Chapter 10

Quantum Dot Solar Cells

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ABSTRACT

Advanced concepts for high efficiency solar cells such as hot carrier effects, Multi-Exciton Generation (MEG), and Intermediate-Band (IB) absorption in low-dimensional nanostructures are under focused research topics in recent years. Among various potential approaches, this chapter is devoted to the device physics and development of the state-of-the-art technologies for quantum dot-based IB solar cells.

INTRODUCTION

By avoiding all the nonradiative recombination processes within the solar cell, the theoretical maximum efficiency to a thermodynamic upper limit becomes ~ 85% for a fully concentrated black-body radiation of 5,800K (Green, 2003; Würfel, 2009). On the other, the maximum efficiency of a single-junction solar cell is limited to the Shockley-Queisser (1961) limit of ~ 31% for AM1.5 spectrum. The main physical processes that limit the efficiency of a solar cell are the losses by thermal dissipation or thermalization, and non-absorption of low-energy below-bandgap photons.

Thus improving the efficiency means developing the methods to reduce these losses. One of the concepts is to split the solar spectrum among multiple bandgap absorbers or sub-cells, e.g. tandem or multijunction cells. The others employ more advanced techniques such as hot carrier effects, Multi-Exciton Generation (MEG), and Intermediate-Band (IB) absorption in low-dimensional nanostructures such as semiconductor quantum dots (Nozik, 2002, 2008; Green, 2003; Luque, 1997). Among various approaches available, this Chapter is devoted to the device physics and development of the state-of-the-art technologies for quantum dot-based IB solar cells.

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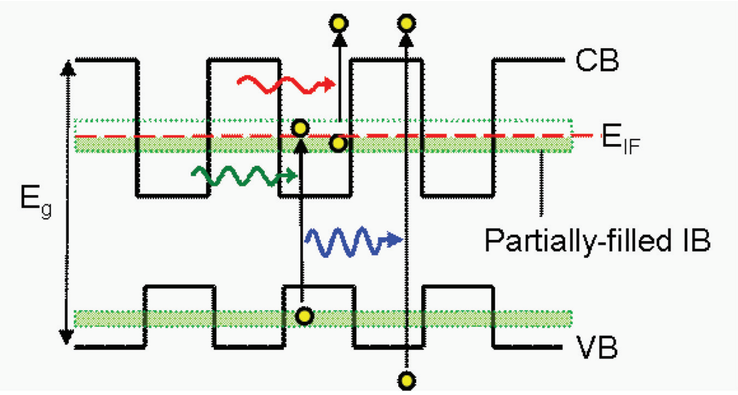
Quantum Dot (QD) superlattice incorporated in the active region of a *p-i-n* single-junction solar cell has attracted significant interest as a potential means of utilizing the sub-bandgap infra-red photons to generate additional photocurrents, through absorption *via* superlattice miniband states, beyond that corresponding to the valence-to-conduction band transitions (Luque, 1997). The QDs also offer the possibility for reducing thermal dissipation loss. If such a nanostructure solar cell were realized, the conversion efficiency could not only exceed the Shockley-Queisser (1961) limit of a conventional single-junction solar cell, which is ~ 31% for AM1.5 spectrum, but further provides a pathway to increase the efficiency up to the thermodynamic limit of > ~ 60% under full concentration.

In a QD solar cell, QDs are required to be homogeneous and small in size, and are regularly and tightly placed in all three dimensions. This configuration then leads to formation of an Intermediate-Band (IB) or a superlattice miniband that is well separated in energy from the higher-order states (Tomić, 2008). Secondly, IB states should ideally be half-filled with electrons in order to ensure an efficient pumping of electrons by providing both the empty states to receive electrons being photo-excited from the Valence Band (VB), and filled states to promote electrons to the Conduction Band (CB) via absorption of second sub-bandgap photons (Martí, 2001). This implies that its own quasi-Fermi level is defined within IB, as schematically shown in Figure 1.

Proposed implementation of QD-IB solar cells must accompany two-step carrier generation *via* IB states and it has been difficult to clearly verify this concept at room temperature. The demonstration of QD-IB solar cells is presently undergoing two research stages. The first is to develop the technologies to realize a high-density QD array or superlattice of low defect density, which is placed in the central active region of the cell. The fabrication of QD arrays is most commonly achieved by taking advantage of spontaneous self-assembly of coherent three-dimensional (3D) islands in lattice-mismatched epitaxy long known as Stranski-Krastanov (S-K) growth in Molecular Beam Epitaxy (MBE). However, the number of QDs is severely limited by the lattice strain accumulation in the crystalline material as the number of stacked QD layers is increased. In S-K growth of InAs/(Al)GaAs system, misfit disloca-

Figure 1. Schematic energy band diagram of QD-IB solar cell shown with possible photo-absorption processes involved. The energy bandgap of host material and quasi-Fermi level of IB are given by E_g and E_{IF}, respectively.



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