



**QUANTUM DOTS
AND
ULTRA-EFFICIENT SOLAR CELLS**

2008

“for the Layman”

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LIMITS ON TRADITIONAL PHOTOVOLTAIC EFFICIENCY

- The efficiency of solar cells is the electrical power it puts out as percentage of the power in incident sunlight. One of the most fundamental limitations on the efficiency of a solar cell is the 'band gap' of the semi-conducting material used in conventional solar cells: the energy required to boost an electron from the bound *valence band into the mobile conduction band*. When an electron is knocked loose from the valence band, it goes into the conduction band as a negative charge, leaving behind a 'hole' of positive charge. Both electron and hole can migrate through the *semi-conducting material*.

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- In a solar cell, negatively doped (n-type) material with extra electrons in its otherwise empty conduction band forms a junction with positively doped (p-type) material, with extra holes in the band otherwise filled with valence electrons. When a photon with energy matching the band gap strikes the semiconductor, it is absorbed by an electron, which jumps to the conduction band, leaving a hole.

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- Both electron and hole migrate in the junction's electric field, but in opposite directions. If the solar cell is connected to an external circuit, an electric current is generated. If the circuit is open, then an electrical potential or voltage is built up across the electrodes.

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- Photons with less energy than the band gap slip right through without being absorbed, while photons with energy higher than the band gap are absorbed, but their excess energy is wasted, and dissipated as heat. The maximum efficiency that a solar cell made from a single material can theoretically achieve is about 30 percent. In practice, the best achievable is about 25 percent.

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- It is possible to improve on the efficiency by stacking materials with different band gaps together in multi-junction cells. Stacking dozens of different layers together can increase efficiency theoretically to greater than 70 percent. But this results in technical problems such as strain damages to the crystal layers. The most efficient multi-junction solar cell is one that has three layers: gallium indium phosphide/gallium arsenide/germanium (GaInP/GaAs/Ge) made by the National Center for Photovoltaics in the US, which achieved an efficiency of 34 percent in 2001

QUANTUM DOT POSSIBILITIES

- Recently, entirely new possibilities for improving the efficiency of photovoltaics based on quantum dot technology have opened up.
 - Quantum dots or nanoparticles are semi-conducting crystals of nanometre (a billionth of a metre) dimensions. They have quantum optical properties that are absent in the bulk material due to the confinement of electron-hole pairs (called excitons) on the particle, in a region of a few nanometres.

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- The first advantage of quantum dots is their tunable bandgap. It means that the wavelength at which they will absorb or emit radiation can be adjusted at will: the larger the size, the longer the wavelength of light absorbed and emitted. The greater the bandgap of a solar cell semiconductor, the more energetic the photons absorbed, and the greater the output voltage.

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- On the other hand, a lower bandgap results in the capture of more photons including those in the red end of the solar spectrum, resulting in a higher output of current but at a lower output voltage. Thus, there is an optimum bandgap that corresponds to the highest possible solar-electric energy conversion, and this can also be achieved by using a mixture of quantum dots of different sizes for harvesting the maximum proportion of the incident light.

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- Another advantage of quantum dots is that in contrast to traditional semiconductor materials that are crystalline or rigid, quantum dots can be molded into a variety of different form, in sheets or three-dimensional arrays. They can easily be combined with organic polymers, dyes, or made into porous films In the colloidal form suspended in solution, they can be processed to create junctions on inexpensive substrates such as plastics, glass or metal sheets.

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- When quantum dots are formed into an ordered three-dimensional array, there will be strong electronic coupling between them so that excitons will have a longer life, facilitating the collection and transport of 'hot carriers' to generate electricity at high voltage. In addition, such an array makes it possible to generate multiple excitons from the absorption of a single photon (see later).

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- Quantum dots are offering the possibilities for improving the efficiency of solar cells in at least two respects, by extending the band gap of solar cells for harvesting more of the light in the solar spectrum, and by generating more charges from a single photon.

EXTENDING THE SOLAR CELL BAND GAP INTO INFRARED

- Infrared photovoltaic cells – which transform infrared light into electricity - are attracting much attention, as nearly half of the approximately 1000Wm^3 of the intensity of sunlight is within the invisible infrared region. So it is possible to use the visible half for direct lighting while harvesting the invisible for generating electricity [3].

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- Photovoltaic cells that respond to infrared – ‘thermovoltaics’ - can even capture radiation from a fuel-fire emitter; and co-generation of electricity and heat are said to be quiet, reliable, clean and efficient. A 1 cm² silicon cell in direct sunlight will generate about 0.01W, but an efficient infrared photovoltaic cell of equal size can produce theoretically 1W in a fuel-fired system.

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- One development that has made infrared photovoltaics attractive is the availability of light-sensitive conjugated polymers - polymers with alternating single and double carbon-carbon (sometimes carbon-nitrogen) bonds. It was discovered in the 1970s that chemical doping of conjugated polymers increased electronic conductivity several orders of magnitude. Since then, electronically conducting materials based on conjugated polymers have found many applications including sensors, light-emitting diodes, and solar cells [4].

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- Conjugated polymers provide ease of processing, low cost, physical flexibility and large area coverage. They now work reasonably well within the visible spectrum.

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- In order to make conjugated polymers work in the infrared range, researchers at the University of Toronto wrapped the polymers around lead sulphide quantum dots tuned (by size) to respond to infrared [5]. The polymer poly(2-methoxy-5-(2'-ethylhexyloxy-*p*-phenylenevinylene)] (MEH-PPV) *on its own absorbs between ~400 and ~600 nm. Quantum dots of lead sulphide (PbS) have absorption peaks that can be tuned from ~800 to ~2000 nm. Wrapping MEH-PPV around the quantum dots shifted the polymer's absorption into the infrared.*

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- The researchers demonstrated a convincing, albeit very small photovoltaic effect, giving a power-conversion efficiency of 0.001 percent. Professor Ted Sargent, the lead scientist, is optimistic however, emphasizing that their device is simply a prototype of how to capture infrared energy [6], and predicts commercial implementation within 3-5 years.

MULTIPLE EXCITONS FROM ONE PHOTON

- Researchers led by Arthur Nozik at the National Renewable Energy Laboratory Golden, Colorado in the United States really grabbed the headline when they demonstrated that the absorption of a single photon by their quantum dots yielded - not one exciton as usually the case - but three of them.

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- The formation of multiple excitons per absorbed photon happens when the energy of the photon absorbed is far greater than the semiconductor band gap. This phenomenon does not readily occur in bulk semiconductors where the excess energy simply dissipates away as heat before it can cause other electron-hole pairs to form

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- In semi-conducting quantum dots, the rate of energy dissipation is significantly reduced, and the charge carriers are confined within a minute volume, thereby increasing their interactions and enhancing the probability for multiple excitons to form.

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- The researchers report a quantum yield of 300 percent for 2.9nm diameter PbSe (lead selenide) quantum dots when the energy of the photon absorbed is four times that of the band gap. But multiple excitons start to form as soon as the photon energy reaches twice the band gap. Quantum dots made of lead sulphide (PbS) also showed the same phenomenon.

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- The findings are further confirmation of Nozik's theoretical prediction in 2000 that quantum dots could increase the efficiency of solar cells through multiple exciton generation. In 2004, researchers Richard Shaller and Victor Klimov at Los Alamos National Laboratory New Mexico were the first to demonstrate this phenomenon experimentally using quantum dots.

CONCLUSION

We have shown that solar cells based on quantum dots could convert more than 65 percent of the sun's energy into electricity, approximately doubling the efficiency of solar cells", said Nozik.