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Concentration effects on the efficiency, thickness and J–V characteristics of the intermediate band solar cells

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ABSTRACT

The J–V characteristics and efficiency as a function of active region thickness of the p-i-n intermediate band solar cells have been calculated. We compared the maximum efficiency point of three different cells made of well-known materials. Each cell includes a different size of quantum dot from other cells in the i-region which causes a different intermediate band position in the bandgap of the host semiconductor. In addition, it is illustrated that the maximum efficiency point increases with increasing the incident light concentration in the radiative limit. This article considered that using light concentrators can be useful to enhance the efficiency of the solar cell with respect to manufacturing and cost improvements.

1. Introduction

The Quantum Dot Intermediate Band Solar Cell (QD-IBSC) is a novel type of SCs which can exceed the maximum thermodynamic energy conversion efficiency limitation or Schockley–Queissar limit by using its IB level [1]. The QDs in the host material create confined energy levels which their position in the one isolated QD depends on the size and shape of the QD and the type of used materials [2]. Recently, several experimental results have been reported for multi-stacked QDs in the intrinsic region of typical p-i-n structure SCs [3–5]. By forming the array of dots, theses energy levels are expected to turn into the IB. This IB has a bandwidth that causes stimulated emission problems. Furthermore, the IB should have a finite width for achieving the best work of the cell [6]. On the other hand, doping QDs in the active region of the cell should be controlled. Coupling between dots is estimated to begin at 100 Å [7]. For this separation between QDs layers, the required doping in the barrier region would be in the range of 3 to 4×10^{18} cm^{-3}. It is expected that doping in the barrier region can usually be controlled reasonably only above $10^{16}cm^{-3}$. This doping level establishes an upper bound of 600 Å for the space between dots [8]. The IB is located within the semiconductor bandgap to divide the total semiconductor bandgap, E_G, into two sub-bandgaps, E_L and E_H (Fig. 1). The efficiency of IBSCs depends on the values of two sub-bandgaps and IB width. Therefore, the value of confined energy levels should be optimized for producing maximum energy conversion efficiency. The photons with energies below the bandgap energy, create one electron–hole pair by pumping an electron from the Valence Band (VB) to the IB and an electron from the IB to the Conduction Band (CB). However, the IBSCs are predicted to increase the maximum energy conversion efficiency and decrease the cost of SCs [9]. This purpose is feasible by introducing light concentrators [10,11], where these optical systems focus the lights on each expensive SC which affects their costs to be reduced [12]. Nowadays, the operation of photovoltaics in different sunlight concentrations takes into consideration for high efficient photovoltaics and it can also be used for the novel concepts which are considered here. Increasing the efficiency of IBSCs occurs due to multiple step excitations happen in the cell which is result of increasing the photogenerated current without reducing the Open-Circuit Voltage (V_{oc}). This article also considers appropriate sub-bandgap and bandgap gap variations due to the change in the QDs sizes. We assumed three different cells, where intermediate band position in each cell is different because of different size of the QDs in each cell's structure. Under ideal conditions, involving Photon Recycling (PR) and full concentration, an efficiency of 63.2% can be achieved for $E_L=0.71$ eV and $E_H=1.24$ eV sub-bandgaps [1]. Maximum efficiency point of these cells has been considered with the elimination of PR. In all kinds of solar cells, unavoidable radiative recombination processes generate luminescent photons that can be emitted out from the cell. Using PR technique, with back

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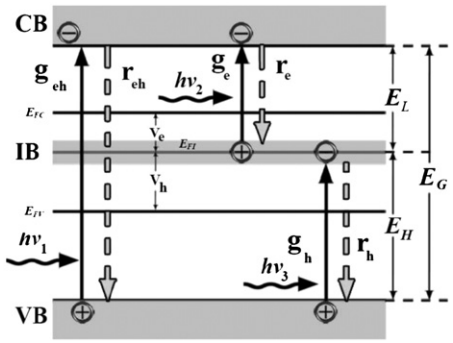

Fig. 1. Illustration of the generation and recombination processes in the QD-IB material.

reflectors or placing textured cell inside the cavity, these loss photons can be absorbed and cause to efficiency enhancement. For real consideration of our purposes and comparison of results from unaffected cells in this paper, we omitted PR effect. Its clear that employing this technique will further enhance the maximum point of efficiency. In addition, the total optimum thickness of the cell will be considered perfectly by eliminating the PR [13].

2. Theory

The complete device is realized by sandwiching the IB material between p-type and n-type semiconductors without an IB level. This has been illustrated in Fig. 1, where the three Quasi-Fermi levels have been labelled with the suffixes E_{FC}, E_{FI}, and E_{FV} for the electrons in CB, IB, and VB, respectively. In our study, we applied and slightly developed a model summarized by Marti et al. [14]. For a same model, the other aspects of the concept which have already not been considered clearly and together has been considered. Simplifying the description of the IBSC operation, we are going to the following processes consisting of carrier recombination and generation rates with this assumption that $\gamma = 1$. We also state that this represents the ideal case where the wavefunctions penetrate the barrier region fully such that it is equally likely to find an electron in the barrier or QD region.

$$g_e = \int \alpha_e F_0 \exp(-\alpha_e x)\, dE, \tag{1}$$

$$g_h = \int \alpha_h F_0 \exp(-\alpha_h x)\, dE, \tag{2}$$

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

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

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

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

where α_e is the absorption coefficient related to transitions from IB to CB, α_h is the absorption coefficient related to transitions from VB to IB, α_{eh} is the absorption coefficient related to transitions from VB to CB. N_{IBe} and N_{IBh} are the density of occupied and empty states in IB, respectively, and F_0 is the number of photons per unit of area on the surface of the cell [2]. If the sun is assumed to be a black body at $T_S = 6000$ K, this density is given by

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

where $\theta_s = 0.267^\circ$ is the semi-angle of the sun solar disk sustained from the Earth $1/\sin^2(\theta_s) \simeq 46\,050$ for 46 050 and $X = \sin^2(\theta)$ is the concentration and k_B is the Boltzmann constant.

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 [7,11].

$$B_e N_{IBh} = \frac{1}{n_0} \frac{8\pi}{h^3 c^2} \int \alpha_e E^2 \exp(-E/k_B T)\, dE, \tag{8}$$

$$B_h N_{IBe} = \frac{1}{p_0} \frac{8\pi}{h^3 c^2} \int \alpha_h E^2 \exp(-E/k_B T)\, dE, \tag{9}$$

$$B_{eh} = \frac{1}{n_0 p_0} \frac{8\pi}{h^3 c^2} \int \alpha_e h E^2 \exp(-E/k_B T)\, dE, \tag{10}$$

From Eqs. (8)–(10), n_0 and p_0 are the concentrations of electrons and holes being in equilibrium in CB and VB, respectively,

$$n_0 = N_C \exp(-E_L/k_B T), \tag{11}$$

$$p_0 = N_V \exp(-E_H/k_B T), \tag{12}$$

where N_C and N_V are the effective density of states in CB and VB and we assumed that they have a same value in our calculations (10^{17} cm^{-3}). This value is in the range of concentration of QDs are doped in the barrier region. Over the equilibrium, Δn and Δp are the excesses of charge carriers in CB and VB,

$$\Delta n = n_0(\exp(eV_e/k_B T) - 1), \tag{13}$$

$$\Delta p = p_0(\exp(eV_h/k_B T) - 1), \tag{14}$$

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

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

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

The efficiency of a solar cell is defined as

$$\eta = \frac{J_{max} V_{max}}{P_0}, \tag{17}$$

where P_0 is incident power from the sun on the cell.

3. Results and discussion

We use $In_xGa_{1-x}As/Al_xGa_{1_x}$ QDs for our structure [2,14]. It is assumed that the absorption coefficients have a same value of 4×10^4 cm^{-1} for their related bandgap and sub-bandgaps and are zero otherwise. We have shown the simulation results for three cells with different IB positions. Owing to the changes of doped QDs in active region, we can change the IB position and also the values of sub-bandgaps (E_L and E_H), which cause modification in the maximum point of efficiency. Three cases of cells will be discussed here where we analyze their efficiency as a function of thickness of active region and also their J–V characteristics when the light concentration decreases from 46 050 suns to 1 sun (from Eqs. (15)–(17)). In the first case, cell 1, we assume a cell 1 with $E_L = 0.74$ eV and $E_H = 1.28$ eV, in the second case, cell 2, $E_L = 0.57$ eV and $E_H = 1.10$ eV and in the third case, cell 3, $E_L = 0.49$ eV and $E_H = 0.99$ eV. This parameters are inconsistence of the values we had chosen for absorption coefficients. Another choice for the absorption coefficients, will generally