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Solar Energy Technologies Program

National Solar Technology Roadmap:

Nano-Architecture PV

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National Solar Technology Roadmap: Nano-Architecture PV

Scope
This roadmap addresses nano-architecture solar cells that use nanowires, nanotubes, and nanocrystals, including single-component, core-shell, embedded nanowires or nanocrystals either as absorbers or transporters.

Technology development stage: Concept and/or Proof-of-principle devices. These technologies are mostly in the stage of concept proposal or proof-of-principle device demonstration, although few have reached the stage of offering decent efficiency (although still not comparable to the more mature technologies, e.g., Si, CdTe, and CIGS).

Target applications: All. The potential target areas depend on the feasibility of incorporating the new concepts into existing technologies. Nanostructures could be grown using more-expansive, but more-controllable techniques, such as molecular-beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD); so they could be incorporated into existing concentrator photovoltaic (CPV) technologies. Alternatively, they could be synthesized by low-cost chemical methods that are more compatible with existing thin-film technologies. They could also be useful for sensitized or inorganic-organic hybrid solar cells.

Background
Quantum confinement allows more flexibility in electronic structure engineering than the conventional route of alloying bulk materials; but it also results in blocking the carrier transport in the confined dimension(s). Quantum dots could maximize the tunability, but suffer from the shortcoming of being fully confined structures that prevent the carrier transport critically needed for solar cells. A number of approaches have been suggested to restore the carrier transport: (1) forming a quantum-dot lattice that facilitates partial transport (similar to that in a molecular crystal), (2) using quasi-one-dimensional systems (nanowires or nanotubes) as the carrier transporter to extract the photogenerated carriers otherwise trapped in the nanocrystal, (3) using the nanowire or nanotube as absorber, as well as transporter. It is relatively straightforward using any of these approach to achieve the most basic goal—tuning the bandgap—but less trivial to also obtain a few other desirable properties specifically for the solar cell. Thus, major effort is required to develop conceptually sound and practical material systems from any of these general approaches.

Roadmap Overview
In the limit of detailed balance with no nonradiative recombination, the solar cell efficiency is determined solely by the bandgap, as long as the absorption is non-zero. However, in reality, both radiative and nonradiative recombinations affect the performance. Besides the correct bandgap and good carrier conductivity, strong absorption and weak recombination are highly desirable—but they are two conflicting requirements. An intuitive solution would be to find a material with two nearby energy bands (separated by a few kT), with the upper one having strong absorption and the lower

one being optically inactive. It is indeed possible to find a bulk material with such features. However, in a bulk material, the electrons and holes may still recombine nonradiatively, because they typically move around in the same region. A properly designed nanomaterial should be able to spatially separate the electron and hole, and thus, maximally suppress the recombination loss. A complete separation might not be possible, but neither is it necessary practically. The charge separation can be realized, for instance, by using heterostructures with type II energy alignments, engineering the surface states of the nanowire, or by spatially modulated *n*- and *p*-type doping. The desirable electronic structure is illustrated in Fig. 1. Examples in the literature with the major features shown in Fig.1 may include semiconductor nanocrystals or nanowires embedded in polymers, semiconductor nanowires embedded in or forming a core-shell structure with another semiconductor with type II energy alignments, and single-component nanowires with a radial *p-n* junction.

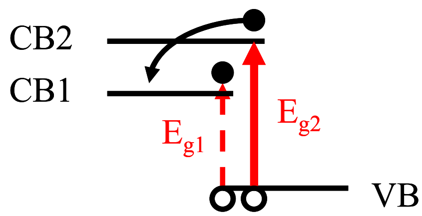

Figure 1. Energy band diagram schematically showing an example of the expected relationship between the absorption and fundamental bandgap, with weak absorption at E_{g1} because of the physical separation between the electron and hole and stronger absorption at E_{g2} with an increased overlapping between the electron and hole. The lateral displacement of the energy levels indicates the spatial separation of the electron and hole.

So far, no nanostructure solar cell has been demonstrated with efficiency above 5%, which, to a large extent, is because the material parameters are not at all optimized according to the guidelines mentioned above. In fact, even for those concepts already with proof-of-principle devices, the electronic structures are usually not clearly known. Therefore, to allow nano-architecture solar cells to reach a reasonable and promising goal—a 15% laboratory efficiency by 2015—major advancement is required in the following key areas: (1) Identify the material systems that could, in principle, offer the desirable material properties; (2) Demonstrate the proof-of-principle solar cell for the system identified in the first step; (3) Optimize the material and device structure so that the realistic potential for each approach could be assessed; (4) Determine the most-promising nanostructures and reach the target efficiency goal; and (5) Determine the feasibility to be incorporated with which mature solar technologies, and thus, the target applications.

Metrics

Parameter	Present Status (2007)	Future Goal (2015)
Concept; Proof-of-principle device	Either with only concept proposals or proof-of-principle devices	By 2010, the material systems that could, in principle, offer the desirable material properties should be identified; the proof-of-principle solar cells should be demonstrated.

Materials; Device structures; Efficiency	Materials might not have the desirable properties; Device structures are not optimized; Efficiency < 3%	By 2015, the most-promising device structures and materials should be identified; the target efficiency of 15% should be achieved in the laboratory; the compatibility with thin-film and/or CPV technologies should be assessed.

Identified Needs

			Nat'l Lab			Industry		
Need	Significance	University	NREL	Sandia	Other	TPP	Incubator	Other
Propose the material systems and device structures that could, in principle, offer the desirable material properties (creative ideas, theoretical modeling, and material synthesis).	Identify the prototype systems for further exploration.	X	X	X	X			
Investigate the mechanisms of carrier generation, relaxation, and transport in a few prototype systems.	Understand how these phenomena in the nanoscale differ from in the macroscale, which is critically important for the device design.	X	X	X	X			
Determine the materials, geometries, and growth methods that can result in promising nanostructures, and demonstrate the proof-of principle solar cells.	Important step to downsize the number of possible material systems and device structures, vital to avoid wasting resources.	X	X	X	X			
Optimize the material and device structure so that the realistic potential for each selected nanostructure in the previous step could be further assessed.	Isolate a few practically feasible materials systems and device structures.	X	X	X	X			
Determine the most-promising approaches and reach the target efficiency goal.	Indicator for the real potential of the winners.	X	X	X	X			

Determine the feasibility of being incorporated with which mature solar technologies, and thus, the target applications.	Essential to further development and commercialization	x	x	x	x		x	