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## Light Trapping In Thin-Fim Solar Cells: Gain in Spite of Defects

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**Abstract.** In this work, we report a nanostructure that grants a significant enhancement in optical efficiency to a thin-film solar cell based on amorphous silicon. The fabrication technique is very cheap and the nanostructure can be easily and rapidly prepared on a large area. This is possible by price of numerous mm-sized defects. In the areas of these defects the optical efficiency suffers. However, the enhancement of optical efficiency in the non-defective regions is so significant that the presence of defects still allows the gain granted by our light-trapping structure compared to a standard anti-reflective coating.

#### 1. Introduction

While the light trapping in epitaxial solar cells was successfully achieved by texturing the photovoltaic (PV) layer, no one light-trapping structure (LTS) was commercialized for amorphous thin-film solar cells (TFSCs) dedicated to flexible substrates and having a lossy bottom electrode. In the literature, the idea of the resonant light trapping in such solar cells still dominates. Nowadays, from plasmonic nanostructures researchers switch to all-dielectric ones. However, their resonances are narrowband, whereas solar spectrum is ultra-broad. To cover the visible light range with a multi-resonant structure is possible but the cost of such the structure will be huge. Arrays of lenses represent a cheaper solution. However, all known attempts to trap the light using them resulted in a very modest enhancement for organic solar cells and in the absence of enhancement for cells based on a-Si. In our group, we have developed nonresonant all-dielectric nanostructures granting a significant gain to a-Si solar cells. However, in our experiments, we used a very cheap technology based on self-assembly. As a result, our LTSs strongly suffered of defects. Removal of the defective regions made our solar cells impractically small. In this paper, we report a nanostructure that grants a so significant enhancement in optical efficiency that the presence of defects still allows the gain compared to a standard antireflective coating (ARC). We report a significant gain obtained for 5 cm large samples based on a-Si.

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#### 2. Theoretical prerequisites

In work [1] we paid attention to the fact that a 300 nm thick layer of a-Si that corresponds to the maximal internal quantum efficiency of the corresponding solar cell is sufficiently thick for total absorption of solar light per one passage if the light is concentrated by a simple focusing of the incident wave beam. The absence of the enhancement is explained by a non-favorable distribution of the photocurrent in the bulk of a PV layer. Really, a lens collects the sunlight into a focal spot, whereas the most of the PV layer remains dark. Therefore, the drop of quantum efficiency compensates the gain in optical efficiency. We have suggested to locate an array of densely packed one-micron spheres of silica on top of the transparent conductive oxide (Al-doped ZnO nano-layer). In these structure the effect of focusing is cascaded for the oblique incidence. Then wave beam incident on one sphere penetrates into adjacent spheres and after total internal reflections and enters the PV layer. The part of the incident wave beam that transmits into the PV layer after one passage through the sphere and the part that transmits into it through the adjacent sphere both experience the focusing effect called photonic nanojet. This is not a usual focusing since the diameter of the sphere is comparable with the wavelength and the geometrical optics does not work. The formation of the nanojet corresponds to the constructive interference of spherical harmonics in the transmitted light. It is inherent only to transparent spheres whose diameter is 3-10 times larger than the wavelength [2]. Cascade focusing results in appearing the additional nanojets. For large angles of incidence  $-45^{\circ}$  and more - the whole volume of the PV layer turns out to be filled by nanojets. Since the light in nanojets is concentrated, the absorption in the PV layer is enhanced compared to the plane-wave regime. And what is important, for large incidence angles the parasitic transmission of light is prevented without the damage for the photocurrent distribution.

Similar structures had been known but in available works they operated either as optical cavities allowing only a narrow-band light trapping or as ARCs granting no light trapping. In the first case the diameters of the spheres are adjusted with the precision of 1-2 nm and in the second case – with the precision of dozens of nm. However, in both cases these spheres have submicron diameters. In our case 1 micron is exactly the optimum between the anti-reflective operation and the light trapping. For larger diameter the reflection losses grow due to the parasitic scattering. For lower diameter the photonic nanojet is not formed. Though for the normal incidence when the cascade focusing is absent our LTS yields to a standard ARC, shown in Fig. 1(a), the gain granted by it for large incidence angles is high. The solar cell operates not only in the midday. Its optical efficiency and photocurrent should be both averaged over the angles of incidence of sunlight corresponding to the daytime. Therefore the impact of the oblique incidence is important. For TFSCs based on a-Si even with 400 nm thick PV layer we experimentally obtained a 17% daytime-averaged gain in the photocurrent compared to the case when the same TFSC was covered by an optimized flat anti-reflective coating [3].

However, this design solution suffered of a serious drawback. The deposition of silica spheres in [3] was achieved by the self-assembly of the solar particles on a moving surface of the conductive oxide. The spheres transfer from the colloid to the surface forming a nice densely-packed monolayer. This method is much cheaper than the spin-coating and colloidal microspheres are also cheap, that looks very promising. However, a defect-free monolayer of spheres cannot be implemented in this way on a cm scale. Several mm-sized defects where the self-assembly failed and the spheres were isolated turned out to be unavoidable. In every square cm of our TFSC there were up to 10 such defects. They result in the strong backscattering from the initial 5 cm large samples. Scattering losses due to the defects compensated or even overcompensated the enhancement granted by the regular part of our LTS. Therefore, in work [3] we have removed the defective domains – the reported samples of TFSCs had millimeter sizes. Such TFSCs are suitable in order to report the enhancement granted by our LTS, however, they are impractically small and have no chances to commercialization.

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This drawback urged us to search different mechanism of light trapping. We found this mechanism in the structure of notches implemented on top of the conducting oxide as shown in Fig. 1(b). Every notch is filled by a semi-diamond of silica and operates like a spherical microlens forming the photonic nanojet. Then the layer of the transparent oxide with densely packed notches becomes both all-angle anti-reflective coating and all-angle LTS without damaging its main function of the transparent electrode for the photocurrent collection. Simultaneously the conical shape of the silica protrusion is much more favorable in the defective areas because it promises lower scattering than the spherical shape. The backscattering cross section of our new microlens is nearly twice lower than that of the same notch comprising a silica sphere and is lower by an order of magnitude than that of a sphere located on the flat surface.

For the LTS described in our work [3] the negative impact of the defective areas was critical. In the new LTS the negative impact of the isolated notches with semi-diamond inclusions, in accordance, to simulations is almost absent.

#### 3. Results

In Fig. 1 one can see the difference in the spatial distributions of the electromagnetic flux density in the reference structure with flat anti-reflective coating and in the suggested structure with patterned Al-doped ZnO. In the first case we observe the plane-wave transmission with the standard decay rate. In the second case we see the collimated wave beam composed under the notch. This color map fully confirms our initial insight of the light-trapping mechanism. Let us stress that this beam collimation is not a resonant effect. In Fig. 1 we show the distributions of the electromagnetic flux at four occasionally chosen wavelengths and in all cases observe the beam collimation.



**Figure 1.** Comparison of the electromagnetic flux density in the reference (a) and suggested (b) structures at 4 wavelengths (normal incidence). Photonic nanojet is seen for the suggested LTS at all wavelengths.

As to the fabrication technology, it is also affordable: we use the Atomic Layer Deposition (ALD) and ion beam etching (IBE) in the small copy of an industrial machine. This technique is much cheaper than the ion beam lithography based on focused ion beams. It can process any samples up to wafer size, at any angle in uniform broad beam of Ar ions. Etching rate is 20 -

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50 nm/min. We prepare a monolayer of colloidal particles on top of a PV layer using the self-assembly. Next, we deposit a layer of Al-doped ZnO by ALD. Al-doped ZnO was successfully deposited on the amorphous silicon substrate in the gaps between the spheres. ALD is done with the ratio of steps 19:1 (19 steps of ZnO to 1 step of Al2O3 deposition). At the last stage we utilize IBE in order to remove the top half of the structure for 10 minutes and 30 sec. The notches filled with the silica semi-diamond particles automatically result from the IBE – conical nano-protrusions do not require any special technique. The optimal size of the silica sphere for our LTS is 1.2  $\mu$ m. Such spheres in colloidal solutions are as available and cheap as one-micron spheres.

Thorough measurements with several samples impinged by obliquely incident light of the solar simulator confirmed our theoretical expectations. In spite of defective regions which cover 30% of the area of our 5 cm large sample, the daytime-averaged enhancement of the PV absorption granted by our LTS is more than double compared to the bare solar cell and exceeds by 50% the enhancement offered by to the standard ARC (without defects). The absorption coefficient of the PV layer in presence of the LTS exceeds 70% and for the incidence angle  $60^{\circ}$  approaches to unity.

#### 4. Conclusions

We have introduced a new LTS suitable for a-Si TFSCs combined with the top-electrode and does not require an additional ARC on its top. Our LTS is not resonant, does not contain lossy inclusions and grants the all-angle operation with a noticeable increase of the PV absorption compared to the flat anti-reflective coating located on top of the same solar cell. The structure can be fabricated in the affordable way that makes it attractive for industrial adaptation. An only expensive step is the application of the ALD machine. However, ALD though still considered as a rather expensive technology in the PV community, is developing and has good perspectives in the mass production of solar cells. Therefore, we believe that our finding is really useful and may give a revitalizing pulse to the development of a-Si solar photovoltaics.

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