Design of anti-reflective graded height nanogratings for photovoltaic applications

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***Abstract*-Design of nanogratings with graded heights is proposed for solar-cell applications. The designed structure gives rise to absorption enhancement in solar-cells by reducing the reflection losses and focusing the incoming radiation into the photoactive layer. The results show that solar-cell efficiency is increased by 15% with graded height nanogratings.**

I. Introduction

Solar energy is a clean, inexhaustible and endless source of the energy. In recent years, increased energy demands and worldwide reduction in the usage of fossil fuels give rise to an increase in the interest in solar energy. Many studies have been carried out to increase cell and module efficiencies and significant steps have been recorded. There are various researches carried out to reduce the reflection of light falling on the solar-cell by utilizing artificial structures known as anti-reflection coatings (ARCs). For instance, Victoria *et al.* numerically and experimentally realized monolayer, bilayer and trilayer ARC designs for multi-junction solar-cells [1]. The importance of angular light distribution and wide spectral bandwidth is also emphasized for optimization of ARCs and two experimental methods are utilized for directly obtaining spectral and angular performance. Another ARC concept was introduced by Chhajed *et al.* that uses a broadband, omnidirectional, graded-index ARC design based on a nanostructured low-refractive-index Silica (SiO_2) fabricated by oblique-angle deposition [2]. By designing three-layer ARC, reflectance percentage has been reported to decrease to 5.9% over wavelength range from 400 to 1100 nm.

In this study, we propose an ARC concept with an additional focusing property to have more efficient absorption in solar-cell photoactive layer by modifying a conventional nanograting structure. Therefore, the main novelty of this proposal comes from the combination of anti-reflection property and optical focusing phenomenon based on a graded-height nanograting (GHNG) structure.

II. Design Parameters And Optical-Electrical Simulation Results

3D representations of the conventional and proposed GHNG structures are given in Figs. 1(a) and (b), respectively. In order to have ARC property, regular TiO_2 grating with Λ=50 nm periodicity is constructed on top of a bulk TiO_2 layer and silicon (Si) solar-cell device with Al back reflector layer as shown Fig. 1(a). By introducing this conventional grating configuration, more solar power is desired to be harvested thanks to the index-matching ARC effect of the grating structure and therefore Fresnel reflections are suppressed. Thicknesses of Si, bulk TiO_2 and TiO_2 grating layers are chosen as t_{Si}=3 μm, $t_{TiO2(bulk)}$=62 nm and $t_{TiO2(grating)}$=400 nm, respectively. Moreover, refractive indices of TiO_2 and Si at λ=500 nm are selected to be n_{TiO2}=2.48 and n_{SiO2}=4.30, respectively. With respect to the aim of this study, regular grating layer (Fig 1(a)) is taken as reference structure and modified by changing the heights of each grating element and therefore a GHNG layer is defined in order to have both ARC and focusing effect in the same structure. The height of each grating element is decreased starting from $t_{TiO2(grating)}$=400 nm with 82 nm steps in each grating period to obtain efficient focusing property inside the Si layer.

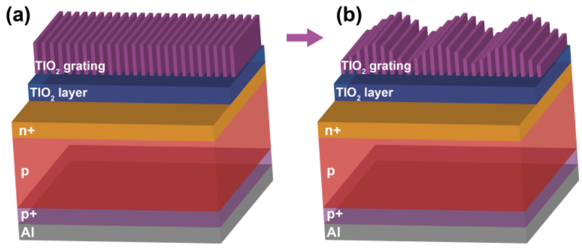

Fig. 1. 3D representation of the solar-cell structure with (a) conventional grating and (b) designed GHNG layers.

A commercial-grade simulator based on the finite-difference time-domain method was used to perform numerical calculations [3]. In order to evaluate the anti-reflection efficiency of different layer compositions, reflectance spectra of various solar-cell cases are calculated as shown in Fig. 2. The given figure shows the reflectance results for five different types of layer compositions, which are {bare Si}, {Si+TiO_2 (62 nm)}, {Si+TiO_2 (462 nm)}, {Si+TiO_2 (62 nm)+Conventional Grating} and {Si+TiO_2+ GHNG}. Here, other layer configurations which do not have the grating feature are also analyzed in terms of reflectance due to the requirement for a detailed comparison among all the cases. In order to compare the reflection losses, average reflectance values are calculated between the wavelength interval of λ=[400 nm - 1100 nm] for each reflection curve. The calculated results show that the lowest average reflectance (9.68%) is obtained for the GHNG structure, however, the average reflectance for the conventional grating case can only be reduced to 18%. Moreover, compared to the non-grating cases, it can be seen from Fig. 2 that the proposed GHNG structure is still better in terms of the reflection losses. These FDTD results demonstrate that a solar-cell with GHNG structure has less reflectance loss than other cases including conventional gratings.

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The electric field (transverse-magnetic polarization) distributions of conventional grating and GHNG are given in Figs. 3(a) and 3(b), respectively. As can be seen from the figures, electric field is localized in different positions inside the GHNG based solar-cell because of the focusing property aroused due to gradient index distribution. In the given figure, the reason for the absence of the usual focusing characteristic is due to the periodic boundary conditions which give rise to constructive interference in specific locations in photo-response layer.

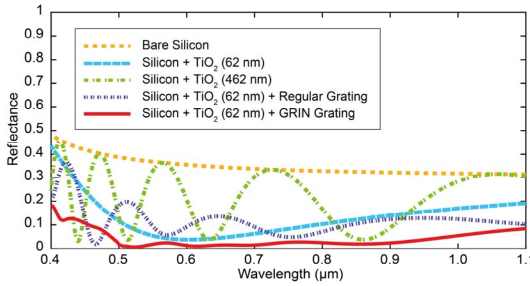

Fig. 2. Front surface reflectance spectra for solar-cells with different structural layer compositions.

Collection efficiency of photo-generated carriers is increased in an effective manner since the incoming radiation is especially focused at the depletion region of the GHNG based solar-cell [4]. Moreover, thanks to the focusing feature, light trapping performance is increased due to the strong oblique reflections on the surface of Al layer. The depth of the localized fields (focal points) can be adjusted by controlling the parameters of the GHNG such as filling ratio, height and curvature degree of the grating elements.

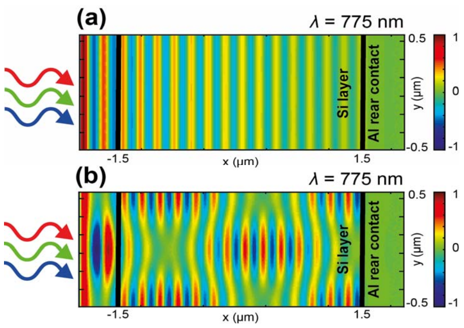

Fig. 3. Electric field distributions at λ=775 nm inside the solar unit-cells with (a) conventional grating and (b) GHNG structure.

A commercial-grade device simulator that self-consistently solves the Poisson and drift-diffusion equations was used to perform the charge transport calculations of the designed solar-cell [5]. Current density-voltage (J-V) curves for each structure case are calculated as shown in Fig. 4 to display the enhancement in the current density of solar-cell. It is observed that the GHNG based solar-cell structure has the highest short circuit current density among the analyzed structures (J_{sc}=26.1 mA/cm^2), however, the conventional grating structure has a lower value (J_{sc}=22.7 mA/cm^2). Furthermore, the power-voltage (P-V) curves in Fig. 5 are also generated to show the increase in the efficiency of solar-cell. In accordance with J-V curves in Fig. 4, maximum efficiency is obtained from the GHNG case (η=16%) whereas the solar-cell with conventional grating has the efficiency of η=13.84 under AM1.5 conditions.

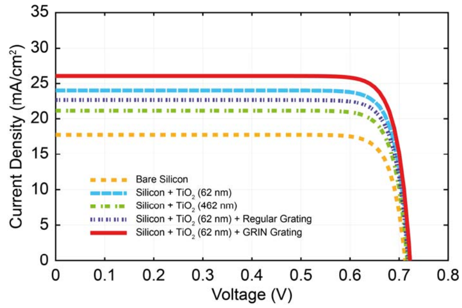

Fig. 4. J-V curves of solar-cells based on different structural layer compositions.

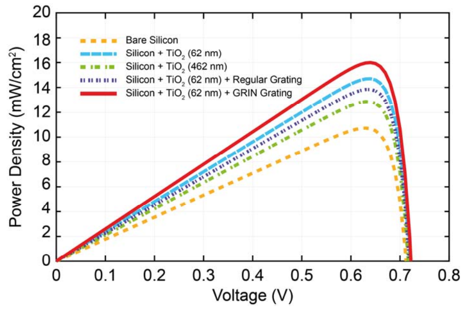

Fig. 5. P-V curves of solar-cells based on different structural layer compositions.

III. CONCLUSION

In summary, we propose a new ARC design with reduced reflection losses and focusing property in order to increase the light trapping and absorption efficiency in photovoltaic applications. Our approach provides an efficient combination of ARC and grating-lens in a single structure that can be a good candidate for boosting solar-cell efficiencies. Additional light trapping scenario for the back reflector will further enhance the performance of the solar-cell if one replace the plain Al back reflector.

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