Quantum Dot Solar Cells

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Recently several design schemes have been proposed to increase the power conversion efficiency of photovoltaic devices. By using two or more p-n solar cell junctions, tandem cells made of different semiconductors, a multi-heterojunction design yields a better match to the solar spectrum than a single-junction cell and may provide the efficiency of conversion greater than 50%. In fact, two-junction solar cells have been fabricated using *GaAs* and *InP* semiconductor allows which provides the highest power conversion efficiency of 30.2% for *AM* 1.5 spectra. Taking into account the recent advances in different optoelectronic devices, it would also seems appropriate to consider whether low dimensional (such as quantum dot) p-i-n structure could provide a new approach to the high-efficiency solar cell problem.

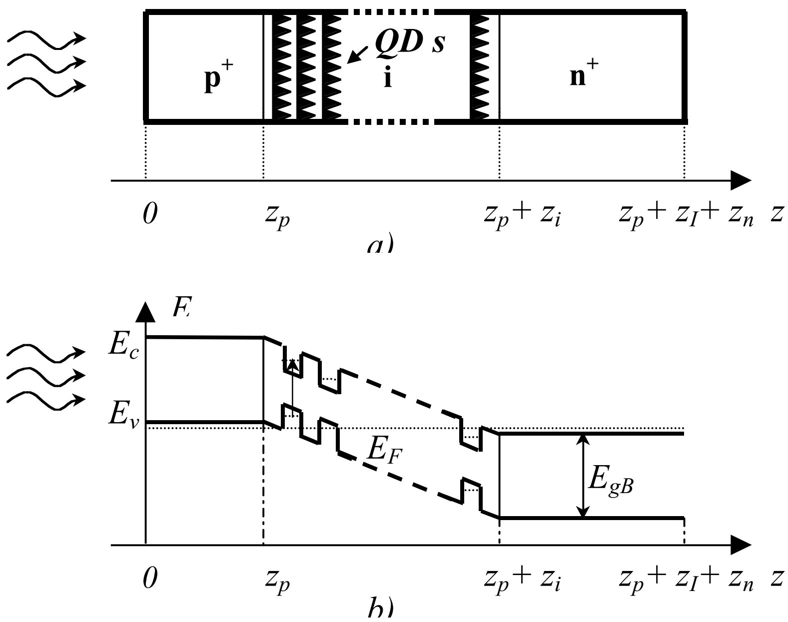

Fig. 1. a) Schematic structure of QD solar cell.
b) Energy-band diagram of p-i-n QD solar cell, showing the p^+- type layer ($0 \le z \le z_p$), intrinsic layer with QDs ($z_p \le z \le z_p + z_i$) and n^+- type layer ($z_p + z_i \le z \le z_p + z_i + z_n$). Depletion layers in p- and n- layers are neglected.

Here we propose a concept of a new device, namely the quantum dot (QD) solar cell. A theoretical model is presented for a practical p-i-n QD solar cell built on the base of the self-organized *InAs*/*GaAs* system. We will study the advantages of the use of QD s in active region for photon absorption in the long-wavelength part of spectrum and increase the power convention efficiency. The model proposed is based on a p^+-i-n^+ cell structure (Fig. 1. a) whose energy band diagram is shown in Fig. 1.b, includes a multi-quantum-dot layers in the intrinsic region of the structure to enhance the photocurrent. The effective band gap for absorption E_{eff} will be determined by the lowest confined states of QD s.

High internal quantum efficiency for the collection of carriers photoexcited in the QD s can occur as a result of channeling the electrons and holes through the coupling between aligned QD s. This effect allows one to separate and inject the generated electrons and holes in QD s, into an adjacent p- and n-regions with high efficiency. By changing the deposition mode one can change the size and shape of the *InAs* islands. Typically the dot size is around 10 *nm* and dot area densities range between $2 \cdot 10^{10}$ cm^{-2} and 10^{11} cm^{-2}. The dot layers are separated by 5÷10 *nm* barrier layer and the real dot density in the active i-region can be ~10^{17} cm^{-3}. Our model for the calculation of the power converting efficiency includes realistic estimates for the light absorption and photocurrent generation in p- and n-type *GaAs* region and *InAs*/*GaAs* QD s i-region, surface and volume minority-carrier recombination and junction thermal generation and recombination currents.

We calculate the photocurrent by solving the minority carrier transport equation at room temperature in uniform p-type and n-type *GaAs* fieldless regions. In the p-type layer, extending from the exposed surface at $z = 0$ to the edge of the depletion region at $z = z_p$, the distribution of minority carriers is governed by the standard equation for electron current density and electron continuity. The model of solar spectrum described by a black body curve, corresponding to a temperature of 5760 *K* was used. Expressions for photogenerated electron current density, total photocurrent collected by p-type, n-type and intrinsic region of the *GaAs* containing QD s made of *InAs* are obtained.

The *InAs* —on *GaAs* QD system usually show an absorption in the range of (1.1÷1.4) *eV*. Carrier confinement in a QD quantizes their energy spectrum into a series of discrete levels, which is reflected in the absorption spectra. Usually the absorption edge is shifted to higher energies due to strong confinement effect and δ - like peaks are prepared in the spectrum corresponding to different hole-electron level transitions. But due to typical dot size fluctuation of 10%, the absorption spectrum usually is inhomogeneously broadened. For the calculations, we used the experimental data for the absorption spectra of the *InAs/GaAs* QD ensemble. The expressions for the photocarrier generation rate in QD s inside the i-region, photocurrent collected from QD s as well as photocurrent generation in the *GaAs* barrier regions within i-region are obtained. During calculations of main parameters of the cell, we assume that the charge carriers generation in QD s are separated and collected via channels of vertically coupled QD s.

The calculations were shown that the inclusion of the QD s in the intrinsic region does indeed enhance short-circuit current without significant losses in the open-circuit voltage and results in significantly improved cell efficiency. Thus, the *InAs/GaAs* p-i-n solar cell, with $3\,\mu m$ width of i-layer and the ideality factor $\nu = 1.2$, can generate the photocurrent density $J_{sc} = 45.17 \dfrac{mA}{cm^2}$ and open-circuit voltage $V_{oc} = 0.746\,V$. Without the QD s the same structure has $J_{sc} = 35.1 \dfrac{mA}{cm^2}$ and $V_{oc} = 0.753\,V$. Accordingly in the first case the cell efficiency is expected to be 25%, while without QD s it is equal to 19.5%.

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