Beyond geometrical shadow factors with nano-scale top contacts

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Abstract

High Concentration PhotoVoltaics (HCPV) solar cells waste about 3% of incoming light (representing about 1% of absolute efficiency) due to absorption and reflection on the top contact metallization grid. Additionally, there is a loss of efficiency of about 1% due to the voltage loss caused by the series resistance at very high concentrations. Both losses are related to the top contact metallization grid as series resistance is in large part due to emitter resistance (related to the spacing in between metallization lines) and grid resistance (related to metal thickness). Halving both the series resistance and the shadow factor of the top contact would boost efficiency by 1% in absolute terms. In this work we show that contact metal lines with sub-wavelength widths have an effective shadow factor that is not the geometrical shadow factor but larger or smaller depending on light wavelength, polarization, contact geometry and material properties. Integrating over the spectral range of interest, a significantly increased transmission into the solar cell is obtained. These results are of great potential to improve solar cell efficiencies and their economical viability, especially in the case of concentrator multijunction tandem solar cells, as the costs of nano-fabrication are divided by the concentration factor (typically around 500).

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Motivation

By a large margin (44% *vs*. 27%), the most efficient solar cells are concentrator multijunction tandem solar cells based on III-V semiconductors.[1] This technology is also known as High Concentration PhotoVoltaics (HCPV). In a HCPV solar panel, a very small and efficient solar cell converts to electricity the light collected in an area hundreds of times larger than the solar cell itself. In this case, the solar cells only represent a very small fraction (<16%) of the total costs of the produced electricity, thus it makes sense to use sophisticated fabrication technologies for these cells (such as nanolithography and semiconductor epitaxy), that would be too costly and impractical for solar cells operating at 1 sun.

We are considering using low cost, large area and scalable nanolithography techniques, such as laser interference lithography to define metal lines with sub-wavelength widths on thin contact layers. Anisotropic dry ion etching should also be used to minimize undercut below the grid. However, before proceeding with the fabrication, we need to understand how sub-wavelength features in the top contact metal grid affect the propagation of sun light into the solar cell.

Methods

Although the problem of light scattering by a free standing, perfectly cylindrical metal wire admits analytical treatment,[2] we have chosen to use numerical 2-dimensional Finite Difference Time Domain (FDTD) calculations in order to simulate a more realistic geometry. This will serve to design and then fabricate nanostructured front contact metal grids with optimal transmission. We present a systematic set of calculations of the dependence of the effective shadow factor on light wavelength, polarization and metal line width. We present results for various material combinations and geometries. We have also investigated how dielectric layers on top of the metal affect reflection and absorption, but so far our best results are obtained with bare metal lines that break the continuity of the antireflective coating.

The typical line width, height and geometric shadow factor used in HCPV are 3 μm, 600 nm and 3% respectively, implying a period of 100μm. As the optimal compromise between shadow factor and series resistance is a very delicate balance, our first aim is to reduce the series resistance of the cell by reducing the emitter resistance, that is, the period of the grating, while leaving the geometric shadow factor and grid resistance unchanged. As an extra benefit, here we show that such geometry results in a reduced effective shadow factor. The photovoltaic part of our simulation cell is constituted of GaAs, the common material for the contact layer in tandem solar cells based on III-V semiconductors. In order to simplify the interpretation of the results, we have not included the window layer and high band gap top cell. Moreover, we have chosen SiO2 as the medium on top of the cell since HCPV solar cells are typically attached to a glass made optical element acting as secondary concentrator.

The line is modeled by a semi-elliptical cross section made of gold with 600 nm height and widths ranging from 100 to 2000 nm in direct contact with the GaAs substrate. An Anti-Reflective Coating (ARC) lies on the GaAs without covering the gold line. This ARC is a bilayer of ZnS/ Si3N4 of 50 nm and 65 nm respectively, which are the optimized values for our system. The simulation region is 10 μm wide with perfect matching layers above and below to absorb all the outgoing radiation and periodic boundary conditions left and right. The Sun light was simulated by a plane wave source launched from the top of the simulation region. We have investigated the effect of conformally covering the line with dielectric layers of various compositions and geometries. We have found that the case of uncovered bare metal lines yields the best results so far. The simulated structure is shown in Fig. 1.

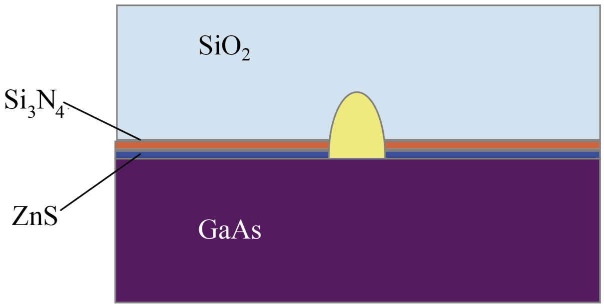

Fig. 1. Sketch of the structure with the best transmission results. The simulation region is 10 µm wide, the gold line is in direct contact with the GaAs substrate. The ARC bilayer of ZnS/Si3N4 (50nm/65nm) lies only over the GaAs leaving the line uncovered. SiO2 is used as the surrounding medium.

The transmission is monitored at the top surface of the GaAs substrate. The effective shadow factor is calculated as $100\cdot(1 - T_l / T_r)$, where T_l is the light intensity measured by the transmission monitor in the simulation with the metal line and T_r is the light intensity measured by the transmission monitor in the reference simulation without the metal line. The GaAs is covered by the ARC in both simulations, but the metal is uncovered by the ARC.

Results

As an illustrative case, the results obtained for 300 nm wide lines are shown in Fig. 2.

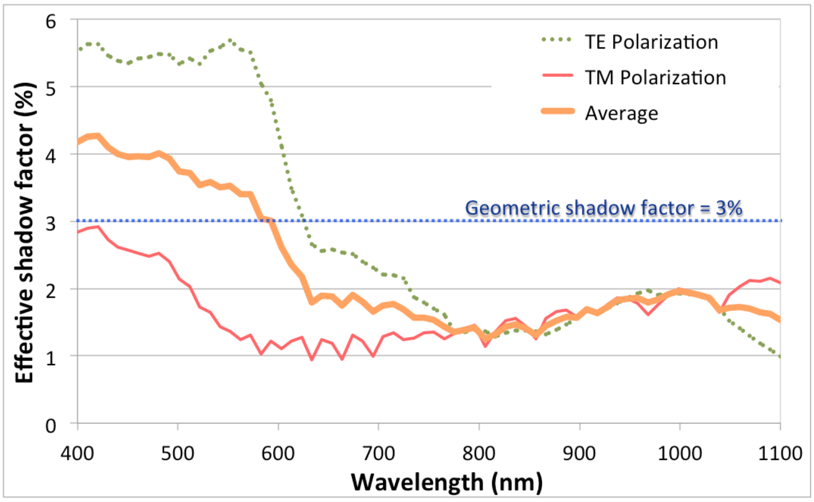

Fig. 2. Effective shadow factor for a 300 nm wide gold line with 600 nm height and a 3% geometric shadow factor. The horizontal dashed blue line represents the geometric shadow factor.

In Fig. 3 we examine the intensity of the electromagnetic field for TE polarized light at two extremes of high and low transmission, 1100 and 400 nm, respectively. Low transmission at 400 nm seems to be associated with a low intensity of the field in the vicinity of the metal, while high transmission at 1100 nm is associated with a high intensity of the field in the vicinity of the metal, possibly due to a surface plasmon-polariton resonance. At short wavelengths, the intensity of the field decays rapidly inside the GaAs due to strong absorption.

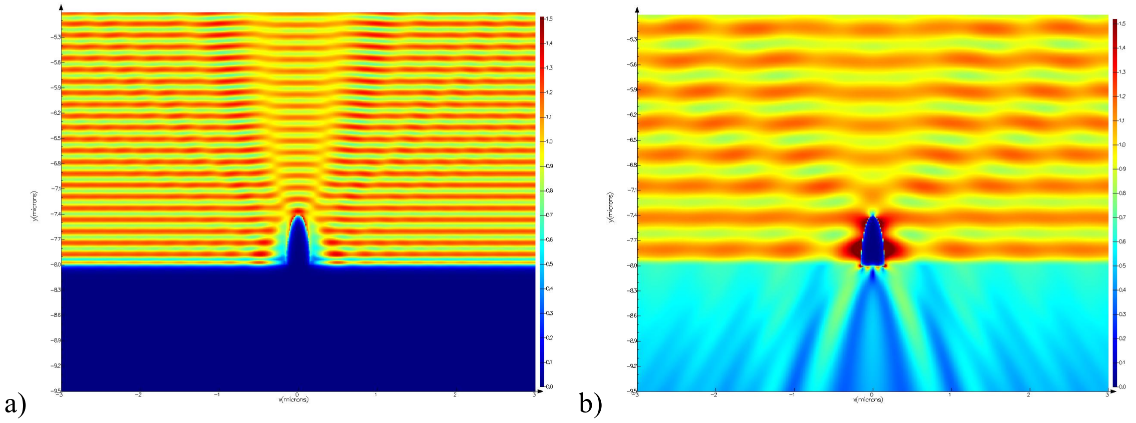

Fig. 3. Electromagnetic field intensity for TE polarized light incident on a 300 nm wide gold line. a) Incident wavelength = 400 nm. b) Incident wavelength = 1100 nm.

Summary

We show that nanostructuring the top contact of solar cells leads to increased transmission into the solar cell. These results are of great potential to improve solar cell efficiencies and their economical viability, especially in the case of concentrator multijunction tandem solar cells, as the costs of nanofabrication are divided by the concentration factor (typically around 500).

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[1] Daniel Derkacs, Rebecca Jones-Albertus, Ferran Suarez, and Onur Fidaner, J. of Photonics for Energy 2, 21805 (2012).

[2] Craig F. Bohren, Donal R. Huffman, "Absorption and Scattering of Light by Small Particles" (Wiley-VCH, 1983).