11. Full solar spectrum conversion via multi-junction architectures and optical concentration

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Status

Significant advances have been made in research to improve the performance of single-junction PV devices. Currently, the best Si and GaAs devices have achieved efficiencies of 25.6% and 28.8%, respectively [26] (see sections 2, 4). The realization of significant further enhancements in the efficiencies of PV energy conversion, however, resorts to MJ architectures using semiconductor materials with subcell band gaps tuned to target different portions of the solar spectrum in order to minimize carrier thermalization losses and to increase spectrum coverage to exceed the SQ limit [24]. In theory, a MJ cell can achieve an efficiency as high as 86.8% with an infinite number of junctions [107] (a value lower than the Landsberg limit [21] due to entropy losses), and a number of different cell designs have been intensively explored by the PV research community as a means through which such forms of performance enhancement can be realized. These include, most notably, devices that embed the semiconductor elements in the form of MJ SC stacks [108] and, to a lesser degree, optical approaches involving various forms of spectrum splitting [109] (see also section 13). In the first design, the subcells are either epitaxially or mechanically stacked together in the order of decreasing band gaps to divide the incident sunlight using the absorption of the subcells (see also section 3). In the second approach, separate optics (e.g., prisms, holograms, and dielectric bandpass filters) are used to split the solar spectrum and to direct different portions to the relevant subcell. It has been persuasively argued that both designs would benefit from high geometric concentration of the solar irradiance as one means to both offset the high material costs encumbered by the III–V semiconductor device elements and to enhance the system power-conversion efficiency. To date, cell stacking designs have achieved the highest benchmark performances in solar energy conversion with world-record efficiencies of MJ cells reaching 46.0% with a four-junction design (InGap/GaAs/GaInAsP/GaInAs) under 508 suns [26]. Exemplary recent progress includes a report from our group of 43.9% efficient quadruple-junction four-terminal microscale SCs that were fabricated by mechanical stacking of a top 3-J device onto a bottom Ge cell via transfer-printing-based assembly [110].

Current and future challenges

For epitaxially grown MJ devices, the difficulty of sustaining lattice matching through multiple layers of growth limits the material selections that are available for use in each subcell and, thus, directly restricts achievable limits for device performance. Mechanically stacked devices, on the other hand, can be fabricated via high-temperature wafer bonding [111] to circumvent this issue but still carries a requirement for current matching at the electrically conducting interfaces, which is difficult to realize as the number of subcells increases to subdivide the solar spectrum. Alternatively, insulating adhesives can be used between mechanically stacked subcells to enable multiterminal connections and, in this way, to avoid the need for current matching. These interfaces need to be carefully designed to minimize reflection losses as well as to manage heat flow and thermal-mechanical stresses at high optical concentration [110]. Additional electro-optical challenges exist for the material used in each subcell. For example, a top wide-band-gap subcell (i.e., $E_g > 1.4\,\mathrm{ev}$) generally cannot be doped to a sufficiently high level to enable efficient carrier collection under high-irradiance concentration; it requires incorporation of highly doped low-band-gap materials that either degrade its optical transparency for low-energy photons or complicate backcontact grid configurations [108].

It has been noted that the limitations associated with stacked MJ devices can be tackled, in principle, by employing external optical components to split and to distribute the solar radiation to an array of spatially separated subcells [112]. By decoupling material compatibility from band-gap optimization, this approach also enables MJ designs with larger numbers of subcells and, thus, higher theoretical efficiencies. As the cell fabrication steps are reduced to provide a set of single-junction devices, simplified process flows for the semiconductor components are possible (see sections 2, 7). The commonly proposed optical designs include holographic gratings and wavelength-selective mirrors (e.g., multilayer dielectric Bragg stacks). Their practical use, however, is hindered by the formidable requirements for high-optical quality as well as the complexity of the optical designs needed to achieve competitive system-level efficiencies.

The high cost of III–V materials, especially in MJ cell contexts, likely necessitates a high-optical-concentration design to achieve commercial viability (see section 12). Optical losses figure importantly in all forms of concentrator PV designs. Stacked cells, for example, are subject to significant Fresnel losses (e.g., 12% of incident photons are lost to reflection before reaching the SCs for a system with three glass/air interfaces) that limit their optical (and, thus, power-conversion) efficiencies. Broadband antireflection (AR) coatings would afford an ideal solution, but materials that can span the refractive index range needed to mitigate these effects have yet to be developed. The use of common light-trapping designs on the PV cells also become more complex as they can scatter light and, otherwise, limit the broad-spectrum performance of high-concentration optics (see section 3). Geometric solar concentrators (GSCs) also require

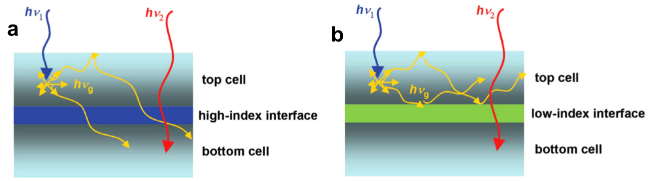

Figure 18. Illustrations demonstrating photon dynamics in a MJ device (reproduced from [116]). (*a*) No photon recycling: the radiative emission from the top cell is coupled to the bottom cell. (*b*) With photon recycling: using a low index interface as an intermediate reflector, the ERE and V_{OC} of the top cell are enhanced.

solar tracking and, even more significantly, do not utilize diffuse light—a significant component of the solar spectrum. (The diffuse component is 10% in AM1.5G illumination; most locations in the United States having 24% to 50% diffuse sunlight [113].)

Advances in science and technology to meet challenges

Light management within and between subcells

It has been shown in single-junction devices that high external radiation efficiencies (EREs), as achieved by luminescence extraction enhanced by photon recycling, are crucial for high PV performance (as demonstrated by the world-record GaAs device where the radiatively emitted photons are reflected by a metal backsurface rather than absorbed by the substrate) [28, 114] (see section 4). Likewise, MJ devices with intermediate reflectors that enhance ERE with photon recycling would improve the V_{OC} for each subcell (figure 18), although these reflectors also need to transmit sub-band-gap photons for the next cell. Different designs have been examined theoretically that provide such effects, such as stacks spaced by an air gap coupled with AR coatings as the intermediate reflector in-between subcells [115]. The elements of this design have been demonstrated experimentally using microscale SCs stacked onto prepatterned air gap spacers using a soft-transfer-printing technique [116]. The opportunities for progress have also been demonstrated theoretically in the design of a high-performance spectrum-splitting PV system that uses polyhedral specular reflectors coupled to spatially separated devices to enhance both photon recycling within a subcell and radiative coupling between them [117].

Improving the optical efficiencies of GSCs

There exist numerous opportunities to improve the performance of concentrator PV systems. Providing improved broadband AR coatings (e.g., porous films with sub-wavelength features to avoid scattering) forms one obvious direction in research to reduce the Fresnel losses associated with concentrating optics. The development of strategies that would allow the utilization of diffuse light within a concentrator PV design is also of significant interest. We might envision, for example, the coupling of a GSC with a luminescent solar concentrator (LSC), wherein, diffuse radiation striking the backplane can be absorbed by the luminophore and can be down-converted into total internal reflection modes that are directed to the embedded PV device elements. A possible geometry for such a system suggested by elements of our past work is one of embedding arrays of microscale SCs directly in the LSC waveguide (figure 19) such that, in addition to diffuse light conversion, the direct illumination from the Sun can be concentrated at the top surface of the devices using a GSC with a higher concentration ratio and optical efficiency [118, 119]. We have shown that QD luminophores (see also sections 5, 6) are particularly advantageous for use in such microcell LSC arrays as compared to traditional organic dyes as they have high quantum yields, large (and tunable) Stokes shifts for reduced reabsorption losses, and better long-term photostability. Their narrow emission peaks also facilitate photonic designs to better trap/manage the luminescent photons to improve optical efficiency [119, 120]. It is also of particular interest to note that high-optical efficiency LSCs may engender specific capabilities for high-performance concentrator PV designs that would be transformational, specifically to obviate the need for solar tracking as well as the intriguing possibility that they might enable new approaches to spectrum splitting using discrete subcell arrays that can achieve efficiencies approaching those associated with monolithic MJ cell stacks.

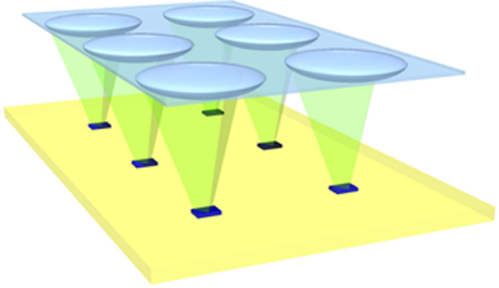

Figure 19. Schematic of a hybrid concentration system with an embedded microscale SC module, both the device and the luminescent waveguide can be configured as a MJ architecture for full spectrum conversion.

Concluding remarks

MJ architectures are required to achieve full spectrum conversion and to surpass the SQ limit. Concentration is advantageous in a MJ system in both improving their efficiency and reducing their cost. This perspective outlines new materials, optical integration strategies, and approaches to spectrum splitting that beget new opportunities through which the grand challenge of full-spectrum conversion might be realized.

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