.
[2] Wang, F.; Banerjee, D.; Liu, Y.; Chen, X.; Liu, X. *Analyst* **2010**, *135*, 1839–54.
[3] Zhang, P.; Steelant, W.; Kumar, M.; Scholfield, M. *J. Am. Chem. Soc.* **2007**, *129*, 4526–7.
[4] Moskovits, M. *Rev. Mod. Phys.* **1985**, *57*, 783.
[5] W. G. van Sark, A. Meijerink and R. E. I. Schropp, Solar Spectrum Conversion for Photovoltaics *DOI: 10.5772/39213* [6] Lakowicz, J. R. *Anal. Biochem.* **2001**, *298*, 1–24.
[7] Esteban, R.; Laroche, M.; Greffet, J.-J. *J. Appl. Phys.* **2009**, *105*, 033107.
[8] Schietinger, S.; Aichele, T.; Wang, H.-Q.; Nann, T.; Benson, O. *Nano Lett.* **2010**, *10*, 134–8.
[9] C. Lin, M. T. Berry, R. Anderson, S. Smith, and P. Stanley May, *Chem. of Materials* **21** (14), 3406-3413 (2009).
[10] H.P. Paudel, L. Zhong, K. Bayat, M.F. Baroughi, S. Smith, P.S. May *et. al.* , *J. Phys. Chem C* **115** (39), 19028–19036 (2011).
[11] H. Paudel, D. Dachhepati, K. Bayat, *et. al.*, S. May, S. Smith, M. Baroughi, *J. Photonics for Energy* **3** 035598 (2013).
[12] Q. Luu, A. Hor, J. Fisher, R.B. Anderson, S. Liu, *et. al.*, P. S. May, S. Smith, *J. Phys. Chem C* (2014).
[13] R. B. Anderson, S. J. Smith, P. S. May, and M. T. Berry, *J. Phys. Chem. Lett.* **5** (1), 36–42 (2014).
[14] J. Fisher, B. Zhao, C. Lin, M. Berry, P. Stanley May, S. Smith, *J. Phys. Chem. C* **119** (44), pp 24976–24982 (2015).
[15] A. Hor, Q. A. N. Luu, P. S. May, M. Berry and S. Smith, *MRS Advances* CJO2016, *Materials360(r) Newsletter, August 16, 2016*.
[16] M. Y. Hossan, A. Hor, Q. Luu, S. J. Smith, P. S. May, and M. T. Berry, *J. Phys. Chem. C*, vol. **121**, pp. 16592–16606, (2017).

Session VI

CubeSat/SmallSat Systems and Technologies

Thin-Film Solar Arrays for Small Spacecraft

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The use of thin-film based solar arrays for space applications has long been recognized as an advantageous power generation option. Thinner materials yield a mass savings, equating to lighter launch loads, larger arrays, and/or more payload allocation. Further, their mechanical flexibility lends itself well to stowage and deployment schemes, allowing for a vast improvement to both specific power (W/kg) as well as stowed power density (W/m^3). A key application of thin-film space solar arrays is in the small satellite community; where spacecraft are largely power starved. Their need for higher power generation coupled with the extreme mass and volume restrictions of the small spacecraft bus is driving the requirement for advanced solar arrays. And, when coupled with the relatively short operational requirements (e.g. <2years) of small spacecraft, yields the perfect application for these thin-film arrays. In this presentation, NASA's recent work on developing the Lightweight Integrated Solar Array and anTenna (LISA-T), a thin-film solar array for small spacecraft, will be discussed. The array configuration will be shown alongside bench top deployment videos, a summary of environmental testing to date, and forward plans to a flight test. Advanced, robotic additive manufacturing of the thin-film web will also be discussed.

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Nano-Enhanced Power System Components for an Advanced Technology Testbed CubeSat

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Historically, the lifetime of satellite missions has been limited by the lifetime of the onboard power system. Improvements to the lifetime of power system components can be realized through the adoption of nanotechnology. The development of next generation, nano-enhanced power system components has several advantages, including increased device performance or efficiency without making a sacrifice to form factor. One pathway for the adoption of certain nanotechnologies by the aerospace industry is the successful implementation of nano-enhanced power system components in a cubesat form factor. This would allow for the demonstration of the technology in space to provide data from a real space environment as well as help provide flight heritage to the components for consideration in future space missions. The cubesat payload utilizes nanomaterial-enhanced power system components (quantum dot/quantum well solar cells; carbon nanotube (CNT) wire harnesses; CNT-enhanced lithium-ion batteries; CNT thermoelectric energy harvesting) to demonstrate the ability of nanomaterial enhanced components to reduce the mass of power system components without sacrificing power availability or performance. Specifically, CNTs can be integrated into small satellite components to reduce mass as well as improve mechanical and electrical properties. The use of CNTs in wire harnesses and lithium-ion batteries (LIBs) can increase the device performance without significantly altering the device dimensions or the device's operating range. In many cases, the use of CNTs widens the viable range of operating conditions, such as increased depth of discharge of LIBs, and increased flexure tolerance of wire harnesses. The use of CNTs as a conductive additive in LIBs has been shown to be more effective in establishing an electrical percolation network than traditional carbon black or graphite. The integration of CNTs into LIBs can also be used to increase the specific energy density of the entire cell, leading to a potential specific energy density >300 Wh/kg, compared to typical commercial cells in the 100 – 200 Wh/kg range. The performance of high areal capacity coin cells has been determined via rate testing at various C-rates. High energy density pouch cells without CNTs has been evaluated under low earth orbit cycle conditions and via rate tests. To date, RIT has successfully synthesized single-wall carbon nanotube material, integrated these materials in prototype power system components, and tested their performance. High energy density pouch cells with CNTs are currently on test.

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Quantum-Dot Enhanced Tandem Solar Cells for CubeSat Nano-Enabled Space Power System

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Development and integration of a quantum dot enhanced upright tandem InGaP/GaAs solar cells with InAs quantum dots (QDs) incorporated in the GaAs junction is a part of CubeSat nano-enabled four-component space power system initiative. The goal of this program is to demonstrate the advantages of the nano-enhanced photovoltaic, energy storage and transmission systems in comparison to the currently available commercial components for applications in space. In particular, adding quantum structures to the solar cells allows bandgap engineering, enabling efficient sub-band photon collection[1]. In addition, it has been shown that QDs can help with enhancing resistance of the solar cells to space radiation, thus reducing their environmental degradation rate[2,3].

In this work, a baseline $In_{0.49}Ga_{0.51}P$/GaAs tandem cell and a cell with InAs QDs in the bottom GaAs junction were optimized for operation under 1 sun AM0 solar spectrum using Synopsis Sentaurus® physical modeling software. The short-circuit current density was enhanced by 3.3% due to incorporation of 10 layers of QDs. A 20 mV reduction of the open-circuit voltage along with fill factor fluctuations were also observed by simulation. However, the overall efficiency was increased by 0.4% absolute compared to the baseline cell without QDs. Based on the simulation results, lattice-matched $In_{0.49}Ga_{0.51}P$/GaAs tandem solar cell structures with strain-compensated 10-period InAs QD superlattices in the intrinsic layer of GaAs sub-cell and $In_{0.49}Ga_{0.51}P$/GaAs baseline tandem without QDs were grown by metalorganic vapor phase epitaxy (MOVPE) on 100mm (100) p-type GaAs substrates offcut by 2˚ to the <110>. To ensure uniformity in surface coverage and size homogeneity, large-area QD growth was optimized by MOVPE on 100 mm substrates yielding a maximum variation in the average coverage density (1.1×10^{11} cm^{-2}) across the substrate of about 8%, with reduction in QD density only near the wafer edge. The MOVPE grown QDs were also uniform in size, with average height and diameter of 1.0 nm and 10.7 nm (±1.1 nm), respectively. A low density (1.5×10^{8} cm^{-2}) of coalesced QDs with the diameters reaching up to 150 nm was also observed. Next, based on the simulation results, tandem cells with and without QDs have been grown and fabricated into 26 cm^2 cells using standard III-V fabrication techniques and electroplated contacts. Non-alloyed 4-micron thick gold contacts were deposited using electroplating, enabling fill factors up to 90% and a metallization cost reduction by 99% in comparison with thermally evaporated contacts. A ZnS/MgF_2 bi-layer antireflection coating was also deposited to limit surface reflection loss. The results and detailed analysis of the solar cells including 1 sun AM0 current-voltage (JV) measurements, light-biased quantum efficiency spectroscopy, and electroluminescence will be presented at the conference and compared to simulation in order to verify and refine our predictive capabilities.

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1 Hubbard, Seth, Christopher Bailey, Stephen Polly, Cory D. Cress, John Andersen, David V. Forbes, and Ryne P. Raffaelle. "Nanostructured photovoltaics for space power." *Journal of Nanophotonics* 3, no. 1 (2009): 031880.
2 Kerestes, Christopher, Cory D. Cress, Benjamin C. Richards, David V. Forbes, Yong Lin, Zac Bittner, Stephen J. Polly, Paul Sharps, and Seth M. Hubbard. "Strain effects on radiation tolerance of triple-junction solar cells with InAs quantum dots in the GaAs junction." *IEEE Journal of Photovoltaics* 4, no. 1 (2014): 224-232.
3 Tatavarti, Sudersena Rao, Zachary S. Bittner, A. Wibowo, Michael A. Slocum, George Nelson, Hyun Kum, S. Phillip Ahrenkiel, and Seth M. Hubbard. "Epitaxial Lift-off (ELO) of InGaP/GaAs/InGaAs solar cells with quantum dots in GaAs middle sub-cell." *Solar Energy Materials and Solar Cells* 185 (2018): 153-157.

Session VII

Advances in III-V Research

Space-Relevant Characterization of III-V/Si Multijunction Solar Cells

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Daniel Lepkowski, Ohio State University
Daniel Chmielewski, Ohio State University
Steve Ringel, Ohio State University
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High substrate costs, as well as weight, typically play a major role in the high costs of-multijunction space solar cell production and deployment. III-V/Si multijunction structures provide a potential solution to this through the use of an exceptionally inexpensive (and lightweight) substrate that also serves as an active cell component, combined with a III-V semiconductor stack tailored to space PV needs to provide high efficiency. This technology has great potential to impact low budget/short duration missions such as CubeSats and LEO satellite constellation programs.

Dual junction (2J) III-V/Si photovoltaic cells have undergone preliminary development in the realms of dissimilar materials integration, metamorphic material development, and device design and fabrication. These devices consist of a $GaAs_{0.75}P_{0.25}$ top cell, metamorphic graded $GaAs_yP_{1-y}$ buffer, a III-V/Si nucleation layer, and an active Si subcell, all of which are undergoing development with the aid of analytical modeling, detailed materials characterization, and data-informed device design. While development continues, a set of non-optimized test devices were recently fabricated for extended characterization. AM0 efficiency of 16.9% is observed, with J_{SC} of 16.9 mA/cm^2 and V_{OC} of 1.70 V with the bottom Si junction acting as the current limiter. Investigations are underway to improve top cell current collection via TDD reduction and to improve bottom cell voltage via more advanced Si subcell design. We will discuss the cell performance characteristic achieved thus far, as well as on characterization of cell temperature coefficients and the results on thermal cycling to assess space conditions robustness. Next steps of cell optimization and design are also discussed.

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Integration of Quantum Dots and Quantum Wells Into InGaAs and GaAs Metamorphic Sub-cells for Radiation Hard 3-J ELO IMM Photovoltaics

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A major concern for the longevity of satellites in Medium Earth Orbit (MEO), or orbital radii from 1.8 to 2.5 times the Earth's radius is high energy radiation exposure leading to the formation of Frenkel defects and subsequent degradation of minority carrier diffusion length, the main cause of solar cell degradation in space. Inverted metamorphic multijunction (IMM) technology increases the mass-specific power at beginning of life (BoL) via removal of the substrate and can enable substrate reuse via epitaxial lift-off (ELO), but may result in a solar cell with lower radiation tolerance due to sensitivity of both the GaAs middle cell and InGaAs metamorphic subcell. In this work, we propose the inclusion of quantum dots (QDs) or quantum wells (QWs) to improve the radiation tolerance of both the GaAs and InGaAs subcells[1]. Studies of QD solar cells have shown that the QD contribution to spectral responsivity remained relatively constant out to fluences that resulted in an 80% reduction in carrier collection in the bulk material.

We report results on QD-enhanced triple-junction IMM solar cells fabricated using epitaxial lift-off (ELO). IMM $In_{0.49}Ga_{0.51}P/GaAs/In_{0.3}Ga_{0.7}As$ devices with and without QDs in the middle GaAs cell were grown on GaAs substrates using metalorganic vapor phase epitaxy (MOVPE). ELO technology was employed to remove the tandem cells from the GaAs substrate and transfer onto flexible, lightweight metal substrates. Incorporating 10 layers of strain compensated InAs QDs into the GaAs middle cell resulted in a 0.42 mA/cm^2 increase in short circuit current density (J_{SC}) with minimal open circuit voltage (V_{OC}) loss. The resultant IMM device with QDs showed an efficiency of 30% under 1-sun AMO with a V_{OC} of 2.90 V and J_{SC} of 16.86 mA/cm^2. As well, EQE studies on 2x10^{15} cm^{-2} ,1 MeV electron irradiated IMM solar cells with QDs embedded in GaAs middle cell indicated that >90% BoL performance was maintained in the QD region of 940nm.

In addition, we have also begun to explore the addition of both QWs and QDs to the InGaAs metamorphic cell. Both structures have been grown by MOVPE on 1eV InGaAs metamorphic templates. As well, devices have been modeled in Synopsis Sentaurus™ TCAD to compare the benefits of both QD and QW enhancement. A V_{OC} reduction from nearly 2.5 V to 2.4 V from the addition of interfaces and an i-region into the InGaAs subcell was simulated, however the effects of this reduction in V_{OC} on cell efficiency is compensated by J_{SC} enhancement. The predicted end of life (EoL=1x10^{15} cm^{-2}, 1 MeV electrons) efficiency for the three devices is 17.24%, 18.31%, and 17.85% for control, QW, and QD respectively. The increase in EoL efficiency for the QW device represents a 6% relative efficiency enhancement. However, actual IMM devices with 10 layers of QW grown in the metamorphic junction showed a 230 mV loss in V_{OC}, which characterization indicated was due to transport of carriers across the QW region, indicative of the difficulty for growing nanostructures into metamorphic materials.

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Resilient, Affordable GaInP/GaAs Solar Cells Grown by Dynamic-Hydride Vapor Phase Epitaxy

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We report the initial development of single- and dual-junction III-V solar cells for space applications grown using dynamic-hydride vapor phase epitaxy (D-HVPE). Achieving high conversion efficiencies while avoiding the use of Ge or low-bandgap mismatched junctions is important for improving the resilience of satellite solar arrays against potential assault from ground- or space-based laser systems. It is important to maintain high efficiencies even without these extra junctions in order to provide sufficient power to satellites. While III-V-based devices have been used in space applications for decades due to their unique combination of high efficiency, low weight, superior stability, and potential for radiation-hard structures, the recent industry push toward large constellations of small satellites, coupled with reduced launch costs, may render traditional III-Vs cost prohibitive despite their advantages. It is important to demonstrate that high-conversion efficiency structures can be achieved using lower-cost, scalable growth technologies.

D-HVPE has several cost advantages over traditional metalorganic vapor phase epitaxy (MOVPE), including the use of much lower cost precursors, while using them more efficiently, as well as very high throughput. Indeed, we showed GaAs growth rates using D-HVPE > 5 µm/min (300µm/h) *without degradation of material or device quality*. Bottom up cost models developed at NREL show that D-HVPE can produce significant cost savings in the near term at relatively low volumes, while achieving 10x lower costs than MOVPE growth when reaching full production maturity.

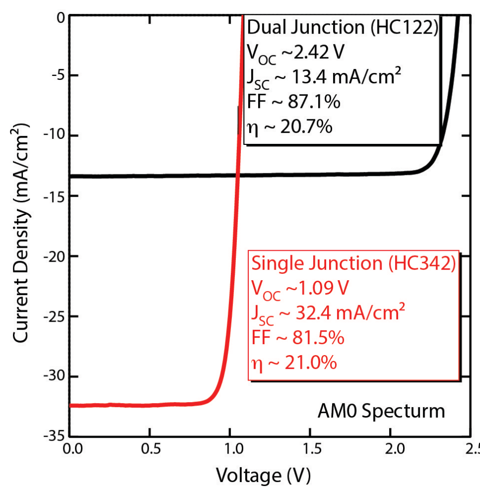

Figure. Current density vs voltage for single (red) and dual (black) junction devices under a simulated AM0 spectrum.

We will show that D-HVPE is capable of growing high-efficiency solar cell structures, which has not been possible in the past. We will present initial D-HVPE-grown GaAs and GaInP/GaAs devices, each with efficiencies > 20% under AM0 spectral conditions (see Figure). We expect, with more development, the two-junction devices to approach 30% efficiency (AM0), with the much lower cost structure delivered by D-HVPE.

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Arcing on Space Solar Cells – Contamination and Damage to Interconnects and Coverslides

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Arcing on space solar cells is well known to produce damage to the cells, interconnects, and cover-glasses. Damage mechanisms include loss of material blown off from the arcsite, contamination of cover-slides and cell edges, producing power loss from loss of transparency or short-circuiting cell junctions, or even physical damage to the cover-glasses. We report here the results of arc-testing a 4-cell flight-like array coupon under inverted potential gradient and normal potential gradient simulated GEO conditions at the Spacecraft Charging and Instrument Calibration Laboratory of the Air Force Research Laboratory at Kirtland Air Force Base, New Mexico. Previous work has established that arcing contamination of cover-glasses can explain the excess power loss of GPS solar arrays at arc rates seen by on-board RFI detectors and the Arecibo radio telescope. The work presented here confirms these prior results, and describes interconnect damage and contamination caused by hundreds of inverted gradient arcs. In addition, severe and unprecedented cover-glass damage is described under normal gradient arcing at voltages possible in GEO space plasmas. These results may have important implications for solar array design and construction. Mitigation techniques will be considered.

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Session VIII

Measurements and Calibration

Reconstituting the U.S. National Solar Cell Balloon Flight Program

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The solar cell qualification standard originally written by Brad Reed of the Aerospace Corporation in 2003, and adopted as AIAA S-111 by the SMC Chief Engineer's Office in 2005 require "balloon-flown standards" (or standards of at least that quality) for solar cell qualification. Since balloon flight capability has not practically existed for NSS programs since 2008, and the barriers to obtain standards of at least balloon flight quality are too high, this has impeded SMC's ability to qualify space solar cells.

Technology insertion into new SMC missions has also been stymied. NSS and USAF acquisition and procurement requirements require a minimum TRL of 6 for technology insertion into new SMC missions. This assignment of TRL 6 at completion of AIAA S-112 for solar panels, which also requires the balloon flight cells, is given by example in SMC in AIAA S-122-2007.

In summary, not having a national solar cell balloon flight calibration capability has slowed research, development, productization, and qualification across the board for USAF missions.

The SMC/AD developed a number of Rapid Innovation Fund topics under the broader $250M DoD RIF program in 2017. Fifty-nine white papers were delivered to these topics, and of the ideas chosen from these white papers, four proposals were selected for funding. Reconstituting a domestic solar cell balloon flight capability was one of those four selected proposals. For this program, SMC/AD is providing $685,000 of completion funding to develop a commercial-based balloon flight capability for characterizing solar cell samples through Angstrom Designs, Incorporated. The project (1) provides accurate, cost-effective processes for characterization and calibration of advanced photovoltaic technologies, (2) offers flight opportunities to complementary experiments (solar intensity measurements, solar spectrum vs. altitude, etc.) and, (3) flies devices from customers who had arrangements with the old JPL balloon-flight program.

The SMC/AD goals for this project are to complete a TRL 5 development platform and characterize up to 16 2x2 cells per flight. In the business model, larger area solar cells would command a higher price per unit. The normal turnaround time could satisfy a program need in 12 weeks, but since the test plane can be duplicated, multiple test planes could be developed in such a fashion to allow 3 weeks between launches for a single gondola. Angstrom Designs will determine whether to manufacture multiple gondolas based on market pull.

The specifications for the project were modified from the NSCAP specification developed by the USAF and NASA after the JPL program was discontinued. These specifications provide a minimum capability to characterize balloon-flown solar cell samples to support the prime contractors, and solar cell and panel manufacturer simulator calibration requirements. TheSMC/AD is looking for industry partners to help us evaluate the project as it progresses.

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Low-Temperature Characterization of Multijunction Solar Cells Using a Combined Characterization Approach

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We combined light current-voltage, dark current-voltage, quantum efficiency, and electroluminescence at varying low temperatures to identify and quantify defects, current mismatch effects, saturation currents, and diode quality of each subcell. We attempt to provide a method for spectral mismatch correction for fill factor for each subcell as well as identify how defects, current mismatch, and radiation will affect performance of multijunction solar cells at LILT, AM 0, and AM 1.5.

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Calibration and Standards With Near-Field Solar Simulation

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Angstrom Designs

Near-field solar simulation, including LED-based solar simulation, enables many new capabilities for space solar cell testing, including the present-day capability to measure 4-junction, 5-junction and 6-junction space solar cells. Near-field simulation also challenges some of the standards used to measure and compare solar simulators.

Many such standards rate solar simulators from A to C based on 3 criteria: spectral matching, temporal stability and spatial non-uniformity (SNU). A simulator with the highest rating in all categories, generally 2%, is called AAA. An AAA simulator on its own is typically not enough for space applications, as isotype current tuning below 2% is often needed. LED solar simulation warrants discussing, and possibly amending, current simulation metrics:

- LED solar simulators do not attempt spectral matching, making the first criteria misleading.
- LED solar simulators typically exceed the class A threshold by over 200x, making the second criteria too coarse.
- LED solar simulators have the ability to break SNU into 2 separate criteria: junction current match (also called inter-cell SNU) and intra-cell SNU.
  - Junction current match is important for all multi-junction or string solar cell measurements. LED solar simulators exceed the class A threshold by over 5x
  - Intra-cell SNU may be critically important for solar cell manufacturer cell testing but may be unimportant for panel level manufacturing test. LED solar simulators can be designed to exceed the class A threshold by over 4x, if needed.

LED solar simulation is highly flexible in its design and configuration. Simulators can be designed to meet the test needs of specific applications, or to be generally applicable. This talk offers a more thorough understanding of the capabilities of LED solar simulation so scientists and engineers can harness this new technology in their labs and cleanrooms.

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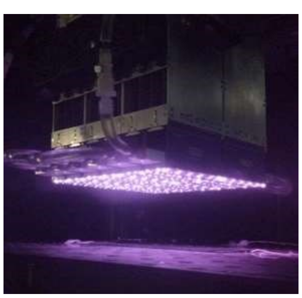
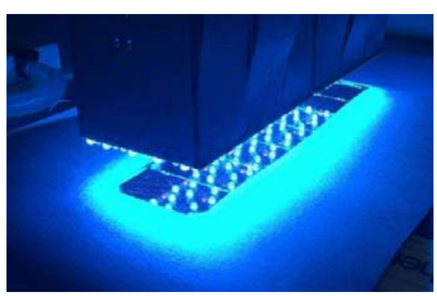
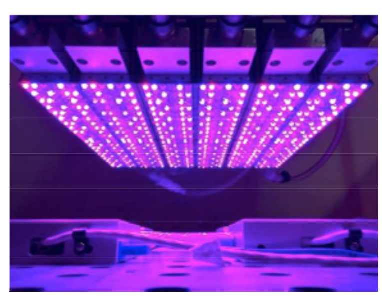

Intelligent Solar Cell Carrier (iSC²) for Solar Cell Calibration Standards

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The AM0 solar cell measurements currently require calibrated balloon standards for tuning solar simulators. The uncertainty in the solar cell measurement is largely dependent on the quality of the calibrated balloon standard used to tune the simulator. Current practices reduce this uncertainty to ~1% while requiring expensive and infrequent methods for obtaining new calibration standards. This paper outlines an effort to reduce the uncertainty of the calibration standard, while providing a solution for low cost and frequent standard creation.

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Session IX

Next Generation Array Concepts

Multi-Mission Modular Array: Mission Adaptability

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For the past 5 years, Lockheed Martin (LM) has been developing a fourth-generation Multi-mission Modular Array (MMA, Reference Fig.1) as an integral technology for its revitalized A2100 bus, the A2100TR, using company Internal Research and Development (IRAD) funding. The MMA is designed to be adaptable to a wide variety of mission architectures, including civil, government/military, and commercial space. The power range of these missions extends from 9 to 26 kW BOL using a modular power concept, with a designed upgrade path to 39 kW BOL by changing the bus voltage from 70V to 100V. MMA adaptability to 28V, 120V and higher voltages has also been factored into the design, along with ability to accommodate multiple string lengths, to meet deep space LILT missions.

The MMA power architecture supports multiple solar cell types, with a preference to use larger area cells to reduce photovoltaic and other assembly costs. Considerable LM investment in automation technology for electrical interconnection, inspection, and other array assembly operations, has significantly enhanced affordability, compared to previous flex array designs. Additionally, a new simplified deployer design greatly enhances array producibility and affordability, by reducing parts count and labor costs, compared to past open-lattice deployer mechanisms. MMA performance robustness in demanding environments, including high radiation, and solar plasma and electric propulsion charging, has been enhanced by design features and significant testing, to prove the reliability and lifetime of the components and materials used.

Further extension of the MMA architecture to support lower and higher power mission requirements is underway, including for small 5-9kW spacecraft and very large 50+ kW spacecraft such as the Power Propulsion Element for the Lunar Orbital Platform-Gateway. The MMA modular Z-fold blanket concept supports mission power increments by simple addition and subtraction of panel segments, which can also be narrowed and widened readily for further adaptability, while employing the same basic circuit module approach. Additional data will be presented in the full paper, to further expand on the adaptable features of the MMA design, to meet current and future NASA mission architectures, with focus on affordability.

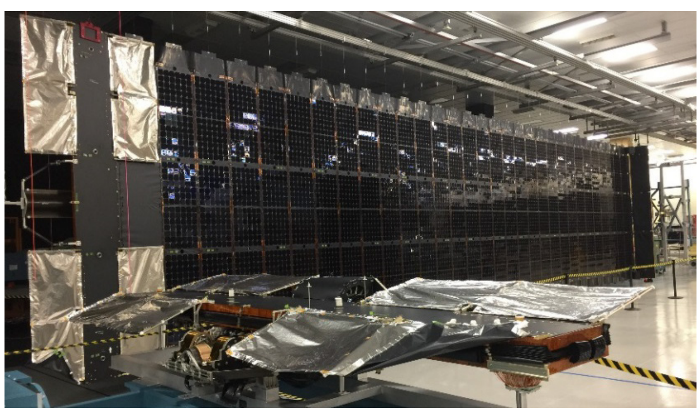

Fig. 1. Lockheed Martin's Multi-mission Modular Array (MMA) – Stowed and Deployed

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Qualification and Insertion of Roll-Out Solar Array (ROSA) for Multiple SSL Spacecraft Platforms and Their Synergy for Future NASA Missions

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SSL and Deployable Space Systems (DSS) are completing the qualification of the advanced flexible roll-out solar array (ROSA) for use on SSL's 1300 Commercial Spacecraft Bus. ROSA provides ultra-low mass, compact stowed volume, high power capability, power modularity, scalability, and affordability. A recent ROSA demonstration flight in 2017 on the International Space Station (ISS) has advanced the ROSA solar array to Technology Readiness Level (TRL) 8. Figure 1 below presents the SSL ROSA qualification wing, which is a full-scale model of a 14-kW BOL wing. ROSA is SSL's long-term common solar array product for mid to high-power spacecraft.

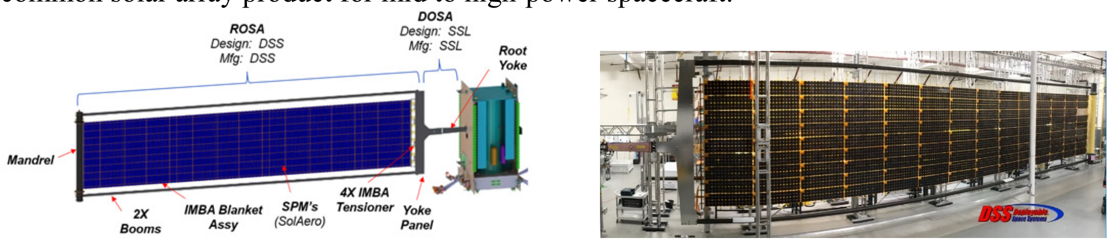

Fig 1. SSL ROSA Qualification Wing

SSL and DSS have also demonstrated how ROSA technology can be scaled to 40+kW Beginning of Life (BOL) on SSL next generation GEO spacecraft. Near-term program insertion considerations involve the use of ROSA to enable novel spacecraft operations and architectures. These include on-orbit satellite servicing spacecraft and persistent platform spacecraft concepts, as shown in Fig. 2 below.

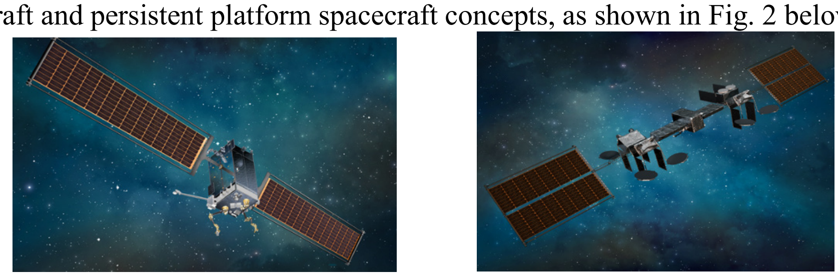

Fig 2. SSL On-orbit Servicing Satellite and SSL Persistent Platform Spacecraft

With the completion of the SSL ROSA GEO qualification and the commercial infrastructure in place, ROSA is an enabling technology that will benefit NASA future missions, such as a 50kW class Power and Propulsion Element for the Lunar Gateway, and eventually manned-missions to Mars.

Fig 1. SSL's Concept of the NASA Lunar Gateway

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Mars Surface Solar Array Structures: Recent SBIR Contracts

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This talk summarizes eight Phase 1 SBIR contracts awarded to U.S. small businesses in 2017-2018 under the subtopic of "Mars Surface Solar Array Structures," managed by LaRC with support from GRC. The Small Business Innovative Research (SBIR) program annually awards 3.2% of NASA's extramural R&D budget to small businesses for competitively selected technical innovations that contribute to important missions and objectives and that show commercial potential.

These eight contracts address this identified need for future Mars surface solar array structures:

Human missions to the Mars surface will require tens of kilowatts of electrical power for life support, science, in-situ resource utilization (ISRU), and other equipment. Possible power sources include nuclear reactors and solar arrays with batteries or regenerative fuel cells. Solar arrays are a mature, reliable technology used on most spacecraft and increasingly for Earth terrestrial power, and also at small sizes up to ~3 m2 for several successful Mars landers and rovers. However, human missions will need thousands of square meters of solar cells to generate the required power. Furthermore, the solar arrays must survive inevitable dust storms and possibly months of dormancy before and between crew visits.

This subtopic seeks structural and mechanical innovations for solar arrays with at least 1000 m^2 of total area that autonomously deploy from Mars landers. Design guidelines for these large deployable solar arrays are:

- Solar arrays must self-deploy.
- Total area: 1000 m^2. Extensibility to 1500+ m^2 is desirable.
- Mass goal: < 1.5 kg/m^2 including all mechanical and electrical components. Packaging goal: < 10 m^3 per 1000 m^2 of deployed area.
- Launch loads: 5 g axial, 2 g lateral, 145 dB OASPL.
- Lander may not have azimuth control (i.e., guaranteed landing clocking angle). State all assumptions concerning array orientation and sun pointing.
- Solar arrays deploy in Mars 0.38 gravity and low winds (use 0.5 g for preliminary design). Solar arrays operate in Mars 0.38 gravity and wind gusts (use 1.0 g for preliminary design).
- Must survive peak winds of 50-100 m/s and simultaneous upward winds of 25-50 m/s (dust devils) with maximum air density of 0.023 kg/m^3.
- Deployable on terrain with up to 0.5 m obstacles/depressions, 15 degree slopes, and potentially hidden hazards (e.g., sand-filled holes). Operating height > 0.5 m to avoid wind-blown sand collection.
- Time to deploy: < 8 hrs.
- Deployed strength: Ideally > 1 g to allow unconstrained Earth deployment qualification.

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International Space Station (ISS) Roll-Out Solar Array (ROSA) Spaceflight Demonstration Mission, Key Results, and Forward Plans

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Abstract — Deployable Space Systems, Inc., (DSS) Roll-Out Solar Array (ROSA) is a new flexible-blanket technology that achieves ultra-high performance and affordability for end-users. Recently, in June 2017, a spaceflight demonstration mission of the ROSA solar array funded by the U.S. Air Force was conducted on the International Space Station (ISS). The 7-day long mission was specifically structured to validate functional deployment, deployed dynamics behavior and deployed stiffness, deployed thermal / dimensional stability, stowed vibration survivability, retraction and re-deployment, photovoltaic power production and on-orbit operating temperature. Results from the highly successful spaceflight mission confirmed all key performance metrics for validating functional deployment, deployed dynamics, vibration survivability, retraction and redeployment, dimensional stability, and power production. The mission also validated many detailed analytical models that are being applied towards future mission applications. The mission success has resulted in a flight ready status of the ROSA technology and has enabled many commercial infusion implementations.

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Session X

Silicon Technologies

Ultrathin Silicon Solar Cells for Powering Future Space Economy

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Next level of space economic development such as global broadband satellite internet, in-orbit manufacturing, asteroid mining, building Lunar and Mars bases, will require many gigawatt of PV electricity to power it. There are two major roadblocks to using that much PV in space: the cost of launch and the cost of solar arrays themselves. Recent progress in rocket reusability can lead to the reduction of the cost of launching the payload into space by a factor of 100 from about $5000/kg to $50/kg. However, the cost of conventional III-V tandem solar cells presently used in space will remain a fundamental barrier. A factor of 100 cost reduction, from $100/W to $1/W is necessary to enable gigawatt-scale space PV.

Silicon is the only solar cell technology which has a potential to achieve less than $1/W cost, can be manufactured at GW scale and can achieve competitive efficiency and reliability. It has recently been theoretically justified that silicon solar cells can also be made radiation hard, if the thickness of silicon absorber is reduced below 50 microns [Fedoseyev 2015]. Thus, thin silicon solar cell technology can become the optimum choice for very high-power space applications where the cost of solar PV constitutes a significant amount in the overall cost.

Regher Solar is developing manufacturing technology for ultrathin high efficiency silicon solar cells, which can be quickly transferred to mass production and achieve <$1/W manufacturing cost to supply the booming space economy. To achieve high efficiency on thin wafers Regher Solar is using bifacial amorphous/crystalline silicon heterojunction technology and copper electroplating which can enable ultrathin silicon solar cells with up to 24% AM0 efficiency. Shingling is proposed as cell interconnection method to replace welding. Shingling increases packing density and together with bifaciality can compensate for lower beginning-of-life efficiency of thin silicon cells compared to III-V tandems. This paper will discuss the target performance parameters for ultrathin silicon solar cells and compare them to the parameters of competing PV technologies such as III-V tandems on Ge substrate, III-V epi lift off tandems, single junction GaAs epi lift off cells and interdigitated back contact Si cells. Recent results will be presented including 21.1% AM0 efficiency of a 50-micron-thick solar cell.

REFERENCES

[Fedoseyev 2015] A. Fedoseyev, A. Raman, S. Bowden, Jea Young Choi, Ch. Honsberg, T. Monga, "Numerical modeling of radiation effects in Si Solar Cell for Space", SPIE, 9358 – 22, 2015.

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Numerical Modeling of Radiation Effects in Si Solar Cell for Space

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Improvements to solar cell efficiency and radiation hardness that are compatible with low cost, high volume manufacturing processes are critical for power generation applications in future long-term NASA and DOD space missions. In this paper, we provide the results of numerical simulation of the radiation effects in a novel, ultra-thin (UT), Si photovoltaic (PV) cell technology that combines enhanced light trapping and absorption due to nanostructured surfaces, separation of photo-generated carriers, and increased carrier density due to UT thickness. Such solar cells have a potential to achieve high conversion efficiencies while shown to be lightweight, flexible, and low–cost, due to the use of Si high volume techniques. Regher Solar is developing manufacturing technology for UT high efficiency silicon solar cells, which can be quickly transferred to mass production and achieve <$1/W manufacturing cost to supply the booming space economy. To achieve high efficiency on thin wafers Regher Solar is using bifacial amorphous/crystalline silicon heterojunction technology and copper electroplating which can enable ultrathin silicon solar cells with up to 24% AM0 efficiency. Higher efficiency solar cells can reduce solar array mass, volume, and cost for space missions.

When solar cells are used in outer space or in Lunar or Marsian environments, they are subject to bombardment by high-energy particles, which induce a degradation referred to as radiation damage. Radiation tolerance (or hardness) of this UT Si PV technology is not well understood. Research, review, and analysis of solar-cell radiation-effects models in literature have been conducted, and physics-based models have been selected and validated [Fedoseyev 2015]. Several different engineering approaches have been investigated to improve Si solar cell radiation hardness. These include Material/ Impurity/Defect Engineering (MIDE), Device Structure Engineering (DSE), and device operational mode engineering (DOME), which have been shown to be effective in reducing the effects of displacement damage in Si based devices [Zheng 2002]. Lithium-doped, radiation-resistance silicon solar cell is an attractive experimentally proven possibility [Wysocki 1966].

In this paper, we provide the results of the accurate numerical simulation of the radiation effects in UT Si PV cells, and radiation damage mitigation techniques. The results of numerical simulation of the radiation effects, coupled with the phenomenon of non-uniform vacancy creation (i.e., maximum displacement damage occurs near the Bragg peak, as described earlier), further indicate that a high-energy protons will cause minimal damage in the ultra-thin 50 µm (or thinner) Si solar cell. These results show that this UT Si PV cell technology can be used for space applications in the high radiation environment.

REFERENCES

[Fedoseyev 2015] A. Fedoseyev, A. Raman, S. Bowden, J. Y. Choi, Ch. Honsberg, T. Monga, "Numerical modeling of radiation effects in Si Solar Cell for Space", SPIE, 9358 – 22, 2015.

[Wysocki 1966] Wysocki J.J. et al., "Lithium-doped, radiation-resistance silicon solar cell", Appl. Phys. Lett., 9, 44 (1966).

[Zheng 2002] Zheng Li, "Radiation Hardness/Tolerance of Si Sensors/detectors for Nuclear and High Energy Physics Experiments", Brookhaven Nat. Lab. report BNL-69639, 2002.

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