

# Enhanced light trapping in thin-film solar cells

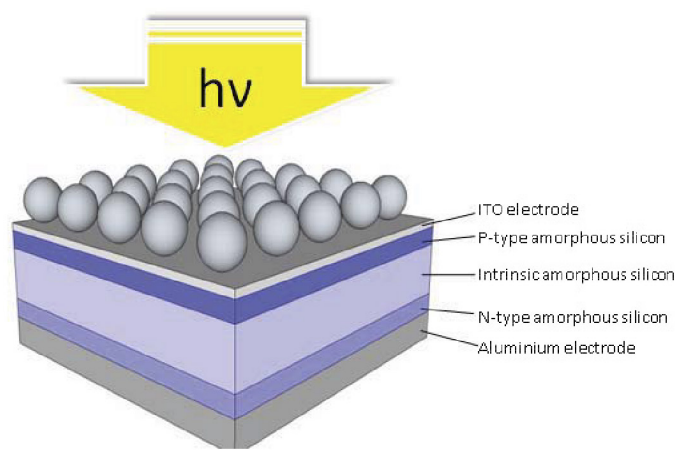
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*Incorporating nanoparticles made of dielectric rather than plasmonic materials reduces parasitic absorption and results in more efficient silicon photovoltaics.*

Solar cells offer a promising way to turn the light energy that the sun provides into electricity. Recent concerns about pollution caused by fossil fuels, as well as the rapid depletion of crude oil in the world, have highlighted the need for sustainable-energy generation. However, more has to be done to reduce the costs and improve the efficiency of solar-energy production. In the current photovoltaics market, silicon-based solar cells still dominate global production and installation, and remain the primary focus of the photovoltaics research community. Research centers on three main points, including reducing semiconductor material by adopting thinner silicon photoactive regions, reducing manufacturing energy and time by implementing advanced silicon-processing techniques, and raising the efficiency of these thin-film cells through innovative light-trapping techniques.

There are limited options to improve light trapping in thin-film silicon solar cells. With a thickness of a few microns or less, thin-film solar cells do not support traditional light-trapping techniques, such as the surface texturing extensively used in wafer-based silicon solar cells (where micron-sized pyramids are etched on the front surface of the wafer to scatter more light into the photoactive region). The subwavelength texturing required for the thin silicon layer increases the surface area as well as the presence of electrically active centers or defects at the surface. As a result, surface-recombination losses at the transparent conducting oxide/silicon interface increase and the performance of such solar cells decreases. Thus, a novel and relatively simple method is required to enhance light trapping with minor modification and/or addition to the processing steps.

An innovative solution is to use scattering from nanoparticles deposited on top of the transparent electrode of a thin-film silicon solar cell. We have used computer simulations to show that silver (Ag) nanoparticles can resonantly couple with the incident light (that is, the incident light and the collective electron

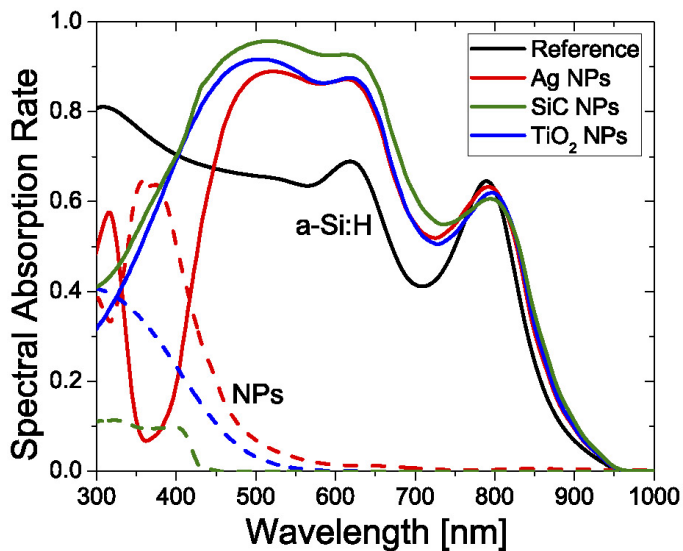


**Figure 1.** Geometry of a nanoparticle-enhanced thin-film amorphous-silicon solar cell. The nanoparticles are deposited on the indium tin oxide (ITO) electrode.  $h\nu$ : Light energy. P-, N-type: Dominated by holes and electrons, respectively.

oscillations in the nanoparticles are in phase) and scatter more light into the active region. This is because the plasmon frequencies, at which Ag nanoparticles are resonantly excited to form strong electron-density oscillations, lie within the solar spectrum. However, the nanoparticles also exhibit very high absorption of incident light at these plasmon-resonance frequencies. Although this parasitic absorption can be significantly reduced for large nanoparticles,<sup>1</sup> it limits the effectiveness of Ag nanoparticles to improve light absorption in the silicon layer.<sup>2</sup>

We noticed that resonant absorption in plasmonic nanoparticles becomes a significant limiting factor towards higher photoelectron generation. Therefore, a thin-film silicon solar cell with nanoparticles that are good scatterers and do not absorb much light could be more efficient. We realized that dielectric nanoparticles are the best choice since they have much smaller (sometimes negligible) absorption compared to metallic nanoparticles at optical wavelengths. We considered<sup>2</sup> a simple thin-film silicon solar-cell model with a 240nm-thick

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**Figure 2.** Spectral absorption rate of the active amorphous-silicon region (a-Si:H, solid lines) without and with silver (Ag), silicon carbide (SiC), and titanium dioxide (TiO<sub>2</sub>) nanoparticles (NPs). Spectral absorption rates of the nanoparticles (dotted lines) are plotted for reference.

amorphous-silicon layer sandwiched between a 20nm-thick transparent indium tin oxide (ITO) electrode and an 80nm-thick aluminum electrode (see Figure 1). Spherical nanoparticles characterized by radius  $R$  and surface coverage  $C$  (percentage of the top surface area covered by nanoparticles) are deposited as a square array on top of the ITO. The model structure is illuminated with monochromatic plane waves, perpendicular to the top surface and covering the entire AM1.5G (sea-level) solar spectrum. To determine spectral absorption of the active silicon region and the nanoparticles, we solved Maxwell's equations in 3D and optimized the array parameters to obtain the maximum optical absorption in the silicon active layer.

To compare enhancements of the optical absorption in the active silicon layer provided by metallic and dielectric nanoparticles, we considered three different nanoparticle materials, including Ag (as the best resonant material showing the least parasitic absorption among all commonly used plasmonic metals), silicon carbide (SiC), which features very small dissipation in the optical regime, and titanium dioxide (TiO<sub>2</sub>), as a low-cost dielectric commercially available in large quantities. We optimized the array parameters for these three materials and compared their best performance for the following optimal configurations:  $R_{Ag}=25\text{nm}$ ,  $C_{Ag}=11\%$ ;  $R_{SiC}=25\text{nm}$ ,  $C_{SiC}=78.5\%$ ; and  $R_{TiO_2}=20\text{nm}$ ,  $C_{TiO_2}=74.5\%$ . The enhancements obtained for

these configurations compared to the reference cell (without any nanoparticles) were 10, 29, and 23%, respectively.

To identify the reason for small enhancements by Ag nanoparticle arrays, we plotted spectral absorption rates of the amorphous-silicon active layer (solid lines) and the nanoparticles (dashed lines) in Figure 2. This illustrates that the materials improve light trapping in different spectral regions. SiC and TiO<sub>2</sub> nanoparticles enhance silicon absorption for wavelengths above 400nm, while Ag nanoparticles improve absorption above 450nm. For shorter wavelengths, the parasitic absorption of all three materials decreases the photoelectron generation compared to the reference cell. This decrease is strongest for Ag nanoparticles because of the resonant interaction with surface plasmons at  $\sim 370\text{nm}$ . We conclude that low-dissipation and high-permittivity dielectrics, such as SiC and TiO<sub>2</sub>, provide sufficient scattering for light trapping of thin-film cells and may be a better choice than plasmonic Ag nanoparticles.<sup>2</sup>

In summary, we have shown that Ag, as a plasmonic material coupling with incident sunlight in a resonant way, provides 10% enhancement of the total optical absorption in the amorphous-silicon active region. However, these nanoparticles also feature high parasitic absorption caused by excitation of the surface plasmons. Therefore, when they are used to enhance the forward scattering of incident sunlight, they do not perform as well as dielectric nanoparticles within the solar spectrum. (The latter do not have huge parasitic absorption as seen in plasmonic metals.) Our next step is to apply what we have learned from our previous work on nanoparticle-enhanced thin-film silicon-based solar cells to third-generation photovoltaic technology such as organic solar cells, where the photoactive organic layer is also very thin and so light trapping is also a critical issue to resolve for increased efficiency.

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#### References

1. Yu. A. Akimov, W. S. Koh, and K. Ostrikov, *Enhancement of optical absorption in thin-film solar cells through the excitation of higher-order nanoparticle plasmon modes*, **Opt. Express** **17**, pp. 10195–10205, 2009. doi:10.1364/OE.17.010195
2. Yu. A. Akimov, W. S. Koh, S. Y. Sian, and S. Ren, *Nanoparticle-enhanced thin film solar cells: metallic or dielectric nanoparticles?*, **Appl. Phys. Lett.** **96**, p. 073111, 2010. doi:10.1063/1.3315942