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A HIGHLY EFFICIENT QUANTUM DOT INTERMEDIATE BAND SOLAR CELL

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Abstract*-The main limitation of the conventional solar cells is the lower conversion efficiency (~20%) which relate to the insufficient photon absorption due the poor match of the sun spectrum with the energy gap of the conventional solar cell materials. Thus, the maximum conversion efficiency of commercial single junction solar cell is less than 25% only. However, if intermediate levels are introduced into the energy gap of a conventional cell material, low energy photons can be absorbed to increase the conversion efficiency over 30%. Thus to enhance the cell efficiency, a device having quantum dot intermediate band is considered as a potential candidate for higher efficiency solar cell. This work analyses the comparison between conventional GaAs solar cells and quantum dot intermediate band GaAs solar cells. MatLab codes have been developed to simulate high performance quantum dot intermediate band 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. Moreover, normalized efficiency of the proposed cell linearly decreased with the increasing operating temperature at the gradient of -0.15%/°C, which indicated better stability of the designed cell.*

Keywords: Solar energy**,** Intermediate Band Solar Cell, Quantum dots, Short circuit current density, Open circuit voltage, Conversion Efficiency, MatLab.

1. INTRODUCTION

Human wishes inexpensive, reliable and sustainable energy source for production of electricity to sustain the development. The Sun which is unlimited sources of renewable energy and photovoltaic (PV) cells still remains the best way yet determined to harness energy from the sun. Solar cell is the most important part of a solar PV system for generation of electricity. Main problem of this solar cell is that its conversion efficiency is very poor for generation of electricity. Maximum theoretical efficiencies of solar cells can be 30% from Shockley quisser limit. Efficiencies of silicon based solar cells are 25.0% (crystalline), 20.4% (multicrystalline), 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]. To increase efficiency of the solar cell beyond this limit the Quantum Dot Intermediate Band Solar Cell (QDIBSC) is very potential. Another big problem of solar PV is the higher initial cost. Until now the cost of PV system is higher than other conventional source of energy. Through minimizing the cost of solar cells the cost of PV system will be reduced. So, it is the main objective of this part of work. To simulate solar cell we need a proper tool. But as QDIBSC is an emerging solar but there is no suitable software to simulate QDIB solar cell. Thus we have chosen MatLab to simulate this cell. Objectives of this work are To investigate of Quantum Dot (QD) solar cells by introducing Intermediate Band (IB),To minimize the absorber layer thickness for low cost production of solar cells and Modeling and simulating of the QDIBSC by using MATLAB.

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 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. That how absorption of maximum spectrum from solar irradiance cab be achieved. This type of device is called an intermediate band solar cell (IBSC). This is a multi-step or ladder approach to increase cell 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.

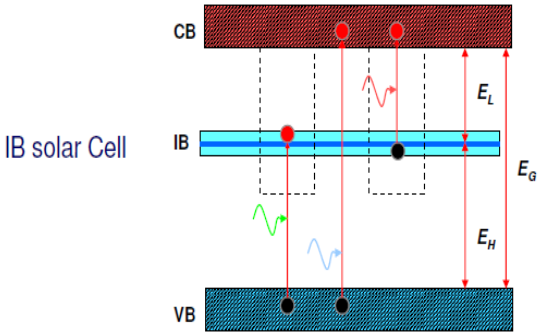


Fig.1: QDIB solar cell.

2. MODEL

Our proposed model is shown in Fig. 2. It is a p-i-n structure where one can chosen GaAs as p and n-type material. I-region is intermediate band which is made of quantum dot (QD). 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.

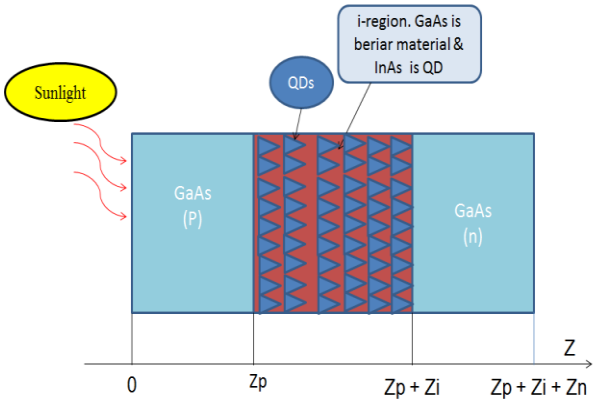


Fig.2: Schematic structure of QDIB solar cell.

The p-i-n QDIB solar cell, showing p-type layer ($0 \leq z \leq z_p$), intrinsic layer of QDs ($z_p \leq z \leq z_p+z_i$), n-type layer ($z_p+z_i \leq z \leq z_p+z_i+z_n$) . Our model for the calculation of the power conversion efficiency will include realistic estimates for the light absorption, photocurrent generation inpandn-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 [2].

3. SIMULATION

Our proposed structure of QDIB solar cells has shown in Fig.3. In the proposed cell structure, p-type GaAs layer of 1.2 µm has been selected as absorber layer. InAs/GaAs QD i-region has been selected about 3 µm. This selection has been made from various observations with different thickness from MatLab simulation. 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 higher efficiency.

The Conventional silicon solar cell requires 100 µm thick absorber layers. In this proposed cell structure, absorber layer size is reduced almost 18 times than conventional Si based solar cells. And the total device size also reduced to less than 6 micron. Now for silicon based solar panel, cost of power per peak watt is $1 [3]. For the proposed cell structure, it will be reduced because of less material required as GaAs is a direct band gap material. This designed cell is an optimized structure with higher cell efficiency. In the simulation part variation of thickness and doping concentration will be analyzed.

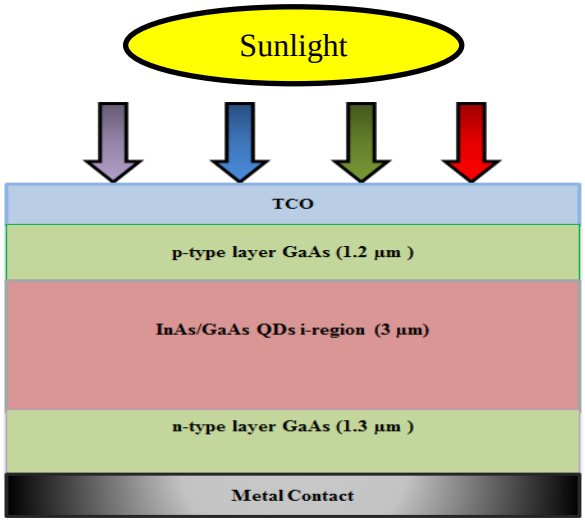


Fig.3: Proposed structure of QD Intermediate Band solar cell.

3.1Equations

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

3.1.1 Photocurrent

For incident light of wavelength λ and flux F(λ) electron hole pair generate in depth of z is;

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

Where R(λ) is the surface reflection coefficient and α(λ) is the light absorption coefficient of GaAs [4]. The spectral distribution of the solar flux incident on the cell surface under the condition 1 Sun illumination, 1.5 AM

can be written as [5]

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

Where h is the Plack's constant, c is the velocity of light, k is the Boltzmann's constant, and T_1=55760 K.
For the photogenerated electron current density at z=z_p [6]

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

Whereeis 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]

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

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

$$G_D(\lambda, z) = F(\lambda)[1-R(\lambda)]\alpha_D(\lambda)\exp[-\alpha_n(\lambda)(z - z_p)] \quad (5)$$

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

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

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

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

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

$$G_B(\lambda, Z) = F(\lambda)[1-R(\lambda)]\exp[-\alpha(\lambda)z_p](1-n_D V_D)\alpha(\lambda)\exp[-(1-n_D V_D)\alpha(\lambda)(z-z_p)] \quad (8)$$

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 fromi region is equal to [6]

$$j_i(\lambda) = j_D + j_B \quad (9)$$

Total photocurrent collected from thei region is equal to

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

Therefore, we can write the short-circuit current density of the cell as [6]

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

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]

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

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.

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

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

E_g (InAs) + confinement energy

Equation of j_{S2} is then

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

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

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

Where

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

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. The cell power and calculated

conversion efficiency now can be at the maximum power point. Equation of efficiency is

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

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]

$$e^{t_{opt}}(1 + t_{opt}) - 1 = \frac{j_{SC}}{j_o} \qquad (18)$$

The number of parameters that can be varied in a particular solar cell model is larger than 50. Obviously, a problem with 50 variables is too ambiguous to solve reliably without help of computer. It is therefore necessary to minimize the number of variable parameters by fixing many of them at reasonable values. It was a real challenge to choose the practically achievable parameters to be used for the different layers of the proposed cells. Many of them depend on fabrication techniques and deposition methods and can thus vary even between devices fabricated in the same batch from the same technology. The Table 1 shows the material parameters used in this modeling, which were selected based on experimental data, literature values, theory, or in some case reasonable estimations.

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 code

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, (R 2010a)) to solve above equations and to simulate parameters of the designed QDIB solar 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 monocrystalline 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 of thin GaAs absorber layer. Moreover, GaAs has a direct band gap of 1.45 eV, 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 layer 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 this 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.

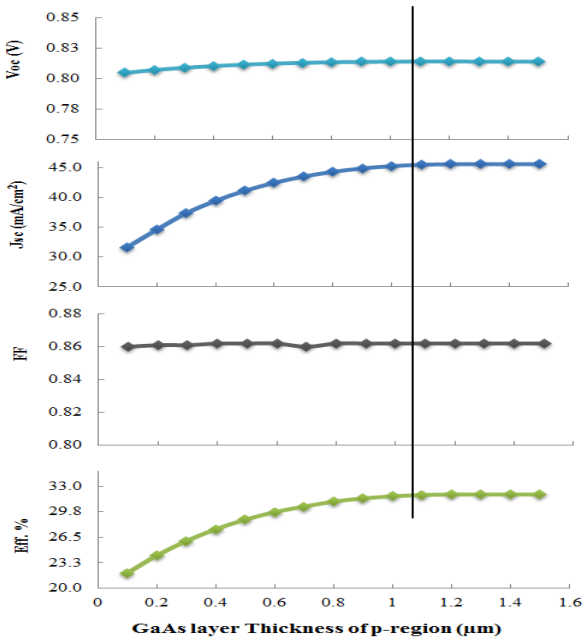


Fig.4: Thickness Variation of p-type material (GaAs)

3.2.2 Thickness Optimization of i-region

The i-region of this cell is made of quantum dots and barrier material. Thickness of this layer has been varied from 0.5µm to 8 µm. No significant variation has been observed from thickness variation of this layer. The V_{OC} remains constant but FF and J_{SC} increase very little. Efficiency also increases very little. But from Fig. 5 it is clear that below 3µm efficiency decrease rapidly with *Jsc*. So the selection has been done at the thickness of 3 µm.

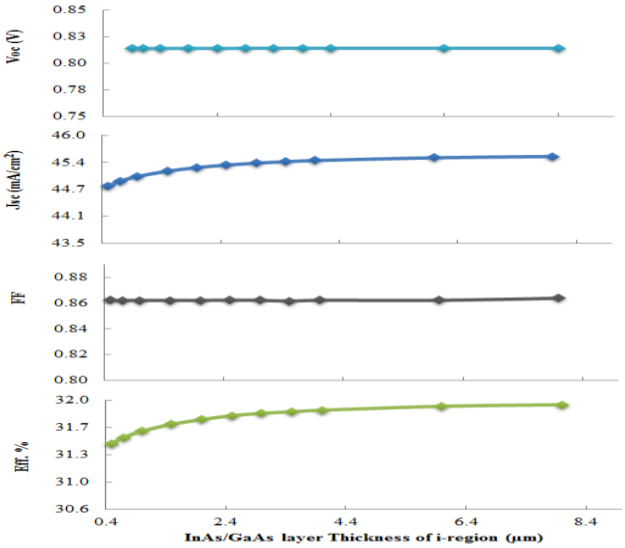


Fig.5: Thickness variation of InAs/GaAs i-region

3.2.3 Thickness Optimization of n-region

In n-type GaAs layer thickness has been varied from 0.5 µm to 1.3 µm. From Fig. 6 one can see that FF remains almost unchanged with variation of thickness. Efficiency and J_{SC} decrease rapidly below 1.3 µm. Decreasing rate of V_{OC} is less than efficiency and J_{SC}. It might be attributed to the shorter minority carrier diffusion length.

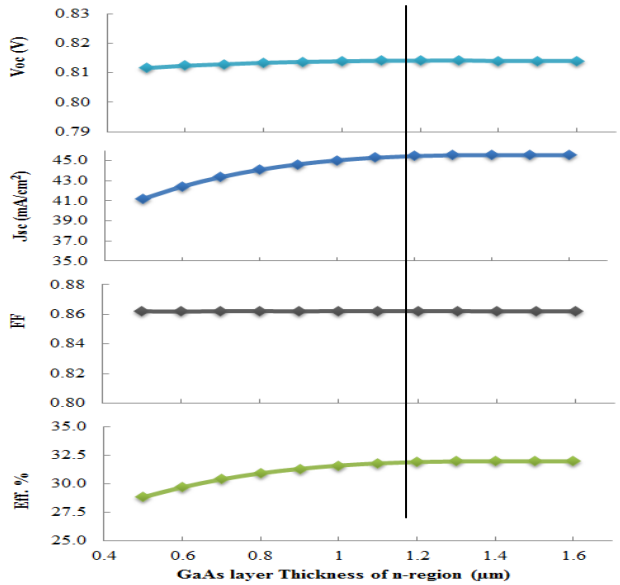


Fig.6: Thickness variation of n-type material (GaAs)

The FF and V_{OC} shows almost constant above 1.3 µm n-type GaAs thickness in this case. Above 1.3 µm of n-region increasing rate of efficiency and J_{SC} is very poor. So the selection has been done at the thickness of 1.3 µm.

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 which is optimum doping for GaAs. The Fig. 7 and Fig. 8 show the variation of cell parameters with respect to acceptor concentration and donor concentration.

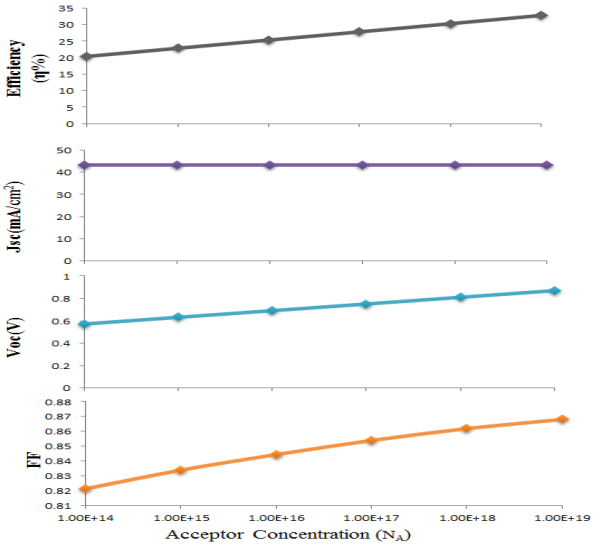


Fig.7: Variation of acceptor concentration (N_A)

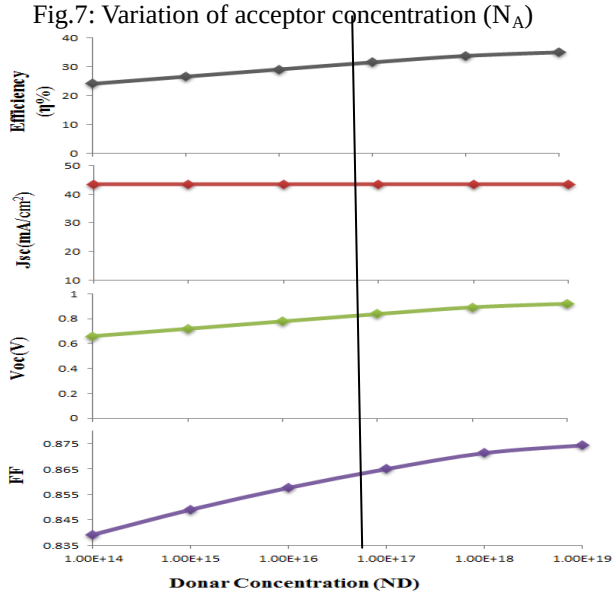


Fig.8: Variation of donor concentration (N_D)

4. RESULT 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 the efficiency of the cell is highest for thickness 1.2 µm for p-type layer, 3µm for i-region and 1.3µm for n-type layer. The cell is optimized at 1.2µm 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 obtained here is 31.83%, the current density, Jsc 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 proposed cell. In Fig. 9 the J-V curve of optimized cell has been shown.

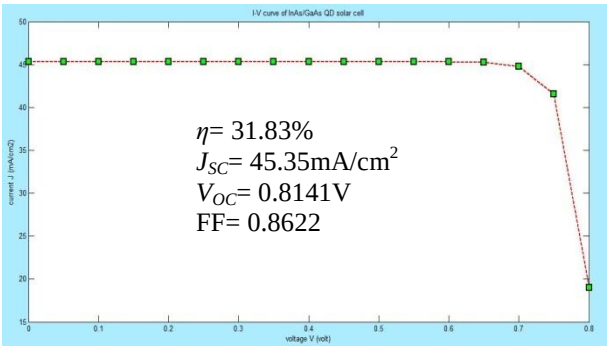
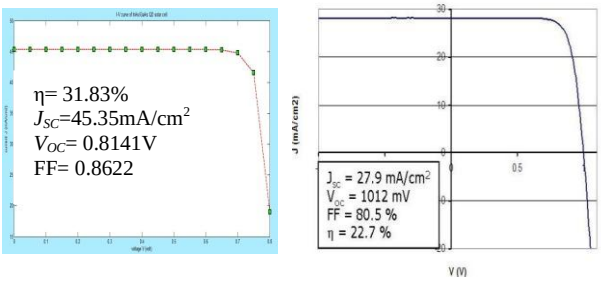


Fig.9: J-V curve of InAs/GaAs QD solar cell

For single junction GaAs solar cell efficiency from recent published works is 22.7% (J_{SC}=27.9mA/cm^2, V_{OC}=1.012V, FF=0.805). Where with intermwdiate band efficiency is 31.83% [x]. Thus, the QDIB solar can be a good solution for low efficiency problem of solar cells. Moreover, this solar cell is less thick than conventional Si based solar cells which redeuce material cost and fabrication cost. In Fig. 10 a comparison has been shown between QDIB solar cells and single junction GaAs solar cells.



(a) (b)

Fig.10: Comparison between (a) InAs/GaAs QDIBSC and (b) conventional GaAs solar cell

4.1 Effect of Operating Temperature

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 from25 °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.. This TC indicates better stability of the cells at higher operating temperature, which are in good agreement with related published works [7, 8].

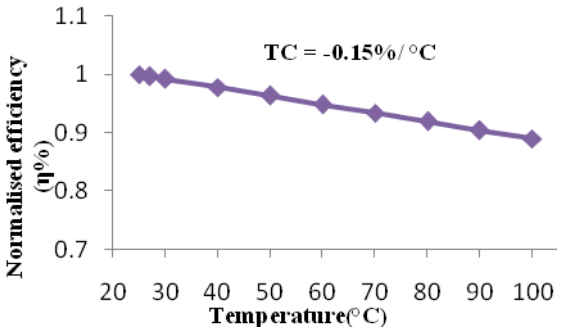


Fig.11: Effect of temperature on InAs/GaAs QDIB solar cell performance

5. CONCLUSIONS

A QDIB solar cell has been designed and simulated with 31.83% conversion efficiency, which has crossed the Shockley quisser limit for single junction conventional solar cells. Only two materials has been used for this solar cell design one is GaAs and another InAs but other multiple material system can be tried. It might be used to fabricate highly efficient solar PV system which will be less expansive and anticipated that will be very cost-effective. Optimization of the front and back contact remains as future work. Ternary materials can be used to vary the band gap of IBQD solar cells for better quantum efficiency and overall cell performance.

6. ACKOWLEDGEMENT

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8. NOMENCLATURE

Symbol	Meaning	Unit
T	Temperature	(K)
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}
f_i	Transport factor	Dimensionless