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Tandem Junction Solar Cells

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Crystalline silicon (Si) solar cells are approaching their theoretical efficiency limit, with Panasonic and Kaneka recently demonstrating cells with efficiencies above 26%, and alternatives to overcome single junction device efficiency limits are needed. This has prompted the research for alternative manufacturing techniques and materials to create high-efficiency, cost-competitive solar cells. Tandem solar cells have the potential to dramatically improve cell efficiency beyond current levels by more efficiently converting the solar spectrum with two or more discrete bandgaps. Combined with low-cost materials, tandem solar cells can enable the U.S. Department of Energy SunShot goals to reach 3 cents/kWh cost of solar power generation by 2030. In a tandem cell, the top cells are designed to absorb shorter wavelengths of light while the bottom cell is designed to absorb longer wavelengths. There are two typical configurations: series-connected tandem and n-terminal tandem. A series-connected tandem cell requires current-matching between the cells while, in an n-terminal tandem device, the different solar cells are externally wired, and their photocurrents do not have to match, resulting in reduced design constraints as well as higher efficiencies than series-connected cells, especially when the currents are not perfectly matched.

This special section of the *SPIE Journal of Photonics for Energy* (JPE) on tandem junction solar cells centers broadly on low cost approaches to high efficiency (>30%) tandem solar cells, tandem structures for concentrating photovoltaics, and modeling of tandem photovoltaic modules.

More specifically, the special section covers several important areas in tandem solar cells. Panday and Chaujar report on a low-cost 29.5% efficient perovskite/SiC passivated interdigitated back contact silicon heterojunction (IBC-SiHJ) mechanically stacked tandem solar cell. Chen et al. use numerical simulations to study hexagonal sinusoidal nanotextures in the perovskite top-cell with a Si bottom where the nanotextures can reduce the reflective losses of the combined tandem device. The authors demonstrate that the current density utilization can be increased from 91% for the optimized planar reference to 98% for the best nanotextured device (period 500 nm and peak-to-valley height 500 nm), where 100% refers to the Tiedje-Yablonovitch limit. MacAlpine et al. examine a tandem module design with GaInP2 mechanically stacked on top of crystalline Si, comparing unconstrained four-terminal (4T) and constrained two-terminal (2T) voltage-matched (VM) architectures. The main finding is that 2T VM configurations combined with module-level integrated power electronics (MLPE) may provide a more practical approach for implementing mechanically stacked tandems than 4T configurations in certain situations. Hamon et al. present innovative GaAs/Si heterojunction tunnel junctions for future III-V/Si series-connected tandem devices. In particular, they investigate the impact of hydrogenation of the GaAs surface during PECVD epigrowth of silicon on GaAs. Their main finding is that, although the hydrogenation of the surface leads to a strong decrease in doping density, thus degrading the sharp doping profile needed for efficient tunnel junctions, the doping level can be recovered after thermal treatment. Lumb et al. also report on tunnel junctions, with a focus on an innovative broken-gap quantum-well structure lattice-matched to GaSb. Such a tunnel junction is a required milestone in order to unlock the potential of GaSb-based fully lattice-matched III-V tandem solar cells with four or more junctions. The advantage of such a structure resides in its low resistivity — due to the high tunneling probability at the quantum well interface — while retaining a high transparency. Wilkins et al. study the use of thin junctions to minimize sensitivity to varying material quality and ensure adequate transmission into lower junctions. The team presented results on InGaAsN(Sb) cells, which exceed the 12.5 $\mathrm{mA/cm^2}$ at 1-sun needed for current matching in a four-junction, GaInP/(Al)GaAs/InGaAsN(Sb)/Ge solar cell and can benefit lattice matched, InGaAsN(Sb)-based multiband photodetectors. Wood et al. report GaAsP self-assisted core—shell p-i-n nanowires grown on Si solar cells. The resulting tandem cell exhibited an enhanced V_{oc} of 1.16 V, increasing from 0.54 V for the Si cell alone. Nevertheless, the efficiency of the tandem cell was only 3.51% as compared with 9.33% for the Si cell due to a current-limiting short-circuit current density from the nanowires. Jeco et al. study the temperature-dependent luminescence coupling (LC) in InGaP/GaAs/Ge triple junction solar cells since LC can reduce the current mismatch in multijunction solar cells. The authors conducted tests from 18ºC and 72ºC and found that the LC effect reduces significantly as the operating temperature increases hence contributes best to the solar cell performance when operated at the lower temperatures.

The articles in this special series provide a good overview of recent progress in tandem junction solar cells, providing insight into the materials and design innovations taking place in this exciting and growing research field.

Fatima Toor received her PhD in electrical engineering from Princeton University in 2009 and currently is an assistant professor at the University of Iowa with a primary appointment at the Electrical and Computer Engineering Department, with secondary appointments at the Physics and Astronomy department, the Informatics Initiative Cluster, and the Optical Science and Technology Center. She is or has been a PI or a co-PI on at least 15 federal, state, and internal university funded grants. In 2016, she was the recipient of the "40 under forty" honor, nominated based on outstanding research performance at the University of Iowa. In 2015 and 2016 she was the finalist for the Rising Star award and in 2017 a finalist for the Research Innovation and Leadership award given by the Technology Association of Iowa.

Arthur Onno received his PhD in electrical engineering from University College London, UK, in 2017. There, he studied direct hetero-epitaxy of III-V materials on silicon for III-V/Si tandem solar cells applications. He is now a postdoctoral research scholar at Arizona State University, in the team of Dr. Zachary Holman. His research focuses on the development of silicon-based tandem solar cell devices using wide bandgap III-V, II-VI, and perovskite top-cell absorbers. Arthur received the Best Student Award during the 33rd European Union PV Solar Energy Conference (EU PVSEC) held in Amsterdam, the Netherlands, in September 2017.

Karin Hinzer received her PhD in physics from University of Ottawa. Currently she is the Canada Research Chair in Photonic Nanostructures and Integrated Devices and associate professor at the School of Electrical Engineering and Computer Science at the University of Ottawa. She joined the University of Ottawa in 2007 where she founded the SUNLAB, the premier Canadian modeling and characterization laboratory for next-generation multijunction solar devices and concentrator systems. In 2015, she was the recipient of the Inaugural Canadian Energy Award and the Ontario Ministry of Research and Innovation Early Researcher Award for her contributions to the fields of photonic devices and photovoltaic systems. She is a member of the College of New Scholars, Artists and Scientists of the Royal Society of Canada, and the recipient of the University of Ottawa Young Researcher Award for 2016. She has published over 130 refereed papers, trained over 85 highly qualified personnel, and her laboratory has spun-off three Canadian companies in the energy sector.