Nanophotonics

Class 8 – Nanophotovoltaics (January 7, 2011)

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For many decades there has been interest in solar cells to solve the energy problem as fossil fuels are becoming scarcer. The most important issue for the use of solar cells is the price per Watt of photovoltaic power.
Much effort is put into semiconductor materials, like silicon, that are inexpensive and widely available.

This assignment shows why Nanophotonics can be of great interest for the solar cell industry.

*** For this assignment, you will need two data files that can both be found on the website.*
File one (AM15_spectrum.ascii) contains the AM1.5 solar spectrum (W/m²/nm).
File two (eps_Si.ascii) contains the (complex) dielectric constants for crystalline Si (c-Si).
Both wavelength ranges are the same and given in nm.

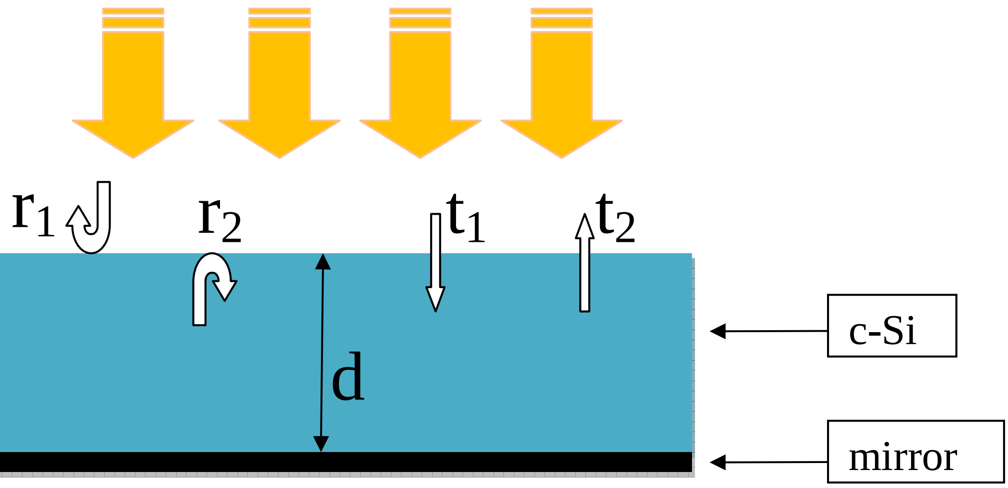
*You can use both Matlab and Mathematica. In Mathematica, use the 'Import' command together with the import format 'Table'. ***

Assignment

a) Calculate the absorption length (propagation length) in c-Si as a function of wavelength. Make a logarithmic plot of your results.

As you can see from the plot, silicon poorly absorbs light at wavelengths close to its indirect bandgap. However, an optically thick solar cell is much more expensive than a thin film solar cell.

In the following part of the assignment we will consider a thin c-Si layer on top of a perfectly conducting mirror illuminated by a plane wave on normal incidence as shown in the figure below. The c-Si layer has a thickness d.



b) Express the Fresnel reflection coefficients r_1 (air→Si) and r_2 (Si→air) as function of n_{air} and n_{Si} at the air/c-Si interface, indicated in the figure. Also give the expression of the transmission coefficients t_1 and t_2. What is the reflection coefficient of the mirror?

We are now going to calculate the total reflectance as a function of wavelength.

c) Show that the total reflectance as a function of wavelength can be written as

$$R(\lambda_0) = I_0 \left| r_1 - \frac{t_1 t_2 e^{i(2dk)}}{1 + r_2 e^{i(2dk)}} \right|^2 \qquad (1)$$

Here, I_0 is the intensity of the incident wave and k the complex wave vector ($k = 2\pi n/\lambda_0$). Explain at what condition R is maximal.

d) Plot the total reflectance as a function of wavelength for a cell with a thickness of 1µm (assume $I_0 = 1$). Also plot the total absorption as function of wavelength. Plot both graphs in the same figure.
Explain how the behavior observed at long wavelengths can be an inherent problem of thin film solar cells.

e) Use the AM1.5 solar spectrum to calculate the total power spectrum absorbed by a 1µm-thick solar cell.

The absorbed energy is not fully converted into electricity. The energy conversion efficiency of a cell is called the spectral response. **In the following we only consider quantum defect losses.**

f) Explain what quantum defect means.

g) In one figure, plot the AM1.5 solar power spectrum as well as the converted-power spectrum for an infinitely thick cell (taking into account reflection at the air-silicon interface) and the converted-power spectrum of the 1µm-thick cell. In both cases, calculate the fraction of the total incident solar power that is converted to electricity (cell efficiency). Explain the important steps in your calculation; a Mathematica code without explanation is not sufficient!

As you see in assignment (g), the efficiency of thin c-Si cells is very low (in reality it is even lower as we neglected many loss mechanisms). The main problem that causes the low efficiency of thin cells is poor light absorption near the indirect bandgap of c-Si.
One way to overcome this problem is to enhance the optical path length in silicon. Nanostructures are a promising way to accomplish this.

h) Metal nanoparticles on top of a solar cell can absorb light and scatter it predominantly into the solar cell. In this way they can work like an anti-reflection coating.
Explain why the light is predominantly scattered in the forward direction.
Explain a second mechanism by which metal nanoparticles on top of a solar cell can enhance the efficiency of thin film solar cells.

i) In many of our experiments we use silver nanoparticles, as silver has less ohmic losses than other metals. However, one can argue that Ag is an expensive material. Consider a square array of spherical Ag nanoparticle with this (typical) geometry: particle radius = 100 nm, array pitch = 500 nm. Calculate the material costs per unit surface ($/m^2) to make such array (you will need Ag density and Ag price per gram; both can be found on Google). What is the impact of Ag material costs on the solar cell price per watt (consider a 1-Sun irradiance of 1000 W/m^2 and a solar cell efficiency of 10%)? Comment on the result.