Research Article

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Front Nanogratings Decorated Ultrathin Film Amorphous Si Solar Cell Performances

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ABSTRACT

Solar cells provide a renewable, clean energy source, reducing reliance on fossil fuels and minimizing environmental impact. They offer economic savings, energy independence, and flexibility for various applications. In this work, the nanophotonic and nanoplasmonic grating structures are integrated in the front side of the active (amorphous Si) layer. The transverse electric and transverse magnetic field distributions were demonstrated by varying the incident wavelengths at a normal incidence angle. Furthermore, improved current densities of distinct ultrathin amorphous Si (a-Si) solar cells decorated with nanogratings (SiO2, Ag, and Si3N4) were explored. The obtained results indicated that the optimized SiO2 nanogratings and Si3N4 film acted as anti-reflection coating (ARC) layers with air medium (AM 1.5) and showed a remarkable current density of 16.25 mA/cm2 in ultrathin a-Si solar cells with a thickness of 180 nm.

Keywords: Solar cell; Renewable source; Photonic; Thin film.

1. INTRODUCTION

Recent research has shown that thin-film solar cells have enormous nanostructures, garnering great attention due to their unique optical performance. To increase the collection of the photons, various light-trapping mechanisms were introduced by the research communities for longer optical path length such as nanogratings, nanoparticles, nanorods, distributed Bragg's reflectors, nano rings, nanodisks, nano-hemispheres, and nanotubes (Ali *et al.* 2022; Sayyed Reza *et al.* 2022; Mohammad, 2024; El-Khamisy *et al.* 2023; Sultan *et al.* 2024). Due to the nanostructures and the material shapes, they play a key role in photovoltaic (PV) cells. The design and simulation methods could minimize the manufacturing cost; Rigorous coupled wave analysis (RCWA), Density functional theory (DFT), Finite element method (FET), and Finite-difference Time-domain (FDTD) methods are well-suited and reported by various researchers (ElKhamisy *et al.* 2024; Lee and Kim, 2013). studied the optical absorption of two different amorphous Si thin-film solar cells using the RCWA method. They demonstrated 25% absorption enhancement within a 30 nm thin absorber (or active) region (amorphous Si) as compared to 100 nm, and finally achieved 14.83 mA/cm^2 in transverse electric (TE) polarization modes. (Mohsin *et al.* 2020) investigated the light-trapping mechanism in thin-film Si solar cells using the FDTD method. They have reached a maximum current density of 23.98 mA/cm^2 with the effect of TiO_2 antireflection coating (ARC, 70 nm), silver nanoparticles (Ag, 50 nm), silicon (Si) absorber (3 µm), and aluminum back reflector (1 µm). (Rani *et al.* 2021) theoretically investigated different sizes (30–100 nm) of silver nanosphere-integrated plasmonic solar cells using the FDTD method. The adopted Ag nanoparticles enhanced the scattering mechanism and reached the highest efficiency up to 15.6% at a 100 nm thick absorber from the visible spectral region. (Tahir *et al.* 2018) numerically optimized gold (Au) nanograting structure for improvement of light-harvesting (absorption) in thin-film a-Si solar cells using the finite elemental analysis method. The grating width varied from 250 to 350 nm and revealed significant light scattering by supporting the fundamental plasmonic mode since light absorption was efficiently improved in an amorphous silicon thin film solar cell device.

The influence of decorated front nanogratings (photonic and plasmonic) in ultra-thin film a-Si solar cells using the FDTD and RCWA methods was addressed in this work. The designing materials, parameters, and methods and the results obtained including field distributions of both polarizations (TE and TM) at various wavelengths and current densities, were presented.

2. DESIGN APPROACH

The design and simulation of ultra-thin amorphous silicon solar cells were done using the FDTD method. The RCWA method was useful for analyzing the field distributions at different wavelengths; the incident wavelength range was from 300 to 1200 nm for transverse electric field (TE) and magnetic (TM) field polarization. This proposed solar cell structure is composed of a front anti-reflection coating (ARC, Si_3N_4 = 20 nm), nanogratings (SiO_2 = 30 nm, Si_3N_4 = 20 nm and Ag = 30 nm), an amorphous silicon absorber of thickness 30 nm, and metal (Ag = 100 nm) as the backside reflector.

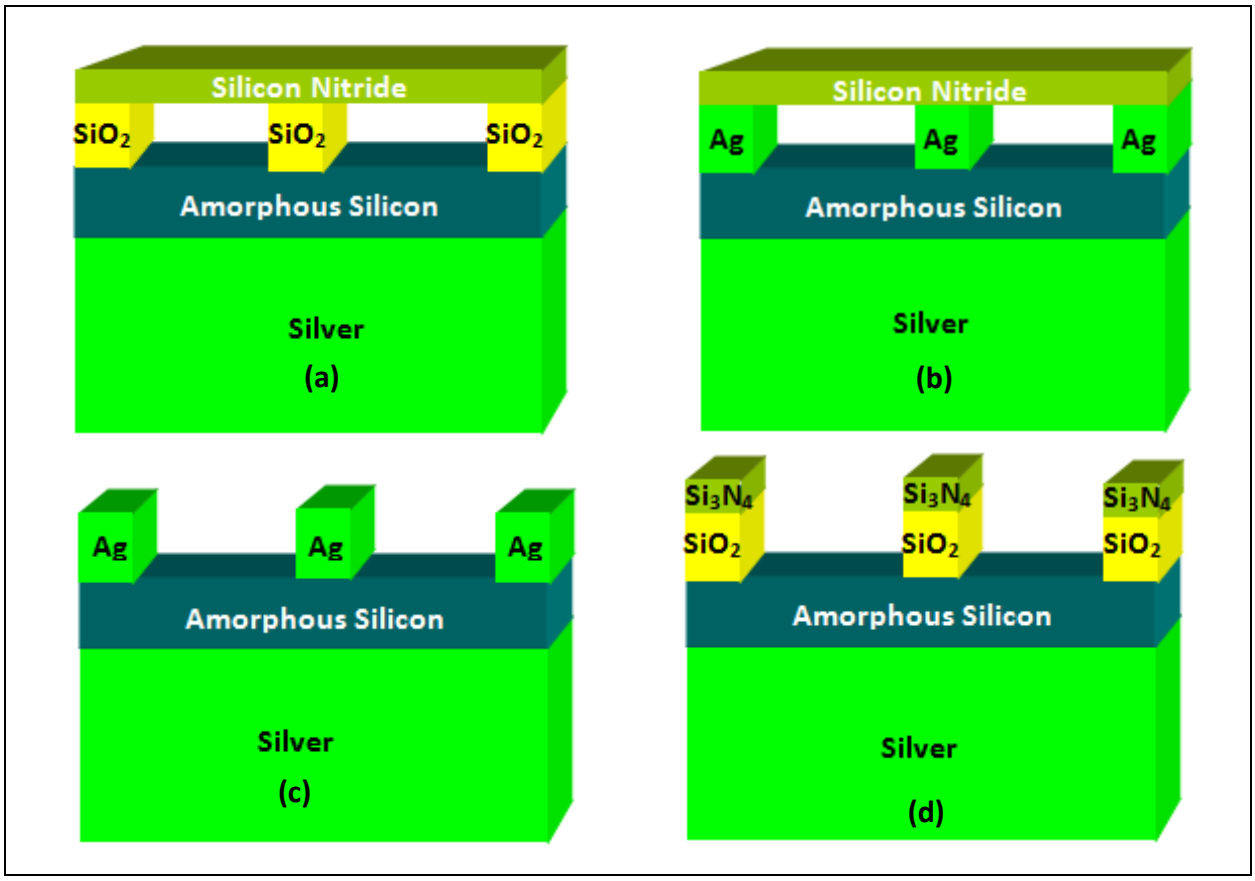


Fig. 1: Schematic diagrams of various ultrathin amorphous silicon solar cells

First, a solar cell named Cell 'A' was integrated with a Si_3N_4 antireflection coating, SiO_2 nanogratings, an amorphous silicon absorber, and an Ag backside reflector. Then, a solar cell named Cell 'B' was integrated with a Si_3N_4 antireflection coating, Ag nanogratings, amorphous silicon (a-Si), and an Ag reflector. Thirdly, the silver nanogratings, a-Si absorber, and Ag reflector were integrated and named Cell 'C'. Finally, in Cell 'D', Si_3N_4/SiO_2 nanogratings were placed on the top of a-Si absorber region with an Al reflector. By using these ultrathin film layers, four different solar cells were produced. The simulation region was terminated with the periodic boundary conditions (PBC) in the x- and y-directions, and the next perfectly matched layer (PML) was considered in the z-direction with periodic boundary conditions, using a homogeneous mesh with steps ranging from 1 to 5 nm. The current density of amorphous silicon absorber layers of different ultrathin-film solar cells was calculated by changing the ARC and texture structures. It aided in reducing the front-side reflection and supported the harvest of light within the absorber region. This simulation performance was considered for the plane wave with air mass 1.5 (AM 1.5) at a normal incidence angle. The designed solar cells with the wavelengths of near-field and far-field are depicted in Fig. 2. Maxwell's equations help explain how light is distributed inside and outside of the ultrathin-film solar cells.

3. RESULTS AND DISCUSSION

As mentioned in the previous works (Mohammad *et al.* 2024; El-Khamisy *et al.* 2023; Sigamani *et al.* 2023), light absorption depends on the various geometrical parameters with proper design and nanostructures. Changing the front side of ultrathin film is one way to enhance light absorption.

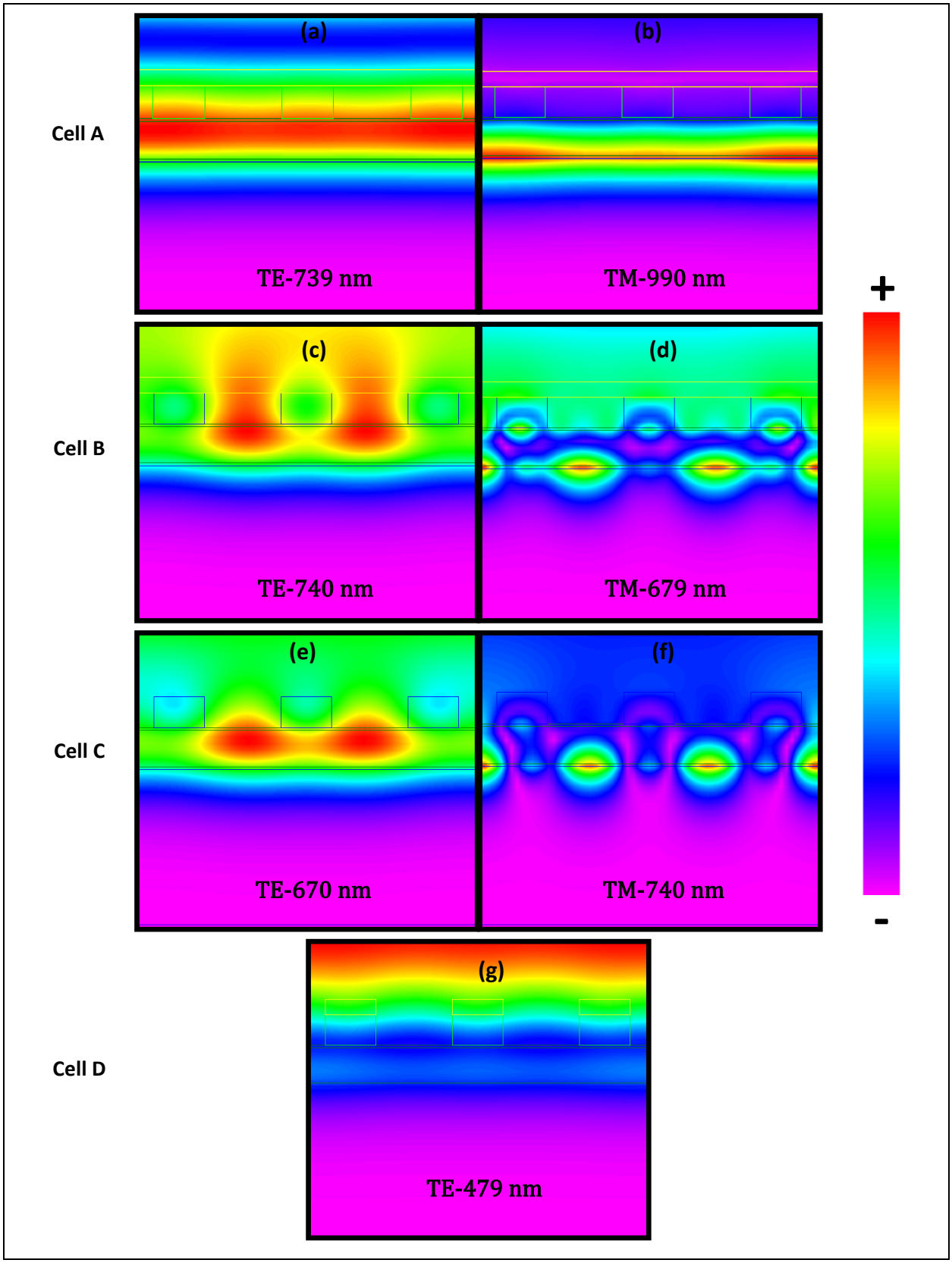


Fig. 2: Transverse electric (TE) and magnetic (TM) field distributions at different incident wavelengths

3.1 Field Analysis: Photonic and Plasmonic Effect

The geometry of the nanostructure determines how efficiently the incident light can trap and couple into the absorber region, as depicted in Fig. 2. First, 'Cell A' shows the strong light trapping in amorphous silicon absorber and surface guiding modes; Bloch modes appear at 739 nm (Fig. 2 a) incident wavelength (TE) within the 30 nm thin absorber region. Under a transverse magnetic (TM) field, the incident wavelength is considered as 990 nm (Fig. 2 b) and shows less intensity of light. However, strongly localized surface plasmon (LSP) polariton and surface-guided modes were noticed in the absorber region. The reduced light distribution and field excitation (Fig. 2 d) were noticed at 740 nm (Fig. 2 c) and 679 nm (Fig. 2 d) from 'Cell B'. The surface-guided modes were noticed in Fig. 2 c and strong light absorption due to the metallic grating and air medium. Fig. 2 d depicts less surface excitation (at 679 nm) between the metal and dielectric surface. Without Si_3N_4 anti-reflection coating (Cell C), the light-trapping mechanism was reduced to 670 nm (TE) and 740 nm (TM) (Saravanan *et al.* 2024). However, a strong field was noticed under TE polarization conditions. Furthermore, the field intensity and distribution were reduced by the integration of Si_3N_4 and SiO_2 nanogratings, as shown in Fig. 2 g (Cell D). Here, we demonstrated the light distribution of incident photons at various incident wavelengths in both polarization modes.

3.2 Current Density

With the effect of front side nanostructure support to absorb maximum photons, contributing to the current density, the spatially dependent current generation was calculated by,

$$E(\lambda) = \frac{hv}{\lambda}\ eV \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$Jsc = \frac{e}{hc}\int_{300}^{1200} \lambda A(\lambda)\frac{dI}{d\lambda}d\lambda \quad \ldots\ldots \quad (2)$$

where, 'E' is the energy of the photon, 'h' is the Planck constant, 'ν' is the frequency, 'λ' is the wavelength of incident solar spectrum (300 - 1200 nm), 'c' is the speed of light (2.99 x 10^8 m/s), 'A(λ)' is the absorption within the absorber region, and 'I' is the incident solar spectrum ($Wm^{-2}\ nm^{-1}$) (Tahir et al. 2018). Further, the current density (J_{sc}) of various ultrathin amorphous silicon solar cells, as shown in Fig. 3.

First, a 16.02 mA/cm2 current density was attained by 'Cell A' (solid black line), and then 14.8 mA/cm^2 by 'Cell B' (solid red line). Next, the current density of 15.8 mA/cm^2 was obtained by the silver-grating integrated ultrathin a-Si solar cell (Cell C, solid blue line) due to plasmonic effects such as surface guided modes and surface excitation between the metal and dielectric interfaces (Fig. 2). Again, 14.08 mA/cm^2 was attained (green line) by 'Cell D' due to the Si_3N_4/SiO_2 dielectric grating structure. Within the 50 nm thin absorber region, 'Cell A' highly reached the current density due to photonics effects such as Fabry-Perot resonance and surface-guided modes (Fig. 4). Overall, here air medium plays an important role and acts as a grating layer.

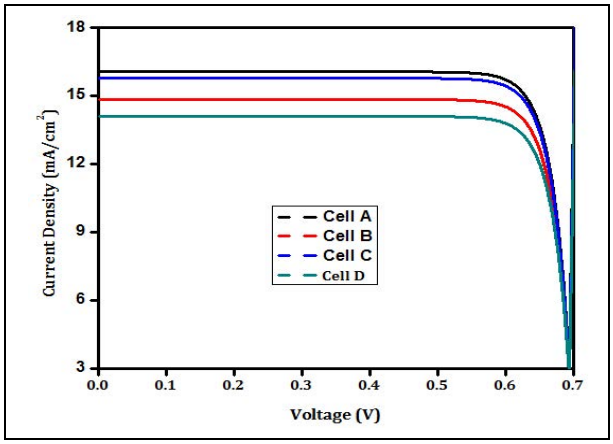


Fig. 3: The current densities of various ultrathin-film a-Si solar cells

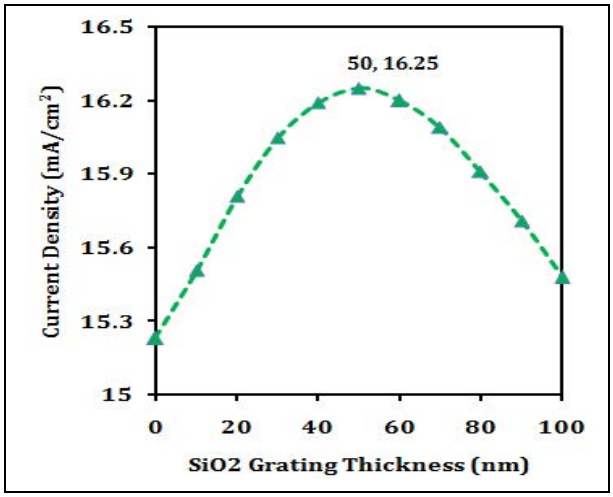


Fig. 4: Thickness of SiO_2 nanogratings vs. Current density

3.3 Optimization of SiO_2 Nanogratings

The impact of SiO_2 nanograting thickness (0–100 nm) is then evaluated, as shown in Fig. 4. As expected, the current density increased with the thickness of the nanogratings until reaching an optimal thickness of 50 nm, after which it decreased. Therefore, the SiO_2 nanograting was optimized, and the maximum current density of 16.25 mA/cm^2 was achieved within a 40 nm-thick absorber region. The light-trapping mechanism enhancement is crucially dependent on the diffraction nanograting, which supports the Bloch modes by using

thin-film solar cells (Aly *et al.* 2021). The Si_3N_4 antireflection coating (ARC) and SiO_2 nanograting-based (within absorbers) amorphous silicon solar cell performances were reported (Dubey *et al.* 2017). They demonstrated an enhanced cell performance of 79% due to SiO_2 nanogratings. Similarly, the SiO_2 ARC and nanogratings (front) integrated within ultrathin amorphous silicon solar cells and shown improved light harvesting due to that noticed significant optical performance (Sigamani and Dubey, 2022). So, these literature surveys confirm that the SiO_2 nanogratings incorporated PV devices showed optimal solar cell performance by enhanced light-harvesting mechanism due to increasing photon path length (omni-directional scattering, refraction and reflection) and the lifetime of the photon.

4. CONCLUSION

In this summary, the design and simulation of various ultrathin amorphous silicon solar cells (180 nm thick) were carried out and their performances were investigated by using the FDTD and RCWA methods. The photonic (Si_3N_4, SiO_2) and plasmonic (Ag) nanostructures are decorated in front of ultrathin amorphous silicon solar cells and studied their optical performance. Under the various incident visible (~700 nm) and infrared (~900 nm) wavelengths, the transverse electric field (TE) and magnetic field (TM) distributions were demonstrated and confirmed the significance of the light-trapping mechanism. The photonic modes (Fabry-Perot, surface guiding) and plasmonic modes (localized field, surface resonance, excitation) play pivotal roles in enhancing light harvesting. Finally, an optimized ultrathin film solar cell achieved a current density of 16.2 mA/cm^2 in a 30 nm-thick amorphous silicon absorber region with Si_3N_4 and SiO_2 front nanogratings. In the future, current density could be significantly improved by considering a few more parameters such as incident angle, active layer thickness, atmosphere temperature, and backside reflector.

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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