Study of thin-film GaAs solar cells with cylindrical Ag nanoparticles and distributed Bragg reflector*

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(Received 14 October 2013)

An efficient light-trapping structure, which consists of the periodic Ag nanoparticles and a distributed Bragg reflector (DBR) with high reflectivity, is presented for the thin-film gallium arsenide (GaAs) solar cells. The effects of both Ag nanoparticles and DBR on the optical absorption of GaAs solar cells are theoretically investigated by using finite-difference time-domain (FDTD) method. The optimization process of parameters for the solar cell with both structures is analyzed systematically. The great absorption enhancement in GaAs layer is demonstrated, especially in the wavelength region near the GaAs band gap. It is observed that the superposition of the two effects excited by Ag nanoparticles and DBR results in the obvious absorption enhancement. By using cylindrical Ag nanoparticles and DBR together, the maximum enhancement factor of the solar cell is obtained as 4.83 in the simulation.

Document code: A **Article ID:** 1673-1905(2014)01-0038-5

DOI 10.1007/s11801-014-3195-7

Gallium arsenide (GaAs) is a major material applied in concentrator solar cells and space solar cells. GaAs-based solar cells have attracted considerable attention in recent years due to their direct band gap and high absorption coefficient in the entire visible region of solar spectrum[1,2]. However, the weak absorption at the wavelengths near the GaAs band gap limits the efficiency of solar cell[3]. It is crucial to give rise to the absorption for GaAs solar cells in the wavelengths close to the GaAs band gap[4,5]. To enhance the light trapping in the wide solar spectrum range, several approaches have been proposed[6-8]. Silicon dioxide (SiO_2), silicon nitride (Si_3N_4) and titanium dioxide (TiO_2) are commonly used in photovoltaic cell as antireflection coatings to reduce the reflectivity of solar cells[9,10]. Another important way is to use the textured back reflector for enhancing light trapping[11,12]. For example, the distributed Bragg reflector (DBR) can be used at the rear of the solar cell to enhance the internal light reflection on the backside of solar cell[13]. Considering the above two approaches, the use of plasmonic nanostructures with photovoltaic devices is another efficient method[14,15]. The use of metallic nanostructures could cause the excitation of localized surface plasmon (LSP) resonance, which could extend the absorption range of GaAs solar cells into the wavelength region near the band gap. These approaches have achieved good effect on enhancing light absorption. However, for the demand of more efficient and low-cost solar cells, it is a crucial work to find the new ways to further enhance the efficiency of solar cells.

In this paper, a theoretical analysis of the absorption of the GaAs solar cell with both Ag nanoparticles and DBR is presented. The finite-difference time-domain (FDTD) method is adopted for the simulation. The effects of the geometric parameters of Ag nanoparticles on the absorption are discussed, and the period of DBR is optimized as well. Moreover, a careful study is taken for the optimization of the parameters of solar cell with both structures. The mutual effects between Ag nanoparticles and DBR are analyzed. Detailed analyses and interpretations are presented for the absorption enhancement. Finally, solar cell with both Ag nanoparticles and DBR is compared with that with Ag nanoparticles and DBR respectively.

The simulation model of a thin-film GaAs solar cell with periodic Ag nanoparticles and DBR is shown in Fig.1. The GaAs solar cell is realized on a semi-insulating GaAs substrate. The bare GaAs solar cell consists of a GaAs substrate, a 30 nm-thick $Al_{0.35}Ga_{0.65}As$ spacing layer and a 50 nm-thick GaAs absorption layer. The spacing layer can reduce the thermal expansion mismatch diffusing from one material into another. The multilayer DBR is composed of some pairs of $AlAs/Al_{0.2}Ga_{0.8}As$ layers with thickness

* This work has been supported by the International Scientific and Technological Cooperation Projects of Guizhou Province in China (No.2011GZ76257), and Program for Innovative Research Team of Guilin University of Electronic Technology (IRTGUET).

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of a quarter of DBR center wavelength, and the DBR center wavelength is set as 800 nm. In Fig.1, r and h represent the radius and the height of Ag nanoparticles, respectively. p is the period of the nanoparticle array in x and y directions. Ag is used as the metal material, because it has the obvious LSP effects and the low light absorption. The optical parameters of these materials are all from Ref.[16].

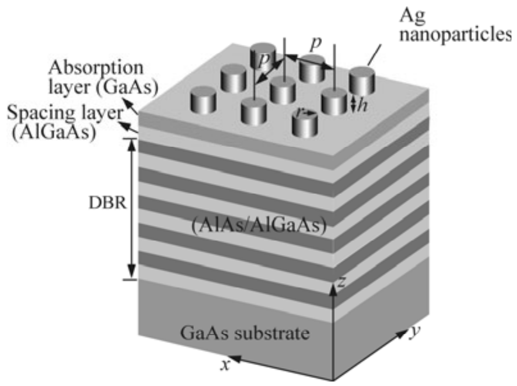


Fig.1 Schematic diagram of the ultra-thin GaAs solar cell with periodic Ag nanoparticles and DBR

Numerical simulations are performed using the FDTD solutions package from Lumerical software. The incident light is a uniform plane wave with the electric field polarized along x-axis. The wavelength range of the source is from 700 nm to 900 nm, which lies in the weak absorption region of GaAs. Perfectly matched layer (PML) absorbing boundary conditions are used on the upper and bottom boundaries. Two power monitors are used for calculating the power absorbed in the GaAs. Here, the absorption factor $A(z, \lambda)$ is defined as the absorption within a given z-depth of the GaAs layer, and $T(z, \lambda)$ is defined as the power transmission coefficient[17], so the absorption factor can be expressed as

$$A(z,\lambda)=T(0,\lambda)-T(z,\lambda)\,, \tag{1}$$

where $T(z, \lambda)$ indicates the total power. The absorption of solar cell refers to the absorption of the 50 nm-thick GaAs layer particularly.

Integrated quantum efficiency (IQE) is defined as

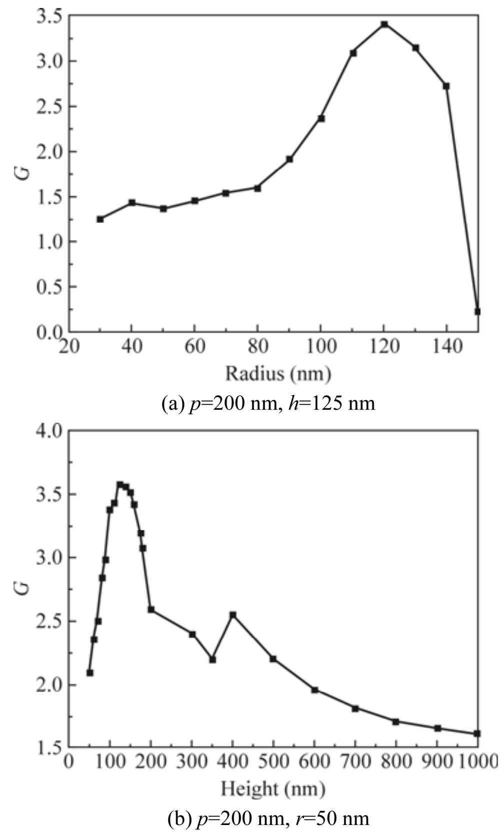
$$IQE(\lambda)=\frac{\int\frac{\lambda}{hc}\frac{P_{\text{abs}}(\lambda)}{P_{\text{in}}(\lambda)}I_{\text{AM1.5}}(\lambda)\mathrm{d}\lambda}{\int\frac{\lambda}{hc}I_{\text{AM1.5}}(\lambda)\mathrm{d}\lambda}\,, \tag{2}$$

where h is Plank's constant, c is the speed of light in the free space, $I_{\text{AM1.5}}$ is AM 1.5 solar spectrum, and $P_{\text{in}}(\lambda)$ and $P_{\text{abs}}(\lambda)$ are the incident light power and absorbed light power at a wavelength within GaAs solar cell, respectively. In Eq.(2), the numerator is equal to the number of photons absorbed by the solar cell, while the denominator means the number of photons falling onto the solar cell. The solar spectrum $I_{\text{AM1.5}}$ is from Ref.[18]. Parameter G is used to define the light absorption enhancement of the solar cell with light trapping structures compared with a bare solar cell, so it is defined as

$$G=\frac{IQE_{\text{particle}}}{IQE_{\text{bare}}}=\frac{\int\lambda P_{\text{t}}(\lambda)I_{\text{AM1.5}}(\lambda)\mathrm{d}\lambda}{\int\lambda P_{\text{bare}}(\lambda)I_{\text{AM1.5}}(\lambda)\mathrm{d}\lambda}\,, \tag{3}$$

where $P_{\text{t}}(\lambda)$ and $P_{\text{bare}}(\lambda)$ represent the light absorption power of solar cells with and without light trapping structure, respectively.

Fig.2 shows the absorption enhancement factor G of the solar cells with different radii and heights of nanocylinder, respectively. As can be seen from Fig.2(a) with p=200 nm and h=125 nm, G firstly increases with the increase of radius, and after achieving the maximum, it begins to decrease dramatically. The maximum G is obtained when the strongest LSP resonance is achieved. The optimal enhancement factor G is 3.41 corresponding to r=120 nm. Fig.2(b) shows the result of absorption enhancement factor G with varied height of nanocylinder with p=200 nm and r=50 nm, which shows the similar trend to that with varied radius shown in Fig.2(a). As depicted in Fig.2(b), G has a maximum value of 3.55 at h=125 nm, when p=200 nm and r=50 nm.



(a) p=200 nm, h=125 nm

(b) p=200 nm, r=50 nm

Fig.2 Changes of absorption enhancement factor *G* of solar cells with Ag nanoparticles with varied radius and height of nanocylinder

Fig.3 illustrates the change of G with the period of nanoparticle array for Ag particles with a set of radii and the fixed height of 80 nm. From Fig.3, G has a dramatic rise as the period increases for each value of nanocylinder radius, until G reaches a maximum, and then it gradually decreases to a unity. The maximum G is 2.85 at r=40 nm, p=120 nm and h=80 nm.

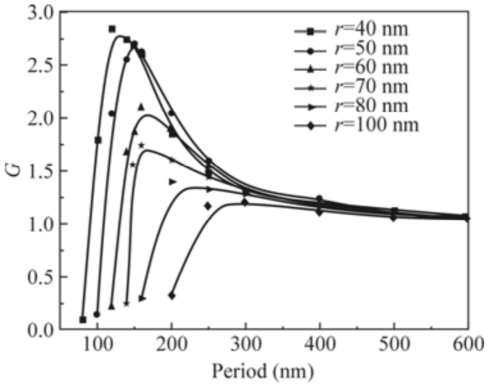


Fig.3 Changes of absorption enhancement factor *G* of solar cells with Ag nanoparticles with varied period of nanoparticle array at *h*=80 nm for different radii

For further optimization process of parameters of Ag nanoparticles, the maximum G is obtained as 3.61 in the simulation, where h=125 nm, r=40 nm and p=120 nm.

Fig.4 illustrates the reflectance spectra and the absorption spectra of solar cells with DBR composed of different pairs of AlAs/AlGaAs layers (n-period DBR) and the absorption spectrum of solar cell without DBR. The thicknesses of AlAs and AlGaAs are set as 66.5 nm and 56 nm, respectively. As shown in Fig.4(a), with the increase of the number of periods, the maximum reflectivity of the AlAs/AlGaAs DBR is increased, while the width of high reflectance region is decreased gradually. Moreover, when the period of DBR is up to 20, the maximum reflectivity is 99.7% over a wide wavelength range. Here, the 20-period DBR is used as the back reflector. It demonstrates from Fig.4(b) that the absorption enhancement is related to the period of DBR. As shown in Fig.4(b), the solar cell with 20-period DBR achieves a maximum absorption at about 780 nm. In this case, the maximum G is 2.37.

By now, the cylindrical Ag nanoparticles and the DBR are introduced, and the related parameters are optimized, respectively. And then both Ag nanoparticles and DBR are employed for the solar cell. The DBR is set as the back reflector on the bottom, while Ag nanoparticles are used as the front light-trapping structure on the surface. First, considering the optimal parameters derived from the discussions above, the spectral behavior of solar cell with both structures is analyzed. In this case, G is calculated by Eqs.(2) and (3) as 3.59. It is observed that the absorption enhancement of solar cell with both structures is lower than that with Ag nanoparticles alone. The result does not meet the expectation. It is estimated that the optimal geometric parameters of the solar cell with both Ag nanoparticles and DBR should be changed. Then the detailed study of the optimal parameters of both structures is taken out.

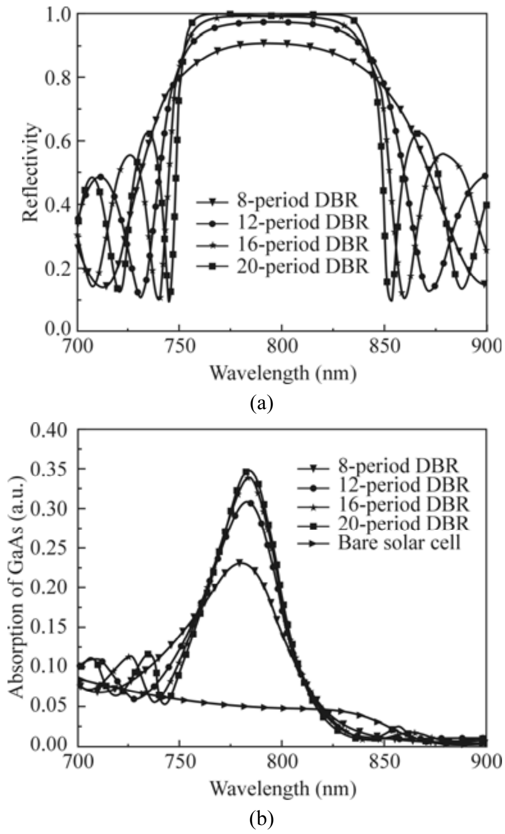


Fig.4 (a) The reflectance spectra and (b) the absorption spectra of solar cells with DBR composed of different pairs of AlAs/AlGaAs layers

Fig.5 illustrates the absorption spectra of solar cells with both Ag nanoparticles and n-period DBR. It can be seen from Fig.5 that the light absorption of solar cells with both structures is significantly enhanced compared with that with 20-period DBR alone. Along with the increase of period of DBR, the absorption peak shows blue shift and the peak increases greatly. It demonstrates that Ag nanoparticles play a positive role in improving the absorption of solar cell with DBR alone. Moreover, in the solar cells with both structures, Ag nanoparticles do not influence the optimal parameters of DBR as discussed previously.

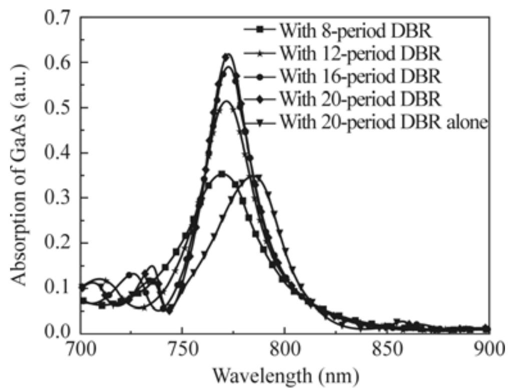
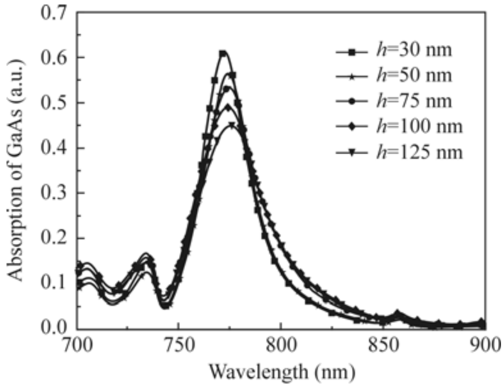
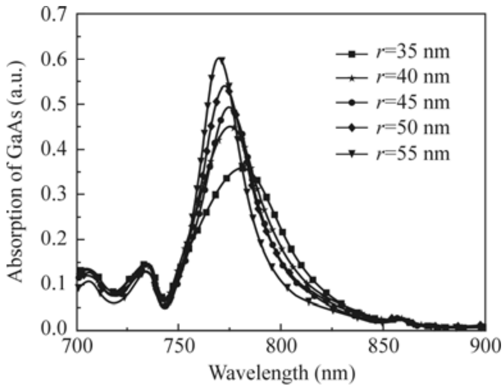


Fig.5 Absorption spectra of solar cells with Ag nanoparticles and *n*-period DBR

In order to verify the optimal geometric parameters of Ag nanoparticles in condition of solar cell with both structures, the detailed analysis is put forward. Fig.6 shows the absorption spectra of solar cells with DBR and Ag nanoparticles with varied height and radius, respectively. In Fig.6(a), the array period p is set as 120 nm and r=40 nm. With the increase of height, the absorption peak shows red shift, the absorption peak value decreases gradually, and the bandwidth of high absorption region is broadened. At h=75 nm, G has a maximum value of 3.81. Fig.6(b) shows the absorption spectra with varied radius for p=120 nm and h=125 nm. With the increase of radius, the absorption peak shows blue shift, and the absorption peak value increases generally. Through the calculation, G has a dramatic rise when the radius increases, and the maximum G=3.83 is obtained when r=50 nm. In the solar cell with Ag nanoparticles alone, the optimal parameters of Ag nanoparticles are p=120 nm, r=40 nm and h=125 nm. The results confirm that the optimal parameters of Ag nanoparticles discussed earlier are not the optimum in the case of solar cell with both Ag nanoparticles and DBR. It is also suggested that the DBR is responsible for the change of optimal geometric parameters of Ag nanoparticles. By the further optimization, the optimal parameters of Ag nanoparticles are obtained as p=130 nm, r=30 nm and h=100 nm, and in this case the maximum G is 4.83.



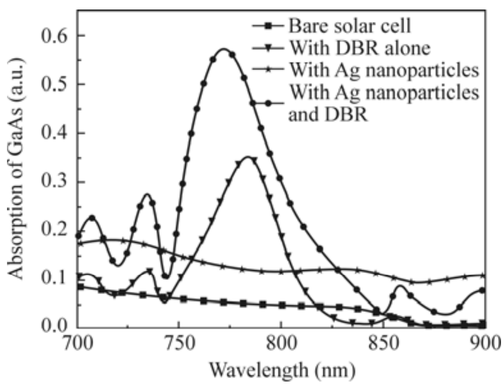
(a) p=120 nm, r=40 nm and varied height



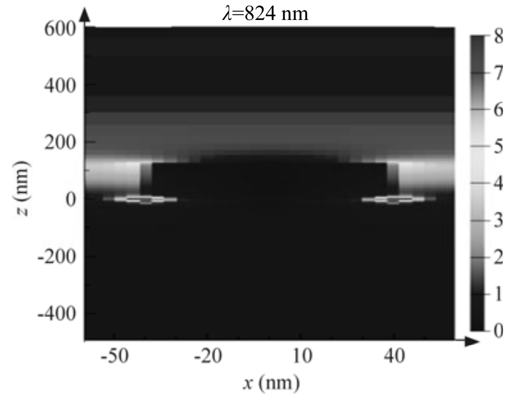
(b) p=120 nm, h=125 nm and varied radius

Fig.6 The absorption spectra of solar cells with DBR and Ag nanoparticles with varied height and radius

The absorption spectra of three types of solar cells are displayed in Fig.7(a) corresponding to the maximum G values. Fig.7(b)–(d) illustrate the electromagnetic field maps for three investigated structures.



(a)



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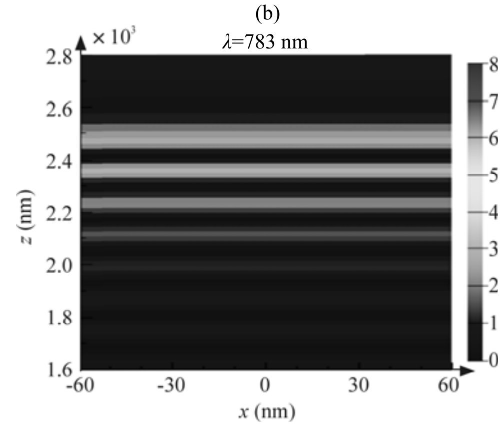
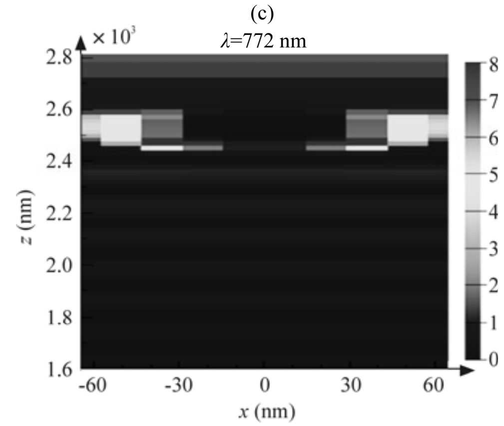


(c)



(d)

Fig.7 (a) Absorption spectra of solar cells with three types of light-trapping structures; Electromagnetic field maps for GaAs solar cells with (b) Ag nanoparticles alone, (c) DBR alone and (d) both Ag nanoparticles and DBR, respectively

From Fig.5, it is clear that the use of DBR and periodic Ag nanoparticles alone can significantly enhance the light absorption, respectively, while the more efficient absorption is achieved when Ag nanoparticles and DBR are combined in the GaAs solar cell, especially in the wavelength range from 740 nm to 850 nm. In this region, the optical absorption is improved dramatically, and the maximum absorption is up to 0.57 at λ=785 nm as shown in Fig.7(a). The great optical confinement has been obtained in a 50 nm-thick GaAs layer by use of periodic Ag nanoparticles and DBR together. It can be ascribed to the superposition of two effects, which are the scattering effect due to LSP resonance excited by Ag nanoparticles and the high reflectivity of DBR. It can be better explained by Fig.7. As shown in Fig.7(b), due to the effect of LSP resonance, the field is mainly distributed at the interface between the Ag nanoparticles and the GaAs layer. In Fig.7(c), the field distribution is uniform at each layer, and the strongest electrical field occurs in the GaAs layer. From Fig.7(d), the superposition of field strengths is observed, and the great absorption enhancement is confirmed.

The absorption enhancements of the absorption layers in GaAs solar cells with cylindrical Ag nanoparticles, DBR and both of Ag nanoparticles and DBR are numerically investigated, respectively. The optimization processes of the parameters of DBR and Ag nanoparticles are presented, respectively. In the solar cell with Ag nanoparticles alone, the scattering effect due to LSP resonance leads to the substantial increase in light absorption. The maximum enhancement factor G=3.61 is obtained. The AlAs/AlGaAs DBR is also utilized to enhance the internal light reflection on the solar cell bottom. When the DBR with 20-period AlAs/AlGaAs layers is used, the maximum reflectivity achieves 99.7%, and the maximum enhancement factor is G=2.37. Moreover, the proposed light-trapping structure consisting of DBR and periodic Ag nanoparticles is demonstrated. Due to the superposition of the two effects which are excited by Ag nanoparticles and DBR, the optical absorption is dramatically enhanced in the wavelength range near the GaAs band gap. The optimal enhancement factor G is 4.83, which is bigger than those of GaAs solar cells with DBR alone and Ag nanoparticles alone.

References

[1] Yang T., Wang X., Liu W., Shi Y. and Yang F., Optics Express **21**, 18207 (2013).

[2] S. M. Hubbard, C. D. Cress, C. G. Bailey, R. P. Raffaelle, S. G. Bailey and D. M. Wilt, Applied Physics Letters **92**, 123512 (2008).

[3] Byung-Jae Kim and Jihyun Kim, Optics Express **19**, A326 (2011).

[4] N. López, L. A. Reichertz, K. M. Yu, K. Campman and W. Walukiewicz, Physical Review Letters **106**, 028701 (2011).

[5] E. D. Kosten, J. H. Atwater, J. Parsons, A. Polman and H. A. Atwater, Light: Science & Applications **2**, e45 (2013).

[6] P. Bermel, C. Luo, L. Zeng, L. C. Kimerling and J. D. Joannopoulos, Optics Express **15**, 16986 (2007).

[7] V. E. Ferry, M. A. Verschuuren, H. B. Li, E. Verhagen, R. J. Walters, R. E. Schropp and A. Polman, Optics Express **18**, A237 (2010).

[8] T. H. Chang, P. H. Wu, S. H. Chen, C. H. Chan, C. C. Lee, C. C. Chen and Y. K. Su, Optics Express **17**, 6519 (2009).

[9] R. Xu, X. Wang, L. Song, W. Liu, A. Ji, F. Yang and J. Li, Optics Express **20**, 5061 (2012).

[10] S. Turner, S. Mokkapati, G. Jolley, L. Fu, H. H. Tan and C. Jagadish, Optics Express **21**, A324 (2013).

[11] L. Zhao, Y. H. Zuo, C. L. Zhou, H. L. Li, H. W. Diao and W. J. Wang, Solar Energy **84**, 110 (2010).

[12] C. Hsu, G. F. Burkhard, M. D. McGehee and Y. Cui, Nano Research **4**, 153 (2011).

[13] Dayu Zhou and Rana Biswas, Journal of Applied Physics **103**, 093102 (2008).

[14] YAN Qi-qi, QIN Wen-jing, WANG Chao, SONG Peng-fei, DING Guo-jing, YANG Li-ying and YIN Shou-gen, Optoelectronics Letters **7**, 410 (2011).

[15] Chao Wang, Wen-jing Qin, Chun-yu Ma, Qiang Zhang, Li-ying Yang and Shou-gen Yin, Optoelectronics Letters **8**, 401 (2012).

[16] E. D. Palik, Handbook of Optical Constants of Solids, Boston: Academic Press, 1991.

[17] James R. Nagel and Michael A. Scarpulla, Optics Express **18**, A139 (2010).

[18] http://rredc.nrel.gov/solar/spectra/am1.5/ASTMG173/ASTMG173.html, Reference Solar Spectral Irradiance: ASTM G-173, 2003.