Electronic Materials and Photonics Division
Room 304 - Session EM+AS-ThM

Photovoltaic Materials, Characterization, and Applications

Moderator: Seth King, University of Wisconsin - La Crosse

11:00am **EM+AS-ThM-10 Translating Materials-Level Characterization of Carbon-Nanotube-Reinforced Composite Gridlines To Module-Level Degradation***, **Sang Han,*** The Univeristy of New Mexico and Osazda Energy*; A. Chavez,* The University of New Mexico and Osazda Energy*; B. Rummel,* The University of New Mexico and Osazda Energy*; A. Jeffries,* Osazda Energy*; N. Bosco,* National Renewable Energy Laboratory*; B. Rounsaville , A. Rohatgi,* Georgia Institute of Technology

Cell cracks in PV modules caused by environmental stressors and extreme weather events can lead to gradual or immediate power degradation. To directly address cell-crack-induced degradation, we have formulated a carbon nanotube additive for commercial silver pastes used in screen printing. We have shown in earlier work that these metal matrix composites do not impact the cell efficiency, while enhancing the metallization's fracture toughness and electrical gap-bridging capability. In this work, we focus on translating materials-level characterization techniques to module-level degradation. We found that we get conflicting results from two different materials characterization methods of measuring the metallization's ability to electrically bridge gaps in cracked solar cells. To determine which materials characterization method correlates better with the mini-module degradation characteristics, we have conducted stress testing for a small dataset of mini-modules.

The first characterization method for measuring the metallization's ability to electrically bridge cell cracks is dubbed as Resistance Across Cleaves and cracKs (RACK), in which a piezoelectric stage pulls apart fractured cells in submicron increments while the resistance of the gridlines on top of the fractured cells is measured until the gridlines electrically fail. The tensile stress applied to the metallization during the RACK test is intended to mimic the stress encountered by the metal gridlines during thermal cycling after cell fracture, in which cell fragments translocate within the module. Another common method for characterizing the metallization's ability to electrically bridge cell cracks is three-point bending test, where a rectangular substrate with two parallel gridlines, laser-diced from a cell, is mounted on an acrylic beam and placed in a three-point bend fixture while the resistance of gridlines is monitored as a crack in the cell is slowly opened. The failure mechanism with this testing method could be an alternative representation of how a cell would fracture when the module is being flexed under heavy mechanical loads or being stepped on.

The two materials-level characterization methods described above are designed to measure the metallization's ability to electrically bridge a cracked cell; however, they give conflicting results as to which composition and geometry of carbon nanotubes performs best. To better understand which materials-level test correlates to module-level degradation, 2x2 minimodules were constructed with pre-fractured cells and subjected to thermal cycling.

11:20am **EM+AS-ThM-11 Effects of Carbon-Nanotube-Reinforced Composite Gridlines on Photovoltaic PERC Cell and Module Efficiency***, **Andre Chavez,*** The University of New Mexico and Osazda Energy*; S. Han,* The Univeristy of New Mexico and Osada Energy*; A. Jeffries,* Osazda Energy*; S. Huneycutt,* The Univeristy of North Carolina at Charlotte*; A. Ebong,* The University of North Caronlina at Charlotte*; D. Harwood, N. Azpiroz,* D2 Solar

Abstract — The addition of carbon nanotubes (CNTs) in commercial silver pastes used for the front metallization of Passivated Emitter and Rear Contact (PERC) solar cells not only helps improve the materials toughness and resilience to cell cracks, but also offers some improvement to cell efficiency. A large data set of 87 cells containing the CNT-enhanced metal matrix composite (MMC) gridlines, when compared to a set of 66 baseline PERC cells, shows an increased efficiency by 0.03%, which is the threshold that cell and module manufactures care about. Six mini-modules, each of which consists of two PERC cells connected in series, were fabricated with the baseline metallization, and six mini-modules were fabricated with MMC-enhanced PERC cells. Three modules were subjected to 200 cycles of thermal shock (TS) from -40 to +85 °C, and the remaining three were subjected to highly accelerated stress testing (HAST), where damp heat is applied at 120 °C for 100 hours and 100% relative humidity. After these two tests, the MMC metallization shows comparable corrosion to the baseline metallization and power loss of less than 0.6% after TS-200 and less than 4% after HAST-100. The inclusion of CNTs to conventional screen printable silver pastes has the ability to improve cell efficiency, while showing statistically identical beginning-of-life cell and module performance as well as corrosion characteristics and infant failure rate (e.g., solder bond failure) comparable to the baseline. These results show strong promise for commercial implementation of the MMC-enhanced metallization to improve PV module reliability.

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-EE0009013.

11:40am **EM+AS-ThM-12 Atomic Layer Deposition of NiO for Single Junction Perovskite and Tandem Perovskite/Silicon Photovoltaics***, N. Phung, C. van Helvoirt,* Eindhoven University of Technology, The Netherlands*; D. Zhang, V. Zardetto, B. Geerligs,* TNO Science and Industry, the Netherlands*; M. Verheijen, E. Kessels, B. Macco, **Mariadriana Creatore**,* Eindhoven University of Technology, The Netherlands

Metal halide perovskite absorbers have attracted major attention due to their excellent opto-electronic properties. Recent advancements in performance and stability of perovskite solar cells (PSCs) have been achieved with the application of self-assembled monolayers (SAMs), serving as hole transport layers in the p-i-n PSC architecture [1]. However, a reproducible implementation of SAM in the PSC device requires knowledge of its surface coverage on ITO since non-covered areas in direct contact with perovskite may lead to shunts and low open-circuit voltage.

In this contribution, we investigate the influence of an atomic layer deposited (ALD) NiO film (7 nm) on the surface coverage of SAM for single junction PSC as well as tandem PSC/silicon devices. NiO is processed either by plasma-assisted ALD [2] or thermal ALD [3]. The latter has also been developed since thermal ALD is often adopted in upscalable technologies such as batch and spatial ALD.

We observe that the SAM of MeO-2PACz ([2-(3,6-dimethoxy-9H-carbazol-9-yl)ethyl]phosphonic acid) inhomogeneously covers ITO. Instead, when adopting NiO as intermediate layer between ITO and SAM, the SAM homogeneity and surface coverage improve, as witnessed by transmission electron microscopy (TEM) and conductive atomic force microscopy. This result is explained in terms of chemisorption reactions between SAM phosphonic acid groups and NiO hydroxyl groups. The SAM homogeneity on NiO leads to higher shunt resistance in the device with respect to the one with SAM directly processed on ITO. Moreover, the combination of NiO and SAM results in a narrower distribution of device performance reaching more than 20% efficient champion device.

The above-mentioned merits of ALD NiO are further exploited in a monolithic tandem device, consisting of a c-Si passivated emitter rear cell (PERC) bottom cell and a perovskite top cell. In the case of ITO/SAM tunnel junction, several devices present electrical shunts in the top cell, leading to a standard deviation of efficiency of 4.6% across device batches. In the case of ITO/NiO/SAM tunnel junction, the tandem device exhibits a narrow distribution of efficiency (standard deviation of 2% across device batches) because of the uniformity and conformality of NiO on ITO, as witnessed by TEM analysis. A champion efficiency of 23.7% is recorded, among the best tandem cell efficiency implementing an industrial standard bottom cell.

[1] Al-Ashouri, *et al.* (2019) Energy & Environ. Sci., *12*(11), 3356.

[2] Koushik *et al*. (2019) J. Mat. Chem. C 7, 12532.

[3] Phung *et al*. (2022) IEEE Journal of Photovoltaics, under review.

[4] Phung, *et al.* (2021) ACS Appl. Mat. Interfaces, 14(1), 2166.

12:00pm **EM+AS-ThM-13 XPS Depth Profiling of Single Film and Two-Layer Heterojunction Metal-Halide Perovskites***, **Jennifer Mann,*** Physical Electronics*; C. Clark, W. Hsu, E. Pettit,* University of Minnesota*; K. Artyushkova,* Physical Electronics*; R. Holmes,* University of Minnesota

The goal of an XPS depth profile is to obtain accurate identification of layer thicknesses and composition as a function of depth within film structures. Monatomic Ar^+ has been available for many years and is often the gun of choice for inorganic thin film profiling despite its issues with preferential sputtering, material migration, and chemical reduction that may occur, thus altering the apparent profile of the analyzed material.

The introduction of C_{60} cluster ion beam and argon gas cluster ion beam (GCIB) sputtering in recent years has expanded the types of materials that may be studied by depth profiling beyond that of inorganic thin films.Cluster type ion guns have shown successful depth profiling of polymer and organic materials as well as inorganic thin film structures while preserving the stoichiometry and chemical structures.

Organo-metal-halide perovskites are of interest due to their promising application in solar cells, where they have achieved efficiencies above 25%.In this work, we present XPS depth profiles of single films of metal-halide perovskites, with an ABX_3 structure(A = MA - methylammonium or Cs, B = Sn or Pb, X = Br or I).Maintaining stoichiometry while sputtering can be very challenging, so in addition, $MAPbI_3$ was analyzed with hard X-ray photoelectron spectroscopy (HAXPES). A Cr Kα (5414.8 eV) X-ray source provides information depths three times greater than the standard Al Kα (1486.6 eV) X-ray source.Using a higher energy photon provides a non-destructive method to probe deeper into the sample, minimizing the contribution from surface oxides and carbon contamination.

XPS depth profiles were obtained on a single layer perovskite film using the two cluster ion guns, available on the PHI *VersaProbe* III - C_{60} and argon gas cluster (GCIB) The viability of each gun in maintaining both the stoichiometry and chemistry of the film as it was sputtered was determined before measuring a more complex perovskite system.

A more complex two-layer heterojunction of organo-metal-halide perovskites was also investigated using optimized ion sputtering conditions.This is a particularly well-suited system for XPS depth profiling due to the accessible thicknesses of the layers and the significant difference in the chemistry of carbon and nitrogen in different organic A-site cation environments. Indeed, this difference is exploited to probe ion migration and mixing across perovskite interfaces.

Author Index

Bold page numbers indicate presenter