(Third Lecture) Techno Forum on Surface Plasmon Applications

Plasmonics for improved photovoltaic devices
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(2011/06/15) GMR and SPP
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Plasmonics for improved photovoltaic devices
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Design Considerations for Plasmonic Photovoltaics
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Plasmonic solar cells
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Clearly, a large fraction of the solar spectrum, in particular in the intense 600–1,100 nm spectral range, is poorly absorbed.

This is the reason that, for example, conventional wafer-based crystalline Si solar cells have a much larger thickness of typically 180–300 μm.

Charge carriers generated far away (more than the diffusion length) from the p–n junction are not effectively collected.

Solar-cell design and materials-synthesis considerations are strongly dictated by these opposing requirements for optical absorption thickness and carrier collection length.
Figure 2. Generalized scatterers for coupling into waveguide modes in a solar cell. Scatterers can consist of particles on top (a), middle (b), or back (c) of the solar cell and could contain layers of metal, dielectrics, transparent conducting oxides, or air on the back surface. Incident sunlight is then scattered into photonic or SPP modes depending on the scattering object and incident wavelength of light. (d) Schematic of a solar cell with various scattering object tilings.
Dispersion relation of SPP

Figure 4. Surface plasmon polariton dispersion relation for an Ag/Air interface. Black (grey) line corresponds to the dispersion relation for the SPP mode (light line). A significant fraction of the solar spectrum (right part of figure) has access to the bound SPP mode.
Plasmonic and photonic modes

Figure 3. Modal profiles at $\lambda = 920$ nm for TM and TE polarizations, with and without metal back contacts. Profiles are normalized to equivalent power under the curve and are calculated from post-processed finite difference time domain simulation.
Plasmonic structures can offer at least three ways of reducing the physical thickness of the photovoltaic absorber layers while keeping their optical thickness constant.

- Metal nanoparticles at the surface of the solar cell
- Metal nanoparticles embedded in the semiconductor.
- Corrugated metallic film on the back surface of a thin photovoltaic absorber layer

Light is preferentially scattered and trapped into the semiconductor thin film.

Light trapping by the excitation of localized surface plasmons.

Light trapping by the excitation of surface plasmon polaritons at the metal/semiconductor interface.
in the limit of a point dipole very near to a silicon substrate, 96% of the incident light is scattered into the substrate.

Very small particles suffer from significant ohmic losses, which scale with volume $v$, whereas scattering scales with $v^2$, so that using larger particles is advantageous to increase the scattering rate.

For example, a 150-nm-diameter Ag particle in air has an albedo (fraction of light emitted as radiation) as large as 95%.
SPP Solar cells

AAO templates

External quantum efficiency (EQE) of two thin film GaAs solar cells without particles

Figure 5. Optically thin GaAs solar cell decorated with Ag nanoparticles deposited by evaporation through an AAO template. (a) Evaporation through the template. (b) SEM image of the AAO template with a hole density of $3.3 \times 10^9$ cm$^{-2}$. (c) SEM image of the deposited nanoparticles using the template of (b). Average particle heights of 55 nm (d) and 220 nm (e) as imaged at 75° from the normal. (f) Normalized external quantum efficiency for two cells with different particle densities. Adapted from reference [22] with permission from the American Institute of Physics.
Light concentration using particle plasmons

100-nm-diameter Ag particle embedded in three different dielectrics (air, Si3N4 and Si). Dipole (D) and quadrupole (Q) modes are indicated.

25-nm-diameter Au particle embedded in a medium with index $n = 1.5$.

dispersion diagram for SPPs on a Ag/Si interface.
200 nm of Si on 300 nm of Ag, with a 60 nm AR coating on top of the Si.

Figure 6. Calculated absorption enhancements for nanostructured c-Si cells with an Ag back contact and an antireflection coating. The Si is 200 nm thick, and the ridges are 100 nm wide and 50 nm tall. Absorption enhancements are relative to an identical structure with a planar Si/Ag interface. In the left panel the scatterers are separated by 6 μm pitch, and in the right by 300 nm. The red (open symbol) curves are for TE polarization, and the blue (closed symbols) are for TM polarization. The dashed lines is at an absorption enhancement = 1, i.e., the case where the absorption is the same as in the planar reference structure.
Other new plasmonic solar-cell designs

plasmonic ‘tandem’ geometries

Plasmonic quantum-dot solar cell

Semiconductor quantum dots are embedded in a metal/insulator/metal SPP waveguide

Optical antenna array

Array of coaxial holes
Large-area (wafer-scale) fabrication of plasmonic solar-cell structures

The simplest way to form metal nanoparticles on a substrate is by thermal evaporation of a thin (10–20 nm) metal film, which is then heated at a moderate temperature (200–300 °C), to cause agglomeration by surface tension of the metal film into a random array of nanoparticles.

More control over the Ag nanoparticle size, aspect ratio and density can be achieved using deposition through a porous alumina template,

Substrate conformal imprint lithography has been developed, in which a sol–gel mask is defined by soft lithography using a rubber stamp, followed by Ag evaporation and lift-off.
Laser interference lithography

2” polished Si-wafers with 200 nm-thick photoresist (PR) layer.

PR film exposed with UV laser interference

2-dimensional PR gratings cured on a heating plate at 110°C for 60s

→Roughness of the PR surface less than 1 nm

different period
different shape
different arrangement on a single wafer
Gold Nanocups
Gold Nanodots
Gold Nanobowls
Silicon nanodots

Smooth and highly regular array of nanosize hemispheres

Tilted SEM image of Si nanodots with $\Lambda = 400$ nm
Summary and outlook

The ability to construct optically thick but physically very thin photovoltaic absorbers could revolutionize high-efficiency photovoltaic device designs. This becomes possible by using light trapping through the resonant scattering and concentration of light in arrays of metal nanoparticles, or by coupling light into surface plasmon polaritons and photonic modes that propagate in the plane of the semiconductor layer.

Guiding and concentration of light using plasmonic geometries allows entirely new solar-cell designs in which light is fully absorbed in a single quantum well, or in a single layer of quantum dots or molecular chromophores.

The extreme confinement of light that can be achieved using plasmonic nanostructures can also enhance nonlinear effects such as up- and down-conversion or multiple carrier generation in nanoscale solar-cell geometries.