INTERMEDIATE BAND SOLAR CELLS

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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}=2.09eV reaches to 59% efficiency when E_{VI} equals to 0.75eV. 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 Quessier 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 nonoporous material [8], iii) Quantum dots [9]. Quantum dot IBSC was fabricated using InAs quantum dots in Spain in Instıtue de Energia Solar [10]. Nowadays the researches are going on about the following topics:

i) Thermodynamic consistency of IBSC model [11]
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→CB, if the photon energy is greater then E_{CV}.
ii) VB→IB, if the photon energy is greater then E_{VI}
iii) IB→CB, if the photon energy is greater then E_{CI}.

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:

$$n_{eq} = N_C e^{\frac{-E_{CI}}{kT}}$$
$$p_{eq} = N_V e^{\frac{-E_{VI}}{kT}} \tag{1}$$

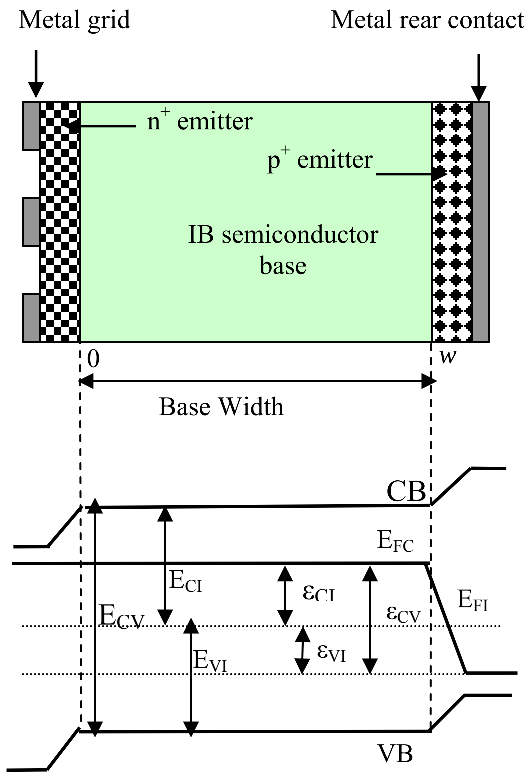

Figure1. IBSC structure and band diagram under illumination.

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 Boltzman constant and T is cell temperature. After the cell is illuminated carrier concentrations (n, p) are:

$$n = n_{eq} e^{\frac{\varepsilon_{CI}}{kT}}$$
$$p = p_{eq} e^{\frac{\varepsilon_{VI}}{kT}} \tag{2}$$

Here, ε_{CI} and ε_{VI} are amount of quasi Fermi level splits under illumination for electrons and holes respectively. Output voltage of IBSC can be expressed as $\varepsilon_{CV} = \varepsilon_{CI} + \varepsilon_{VI}$. So the ratio of carrier concentrations before and after illumination can be written as:

$$n' = \frac{n}{n_{eq}} = \exp(\frac{\varepsilon_{CI}}{kT})$$
$$p' = \frac{p}{p_{eq}} = \exp(\frac{\varepsilon_{VI}}{kT}) \tag{3}$$
$$n'p' = \exp(\frac{\varepsilon_{CV}}{kT})$$

III. BALANCE EQUATIONS AND CURRENT VOLTAGE RELATIONS

In this study the current voltage (J-V) relations in IBSC is derived using balance equations [5].
The variation of number υ of photons in a mode can be calculated as below, based on balance equations.

$$\nabla \upsilon = \begin{bmatrix} \alpha_{CV}(\upsilon - \upsilon_{CV}) + \alpha_{CI}(\upsilon - \upsilon_{CI}) \\ + \alpha_{VI}(\upsilon - \upsilon_{VI}) \end{bmatrix} \tag{4}$$

where α_{CV}, α_{CI} and α_{VI} are the absorption coefficients due to transitions between valance band to conduction band, intermediate band to conduction band and valance band to intermediate band respectively. υ_{CV}, υ_{CI} and υ_{VI} are Bose Einstein factors:

$$\upsilon_{XY} = \frac{1}{\exp(\frac{\varepsilon - \varepsilon_{XY}}{kT}) - 1} \tag{5}$$

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]:

$$\frac{\delta_n}{\delta_t} = \frac{2}{h^3c^2}\int[\alpha_{CV}(\upsilon - \upsilon_{CV}) + \alpha_{CI}(\upsilon - \upsilon_{CI})]\varepsilon^2 d\varepsilon d\Omega + \left.\frac{\delta_n}{\delta_t}\right|_{nr} \tag{6}$$

Where, h is Planck constant, c is speed of light and ε is energy. $\left.\frac{\delta_n}{\delta_t}\right|_{nr}$ is used for nonradiative recombination. A similar equation can 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 ε_{CV} , ε_{CI} and ε_{VI} values:

$$J = J_e(0) + J_p(0) = \frac{I_e(0)}{A} + \frac{I_p(0)}{A} = \frac{1}{A}\int_S \nabla J_e dU \qquad (7)$$

$$J = \frac{1}{A}\int_S e\frac{\delta n}{\delta t}dU + J_p(0) \qquad (8)$$

$$J_e = e\int_\varepsilon \frac{\alpha_{CV} + \alpha_{CI}}{\alpha_{CV} + \alpha_{CI} + \alpha_{VI}}(F_{abs} - F_{emi})d\varepsilon - J_{B,e} + J_p(0) + J_n(w) + \frac{n_{eq}w}{\tau_C} \qquad (9)$$

$$J_h = e\int_\varepsilon \frac{\alpha_{CV} + \alpha_{IV}}{\alpha_{CV} + \alpha_{CI} + \alpha_{VI}}(F_{abs} - F_{emi})d\varepsilon - J_{B,h} + J_p(0) + J_n(w) + \frac{p_{eq}w}{\tau_V} \qquad (10)$$

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. $\frac{n_{eq}w}{\tau_C}$ and $\frac{p_{eq}w}{\tau_V}$ represent the nonradiative recombination at conduction band and valance band respectively. w is the thickness of base layer and τ_C and τ_V are life times of electrons and holes. $J_n(w)$ 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):

$$F_{abs} = (1 - \sin^2\theta_S)\pi \left(1 - \exp\left(-(\alpha_{CV} + \alpha_{CI} + \alpha_{VI})2\omega\right)\right)\upsilon(0) \qquad (11)$$

$$F_{emi} = \pi\left(1 - \exp[-(\alpha_{CV} + \alpha_{CI} + \alpha_{VI})2\omega]\right) \left(\frac{\alpha_{CV}\upsilon_{CV} + \alpha_{CI}\upsilon_{CI} + \alpha_V\upsilon_{VI}}{\alpha_{CV} + \alpha_{CI} + \alpha_{VI}}\right) \qquad (12)$$

After performing the integral in (10), υ_{CV} , υ_{CI} and υ_{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 ε_{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 $\alpha_{CI} = \alpha_{VI} = \alpha_{CV} = 10^4 cm^{-1}$ values are used for the cells, those have base widths ω greater than 10µm. 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}= *2,09eV*, the maximum efficiency of %59 is achieved when ε_{VI} *=0.75eV.*

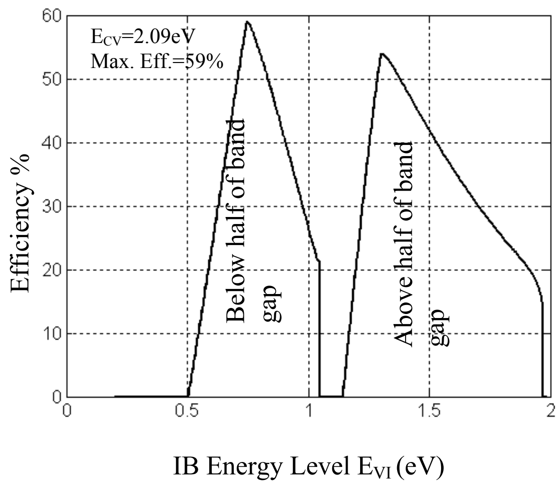

Figure2. Efficiency variation with IB energy level E_{VI}

Same calculations were performed for another IBSC with E_{CV}=2.43eV, and a maximum efficiency of 47% is obtained for E_{VI}=0.92eV. 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].

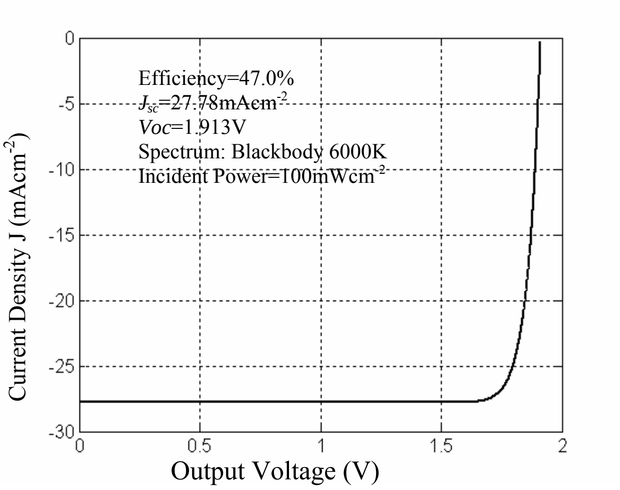

Figure3. Current density- Voltage characteristic of the IBSC with E_{CV}=2.43eV and E_{VI}=0.92eV.

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}=2.09eV, when E_{VI}=0.75eV (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}=2.43eV, 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..

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