The External Light Trapping Using Down-Conversion Polymer and Diffuse Trench Reflectors

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***Abstract* — External light trapping has been proposed as an alternative to internal light trapping. The advantage is that the electrical and optical characteristics can be designed separately. This enhances the degree of improvement that nano-photonics can contribute to the solar cell efficiency and J_{SC}. In this work, we use diffuse trench reflectors with down-conversion polymer to demonstrate the concepts of a low-cost, widely applicable scheme for the external light trap. A >50% enhancement of the J_{SC} can be observed with proper designs and configurations. The proposed external light trap can be applied to nearly all thin-film solar cell technologies since the external optical components do not affect the electrical diode characteristic of the solar cells. The efficient external light trap is attributed to the high reflectance of the disuse mirror and its wide-angle diffractions, optical confinement due to the trench reflector, and the additional short-wavelength spectral enhancement by the down-conversion mechanism.**

I. Introduction

The advanced photonic management for optoelectronic devices has been an important subject over the past decades. Previously, the light trap is accomplished using randomly textured surfaces, grating couplers, or photonic crystals directly beneath the solar cell active layers [1, 2]. The potential complications of this internal light trapping scheme is that the electrical and optical behavior of the device are interwoven, leading to the need for co-optimization of device electrical and optical characteristics. It has been shown that high-aspect-ratio photonic nanostructures are extremely beneficial for solar cell light trapping, but the thin-film morphology on the highly textured substrate is by no mean leading to decent electrical diode [3]. The coupled electrical-optical simulation is then proposed and widely studied, to simultaneously optimize the solar cell electrical and optical characteristics [3, 4].

External light trapping has been proposed recently to overcome the above-mentioned issues of conventional light trapping [5-7]. The degree of enhancement by external light trapping can, therefore, be much higher than what is achievable by internal ones. In this work, we use diffuse trench reflectors with down-conversion polymer to demonstrate the effectiveness of this design. In some senses, the external light trap is similar to the solar concentration at low concentration ratio. As a result, the key difference between the scheme proposed here and conventional lens-based III-V concentrator is the cost. As long as the cost of the external light trap is not higher than the internal light trap, the strong photon confinement provided by the external trapping is very competitive.

The last factor further enhances the external light trap here is by using spectrum conversion. The down conversion mechanism of phosphorous shift the high energy solar photons to around λ=600nm where the external quantum efficiency (EQE) is the highest for amorphous silicon solar cells. For other solar cell materials, various down conversion polymers are readily available to be incorporated into our diffuse trench reflector scheme. Further improvement in efficiency and J_{SC} can be achieved by using microcell configurations although the cost can be elevated.

II. Experiment Methods

FTO-coated glass is cleaned firstly by acetone and IPA. Afterward, the p-i-n amorphous silicon (α-Si) or amorphous silicon carbide (α-SiC) film is deposited on FTO glass, and the thickness is illustrated in Fig. 1. The p-i-n Si/SiC film is deposited by very high-frequency plasma-enhanced chemical vapor deposition (VHF-PECVD) at 250°C. The ITO is deposited by sputtering. A stencil mask is placed on the α-Si film during ITO deposition to form the patterned ITO electrodes. Finally, reactive ion etching (RIE) using CF_4/Ar at 20 mtorr is employed to etch the portion of silicon film which is not covered with ITO, and the contact to the bottom FTO layer is achieved.

For phosphor layer, the 1g EY4254 silicate phosphor from Intematix Corporation is added into 6.6g Polydimethylsiloxane elastomer from Dow Corning Corporation. Afterward, the phosphor-mixed solution is sent to the small vacuum chamber to eliminate the bubbles in the solution. The phosphor-mixed solution is then spin-coated on the petri dish under 300 rpm and 30 seconds. Finally, the petri dish was put into the oven at 70°C for 2 hours. The photoluminescence and photoluminescence excitation spectrums are shown in Fig. 1.

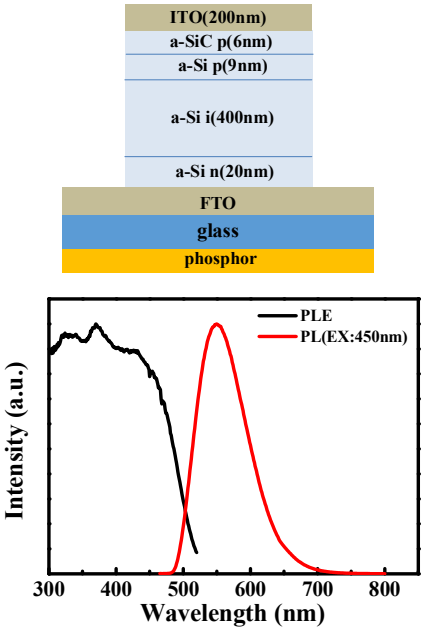

Fig. 1. (Top) The amorphous Si/SiC solar cell is used as an example to demonstrate the effectiveness of external light trapping. (Bottom) The photoluminescence (PL) and photoluminescence excitation (PLE) spectrums for the phosphor.

III. Results and Discussions

Fig. 2 illustrates the EQE for a standard configuration where the solar photons are incident through an up-down converter and then into the solar cells. It can be seen that the current down-conversion phosphor is effective to increase the short wavelength response. It can be seen that under such a standard down-conversion set-up, the short wavelength EQE is clearly increased proving the effectiveness of our down-conversion polymer. Nevertheless, the long-wavelength EQE is reduced by adding the down-conversion polymer. This is due to the re-emission of the photons by phosphor is isotropic leading to loss.

Fig. 3 plots the configurations for the external light trapping. The diffuse medium is applied to the surface of the trench to form a diffuse trench reflector. The incoming photons can be reflected effectively, even if the photons are not directly impinging on the solar cells. In concept, this is to some degree similar to a low-cost solar concentration. In addition to the trench, the down conversion polymer is important for the further increase of the J_{SC}. The conversion of short wavelength photons to middle wavelength are achieved by using down-conversion phosphor. From the PLE spectrum in Fig. 1, it can be seen that the emission wavelength of the phosphor is around 600nm, which is near the EQE peak of the standard α-SiC/α-Si.

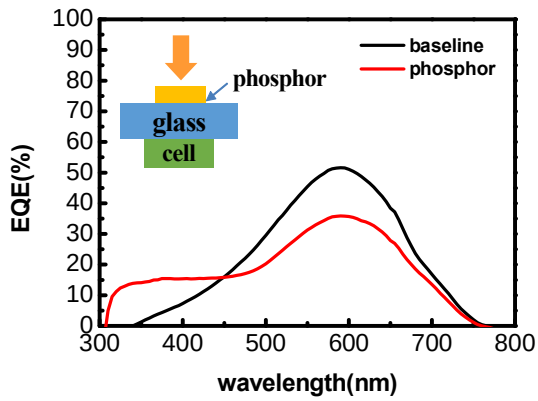

Fig. 2. The EQE when the light is incident from the phosphor side. The configuration is illustrated in the inset.

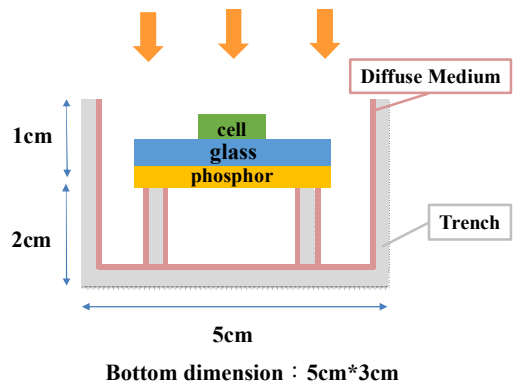

Fig. 3. The external light trapping scheme using phosphorous down-conversion polymer and the diffuse medium trench reflector.

The effect of down-conversion polymer is demonstrated clearly in Fig. 4. The diffuse trench reflector enhances the light scattering and light collection. The high reflectance and the wide diffraction angles of the trench is very effective for concentrating the solar photons into the solar cells. The glass substrate can act as a waveguiding layer in this case, to gradually guiding the solar photons into the solar cells. A further photonic design in this glass waveguide can be significant and can further increase the solar photon collection. The J_{SC} is increased from 12.01mA/cm^2 to 16.81mA/cm^2 in the case of diffuse trench reflector. The

down conversion polymer further increases the J_{SC} to 18.58mA/cm^2. The underlying physics is that the spectrum conversion to enhance the charge collection efficiency. Short wavelength photons can subject to surface absorption issue due to very high absorption coefficient in semiconductors for photon energy significantly greater than the bandgap energy. In this case, the e-h pair generated is unlikely to be collected by the P-N junction. Down conversion eliminates this issue by converting the short wavelength photons to middle wavelength photons where the EQE is at peak.

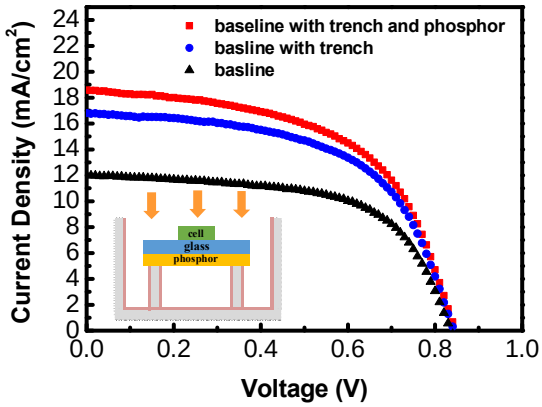

Fig. 4. The J-V characteristics for a external light trapped solar cell. It can be observed that the down conversion phosphor further increases the J_{SC}.

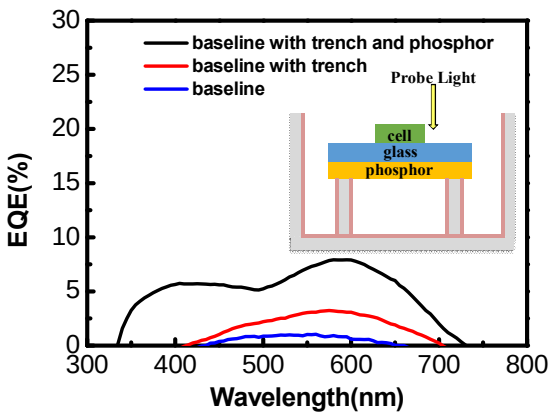

Fig. 5. The EQE when the light is not directly incident upon the cell. In the external light trapping, the solar photons can be collected even if they are not directly impinging on the cell.

To further investigate the photon collection phenomenon in our external light trap schemes, the EQE for the side illumination is illustrated in Fig. 5. When photons are not directly incident on the solar cell, it is a waste if there is no external light trapping. The effectiveness of diffuse trench and the down-conversion polymer is shown in Fig. 5. The addition of the trench and phosphor can enhance the photon collection over a broad wavelength range. The collection of the solar photons in Fig. 5 is due to the absorption and re-emission of the photons by the phosphor and the effect of diffuse trench. To further increase the enhancement, a deeper trench depth, a designed glass waveguiding structure, and the use of microcell configuration can be very effective.

IV. Conclusions

In this work, we use diffuse trench reflectors with down-conversion polymers to demonstrate the effectiveness of external light trap. A >50% enhancement in J_{SC} is observed while the cost of making the external light trap structure is minimal. The physics behind the elevated J_{SC} is due to the strong optical confinement by the trench configurations and the wide-angle diffraction of the diffuse medium. The glass substrate can also support waveguiding in the in-plane directions. Additionally, the spectrum conversion by the down-conversion polymer further enhances the J_{SC} by 2mA/cm^2 in this study. Future improvement can be the use of up-conversion polymers to harvest long wavelength photons or the realization of multi-exciton generation. Microcell configuration can also be beneficial for external light trap, but it can add additional cost. We believe the proposed scheme for external light trap is very promising for future advanced photonics for solar cells.

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