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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].

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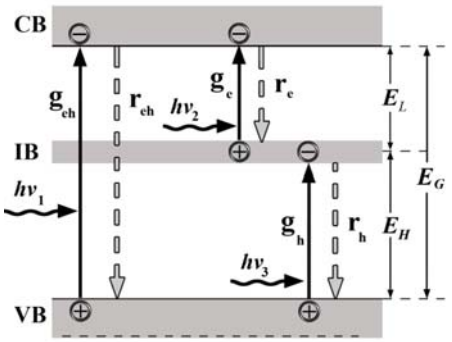

Fig. 1 Illustration of the generation and recombination processes in the QD-IB material.

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.

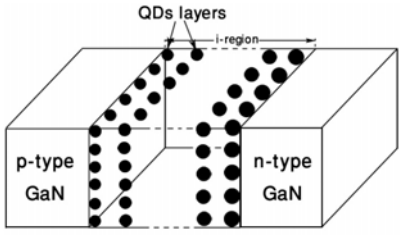

Fig. 2 The structure of QD-IBSC

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.

$$g_e = \gamma \int \alpha_e F_0 \exp(-\alpha_e x) dE, \quad (1)$$

$$g_h = \gamma \int \alpha_h F_0 \exp(-\alpha_h x) dE, \quad (2)$$

$$g_{eh} = \int \alpha_{eh} F_0 \exp(-\alpha_{eh} x) dE, \quad (3)$$

$$r_e(x) = \gamma B_e N_{IBh} \Delta n(x), \quad (4)$$

$$r_h(x) = \gamma B_h N_{IBe} \Delta p(x), \quad (5)$$

$$r_{eh}(x) = B_{eh} \Delta n(x) \Delta p(x), \quad (6)$$

Where, α_e is the absorption coefficient related to transitions from the IB to the CB, α_h is the absorption coefficient related to transitions from the VB to the IB, α_{eh} is the absorption coefficient related to transitions from the VB to the CB. B_eNI and B_hNI are the density of occupied and empty states at the IB, respectively. F_0 is the number of photons per unit of area on the surface of the cell. If the sun is assumed to be a blackbody at T_S = 6000 K, this density is given by,

$$F_0 = \frac{\sin^2\theta_s}{\sin^2\theta} \frac{2\pi}{h^3c^2} \int \frac{E^2}{\exp(E/k_BT_s)-1} dE, \quad (7)$$

Where θ_s is the semi-angle of the sun solar disk sustained from the Earth ($1/\sin^2\theta_s \approx 46050$) 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],

$$B_e N_{IBh} = \frac{1}{n_0} \frac{8\pi}{h^3c^2} \int \alpha_e E^2 \exp\left(\frac{-E}{k_BT}\right) dE, \quad (8)$$

$$B_h N_{IBe} = \frac{1}{p_0} \frac{8\pi}{h^3c^2} \int \alpha_h E^2 \exp\left(\frac{-E}{k_BT}\right) dE, \quad (9)$$

$$B_{eh} = \frac{1}{p_0 n_0} \frac{8\pi}{h^3c^2} \int \alpha_{eh} E^2 \exp\left(\frac{-E}{k_BT}\right) dE, \quad (10)$$

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

$$n_0 = N_C \exp(\frac{-E_L}{kT}), \quad (11)$$

$$p_0 = N_V \exp(\frac{-E_H}{kT}), \quad (12)$$

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

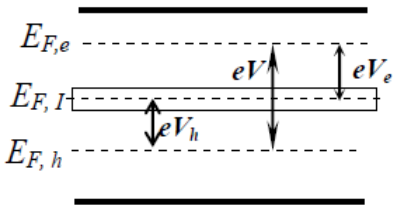

Fig. 3 Band gap diagram of biased QD-IBSC

Δn and Δp are the excess carriers (electrons and holes) in the CB and VB, respectively, over that of the equilibrium,

$$\Delta n = n_0 \left[\exp(\frac{eV_e}{kT}) - 1 \right], \quad (13)$$

$$\Delta p = p_0 \left[\exp(\frac{eV_h}{kT}) - 1 \right], \quad (14)$$

Where, eV_e (eV_h) is the split between the electrons (holes) and intermediate band quasi-Fermi levels at the n+-emitter/ IB (p+-emitter/IB) material junction (Fig. 3).

Now, the current–voltage characteristic of the SC, under the condition that $V=V_e+V_h$, can be obtained from the simultaneous solution of the two following equations:

$$J(V) = \int (g_e + g_{eh}) dx - r_e W - r_{eh} W, \quad (15)$$

$$J(V) = \int (g_h + g_{eh}) dx - r_h W - r_{eh} W, \quad (16)$$

Physically, the parameters EFF can be taken to mean as a scale of quantity of the electrons which are confined at QDs. It depends on the electron wave function penetration into the barrier layer and distance between the dot arrays.

EFF is equal to unit for complete penetration of wave functions into the barrier region and proper distance between dots. For other probabilities of wave function penetration and distance between dots, this parameter reduces from unity [11].

III. Results and Discussion

Results for an optimum gap of about E_L = 0.71 eV and E_H = 1.24 eV have been shown. The efficiency as a function of thickness is calculated for three EFF values of 1, 0.5 and 0.35. In addition, when the light concentration is lowered from 46050 suns to 1000 suns and even to 1 sun, it displays that the limiting efficiency is reduced. Here, it must be noted that all simulation results are given for radiative limit and without PR effect. Excluding the PR leads to a reduction in efficiency from 63.2% to 58.3% for EFF=1(= γ).

Fig. 4 displays the energy conversion efficiency versus thickness for γ=1 and for three different concentrations of sunlight. For light concentrations of 46050 suns, 1000 suns and 1 sun, the maximum points of efficiency are calculated to be 58.3%, 52.4% and 32.5%, respectively.

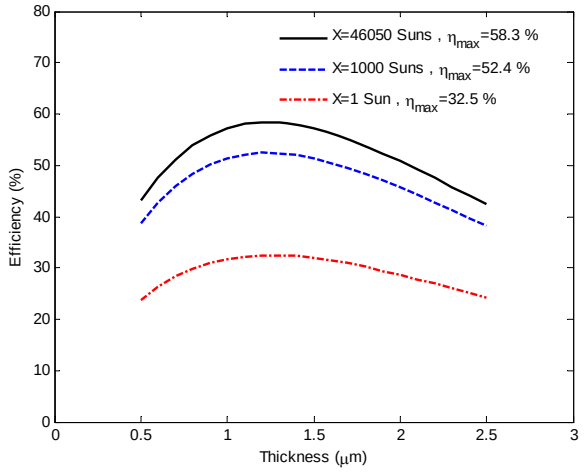

Fig. 4 Efficiency vs. Thickness in three different sunlight concentrations and for γ=1.

For the case of weak penetration of electron wave functions

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.

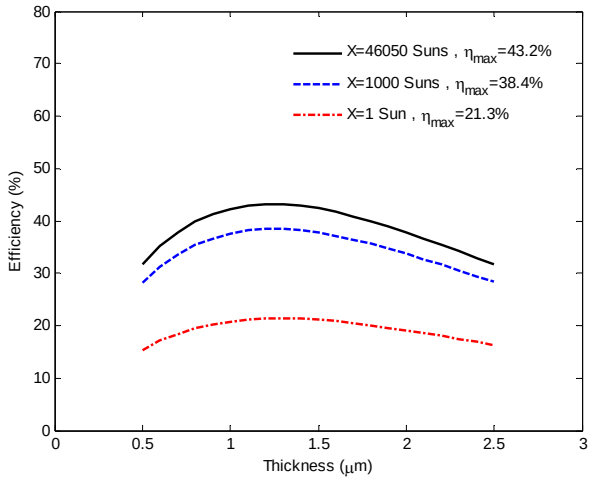

Fig. 5 Efficiency vs. Thickness in three different sunlight concentrations and for γ=0.52.

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.

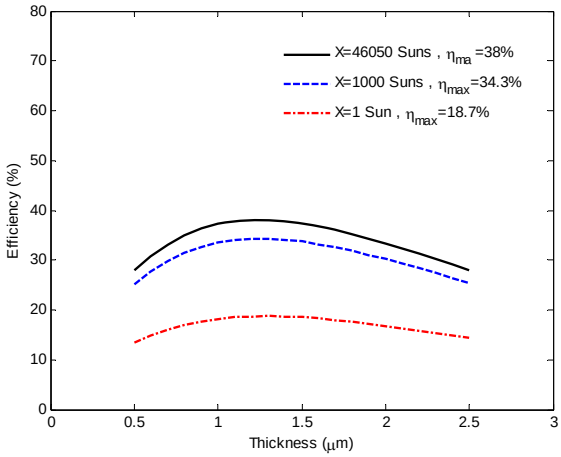

Fig. 6 Efficiency vs. Thickness under three different sunlight concentrations and for γ=0.35.

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 an 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.

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