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ENHANCED PHOTOVOLTAIC PROPERTIES OF InAs/GaAs QUANTUM-DOT INTERMEDIATE-BAND SOLAR CELLS BY USING CYLINDRICAL QUANTUM DOTS

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Results of recent studies on the light absorption and efficiency of single-junction solar cells show that the efficiency of these cells has approached its value in the Shockley–Queisser limit (33.5%). We suggest a solution to increase efficiency by proposing a new structure of single-junction solar cells. Considering the effects of electron-hole generation rate and surface recombination on efficiency, studies have been conducted to increase efficiency. In this paper, by using an intermediate-band consisting of cylindrical quantum dots, thin-film layers such as GaAs, an anti-reflection coating,and$Al_{0.2}Ga_{0.8}As$as a back surface field, considerable improvement is achieved in the generation rate, current density, open-circuit voltage, and, eventually, efficiency of the cell. Results indicate that efficiency is not equal at all frequencies and bands and it is based on the material and structure. Moreover, absorption is improved by increasing the number of quantum dots. By using cylindrical quantum dots, the open-circuit voltage and cell efficiency enhancement are respectively obtained 20% and 17% compared to the reference cell.

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1. Introduction

Numerous studies have been done in recent years in order to enhance the light absorption, electron-hole generation rate, and efficiency of solar cells. Some studies have proposed intermediate-band solar cells with different structures and large bandgap materials as window layer in order to decrease surface recombination [1]. Using light-trapping configurations, high absorption materials, and intermediate-band of quantum dots in single-junction cells can enhance light absorption, electron-hole generation rate, and efficiency of the cells [2]. However, less attention has been paid to the use of intermediate-bands with cylindrical quantum dots [3]and the spherical and pyramidal quantum dots used in most papers [4,5].Therefore, thin-film solar cells and quantum dots have been utilized as the second and third generation solar cells, respectively [6,7].Considering the Shockley–Queisser limit, single-junction solar cells can have the maximum efficiency of 33.5% [8].

Studies have demonstrated that efficiency approaches this value and reaches 28.8% using the GaAs single-junction solar cell [9]. Intermediate-band solar cells were first discussed by Luque and Martí and the theoretical efficiency of 63.1% is achieved for an ideal intermediate-band cell that significantly improved compared to the Shockley–Queisser limit [10]. In an intermediate-band cell, photons with the energy levels of lower than the bandgap can be absorbed by transferring an electron from the valence band to the intermediate-band and, then, from the intermediate-band to the conduction band that markedly increase the efficiency.

If light absorption is done in a wide spectrum, quantum dots can be used for the intermediate-band in order to increase light absorption which, in turn, enhances the cell efficiency.

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Quantum dots are particles with semiconductor properties with the dimensions of 1 to 10 nm which can be used in the intermediate-band, which is the topic of the present paper.

Because of adjustable bandgap and strong light absorption ability, quantum dots are good choices for solar cells. They have the atom-like density of state which not only results in an extra photocurrent but also keeps the value of open circuit voltage constant [11].

Moreover, the use of materials with large absorption coefficients and small thickness, with low light reflection, and the light trapping method has been recommended for increasing light absorption. In fact, less reflectivity depends on not only the incorporated material, but also the refractive index of the medium in which light shines [12]. Moreover, the efficiency of solar cells can be enhanced by concentrating incident light on the cell [13].

The size and shape of quantum dots affect light absorption and cell efficiency. Investigations indicate that with an equal shape and surface coverage, smaller quantum dots increase the absorption of the intermediate-band solar cells in the ground state [14]. The cell efficiency significantly increases by adding to the number of junctions.

In the present paper, an intermediate-band solar cell consisting of 10 layers of InAs cylindrical quantum dots and anti-reflective coating with the refractive index of 1.7 is proposed. In order to decrease surface recombination, two thin layers of p-$Al_{0.8}Ga_{0.2}As$ and n-$Al_{0.2}Ga_{0.8}As$ with large bandgaps are positioned above and below the structure. According to the results, considerable improvement is achieved in light absorption spectrum and efficiency.

The rest of the paper is categorized as follows. In section 2, the quantum-dot intermediate-band solar cell is explained. Section 3 presents the structure. In section 4, the results of simulating the reference cell with pyramid quantum dots are compared to those of the proposed cell. And finally, a conclusion has been drawn in section 5.

2. Quantum-dot intermediate-band solar cells

Different types of structures have been proposed to increase the efficiency of the solar cells, because of the limitation in the efficiency of solar cells, among them multi-junction intermediate-band solar cells have attained efficiencies above the Shockley–Queisser limit [15]. For a triple-junction cell, the efficiency of 37.5% has been achieved without light concentration [16]. However, the cost and complexity of production are also increased [17]. The high cost of production and growth of materials in multi-junction cells has motivated researchers to look for and study other methods for achieving high efficiencies.

A simple illustration of intermediate-band solar cells is presented in Fig. 1.The general equation under the one sun illumination for analyses the current voltage relationship is given by:

$$\boldsymbol{I} = \boldsymbol{J}_L - \boldsymbol{J}_D \left(\boldsymbol{e}^{\frac{qv}{AKT}} - \mathbf{1} \right) \tag{1}$$

where q is the charge of an electron, A is the ideality factor and it depends on voltage and material quality, K is the Boltzmann's constant. T is the temperature in kelvin, J_L is the light current density and J_D is the dark current density [18].

In the intermediate-band, photocurrent consists of J_{CV} , J_{CI} , J_{IV} ,where:

$$J_{CV} = q\left[s_x n_s N\left(E_{CV}, \infty, T_S, 0\right) + \left(1 - s_x n_s\right) \times N\left(E_{CV}, \infty, T_C, 0\right) - N\left(E_{CV}, \infty, T_C, \mu_{CV}\right)\right] \tag{2}$$

$$J_{CI} = q\left[s_x n_s N\left(E_{CI}, E_{CV}, T_S, 0\right) + \left(1 - s_x n_s\right) \times N\left(E_{CI}, E_{CV}, T_C, 0\right) - N\left(E_{CI}, E_{CV}, T_C, \mu_{CI}\right)\right] \tag{3}$$

$$J_{IV} = q\left[s_x n_s N\left(E_{IV}, E_{CV}, T_S, 0\right) + \left(1 - s_x n_s\right) \times N\left(E_{IV}, E_{CV}, T_C, 0\right) - N\left(E_{IV}, E_{CV}, T_C, \mu_{IV}\right)\right] \tag{4}$$

where J_{CV} , J_{CI} , J_{IV} are the current density of the transition from the valence band to the conduction band, intermediate band to the conduction band and valence band to the intermediate band respectively. s_x is the sun number, and $n_s = 2.1646\times10^{-5}$, E_{CV} , E_{CI} and E_{IV} are the bandgap energies between different energy bands, T_S is the temperature of incident spectrum, T_C is the temperature of solar cell, μ_{CV} , μ_{CI} , μ_{IV} are the chemical potentials between the different energy bands and N is the flux of photons:

$$N\left(E_1,E_2,T,\mu\right)=\frac{2\pi}{h^3c^2}\int_{E_1}^{E_2}\frac{E^2}{e^{\frac{(E-\mu)}{KT}}-1}dE \quad (5)$$

where E_1 and E_2 are the lower and higher energies of photo flux density, h is the plank constant, $c$is the speed of light, and $\mu$is the chemical potentials[19]. Thus, by increasing the number of photons absorbed in the cell, current density and solar cell efficiency are expected to rise without voltage reduction.

The electron-hole generation rate in intermediate-band solar cell is calculated as:

$$G(\lambda,y)=\alpha(\lambda)[1-R(\lambda)]\phi(\lambda)\exp[-\alpha(\lambda)y] \quad (6)$$

where λ is the wavelength of incident light, $\alpha(\lambda)$ is the absorption coefficient of the active layer, $R(\lambda)$ is the reflection coefficient of the cell, and $\phi(\lambda)$ is the flux of the incident light [20].
In a quantum-dot based solar cell, the equation of electron-hole pair generation rate is achieved by:

$$G_q(\lambda,y)=\phi(\lambda)[1-R(\lambda)]\alpha_q(\lambda)\exp[-\alpha_q(\lambda)(y-y_p)] \quad (7)$$

where α_q is the absorption coefficient of the quantum dot. According to Eq. (7), the electron-hole pair generation rate which is important in order to calculate solar cell efficiency, has a direct relationship with the absorption coefficient of the quantum dot [20,21].

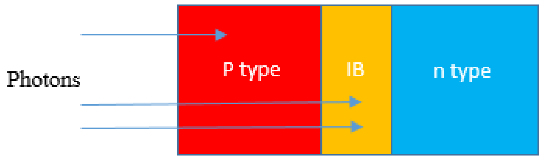


Fig. 1. General structure of an intermediate-band solar cell.

3. Proposed structure

Fig. 2 illustrates the proposed solar cell based on the quantum-dot intermediate-band structure. In this structure, an anti-reflection coating with the refractive index of 1.7 and a GaAs thin layer as an active area are utilized. By using of thin layers with 2 μm thickness, the production cost decreases. Since generation rate is directly related to the absorption of the active layer, thin layers of GaAs can be employed for increasing the absorption and thus, the current of the cell [22]. Because of the larger bandgap of AlGaAs, two thin layers of p-$Al_{0.8}Ga_{0.2}As$ and n-$Al_{0.2}Ga_{0.8}As$ are positioned on the two sides of the active layer in order to decrease the surface recombination which is the remarkable parameter to improve efficiency [23].

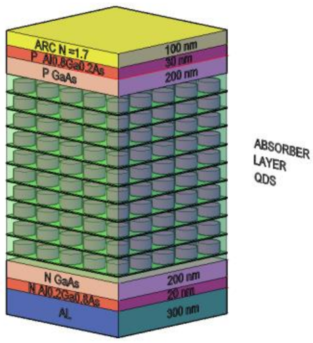


Fig. 2. The schematic of the proposed solar cell and thicknesses of different layers. Details of the structure are expressed in the Table 1.

Table 1. Details of proposed structure.

Material	Thickness	Doping
Base-Al	200nm	n^+ (4×10^{18} cm^{-3})
Emitter-Al	200nm	P^+ (3×10^{18} cm^{-3})
$Al_{0.2}Ga_{0.8}As$	20nm	n^+ (4×10^{18} cm^{-3})
GaAs	200nm	n (2×10^{17} cm^{-3})
InAs cylindrical QDs	10 layer square array r=10nm, h=10nm, pitch=30nm	
GaAs	200nm	p (1×10^{18} cm^{-3})
Window-$Al_{0.8}Ga_{0.2}As$	30nm	P^+ (3×10^{18} cm^{-3})
ARC (n=1.7)	100nm	

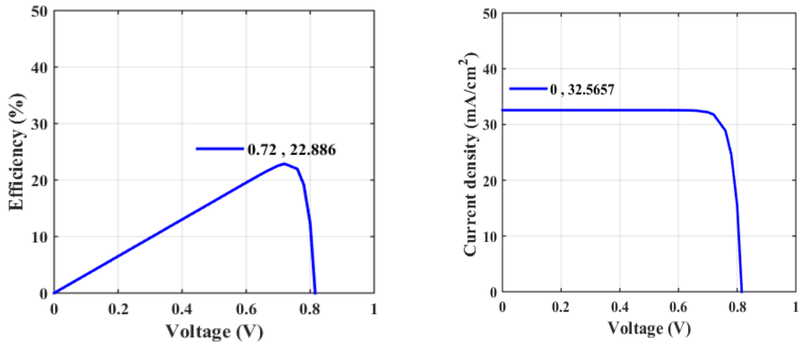
* ARC=Anti-reflection Coating

In the intermediate-band, 10 layers of cylindrical quantum-dot array with the radius and height of 10 nm and center-to-center distance of 30 nm are used. According to our results, incorporated cylindrical quantum dots have higher absorption than other structures.

This structure is proposed with the aim of enhancing the intensity of light absorption as well as efficiency in the active layer. By using 10 layers of quantum dots and increasing the number of dots, photon absorption probability and, therefore, current can be enhanced without decreasing the voltage, resulting in the enhancement of the cell efficiency. Quantum-dot layers are separated with a gallium phosphide (GaP) layer as the strain compensator in order to prevent the change or defect in the structure due to the pressure of layers.

4. Results

The proposed solar cell is simulatedand compared with the reference one. In the reference cell, the following is used: AlGaAs as the upper layer, high impurity p-GaAs, and then a p-GaAs layer. In the n region, four layers of GaAs are utilized. The obtained current density and efficiency are 32.94 mA and 23.15%, respectively [24]. The results of the reference paper are expressed in the Fig. 3.



(a) *(b)*

Fig. 3. (a) Efficiency-voltage curve and (b) current density-voltage curve of the reference solar cell

Open-circuit voltage and current density are enhanced in the proposed cell by changing the number of quantum dots, altering their shape from pyramid to cylindrical, and using a back surface field layer. Fig 4 shows that for most of the shape of quantum dots if the angle of incident light gets closer to 90 degrees, absorption is increased. According to Fig. 4, cylindrical quantum dots incorporated in this study have higher absorption than other forms of quantum dots and Fig.5 demonstrated that by increasing the number of cylindrical quantum dot layers, absorption is increased. Since increasing the number of cylindrical quantum-dot layers may put pressure on the layers and, therefore, cause a defect in the cell, 3nm-thick GaP is used under each layer.

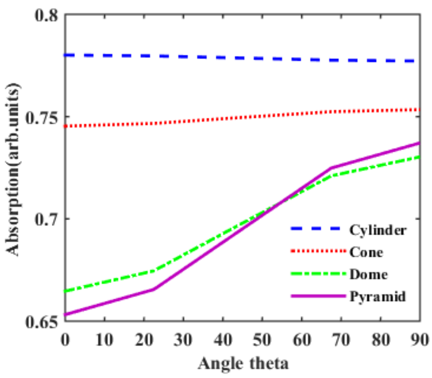


Fig. 4. Quantum-dot absorption versus incident light angle

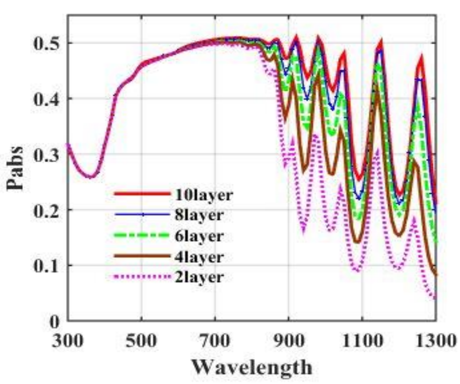


Fig. 5. Wavelength-absorption curve for different number of cylindrical quantum dot layers.

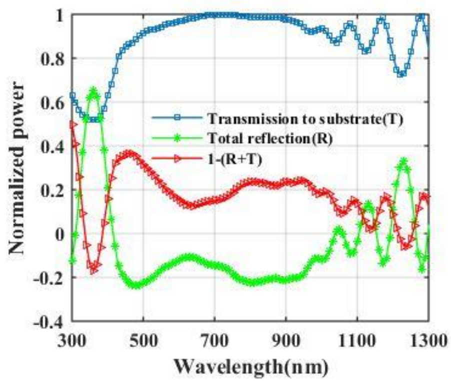
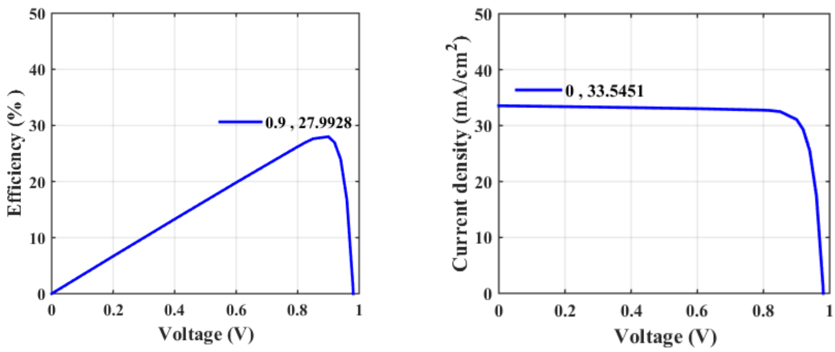


Fig. 6. Transmission, total reflection and absorption of proposed structure.

A 20nm-thick n-$Al_{0.2}Ga_{0.8}As$ layer is employed in order to further decrease the surface recombination rate. Optical characteristics including electron-hole generation rate are significantly improved by increasing the number of quantum dots. By using a material with a refractive index of 1.7 on the surface of the cell, reflection has been reduced. Also, in Fig.6, transmission to substrate (T), total reflection (R) and absorption (1-(R+T)) for incident light from 300nm to 1300nm has been illustrated and showed that reflection at visible spectrum and near infrared have been reduced. Following the changes in the shape and number of quantum dots, the short circuit current and the efficiency have increased, as shown in Fig. 7.

It should be noted that the results are calculated under AM1.5 standard spectrum. In order to validate the accuracy of the simulation and optical stability, the simulation is repeated. The results of the reference and proposed cells are compared in Table 2.



(a) *(b)*

Fig. 7. (a) Efficiency-voltage curve and (b) current density-voltage curve of the proposed solar cell

Table2.Comparison of the results of reference and proposed solar cells.

Structure	V_{oc} (V)	J_{sc} (mA/cm^2)	η (%)
Reference cell	0.81	32.94	23.15
Proposed cell	0.98	33.54	27.99

5. Conclusions

In this paper, the intermediate-band solar cell consisting of 10 layers of InAs cylindrical quantum dots and anti-reflection coating has been proposed and simulated. With alterations in the shape and number of quantum dots, 10 layers of cylindrical quantum-dot square arrays were used with the radius and height of 10 nm and pitch of 30nm, which resulted in an increase in light absorption and electron-hole generation rate. Moreover, an extra n-$Al_{0.2}Ga_{0.8}As$ layer was utilized in order to decrease surface recombination, which led to remarkable improvement in efficiency, such that the new structure caused 17% improvement in the output efficiency of the proposed cell compared to the reference cell. By using InAs quantum dots and increasing their number, the obtained Current density, open-circuit voltage and efficiency of the proposed cell are increased by 3.3%, 20% and 17% compared to the reference cell.

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