Blucher Material Science Proceedings
Novembro de 2014, Número 1, Volume 1
www.proceedings.blucher.com.br/evento/mm-fgm2014

☐ Oral Presentation

☑ Poster Presentation

MM&FGM2014
São Paulo, Brazil Oct.19-22 2014

Optimal light-trapping design in thin-film solar cells enhanced with SiO_2/ATO/Graphene layered structure

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Abstract

Antimony doped tin oxide (ATO), as one kind of transparent conductive oxides (TCO), is applied as electrodes in thin film solar cells. On the basis of the traditional glass/TCO structure on top of amorphous silicon thin-film solar cells, graphene is introduced to form the glass/TCO/Graphene and the glass/Graphene/TCO layered structure, which is aimed at both enhancing the optical absorption of thin-film solar cells as an antireflection coating (ARC) and increasing the electrical conductivity as a TCO electrode. In this paper, SiO_2/ATO/Graphene and SiO_2/Graphene/ATO structure are selected for the optimal light-trapping design by using differential evolution method. The effect of graphene is mainly investigated and the thickness of the layers of proposed structure is optimized to enhance the optical absorption of thin-film solar cells to the greatest degree. The theoretical calculation results clearly demonstrate that the proposed SiO_2/ATO/Graphene layered structure is obviously superior to the SiO_2/Graphene/ATO structure, and it can obtain a higher light-trapping enhancement in the whole visible and near-infrared wavelength range because of the graded refractive index distribution profile.

Keywords: Light trapping; thin-film solar cells; graphene; layered structure; differential evolution (DE).

1. Introduction

Amorphous silicon (α-Si) thin-film solar cells have attracted significant interest in research fields because of the low cost, nontoxicity and mature processing technology [1, 2]. Among key materials for α-Si thin-film solar cells, transparent electrodes play an important role in the performance of solar cells because the main features of solar cells, such as fill factor and short-circuit current density, are critically dependent on the series resistance and optical transmittance of the transparent electrodes. Antimony doped tin oxide (ATO), as one kind of transparent conductive oxides (TCO), is applied as electrodes in thin film solar cells. On the basis of the traditional glass/TCO structure on top of amorphous silicon thin-film solar cells, graphene is introduced to form the glass/TCO/Graphene and the glass/Graphene/TCO layered structure, which is aimed at both enhancing the optical absorption of thin-film solar cells as an antireflection coating (ARC) and increasing the electrical conductivity as a TCO electrode [3].

In this paper, SiO_2/ATO/Graphene and SiO_2/Graphene/ATO structure are selected for the optimal light-trapping design by using differential evolution method. The effect of graphene is mainly investigated and the thickness of the layers of proposed structure is optimized to enhance the optical absorption of thin-film solar cells to the greatest degree. The theoretical calculation results clearly demonstrate that the proposed SiO_2/ATO/Graphene layered structure is obviously superior to the SiO_2/Graphene/ATO structure, and it can obtain a higher light-trapping enhancement in the whole visible and near-infrared wavelength range because of the graded refractive index distribution profile.

2. Simulation model

In this paper, a SiO_2/ATO/Graphene structure is proposed as transparent electrodes on amorphous silicon (α-Si) thin-film solar cells. Figure 1 depicts the sketch of a graphene-based thin-film *a*-Si:H solar cell and geometric structure of SiO_2/ATO/Graphene coatings. In Fig. 1, the graphene transparent electrodes have a layer number of L with a thickness of $L\times0.34$ *nm*. The proposed SiO_2/ATO/Graphene coatings have two structural parameters including the thickness d for SiO_2 layer and the layer number L of graphene, which need to be optimized.

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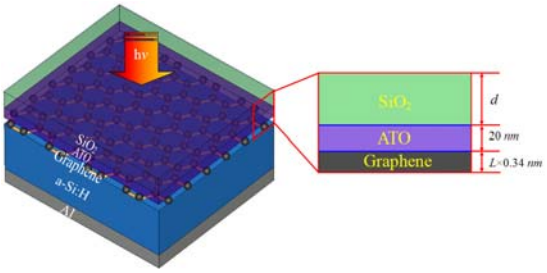

Fig. 1. Sketch of a graphene-based thin-film *a*-Si:H solar cell and geometric structure of SiO_2/ATO/Graphene deposited on top of amorphous silicon thin-film solar cells. hv: Light energy.

In Fig. 1, the thicknesses of amorphous-silicon layer and aluminum electrode are 240 *nm* and 80 *nm* respectively which refer to the literature [4]. The ATO layer has a fixed thickness of 20 *nm*. To assess the performance of the graphene-based thin-film solar cells, it is necessary to know the optical property of graphene. A recent experimental measurement on light transmission through suspended graphene membranes demonstrated that the graphene opacity is a constant independent of the wavelength [5]. Based on the measurement, the complex refractive index of graphene in the visible spectrum was estimated to be $n = 3.0 + iC_1\lambda/3$ with C_1=5.446 μm^{-1} [6], which can be useful for accurate prediction of the optical behavior of graphene structures. In our simulated calculation, the graphene layer is presumed to be homogeneous and its thickness is equal to $d = L \times 0.34$ *nm* [7, 8], where L is the number of graphene layers.

The solar cell is simulated using the finite-difference time-domain (FDTD) method [9, 10], by solving 3D Maxwell's equations with perfectly matched layer boundary conditions for monochromatic, normally incident plane waves. In order to analyze the optical performance of the solar cell, we assume that frequencies ω of the incident waves cover the whole solar spectrum with irradiance $F(\omega)$ corresponding to the AM1.5G standard. The optical data for all the materials used in the simulated calculations are taken from the SOPRA database [11], and the complex refractive index data for amorphous silicon and aluminum are taken from SIAM1.mat and AL.mat respectively. The refractive index of the ATO film layer is 2.01 in the visible spectrum which refer to the literature [12].

In our optical simulations, we calculate the spectral power absorbed by the amorphous silicon layer, defined as follows:

$$Q(\omega) = \frac{\omega\varepsilon_0}{2}\int_V \mathrm{Im}[\varepsilon(\omega)]\cdot|E|^2\, dV \tag{1}$$

In the Eq. (1), the V represents the element volume, characterized by complex and frequency-dependent relative dielectric permittivity $\varepsilon(\omega)$, E is the electric field, whose distribution can be obtained in the simulation, and ε_0 is the permittivity of free space. What's more, in order to investigate the broadband enhancement of the optical absorption, we calculate the overall power absorbed inside the amorphous silicon layer by integrating the spectral absorbed power $Q(\omega)$ over the AM1.5G solar spectrum, defined as follows:

$$G = \int_{AM1.5G} Q(\omega)d\omega \tag{2}$$

The overall enhancement E then can be calculated using the following equation:

$$E = \frac{G - G(\mathrm{Ref})}{G(\mathrm{Ref})} \tag{3}$$

In the Eq. (3), $G(\mathrm{Ref})$ is denoted for the reference cell with bare ATO transparent electrode.

3. Single factor analysis

To improve the performance of proposed SiO_2/ATO/Graphene structure, a systematic study on the influence of the structural parameters on the efficiency of the enhancement is performed. In this section, we have analyzed single factor influence of structural parameters respectively, including the layer number L for graphene layer and the thickness d for SiO_2 layer.

Firstly, in order to investigate the broadband enhancement of the light trapping, we analyze the dependence of the broadband light-trapping enhancement E on layer number L of graphene, which is depicted in Fig. 2(a). In our optimization, the thickness d of SiO_2 layer is fixed to 80 *nm*. According to Fig. 2(a), it is seen that there exist optimum value of layer number L for graphene which maximizes the overall broadband enhancement E. This figure reveals that with the increasing of layer number L from 2 to 18, the broadband light-trapping enhancement E firstly increases slowly, and reaches the optimal values of E = 15.98% when layer number L is 10, then it begins to decrease dramatically. When the layer number L is 12 or higher, its enhancement become negative because majority of incident light has been absorbed by graphene layer themselves.

Moreover, Fig. 2(b) analyzes the dependence of the broadband light-trapping enhancement E on thickness d of SiO_2 layer. In the optimization, the layer number L of graphene is fixed to 10. It is seen that with the increasing of thickness d from 20 *nm* to 100 *nm*, the broadband light-trapping enhancement E firstly increases remarkably, then it begins to decrease slowly. When d= 60 *nm*, it reaches its optimal values of E = 16.22%. Therefore, the optimization results of Fig. 2(a) and Fig. 2(b) reveal that the control of the layer number L of graphene layer and the thickness d of SiO_2 layer as design parameters can significantly enhance the performance of light trapping for α-Si thin film solar cells.

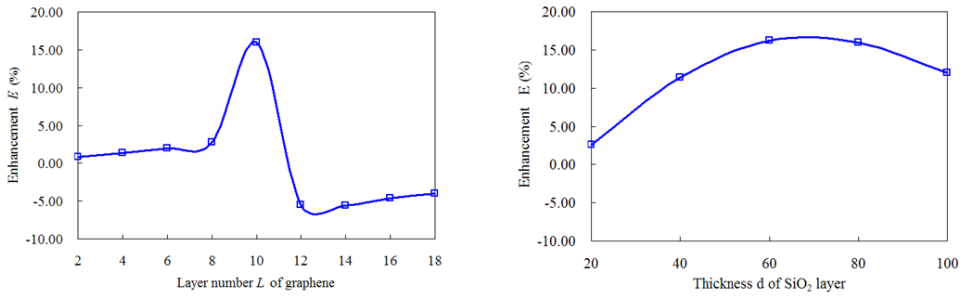

Fig. 2. (a) Dependence of the broadband light-trapping enhancement E on layer number L of graphene. (b) Dependence of the broadband light-trapping enhancement E on thickness d of SiO_2 layer.

4. DE-based design and optimization

To improve the performance of proposed SiO_2/ATO/Graphene structure, a differential evolution (DE) algorithm [13] is employed to optimize the structural parameters in order to enhance the optical absorption of graphene-based *a*-Si:H thin-film solar cells to the greatest degree. The block diagram of the DE design for parameters optimization of electromagnetic problems has been illustrated in detail in our previous literature [14]. In this paper, the goal of DE is to pursue the optimal structural parameters, including the thickness d for SiO_2 layer and the layer number L for graphene, in order to enhance the optical absorption of graphene-based solar cells to the most degree. Therefore, the fitness function of DE can be defined as follows:

$$Maximize: \quad E = \frac{G - G(\mathrm{Ref})}{G(\mathrm{Ref})} \tag{4}$$

$$Subject\ to: \quad 0\,nm < d \le 100\,nm \tag{5}$$

$$0 < L \le 20 \tag{6}$$

The optimal solutions of SiO_2/ATO/Graphene structure optimized by DE are listed in Table 1. From the optimization results of Table 1, it is seen that the optimal SiO_2/ATO/Graphene structure can achieve 16.71% enhancement compared to the bare ATO structure when the d is equal to 70 *nm* and the L is equal to 10.

Table 1. The optimal solutions of SiO_2/ATO/Graphene structure

Structure	d (*nm*)	L	E
SiO_2/ATO/Graphene	70	10	16.71%

To investigate the broadband enhancement performance of the light trapping, we compare the spectral absorption rate of the *a*-Si:H active region for optimal SiO_2/ATO/Graphene structure and bare 20 *nm* ATO structure, which is depicted in Fig. 3. Figure 3 clearly illustrates that the proposed SiO_2/ATO/Graphene structure can remarkably enhance the light trapping of thin-film solar cells compared to the bare ATO structure. The optimal SiO_2/ATO/Graphene structure can enhance the optical absorption of silicon for wavelengths above 375 *nm* which cover the whole violet light spectrum. Therefore, the optimal SiO_2/ATO/Graphene structure almost can enhance the optical absorption of *a*-Si thin film solar cells in the whole visible and near-infrared wavelength range compared to the conventional bare ATO structure.

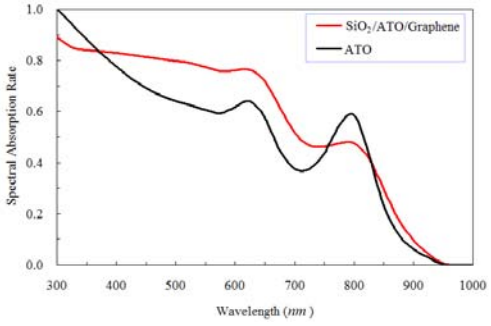

Fig. 3. Spectral absorption rate of the *a*-Si:H active region as functions of incident wavelength for optimal SiO_2/ATO/Graphene structure and bare 20 *nm* ATO structure.

Furthermore, in order to investigate the light trapping performance of proposed SiO_2/ATO/Graphene structure, we have also compared its optical absorption enhancements with optimal SiO_2/Graphene/ATO structure. In the SiO_2/Graphene/ATO structure, the graphene coating is deposited between the SiO_2 layer and the ATO layer. The optimization results clearly show that the optimal SiO_2/Graphene/ATO structure can achieve 14.87% enhancement compared to the bare ATO structure when the d is equal to 70 *nm* and the L is equal to 10. Therefore, it is demonstrated that the optimal SiO_2/ATO/Graphene structure can obtain 16.71% enhancement which has obviously exceeded the light trapping enhancement of 14.87% for the optimal SiO_2/Graphene/ATO.

Figure 4 illustrates the spectral absorption rate of the *a*-Si:H active region for optimal SiO_2/ATO/Graphene structure and optimal SiO_2/Graphene/ATO. From the comparison results of Fig. 4, it can be seen that the light trapping performance of optimal SiO_2/ATO/Graphene structure is superior to that of optimal SiO_2/Graphene/ATO. The optimal SiO_2/ATO/Graphene structure almost has higher spectral absorption rate in the whole visible and near-infrared wavelength range compared to the optimal SiO_2/Graphene/ATO structure. The reason may be that Graphene has a refractive index *n* between ATO and *a*-Si, therefore, the refractive index *n* of SiO_2, ATO, Graphene and *a*-Si increases gradually which will achieve a better graded refractive index distribution profile than that of SiO_2/Graphene/ATO structure.

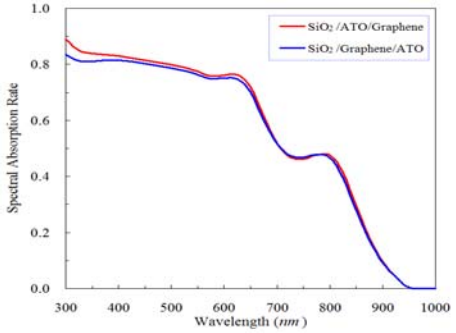

Fig. 4. Spectral absorption rate of the *a*-Si:H active region as functions of incident wavelength for optimal SiO_2/ATO/Graphene structure and optimal SiO_2/Graphene/ATO structure.

5. Conclusion

In this paper, SiO_2/ATO/Graphene and SiO_2/Graphene/ATO structure are selected for the optimal light-trapping design by using differential evolution method. The effect of graphene is mainly investigated and the thickness of the layers of proposed structure is optimized to enhance the optical absorption of thin-film solar cells to the greatest degree. The optimal SiO_2/ATO/Graphene structure almost can enhance the optical absorption of α-Si thin film solar cells in the whole visible and near-infrared wavelength range compared to the conventional bare ATO structure. Finally, the theoretical calculation results clearly demonstrate that the proposed SiO_2/ATO/Graphene layered structure is obviously superior to the SiO_2/Graphene/ATO structure, and it can obtain a higher light-trapping enhancement in the whole visible and near-infrared wavelength range because of the graded refractive index distribution profile.

References

1. A. V. Shah, H. Schade, M. Vanecek, J. Meier, E. Vallat-Sauvain, N. Wyrsch, U. Kroll, C. Droz, and J. Bailat, "Thin-film silicon solar cell technology," Prog. Photovolt. Res. Appl. **12**(23), 113–142 (2004).
2. D. E. Carlson and C. R. Wronski, "Amorphous silicon solar cell," Appl. Phys. Lett. **28**(11), 671–673 (1976).
3. Y. X. Zhao, F. Chen, Q. Shen, and L. M. Zhang, "Light trapping design of graphene transparent electrodes for efficient thin-film silicon solar cells," Applied Optics **51**(25), 6245–6251 (2012).
4. Yu. A. Akimov, W. S. Koh, S. Y. Sian, and S. Ren, "Nanoparticle-enhanced thin film solar cells: metallic or dielectric nanoparticles?" Appl. Phys. Lett. **96**(7), 073111–073113 (2010).
5. R. R. Nair, P. Blake, A. N. Grigorenko, K. S. Novoselov, T. J. Booth, T. Stauber, N. M. R. Peres, and A. K. Geim, "Fine structure constant defines visual transparency of graphene," Science **320**(5881), 1308 (2008).
6. M. Bruna and S. Borini, "Optical constants of graphene layers in the visible range," Appl. Phys. Lett. **94**(3), 031901 (2009).
7. L. Wu, H. S. Chu, W. S. Koh, and E. P. Li, "Highly sensitive graphene biosensors based on surface plasmon resonance," Opt. Express **18**(14), 14395–14400 (2010).
8. S. H. Choi, Y. L. Kim, and K. M. Byun, "Graphene-on-silver substrates for sensitive surface plasmon resonance imaging biosensors," Opt. Express **19**(2), 458–466 (2011).
9. K. S. Yee, "Numerical solution of intitial boundary value problems involving Maxwell's equations in isotropic media," IEEE Trans. Antenn. Propag. **14**(3), 302–307 (1966).
10. R. J. Luebbers, F. Hunsberger, K. S. Kunz, R. B. Standler and M. Schneider, "A frequency-dependent finite-difference time-domain formulation for dispersive materials," IEEE Trans. Electromagn. Compat. **32**(3), 222–227 (1990).
11. http://www.sopra-sa.com.
12. C. Y. Shen, H. J. Feng, Z. H. Xu, and S. Z. Jin, "GaInN light-emitting diodes with omni-directional reflector using nanoporous SnO2 film," Chinese Optics Letters, **6** (2), 152–153 (2008).
13. R. Storn and K. Price, "Differential evolution—a simple and efficient heuristic for global optimization over continuous spaces," J. Glob. Optim. **11**(4), 341–359 (1997).
14. Y. X. Zhao, F. Chen, Q. Shen, Q. W. Liu, and L. M. Zhang, "Optimizing low loss negative index metamaterial for visible spectrum using differential evolution," Opt. Express **19**(12), 11605–11614 (2011).