Study predicts nanoscience will greatly increase efficiency of next-generation solar cells

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As the fastest growing energy technology in the world, solar energy continues to account for more and more of the world's energy supply. Currently, most commercial photovoltaic power comes from bulk semiconductor materials. But in the past few years, scientists have been investigating how semiconductor nanostructures can increase the efficiency of solar cells and the newer field of solar fuels.

Although there has been some controversy about just how much nanoscience can improve solar cells, a recent overview of this research by Arthur Nozik, a researcher at the National Renewable Energy Laboratory (NREL) and professor at the University of Colorado, shows that semiconductor nanostructures have significant potential for converting solar energy into electricity.

In his overview, which is published in a recent issue of Nano Letters, Nozik has summarized the current status of several approaches to improving photovoltaics with nanoscience. As he explains, the advantages of semiconductor nanostructures arise from the quantum confinement of negative electrons and positive holes into very small regions of space in the nanocrystals. Quantum confinement can occur in one, two or three dimensions; in three dimensions, the semiconductors are called quantum dots. In any regime, the quantum confinement produces quantization effects, resulting in unique optical and electronic properties.

"There are two main theoretical advantages of incorporating quantum dots into solar cells and photovoltaics: higher efficiency and lower cost," Nozik told PhysOrg.com. "There is a theoretical possibility based on thermodynamic calculations of increasing the efficiency of present day solar cells by a very significant amount of 50-100%. In addition, quantum dots could lower the capital cost of solar cell production in terms of cost per unit area. The combination of lower cost per unit area and higher conversion efficiency would lower the cost of photovoltaic power expressed as cost per peak watt. Present silicon cells are expensive (about three times the cost of conventional electricity), but quantum dots are based on less expensive low-temperature solution chemistry methods, plus they could produce higher conversion efficiencies. However, there is still a lot of work to be done before quantum dots are commercially available."

The basic principle of photovoltaic solar cells is to absorb photons from incident solar radiation with energies above the semiconductor band gap, and use the photons to create free electrons and holes (called charge carriers). In order to increase the efficiency of the system, it is important to form as many charge carriers as possible from the absorbed photons. This is where the quantum confinement effects become very useful, as the effects couple photogenerated electrons and holes into bound electron-hole pairs called excitons, and encourage the efficient formation of more than one exciton from a single absorbed photon. In quantum dots. the process is called multiple exciton generation (MEG). Among its advantages, MEG is more efficient and can occur with lower-energy photons in the visible region of the solar spectrum compared to a multiplication process of charge carriers in bulk semiconductors (a process called impact ionization, which is generally restricted to the ultraviolet region where solar photons are absent or scarce).

To generate multiple excitons, the MEG process must compete with the rapid cooling of initial photogenerated high-energy excitons (called "hot

excitons"). The hot excitons are created by the absorption of energetic blue or near-ultraviolet photons. In bulk semiconductors at room temperature and above, the photogenerated electrons and holes are uncoupled and exist as free charge carriers (called "hot carriers"). The excess energy of hot excitons or hot carriers can quickly lose their excess kinetic energy through electron-phonon interactions and convert it into heat, which accounts for significant loss of conversion efficiency. However, Nozik notes that, despite some controversy, recent studies have shown that the rate of MEG can be much faster than the hot exciton cooling rate, resulting in an overall higher efficiency of electron-hole pair multiplication. But despite early initial reports of quantum yields of 200% in quantum dot photoelectrochemical solar cells, no quantum dot-based photovoltaic device to date has shown an actual enhanced power conversion efficiency due to MEG.

"Generally, the goal is to produce systems that have efficiencies close to the theoretical limit," Nozik said. "The theoretical efficiency is about 45%, while the lab efficiency of present quantum dot solar cells is about 3-5%. That's a big gap; we need to understand what limits the efficiency in these new approaches."

Despite the controversy about MEG, Nozik concludes that the possibilities for quantum dot solar cells and other nanostructures that use quantum confinement look promising, although much more work still needs to be done. One issue that may help MEG to reach its full potential is to ensure that the additional excitons are being quickly collected, since they decay within about 20-100 picoseconds after formation. Most importantly, Nozik emphasizes that researchers should strive toward reaching the maximum theoretical efficiency of solar cells.

"There's a certain degree of controversy about these third generation approaches because they're new and not completely understood," Nozik said. "In the past, some results could not be reproduced in different labs.

But now more and more people in recent years are reproducing positive results. Los Alamos and NREL are measuring these effects in a new U.S. DOE Energy Frontier Research Center with different techniques, and getting the same answer. So it is a real effect, a positive effect. However, some people are still skeptical and think that we're never going to reach those values [of theoretical efficiency]. But there is no fundamental reason why we can't reach those values. It just takes more research, more effort, and more understanding."

More information: Arthur J. Nozik. "Nanoscience and Nanostructures for Photovoltaics and Solar Fuels." *Nano Letters* ASAP. DOI: 10.1021/nl102122x

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