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Light concentration effects on the performance of the p-i-n quantum dot solar cells: A simulation study

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ABSTRACT

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 in the i-region that causes different intermediate band position. Numerical optimizations have been done by adjusting parameters such as the combination of band gap, mismatch as well as the specific structure of the cell. 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 SC which can exceed the maximum thermodynamic energy conversion efficiency limitation or Shockley–Queissar limit by using its IB levels [1–4]. Theoretical models predict that the maximum solar energy conversion is up to 63% for this type of SC [1,5] where exceed maximum thermodynamic energy conversion efficiency limitation of conventional solar cells where has been calculated by Shockley and Queisser in 1961 [6]. QDs in the host material create confined energy levels and the position of the confined energy level in the one isolated QD depends on the size and the shape of the QD and the type of used materials [7–9]. Recently, several experimental results have been reported for multi-stacked QDs in the intrinsic region of typical p-i-n structure SC [10–12]. When QDs stacked in the i-region of a SC structure, the interface states are recombination-generation centers and can provide additional tunneling paths between the components of the cell or have the role of charge storage centers (Fig. 1).

The interface effects can be appeared by the strain-induced dislocations in the cell. So they can have unfavorable effect on the performance of the cell if they reduce the open circuit voltage [13,14]. The experimental works have done to growth strain free samples for nanostructure solar cells to enhance the performance of the cell [15–17]. By forming the array of dots, this energy level is expected to turn into the IB but it produces a bandwidth of the IB that causes stimulated emission problems. Furthermore IB should have a finite width for achieving the best work of the cell [4,18]. On the other hand, QDs' doping in the active region of cell should be controlled. Coupling between dots is estimated to begin at 100 [19]. For this separation between dots, the required doping in the barrier region would be in the range of $3–4 \times 10^{18}\ cm^{-3}$. On the other hand, it is expected that doping in the barrier region can usually be controlled reasonably only above $10^{16}\ cm^{-3}$ [8]. This doping level establishes an upper bound of 600 for the space between dots [4,20]. 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 value 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 which have the 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). IB solar cells are predicted to increase the maximum energy conversion efficiency and decrease the cost of SCs [21]. This purpose is feasible by introducing light concentrators [22], where these optical systems focus the lights on each expensive SC and this affects their costs [23]. Nowadays, operation in different sun concentration photovoltaics (CPV) is take into consideration for high efficient photovoltaics and it can also be used for the novel concepts which are considered here. Increasing the efficiency of IB occurs due to multiple step excitations and

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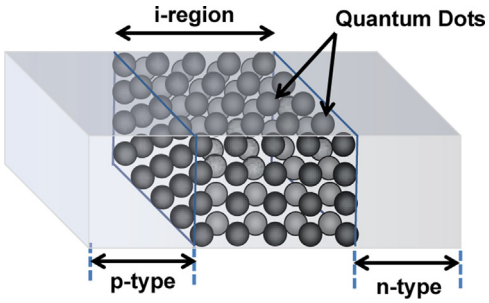

Fig. 1. A schematic diagram of proposed p-in quantum dot intermediate band solar cell.

it results in increasing the photogenerated current without reducing the open-circuit voltage (V_{oc}). Under ideal conditions, involving Photon Recycling (PR) and full concentration, an efficiency of 63.2% can be achieved for $E_L = 0.74$ eV and $E_H = 1.28$ eV sub-bandgaps [1].

This article considers optimum gap variations due to the change in QD sizes. We assume three different cells, where intermediate band position in each cell is different. Maximum efficiency point of these cells has been considered with the elimination of PR. In addition, the total thickness of the cell should be optimized by eliminating the PR.

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. 2, where the three quasi-Fermi levels have been labeled with the suffixes E_{FC}, E_{FI}, and E_{FV} for the electrons in CB, IB, and VB respectively.

In our study, we used and developed a model which has been studied by Marti et al. [24]. For simplifying the description of the IBSC operation, we are going to the following processes consisting of carrier recombination and generation rates,

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

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

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

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

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

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

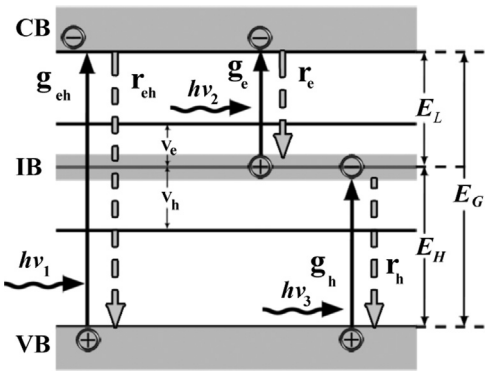

Fig. 2. Illustration of the generation and recombination processes in the QD-IB material.

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 [8]. If the sun is assumed to be a blackbody at $T_S = 6000$ K, this density is given by,

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

where θ_s is the semi-angle of the sun solar disk sustained from the Earth ($\sin^2(\theta_s)$ 46050) 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 [19,22].

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

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

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

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

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

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

where N_C and N_V are the effective density of states in CB and VB. Over the equilibrium, Δn and Δp are the excesses of charge carriers in CB and VB,

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

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

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:

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

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

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. Now by using Eqs. (15)–(17), we find out a relation between the efficiency of the cell and total thickness of the device.

3. Results and discussion

Reference materials of the QD-IBSCs made of $In_x Ga_{1-x} As/Al_x Ga_y As$ QDs have been selected [8,24]. Absorption coefficient of selected reference materials is about 4×10^4 cm^{-1}. We have shown