Special Section Guest Editorial: Novel Photovoltaic Device Architectures

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As the Intergovernmental Panel on Climate Change (IPCC) reports (https://www.ipcc.ch/report/ar6/wg2/), limiting global temperature increase to 1.5 °C by the end of the 21st century requires a rapid and profound transformation of our energy generation landscape. Solar photovoltaics (PV) is a mature technology ready to contribute to this challenge. Throughout the last decade, a higher capacity of solar PV was installed globally than any other power-generation technology, and cumulative capacity at the end of 2019 accounted for more than 600 GW globally. This is an achievement to be celebrated by the PV industry and confirms the potential of this renewable power-generation technology. However, despite the maturity of the PV industry, innovations are still needed to increase the scale and sustainability of PV and to diversify the application of these systems in various scenarios—for example, electrification of transport, building-integrated PV, and high power and compact PV systems for resource-limited applications, such as CubeSATs and space power systems, and for lightweight mobile power applications, such as in camping and mobile fighter scenarios. These PV innovations will be led by exploration of new materials for PV absorbers, advanced—although not necessarily more complex—device architectures, and novel photon management systems that can effectively utilize high-efficiency concepts. This special section of the SPIE *Journal of Photonics for Energy* (JPE) on novel PV architectures (https://www.spiedigitallibrary.org/jpe-novel-photovoltaic-device-architectures) includes contributions from leading research groups studying next-generation solar cell designs and novel photon management approaches, which hold the promise for next-generation applications and breaking the Shockley–Queisser efficiency limit for solar cells.

The article by Ferry et al. (https://doi.org/10.1117/1.JPE.12.022204) discusses pathways towards efficient hot carrier solar cells (HCSCs) via band structure engineering and the potential of valley photovoltaics, in which carriers are transferred to higher-lying valleys of the conduction band to enable efficient and practical HCSCs. Specific emphasis in this work is on the realities of creating and sustaining a phonon bottleneck and inhibited thermalization losses in HCSC structures, and the need for light concentration in such architectures when considering the practical nonequilibrium phonon densities that can be excited under solar illumination, in addition to the challenges associated with hot carrier extraction in valley PV structures.

In the first of two contributions of Giteau and coworkers (https://doi.org/10.1117/1.JPE.12.032208) the resilience of hot-carrier multijunction solar cells (HCMJSCs) against nonidealities that might inhibit conventional HC protocols is discussed via two test systems, namely the multijunction solar cell (MJSC) and the conventionally proposed HCSC. Three deviations from the ideal case—nonoptimal design, internal limitations, and nonstandard operation conditions—are explored by these authors. The results indicate that the HCMJSC maintains a high efficiency even when materials with nonoptimal bandgaps are considered, broadening the range of candidate systems available for its implementation. This work also shows that the requirement for hot carrier thermalization is much less stringent in HCMJSCs than with the standard HCSC architecture, suggesting the HCMJSC can surpass the best MJSC efficiency with practical thermalization coefficients. Finally, this paper describes results on the influence of nonstandard illumination by varying the AM spectrum, and that estimate numerically the yearly averaged efficiency of devices installed in two different locations. This is often an under-appreciated aspect of PV, as the solar spectrum varies sufficiently across the globe to warrant different

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absorber materials and device geometries in different locations. Preliminary results on temperature dependence are also presented. Earlier this year, JPE Editor-in-Chief Sean Shaheen interviewed the co-authors about the intriguing findings of the study reported in this paper. The interview can be found here: https://doi.org/10.1117/1.JPE.12.032202.

The second contribution of Giteau et al. (https://doi.org/10.1117/1.JPE.12.022203) presents a theoretical framework to evaluate and optimize resonant light absorption in a thin slab with quantum structure. Using numerical simulations, this paper shows that the position of the layers can make the difference between strong absorption enhancement and completely suppressed absorption, and that an optimal position leads to a resonant absorption enhancement two times larger than average. These theoretical results are confirmed experimentally by measuring the absorption enhancement from photoluminescence (PL) spectra in InAs/GaAs quantum dot samples. The work reported in this contribution provides an additional degree of freedom to substantially improve absorption, encouraging the development of quantum wells and quantum dots-based devices such as intermediate-band solar cells.

Work from Piyathilaka et al. (https://doi.org/10.1117/1.JPE.12.032209) reports on seminal results for type-II multiple quantum well (MQW) superlattices based on InAs/AlAsSb for ground- and excited-state charge carrier transport and excited-state charge carrier dynamics. This work finds that ground-state transport matches well to impurity and optical phonon interactions, while the excited-state transport shows increased terahertz photoconductivity for the correct excitation conditions, which have previously been linked to a metastability in these systems in the early time response after photoexcitation. For increased excitation intensities, the increased contribution of Auger-scattering results in lower carrier mobilities and carrier reheating. The net result is stronger scattering of carriers energetically deeper into their respective bands, where they exhibit a much slower carrier recombination rate and—it is proposed—results in an increase in carrier temperature as a consequence of a phonon bottleneck, promoting longer-lived nonequlibrium phonons and hot carriers. The authors suggest that, in addition to a previously reported phonon bottleneck, these carrier dynamics offer potential pathways to stabilize hot carriers with further bandgap engineering.

Another work on III-V solar cells, contributed by Sarollahi et al. (https://doi.org/10.1117/1.JPE.12.022205), reports on the optical properties of Λ-graded indium gallium nitride (InGaN) solar cells. Graded InGaN well structures with the In composition increasing to $x_{\max}$ and then decreasing in an Λ-shaped pattern are designed so that, due to polarization doping, alternating p- and n-type regions are naturally created. The results show that a maximum efficiency of $\cong 5.5\%$ under fully strained condition occurs for $x_{\max} = 60\%$. Solar cell efficiency under relaxed conditions increases to a maximum of 8.3% for $x_{\max} = 90\%$. Vegard's law predicts the bandgap under relaxed conditions, whereas a Vegard-like law is empirically determined from the output of nextnano™ for varying In compositions to calculate the solar cell parameters under strain.

A third article on III-V solar cell architecture based on intermediate band solar cells (IBSCs) composed of highly mismatched alloys such as gallium nitride arsenide (GaNAs), by Ahsan et al. (https://doi.org/10.1117/1.JPE.12.032210), explores minimizing the deleterious S-shape current density–voltage (*J*–*V*) curve of this IBSC system. The team characterized GaNAs IBSC devices grown with and without barriers, with and without antimony (Sb), and with and without indium (In) using molecular beam epitaxy (MBE), and also with the photocarrier collection analysis using equivalent circuit models. The characterization studies identified that the two-step below-bandgap photon absorption (TSPA) and the resulting S-shape *J*–*V* of this system depend on two critical factors: (i) high carrier recombination currents across the GaNAs sub-gap between the conduction- and intermediate bands, and (ii) the counterdiode effect of the AlGaAs IB electron barrier. The team demonstrated dramatic improvements in the S-shape *J*–*V* feature of the IBSC when lattice-strain was compensated for in GaInNAsSb epitaxial layers.

In one of the articles in the special section that relates to the contemporary perovskite fever, Shamna and Sudheer (https://doi.org/10.1117/1.JPE.12.032211) present simulated analysis of an all-inorganic double perovskite, lead-free absorber-based perovskite solar cell (PSC) based on cesium platinum iodide (Cs_2PtI_6) absorber. The team conducts the simulations utilizing solar cell capacitance simulator (SCAPS 1D) software. The simulation result is validated by comparing with experimentally reported Cs2PtI6 based PSC. The team determined PSC performance with six different electron transport layers (ETLs), ten hole transport layers (HTLs), and nine metal contacts, investigated by simulation. Among all the tried configurations FTO/ZnO/Cs2PtI6/ molybedenum oxide (MoO_3)/carbon(C) yielded the highest power conversion efficiency (PCE) of an encouraging 20.45%.

Two articles in this special section describe the role of novel photon management in solar cells. The first is an article by Chrysler et al. (https://doi.org/10.1117/1.JPE.12.022206) which examines the potential of a multijunction spectrum-splitting PV solar energy system incorporating perovskite PV cells with energy bandgaps of 2.30, 1.63, and 1.25 eV, and with conversion efficiencies of 10.4%, 21.6%, and 20.4%, respectively. Initial designs include a cascaded volume holographic lens for spectral separation into three spectral bands that are absorbed in the constituent solar cells. In the second system, a rigorous coupled wave model is developed for computing the diffraction efficiency of a cascaded hologram. This model accounts for cross-coupling between higher diffraction orders in the upper and lower holograms, which has not been considered in previous works but is included here with the experimental verification. Finally, Chrysler et al. describe the optical losses in the systems proposed, which are analyzed and the potential to achieve a high power conversion efficiency of 26.7% is presented.

The second article on photon management for solar cells, contributed by Sergeev and Sablon (https://doi.org/10.1117/1.JPE.12.032207), demonstrates that a nonreciprocal converter with an ideal multijunction cell can approach the Carnot efficiency, whereas operating exactly at the Carnot limit requires an infinite number of photon recycling processes. This requirement resolves the famous thermodynamic paradox of the optical diode, because any small dissipation in the cell or optical system enhanced by infinite recycling will stabilize the converter operation below the Carnot limit. The performance of this converter with available GaAs solar cells is evaluated.

A final article, by Abdellatif et al. (https://doi.org/10.1117/1.JPE.12.022202), reports upon utilization of machine learning on postprocessed scanning electron microscope (SEM) images of titanium dioxide (TiO_2) in bifacial dye-sensitized solar cells (DSSCs) to optimize TiO_2 fabrication and deposition techniques, and hence enhance the solar cell performance. Postprocess imaging of SEM measurements was utilized to estimate the film porosity, and the refractive index was calculated from the T–λ spectra. Four sets of samples with complete bifacial DSSCs were fabricated and characterized. The fabricated cells showed an overall conversion efficiency of 7.9% with a maximum current of 23.42 mA under optical injection of the AM1.5G spectrum from the front side and LED indoor lighting from the counter electrode.

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