Thin-film solar cell enhanced by broadband plasmonic nanoantennas

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Abstract

We suggest a design solution of a thin-film solar cell enhanced in a very broad frequency band. The design is based on the recently invented cheap technology, which allows one to prepare large-area arrays of nanoantenas (NA) printed on a polyethylene or another cheap plastic film. Such arrays of NA operate as so-called plasmonic light concentrators for thin-film solar cells and the substrate of NA act as a Fabry-Perot resonator to prevent the reflection of the incident field. The significant advantage of this design is compatibility with the advanced technology which makes possible the large-area variant of plasmon-enhanced solar panels.

1. Introduction

Thin-film Si and GaAs solar cells represent the third generation of solar cells, which are dramatically cheaper and/or more efficient than other known types of solar cells. The main difficulty for a thin-film solar cell (TFSC) is harvesting light. The goal is to concentrate the incident light (practically a plane wave) inside the thin nanofilm of p-doped Si (or GaAs). The main problem becomes how to concentrate the incident light energy in the optically thin photovoltaic layer avoiding strong transmission of the incident light into the wafer and its reflection.

Recently, many works devoted to arrays of plasmonic nanoparticles (PNP) located on top of TFSC (covered with an insulating nanofilm) were published, e.g. [1-7]. At their plasmon resonance illuminated plasmonic nanoparticles can create a contribution into the reflected wave which nearly cancels with the contribution produced by the other parts of structure. Also PNP create hot spots whose maxima are located at the interface between them and their insulating substrate. Due to the hot spots energy of the incident light is harvested inside the photovoltaic layer and usefully absorbed. The evident advantage of this method is the relative simplicity of obtaining the grid of silver nanoislands achievable by rather cheap self-assembly methods. However, notice that this fabrication method is very slow. Needed time resources restrict the industrial applications of such plasmon-enhanced solar cells, especially it is not realistic for large area panels.

The role of PNP is not only to prevent the reflection from the photo-absorbing nanofilm, but to prevent the transmission of the energy into the wafer substrate. These plasmonic nanostructures perform their task converting the incident plane wave into the set of hot spots located inside the absorbing film. However, the same effect can be achieved placing refracting lossless layers - one on top of the absorbing film, another between it and the wafer. This two-layer structure can implement the Fabry-Perot resonator for the standing wave confined between the wafer and upper interface of the structure. We suggest combining this Fabry-Perot resonance and the multi-frequency plasmonic enhancement to obtain the ultra-band enhancement of the thin-film solar cells.

2. Design of the thin-film solar cell

Our design solution is based on the new cheap technology suggested by researchers from Idaho University [8] and then developed in [9]. Their structure is a large-area array of broadband IR nanoantennas (NA). Billions of IR NA have been printed on a large-area polyethylene (or similar polymer) substrate. The only requirement of the technology is not very high resolution (order of 50 nm in our design) which allows one to avoid the electron or ion beam lithography.

We suggest using the structure schematically shown in Fig.1. NA are the trapezoidal form plasmonic structures put on the plastic substrate. The fabrication of the plasmonic light concentrator for large-area panel of TFSC can be done as follows. First, one prepares the plastic sheet with printed NA, second, the sheet is placed on top of the panel of solar cells so that NA were in contact with the light-absorbing layer and third, the extra amount of the plastic is chemically removed. The NA shown in Fig. 1 (a) is in fact a three-resonance system, but all these resonances overlap and form a broad band around 1 micron wavelength. The structure shown in Fig 1 (b) corresponds to the Fabry-Perot enhancement for a selected frequency and to the broadband plasmonic enhancement at 1 µm.

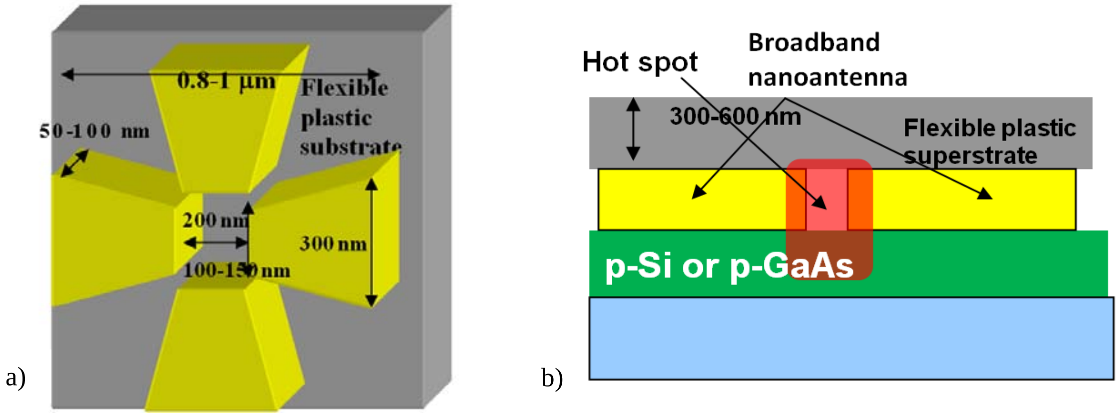

Fig. 1: A unit cell of the array of near IR broadband nanoantennas of gold strips printed on a plastic film and used as subwavelength light concentrators for a near-IR TFSC: (a) – top view, (b) – cross section view. The bottom layer (shown as blue) prevents the propagation of light into the wafer. The upper layer (substrate of nanoantennas) prevents the reflection of light. An expected IR hot spot is schematically shown by red color.

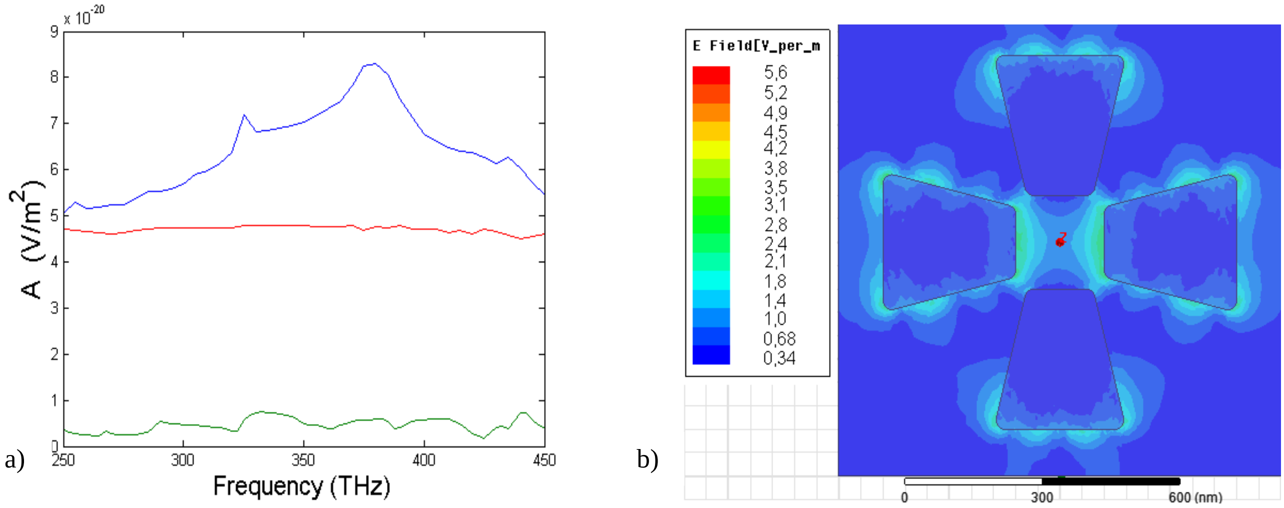

Fig. 2: (a) – dependence of the absorption coefficient *A* on frequency: red – absorption in the photovoltaic layer put directly on the substrate without NA and Fabry-Perot resonators, blue – broadband enhanced absorption in the photovoltaic layer, green – absorption in the NA; (b) - local field intensity enhancement in the plane of a near IR broadband nanoantenna at f = 375 THz.

We performed full-wave simulations in Ansoft HFSS commercial software in which the structure shown in Fig.1 was excited by a plane wave with a normal incidence. To estimate the efficiency of the energy harvesting we calculated the absorption coefficient $A = \int |E|^2 \varepsilon'' dV$, where $|E|$ is the amplitude of the electric field, ε'' is the imaginary part of the permittivity of the material and V is the volume of the single unit cell. Figure 2 shows the dependence of the absorption coefficient on frequency for three cases: first one is absorption in the photovoltaic layer without NA and Fabry-Perot resonators, second is broadband enhanced photo-absorption and the last one is absorption in the NA.

The combination of the plasmon resonance of the NA and Fabry-Perot resonance of the dielectric layers leads to the broadband enhancement of the energy harvesting. The total increase of the photoabsorption coefficient is 36% in the range 250-450 THz. In the same time heat losses in NA are negligibly small, which allows better efficiency and prevents heating of the NA which could worse the photovoltaic conversion.

3. Conclusion

We suggest new design of nanoantennas suitable for plasmon-enhanced thin-film solar cells, which corresponds to the plasmonic suppression of both reflection from the photo-absorbing layer and transmission through it to the wafer (i.e. enhancement of the photovoltaic conversion). The significant advantage of the design is compatibility with the advanced technology which makes possible the large-area variant of plasmon-enhanced solar panels. The tolerances in fabrication are not so strict as for known regular plasmonic light concentrators and the field enhancement is better than for random plasmonic light concentrators (hot spots are mainly inside the absorbing layer and not mainly inside plasmonic particles). The novelty of the design is its original geometry which allows the multi-frequency resonances. This design implies the use of the recently suggested large-area technology of the nanoantenna fabrication, which not only decreases the costs. The optimization of the field distribution across the structure (which leads to the best photovoltaic conversion) is now achieved due to two mechanisms: plasmon resonance and the Fabry-Perot resonance. As a result the enhancement will occur over the whole frequency band in which the efficient photovoltaic conversion holds. We believe that our approach to the fabrication of the plasmonic light concentrator opens the door to the mass production of plasmon-enhanced thin-film solar cells suitable for large-area panels.

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