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Searching for optimal solar-cell architectures

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Quasi-1D systems represent the most desirable design for optoelectronic applications where carrier conductivity is required.

In recent years a variety of nanostructure-based concepts have been proposed for solar-energy applications. The most frequently cited rationales for going to nanoscales include the ability to tune electronic structures via quantum confinement and the low synthesis cost. However, these considerations are not unique to nanomaterials. In fact, a large number of yet-to-be-explored bulk semiconductor materials and their alloys could potentially satisfy the basic material (including band-gap) requirements. They could be made as low-cost thin films. Therefore, two additional requirements are at least equally—if not more—important: having intrinsic advantages over existing materials or architectures, which might need a long-term effort to realize the benefits, and relaxing the stringent criterion for material quality in traditional device architectures, yet offering reasonable efficiency (at least comparable to modern thin-film solar cells). In the mean time, we should remain open minded as to wherever the effort might take us in terms of new science and cross-cutting benefits (such as the possible development of edge-cutting fronts).

For an individual solar cell, two major efficiency-loss mechanisms operate, including thermalization and recombination. Thermalization losses can be reduced either through a multi-junction approach or by carrier multiplication (for instance, multiple-exciton generation). Recombination losses can be reduced by modifying the device architecture from the conventional planar electron–hole (p–n)-junction structure. The interdigitated back-contact silicon solar cell developed by SunPower is a successful nonplanar-design example. It consists of an array of quasilateral p–n junctions fabricated to improve carrier collection. Quasi-1D systems take this idea one step further while simultaneously exploring quantum effects and new functionalities in reduced dimensionality and novel structural geometries as well as tailoring material properties to specific applications.

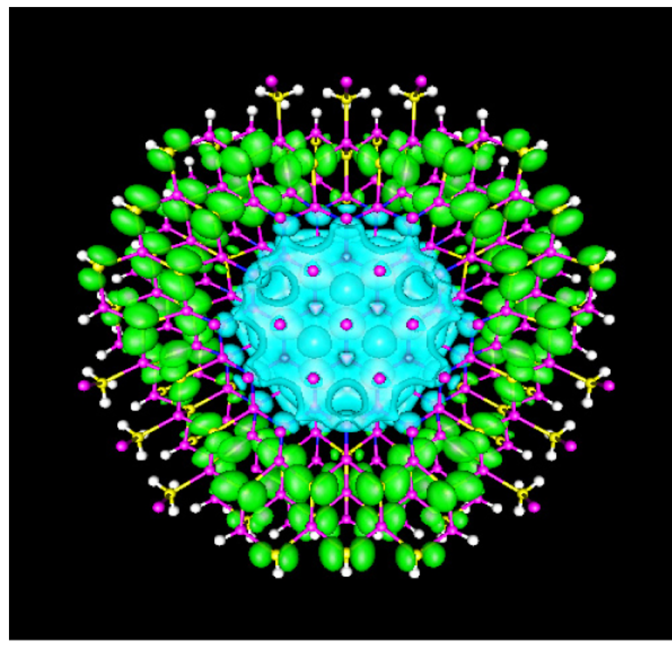

Figure 1. Cross-section of the electron (cyan) and hole (green) charge distributions in a gallium nitride/gallium phosphide core–shell nanowire.

Typical planar devices have a number of intrinsic shortcomings. They require a long carrier-diffusion length, unnecessary lateral carrier diffusion (both implying stringent material-quality requirements), and inevitable intrinsic radiative and nonradiative (Auger) recombination. It is well established that—for a semiconductor material characterized by a given density of nonradiative centers—restricting the carrier motion sequentially to increasingly lower dimensionality renders the nonradiative centers less and less effective.[1] However, for applications where carrier conductivity is required, quasi-1D is the optimized dimensionality. This can rival many living or naturally occurring systems where energy transfer to a receptor is channeled through a fiber or tube.

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Solar cells employing arrays of nanowires as their active layer for light absorption and carrier transport are nanoextensions and optimizations of conventional planar devices with contact grid lines or back-contact cells. A practical advantage of nanowire solar cells with lateral junctions is that electron–hole separation can occur on very short spatial scales, and thus nonradiative recombination can be suppressed more effectively than in the planar architecture or any of its variations. Equivalently, the new architecture may relax the stringent requirements for material quality, which may lead to a reduction in material cost.

There are two primary ways to achieve lateral charge separation in a nanowire solar cell, a core–shell p–n junction,[2] and a type-II core–shell structure (which functions like a p–n junction but without the need for doping).[3] Both types of junction function on mesoscopic (submicron) scales, but only the type-II core–shell structure remains functional in the quantum region.[4] A fundamental advantage of the latter, on true nanoscales, is that it can effectively reduce intrinsic recombination losses, both radiative and nonradiative.[3] In addition, nanowire arrays may also provide the functionality of light trapping. They can therefore simultaneously perform four key functions: light harvesting, energy conversion, charge separation, and charge transport. With modifications, quasi-1D systems—and the core–shell structure in particular—could be useful for other solar-energy applications such as hydrogen generation via photoelectrochemical water splitting and thermoelectrics.[3]

The type-II approach has been adopted in a number of nanophotovoltaic devices, including dye-sensitized and quantum-dot solar cells. It uses a quasi-electric field near the interface of the heterostructure (instead of a real electric field in a p–n junction) to generate the charge separation. Figure 1 shows the electron and hole charge distributions for 2.4nm gallium nitride/gallium phosphide core–shell nanowires, exhibiting the expected charge-separation effect and a band gap of 1.22eV. A II-VI version of such a nanowire array, zinc oxide/zinc selenide, has been synthesized. It has the expected basic properties, although it has not yet been developed into a functional solar cell.[5] However, a coaxial p–n-junction silicon-nanowire solar cell has recently been demonstrated.[6]

In conclusion, quasi-1D is logically the optimized dimensionality for optoelectronic applications where carrier conductivity is required. In addition, a coaxial nanowire-type structure with a lateral junction for charge separation seems very appropriate for solar-cell and photodetector applications. Our current effort focuses on demonstrating a proof-of-concept solar cell based on an array of type-II core–shell nanowires. In the future we will explore other material combinations with more appropriate material properties (such as band gaps and lattice constants) and search for optimized structural designs for device performance and light harvesting.

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