Enhancement of Optical Absorption in an Amorphous Silicon Solar Cell with Periodic Grating Structure

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Abstract

A flexible optical design for light trapping in amorphous silicon thin film solar cells (a-Si TFSC) is developed to increase the optical path length in the absorber layer, to enhance the absorption. The design of the a-Si TFSCs includes periodic grating structures, using an anti-reflection structure and metallic reflection grating. Light trapping in the solar cells and the impact of the structure parameters are studied numerically by using the Rigorous Coupled Wave Analysis enhanced by the Modal Transmission Line theory. The results have revealed that the reflectivity reaches minimum values for the cell with a period of 0.5 μm, a fill factor of 0.1 and a groove depth of 0.4 μm. The performance of the cell has also been compared with that of a cell with a flat reflecting surface. It is found that the grating structure increases the absorption by up to 10%.

***Keywords**: Rigorous Coupled Wave Analysis; Absorption; Thin Film Solar Cells; Grating; Reflection*

1. Introduction

Amorphous silicon (a-Si) thin film solar cells (TFSCs) have the advantages of low cost, promising high-performance, easy fabrication by chemical deposition techniques and fairly high absorption coefficient [1-4]. In order to improve TFSCs efficiencies, it is essential to reduce the reflection so that to enhance the light absorption. Introducing textured interfaces can lead to reduced reflection losses.

The schematic cross-section of a flat TF-Si solar cell is shown in Figure 1(a). The schematic cross-section of the suggested design is shown in Figure 1(b). The cell consists of a dielectric gratings on the foil substrate, a silver back contact Ag (100 nm), ZnO (50 nm), n-a-Si:H (20 nm), i-a-Si:H absorber (200 nm), p-a-Si:H (15 nm) and ITO front transparent conductive oxide contact (60 nm). The gratings can be imprinted directly by hot embossing in a plastic substrate, or in a barrier layer in case of the steel foil [5]. In this structure there is antireflection effect at the front interface and efficient light scattering at the metallic reflection grating and other textured interfaces. The dielectric layer can be seen as an anti-reflection grating, the silver film can be seen as metallic diffraction grating in the role of back reflector and diffuser at the same time [6].

For reducing the metallic loss we inserted a Zn O layer between the a-Si layer and the metallic diffraction gratings [7]. Because ZnO is a semiconductor with a wide direct band gap and has stronger resistance to hydrogen plasma, it has superior transparency and a lower extinction coefficient (less than 0.5) in longer wavelength region. ZnO layer can reduce the metallic loss and enhance the back reflection. When the angle of incidence of the ray at the a-Si/ZnO interface is less than the critical angle between a-Si and the ZnO layers, light will be totally internally reflected, and the effective path length will be increased due to multiple reflections [8]. The incident light on solar cell is affected by the following three processes. First, the incident light with shorter wavelengths would be absorbed by the top homogeneous layer of a-Si. When the incident wavelengths is larger than the period of the periodic grating structures, the light would not be totally absorbed by silicon and reflected by the lower electrode then forming a resonant pattern. Second, the incident light undergoes typical diffraction on the grating structures. Third, the incident wavelengths that can be diffracted at angles nearly parallel to the interface, generating waveguides modes, will be strongly absorbed in the solar cell. Combining all of the effects, the designed grating structures on the back surface will increase the absorption efficiency of the TFSCs [1].

In this work, simulations are utilized to investigate the reflectivity of the entire TF-Si solar cell structure to find out the optimum structure parameters of the grating which are: the period (a), the fill factor (f), and the height of the grating (h), Figure 1(b). The calculations were performed for different angles of incidence.

2. Principle and Numerical Modeling

The coupled method used in the analysis of TFSC requires information about the optical near field as well as the far field. Near field information is needed to calculate the local absorption in the solar cell, and far field information is needed to calculate reflection, transmission and absorption spectra. Rigorous coupled wave analysis (RCWA) is usually used for a rigorous wave optical simulation of the electromagnetic field inside a certain structure [9]. In our approach, the core algorithm, which is based on the (RCWA) [10] enhanced by the Modal Transmission Line (MTL) theory, is used to find the solution of Maxwell's equations for the light propagation in the structure. The calculation of reflectance and absorption includes three steps: (1) obtaining the expressions of electromagnetic field in incident region and transmitted region, (2) Fourier expansion of electromagnetic field and dielectric constant in the TF-Si solar cell, (3) using boundary condition for electromagnetic field at different interface, obtaining the amplitude and the diffraction efficiency of different levels by some mathematical methods [6].

For 2D or 3D structures with arbitrary incident directions, the vectorized forms of the equations are taken into account. By factoring out an assumed time harmonic factor exp ($-i\omega t$), Maxwell's equations can be expressed as the following form:

$$H_x = \frac{i}{\omega\mu_0}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y}\right) \tag{1a}$$

$$H_y = \frac{i}{\omega\mu_0}\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z}\right) \tag{1b}$$

$$H_z = \frac{i}{\omega\mu_0}\left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right) \tag{1c}$$

$$E_x = \frac{i}{\omega\varepsilon_0\varepsilon(x)}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}\right) \tag{1d}$$

$$E_y = \frac{i}{\omega \varepsilon_0 \varepsilon(x)} \left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \right) \tag{1e}$$

$$E_z = \frac{i}{\omega \varepsilon_0 \varepsilon(x)} \left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right) \tag{1f}$$

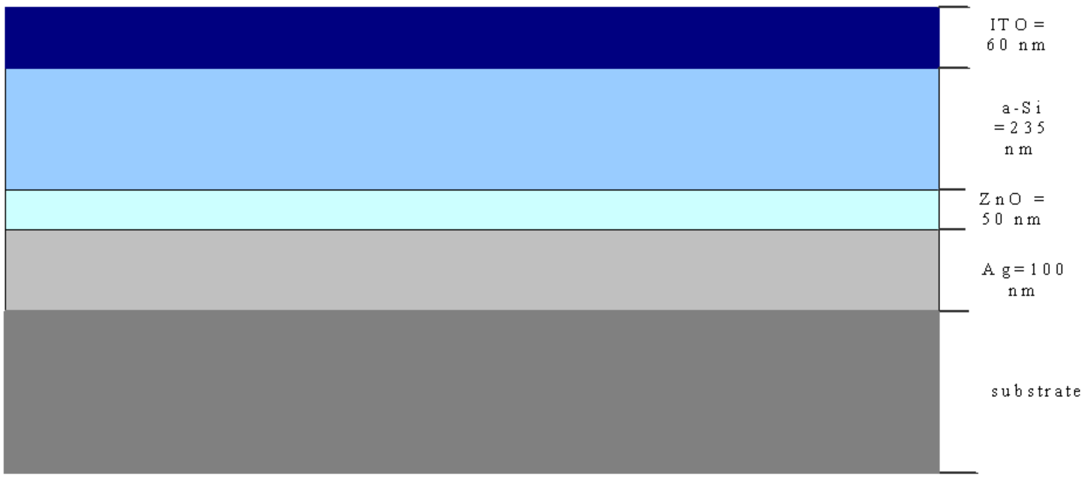

Figure 1. (a) a Flat a-Si (TFSC) Solar Cell

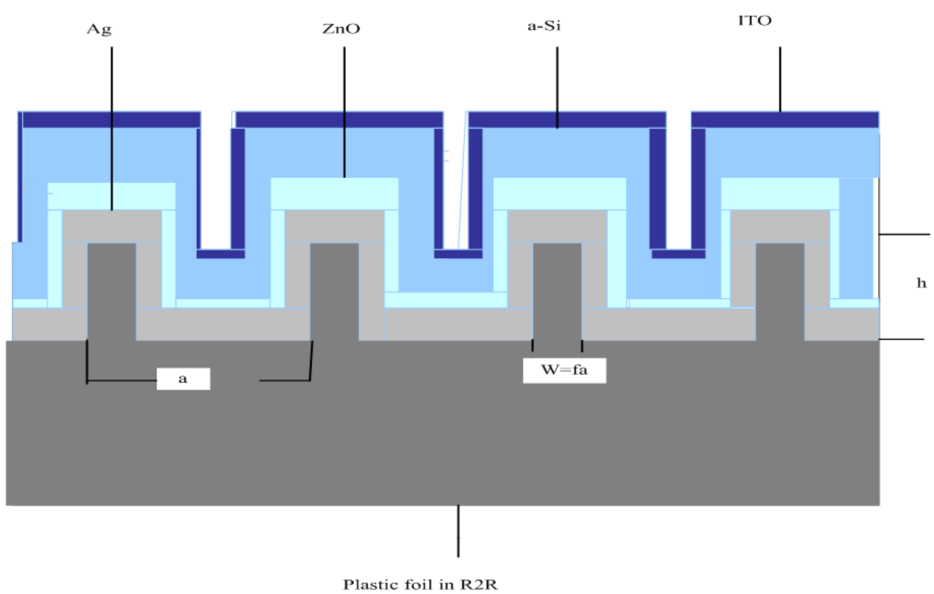

Figure 1. (b) The Suggested TF-Si Solar Cell Structure

where t is the time, ω is the angular frequency, ε_0 is the vacuum permittivity, μ is the magnetic permeability of the material, E is the electric field intensity and H is the magnetic field intensity. The medium is characterized by a diagonal index tensor with respect to the principal axes with diagonal elements $\varepsilon_{r,x}, \varepsilon_{r,y}, \varepsilon_{r,z}$. By substituting Eqs. (1c), (1f) into Eqs. (1a), (1b), (1d), (1e), we derive the following transverse format of Maxwell's equations:

$$\frac{\partial E_x}{\partial z} = \frac{i}{\omega\varepsilon_0}\frac{\partial}{\partial x}\left[\frac{1}{\varepsilon(x)}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right)\right] + i\omega\mu_0 H_y \quad (2a)$$

$$\frac{\partial E_y}{\partial z} = \frac{i}{\omega\varepsilon_0\varepsilon(x)}\left[\frac{\partial}{\partial y}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) - \omega^2\mu_0\varepsilon_0\varepsilon(x)H_x\right] \quad (2b)$$

$$\frac{\partial H_x}{\partial z} = \frac{i}{\omega\mu_0}\frac{\partial}{\partial x}\left[\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right)\right] - i\omega\varepsilon_0\varepsilon(x)E_y \quad (2c)$$

$$\frac{\partial H_y}{\partial z} = \frac{i}{\omega\mu_0}\frac{\partial}{\partial y}\left[\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right)\right] + i\omega\varepsilon_0\varepsilon(x)E_x \quad (2d)$$

For scattering problems, we want to calculate the reflected and transmitted light waves from the incident field. A direct solution in the spatial domain of Eq. (2) with proper boundary conditions is computationally expensive. Moreover, in order to calculate accurate diffraction efficiencies for all diffraction orders, fine simulation grids are essential. The RCWA and MTL methods are based on the Fourier domain; they are efficient solutions for the amplitude of each diffraction order. For light collection we want to find out the optimal structure parameters. For each layer, the horizontal thickness is a quarter of the vertical thickness [6]. According to the absorption spectrum of a-Si [11] and the AM 1.5 G solar energy spectrum, the wavelength range of the spectrum in this work research is from 0.3 to 0.7. The simulations are done for both polarizations, transverse electric (TE) and transverse magnetic (TM), and the average values are given. The complex dielectric constant of metal at optical frequencies is approximated by the Drude model as follows [12]:

$$\varepsilon(\omega) = \varepsilon_0\varepsilon_\infty - \frac{\varepsilon_0\omega_p^2}{\omega^2 + i\omega\gamma}$$

(3)

where ε_0 is the permittivity of free space, ε_∞ is the dc dielectric constant, ω is the light frequency, ω_p is the plasma frequency, γ is the damping frequency. $\omega_p = 1.3\times10^{16}$ rad/s,

γ $=9.6\times10^{13}$ rad/s.

The complex refractive index of the materials at different wavelengths, used in the proposed TF-Si solar cell is shown in Figure 2. The values are obtained from Ref. [13], where n is the refractive index and κ is the extinction coefficient.

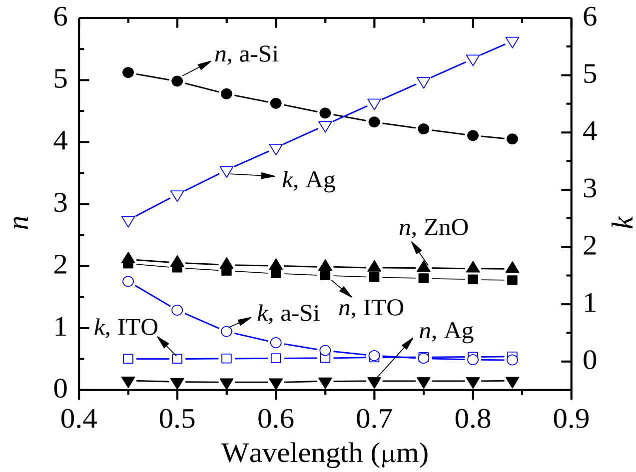

Figure 2. The Complex Refractive Index of the Materials with Different Wavelengths

3. Results and Discussion

The reliability of RCWA and MTL has been tested by comparing the calculated values of the reflectivity of a bare Si wafer with measurements by [14]. The results in Figure 3 show very good agreement between the simulated and the measured values. The reflection from an a-Si (TFSC) solar cell with a flat back reflecting surface is also shown in Figure 3. When the incident wavelength is around 0.55µm, the reflectivity of the solar cell is below 10%, but it increases to reach about 35 % at 0.35µm. The reflectivity can be decreased further by changing the structure of the reflecting surface.

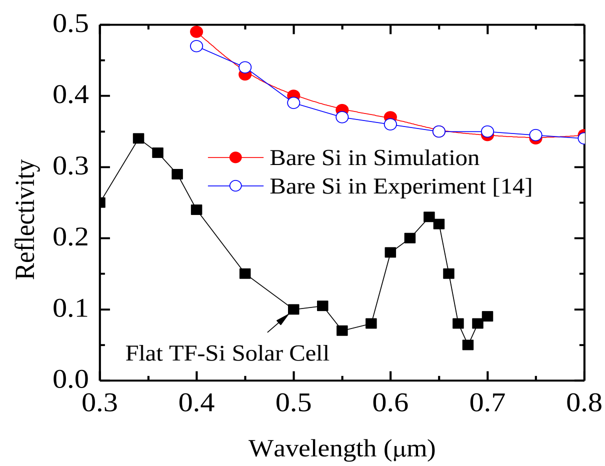

Figure 3. The Measured and Simulated Reflectivity of a Bare Silicon Wafer

The reflectivity of an a-Si TFSC solar cell dependence on the parameters of the grating has been studied by using the RCWA method. The reflectivity was calculated as a function of the incident wavelength, at normal incidence, with heights of the grating (*h*) (0.2, 0.3, 0.4, 0.5 and

0.6) µm, filling factor (*f*) (0. 1, 0.2 and 0.3) and grating period (*a*) (0.5, 0.6, and 0.8) µm . Figure 4 shows the variation of reflectivity with grating height when *a* = 0.5 µm and *f* = 0.1. The reflectivity reaches a minimum of less than 5 % in the wavelength range 0.5-0.6 µm when *h* =0.4 µm. The maximum is about 25 % at 0.35 µm wavelength. There is another peak of about 7 % at wavelength 0.65µm .

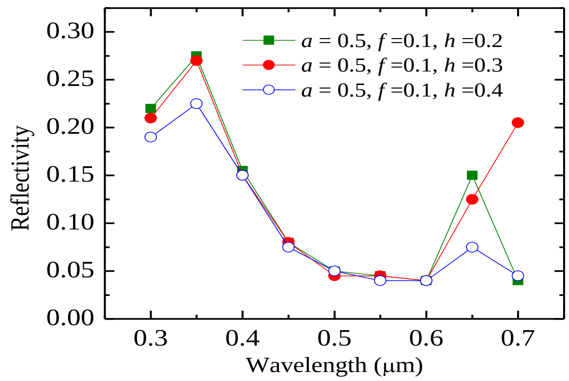

Figure 4. The Reflectivity of the Solar Cell as a Function of the Incident Wavelength with *a* = 0.5 µm, *f* = 0.1, but with Values of Different *h*, at Normal Incidence

Figure 5 shows the reflectivity when *a* = 0.5µm and *f* = 0.2, at normal incidence. Again the minimum reflection is when *h* = 0.4µm , but in this case the reflection at the 0.35 µm wavelength is about 23 % and that at 0.65µm is nearly 10%. Since solar energy in the wavelength range 0.6 - 0.7 µm is greater in the wavelength range 0.3 - 0.4 µm , the combination of *h* = 0.4 µm , *f* = 0.1 and *a* = 0.5µm seems to be more attractive

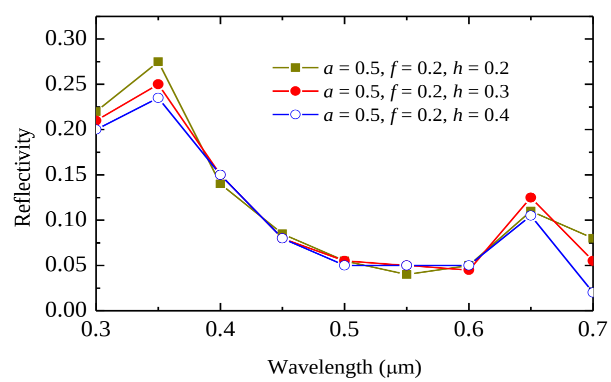

Figure 5. The Reflectivity of the Solar Cell as a Function of the Incident Wavelength with the*a* = 0.5µm, f = 0.2, but with Different Values of *h*, at Normal Incidence

Figure 6 shows the reflection from the cell when *a* = 0.6 μm and *f* = 0.2. The *h* =0.6 μm gives the minimum reflection, but the 0.65 μm peak reaches about 10 %.

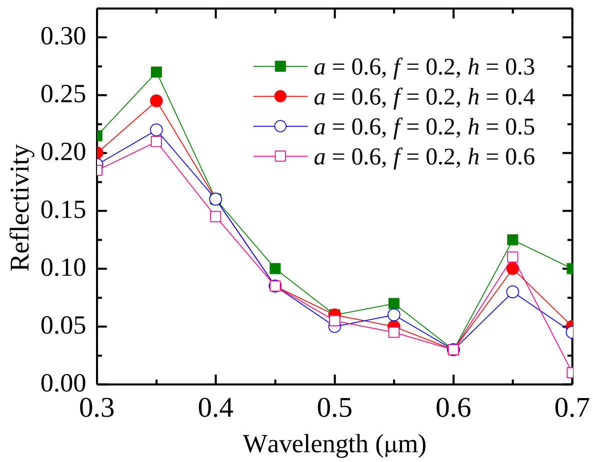

Figure 6. The Reflectivity of the Solar Cell as a Function of the Incident Wavelength with *a* =0.6 μm, *f* =0.2, but with Different Values of *h*, at Normal Incidence

Figures 7, 8 and 9 show that increasing the value of *a* beyond 0.5 μm and *f* beyond 0.1 and *h* beyond 0.4 μm, does not decrease the reflectivity.

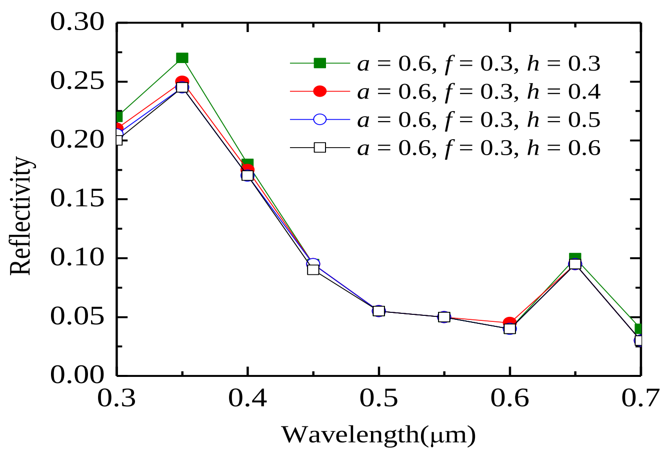

Figure 7. The Reflectivity of the Solar Cell as a Function Wavelength with *a* =0.6μm, *f* =0.3, at Normal Incidence

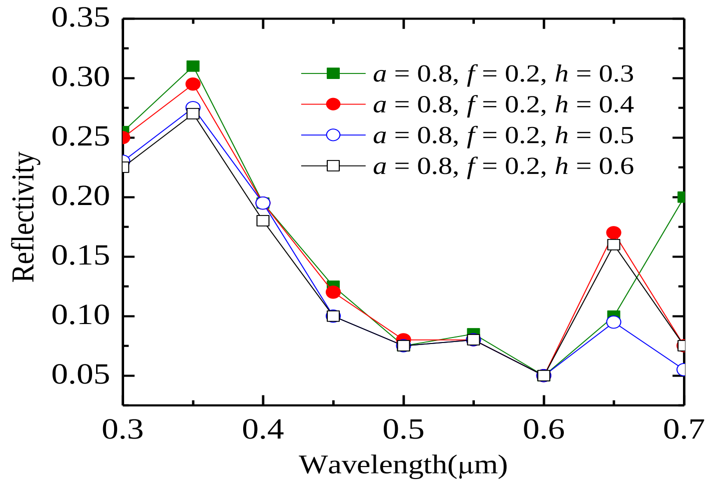

Figure 8. The Reflectivity of the Cell when *a* =0.8 μm and *f* =0.2, but with Different Values of *h*, at Normal Incidence

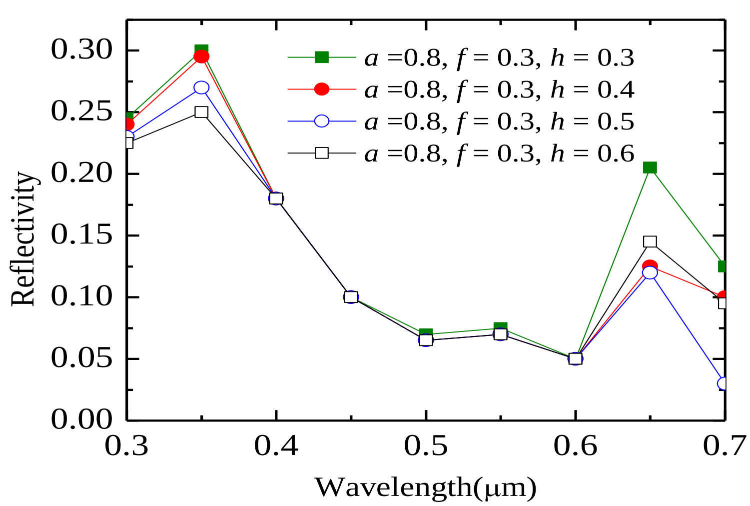

Figure 9. The Reflectivity of the Solar Cell with the *a* =0.8 μm, *f* =0.3, but with Different Values of *h*, at Normal Incidence

Figure 10 shows the reflectivity of the solar cell at different angles of incidence with a=0.5μm , f=0.1 and h=0.4μm . The reflection changes very little between 0^0 and 40^0 angle of incidence, except at the wavelengths 0.5 - 0.7μm .

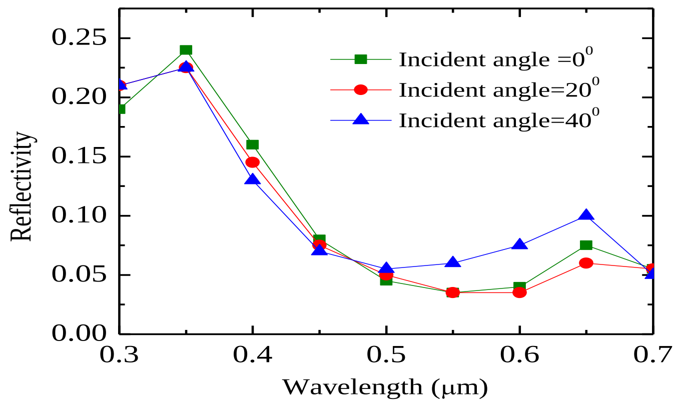

Figure 10. The Reflectivity of the Designed TF-Si Solar Cell as a Function of the Incident Wavelength with the *a* =0.5μm, *f* =0.1 μm but *h* =0.4μm μm with Different Incident Angles

When the period of the grating is comparable to the incident wavelength the diffraction angles are large enough to propagate into their neighboring unit cell. Diffracted waves can thus interface constructively within the thin absorber layer [15]. Based on the above results, we introduce the grating with a = 0.5μm , f = 0.1, h = 0.4 μm on the substrate of the TF-Si solar cell.

When the designed TF-Si solar cell has the lowest reflection, the electric field strength in the a-Si layer is the strongest [6]. The effect of the grating at the air/ITO interface cannot be neglected. This interface will act as a phase grating. It is known that phase gratings can be very effective in the suppression of the 0th diffraction order [16].

Figure 11 shows the absorption of the a-Si solar cell with the periodic grating (a=0.5μm , f=0.1, h=0.4μm) on the substrate, the absorption of the a-Si solar cell has been enhanced. The absorption enhancement is only about 0.4%~10.8% in the wavelength range of 0.3~0.7μm .

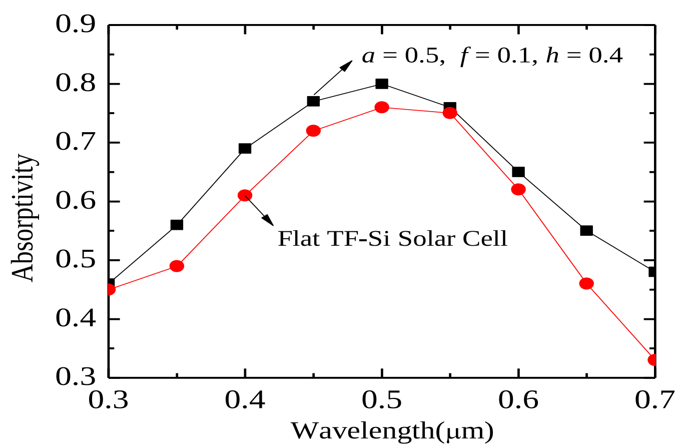

Figure 11. The Absorptivity of the a-Si Solar Cell

4. Conclusion

We have presented our design of periodic grating structures in amorphous TF-Si solar cells on plastic foil. We identified the periodic structures on plastic substrate for both top anti-reflection and back reflector. The reflectance of a-Si:H solar cells with periodic gratings was investigated by rigorous coupled wave analysis (RCWA). The reflectivity of the TF-Si solar cell with a period of 0.5 μm , a filling factor of 0.1 and grating height of 0.4 μm reached a minimum of less than 5 % in the wavelength range 0.5~0.6 μm. The maxima were about 25 % and 7 % at 0.35μm and 0.65 μm, respectively. The reflection changes very little between 0^0 and 40^0 angle of incidence, except at the wavelengths 0.5~0.7 μm . The absorption of the a-Si solar cell with the gratings is enhanced by more than 20% in the wavelength range of 0.3~0.7μm .

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