Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2018, 5(2): 113-117

Research Article ISSN: 2394 - 658X

Enhancement of Ultrathin Amorphous Silicon Solar Cells Performance Using Dual Gratings

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ABSTRACT

We analytically explore the high optical performance of an ultrathin amorphous silicon (a-Si) solar cell by rigorous coupled wave analysis (RCWA) method. By studying the absorption spectrum and field intensity profiles, we have investigated the importance of the grating structure via scattering and diffraction mechanism. A significant improvement is observed with the cell efficiency (η) as high as ~19% and the current density (Jsc) about ~29.47mA/cm^2 within 50nm thick a-Si absorber region for the perpendicular polarization case (TE). In addition, this optimal design is compared with the various solar cells based on the different back reflector. The demonstrated design includes indium tin oxide (ITO) as a perfect anti-reflection coating (ARC) and good transparent conducting oxide layer as well. Overall, an ultrathin a-Si solar cell based on dual grating structure could show enhanced optimal performance.

Key words: Solar cells, RCWA method, cell efficiency, current density, back reflector, dual gratings

INTRODUCTION

Nowadays, enormous attentions have been paid towards the a-Si thin film solar cells to their strong absorption an entire visible region which generates the maximum number of the electron-hole pair in the absorber region. Thin film solar cell technology has the advantage of reduced materials quantity, light-weight, more flexible devices and low cost as compared to others. This technology has some unfavourable conditions such as less photon collection in longer wavelength as compared to shorter wavelength region [1-2]. To overcome such issues, the efficient light trapping schemes are facilitated to confine the red and near-infrared part of the spectral region with the use of metal nanostructure such as particles, gratings, wire, porous (Si) structure etc [3-6].

Feng *et al* have reported the design and optimization of thin-film C-Si solar cells and observed the improved performance (~19%) by using the diffraction grating and distributed Bragg reflectors [7]. Mutitu *et al* have presented the design and PECVD fabrication of hybrid dielectric metallic back reflectors for a-Si solar cells and reported a large number of DBR layers requirement to have maximum reflectance [8]. Abass *et al* have numerically studied the dual-interface grating (DIG) systems for the enhancement of the optical behaviour in thin film silicon solar cells using both plasmonic and dielectric (photonic) modes. This designed solar cell was integrated with the silver (Ag) grating at the bottom of the active region as well ITO gratings at the top. The various grating periods at the specific interfaces shows bright expose and guiding modes at normal incidence angle. Due to plasmonic and photonic effects, they could observe the strong coupling to a higher order guided modes and achieved broader absorption enhancement in UV-Visible region [9]. Ma *et al* have demonstrated an efficient light trapping mechanism by using ultrathin crystalline silicon solar cell with the conventional grating structure. The optimized crystalline silicon solar cell could yield 33.9mA/cm^2 current density using the 3D RCWA method. Their reported results were found to the Yablonovitch limit in the near-visible and infrared region. These results were emphasized for the composite grating and played a pivotal role to enhance the optical performance of the solar cells [10].

In this paper, we present the design of an ultrathin a-Si solar cell with different back reflectors for the better optical performance. In preceding section, the designing approach and the simulated structure are presented. In later part of the paper results and conclusions are discussed.

DESIGNING APPROACH

The design architecture of ultrathin a-Si solar cell is shown in fig. 1 (inset). The designed solar cell was composed of indium-tin-oxide (ITO) anti-reflection coating (80nm), 50nm absorber (a-Si), 20nm gratings (ITO/Ag) and 200nm substrate (Ag). The metal substrate serves as a perfect back reflector and top ITO layer acting as a contact layer. In order to get improved absorption in an entire wavelength region, the metal back reflector is a reasonable choice and it has more possibility of optical enhancement at longer wavelength region [11]. Within absorber region, ITO and metal gratings are embedded to increase the reflection light at larger diffraction angle in order to increase the photon residential time. Noble metals (Ag, Au & Al) nanostructure has been engineered within the complete solar cells to increase the optical path length into the absorber layers [12, 13]. The gratings were used to fold back the incident light into the absorber region by prolonging the photon path length. Several numerical methods are available to solve the Maxwell equations for simple structures such as finite-difference-time-domain (FDTD), finite element method (FEM), RCWA method etc. The proposed ultrathin C-Si solar cells were analyzed by using RCWA method. This method is known as a simple and fast method in which periodic boundary conditions (PBC) is applied in x- and y-axis whereas the perfect match layer (PML) is at z-axis.

RESULTS AND DISCUSSION

In this section, we have explored the study of five different solar cells named as cell ‘A’ (ARC+ substrate), cell ‘B’ (ARC+Top GRA+Substrate), cell ‘C’ (ARC+Bot GRA+Substrate), cell ‘D’ (ARC+Dual GRA) and cell ‘E’ (ARC+Dual GRA+Substrate). Figure 1 shows the absorption spectra of the various designed solar cell for the perpendicular polarization case (TE). Here, a weak absorption can be observed from the cell ‘A’ due to less scattering and no diffraction mechanism. The improved optical spectra can be observed for the cells ‘B’ and ‘C’ because of the top dielectric and bottom metal gratings. Especially, cell ‘C’ has two significant (broad curve) contributions to the improvement of a collection of the photons comes from 700 to 800nm and 1000 to 1100nm with the effect of metallic gratings. These peaks are broader and located where the reference solar cell absorption is low. Similarly, the dual grating (Cell ‘D’) structure without metal substrate provides the considerable effect in the visible and near-infrared spectral region.

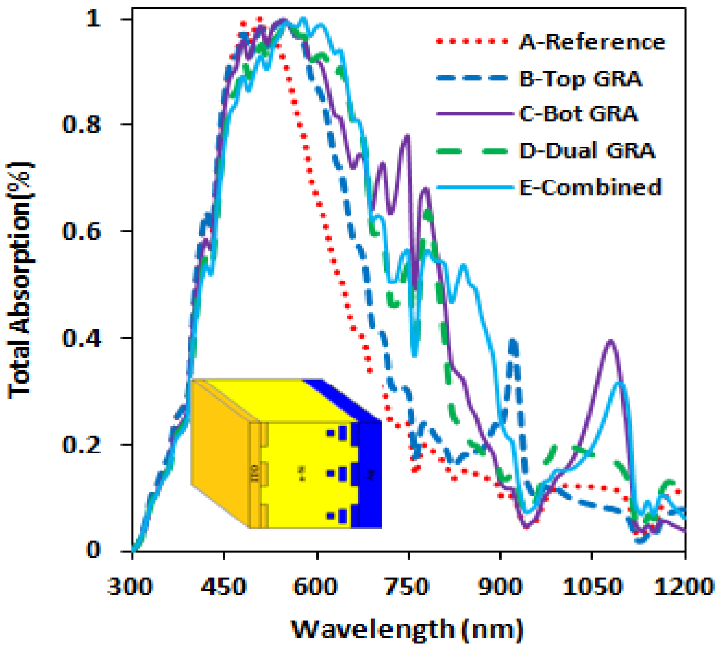

Fig. 1 Absorption Spectra and Schematic Diagram (inset) of an Ultrathin a-Si Solar Cell [14]

Overall, the final solar cell ‘E’ shows significant absorption enhancement to a broader spectral region. The interfaces of the gratings, width (period), fill factor (FF) and thickness (height) were well chosen for the improved photonic effects and guided modes coupling between the absorber region which could improve the performance [11].

It can be observed that the optical performance was improved with the use of a single (dielectric/metallic) or double (dielectric and metallic) gratings due to the significant role with respect to reference cell ‘A’. Solar cell ‘B’ shows about 41% absorption due to the strong photonic effect (Fabry- Perot resonance & localized electromagnetic guiding modes). Similarly, metal has unique optical properties in photonics field to control the light at sub-wavelength due to its maximum electron concentration capacity [15]. The metal and dielectric interfaces are yield the surface plasmon polariton (SPP), localized surface plasmon (LSP) and excitation on/around the metallic surface due to that cell 'C' shows 60% absorption enhancement [16-17]. Finally, cell 'E' generate yields 60.4% absorption due to the photonic and plasmonic modes. The optimal ultrathin amorphous silicon solar cell 'E' could achieve ~19.02% cell efficiency with ~29.47mA/cm^2 current density. The investigation of cell efficiency (η) of the solar cell is the ratios of the product of short-circuit current (Jsc), open-circuit voltage (V_{oc}), fill factor (FF) to incident power (P_{in}). It can be written as,

$$\eta = \frac{J_{sc} \text{x} V_{oc} \text{x} FF}{P_{in}}$$

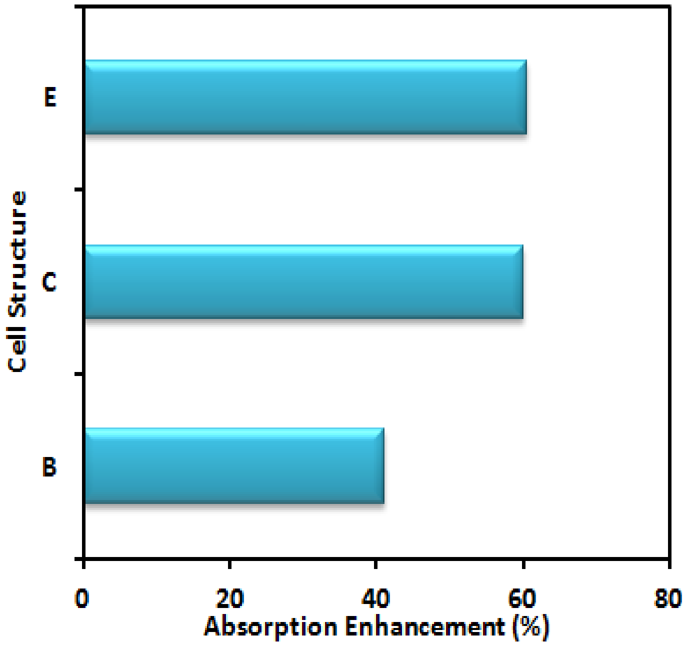

Fig. 2 Absorption Enhancement vs. Types of Solar Cell (TE Mode)

The diffraction gratings are most helpful for spatial separation of various wavelengths of light. Due to the dual grating (cell 'E') the collection of the photon is significantly enhanced as shown in fig. 3(a) for the TE polarization condition. Here, the metal and dielectric gratings have generated the strong field in the absorber layer. From this spectral curve, we have selected few highest peaks (580, 780, 840, 920, 1180 &1160nm) to analyze the field distributions as shown in fig. 3(b)-(g). The estimated light absorption at specific wavelengths are presented in table-1. The highest photon collection can be observed at a 580nm wavelength as shown in fig. 3(b) when the thickness of the dielectric layers are less as compared to the incident wavelength which might have support the localized (electromagnetic) modes [15].

Similarly, the strong field with Fabry-Perot (FP) resonance can be observed at the 780nm wavelength (fig. 3(c)) corresponding to the 71.3% light absorption as compared to the incident spectrum. At longer wavelength (fig. 3(d-g)), the standing wave pattern is appeared in the horizontal direction (X-axis) as the guided mode resonance (GMR). The surface guided mode resonance was appeared due to the strong field at an 840nm wavelength as shown in fig. 3(d). At 840nm, the incoming photon energy is concentrated and almost absorbed (>85%) photons within the absorber region. In longer wavelength, the strong field at the bottom Ag grating generates the surface guided modes in the absorber as shown in fig. 3(e). Figure 3(f)-(g) represents the reduced field intensity as compared to the previous one (920nm) without surface guided modes. However, the low field guided modes between the bottom gratings at 1100nm and 1160nm can be noticed. To overcome this problem novel engineering light trapping schemes are required. Zhang *et al* reported that the role of front grating was inefficient in the longer wavelength when the illuminated light came to Ag back reflector [11]. Further by optimizing the design, this problem can be minimized to an optimal level.

Table -1 Estimate absorption for the solar cell 'E'

Wavelength (λ) in nm	Absorption (%)
580	91.2
780	71.3
840	85.5
920	45.0
1100	56.0
1160	23.0

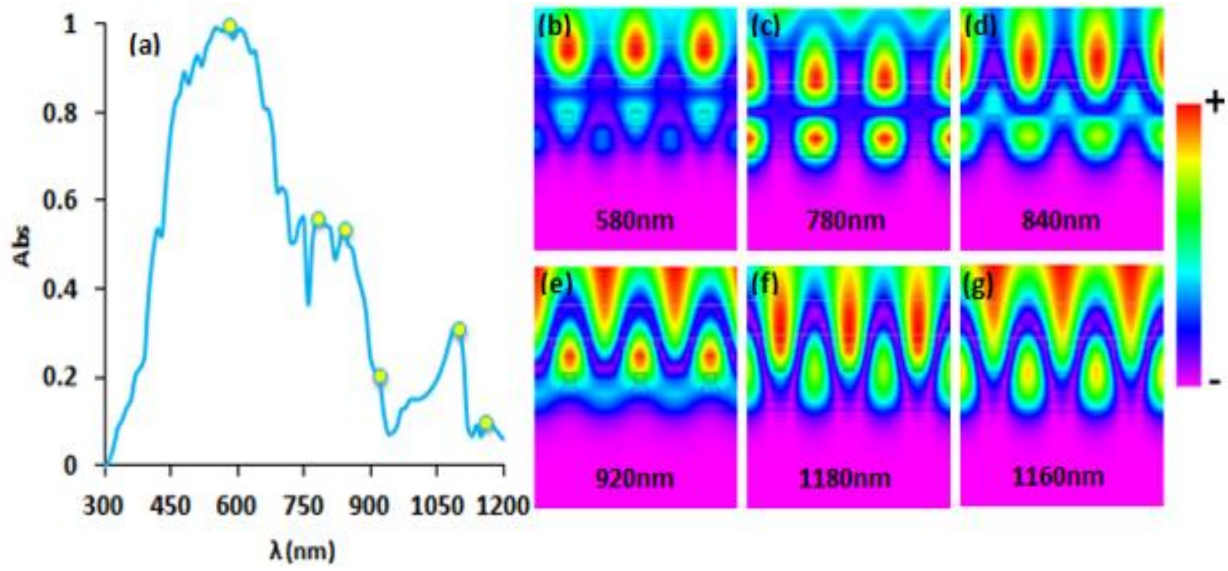

Fig. 3 Absorption Spectrum (a) and Transverse Electric Field Distribution at Different Wavelength of 580nm (b), 780nm (c), 840nm (d), 920nm (e), 1180nm (f) and 1160nm (g), respectively

CONCLUSION

In conclusion, the ultrathin a-Si solar cell structures with dual gratings have been designing and explored. By changing the grating (single or dual) layers of top and bottom of the solar cell structure, notable cell efficiency (~19.02%) and current density (~29.47mA/cm^2) were achieved. This result was due to the support of localized surface guided modes and Fabry-Perot resonance. Comparing with reference solar cell, the optimal design could enhance the absorption (~60.4%) within 50nm absorber region for the TE polarization condition. The proposed cell structure would be feasible to design and fabricate solar cell with strong light trapping mechanisms.

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