Plasmonics in Thin Film Solar Cells

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Abstract. Thin film solar cells made of amorphous or microcrystalline silicon provide renewable energy at the benefits of low material consumption. As a drawback, these materials don't offer the high carrier mobilities of their crystalline counterpart. Due to low carrier mobilities, increased process times and material consumption, thick absorbing layers have to be avoided. For maintaining the absorption of the impinging light as high as possible, such thin film devices ask for photon management. Here we show how metallic nanoparticles that sustain the excitation of localized plasmon polaritons placed atop of the solar cell or in between two absorbing layers can increase the efficiency of solar cells. Numerical results for 1D as well as 2D periodic arrangements of nanoparticles will be shown.

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METALLIC NANOPARTICLES ATOP THIN FILM SOLAR CELLS

A principal sketch of the geometrical layout of the solar cells under investigation is shown in Fig. 1[1, 2]. Metallic nanowires are periodically arranged on top of a finite layer that is assumed to be composed of the solar cell material; namely amorphous silicon (aSi). Normal incidence is assumed. A plane wave is furthermore assumed which is linearly polarized; having a magnetic field component that is parallel to the nanowires. Absorption in the cells is computed by relying on the rigorous coupled wave analysis (RCWA) [3]. The method was chosen since it is adapted to the periodic nature of the sample and it allows for the calculation of the electromagnetic field everywhere in space. For calculating the absorption inside the relevant spatial domain, namely the aSi layer, the divergence of the Poynting-vector is calculated and integrated over the aSi-layer. This provides as measure for absorption of the solar cell for a given wavelength. Integrating the spectrally resolved absorption weighted with the standard solar spectrum gives the number of absorbed photons[4]. The maximum increase of the number of absorbed photons has to be the primary target. It will serve as a direct measure to estimate how good such a cell is that comprises micro- and nanostructured materials for the purpose of photon management. In most cases absorption enhancement was computed. There the number of absorbed photons by a solar cell with photon management is normalized against absorption in the same cell without photon management.

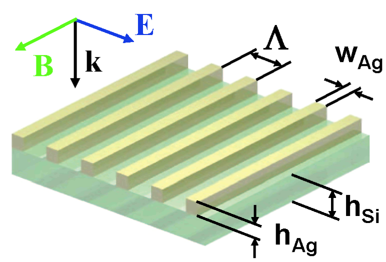

FIGURE 1. Sketch of the investigated solar cells where metallic nanowires are placed atop. Free geometrical parameters of the system that can be adjusted to maximize the absorption in the solar cell of thickness h_{Si} are the thickness and the height of the metallic nanowires h_{Ag} and w_{Ag} and their period Λ. The entire cell is considered to be embedded in a dielectric substrate and a superstrate.

The physical mechanism why we wish to incorporate metallic nanoparticles into a solar cell is their ability to sustain the excitation of a localized plasmon polariton [5]. In the limit of small particles, their scattering response is dipole dominated. The nanoparticle then couples sufficiently good to the illumination. The dipole can be driven into resonance at a wavelength that can be tailored to a large extent by modifying the geometry of the nanoparticle. In the realm of solar cells the action that matters most is the strongly enhanced near field amplitude and the large scattering cross section. Both features are beneficial to increase the absorption in the solar cell. However, care has to be taken since only scattered light with energies below the resonance will interfere constructively with the incident light, since the dipole oscillates in phase. It leads to an increase of the incoupled light into the absorbing layer. By contrast, scattered light at higher energies suffer from destructive interference with incident light since the dipole oscillates π out of phase. This is detrimental. Moreover, prior being beneficial the intrinsic absorption of light in the nanoparticle has to be compensated. Therefore, the design has to be

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carefully chosen to match the plasmon resonance to the spectral properties of the material the solar cell is made of. Some rational ideas might serve here as a guide.

At first, the relevant spectral domain for earth bound solar cells starts at 400 nm. When shifting the resonance wavelength of the nanoparticles below 400 nm, the solar cell would suffer only marginal from an increase of losses. Very small silver particles should be capable for such a task, but since absorption dominates over scattering for small particles; this is not beneficial. Therefore, larger particles should be considered for which scattering dominates over absorption. This comes at the cost of increasing resonance wavelength. Moreover, the photon management has its most impact close to the absorption edge of the solar cell. Therefore, the resonance wavelength of the localized plasmon polariton should be around 600 nm.

First calculations (not shown here) indicate furthermore that the period at which the particles are arranged should be 1.5 times larger than their width. Larger periods would dilute the sample in excess, causing a decline of their impact. Smaller periods would lead to proximity in excess and hence to a strong inter-particle coupling, which increases non-radiative losses.

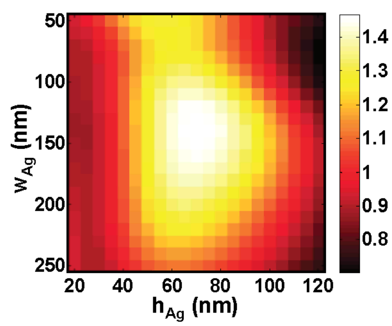

FIGURE 2. Relative increase of the number of absorbed photons versus nanowire height and width. The period was set to be 1.5 × the width and the thickness of the solar cell was 90 nm.

The impact on the absorption enhancement of possible geometrical parameters for the nanowire is shown in Fig. 2. The solar cell was chosen to be 90 nm thick aSi-layer. It can be seen, that for a careful choice of the nanowire geometry an enhancement up to a factor of 1.5 can be achieved. This is enormous when compared to the incremental increase in the efficiency of solar cells that are usually at the focus of interest.

In our contribution we will outline the guidelines that have to be imposed on the design of such solar cells in detail and discuss the impact of other geometrical parameters. Furthermore, the impact of a substrate and/or superstrate on the efficiency enhancement of a solar cell is accessed. Also two-dimensional geometries are considered which are less sensitive to the chosen polarization [6]. In most of these cases it turns out that the a factor of 1.5 for the absorption enhancement seems to be feasible and reliable.

METALLIC NANOPARTICLES BETWEEN TWO ABSORBING LAYERS

Another approach to make use of localized plasmon polaritons is as in intermediate reflector in a tandem cell. Whereas the voltage provided by such cells is the sum from the top and the bottom cell, the overall current of a tandem solar cell is limited by the cell that generates the lowest current, i.e. which absorbs the least photons. State of the art thin film solar cells are made of aSi and microcrystalline silicon (μcSi). Due to reasons that were outlined in the first section, the applicable thickness of the aSi-top-cell is limited, its absorption cannot be increased arbitrary and hence it limits the current. In most cases it is reasonably assumed that the μcSi-bottom cell by contrast can always be made thick enough to provide current matching [7]. If the absorption of the top cell could be significantly increased, the overall current as well as the cell efficiency would increase too. Recent research [8] concerned dielectric intermediate reflecting layers (IRL) [see fig. 3 a)] which can enhance the back reflected light and therefore the current in the top-cell. By optimizing their thickness a reflection peak can be tuned towards the absorption edge of the top cell.

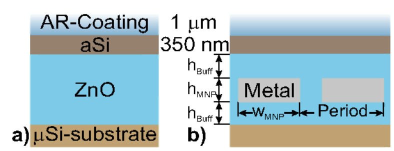

FIGURE 3. Sketch of the tandem cells under investigation. a) with a purely dielectric IRL, b) metallic nanowires embedded in a dielectric matrix.

Here we aim to ameliorate such IRLs by studying the impact of appropriately tailored metallic nanowires embedded in a dielectric matrix [see fig. 3 b)] on the generated current of the top as well as the bottom cell. The generated current of each subcell is individually calculated according to the method outline above by integrating the divergence of the Poynting vector. Again, normal incidence of light whose magnetic field is parallel to the nanowires is assumed. Fresnel reflection losses at the front surface are minimized by a continuous increase of the refractive index. Around the absorption edge of the top cell, the μcSi-bottom cell is thick enough to absorb the transmitted light, hence no light reaches the bottom cell back contact. Thus the bottom cell can be treated as an infinite layer, reducing at the same time the computational effort.

To let the resonance wavelength of the metallic nanowires be determined predominantly by its shape and not by the permittivities of the surrounding silicon, a buffer layer with a thickness of at least 40 nm is introduced at the top and the bottom of the nanowires [see fig. 3 b)].

Since the top cell has to be improved around its absorption edge, light with wavelengths below the resonance wavelength of the metallic nanowires should be already absorbed within the top layer. The aim is to tune the nanowire geometry in order to match the plasmonic resonance with the absorption edge since wavelengths around the resonance will be reflected efficiently, thus nearly doubling their path length inside the top cell and thus their absorbance. As a positive side effect light with longer wavelengths will be scattered efficiently into the forward propagating direction, e.g. into the bottom cell, with only minor losses. Thus, metallic nanowires promise to serve as spectrally selective IRLs with extraordinary quality.

By optimizing the geometrical parameters, as there are width and height of the metallic nanowires as well as their period and the height of the dielectric buffer, an increase of the top cell current by a factor of 1.08 could be achieved when comparing to a cell with an already optimized purely dielectric IRL, or factor of 1.15 when compared to a tandem cell with no IRL at all.

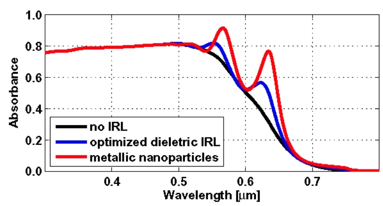

FIGURE 4. Absorption in a 350 nm aSi layer for the cases of no IRL (black line), an optimized dielectric ZnO-layer (blue line) and an optimized Ag-nanowire ZnO layer (red line).

Figure 4 shows the absorption spectra of the top cell for tandem cells containing no IRL, an optimized purely dielectric IRL, and the optimized IRL consisting of metallic nanowires embedded in a dielectric matrix. A clear increase of the absorption for wavelengths between 550 and 650 nm can be observed.

Tandem cells containing bi-periodically arranged nanodiscs and nanobricks were also investigated. Here, it could be observed, that nanobricks would feature a stronger back reflection but their resonance wavelength was shifted too far to the red. For nanodiscs the back reflection was weaker but with the desired spectral domain, allowing for current improvements by a factor of 1.08 for unpolarized light.

Overall, it could be shown that purposefully tuning the shape and hence the resonance wavelength of metallic nanoparticles can help to steer spectrally selective the absorption of impinging light within a complex system, such as a solar cell.

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