Plasmonic Photovoltaics

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Cell Designs
The integration of plasmonics with photovoltaic devices allows for the confinement and guiding of light into subwavelength volumes. The concentration of light into small volumes allows for the reduction of absorber layer thicknesses, potentially enabling increased carrier collection efficiencies in thin, polycrystalline silicon films or quantum dot structures which have low minority carrier diffusion lengths. Although both resonant and non-resonant excitation are effective, the position of resonance can be tuned across the visible depending on the particular cell.

In the above design, silver nanoparticles are deposited on top of a standard thin-film silicon cell. The large resonant scattering cross section of the nanoparticles leads to efficient scattering of incident light into propagating waveguide modes. The shape of the nanoparticles can be controlled for enhancement in particular regions.

In the design below, the back contact of a cell is patterned with subwavelength scattering objects to convert incident light into propagating SPs on the semiconductor-metal interface and other waveguide modes. We focus on the design of the scattering object for broadband, all-angle response.

Method of Analysis
Our simulation method allows us to filter the modes in the waveguide in Fourier space, and separately analyze the energy content of each. The plots to the left show the H, field amplitudes for the waveguide before and after filtering, and a mode profile for each. After converting each mode to the Poynting vector, we back out an incoupling cross section σ, which measures the effective width of the scatterer.

Incoupling and Resonances
We identify the features in the incoupling spectrum as the convolution of three physical phenomena: SPP resonance, groove magnetic dipole resonance, and Fabry-Perot resonances in the thickness of the film. From the field magnitudes at the groove mouth in both finite and semi-infinite films, we find the SPP resonance occurs at 680 nm and the groove resonance at 1100 nm. We quantify the positions of the Fabry-Perot resonance by plotting a figure-of-merit F = A'Q, where A is the absorbance in the film and Q is the quality factor of the cavity.

$$Q = \frac{4\pi}{\lambda} \left[ 1 - \exp(-2\alpha t) \right] \left[ 1 - R_1 \right] \left[ 1 - R_2 \right]$$

where t is the thickness of the film, α, and R, the reflectance at the Si/Ag and Si/Ag interfaces, and α is the absorption coefficient.

Scattering by a Single Groove
The graph to the left shows the relationship between the physical width of the groove w and the effective width of the groove w_eff at the magnetic dipole frequency. Subwavelength grooves scatter efficiently into SPP modes, whereas the large grooves with independent edges scatter mostly into photonic modes. The Fabry-Perot modes within the depth of the groove also contribute to incoupling, although the effect is smaller.

Ridge Scattering
Changing to a ridge of the same aspect ratio dramatically changes the modal incoupling ratio, scattering preferentially into photonic modes across the spectrum.

Angles of Incidence
$$\lambda = 1000 \text{ nm} \pm 350 \text{ nm pitch}$$

$$N_o = \nabla \cdot S = \frac{1}{2} \omega \varepsilon_0 |\mathbf{E}|^2 d\mathbf{z}$$

Absorption Enhancement
For one groove, absorption enhancement is isotropic up to 60°. For two and three groove systems, there is a slight narrowing of the angle but it remains relatively isotropic.

Multiple Grooves
Pairs of grooves lead to enhancement and suppression due to SPP interference with maxima at 190° and minima at 570°. By changing the pitch the enhanced peak can be tuned between 800 and 1000 nm. Adding a third groove at the same pitch can further enhance the two-groove spectrum, but does not create any new peaks.

Summary
- Quantitative resolution of incoupling into both SPP and photonic modes
- Incoupling ability relatively insensitive to angle of incidence, with slightly narrower response for multiple grooves
- Three physical phenomena determine incoupling spectrum: SPP resonance, groove resonance, and Fabry-Perot resonance in the film
- Multiple grooves can be arranged for constructive interference, tunable between 800 and 1000 nm.

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References: