Photocurrent enhancement in plasmonic solar cells attached to luminescent solar concentrators

Renze Wanga, Xingjun Wanga, Zhiping Zhou* a

State Key Laboratory of Advanced Optical Communication Systems and Networks,
School of Electronics Engineering and Computer Science,
Peking University, Beijing, 100871, China

ABSTRACT

Luminescent solar concentrators (LSCs) generally consist of transparent polymer sheets doped with luminescent species. Incident sunlight is absorbed by the luminescent species and emitted with high quantum efficiency, so that the emitted light is trapped in the sheets and travels to the edges where it can be collected by solar cells. Unlike regular solar spectrum, the emission spectrum of LSCs based on Lumogen Red dye red shifts and concentrates to a small range of wavelengths (600nm to 700nm). Therefore, hydrogenated amorphous silicon (a-Si:H), whose bandgap is around 750nm, can absorb the emission light without many thermalization losses.

Due to the low diffusion lengths in a-Si:H, thin absorbing layer should be applied, causing insufficient light absorbance. In this letter, we propose a structure that coupling nanostructured plasmonic back contact to LSC solar cell. After optimization, numerical results show that the photocurrent intensity increases by a factor of 1.30 compared with LSC solar cells with randomly textured back contacts. In contrast, when illuminated by one Sun, the photocurrent for textured cell compares to that for nanostructured cell.

The remarkable photocurrent enhancement in LSC cells is attributed to two main reasons. First, the wavelengths, where nanostructured cell shows higher absorbance compared with textured one, are identical with the emission peak of LSC. Second, the light interferences constructed in flat cells, which cause the absorbance curve to red shift and match with the emission spectrum, are depressed in textured cell, but are maintained in nanostructured cell. The second reason is described in detail.

Keywords: Plasmonic solar cells, Randomly textured solar cells, Photovoltaics

1. INTRODUCTION

Luminescent solar concentrators (LSCs) generally consist of transparent polymer sheets doped with luminescent species. The species absorb incident sunlight, and emit them with high quantum efficiency, so that the emitted light is trapped in the sheets and travels to the edges where it can be collected by photovoltaic devices. Polymethylmethacrylate (PMMA) based Lumogen Red dye has been studied as a promising material for LSCs in recent years, whose emission spectrum red shifts and concentrates to a small range of wavelengths (between 580nm and 780nm). Since the bandgap of hydrogenated amorphous silicon (a-Si:H) (750nm) well matches the emission spectrum of LSCs, a-Si:H is a promising material for solar cells attached to LSCs.

The electronic diffusion length of a-Si:H is only a few hundreds of nanometers. It seriously limits the thickness of the
solar cell material and hence, the absorbance. Therefore, methods to enhance near-bandgap light absorption are needed. When illuminated by one Sun, an extensively studied method is to couple plasmonic structures to the back contacts of solar cells, so that the incident light is remarkably scattered and reflected back, causing optical path lengths inside the solar cells to be enhanced. Alternatively, randomly textured back contacts can be utilized to enhance light absorption in solar cells.

In this research, we numerically study the photocurrent enhancement in a-Si:H solar cells attached to LSCs. The plasmonic back contacts and randomly textured ones are compared. When illuminated by one Sun, the two strategies present the similar photocurrent (Jsc). In contrast, when attached to LSCs, plasmonic solar cells show remarkably higher efficiency compared with those with randomly textured contacts. The reasons for this situation are carefully analyzed.

2. SIMULATION

The sketch of plasmonic solar cell (PSC) attached to LSC is shown in Fig.1. An air gap between the LSC and the solar cell represents equal out-coupling conditions for all edges of the LSC. The refractive index of ITO is 2.08+0.004i. The zinc oxide (ZnO) (refractive index is 1.93+0.004i) layer is used to prevent excess surface recombination caused by metallic structure. Silver is chosen as the material for the plasmonic structures since its scattering efficiency is relatively higher than other noble metals in the visible range. The complex refractive index for the a-Si:H layer and silver are taken from published references. The thickness of a-Si:H layer is 150nm, and 200nm back plain silver layer (serve as a prefect back reflector) is applied. The nano-patterned hemispheres are separated with a constant period of 500nm, and their diameters are 250nm. Under the illumination of LSCs, the thicknesses of the ITO layer and ZnO layer are jointly optimized (the thicknesses of ITO are swept from 0 to 200nm, and the thicknesses ZnO are swept from 130nm to 230nm. The interval is 10nm). The components of randomly textured solar cell (RTSC) (not shown) are the same as the plasmonic one, but each layer is randomly textured with root mean square (RMS) of 25nm. The cell contained flat layers with same thicknesses are also simulated. Three dimensions Finite Difference Time Domain (3D FDTD) method is used to simulate the absorption in the cell.

Fig.1. Sketch of the investigated LSC solar cell.

To estimate the output Jsc, we simplify the system by assuming that every absorbed photon generates a single electron-hole pair, which contributes to the external current with unity quantum efficiency. In this assumption, Jsc can be
described as:

\[ J_{sc} = \int_{\lambda_1}^{\lambda_2} \frac{e^{\lambda}}{hc} I(\lambda) A(\lambda) d\lambda \]  

(1)

where \( \lambda_1 \) and \( \lambda_2 \) respectively represent the maximum and minimum wavelength of incident light (one Sun or LSCs). \( I(\lambda) \) is the spectral irradiance (power density) of incident light, \( A(\lambda) \) is the absorbance. The sampling interval in the numerical integration is 1 nm.

3. RESULT AND DISCUSSION

In order to confirm the accuracy of the simulation method, PSC and flat cell is simulated when illuminated by one Sun. The geometric parameters are set to be the same as the reference \(^{12}\), i.e., 80nm ITO layers and 130nm ZnO layers. The \( J_{sc} \) in PSC is enhanced by a factor of 1.48 when compared with the flat cell, similar to the experimental results in the reference, confirming the accuracy of the simulation method.

When illuminated by one Sun, the spectrally absorbance curves of flat cell, PSC, and RTSC are shown in Fig. 2a. In shorter wavelengths (below 550nm), the light absorbance in RTSC is higher than in PSC, while in longer wavelengths (between 600nm and 700nm), PSC shows better light absorption efficiency. As a result, when illuminated by one Sun, the \( J_{sc} \) in RTSC is similar to that in PSC.
When illuminated by the LSC, the optimal thicknesses of ITO and ZnO layers in PSC are 150nm and 190nm, respectively. The spectrally absorbance curves of the cells are shown in Fig. 2b. In this case, the J_{sc} in PSC is 88% and 58% larger when respectively compared with the flat cell and RTSC. One should keep in mind, the optimal geometric parameters of the cells are considerably different when illuminated by one Sun and by the LSCs. Therefore the absorption curves in Fig. 2a and Fig. 2b are not the same.

When illuminated by one Sun, the value of J_{sc} in PSC and RTSC are similar. In contrast, when illuminated by the LSC, J_{sc} in PSC are larger than in RTSC. The phenomenon is mainly attributed to two reasons. First, the light scattering efficiency in PSC is higher than that in RTSC at longer wavelengths (between 600nm and 750nm), where the emission intensity of LSC concentrates. Second, the light interference effects in the absorbing layers improve absorption efficiency (As Fig. 2b shown, light absorbance peak of flat cell (blue line) is near 625nm, where the light absorption coefficient of a-Si:H is poor. Therefore, the absorption peak is attributed to the light interferences inside the absorbing layer.). The randomly textured back reflectors lead to non-specular light reflection \(^{17}\), thus removing the coherent interference effects. In contrast, the periodic plasmonic structures lead to specular light reflection \(^{17}\), therefore maintain the interferences. When PSC is applied, the light absorbance at 625nm remains almost constant. In contrast, when RTSC is utilized, the light absorbance near 625nm obviously drops, confirming the second reason.

In order to further confirm the second reason, the cells under the illumination of one Sun are investigated. As Fig. 2a shown, light absorbance peak of flat cell (blue line) is near 580nm, where the absorption coefficient of a-Si:H is high enough that photons will be totally absorbed before passing through. In another word, no interferences near 580nm exist inside the absorbing layer, and the absorbance peak is attributed to the interferences inside the antireflection layer (ITO layer), which will not be influenced by the back reflectors. As a result, neither PSC nor RTSC leads to absorbance decrease near 580nm.
4. CONCLUSION

In this research, we couple nanostructured plasmonic back contact to LSC solar cell, tuning its geometric parameters, confirming that its photocurrent is much larger compared with the frequently used structure – textured solar cell. The reasons for the superiority of nanostructured solar cells are analyzed in detail. Most researches related to LSCs focus on enhancing the efficiency of concentrators. We pay attention to the matching between the plasmonic solar cell and the LSC. In this research, only one shape of nanostructure has been investigated. In the future, more kinds of plasmonic solar cells attached to LSCs will be studied.

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REFERENCES