Optik 127 (2016) 4799–4802

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Influence of the inverse Auger process on the performance of $In_xGa_{1-x}N/GaN$ quantum dot solar cells

Hossein Movla*

Azar Aytash Co., Technology Incubator, University of Tabriz, Tabriz, Iran

ARTICLE INFO

Article history:
Received 15 December 2015
Accepted 19 January 2016

Keywords:
Semiconductor quantum dots
Intermediate band
Electrical modeling
Drift-diffusion

ABSTRACT

It has been proposed that the use of self-assembled nano sized quantum dot (QD) arrays can break the Shockley–Queisser efficiency limit by extending the absorption of solar cells into the low-energy photon range while preserving their output voltage. This would be possible if the infrared photons are absorbed in the two sub-bandgap QD transitions simultaneously and the energy of two photons is added up to produce one single electron–hole pair, as described by the intermediate band model. This paper indicates the energy conversion efficiency of a quantum dot multilayer solar cell considering impact ionization effect. A p–i–n $In_xGa_{1-x}N/GaN$ quantum dot solar cell structure has been taken into account in the calculation. It is shown that the efficiency of a cell strongly depends on the impact ionization in stacked quantum dots at i-region of the cell. In our proposed structure it is demonstrated that, if averaged probability of impact ionization, P, varies from zero to one, maximum efficiency increases by more than 12% (from 43 percent in $P=0$ to 55 percent in $P=1$). Also it is demonstrated that by decreasing θ, maximum efficiency increases and reaches to its maximum, 59%, in $\theta=2$.

1. Introduction

The maximum energy conversion efficiency limit of conventional solar cells (SC) with concentrated solar has been calculated by Shockley and Queissar which is named as detailed balance limit or S–Q limit [1–4]. Detailed balance limit calculation has shown that maximum efficiency of conventional p–n junction solar cells in the unconcentrated solar radiation is about 31% and in full concentration, 46,050 suns, is about 43% [1,5]. By developing the manufacturing technology of solar cells, such as, reducing the mismatch between p and n junction, doping control in both p and n regions, controlling the shunt and series resistance of cell and improving the growth techniques, experimental efficiency of cell in unconcentrated condition has reached 27.6% which is close to the theoretical calculations (31%) [6]. But the cost of the conventional solar cells is too high and electricity production from solar cell is more than five orders greater than other energy resources. The main reasons that the efficiency of single junction solar cells (like crystalline Si) is limited to 31% are given below as [7,8]:

- Not absorbing the significant fraction (20%) of the photons in the solar spectrum that are below the bandgap,
- High energy photons loss due to thermalization of high-energy charge carriers in the conduction band due to phonon scattering,
- Reflection from the surface of the cell,
- Non-radiative recombination in the transitions between the band gaps.

It is expected that by controlling the above mentioned parameters and improving material properties used in cell, exceeding the S–Q limit can be possible. In recent years, new types and new concepts of solar cells have been reported [2,9–11]. The idea of nano structure quantum dot (QD) solar cell has been suggested to exceed S–Q limit [1,12,13]. QD SC produces quantum confined levels and causes the increase in the effective band gap for absorption of sub-band-gap photons. QD solar cells are renowned as intermediate band solar cells (IBSCs), due to the extra band in the band gap of the host semiconductor. When QDs are stacked in 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 [4,14,15]. Early studies are based on a p–i–n GaAs/InGaAs quantum dot IBSC structure in which quantum dots are stacked in i-region of the cell [16]. Shockley and Queissar calculation showed the variation of cell efficiency in terms of semiconductor band gap in which

* Tel.: +98 9146352945.
E-mail address: h.movla@gmail.com

http://dx.doi.org/10.1016/j.ijleo.2016.01.156

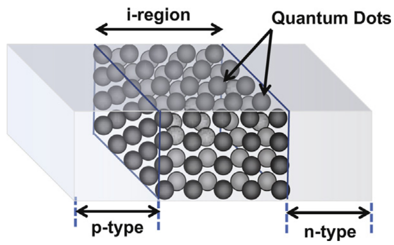

Fig. 1. A schematic diagram of proposed p–i–n quantum dot intermediate band solar cell.

maximum power conversion occurred in 1.1 eV [17]. Efficiency peak at this band gap, 1.1 eV, is lower than GaAs gap (1.42 eV). Furthermore, it is expected that choosing the best materials is one of the approaches to improve the IBSC performance. The lattice dislocation densities of III-nitride semiconductors are more than five orders of magnitude greater than other compound semiconductors, but surprisingly, these defects have a small impact on the performance of cell which is still not fully understood [18]. Also, it is shown that group III-nitride based solar cells have the potential to achieve limited efficiencies greater than the single junction limit [19]. The band gap of $In_xGa_{1-x}N$ can vary due to In concentration to make a overlap with solar spectrum (0.77–3.5 eV) [18]. Same as our previous works [4,13,15,20], a p–i–n $In_xGa_{1-x}N$/GaN structure has been taken into account in the calculation. Fig. 1 illustrates the proposed structure of solar cell. The sandwich structure of GaN barrier layers arranges $In_xGa_{1-x}N$ QD layers in i-region.

Energy band diagram of IBSC has been shown in Fig. 2. It contains the usual semiconductor valence band (VB) and conduction band (CB) but, in addition, there is an intermediate band (IB). 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. 2). 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 [1]. In this system, photons with energies lower than the host material bandgap's, $h\nu_1$ and $h\nu_2$, can be absorbed and pump electrons from the VB to the CB and as a result, rise up the photocurrent of the cell [21,22]. However, in quantum dots, the rate of Auger processes, including the inverse Auger process or impact ionization of exciton multiplication, is greatly enhanced because of carrier confinement and the concomitantly increased electron–hole Coulomb interaction. Impact ionization process produces an enhanced photocurrent or photovoltage. These processes require sufficient rates of photogenerated carrier pairs, transport, and interfacial transfer across

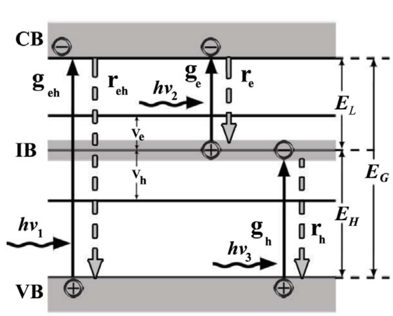

Fig. 2. Illustration of the generation and recombination processes in the QD-IB material.

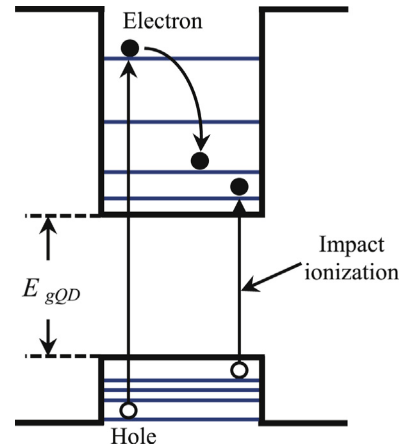

Fig. 3. Impact ionization process in QD solar cells.

the contacts of the semiconductor compared with the rate of carrier cooling [23,24]. Impact ionization processes have been shown in Fig. 3. In this figure, by absorbing a high energy photon in the QD, electron–hole pair has been produced. Here, a hot electron of the conduction band makes a transition to a lower energy in the same band, as a result of a collision with an electron in the valence band. This latter electron is promoted to the conduction band in result of this inelastic scattering by the first electron. In addition, the rate of impact ionization should be greater than the rate of carrier cooling and other relaxation processes of hot carriers [2,23].

For an appropriate distance between QD layers, when an array of QDs are stacked in i-region of a p–i–n structure, the electron wave function can penetrate into the barrier region and overlap with other wave functions of the electrons in neighbor QDs and so, it is possible to create an intermediate band in the band gap of the host semiconductor. Furthermore, for an inappropriate distance between QD layers, the electron wave function in the QDs becomes more localized and this intermediate band cannot be produced. If the wave functions of the electrons do not penetrate the barrier region, spacing between dots significantly reduces the performance of device. Hence, QDs should be placed as close together as possible in order to provide an intermediate band [25]. This paper indicated a theoretical model to calculate the effects of impact ionization on the performance of quantum dot IBSC.

2. The model

To illustrate impact ionization, let the high-energy photons of sun light have energy $E > \theta E_g$ for $\theta > 2$, where θ depends on the material type [26] and given by,

$$\theta = 1 + \frac{2m_e + m_h}{m_e + m_h}, \tag{1}$$

here m_e and m_h are effective mass of electron and effective mass of hole, respectively. So, θE_g has more excess energy than threshold energy for impact ionization and then the modified S–Q ultimate efficiency can be expressed by [27],

$$\eta = \frac{1}{D}\left[x_g \int_{x_g}^{+\infty} f(x)g(x)dx + P\int_{\theta x_g}^{+\infty} f(x)g(x)dx\right], \tag{2}$$

where we have considered $T = 5785$ K as temperature of the sun surface, variables $x = E/kT$, and $x_g = E_g/kT$ are defined. So, mean occupation number of photons with energy xkT can be expressed by,

$$f(x) = \frac{1}{\exp(x) + 1}, \tag{3}$$