

Performance Analysis of Intermediate Band Solar Cell (IBSC)

Md. Kamal Hossain^[1], Md Dulal Haque^[2], Sumonto Sarker^[3], Md. Arshad Ali^[4], Md. Mizanur Rahman^[5], Md. Mahbub Hossain^[6]

(Department of Telecommunication & Electronic Engineering, Hajee Mohammad Danesh Science & Technology University, Dinajpur-5200, Bangladesh)

ABSTRACT: To increase the efficiency of a single-junction solar cell the intermediate band solar cell is proposed. Renewable energy sources have become increasingly important; because of global environmental concerns. The intermediate band solar cell (IBSC) with potential to enhance the efficiency of the conventional single-junction cell. IBSCs have constraining efficiencies of 63.3%. In this solar cell an intermediate band placed in the band gap between the conduction and valence band. This implies that absorption of photons with energy below the band gap of the semiconductor is possible, and the photocurrent is thus increased. At the point when the carrier concentration in each of the three bands are portrayed by their own semi Fermi level the intermediate band does not influence the voltage if carriers are extricated from the conduction band and the valence band. An increment of proficiency is hence possible.

KEYWORDS—IBSC, Quasi-Fermi level, Solar Irradiance, Efficiency, Photon Energy.

I. INTRODUCTION

According to the U.S. Energy Information Administration (EIA), the world's total energy consumption in 2007 was 495.2 quadrillion British Thermal Units (BTU) with 86% derived from fossil fuels² [11]. In the event that all nonrenewable sources²⁹ are considered, there is an extra 6% from atomic, bringing the world's total energy production from this category to 94%. The present asymmetries in the appropriation of nonrenewable wellsprings of vitality is unsustainable, meaning we can assume with complete assurance that with the status quo of energy production, exploitation of nonrenewable resources will consist in the progressive exhaustion of an initially fixed supply in which there will be no significant additions. At the point when will non-renewable be depleted? This is an exceptional inquiry encompassed by various territories of open deliberation. In 1956, M. King Hubbert explored this concept by realizing that there will be a point in time when the maximum rate of fossil fuel extraction will be reached and subsequently the rate of extraction enters a terminal decrease until the limited asset is totally depleted. The point in time when this most extreme rate is come to simply before the terminal decrease is called "peak". He was the first to offer ascent to the term crest and create extrapolating models anticipating top, utilizing his models to precisely focus top for U.S. oil creation would happen between years of 1965 and 1970 [12]. Further bothering the misuse of nonrenewable assets is the way that vitality interest is expanding. By 2035, the world's vitality utilization is anticipated to be 738.7 quadrillion BTU [11] or an increment of 49% from 2007. The essential thought of a sunlight based cell is to change over light vitality into electrical vitality. The vitality of light is transmitted by photons, little parcels or quantum of light. Electrical vitality is put away in electromagnetic fields, which thusly can make a current of electrons stream. In this manner a sun oriented cell changes over light, a stream of photons, to electric current, a stream of electrons. At the point when photons are consumed by matter in the sun based cell, their vitality energizes electrons higher vitality states where the electrons can move all the more openly. The measure of sun powered irradiance that hits the earth every year is pretty nearly 763,000 quadrillion Btu³ or more than 1000 times more vitality than what human vitality utilization is anticipated to be 2035. In the event that a modest part of vitality that earth gets could be changed over to helpful vitality, all our energy supply problems would be solved. So what is keeping us from tapping into this seemingly endless amount of energy that falls on the earth every day to solve the scarcity, environmental, and economic problems associated with non-renewable? The two main market penetration barriers of solar conversion devices include the current condition of innovation and financial aspects, both entwined.

1.1 World energy market

Most wellsprings of vitality on Earth begin from the Sun, the most dominant in today’s world energy market being the burning of fossil fuels. At the present rate of utilization it is evaluated world supplies of oil will just last give or take an additional 30 years and coal supplies enduring an additional 250 years [13]. The urgency to find an efficient alternative energy source is compounded by the impact of a dangerous atmospheric deviation anticipated to result in calamitous outcomes including rising ocean levels and expanded recurrence of amazing climate occasions.

1.2 The standard solar cell

The solar cell converts sunlight into electric power, and thus understanding the radiation from the sun is therefore important for simulating the efficiency of a solar cell. A standard solar cell is shown schematically in figure 1.1. At the front surface there is a metallic grid (gray). Between the grid lines there is an anti-reflective layer (dark blue) covering a p-n junction (green/blue) made of a single semiconductor. The back surface of the cell is covered by a back contact (dark gray). Also shown is the external circuit where the electrons do work. The operation principle is described in the text. Sunlight is incident on the surface covered by a metallic grid acting as an electrical contact. Between the grid lines photons are absorbed in a semiconductor which is covered by an anti-reflective coating to reduce reflection. Photons with energies larger than the band gap E_G of the semiconductor excite electrons from the valence band to the conduction band, resulting in free charge carriers; electrons and holes. The charge carriers are separated by either a gradient in the charge carrier density or an electric field.

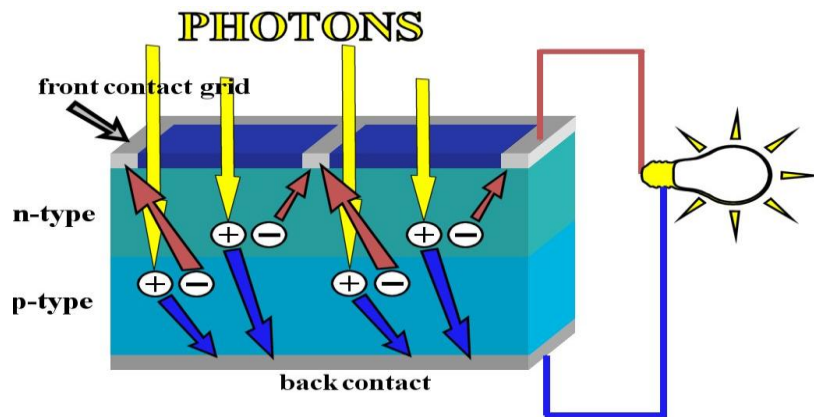


Figure 1.1: Structure of a standard solar cell shown schematically [2].

II. Intermediate band solar cells

Luque et al initially displayed the idea of expanding the productivity of sun based cells by photon incited moves at middle of the road levels in 1997 [1]. The intermediate band solar cell (IBSC) has the capability of accomplishing 63.1% productivity under most extreme concentrated daylight. This efficiency was calculated as occurring when the energy gap between the valence band and the conduction band was roughly 1.93 eV and when either the energy gap between the valence band and intermediate band or the conduction band and intermediate band was more or less 0.70 eV. The optimum efficiency of the IBSC relies on a material with three bands: a valence band (VB), an intermediate band (IB) and a conduction band. In addition, in order to achieve high efficiency, the Fermi level of the material must be located within the intermediate band (see figure 2.1).

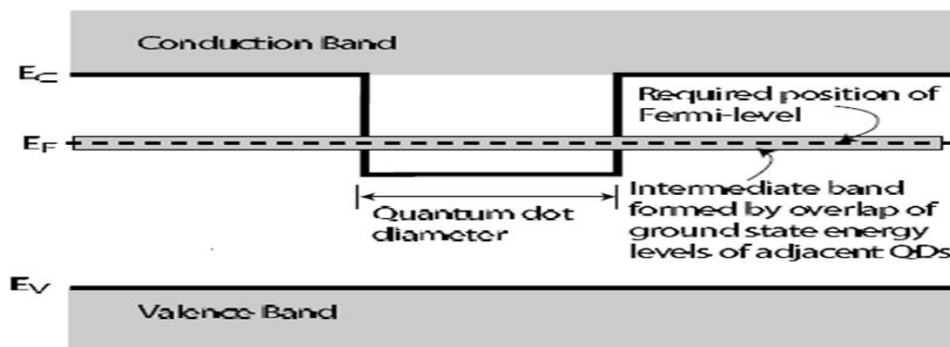


Figure 2.1: Band diagram of a quantum dot intermediate band solar cell.

Under these conditions there will exist both a supply of electrons fit for photon impelled move to the conduction band and in addition an expansive population of gaps that permit electrons to move from the valence band to the intermediate band. In respect to a material with two groups whose gap is equal in value to the widest band gap of the intermediate band solar, E_C-E_V in figure 2.1, the intermediate band solar cell will show an increase in photocurrent. Photon absorption is changed over into photocurrent that is extracted at a voltage restricted by the amplest band gap of the material, E_C-E_V in figure 2.1.

2.1 Generation and recombination

This area is taking into account [5]. The formation of free charge carrier in a semiconductor requires energy and is called generation. Recombination is the opposite occasion and discharges energy. In solar cells the most imperative generation procedure is absorption of photons. Diverse recombination procedures are demonstrated in figure 2.2. The procedures indicated are radiative recombination, non radiative recombination by means of trap states and non-radiative Twist drill recombination. All in all, every generation procedure is given its own particular generation rate G per unit time and unit volume. The recombination procedures have distinctive recombination rates, signified U . The rates will as a rule take distinctive qualities for electrons and holes. In warm harmony the recombination and generation rates are parallel.

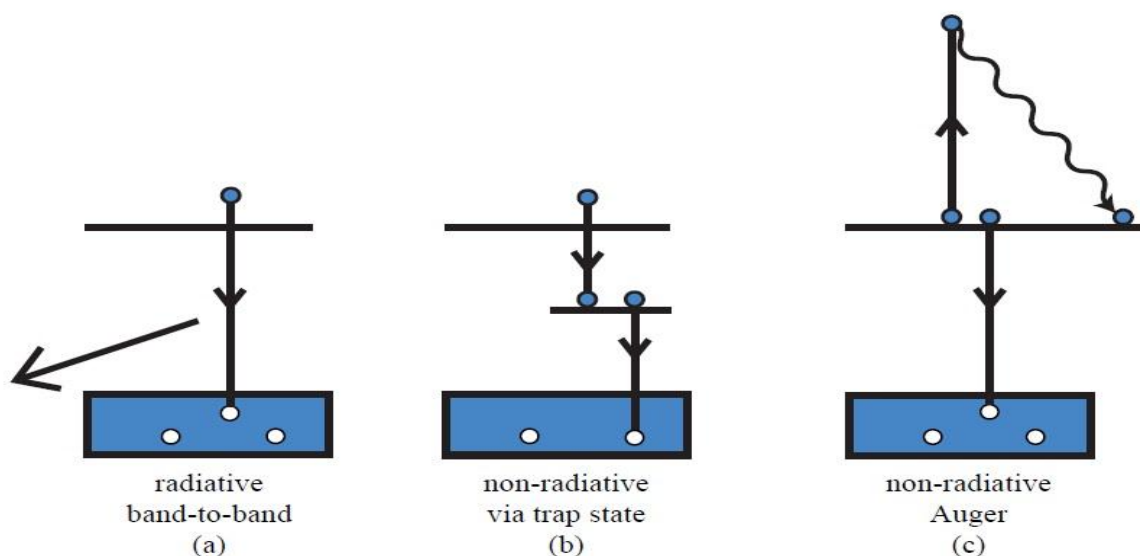


Figure 2.2: Recombination processes: (a) radiative, (b) non-radiative via trap states and (c) non-radiative Auger recombination.

Since it is the disturbance from thermal equilibrium which is important, the excess (over the thermal) generation and recombination rates are used. The only generation process considered in this thesis is absorption of photons from sunlight. When the photon energy is larger than the band gap of the semiconductor, an electron-hole pair may be generated. The recombination processes can be divided into unavoidable and avoidable processes. Unavoidable processes cannot be avoided through the use of perfect materials. They are identified with physical procedures in the material. Both radiative recombination and Auger recombination fall into this class. The third process emerges on the grounds that materials are not immaculate and dependably contain a few defects. Recombination may happen by means of imperfection states in the taboo crevice, starting now and into the foreseeable future alluded to as trap states taking after the terminology in [5], and the procedure is known as non-radiative. The era of charge bearers because of photon reusing is excluded in the model. Photon reusing is the procedure where photons produced by radiative recombination are reabsorbed in the material to create charge bearers. This procedure is discarded in the model of the reference cell and is additionally excluded here. In the constraining case the main recombination procedure included is radiative recombination. By having an intermediate band three radiative recombination processes are possible:

- 1) Recombination between the conduction band and the valence band
- 2) Recombination between the conduction band and the intermediate band
- 3) Recombination between the intermediate band and the valence band

2.2 Current and voltage equation for a solar cell

The general current-voltage characteristic for a solar cell under illumination is given as

$$J = J_{light} - J_0 \left(e^{\frac{qV}{k_B T}} - 1 \right) - J_{dep,0} J_0 \left(e^{\frac{qV}{2k_B T}} - 1 \right) \dots \dots \dots (2.1)$$

From this equation the solar cell can be modeled as a circuit consisting of an ideal current source with current density J_{light} and two diodes in parallel with ideality factors equal to 1 and 2 as can be seen in figure 2.3.

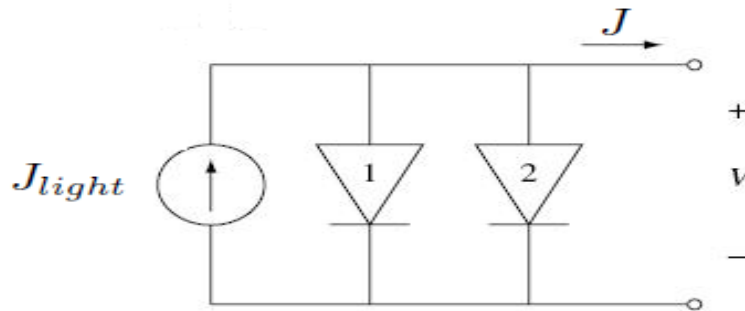


Figure 2.3: Modeling the solar cell as a circuit consisting of an ideal current source and two diodes in parallel with ideality factor 1 and 2 [3].

Equation (2.1) can be rewritten by introducing the diode ideality factor A_0

$$J = J_{light} - J_{dark} \left(e^{\frac{qV}{A_0 k_B T}} - 1 \right) \dots \dots \dots (2.2)$$

A_0 has a value between 1 and 2 and varies with voltage and material quality. When non-radiative recombination in the depletion region dominates A_0 has a value approximately equal to 2, while when the recombination in the depletion region is not as important as the recombination in the p- and n-layers, A_0 has a value of 1. Often only the diode in figure 2.3 with ideality factor equal to 1 is considered; meaning that recombination in the depletion region is not included. This gives the current-voltage behavior shown in figure 2.4. There three important points are identified, that is the short-circuit current density J_{sc} , the open circuit voltage V_{oc} and the current density J_m and voltage V_m that gives the maximum power density $P_m = J_m V_m$. The short-circuit current density can be found by setting V equal to 0 in equation (2.2) and is equal to the photocurrent density J_{light} . The open circuit voltage can be found by setting J equal to 0 in equation (2.2) and is equal

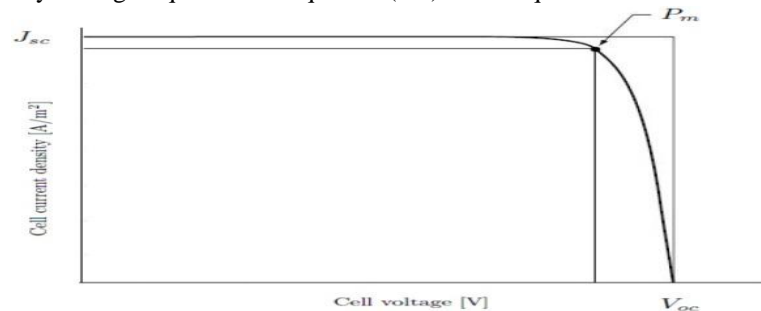


Figure 2.4: Current-voltage behavior for a solar cell showing the short-circuit current density J_{sc} , the open circuit voltage V_{oc} and the current density J_m and voltage V_m that gives the maximum power density $P_m = J_m V_m$.

$$V_{oc} = \frac{A_0 k_B T}{q} \ln \left(\frac{J_{light}}{J_{dark}} + 1 \right) \dots \dots \dots (2.3)$$

The open circuit voltage differs subject to the recombination in the solar cell which are again reliant on the band gap of the semiconductor. The open circuit voltage is relied upon to change directly with the band hole of the semiconductor [4].

To obtain efficient solar cells, the main subject is to maximize the power. The ratio of maximum power density to the product of J_{sc} and V_{oc} is given the name fill factor, FF

$$FF = \frac{P_m}{V_{oc} J_{sc}} \dots \dots \dots (2.4)$$

The fill factor is always less than one and describes the squareness of the JV-curve. The most important term describing solar cells is the conversion efficiency, η , given as

$$\eta = \frac{P_m}{P_{in}} \dots \dots \dots (2.5)$$

where P_{in} is the incident power density, a quantity determined by the incident light.

III. Working principle for the intermediate band solar cell

The intermediate band solar cell uses a greater amount of the approaching photons from the sun through the utilization of the intermediate band. Notwithstanding the conduction band (CB) and the valence band (VB) the intermediate band solar cell contains an intermediate band (IB) put in the band gap between the conduction and valence band. As seen in figure 3.1 the band gap of the semiconductor E_G is isolated into two sub-band gap E_L and E_H . $E_H \equiv E_I - E_V$ is the difference between the balance Fermi energy of the intermediate band and the highest point of the valence band. $E_L \equiv E_C - E_I$ is the energy difference between the base of the conduction band and the balance Fermi energy of the intermediate band, and we have that $E_G = E_H + E_L$. The width of the intermediate band is assumed to be negligible. The conduction band, valence band and intermediate band are shown along with the equilibrium Fermi energy of the intermediate band. By absorbing photons three transitions are possible.

- (1) an electron is transferred from the conduction band to the intermediate band.
- (2) an electron is transferred from the intermediate band to the conduction band.
- (3) an electron is transferred from the valence band to the conduction band. The symbols are explained in the text.

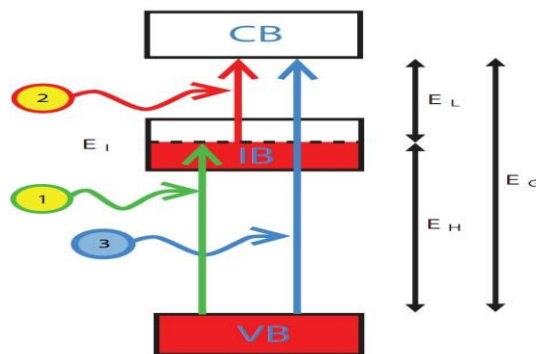


Figure 3.1: Band diagram of a material containing an intermediate band

The division of the aggregate band gap into two sub-band gaps makes retention of photons with energies not exactly the aggregate band gap conceivable, prompting an expanded photocurrent. To create an electron-hole pair by absorption of photons with energies less than E_G , two transitions are necessary. In one of the transitions an electron is transferred from the valence band to the intermediate band leaving a hole behind in the valence band, visualized as transition (1) in figure 3.1. In the second transition the electron is transferred from the intermediate band to the conduction band, visualized as transition (2) in figure 3.1. In addition we have the "normal" creation of an electron-hole pair by absorption of a photon and the direct transfer of an electron from the valence band to the conduction band, visualized as transition (3) in figure 3.1. The intermediate band has to be partially filled with electrons to make both transition (1) and (2) possible. A partially filled band contains both void states to oblige electrons being exchanged from the valence band to the transitional band and filled states to discharge electrons being pumped into the conduction band. The Fermi energy of the intermediate band has to be placed within the intermediate band to fulfill this condition.

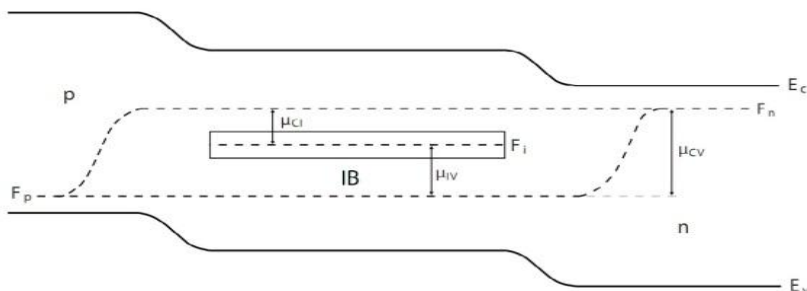


Figure 3.2: Quasi-Fermi levels and quasi-Fermi level splits in an intermediate band material placed between a p- and a n-layer. The symbols are explained in the text.

To get a high efficiency solar cell the photocurrent, as well as the voltage of the cell must be upgraded. A crucial condition in the hypothesis of intermediate band solar cells is that transporter focus in each of the groups can be depicted by its own particular semi Fermi level; F_p for holes in the valence band, F_i for electrons in the intermediate band and F_c for electrons in the conduction band, as shown in figure 3.2. This condition is fulfilled when the carrier relaxation time within each band is much shorter than the carrier recombination time between bands [6]. The quasi-Fermi level in the intermediate band is assumed to be fixed to its equilibrium position. No charge bearers are transported through the intermediate band, which is detached from the outside contacts by a p- and a n-layer put on every side of the moderate band material. The p-layer fixes the semi Fermi level for openings in the valence band in the middle of the road band material, while the n-layer fixes the semi Fermi level for electrons in the conduction band in the intermediate band material. The voltage V of the cell is given by [7]

$$qV = F_n - F_p \dots\dots\dots(3.1)$$

which has the same form as in a standard p-n solar cell. The voltage of the cell is thus unaffected by the intermediate band. The increase of the photocurrent in the intermediate band solar cell gives a higher efficiency.

3.1 Intermediate band solar cell design

The p- and n-layers in the intermediate band solar cell studied over in this proposition are in figure 3.3 indicated together with the area in the middle of where the intermediate band layer is put. The upper p-layer is trailed by an intrinsic layer of width $w_{ip,min}$. $w_{ip,min}$ is the base width of the consumption locale between the p-layer and the intrinsic layer by setting V_p equivalent to a voltage $V_{max,p}$ equivalent to the open-circuit voltage over the p-i intersection. This intrinsic layer is incorporated since we need the majority of the intermediate band layer to be contained in a flat band region. For all voltages the width $w_{ip,min}$ close to the p-layer is depleted, and it is then not necessary to have an intermediate band layer here.

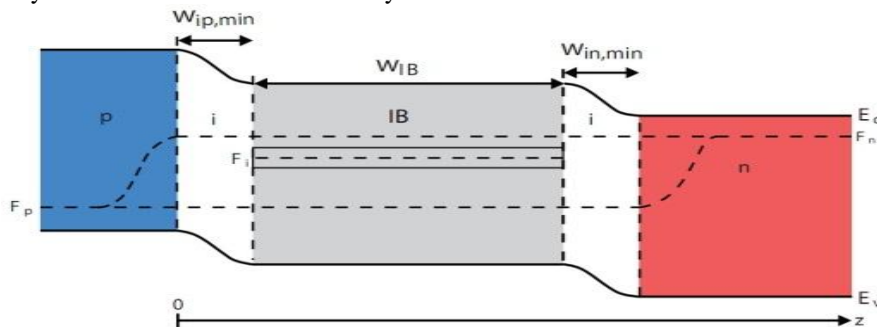


Figure 3.3: The structure of the forward biased intermediate band solar cell used in the modeling. Also shown are the quasi-Fermi level F_c of the electrons in the conduction band, the quasi-Fermi level F_i of the electrons in the intermediate band and the quasi-Fermi level F_p of the holes in the valence band.

After the intrinsic layer of width $w_{ip,min}$ takes after a intermediate band material of width w_{IB} , and we then have a second intrinsic layer of width $w_{in,min}$. $w_{in,min}$ is the base width of the consumption locale between the n-layer and the i-layer by setting V_n equivalent to a voltage $V_{max,n}$ equivalent to the open-circuit voltage over the i-n intersection. At last the n-layer is set beneath the intrinsic material. The widths of the exhausted districts of the p-i and i-n intersection, w_{ip} and w_{in} , are subject to voltage. At the point when the thicknesses of the i-layers are equivalent to $w_{ip,min}$ and $w_{in,min}$ the i-layers on the p- and n-side are exhausted at all voltages. The piece of the intermediate band material contained in the drained districts close to the p-layer and the n-layer is in the models accepted to act like an intrinsic material with no quantum dots subsequent to the quantum dots in these areas are totally full or unfilled of electrons. Just the piece of the intermediate band material that is in the flat band district is taken to take after the conduct of a middle of the intermediate band material.

IV. Mathematical model of intermediate band solar cell

Intermediate band solar cell to analyses the current voltage characteristic the general equation under the illumination is given below:

$$I = J_{light} - J_{dark} \left(e^{\frac{qV}{A_0 k_B T}} - 1 \right) \dots\dots\dots(4.1)$$

Where A_0 is the ideality factor has a value between 1 and 2 and varies with voltage and material quality. k_B is the Boltzman constant J/K. T is the temperature used in article for solar cells in K. q is the charge of an electron in C. J_{light} is the light current density and J_{dark} is the dark current density. This equation used to analyses the current voltage relationship.

4.1 Relation between band density and concentration factor

Solar cells oblige some type of implicit asymmetry that will permit helpful energy to be separated before electrons and openings recombine. The dominant part of solar cells comprise of a p-n or p-i-n intersection to permit high carrier mobility and current to only flow in one direction. It should be noticed the partition of semi Fermi levels stays consistent all through the gadget expecting unending portability; truly this is a sensible rough guess for good quality solar cells. At the point when there is a sudden move from p-sort doping to n-sort doping the electrons and openings will diffuse to frame an area of lower electron and opening fixation known as the consumption district. The density state of conduction band is given by

$$N_c = 2 \left(\frac{2\pi m_e k_B T}{h^2} \right)^{\frac{3}{2}} \dots \dots \dots (4.2)$$

$$m_e = (0.0632 + 0.0856x + 0.023x^2)m_0 \dots \dots \dots (4.3)$$

and

$$m_h = (0.50 + 0.2x)m_0 \dots \dots \dots (4.4)$$

where k_B is Boltzmann's constant, T is the temperature of the cell, e is the charge of an electron, N_c is the density of states in the conduction, m_0 is the mass of electron, m_e and m_h are the effective electron and hole masses respectively and x is the concentration factor.

4.2 Relation between voltage and concentration factor

The solar cell absorbs sunlight only from a small angular range, and this can be increased by using concentrators based on lenses or mirrors. Light is thus collected over a large area and focused to a solar cell of a smaller area. By using a ratio X between the collector and cell area the incident flux density is increased by a concentration factor equal to X . The photocurrent is directly proportional to the photon flux F . The photocurrent is thus increased by a factor X , and the open-circuit voltage increases logarithmically to

$$V_{oc}(X) = \frac{A_0 k_B T}{q} \ln \left(\frac{X J_{light}}{J_{dark}} + 1 \right) \dots \dots \dots (4.5)$$

By assuming a constant fill factor the efficiency $\eta(X)$ is increased by a factor equal to

$$\frac{\eta(X)}{\eta(1)} = 1 + \frac{A_0 k_B T}{q V_{oc}(1)} \ln X \dots \dots \dots (4.6)$$

where $\eta(1)$ and $V_{oc}(1)$ are the efficiency and open-circuit voltage using no concentration, respectively. Concentration also increases the series resistance of the cell giving an increased voltage loss, and the temperature is raised leading to an increased dark-current. Both these effects lowers the open-circuit voltage and degrade the performance of the cell. Concentration may also give high injection conditions. This means that the photo generated carrier densities are comparable to the doping densities in the doped layers. The radiative and Auger recombination rates then become non-linear with the carrier densities n and p , meaning that the total current cannot be divided into an independent dark-current and a photocurrent. The concentration thus has an optimum value obtaining the highest efficiency for a solar cell.

4.3 Solar spectrum

The solar spectrum resembles as mentioned the spectrum of a black body with temperature 5760 K, and this spectrum is shown in figure 6.1. The emitted light is distributed over wavelengths from the ultraviolet to the visible and infrared part of the spectrum. Light is absorbed and scattered as it passes through the atmosphere. The attenuation of the light is quantized using the Air Mass. The Air Mass is the ratio between the optical length from the earth to the sun when the sun is placed at an angle γ_s and when the sun is placed directly overhead [5]

$$AM = \frac{1}{\cos \gamma_s} \dots \dots \dots (4.7)$$

The power density from the Sun just outside the Earth's atmosphere is given by the solar constant $1353 \pm 21 Wm^{-2}$ [3], dropping to approximately $1000 Wm^{-2}$ on average at the Earth's surface attenuated by absorption in the atmosphere. Figure 6.1 compares the extraterrestrial solar spectrum, Air Mass 0 (AM0) to the standard terrestrial AM1.5 spectrum. The standard for solar cell efficiency measurements is the AM1.5 spectrum with an energy density of $1000 W/m^2$. The extraterrestrial solar spectrum can be closely modeled as a 6000K blackbody spectrum with the generalized Planck equation

$$n(E, T, \mu) = \epsilon(E) \frac{2\pi}{c^2 h^3} \frac{E^2}{e^{\frac{E-\mu}{k_B T}} - 1} \dots \dots \dots (4.8)$$

where n is the photon flux as a function of energy E , ϵ is the emissivity, μ is the photon chemical potential and T is the temperature. For a blackbody, $\epsilon = 1$ for all energies and $\mu = 0$. The total density from the sun can be

obtained by multiplying the photon flux by the photon energy, E, and integrating over all energies to obtain the Stefan-Boltzmann law.

$$\int_0^{\infty} En(E, T) dE = \sigma T^4 \dots \dots \dots (4.9)$$

Where $T = T_{\text{sun}} = 6000\text{K}$ equation 4.8 describes the photon flux at the surface of the sun and equation 4.9 describes the energy density at the surface of the sun. On Earth we receive sunlight from the solar disc subtending only a fraction of the hemisphere visible to the solar cell thus a dilution factor of $f_{\text{o}} = 2.16 \times 10^{-5}$ must be included to calculate the photon flux and energy density on Earth

4.4 Intermediate band solar cell with only radiative recombination in the flat band region

The electron and hole concentrations in the conduction band and valence band are influenced by the presence of an intermediate band. The electron concentration in the conduction band in an intermediate band material equals $n = \Delta n + n_{0,IB}$, where $n_{0,IB}$ is the equilibrium electron concentration in the conduction band and Δn is the optically generated electron concentration. n can be expressed as

$$n = N_C e^{-\left[\frac{E_C - F_i}{k_B T}\right]} e^{\frac{F_i - F_n}{k_B T}} = n_{0,IB} e^{\mu_{CI}/k_B T} \dots \dots \dots (4.10)$$

where the last equality only holds if the quasi-Fermi level F_i of the intermediate band is pinned to its equilibrium position E_i [8]. N_C is the effective density of states in the conduction band and

$$n_{0,IB} = N_C e^{-\frac{E_i}{k_B T}} \dots \dots \dots (4.11)$$

In the same way the hole concentration in the valence band in an intermediate band material equals $p = \Delta p + p_{0,IB}$, where $p_{0,IB}$ is the equilibrium hole concentration in the valence band and Δp is the optically generated hole concentration. p can be expressed as

$$p = N_V e^{-\left[\frac{F_i - E_V}{k_B T}\right]} e^{\frac{F_i - F_p}{k_B T}} = p_{0,IB} e^{-\frac{E_H}{k_B T}} \dots \dots \dots (4.12)$$

where N_V is the effective density of states in the valence band and

$$p_{0,IB} = N_V e^{-\frac{E_H}{k_B T}} \dots \dots \dots (4.13)$$

4.5 Intermediate band solar cell including both radiative and non-radiative recombination in the flat band region

In the limiting case only radiative recombination is included in the intermediate band material. Non-radiative recombination is present unless in the limit of perfect materials [5], and it has to be included in a more realistic model. Data for quantum dot solar cell prototypes grown by molecular beam epitaxy indicates that recombination is dominated by non-radiative processes possibly caused by defects at the interfaces between the dot and barrier material [9]. In this section non-radiative recombination is included in the model of the intermediate band solar cell.

The non-radiative recombination processes present in an intermediate band material are:

- 1) Non-radiative recombination between the conduction band and the valence band
- 2) Non-radiative recombination between the conduction band and the intermediate band
- 3) Non-radiative recombination between the intermediate band and the valence band

4.6 Material and sample parameters

As is clear from the preceding chapters several material parameters are involved in the expressions determining the current-voltage characteristic of a solar cell. To obtain the current voltage characteristic for specific solar cell numerical values for all these parameters must be known. The numerical values can either be measured for the solar cell in question or data has to be taken from literature. In this thesis data from literature is used, and material parameters are given. The solar cells considered in this thesis are made of InAs, GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$. The thicknesses and doping concentrations for the intermediate band solar cell made of InAs quantum dots in $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ are given in table 4.2. The mobility and lifetimes in $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ for these doping concentrations are given in table 4.2.

Doping (cm ⁻³)	μ_p (cm ² /Vs)	μ_n (cm ² /Vs)	Γ_p (ns)	Γ_n (ns)
2×10^{19} (p ⁺)	-	1325	-	0.6
2×10^{18} (p)	-	1245	-	2.99
1×10^{14} (i)	378	8005	$\sqrt{7}\sqrt{7}$	
2×10^{17} (n)	245	-	33	-
2×10^{18} (n ⁺)	255	-	7.5	-

Table 4.1: Values of mobility and lifetimes in GaAs.

Doping (cm ⁻³)	μ_p (cm ² /Vs)	μ_n (cm ² /Vs)	Γ_p (ns)	Γ_n (ns)
2×10^{19} (p ⁺)	-	822	-	0.41
2×10^{18} (p)	-	1000	-	2.32
2×10^{17} (n)	102	-	3.2	-
2×10^{18} (n ⁺)	64	-	0.8	-

Table 4.2 Values of mobility and lifetimes in Al_{0.35}Ga_{0.65}As

V. Efficiency of intermediate band solar cell

The third generation solar cells use different procedures to build the efficiency past the itemized equalization farthest point of 30.5 % for a single band gap material. The approaches to acquire efficiencies past this utmost are clarified in segment 5.1. The primary accentuation of this section is the intermediate band solar cell. General hypothesis concerning intermediate band solar cells is given in segment 5.2. Solar cell productivity is the proportion of the electrical yield of a solar cell to the episode vitality as daylight. The vitality change productivity (η) of a solar cell is the rate of the sun oriented vitality to which the cell is uncovered that is changed over into electrical vitality. This is computed by isolating a cell's energy yield (in watts) at its greatest force point (Pm) by the data light (E, in W/m²) and the surface territory of the solar cell (Ac in m²). The most imperative results from the hypothetical studies is that the partial filling of the intermediate band can be accomplished through photograph filling. For high light introduction the productivity is comparative for a photograph filled and prefilled (e.g. because of doping) IB sun oriented cell. The hypothetical examinations have likewise included advancement of a float dispersion model for photograph filled IB sunlight based cells, investigations of how thermalization of the populace in the IB influences the cell execution for a limited IB width lastly, how the IB sun powered cell can perform better if frightfully particular channels are being used.

5.1 Strategies to increase the efficiency

This segment is taking into account [3]. As said the restricting efficiency of a single band gap solar cell is 30.5 % by utilizing the guideline of itemized parity. The two most critical explanations behind this preferably low efficiency are that photons with vitality lower than the band hole of the semiconductor are not retained and that transporters created with $E > EG$ lose active vitality by warm dissemination. Solar cell materials with more than one bandgap offer the likelihood to build the productivity of the solar cell past that of a single bandgap cell. The intermediate band solar cell (IBSC) is one such probability, where a intermediate band (IB) is set in the generally illegal bandgap of the solar cell material. Research on this gadget is spurred by high hypothetical efficiencies. The most extreme proficiency of an IBSC, having the perfect bandgaps of $EL=0.71$ eV, $EH=1.24$ eV and $EG=1.97$ eV, is as high as 63.2 %. The single bandgap cell has a productivity farthest point of 40.7%. Theoretical efficiency limits for the intermediate band solar cell have been calculated under the assumption that the absorptivity of the solar cell is 1 for all photon energies larger than the smallest subband gap. In the present work, efficiency limits have been calculated under the assumption that the cell is covered by spectrally selective reflectors. The efficiency limit for the 1 sun 6000 K black body spectrum is found to increase from 46.8% to 48.5% and the limit for the AM1.5G spectrum (as defined by ASTM G173-03) is found to increase from 49.4% to 52.0%.

The conditions for cell estimation are institutionalized for examination purposes yet may not reflect genuine working conditions. Standard cell test conditions are 1000 Wm⁻², 33°C. Concentrator cells are measured utilizing the immediate pillar AM1.5 range while other physical cells utilize the worldwide AM1.5 range that additionally incorporates diffuse light. All the cells are tried on a temperature controlled piece and warming impacts are overlooked. In genuine establishments the cell temperature rises prompting a proficiency reduction. The transitional band sun powered cell has the capability of accomplishing 63.1% productivity under greatest concentrated daylight. This proficiency depends upon a material with three groups: a valence band, and intermediate metallic band and a conduction band. With a specific end goal to accomplish high efficiencies, the Fermi level of the intermediate band must be well inside of the moderate band. The restricting efficiency

utilizing no focus is 46.0% for the band holes EL = 0.93 eV and EH = 1.40 eV [8]. Utilizing most extreme focus the constraining efficiency is 63.2% for the band crevices EL = 0.71 eV and EH = 1.24 eV

VI. Simulation and result

In this chapter results from the intermediate band solar cell is given. In my modeling the normalized Air Mass 1.5 spectrum is used giving an incident power density of 1000 W/m². Tabulated measured data for the Air Mass 1.5 are taken from [10].

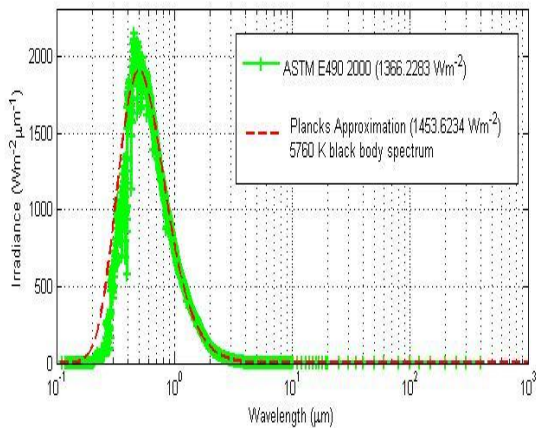


Figure 6.1: AM1.5 Solar Irradiance Vs Wavelength 0-1000 μm

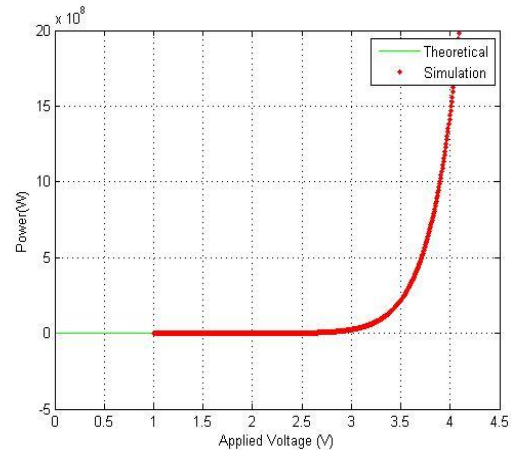


Figure 6.2: Power Curve at T=303K

The intermediate band solar cell two models are used, a simple model with only few layers included and a complete model with anti-reflective coating, window and front back surface field layers included. Power is increasing when photon energy is higher which is level in figure 6.2 and current is increasing in the same way which shown in figure 6.3.

When a load is connected to the solar cell, the current decreases and a voltage develops as charge builds up at the terminals. The resulting current can be viewed as a superposition of the short circuit current, caused by the absorption of photons, and a dark current, which is caused by the potential built up over the load and flows in the opposite direction. As a solar cell contains a PN junction (LINK), just as a diode, it may be treated as a diode. By increasing the lifetimes, the change in the current voltage curve is not seen, while decreasing the lifetime by factor 10³ the change in the current voltage curve is clearly visible. The reason for this is the same as mentioned for the quantum efficiencies, when the diffusion lengths are much longer than the widths of the p- and n- layer they do not affect the dark-current much.

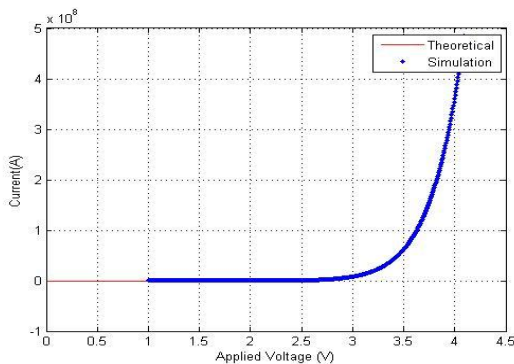


Figure 6.3: Light I-V Curve at T=303K

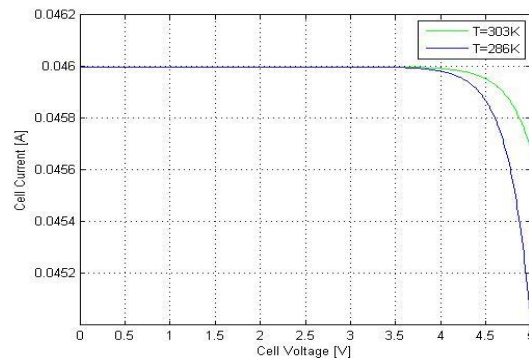


Figure 6.4: Current Voltage characteristic curve at T=303K and T=286K

The productivity and the photocurrent and voltage are extricated from the sunlight based cell. Effectiveness is the measure of what number of photons are changed over into recoverable electrons by the consolidated impact of the cell voltage and the photocurrent and the resistances and so on measured into the fill element. The productivity measure should not change that much with irradiance aside from on account of warming the cell excessively. Then again, the photocurrent will change as much as less or more photons strike the cell and the voltage will change if the cell is warmed. At low light levels the dim current or the current from the parallel shunt resistance overwhelms the fill element. The level area in the effectiveness versus fixation is the place the fill element is diminishing with expanding light on the grounds that it is constrained by arrangement resistance and the voltage is as yet expanding logarithmically with light.

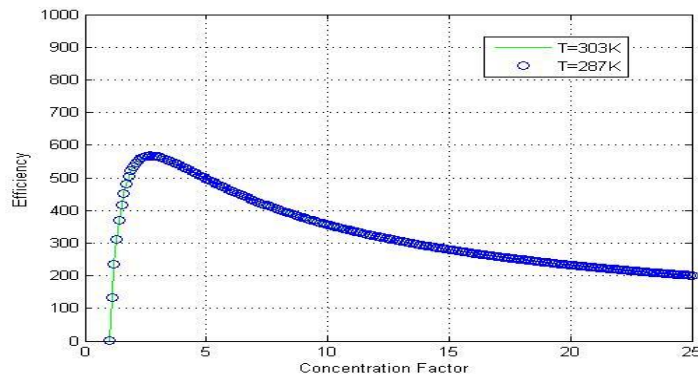


Figure 6.5: Efficiency Vs Concentration Factor at T=303K and T=287K

The conduction band measures the scope of vitality needed to free an electron from its bond to a particle. Once liberated from this security, the electron turns into a 'delocalized electron', moving openly inside of the nuclear grid of the material to which the particle has a place. Different materials may be grouped by their band gap: this is characterized as the contrast between the valence and conduction bands. In protectors, the conduction band is much higher in vitality than the valence band and it takes substantial energies to delocalize their valence electrons. Protecting materials have wide band holes. In semiconductors, the band gap is little. This clarifies why it takes a little vitality (as warmth or light) to make semiconductors' electrons delocalize and conduct power, subsequently the name, semiconductor. In metals, the Fermi level is inside no less than one band. These Fermi-level-intersection bands may be called conduction band, valence band, or something else relying upon condition.

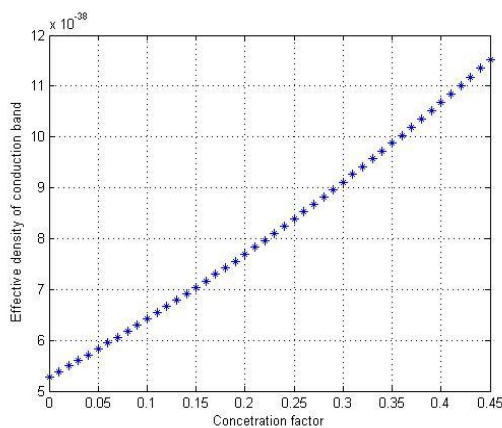


Figure 6.6: Conduction band density Vs Concentration factor at T=303K

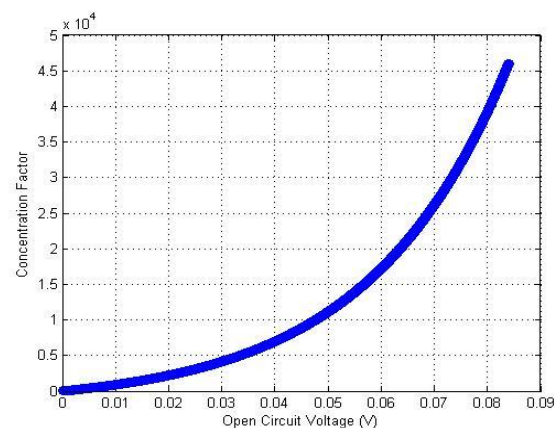


Figure 6.7: Concentration factor Vs Open circuit voltage

VII. Further work

This proposition is in light of a systematic methodology. One errand is to utilize numerical strategies to model a reference cell and a intermediate band solar cell taking into account the comparisons introduced in this theory. By utilizing numerical strategies radiative recombination can be incorporated in the i-layer in the p-i-n solar cell. The current-voltage characteristic under high-infusion may be inferred utilizing numerical techniques. Another assignment is to keep on utilizing the expository approach and develop the models given in this theory. The model of the reference cell can be further stretched out to incorporate band hole narrowing in the intensely doped layers. Al_xGa_{1-x}As solar cells with other aluminum focuses than x=0.35 can be demonstrated to find the greatest efficiency for different estimations of the band gap EG. To get a solar cell with the most elevated efficiency, the thickness and doping centralization of the considerable number of layers in the reference cell may be fluctuated. An estimation of the arrangement and shunt resistances in the solar cells may be done and included in the model. The complete model of the intermediate band solar cell may be stretched out to model the intermediate band material put in the drained districts another way then regarding it as a characteristic material. A more practical instance of covering assimilation coefficients might likewise be incorporated in the model. How the estimations of the assimilation coefficients affect the present voltage trademark may.

VII. Conclusion

In this expert proposition intermediate band solar cells and suitable reference cells have been demonstrated for two unique estimations of fixation, $X=1$ and $X=1000$. The displaying of the reference cells demonstrates the significance of utilizing a window layer and intensely doped p⁺- and n⁺-layers to get a low successful surface recombination speed together with an against intelligent covering minimizing the reflection misfortunes. By utilizing these layers a high quantum productivity is gotten. Because of the non-presence of a model of a p-i-n solar cell with parts of the intrinsic material put in a level band region, a model of such a solar cell was produced. A comparative model with an intermediate band material put in the level band district was likewise created. A straightforward model of an intermediate band solar cell where just the intermediate band material is considered was taken from writing. Both radiative and non-radiative recombinations were incorporated in the flat band region of the intermediate band material in the models of the intermediate band solar cell. The force change proficiency of an intermediate band solar cell was anticipated to increment as the temperature of the cell was diminished because of a lessening in radiative and non-radiative recombination. A basic matlab model for ascertaining I-V bends and proficiency hypothetically anticipated how the effectiveness changed with temperature. By contrasting the outcomes from the demonstrating and trial information it is found that the model of the reference cell gives too high estimations of present and open-circuit voltage. The purpose behind this is relied upon to be the close estimation of disregarding band gap narrowing in the vigorously doped and layers and utilizing a reflectivity equivalent to zero when a hostile to reflective covering is available. Reenacting results uncovered that the effectiveness of our specimen GaAs intermediate band solar cell expanded reliably with diminishing temperature however errors in the middle of hypothesis and investigation were apparent.

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Author's Biography



Md. Kamal Hossain received his B.Sc. degree in Telecommunication & Electronic Engineering from Hajee Mohammad Danesh Science & Technology University, Dinajpur, Bangladesh in 2015. His main working interest is based on software engineering, database optimization, discrete mathematics, Teletraffic Engineering, Digital Signal Processing and Networking. He likes cultural activities beside all other daily activities.



Md. Dulal Haque completed both B.Sc and M.Sc degree in Applied Physics and Electronic Engineering from Rajshahi University, Bangladesh. At present, He is serving as an assistant professor in the department of Telecommunication and Electronic Engineering at HajeeMohamadDanesh Science and Technology University, Bangladesh. His research interest is on electronic device fabrication and wireless communication.



Md. Arshad Ali Completed B.Sc in Computer Science and Engineering from Hajee Mohammad Danesh Science and Technology University, Bangladesh. He is serving as an assistant professor in the department of Computer Engineering at Hajee Mohammad Danesh Science and Technology University, Bangladesh. His research interest is Software development and Microwave.