

Light management in thin-film solar cells

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Photovoltaics, the conversion of sunlight to electricity, is a promising technology that may enable the generation of electrical power at a very large scale. Worldwide photovoltaic energy production was >5 GW in 2008, and is expected to rise above 20 GW by 2015. Thus, photovoltaics has the potential to make a significant contribution to solving the energy problem that our society faces in the next generation. To make power from photovoltaics competitive with fossil fuel technologies, the cost needs to be reduced by a factor of 2-5. Currently the majority of the solar cell market is based on crystalline silicon wafers with a thickness of 180-300 μm and a major fraction of the cell price is due to Si materials and processing costs. Because of this, there is great interest in thin-film solar cells, with film thickness in the range 1-2 μm , that can be deposited on cheap module-sized substrates such as glass, plastic or stainless steel. Thin-film solar cells are made from a variety of semiconductors including amorphous and polycrystalline Si, GaAs, CdTe, CuInSe_2 , as well as organic semiconductors and quantum dot solids.

Thin-film solar cells offer many benefits over their bulk counterparts. First of all, thinner cells require less material to fabricate, reducing materials and processing costs. Second, for materials that are scarce in the earth's crust, such as e.g. In and Te, the reduced material requirement of a thin film is a great advantage. Third, thinner cells suffer less from bulk carrier recombination, which leads to a higher open circuit voltage. Fourth, carrier collection is more easily done in a thin cell leading to a higher photocurrent. And fifth, for some materials that degrade under illumination, such as hydrogenated amorphous Si, thinner cells show strongly reduced photodegradation over time.

While a thin film solar cell thus offers many advantages, it has one major limitation: the absorbance of near-bandgap light is small, in particular for the indirect-bandgap semiconductor silicon. Polycrystalline Si thin film cells must be several microns thick and for the direct semiconductors GaAs, CdTe, CuInSe_2 a layer thickness of 1 μm is required to entirely capture the sub-bandgap spectrum; amorphous Si cells (with the optimum thickness determined by light absorption and carrier collection) are typically 200-400 nm thick. Therefore, structuring the thin-film solar cell so that light is trapped inside in order to increase the absorbance ("light trapping"), while reducing the thickness, is very important.¹

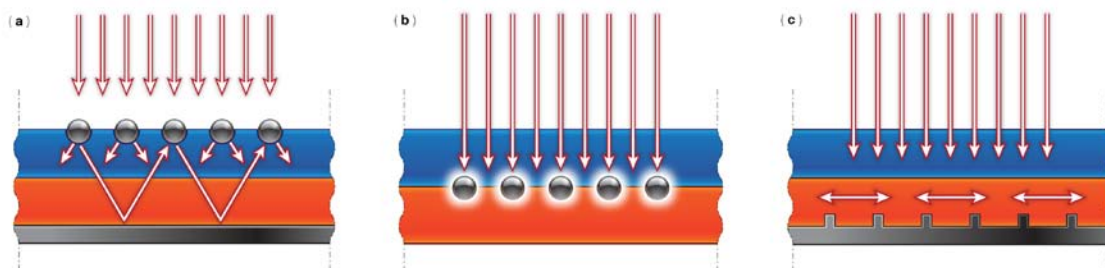


Figure 3 **Light management in thin-film solar cells** (a) Light trapping by scattering from metallic or dielectric nanostructures at the surface of the solar cell. Light is preferentially scattered and trapped into the semiconductor thin film by multiple and high-angle scattering, causing an enhancement of the effective optical path length in the cell. (b) Light trapping by the excitation of localized surface plasmons in metal nanoparticles embedded in the semiconductor. The excited particle's near field causes the creation of electron-hole pairs in the semiconductor. (c) Light trapping occurs by scattering of light from a corrugated metal back surface couples to surface plasmon polariton or photonic modes that propagate in the plane of the semiconductor layer. From: H.A. Atwater and A. Polman, *Nature Mater.* **9**, 205 (2010).

In this presentation I will describe how light trapping in thin-film solar cell can be achieved using suitably engineered metal and dielectric nanostructures that are integrated within the thin-film solar cell design. Properly engineered light trapping geometries can strongly increase the solar cell efficiency and reduce its thickness. I will review three light trapping geometries indicated schematically above. All designs use the controlled scattering and/or optical near field enhancement due to the excitation of surface plasmons or Mie resonances in metal or dielectric nanostructures in order to enhance the absorption of light in a thin-film solar cell.

In particular, I will address two designs that we have experimentally realized and that have led to a significant enhancement of photocurrent and open circuit voltage in thin film Si solar cells. Nanostructures at the surface (geometry (a) above) act as efficient scatterers of light, causing a redistribution of light in the solar cell and thus an enhancement of the effective path length.^{2,3} We show how suitably designed arrays of Ag nanoparticles can provide near-perfect impedance matching between incident light and the Si active layer. We also experimentally demonstrate clear enhancements of the photocurrent due to near-infrared light that is otherwise poorly absorbed in the cell.

In a second design, metallic nanoparticles are integrated with the metallic backcontact of thin-film amorphous Si solar cells (geometry (c) above). The nanopatterned solar cells show strongly enhanced photocurrents in the 550-800 nm spectral range, demonstrating efficient light trapping. Using a novel technique, angle-resolved photocurrent spectroscopy, we identify the coupling between the incident and scattered light and the waveguide modes in the solar cell.^{4,5} Using an optimized light scattering geometry we demonstrate the first Si solar cell thinner than 100 nm with an efficiency > 9%.

Our work shows that ultra-thin solar cells should be considered as *nanoscale optical integrated circuits* in which the coupling, guiding and absorption of light must (and can) be controlled at the nanoscale. I will show how numerical Finite Difference Time Domain (FDTD) simulations, incorporating both optical and electrical effects at the nanoscale, play a key role in understanding and engineering these novel designs. Our work can be applied on any thin film solar cell geometry and material. Finally, we introduce a novel Substrate Conformal Imprint Lithography (SCIL) technique that enables the fabrication of large-area nanopatterned surfaces at low-cost, enabling large-scale integration of the light management concepts described in this presentation.

This work is carried out in collaboration with the group of Ruud Schropp at the Debye Institute, Marc Verschuuren at Philips Research and the group of Harry Atwater at CALTECH.

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