Electron Filling Factor and Sunlight Concentration Effects on the Efficiency of Intermediate Band Solar Cell

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Abstract—For a determined intermediate band position, the effects of electron filling factor and sunlight concentration on the active region thickness and efficiency of the quantum-dot intermediate band solar cell are calculated. For each value of electron filling factor, the maximum point of efficiency obtained and resulted in the optimum thickness of the cell under three different sunlight concentrations. We show the importance of filling factor as a parameter to be more considered. The photon recycling effect eliminated in all calculations.

Keywords—Intermediate band, Sunlight concentration, Efficiency limits, Electron filling factor

I. INTRODUCTION

The concept of Intermediate Band (IB) Solar Cells (SCs) offered the promise of achieving higher conversion efficiency devices than the multi-junction SCs [1]. Like the conventional solar cells, IB SCs exploit one-photon absorption for photocurrent generation. However, these SCs also use the induced two-consecutive-photon which cause electron transitions via the intermediate states and generate an extra photocurrent [2, 3]. In fact, the IB SC concept exploits nonlinearity in absorption and it must be gained from the sunlight concentration (Fig. 1). Recently, the IB SCs have been fabricated from InAs quantum dots (QD) sandwiched between n and p-doped GaAs layers (Fig. 2) [4]. The bands of the structure remain flat by transition layers can add between junctions and keep up the built-in potential [5, 6]. This paper considered the use of GaAs/InAs QD in IBSC structure. The band gaps of this cell assumed to be the optimum values for operation at maximum concentration (E_L = 0.71 eV and E_H = 1.24 eV) [8, 9].

For three different values of Electron Filling Factors (EFF) of electron and three different sunlight concentrations, we plot the efficiency versus thickness of the cell.

II. THEORY

The complete device is realized by sandwiching the IB material between two ordinary semiconductors without an IB, one of them is p-type and another is n-type. In order to simplify the description of the cell operation, following processes consisting of carrier recombination and generation rates will be present.

\[ g_e = \int \alpha_e F_0 \exp(-\alpha_e x) dE, \]  
\[ g_h = \int \alpha_h F_0 \exp(-\alpha_h x) dE, \]  
\[ g_{eh} = \int \alpha_{eh} F_0 \exp(-\alpha_{eh} x) dE, \]  

Fig. 1 Illustration of the generation and recombination processes in the QD-IB material.

Fig. 2 The structure of QD-IBSC
\[ r_e(x) = \gamma B_e N_{Ibe} \Delta n(x), \]  
\[ r_h(x) = \gamma B_h N_{Ibe} \Delta p(x), \]  
\[ r_{eh}(x) = B_{eh} \Delta n(x) \Delta p(x), \]

Where, \( \alpha_e \) is the absorption coefficient related to transitions from the IB to the CB, \( \alpha_h \) is the absorption coefficient related to transitions from the VB to the IB, \( \alpha_{eh} \) is the absorption coefficient related to transitions from the VB to the CB, \( B_{NI} \) and \( B_{NI} \) are the density of occupied and empty states at the IB and VB, respectively. \( F_0 \) is the number of photons per unit of area from the Earth (1/sin 2 \( \theta \)) on the surface of the cell. If the sun is assumed to be a blackbody at TS = 6000 K, this density is given by,

\[ F_0 = \frac{\sin^2 \theta}{\sin^2 \theta} \frac{2\pi}{h^3 c^2} \int \frac{E^2}{\exp(E/k_b T) - 1} dE, \]  

Where \( \theta \) is the semi-angle of the sun solar disk sustained from the Earth (1/sin 2 \( \theta \), \( \approx 46050 \)) and \( X = 1/\sin^2 \theta \) is the concentration.

\( B_e, B_h \) and \( B_{eh} \) are the radiative recombination coefficients for their related transitions, respectively. For non-degenerated material, they are linked to the absorption coefficients through Roosbroek–Schockley-like relationships [10],

\[ B_e N_{Ibe} = \frac{8\pi}{\hbar^5 c^2} \int \alpha_e E^2 \exp\left(-\frac{E}{k_b T}\right) dE, \]  
\[ B_h N_{Ibe} = \frac{8\pi}{\hbar^5 c^2} \int \alpha_h E^2 \exp\left(-\frac{E}{k_b T}\right) dE, \]  
\[ B_{eh} = \frac{8\pi}{\hbar^5 c^2} \int \alpha_{eh} E^2 \exp\left(-\frac{E}{k_b T}\right) dE, \]

In Eq. (8) to (10), \( n_0 \) and \( p_0 \) are the electron and hole concentrations in equilibrium in the CB and VB, respectively,

\[ n_0 = N_C \exp\left(-\frac{E_L}{kT}\right), \]  
\[ p_0 = N_V \exp\left(-\frac{E_H}{kT}\right), \]

Where, \( N_C \) and \( N_V \) are the effective density of states in the CB and VB.

\[ \Delta n = n_0 \left[ \exp\left(\frac{E_L}{kT}\right) - 1 \right], \]
\[ \Delta p = p_0 \left[ \exp\left(\frac{E_H}{kT}\right) - 1 \right], \]

Where, \( n_0 \) and \( p_0 \) are the density of occupied and empty states at the IB and VB, respectively.

\[ \Delta n = n_0 \left[ \exp\left(\frac{E_L}{kT}\right) - 1 \right], \]
\[ \Delta p = p_0 \left[ \exp\left(\frac{E_H}{kT}\right) - 1 \right], \]

Where, \( E_{L} \) and \( E_{H} \) are the electron and hole concentrations in equilibrium in the CB and VB, respectively, over that of the equilibrium.

\[ \Delta n = n_0 \left[ \exp\left(\frac{E_L}{kT}\right) - 1 \right], \]
\[ \Delta p = p_0 \left[ \exp\left(\frac{E_H}{kT}\right) - 1 \right], \]

Where, \( E_{L} \) and \( E_{H} \) are the electron and hole concentrations in equilibrium in the CB and VB, respectively.
of the dot into barrier or a improper distance between dots, the value of EFF is assumed to be given by 0.52 (Fig. 5). For this value, the maximum points of efficiency of 43.2%, 38.4% and 21.3% are obtained for light concentrations of 46050 suns, 1000 suns and 1 sun, respectively.

In Fig. 6, as the last consideration, the maximum point of efficiency versus thickness has been calculated for EFF= 0.35. For light concentrations of 46050 suns, 1000 suns and 1 sun the maximum points of efficiency are attained to be about 38%, 34.3% and 18.7%, respectively.

Finally, it is worth mentioning that the space between the dots arrayed in the active region of the cell is an effective parameter to be considered. QD layers should be safely stacked close together as possible. In this condition, the wave function of the electrons will penetrate into barrier region and will construct the intermediate band. As a matter of fact, for producing IB and having a way to absorb the low energy photons, to have a precise control over the manufacturing and fabricating processes are needed. The parameter EFF describes the quality of these phenomena.

IV. CONCLUSION

In summary, the EFF and sunlight concentration effects on the maximum point of efficiency of an intermediate band solar cell have been calculated. EFF gives us a standard of dots’ spacing and intermediate band production. Whatever EFF becomes closer to unity, the wave function of electrons can better penetrate into the barrier region and construct the intermediate band. In addition, it has been shown that reduction of sunlight concentration causes the reduction in peak of the efficiency. For the all calculations, the optimum thickness remains constant around 1.3 μm.

REFERENCES


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