Dept. of Mech. Eng.
CUET

Published Online March 2015 (http://www.cuet.ac.bd/merj/index.html)

Mechanical Engineering Research Journal

Vol. 9, pp. 90–95, 2013

ISSN: 1990-5491

HIGHLY EFFICIENT QUANTUM DOT INTERMEDIATE BAND SOLAR CELL (QDIBSC) WITH GaAs

A. Das[1], M. M. Rahman[1], M. A. Matin[1*] and N. Amin[2]

[1]Department of Electrical & Electronic Engineering, Chittagong University of Engineeringand Technology (CUET), Chittagong 4349, Bangladesh
[2]Department of Electrical, Electronic and System Engineering, University Kebangsaan Malaysia (UKM), 43600, Malaysia

Abstract: The main limitation of the conventional solar cells is that input photons are not efficiently absorbed due to a poor match of the spectrum to the energy gap of the conventional solar cell materials. Thus the maximum conversion efficiency of commercial single junction solar cell is less than 20% only. However if intermediate levels are introduced into the energy gap of a conventional cell material, low energy photons can be utilized to increase the conversion efficiency. Thus to enhance the cell efficiency, a device having quantum dot intermediate band is considered as a potential candidate. This work analyses the comparison between conventional solar cells and quantum dot intermediate band solar cells. The MATLAB codes are used to simulate this solar cell. An innovative design of a quantum dot intermediate band solar cell with conversion efficiency of 31.83% (J_{SC} = 45.35mA/cm^2, V_{OC} = 0.8141V, FF = 0.8622) is presented in this paper.

Keywords: *Intermediate band solar cells, quantum dots, short circuit current density, open circuit voltage, fill factor, conversion efficiency*

NOMENCLATURE

Symbol	**Meaning**	**Unit**
J_{SC}	Short circuit current	(mA/cm^2)
V_{OC}	Open circuit voltage	(V)
FF	Fill Factor	Dimensionless
η	Efficiency	Dimensionless
N_D	Donor concentration	(cm^{-3})
N_A	Acceptor concentration	(cm^{-3})
	Transport factor	
f_i		Dimensionless

1. INTRODUCTION

Solar cell is the most important part of a solar system. The main problem of this solar cell is that its efficiency is very poor for generation of electricity. Maximum theoretical efficiencies of solar cells can be 31%. It is called Shockley quisser limit. Efficiencies of silicon based solar cells are 25.0% (crystalline), 20.4% (multi-crystalline), and 20.1% (thin film transfer) [1]. For thin film solar cells efficiencies are 28.8% (GaAs), 18.4% (GaAs multi crystalline), 22.1% (InP), 20.3% (CIGS thin film) [1]. The Quantum Dot Intermediate Band Solar Cell (QDIBSC) was used to increase the efficiency of the solar cell beyond this limit. Another problem of solar cell is higher cost. The cost of PV system is very high. Minimizing the cost of solar cell will minimize the cost of PV system. So, it is the main objective of our work. A proper tool is required to simulate the cell. But for QDIBSC suitable software is yet to be developed. Thus MATLAB program has been used to simulate this cell.

The main limitations of the photovoltaic conversion device are that low energy photons cannot excite charge carriers to the conduction band, therefore do not contribute to the device’s current, and high energy photons are not efficiently used due to a poor match to the energy gap. However, if intermediate levels are introduced into the energy gap of a conventional solar cell, then low energy photons can be used to promote charge carriers in a stepwise manner to the conduction band. In addition, the photons would be better matched with energy transitions between bands. Fig.1 illustrates this type of structure. In this case, there is one intermediate bands between the valence and conduction bands. When photon energy match energy gap between VB and CB it transfers electron from VB to CB (blue

---

[*] **Corresponding author:** Email: imamatin@cuet.ac.bd; Tel: +8801713109853

light). Photon having energy greater than VB-IB energy gap but lower than VB-CB (green light), transfers electrons from VB to IB and photon having energy greater than IB-CB energy gap (red light), transfers electrons from IB to CB [2]. This is how it can absorb maximum spectrum from solar irradiance. This type of device is called an intermediate band solar cell (IBSC). This is a multi-step or ladder approach to increase efficiency. It will be shown that the maximum efficiency of a photovoltaic conversion device using one or two intermediate bands is greater than the single band gap conventional device.

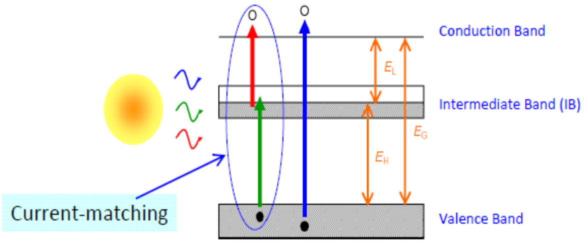

Fig. 1: QDIB solar cell.

2. MODEL

Our proposed model has been shown in Fig. 2. It is a p-i-n structure where we have chosen GaAs as *p* and *n*-type material. *i*-region is intermediate band which is made of quantum dot. InAs is QD material and GaAs is barrier material on which QDs are arranged. QD arrangement in intermediate band has been shown in Fig. 2.

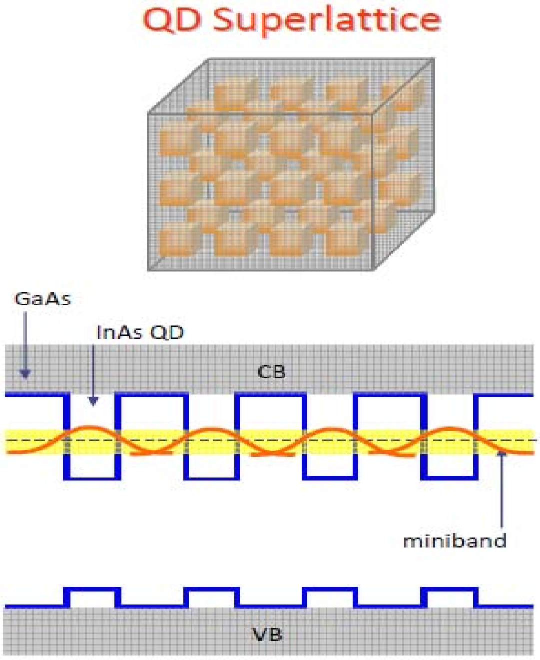

Fig. 2: Schematic structure of QDIB solar cell.

The model for the calculation of the power conversion efficiency will include realistic estimates for the light absorption, photocurrent generation in *p* and *n*-type GaAs regions and InAs/GaAs QDs *i*-region, as well as the surface and bulk minority-carrier recombination and junction generation-recombination currents. High-density array of QDs can be fabricated using the well-known stacking technique in the Stranski–Krastanow growth mode [3].

3. SIMULATION

The proposed structure of QDIB solar cells has given below. In the proposed cell structure, p-type GaAs layer of 1.2 µm has been selected as an absorber layer. InAs/GaAs QD *i*-region has been selected about 3 µm. This selection has been made from various observations with different thickness. Another layer thickness of n type GaAs has been selected 1.3 µm. Sun light strike at the p-type material over which a transparent conductor is connected as front contact and in the back surface a metal conductor is connected as back contact material as if it can be an ohmic contact to the cell. This designed cell is an optimized structure with high efficiency. The conventional silicon solar cell requires 100 µm thick absorber layers. In this proposed cell structure, absorber layer size is reduced almost 18.2 times than conventional Si based solar cell. And the device size also reduced. Now for silicon based solar panel, the cost of power per peak watt is $1 [4]. For the proposed cell structure, it is reduced because of less material required as GaAs is a direct band gap material. This designed cell is an optimized structure with high efficiency. In the next sections variation of thickness and doping concentration will be discussed.

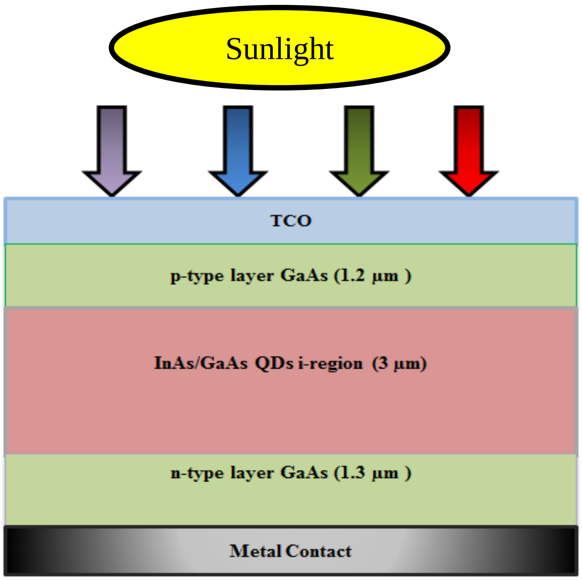

Fig. 3: Proposed structure of QD Intermediate Band Solar cell.

3.1 Equations

Governing equations that is used in simulation have been given below.

3.1.1 Photocurrent

For incident light of wavelength λ and flux $F(\lambda)$ electron hole pair generates in depth of z is

$$G_p(\lambda, z) = \alpha(\lambda)[1 - R(\lambda)]F(\lambda)\exp\,[-\alpha(\lambda)z] \tag{1}$$

Where *R(λ)* is the surface reflection coefficient and *α(λ)* is the light absorption coefficient of GaAs [5]. The spectral distribution of the solar flux incident on the cell surface under the condition 1 Sun, 1.5 AM can be written as [6]

$$F(\lambda) = 3.5x10^{21}\lambda^{-4}\left[\exp\left(\frac{hc}{kT_1\lambda} - 1\right)\right]^{-1}\frac{photon}{cm^2.s.\mu m} \tag{2}$$

Where h is the Plack's constant, c is the velocity of light, k is the Boltzmann's constant, and T_1 = 55760 K.

$$j_n = eF(\lambda)[1 - R(\lambda)]\frac{a_n(\lambda)}{\alpha_n(\lambda)^2 - 1}\beta_n\left[b_n + a(\lambda) - \exp\left(-\frac{z_p a_n(\lambda)}{L_n}\right)\left[[b_n + a_n(\lambda)]\cosh\left(\frac{z_p}{L_n}\right) + [1 + b_n a_n(\lambda)]\sinh\left(\frac{z_p}{L_n}\right)\right]\right] \tag{3}$$

Where e is the absolute value of the electronic charge, $\beta_n = [\cosh\left(\frac{z_p}{L_n}\right) + b_n\left(\frac{z_p}{L_n}\right)]^{-1}$, $b_n = \frac{S_n L_n}{D_n}$, and $a_n(\lambda)=\alpha(\lambda)L_n$..

The total photocurrent collected by p-type is equal to [6]

$$J_n^p = \int_0^{\lambda_1} j_n(\lambda)d\lambda \tag{4}$$

Where, $\lambda_1 \approx 0.9\mu m$ is the GaAs absorption cut-off wavelength. For n-type equation is same but it has to take into account the attenuation of the light through the *p*-type and intrinsic region of the GaAs containing QDs made of InAs. It can present the photocarrier generation rate in QDs inside the *i* region as [6]

$$G_D(\lambda, z) = F(\lambda)[1 - R(\lambda)]\alpha_D(\lambda)\exp\left[-\alpha_n(\lambda)\left(z - z_p\right)\right] \tag{5}$$

Where, $\alpha_D(\lambda)$ is the absorption coefficient. The photocurrent collected from the QDs is equal to [6]

$$j_D(\lambda) = e\int_{z_p}^{z_p + z_i} G_D(\lambda, z)dz \tag{6}$$

Photocurrent generation in the GaAs barrier regions within the *i*- region [6]

$$j_B(\lambda) = e\int_{z_p}^{z_p + z_i} G_B(\lambda, z)dz \tag{7}$$

To write the equation of generation rate in the barrier region we shall take into account that only the fraction (1-$V_D n_D$) of *i*-region is occupied by the GaAs barrier region [6]

$$G_B(\lambda, Z) = F(\lambda)[1 - R(\lambda)]\exp\left[-\alpha(\lambda)z_p\right](1 - n_D V_D)\alpha(\lambda)\exp\left[-(1 - n_D V_D)\alpha(\lambda)\left(z - z_p\right)\right] \tag{8}$$

Where, V_D is the single QD volume and n_D is the QDs volume density. Therefore, the net photocurrent generated by light of given λ collected from *i*-region is equal to [6]

$$j_i(\lambda) = j_D + j_B \tag{9}$$

Total photocurrent collected from the *i*- region is equal to

$$j_i = e\left[\int_0^{\lambda_1} j_B(\lambda)d\lambda + \int_{\lambda_1}^{\lambda_2} j_D(\lambda)d\lambda\right] \tag{10}$$

Therefore, the short-circuit current density of the cell can be written as [6]

$$j_{SC} = f_i(J_n^p + J_p^n + J_i) \tag{11}$$

Where f_i is a transport factor, which means the mean probability of an electron or hole crossing the *i*- region without capturing and recombination. We assumed the effective diffusion-drift length of carriers to be larger than the *i*-layer width so that most of photocarriers generated in quasinatural regions and inside the *i*-region are swept out by the junction field without suffering recombination losses so, f_i = 1.

3.1.2 Efficiency Calculation

The equation of current density can be represented by [6]

$$J = J_{SC} - J_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \tag{12}$$

Where, J_o is the reverse saturation current of the junction. The reverse saturation current is formed by the minority carriers that are generated due to thermal excitation at the depletion layer edges (j_{S1}) and in the interior of the *i*-region (j_{S2}). Such a current is controlled by the band gap of GaAs E_{gB} and average band gap of the *i*-region [6]

$$E_{eff} = [1 - n_D V_D]E_{gB} + n_D V_D E_{gD} \tag{13}$$

Where, E_{gD} is the band gap of QDs, which should be taken as [6]

E_g (InAs) + confinement energy

Equation of j_{S2} is

$$j_{S2} = A^{eff}\exp\left(-\frac{E_{eff}}{vkT}\right) \tag{14}$$

Here v is the ideality factor, $A^{eff} = \frac{e4\pi n^2 kT}{c^2 h^3 E_{eff}^2}$, and n is the average refractive index of the *i*-region. The equation of other dark current component j_{S1} is

$$j_{S1} = A\exp\left(-\frac{E_{gB}}{vkT}\right) \tag{15}$$

Where

$$A = eN_C N_V\left(\frac{D_p}{N_D L_P} + \frac{D_n}{N_A L_A}\right) \tag{16}$$

Here N_C and N_V are the effective density of state in GaAs, N_D and N_A are the donor and acceptor concentration in the *n*-type and *p*-type regions, correspondingly. We can now calculate the cell power conversion efficiency at the maximum power point. Equation of efficiency is [6]

$$\eta = \frac{V_{opt}J_{opt}}{p_o} = \frac{kT}{e}t_{opt}[j_{SC} - j_o(e^{t_{opt}} - 1)]/P_o \tag{17}$$

Where, P_o = 100 mW/cm^2 is the incident solar flux (for 1 sun, AM 1.5 condition) and t_{opt} has to be defined from the equation [6]

$$e^{t_{opt}}\left(1+t_{opt}\right)-1=\frac{J_{SC}}{J_o} \tag{18}$$

Table 1 Device Parameter for simulation of InAs/GaAs QD solar cell [6]

Parameters	Unit of measure	Value
Surface recombination velocity for electrons (S_n)	cm s^{-1}	$6x10^3$
surface recombination velocity for hole (S_p)	cm s^{-1}	$6x10^3$
diffusion length of electrons (L_n)	µm	2
diffusion length of hole (L_p)	µm	3
diffusion constant of electrons(D_n)	cm^2 s^{-1}	200
diffusion constant of hole (D_p)	cm^2 s^{-1}	10
volume of QD (V_D)	cm^3	$1.77x10^{-18}$
volume density of QDs (n_D)	cm^{-3}	$1.7x10^{17}$
surface reflection coefficient [R(λ)]		0.1
band gap of GaAs (E_{gB})	eV	1.4
band gap of QDs (E_{gD})	eV	0.95
acceptor concentration (N_A)	cm^{-3}	$1.4x10^{18}$
donor concentration (N_D)	cm^{-3}	$1.7x10^{17}$
p-region length (Z_p)	µm	1.2
i-region length (Z_i)	µm	3
n-region length (Z_n)	µm	1.3
transport factor	f_i	1
ideality factor (υ)		1

3.2 Simulation by MATLAB

The popularity of MATLAB is partly due to its long history, and thus it is well devolved and well tested. MATLAB is programmable and has the same logical, relation, condition, and loop structures as other programming languages, such as FORTRAN, C, BASIC, and Pascal. Thus, it can be used to teach programming principles. So we have used MATLAB (version 7.10.0.499, (R2010a)) to solve above equations and to simulate parameters of the cell.

3.2.1 Thickness Variation of p-Layer

One of the challenging issues of solar cells is related to the lesser material usage. The mono-crystalline GaAs has a high absorption coefficient of over $2.3x10^5$/cm, which means that all the potential photons of sunlight with energy greater than the band gap can be absorbed within 1-3 µm thin GaAs absorber layer. Moreover, GaAs has a direct band gap of 1.4eV, hence, the lesser thickness required for GaAs absorber layer can lead to reduced cell material usage and lower cost of fabrication. It is clear, from Fig. 4 that all the cell output parameters gradually decreased from 1.2 µm to 0.1 µm of *p*-type GaAs thickness. However, the J_{sc} and conversion efficiency show higher decreasing rate from 1.2 µm to 0.1 µm of GaAs thickness, but *FF* and V_{OC} follows the slow rate of decrease. Along with V_{OC}, *FF* and eventually the cell conversion efficiency change is very poor above 1.2 µm of *p*-type GaAs thickness. It might be attributed to the shorter minority carrier diffusion length. The loss of efficiency in thin *p*-type GaAs cell is mainly due the loss in V_{OC} and J_{SC} which might be attributed to the long wavelength region, the quantum efficiency decreases with the decrease of *p*-type GaAs absorber thickness as found in the simulation. The combined effect on cell conversion efficiency showed rapid decreasing cell performance below 1.2 µm of *p*-type GaAs thickness, indicating that thickness reduction below 1.2 µm of *p*-type GaAs absorber is not appreciable with the selected material parameters and with this cell structure. So thickness of 1.2 µm has been chosen for GaAs *p*-layer.

3.2.2 Thickness Variation of i-region

I-region of this cell is made of quantum dots and barrier material. The thickness of this layer has been varied from 0.5µm to 8µm. No significant variation has been observed varying thickness of this layer. V_{OC} remains constant. *FF* and J_{SC} increase very little. Efficiency also increases very little. But from Fig. 5 we can see that below 3 µm the efficiency decrease rapidly than other parameters. So we have an optimized thickness at 3 µm.

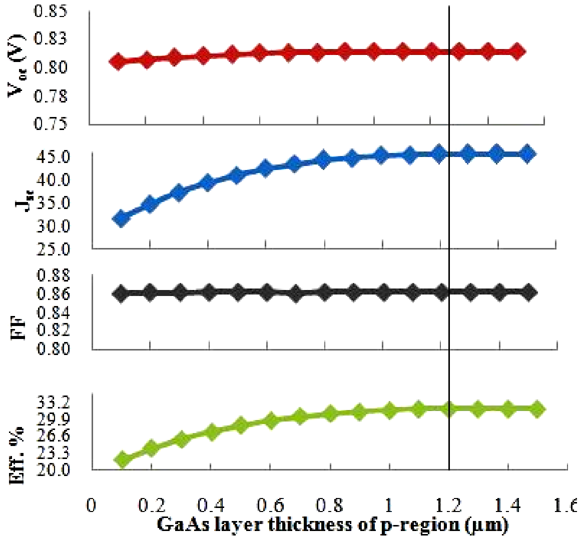

Fig. 4: Thickness variation of p-type material (GaAs)

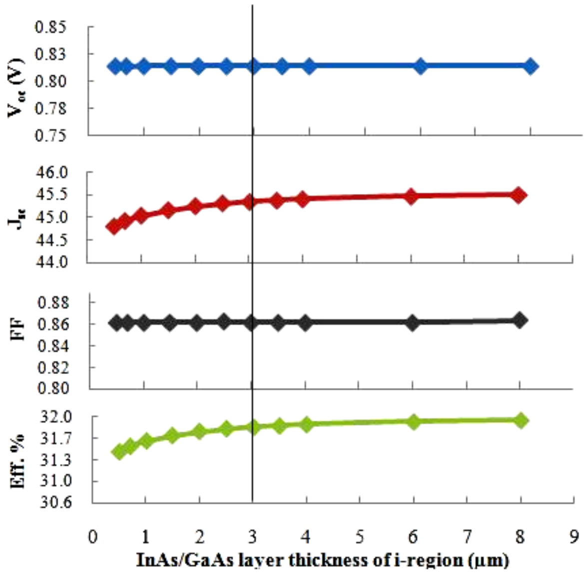

Fig. 5: Thickness variation of InAs/GaAs *i*-region

3.2.3 Thickness Variation of n-region

In n-type GaAs layer thickness has been varied from 0.5

µm to 1.3 µm. From Fig. 6 we can see that *FF* remains almost unchanged with a variation of thickness. Efficiency and J_{SC} decrease rapidly below 1.3 µm. Decreasing rates of V_{OC} is less than efficiency and J_{SC}. It might be attributed to the shorter minority carrier diffusion length. FF and V_{OC} shows almost constant above 1.3 µm *n*- type GaAs thickness. Above 1.3 µm increasing rate of efficiency and J_{SC} is poor. So we have optimized the cell at 1.3 µm.

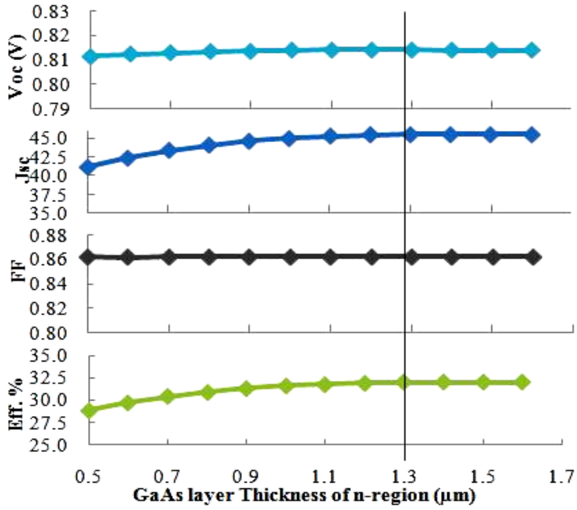

Fig. 6: Thickness variation of n-type material (GaAs)

3.2.4 Doping Concentration Analysis

Doping concentration plays very important rule for solar cell performance. Doping concentration varied from $1x10^{14}$ cm^3 to $9x10^{19}$ cm^{-3} for both donor and acceptor concentrations. We have selected $1.4x10^{18}$ cm^{-3} (N_A) and $1.7x10^{17}$ (N_D) for acceptor and donor concentration.

4. RESULTS AND DISCUSSION

After simulating various cells for different doping concentration and thickness of *p*-type, *n*-type and *i*-region of layer, it is observed that t1he efficiency of the cell is highest for thickness 1.2 µm for p-type layer, 3 µm for *i*-region and 1.3 µm for n-type layer. The cell is optimized at 1.2 µm p-layer1.3 µm of n-layer 3µm for *i*-region with doping concentration of $1.4x10^{18}$ cm^{-3} (N_A) and $1.7x10^{17}$ (N_D). From simulation we have observed that efficiency increase with increase of doping concentration. The cell is optimized at doping $1.4x10^{18}$ cm^{-3} (N_A) and $1.7x10^{17}$ (N_D) because those are achievable for GaAs. The efficiency (η) obtained here 31.83%, the current density, J_{sc} is 45.35mA/cm^2, fill factor, *FF* is 0.8622and open circuit voltage, V_{OC} is 0.8141v. Due to introducing intermediate band between *p* and *n* layer J_{SC} has increased significantly, which increase efficiency of the cell. In Fig. 9 J-V curves of optimized cell has been shown.

For single junction GaAs solar cell efficiency is 22.7% (J_{SC} = 27.9mA/cm2, V_{OC} = 1.012V, *FF* = 0.805). Where, with intermediate band efficiency is 31.83%. So we can say that QDIB solar can be a good solution for the low efficiency problem of solar cell. Moreover, this solar cell is less thick than Si solar cells, which reduce material cost and fabrication cost. In Fig. 10 a comparison has been shown between QDIB solar cells and single junction GaAs solar cells.

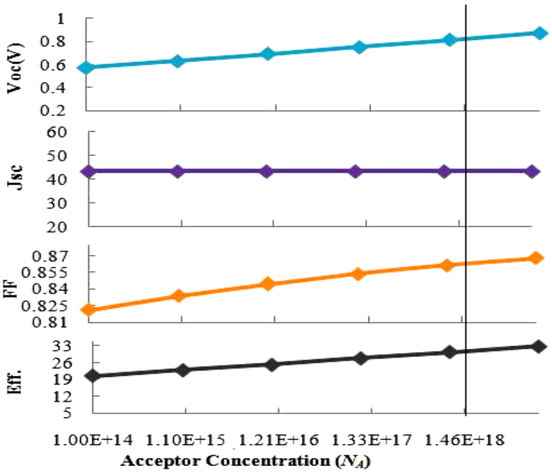

Fig. 7: Variation of acceptor concentration (N_A).

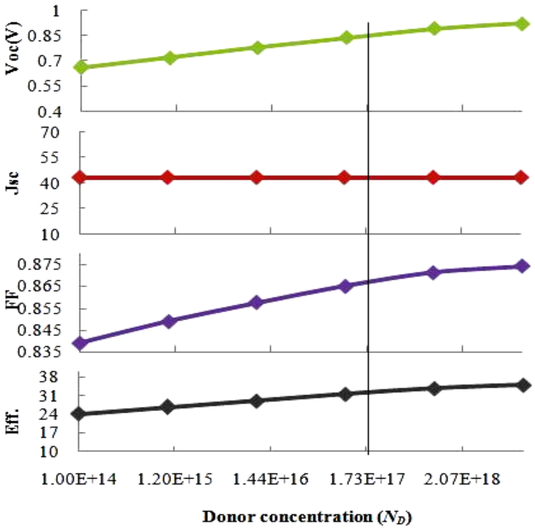

Fig. 8: Variation of donor concentration (N_D)

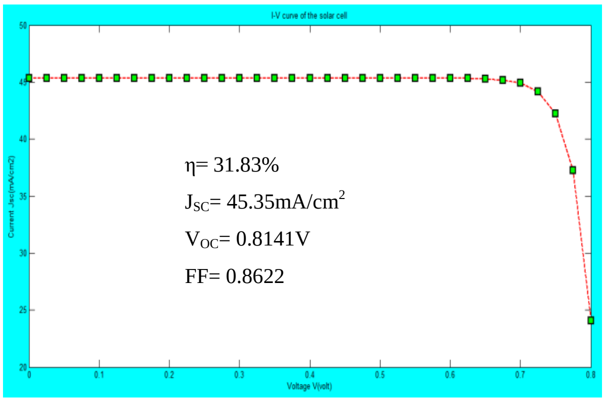

Fig. 9: J-V curve of InAs/GaAs QD solar cell.

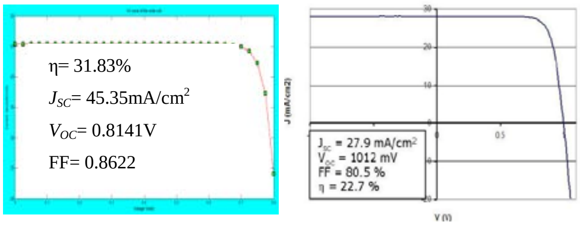

Fig. 10: Comparison between InAs/GaAs QDIBSC and conventional GaAs solar cell

4.1 Effect of Operating Temperature and Cell Stability

Up to now, the cell structure with all layer thickness along with material parameters such as doping concentration, thickness were selected at the operating temperature of 27°C.For practical application, the designed solar cell needs to be used in the field where the operating temperature will be higher than 27°C.In real cases, operating temperature plays a very important role, which affects the performance of the solar cells in terms of stability. At higher operating temperature, parameters such as the effective density of states, absorption coefficients, electron and hole mobility and carrier concentrations and band gaps of the cell materials are affected. A simulation has been done to understand the effect of higher operating temperature on the proposed cell efficiency with temperature ranged from 25°C to 100°C. The simulation results are shown in Fig. 11. It is evident from the Fig. 11 that the conversion efficiency linearly decreases with operating temperature at a temperature coefficient (TC) of -0.15%/°C.

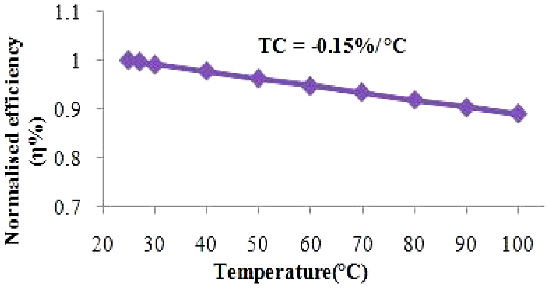

Fig. 11: Effect of temperature on InAs/GaAs QDIB solar cell performance.

5. CONCLUSIONS

We found the efficiency of QD solar cell is 31.83% which has crossed the limit of Shockley quisser limit. So it can be used for mass power generation. We have used only two materials for this solar cell one is GaAs and another InAs. The thickness of this solar cell is less than other conventional solar cell. So less material is needed to fabricate this solar cell. It will also less the fabrication cost of this solar cell as well as the cost of this solar cell. It also can be used to fabricate high efficient solar panel, which will be less expansive and will be very economic. We hope it also boost up solar business in word economy market. In future we work on its front and back contact can be done. Ternary materials can be used to vary its bandgap.

6. ACKOWLEDGEMENTS

Above all, we would like to express our gratitude to the Almighty God. We would like to acknowledge researcher sir Dr. Steven Evans Jenks (Manager, Energy and Sustainability Programs at NJ Transit, Newark, New Jersey, Renewables & Environment) for his help regarding simulation of QDIBSC using MATLAB. We would like to thank all the teachers of The Department of Electrical and Electronics Engineering, Chittagong University Engineering Technology (CUET).

7. REFERENCES

[1] M. A. Green, K. Emery, Y. Hishikawa, W. Warta and E. D. Dunlop, "Progress in Photovoltaics: Research and Applications", Vol. 21, 2013 [Wiley Online Library] Available: http://onlinelibrary.wiley.com/doi/10.1002/pip.2352/abstract, Date: 22 Dec 2012.

[2] A. Marti, L Cuadra and A. Luque. "Quantum Dot Intermediate Band Solar Cell", lnstiuto de Energia Solar - ETSIT de la Universidad Politecnica de Madrid Ciudad Universitaria sn- 28040, IEEE, pp. 340-343. Madrid 2000.

[3] Y. Nakata and Y. Sugiyama, In Semiconductors and Semimetals, Vol. 60, edited by M. Sugaware, Chap. 2, New York, 1999.

[4] A. Hutchinson "Solar Panel Drops to $1 per Watt: Is this a Milestone or the Bottom for Silicon-Based Panels?" 2009 [Online] Available: http://www.popularmechanics.com/science/energy/solar-wind/4306443 Date: Feb 25, 2009.

[5] T. S. Moss and T. D. F. Hawkins, "Infrared Physics", Vol. 1, Pages 105–166, Elsevier B.V. Melbourne, Australia, 1961.

[6] V. Aroutiounian, S. Petrosyan, and A. Khachatryan, "Quantum Dot Solar Cells", Journal of Applied Physics, Vol. 89, pp. 2268–2271, 2000.