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Modeling and Simulation of Plasmonic Thin FilmGaAs Solar Cells using Rigorous Coupled Wave Analysis Method

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Abstract: Plasmonic solar cells have shown better light absorption due to use of metal nanoparticles, square or triangular gratings, nanocones etc.due to their light scattering capacity whichinducessurface plasmons.Inthis work, wepresent the modeling and simulation of plasmonic thin film solar cells using rigorous coupled-wave analysis approach. Our simulated result showed solar cell efficiency about 22 and 24% for thetransverse electric (TE) and transverse magnetic (TM) modes respectively. The enhanced cell efficiency for the transverse magnetic fieldis attributed to the plasmonic effect induced by the metal grating. In this study, we explore the various designing parameters of plasmonic solar cells.

Keywords: Solar cells, Simulation, RCWA Method, Absorption, Transverse Magnetic mode.

1. Introduction

Currently, the world's energy consumption is lesser than the earth's energy per hour received by the solar radiation of the sun. The electricity production via solar energy is crucial in order to overcome the problem of energy crises to worldwide. The solar cells are the best candidate as the carbon-free energy source in the view of global warming. The silicon thin film solar cells possess weak absorption of sunlight due to the thin layer of absorbing region. Therefore, performance enhancement of these solar cells is the topic of research today. Importantly, two ways are favorable to increase the efficiency of silicon thin film solar cells; 1) by employing a material of appropriate energy gap to absorb the maximum solar spectrum and by optimizing the optical, electrical and structural properties and 2) by employing new device engineering which can support effective charge collection with the better light absorption in the higher wavelength range of the solar spectrum. An optimal design engineering of the solar cells is important to enhance the cell efficiency by the scattering and coupling effect.

Among solar cells, GaAs based solar cells have received attention of the scientific community due to their better cell efficiency.In comparison to the conventional solar cell materials,GaAs is one of the demanded due to the absorption of high energy photons in short region, high crystal quality with a better operating frequency. A design of GaAs thin film solar cells by employing a periodic array of silver nanoparticles have been reported which showed an improvement in the light absorption due to the induced surfaceplasmon associated to the metal nanoparticles. A relative improvement in short-circuit current 31% was obtained with respect to a planar solar cell [1]. In another approach, a modeling of GaAs solar cells by using finite-difference time domain (FDTD) method and later fabrication have been demonstrated. A two-dimensional microspheres assembly was employed and found to be responsible for the enhanced light harvesting withthe cell efficiency 25 % [2]. Amodeling of GaAs solar cells with a double layer antireflection coating, silica nanosphere array at the top and a back reflector respectively have been used and studied for its performance by varying the cell thickness. The solar cell of 100 nm thickness has shown improved performance after the optimization of sphere size and its inter spacing distance [3]. A light trapping mechanism using GaAs nanoneedle arrays have been discussed by employing rigorous coupled-wave analysis (RCWA) and finite element method (FEM)methods. Theenhanced light absorption was noticed which has been regarded to the graded refractive index of nano-needle arrays that could efficiently couple and guided the light. With the optimization of solar cell design parameters, about 90 % enhanced light absorption was demonstrated[4]. By masked deposition, an experimental approach of fabricating silver nanoparticles based GaAs solar cells were presented. A strong scattering of light due to the induced surface plasmons with increased optical path length of the photons were noticed as a consequence increased short-circuit current density by 8% was obtained [5].

This work presents the modeling and simulation of plasmonic thin film GaAs Solar Cells using rigorous coupled wave analysis method. Our design efforts show the enhanced light absorption.

2. Design & Simulation Approach

The proposed design of GaAs solar structure is shown in **figure 1**. The optical modeling was performed by using rigorous coupled wave analysis.The optical modeling is performed by using rigorous coupled wave analysis (RCWA) method which is widely used to solve optical equations. In this method, space and times are divided into a grid levels and simulated time is evaluated in electromagnetic fields. The proposed solar cell designconsists of a thin layer of anti-reflective coating (Si_3N_4) withits thickness about 70nm, a GaAs active layer of thickness 500 nm as absorbing region andthe silver (Ag) grating with thickness 160nm and width 150 nm.The thickness of the bottom Ag layer was 335 nm.

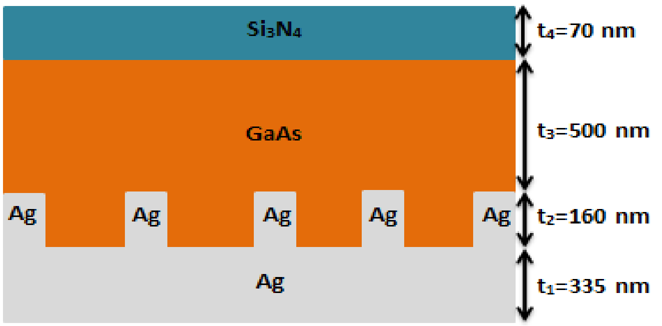

Figure 1. Schematic diagram of proposed GaAs solar cell structure.

We have performed thesimulation with the ideal conditions like zero shadow loss at normal incident angle of light illumination. Here, we have studied effect of the grating thickness, grating width and antireflection coating (ARC) thickness for the performance evaluation of GaAs solar cell.

3. Results and Discussion

Figure 2 shows the short-circuit current (Jsc) density in accordance to the grating thickness (Gt) for the transverse electric (TE)polarization. An exponential increase in the Jsc is observed with its maximum value about 353A/m^2 at 100 nm grating thickness. Beyond 100 nm, a fall in Jsc is also observed. **Figure 2(b)-2(d)** depicts the electric field distribution in the solar cells.

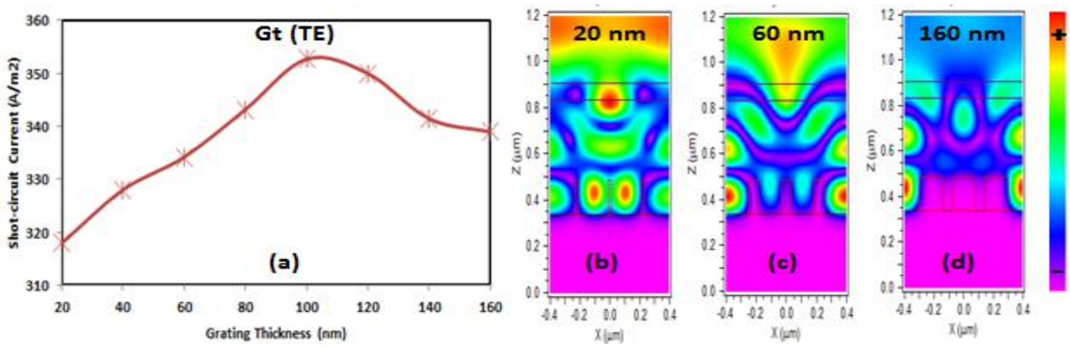

Figure 2. Short-circuit current density versus grating thickness (fig.a) and electric field profile for grating thickness 20 (fig.b), 60 (fig.c) and 160 nm (fig.d) respectively.

A different field profile can be seen in the active region however, enhanced field is observed near the gratings in the case of **figure 2(b)** while it is dominated in the case of **figure 2(d)**. Similarly, an enhancement in the short-circuit current can be observed for the transverse magnetic polarization (TM) case as shown in **figure 3(a)**. This enhancement in the Jsc is due to the plasmonic effect induced by the metal gratings.

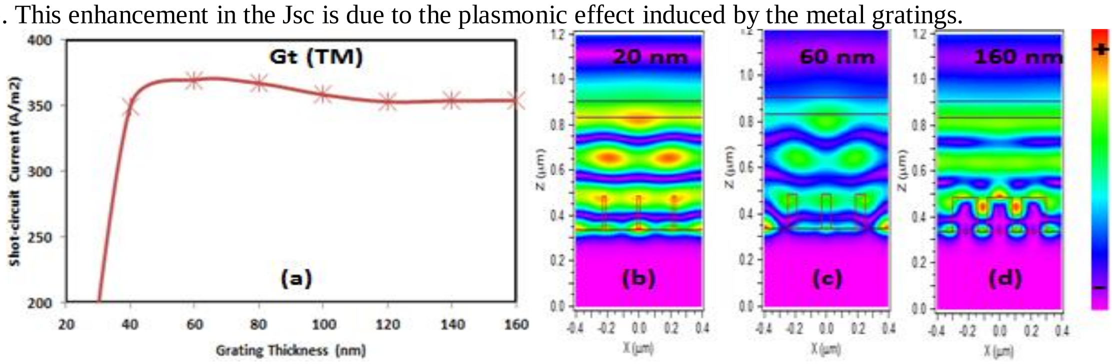

Figure 3. Short-circuit current density versus grating thickness (fig.a) and magnetic field profile for grating thickness 20 (fig.b), 60 (fig.c) and 160 nm (fig.d) respectively.

The magnetic field distribution is dominant in this case which can be seen with the surface plasmons induced at the tip of gratings as shown in **figure 3(b)- 3(d)**. This resembles the oscillation of electrons induced due to the metal effect. The localized photons can also be observed at the tip of the gratings in particularly in **figure 3(b)**.

The grating width is also an important parameter which affects the efficiency of the solar cells. **Figure 4(a)** shows the short-circuit current density as a function of grating width which is exponentially increasing.

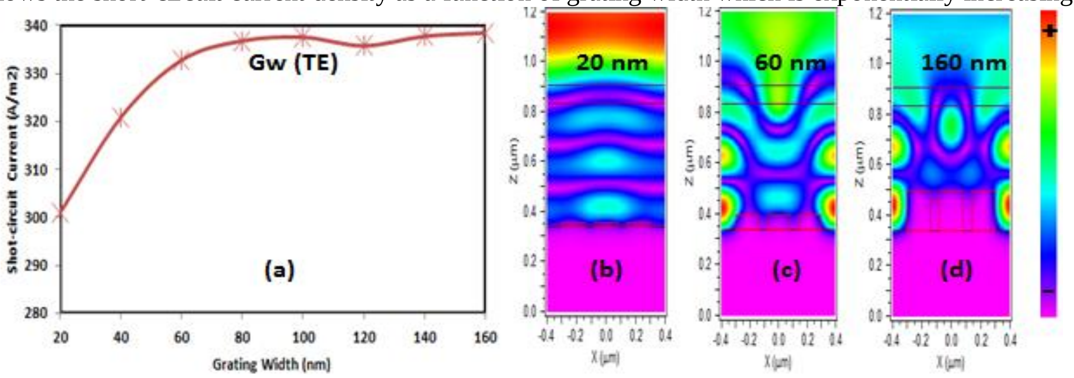

Figure 4. Short-circuit current density versus grating width (fig.a) and electric field profile for grating width 20 (fig.b), 60 (fig.c) and 160 nm (fig.d) respectively.

The maximum obtained Jsc is about 338 nm at grating width 160 nm. The electric filed distribution is depicted in **figure 4(b)-4(d)**. The wave-guiding effect can be observed in the **figure 4(b)** and **4(c)**. In a similar way, we have studied the short-circuit current density as a function of grating thickness for the transverse magnetic polarization (TM) case and plotted **figure 5(a)**.

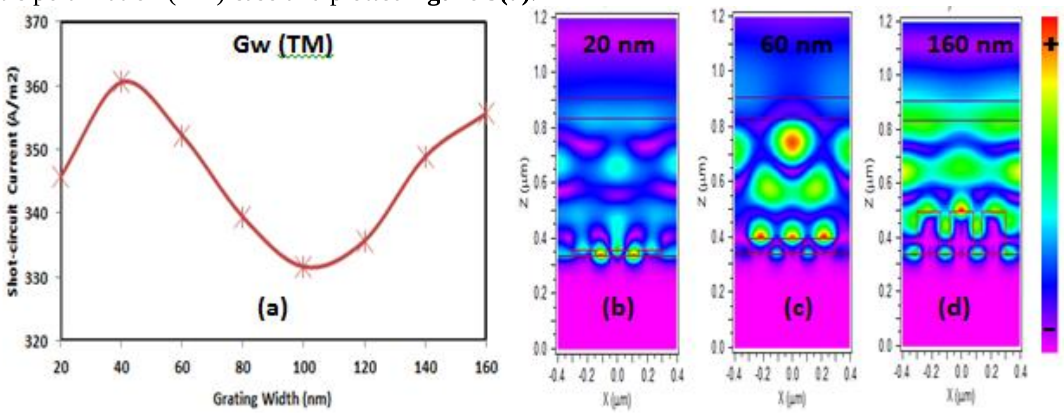

Figure 5. Short-circuit current density versus grating width (fig.a) and magnetic field profile for grating width 20 (fig.b), 60 (fig.c) and 160 nm (fig.d) respectively.

Depending upon the grating width, an increase or decrease in the short-circuit current density is observed. However, the maximum obtained Jsc is 361 at 40 nm. The localized plasmons are visible in the **figure 5(c)** and surface plasmons are dominant for the grating thickness 160 nm as depicted in **figure 5(d)**.Gratings are important in order to have good light harvesting in the active region by providing light scattering and coupling.

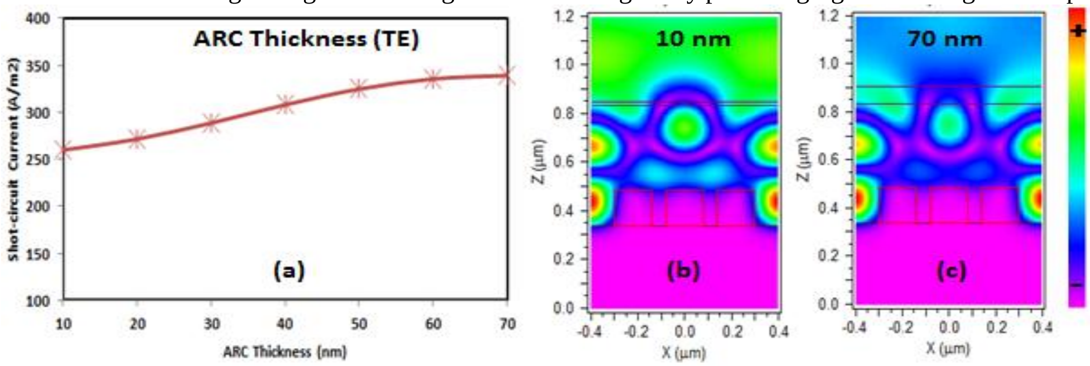

Figure 6. Short-circuit current density versus anti-reflection coating thickness (fig.a) and electric field profile for ARC thickness 10 (fig.b), and 70 nm (fig.c) respectively for the TE case.

In addition, anti-reflection coating (ARC) thickness is predominant parameter to have enough light diffusion towards the active region with minimum reflections through it. **Figure 6(a)**depicts an enhancement in the short-circuit current with an increase of the ARC thickness. The maximum obtained Jsc is 339 A/m^2 at 70 nm ARC thickness. A distinct light guiding mechanism can be seen in the active region as plotted in **figure 6(b)** and **6(c)**.

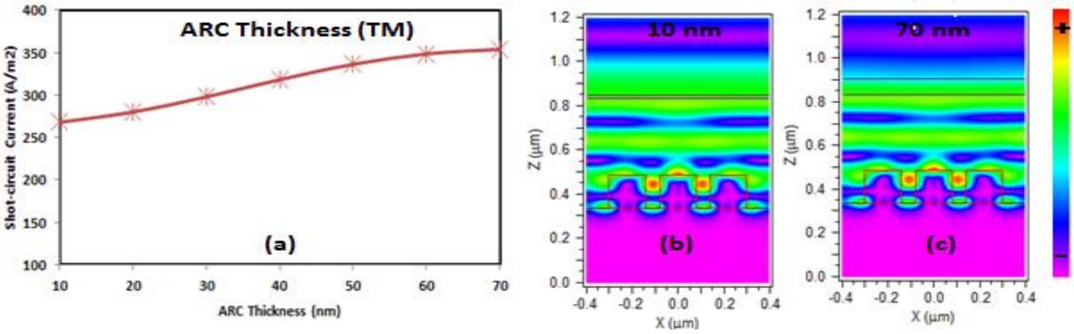

Figure 7. Short-circuit current density versus anti-reflection coating thickness (fig.a) and magnetic field profile for ARC thickness 10 (fig.b), and 70 nm (fig.c) respectively for the TE case.

An improvement in the short-circuit current density can be noticed in the **figure 7(a)** which is plotted for TM polarization case. However, surface plasmons with localized polaritons is observable in both the **figures 7(b)** and **7(d)** respectively. The magnetic field distribution is dominant as compare to the electric field plotted in **figure 6(b)** and **6(d)**.

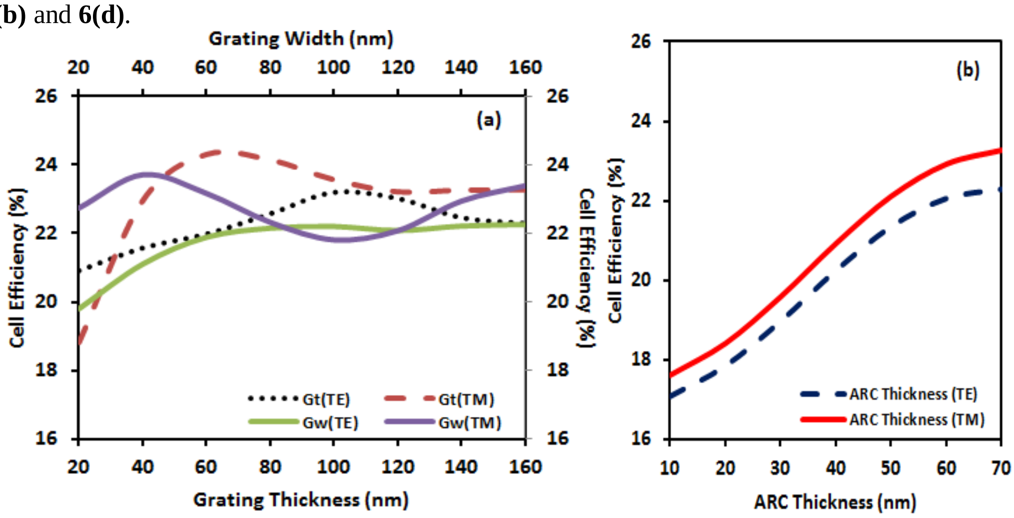

Figure 8. Solar cell efficiency versus grating parameters (fig.a) and thickness (fig.b) respectively.

Figure 8 shows the summary of the simulation performed with the various parameters. The metal grating effect is found to be more dominat for the contribution of enhanced cell efficiency due to the induced surface plasmons as remarkable in **figure 8(a)**. The maximum obtained cell efficiencies are 24.6 and 23.7 % with the grating thickness 60 and the grating width 40 nm respectively, for the TM polraization. For TE polarization, the obtained cell efficiencies are 22.3 and 23.2 % with the grating thickness 160 and the grating width 100 nm respectively.**Figure 8(b)** shows the cell efficiency in accordance with anti-reflection coating thickness. The solid red curve indicates the enhanced efficiency as compared to the dotted blue curve. This enhancement is attributed to the localized plasmons and surface plasmons.

4. Conclusions

We have studied the modeling and simulation of GaAs thin film solar cells. Various parameters such as ARC thickness, grating width and grating height is evaluated for the optimal performance of the proposed design of GaAs solar cell.The enhanced cell efficiency~25 and 24 % were obtained with the grating thickness 60 and the grating width 40 nm respectively, for the magnetic transeverse case. This enhanced efficiency has been attributed to the induced surface plasmons which carries the oscillating electrons guided in-between the semiconductor and the metal interface.

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