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Elements of the design and analysis of quantum-dot intermediate band solar cells

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Abstract

We have demonstrated recently that two below bandgap energy photons can lead to the creation of one electron–hole pair in a quantum-dot intermediate band solar cell (QD-IBSC). To be effective, the devices used in the experiments were designed to a) half-fill the intermediate band with electrons; b) to allocate the quantum dots in a flat-band potential region, and c) to prevent tunnelling from the n emitter into the intermediate band. QD-IBSCs have also shown degradation in their open-circuit voltage when compared with their counterparts without quantum dots. This loss is due to the presence of the intermediate band (IB) together with the incapacity of the quantum dots to absorb sufficient below bandgap light as to contribute significantly to the photogenerated current. It is predicted, nevertheless, that this voltage loss will diminish if concentration light is used leading to devices with efficiency higher than single gap solar cells. A circuit model that includes additional recombination levels to the ones introduced by the IB is described to support this discussion.

Keywords: Quantum dots; Intermediate band; Photovoltaics; Solar cells; Solar concentration; Novel concepts; InAs; GaAs; Efficiency; Circuit model

1. Introduction

The intermediate band solar cell is a novel type of solar cell conceived to use the energy of below bandgap energy photons. To this end, it requires the existence of an intermediate band (IB) located within the semiconductor bandgap (Fig. 1). This band divides the total bandgap of the semiconductor, E_G, into two sub-bandgaps, E_L and E_H. Thanks to this band, two below bandgap energy photons, as those labelled "1" and "2" in Fig. 1, can create one electron–hole pair by pumping an electron from the valence band (VB) to the intermediate band (photon "1") and an electron from the IB to the conduction band (CB) (photon "2"). To this end, the IB should be half-filled with electrons in order to provide both empty states to receive electrons from the VB as well as electrons to supply to the CB. It is also worthwhile noticing that the creation of an electron–hole pair through the IB does not imply a phenomenon of simultaneous collision between three particles (two photons and one electron) since the electron pumped from the VB to the IB does not have to be the same electron promoted by the second photon to the CB. This electron–hole pair adds to the ones conventionally generated by the absorption of a single photon (photon "3") creating a transition from the VB to the CB.

On the other hand, carrier relaxation within the bands is assumed to be a much faster process than carrier recombination between bands. This leads to the assumption that the carrier concentration in each band is described by its quasi-Fermi level ($E_{F,C}$, $E_{F,V}$ and $E_{F,I}$ for the CB, VB and IB respectively). From the plot in Fig. 1 it can be understood that, since the output voltage of the cell, V, is related to the quasi-Fermi level split by $eV=E_{F,C}-E_{F,V}$, with e being the electron charge, the output voltage of the cell is still limited by the total bandgap E_G and not by E_L or E_H.

The concepts expressed above are sufficient to follow the work that will be described in this paper. More details related to the IBSC theory can be found in Refs. [1–5]. The existence of IB materials has been predicted to exist in several systems, as for example $Ti_xGa_{1-x}P$ [6], transition metal-doped chalcopyrite-type semiconductors [7] and II–VI compounds doped with

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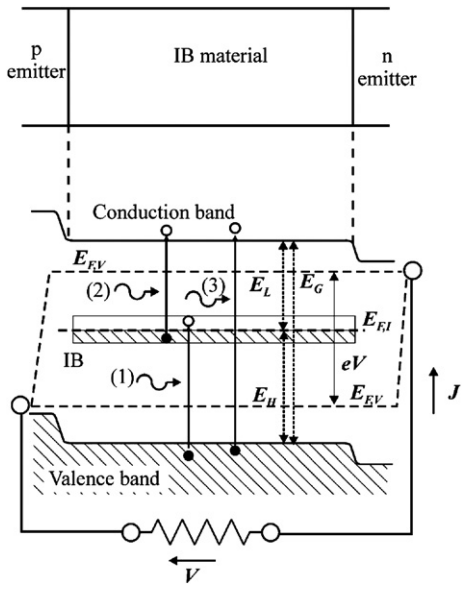

Fig. 1. Simplified bandgap diagram under bias of an intermediate band solar cell indicating several magnitudes of interest such as quasi-Fermi energy levels ($E_{F,C}$, $E_{F,I}$ and $E_{F,V}$) and bandgaps (E_L, E_H and E_G). The top figure shows the correspondence of the bandgap diagram with the layer structure.

Cr [8–10]. Intermediate band materials have been synthetised employing diluted II–VI oxide semiconductors [11] and $GaN_xAs_{1-y}P_y$ alloys [12]. In the latest two examples, the formation of the IB is explained on the basis of the band anticrossing model [13].

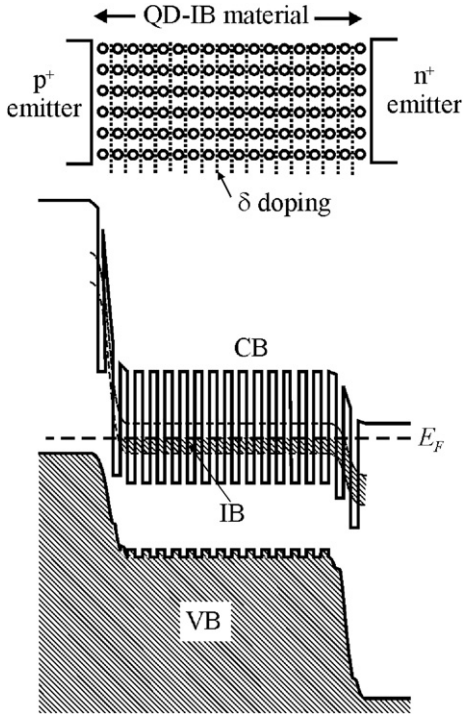

Fig. 2. Simplified bandgap diagram of a quantum-dot intermediate band solar cell in equilibrium. The δ-doping is introduced at the barrier region to half-fill the IB with electrons.

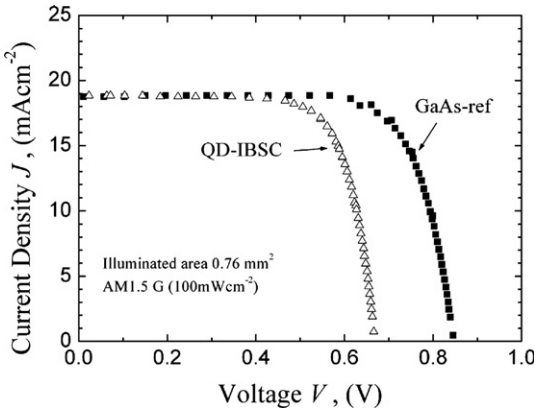

Fig. 3. Typical current–voltage characteristic of a QD-IBSC compared with a reference GaAs cell consisting of the same structure but without quantum dots (300 K).

Quantum dots (QDs) have also been proposed [14] for engineering intermediate band solar cells. It has been only under this approach that, to our knowledge, actual intermediate band solar cells (QD-IBSC) have been manufactured [15] and has it even been possible to obtain evidence of operation according to the IBSC principles [16,17]. Our groups have been working on this approach since the year 2000 and we take the opportunity of this paper to compile some of the elements of design and analysis that have guided our approach and that remain still unpublished.

2. Field damping layer design

Under the QD approach, the IB arises from the energy levels of the electrons confined by the potential well created by the conduction band offset appearing between the barrier and dot materials [18,19] (Fig. 2). Additional doping, at the rate of one donor per QD, is usually inserted at the barrier region (δ-doping) to half-fill the IB with electrons by modulated doping effect [20].

The InAs/GaAs material system has been our preferred choice for taking to practice the QD-IBSC concept because this is one of the best known material systems for implementing semiconductor QDs. Although not being an optimum material system for implementing the IBSC from the point of view of potential efficiency, this approach has allowed us to quickly implement operating devices in which it has been possible to test the principles of operation of the IBSC. Additional details of the internal structure of the devices used in the experiments can be found elsewhere and will not be repeated here [17,21,22].

Fig. 3 shows a typical result comparing the current–voltage characteristic of a QD-IBSC with that of a GaAs reference solar cell made with the same structure, but without QDs. The QD-IBSC consisted of 10 layers of QDs. As it can be observed, photocurrent in the QD-IBSC seems to be the same than the one obtained for the GaAs reference cell. Moreover, voltage is degraded, contrary to what it appears it would be expected.

The problem of the voltage degradation will be discussed in detail in the next section. Concerning the photocurrent,