Research Article

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Improvement of Quantum Efficiency and Photon Absorption from Electromagnetic Waves: Amorphous Silicon Thin Film Solar Cell

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ABSTRACT

In this work, the performance of amorphous silicon (a-Si) thin film solar cell is demonstrated by integrating Ag at the bottom and indium tin oxide (ITO) nanostructures at the top, using the rigorous coupled wave analysis method. Among the various materials, amorphous silicon plays a significant role due to its ability to harvest photons from electromagnetic waves and its naturally abundant. The integration of photonic (ITO) and plasmonics (Ag) nanostructures are crucial for enhancing light-harvesting mechanisms through nanoscale engineering. In that way, the Fabry-Perot resonance, guided waves are helping to increase the life time of the light particle (photon) under transverse electric (TE) modes. Consequently, the localized field, surface excitation, and surface guided waves are also enhancing the light trapping mechanism under transverse magnetic (TM) field modes. Finally, the designed a-Si thin film solar cell yielded the highest conversion cell efficiency of 18.79% and a short-circuit current density of 28.57 mA/m^2 in TE modes. However, TM modes received 18% of conversion efficiency and 27.46 mA/m^2 of current density.

Keywords: Solar cell; Amorphous silicon; Absorption; Quantum efficiency; ITO

1. INTRODUCTION

In photovoltaic technology, ultrathin film amorphous silicon solar cell is gaining great interest due to the natural abundanceof silicon and low fabrication cost (Dubey et *al.* 2014; Saravanan et *al.* 2014). In addition, several light-trapping strategies play a pivotal role in the improvement of photon collection, these include the optimization of anti-reflection coatings (ARC), the use of distributed Bragg reflectors, nanoparticles, as well as photonic and plasmonic nanostructures. For designing thin film solar cell device, various theoretical methods such as finite-difference time domain method, rigorous coupled wave analysis (RCWA), plane wave expansion, finite difference frequency domain, and finite element method,are utilized (Pavan *et al.* 2025). Research communities are continuously working on the optimization of thin film solar cell parameters including thickness of each layer, the selection of the materials, and designing nanostructure shape and size. Pavan *et al.* (2025) reported the enhancement of light harvesting and conversion cell efficiency due to the selection of the materials, shape and size for anti-reflection coating materials.Nowadays, researchers are continuously working on the improvement of conversion efficiency with low-cost. The efficient light trapping mechanism is crucial in the thin film solar cell and becomes the pivotal role for the commercial production. Several light techniques have been investigated from the last few decades by the scientific communities. Law *et al.* (2008) proposed PbSe nanocrystals based solar cells using theoretical and experimental approaches.They investigated the internal quantum efficiency and external quantum efficiency (<100%) of PbSe active layers. The obtained results revealed a good agreement in between theoretical (modeling) and experimental results. Ning *et al.* (2007) investigated the design and optimization techniques for a highly efficient light-trapping structure to improve the efficiency of thin film amorphous silicon solar cells. They optimized each element or parameters of the cell structure which was majorly contributing to the enhancement of thin film solar cells and also reported that the nanogratings played key role for the improved cell efficiency. Leonid and Toyama (2014) presented the CdS and CdTe thin film solar cell and theoretically demonstrated the current voltage characteristics and quantum efficiency. This research paper presents some simulated results of variety of grating structure, the higher order diffraction angle with the transmission of light, study of the light reflection, and uncovers the mechanism at the back light extraction from the grating

structures. The mechanism of the light trapping interaction (guided mode) among the front and back gratings is analyzed, which considerably increases the light trapping by 154% compared to the reference solar cell. These simulation results demonstrate that the designed structure gives improved light harvestings. The optimizations of the designed metal and dielectric based solar structures contribute more to the significant outcome of short circuit current, absorption and quantum efficiency.

2. METHODOLOGY

Amorphous silicon thin film solar cells are among the most well-developed technologies in the photovoltaic market. Rigorous coupled wave analysis is also known as simple method. This designing and simulation work was carried out by using RSoft synopsis tool. First, a 100-nm thick silver (Ag) back reflector was used as the substrate. On top of this back reflector, a 50-nm thick amorphous silicon absorber layer was deposited, which incorporates integrated nanogratings with a height of 20 nm.

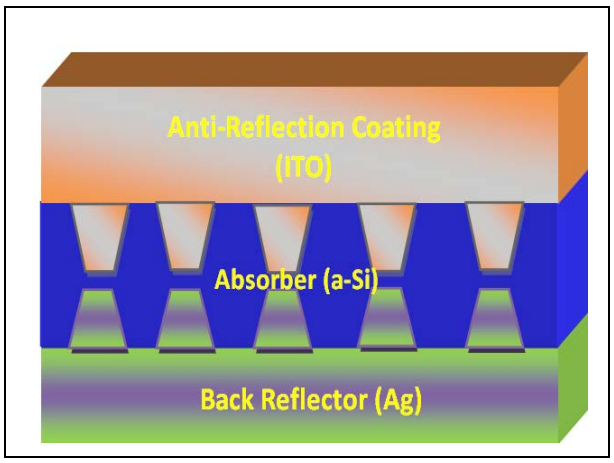


Fig. 1: Schematic diagram of thin film amorphous silicon solar cell

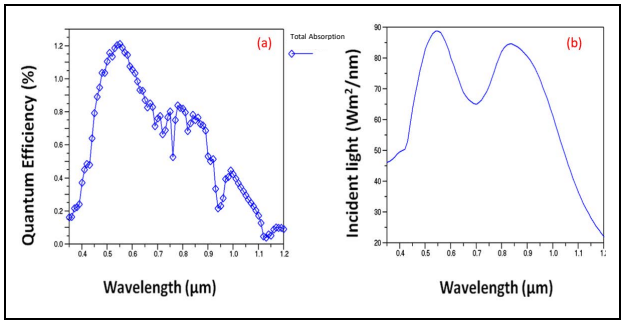


Fig. 2: (a) Quantum efficiency and (b) Incident light absorption spectrum of amorphous silicon solar cell with TE modes

By incorporation of nanogratings, the remaining 10 nm of amorphous silicon region is considered as absorber region. The anti-reflection coating layer was coated to the amorphous silicon absorber to reduce light reflection and increase the transmission of irradiating light particles (photons).

Each photon has some energy (E=hυ). Here, the periodic boundary conditions and perfectly matched layer conditions are applied along the Cartesian coordinate axes (X, Y and Z). These boundary conditions absorb the electromagnetic (EM) waves preventing reflections and effectively simulating an infinite spatial domain. It will support the high accuracy of simulation results.

3. RESULTS AND DISCUSSION

The collected photons from solar spectrum are utilized to convert electrons or other charge carriers within the amorphous silicon active layers. Fig. 2(a and b) depicts the light absorption from the solar spectrum under AM 1.5 conditions. These solar spectrumexhibited the maximum photon absorption at a wavelength of 550 nm, with a subsequent reduction in absorption at other wavelengths. Under visible spectrum, light absorption was reduced considerably, indicatingthe need for more suitable materials to enhance the photon collection.Fig. 2(b) illustrates the conversion of incident photons into electrons or other charge carriers. It is useful to find the ratio of number of charge carriers generated relative to the number of photon particles striking the sensitive area of the solar cell device. This quantum efficiency indicates highly sensitive and efficient device to convert as useful charge carriers to produce electricity. With this device under transverse electric modes, 18.79% of conversion cell efficiency was obtained. The significant results are the filling factor of 84.58%, an optimal bias voltage of 0.62V, an optimal bias current density of 27.42 mA/cm^2 and a short-circuit current density of 28.57 mA/cm^2. This light trapping mechanism is possible with various photonic effects such as Fabri-Perot resonance, surface guided modes etc. (Sigamani *et al.* 2022; Dubey *et al.* 2025).

Fig. 3(a and b) depicts the light absorption under TM field under AM 1.5 condition. Thesolar spectrum shows the maximum photon absorbed at 600 nm wavelength and reduced absorption in the longer wavelength region as shown in Fig. 3(a). Under visible spectrum, light absorption was reduced considerably, indicating the need for more suitable materials to enhance the photon collection. The collection of the photons and the enhancement of light-harvesting mechanism are enabled by distinct plasmonic effects such as localized plasmonic modes, surface excitations, and surface-guided modes (Prashant *et al*. 2022; Pavan *et al.* 2025). Fig. 3(b) shows the conversion of photons collection into electrons or other charge carriers. It is useful to find the

ratio of number of charge carriers generated relative to the number of photon particles striking the sensitive area of the solar cell device. This quantum efficiency indicates highly sensitive and efficient device to convert as useful charge carriers to produce electricity.

With this device under transverse electric modes, 18.06% of conversion cell efficiency was obtained. The significant results are the filling factor of 84.58%, an optimal bias voltage of 0.61V, an optimal bias current density of 26.36 mA/cm^2 and a short-circuit current density of 27.46 mA/cm^2. The fabrication of this amorphous silicon thin film solar cell could be possible by using advanced methods like plasma enhanced chemical vapor deposition, RF sputtering, and photolithography techniques.

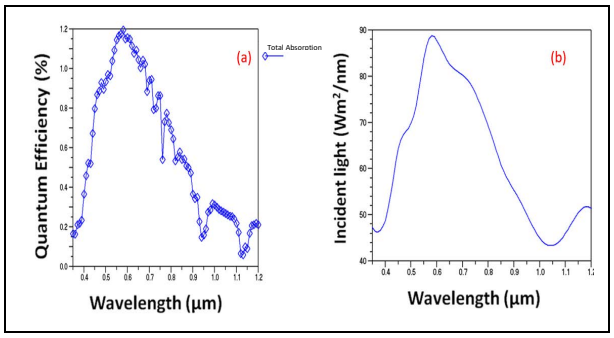


Fig. 3: (a) Quantum efficiency and (b) Incident light absorption spectrum of amorphous silicon solar cell with TM modes

4. CONCLUSIONS

In summary, the design and simulation of amorphous silicon thin film solar cells by using rigorous coupled wave analysis method. The proposed structure integrated an amorphous silicon active layer, silver back reflector at the bottom, ITO nanostructures at the top of the solar cell. The integration of photonic (ITO) and plasmonics (Ag) effects were capable for the enhancement of light harvesting mechanism. It has yielded 18.79 and 18% the highest conversion cell efficiencies and 28.57 and 27.46 mA/m^2 short-circuit current density under TE and TM modes. Furthermore, the optical performances can be improved by optimizing the size and shape of the dielectric and metallic structures at nanoscale level. This amorphous silicon thin film solar cells could be economical, environmental abundant material and experimentally feasible with advanced techniques.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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