ABSTRACT

Intermediate band solar cell (IBSC) is a novel photovoltaic converter with the potential of exceeding the performance of conventional p-n solar cells. This novel photovoltaic converter bases on partially filled intermediate band (IB) located within a higher forbidden gap. So, sub band gap photons are also absorbed and photocurrent is enhanced. This paper studies the variation of efficiency by the IB energy level. For a photovoltaic material, once the $E_{CV}$ value is defined, IB energy level can be determined for performing maximum efficiency. The IBSC with $E_{CV}=2.09$ eV reaches to 59% efficiency when $E_V$ equals to 0.75 eV. The J-V characteristic of this cell is derived using detailed balance equations.

I. INTRODUCTION

The theoretical efficiency limit for a conventional p-n solar cell was determined by Shockley and Queisser using detailed balance argument [1]. Many approaches have been experienced in order to enhance the solar cell efficiency like tandem cells, quantum well cells etc. [2,3,4] The structure of intermediate band solar cell (IBSC) and its efficiency performance for ideal case was presented by A. Luque in 1997 [5]. In IBSC, an energy band is inserted inside the forbidden gap of the cell material. By this way, photons whose energy level is lower than $E_{CV}$ can be absorbed. So photocurrent is increased without degrading the output voltage. Maximum efficiency under ideal condition was presented as 63.2% for IBSC [6]. The problem for IBSC is how to locate the intermediate band in the forbidden gap. To achieve this, there are three approaches: i) Direct synthesis [7], ii) Highly nonporous material [8], iii) Quantum dots [9]. Quantum dot IBSC was fabricated using InAs quantum dots in Spain in Instituto de Energia Solar [10]. Nowadays the researches are going on about the following topics:

ii) Absorption overlap and its effects on efficiency [12]
iii) Inserting more than one intermediate band [13]
iv) Effects of Auger recombination on the performance of IBSC [14].

In this study the equations for calculating current-voltage (J-V) characteristics of IBSC are derived using detailed balance argument. The variation of efficiency of IBSC for varying intermediate band energy level is examined and the IB energy level for maximum efficiency is determined.

II. OPERATIONAL PRINCIPLES OF IBSC

IBSC is a n⁺-i-p⁺ structure (see Fig. 1). The base layer includes an intermediate energy band inside the forbidden gap. N⁺ and p⁺ type emitters are very thin so it is assumed that emitters do not absorb any photons. The incoming photons to base layer can cause three different transitions between valance band (VB), conduction band (CB) and IB depending on their energy:

i) $VB \rightarrow CB$, if the photon energy is greater then $E_{CV}$.
ii) $VB \rightarrow IB$, if the photon energy is greater then $E_V$.
iii) $IB \rightarrow CB$, if the photon energy is greater then $E_C$.

For conventional solar cells [3,4], only the first transition listed above is possible. So photons whose energy is lower than $E_{CV}$ are wasted. In IBSC, these type of photons can also generate electron-hole pairs and increase photocurrent without degrading output voltage. The carrier concentration of the IBSC can be calculated as below:

$$n_{eq} = N_C e^{-\frac{E_{eq}}{kT}}$$

$$p_{eq} = N_V e^{-\frac{E_{eq}}{kT}}$$

(1)
where \( n_{eq} \) and \( p_{eq} \) are equilibrium free carrier concentrations before illumination. \( N_C \) and \( N_V \) are effective density of states at conduction and valance bands respectively. \( k \) represents Boltzmann constant and \( T \) is cell temperature. After the cell is illuminated carrier concentrations \((n, p)\) are:

\[
\begin{align*}
n' &= n = \exp\left(\frac{e_{CI}}{kT}\right) \\
p' &= p = \exp\left(\frac{e_{VI}}{kT}\right)
\end{align*}
\]

The variation of number of photons in a mode can be calculated as below, based on balance equations.

\[
\nabla \nu = \left[ \alpha_{CV} (\nu - \nu_{CV}) + \alpha_{CI} (\nu - \nu_{CI}) \right] + \alpha_{VI} (\nu - \nu_{VI})
\]

where \( \alpha_{CV} \), \( \alpha_{CI} \) and \( \alpha_{VI} \) are the absorption coefficients due to transitions between valence band to conduction band, intermediate band to conduction band and valance band to intermediate band respectively. \( \nu_{CV} \), \( \nu_{CI} \) and \( \nu_{VI} \) are Bose Einstein factors:

\[
\nu_{XY} = \frac{1}{\exp\left(\frac{\nu - e_{XY}}{kT}\right) - 1}
\]

where \( XY \) suffixes are used instead of \( C \), \( V \) and \( I \) suffixes.

In equation (4) the first expression in the brackets corresponds to absorption of photons and the second corresponds to emission of photons. Due to the absorption and emission processes in a semiconductor a variation in the number of free carriers occurs. This variation is [15]:

\[
\frac{\delta_n}{\delta t} = \frac{2}{h^2 c^2} \left[ \alpha_{CV} (\nu - \nu_{CV}) \right] e^\gamma d\alpha d\Omega + \frac{\delta_n}{\delta t}_{nr}
\]

Where, \( h \) is Planck constant, \( c \) is speed of light and \( \epsilon \) is energy. \( \frac{\delta_n}{\delta t}_{nr} \) is used for nonradiative recombination. A similar equation can be derived for the holes, too.
Using equation (4), in (6) and taking the integral with appropriate limits, the absorption and emission expressions are obtained. Using continuity equations, the current density equation is obtained as below under assumption of constant $\varepsilon_{CV}$, $\varepsilon_{CI}$ and $\varepsilon_{VI}$ values:

$$J = J_e(0) + J_p(0) + \frac{I_e(0)}{A} + \frac{I_p(0)}{A} = \frac{1}{A} \int S \delta \alpha \delta \varepsilon_{abs} d\varepsilon$$

Using continuity equations, the current density equation is obtained as below under assumption of constant $\varepsilon_{CV}$, $\varepsilon_{CI}$ and $\varepsilon_{VI}$ values:

$$J = \frac{1}{A} \int S \delta \alpha \delta \varepsilon_{abs} d\varepsilon + J_p(0)$$

$$J_e = \int \frac{\alpha_{CV} + \alpha_{CI}}{\alpha_{CV} + \alpha_{CI} + \alpha_{VI}} (F_{abs} - F_{emi}) d\varepsilon - \frac{n_{eq} W}{\tau_C}$$

$$J_h = \int \frac{\alpha_{CI} + \alpha_{IV}}{\alpha_{CV} + \alpha_{CI} + \alpha_{VI}} (F_{abs} - F_{emi}) d\varepsilon - \frac{p_{eq} W}{\tau_V}$$

Where $J_e$ and $J_h$ are electron and hole current densities. $J_{B,e}$ and $J_{B,h}$ are called internal recombination. The internal recombination is zero when there is no overlap between absorption coefficients. That means a photon can cause only one type of transition between bands. $n_{eq} W / \tau_C$ and $p_{eq} W / \tau_V$ represent the nonradiative recombination at conduction band and valance band respectively. $W$ is the thickness of base layer and $\tau_C$ and $\tau_V$ are life times of electrons and holes. $J_s(w)$ and $J_p(0)$ are the minority carrier current densities of the emitter layers. $F_{abs}$ represents the absorption of photons while $F_{emi}$ represents the emission of photons. These expressions are found as below using equations (4-6):

$$F_{abs} = (1 - \sin^2 \theta_s) \pi$$

$$F_{emi} = \pi (1 - \exp[-(\alpha_{CV} + \alpha_{CI} + \alpha_{VI}) \omega])$$

$$\frac{\alpha_{CV} \varepsilon_{CV} + \alpha_{CI} \varepsilon_{CI} + \alpha_{VI} \varepsilon_{VI}}{\alpha_{CV} + \alpha_{CI} + \alpha_{VI}}$$

After performing the integral in (10), $\varepsilon_{CV}$, $\varepsilon_{CI}$ and $\varepsilon_{VI}$ were related with $n'$, $p'$ and $n'p'$ trough equations (3-5). So, a relation between current and voltage was obtained. Giving varying values to $\varepsilon_{CV}$ (means to $n'p'$) and expressing $n'$ in $p'$ or ($p'$ in $n'$), J-V characteristic of the IBSC was drawn. The numerical results will be presented in section III.

VI. NUMERICAL RESULTS

In this study, non-overlapping absorption coefficients of $\alpha_{CI} = \alpha_{VI} = 10^3$ cm$^{-1}$ values are used for the cells, those have base widths greater than 10um. In the analysis, the variation of efficiency depending on the intermediate band energy level is observed. In this way the IB energy level for performing maximum efficiency is obtained. As shown in Fig. 2 for the IBSC with $E_{CV} = 2.09$eV, the maximum efficiency of %59 is achieved when $E_{VI} = 0.75$eV.

![Figure 2](image)

During calculations, the sun is assumed to be a blackbody radiator at 6000K and the incident power used is 100mWcm$^{-2}$ which corresponds to one sun illumination. The IBSC supplied a short circuit current ($J_{sc}$) of 27.8mAcm$^{-2}$ and an open circuit voltage ($V_{oc}$) of 1.913V. For the same cell, when $E_{VI}$ is selected as 0.93eV, the efficiency is 46% which is in agreement with reference [15].

Same calculations were performed for another IBSC with $E_{CV} = 2.43$eV, and a maximum efficiency of 47% is obtained for $E_{VI} = 0.92$eV. For these values, the J-V characteristic of the IBSC is drawn as shown in Fig. 3. During calculations, the sun is assumed to be a blackbody radiator at 6000K and the incident power used is 100mWcm$^{-2}$ which corresponds to one sun illumination. The IBSC supplied a short circuit current ($J_{sc}$) of 27.8mAcm$^{-2}$ and an open circuit voltage ($V_{oc}$) of 1.913V. For the same cell, when $E_{VI}$ is selected as 0.93eV, the efficiency is 46% which is in agreement with reference [15].
V. RESULTS AND DISCUSSION

In this paper, the structure of IBSC was presented. The current voltage relation has been derived using balance equations. The variation of efficiency in IBSC due to the variation of intermediate band energy level has been investigated. Two n+-i-p+ solar cell structures, having different energy gaps ($E_{CV}$), are used to obtain the J-V characteristics and the maximum efficiency of the IBSCs. The maximum efficiency of 59% was achieved for the first cell that has $E_{CV}=2.09$eV when $E_{VI}=0.75$eV (Fig. 2).

Assuming that the sun is a blackbody radiator of 6000K and using a 100mWcm$^{-2}$ incident power, the short circuit current ($J_{sc}$) and the open circuit voltage ($V_{oc}$) of the cell are obtained as 42.44mAcm$^{-2}$ and 1.614V respectively.

For the second cell having $E_{CV}=2.43$eV, $E_{VI}$ was found as 0.92eV for achieving the maximum efficiency of 47%. For this cell (Fig. 3), $J_{sc}$ is 27.78mAcm$^{-2}$ while $V_{oc}$ is 1.913V. The results have shown that inclusion of intermediate band in intrinsic region does indeed enhance the short circuit current without degrading output voltage and improve the cell efficiency.

In this study, absorption coefficients are assumed to be constant. The calculations can be improved by taking the variation of absorption coefficient with energy into account. Also, overlap of absorption coefficients can be included. Besides, all of these calculations are based on direct band gap materials, indirect band gap materials can also be investigated.

REFERENCES

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