Scientists design solar cells that exceed the conventional light-trapping limit

January 20 2012, by Lisa Zyga

Scientists have found that the key to overcoming a light-trapping limit lies in increasing the density of optical states in the absorbing material. The finding could lead to the design of highly efficient solar cells that are also very thin, and therefore inexpensive. Image credit: National Renewable Energy Lab

(PhysOrg.com) -- The best performing solar cells are those that are thick enough to absorb light from the entire solar spectrum, while the cheapest solar cells are thin ones, since they require less, and potentially cheaper, material. In an attempt to combine the best of both worlds, a team of scientists has outlined designs for solar cells that can absorb light from the entire solar spectrum yet are as little as 10 nanometers thick. The new design approach, which could lead to improved low-cost solar cells, requires overcoming a thermodynamic light-trapping limit proposed in the 1980s.

The scientists, Dennis Callahan, Jeremy Munday, and Harry Atwater, of the California Institute of Technology in Pasadena, California, have reported the new method of light trapping beyond the conventional limit in a study published in a recent issue of Nano Letters.

Their work addresses a 1982 study that proposed a thermodynamic limit on how much of the optical wavelength range can be absorbed by homogeneous bulk semiconductor slabs. The limit requires these materials to have a minimum thickness in order to absorb light from the full solar spectrum. As a result, today's semiconductor solar cells are generally designed with thick absorbing layers in order to trap as much sunlight as possible, which can be expensive and complicated to fabricate.

Previous analyses of this light-trapping limit (which is sometimes called the ray optic limit or ergodic light-trapping limit) have shown that some solar cells actually do exceed the limit by taking advantage of wave interactions. Although researchers have theoretically explained how this happens in select cases, there is no general explanation that can be extended to the wide variety of proposed light-trapping schemes that may also be capable of exceeding the limit.

Here, the Caltech scientists have proposed that the key to overcoming the light-trapping limit lies in increasing the density of a semiconductor's optical states. Because each of these states can accept light of a certain wavelength, having more of them can increase the amount of light a material can absorb.

“It is now clear how to think about and design solar cells that can potentially exceed this previous light-trapping limit,” Callahan told *PhysOrg.com*. “All you have to do is think of a way to increase the density of optical states, and then populate these states. There are lots of tools and methods that have been designed for increasing the density of optical states for other areas of research, for example optical communication and quantum optics. But now solar cell researchers can take these ideas and put them in the appropriate context for solar cells with the help of our work. Also, if someone is working with a particular type of solar cell, it should now be clear whether it has potential to exceed the previous limit or not.”

The researchers demonstrated that any semiconductor material can exceed the light-trapping limit when the local density of optical states (LDOS) of its absorbing layer exceeds the LDOS of the bulk semiconductor material. They also show that enhancing the LDOS of the absorber to a level needed to absorb 99.9% of the solar spectrum is feasible even for semiconductors as thin as 10-100 nanometers (compared with micrometer-thick layers used in today’s commercial devices).

“Our results suggest that if you can engineer the electromagnetic environment in the right way it should be possible to go as thin as 10 nm,” Callahan said. “It’s just a matter of how to design it appropriately and without introducing unwanted parasitic losses. This is certainly a challenge, but is something we are currently thinking about. Now, a 10-nm solar cell is likely impractical for other reasons such as the need for multiple layers, surface recombination, potential quantum effects, etc., but is still within the realm of possibility.”

The most important limit to increasing the absorbing layer’s LDOS arises due to the “density of states sum rules,” which say that increasing the LDOS in one region of the spectrum results in a decrease in another region of the spectrum. As the scientists explain, this conservation of LDOS occurs naturally by a process called spectral reweighting, and can also potentially be artificially engineered. Although this rule imposes an upper bound on the absorbance of a solar cell, the researchers explain that it shouldn't limit solar cell absorbance for practical purposes. This is because LDOS enhancement is only needed in the solar spectrum, while LDOS can be decreased in any region outside of the solar spectrum, a much larger area. For this reason, other physical and practical limits, such as saturation or fabrication challenges, will likely become relevant before a limit is reached for increasing the LDOS.

The scientists also showed that a variety of solar absorber designs can meet the fundamental criteria proposed here for exceeding the conventional light-trapping limit, i.e., exhibiting an LDOS that is higher than that of the bulk material. Some designs include using plasmonic materials, dielectric waveguides, photonic crystals, and other devices.

"We are currently trying now to find ways to engineer and increase the density of optical states as high as we can within a practical solar cell design," Callahan said. "This is a challenging task for high index materials like silicon, but there are many possibilities which we are currently examining that look promising."

More information: Dennis M. Callahan, et al. "Solar Cell Light Trapping beyond the Ray Optic Limit." *Nano Letters* 2012, 12, 214-218. DOI: 10.1021/nl203351k