

Chapter 14

Quantum Well Solar Cells: Physics, Materials and Technology

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ABSTRACT

Quantum well solar cells with p-i-n structure are presented. The physical processes in multiple quantum well solar cells, the materials commonly used for photovoltaic applications, and technological aspects are analyzed. The quantum confinement effect produces resonant energy levels located in the valence and conduction bands of well layers. In addition, it produces energy quantum confinement levels located in the energy band gap of both well and barrier layers. The absorption on both resonant and quantum confinement levels leads to an extension of the internal quantum efficiency in near infrared domain.

Several structures with different absorbers from 3-5 and 4 groups are described and discussed. Various technological and design solutions, such as multiple quantum well solar cells with graded band gap, with tandem configurations, with strain-balanced structure, and strain-balanced structure improved with nanoparticles deposited atop are analyzed. The cell parameters are discussed and related to the materials and technology.

INTRODUCTION

Solar energy represents a clean, renewable energy (Myong, 2007). As solar light is at our disposal, it represents a primary source of abundant clean energy. The internal quantum efficiency close to

100% in bulk heterojunction Solar Cells (SCs) (Park, et Al., 2009) makes SCs promising candidates among renewable energy sources. Almost 100% internal quantum efficiency means that every absorbed photon produces a separated electron-hole pair and that all these carriers are collected at the electrodes. The role of SCs is to convert the solar energy into electrical energy. In

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a semiconductor one photon absorption generates an electron-hole pair. These non-equilibrium carriers do not comply with the equilibrium statistics; therefore, they recombine after their lifetime. During their lifetime, the non-equilibrium carriers move through an external circuit, and their energy can be utilized. This is a simplified functioning principle of a solar cell.

The first aspect that has to be analyzed generally in SCs, and particularly, in Quantum Well (QW) SCs is light absorption. The calculation of the absorption coefficient ($\alpha(\lambda)$) is essential for the modeling of solar cells. The main absorption phenomenon is the band-to-band absorption that generates an electron-hole pair. There are two types of semiconductors, with direct or indirect energy band gap, considering the position of the conduction band minimum (E_c) related to the valence band maximum (E_v) in the \vec{k} wave vector space. The most of 3-5 (GaAs) and 2-6 (CdTe) semiconductors have a direct gap, while the semiconductors from group 4 (C, Si, and Ge) have an indirect gap. The calculus of the absorption coefficient depends on the gap type (direct or indirect), and on both values of the orbital quantum number (l) for the valence band and conduction one. The absorption coefficient is found by determining the absorption rate and by evaluating the Einstein coefficients (Iancu, Mitroi, & Fara, 2009; Ciurea & Iancu, 2010; Iancu, Mitroi, Lepadatu, Stavarache, & Ciurea, 2011). Besides the band-to-band absorption, one should take into account the excitonic and inter-band absorption, and also the absorption on free charge carriers, impurities, phonons, and defects.

To achieve higher conversion efficiencies, multi-bandgap absorber systems such as multiple QWs and Superlattice (SL) were proposed (Barnham, & Duggan, 1990).

In the third generation of solar cells, nano-materials based SCs have to be included. In QW SCs, for the first time, the idea of extending the spectral absorption appeared (Barnham, & Dug-

gan, 1990). This idea was confirmed by the first experimental application, which used a *p-i-n* cell with an intrinsic region (*i*) in a GaAs/Al_{0.3}Ga_{0.7}As multi-layered structure (Barnham, et al., 1991). Since the 1990s, the solar cells with multi-layered structures have been intensively studied (Anderson, 1995; Lynch, et al., 2005; Kirchartz, et al., 2009; Munteanu & Autran, 2011).

Usually, the layers have thicknesses from tens to hundreds of nanometers. The last ones are actually submicronic structures, and therefore, at these thicknesses, the quantum effects are weak. However, they are named quantum well structures, even if the consecrated terminology is of multi-layered photovoltaic cells.

Only recently, multi-layered cells with proper quantum sizes—less than 10 nm (multi-layered photovoltaic cells with quantum wells) were studied (Kirchartz, et al., 2009; Berghoff, et al., 2010; Munteanu & Autran, 2011). Indeed, the quantum effects at low size (less than about 20 interatomic distances, approximately 5 nm) become dominant, so that the continuous band structure is replaced by a discrete spectrum or at most with a quasiband structure due to quantum confinement effects (Nishida, 2005; Ciurea, et al., 2006; Ciurea & Iancu, 2010). Even the momentum conservation law is no longer valid (Heitmann, et al., 2004) at these sizes.

QW SCs as well as quantum dots SCs are based on the advantages offered by the low dimensional systems (Ciurea & Iancu, 2007, 2010). In low dimensional systems, the light absorption domain is extended, and densities of states are modified by restricting the size at least on one direction to the order of magnitude of the electron wave function. In addition, the thermalization can be reduced. (Myong, 2007; Iancu, et al., 2011). These systems are 0D (quantum dots), 1D (nanowires), and 2D (nanolayers which can be described by quantum wells). A low dimensional structure has a nanometric size on at least one direction. At low size one has a strong quantum confinement effect, while the nature of the material type plays

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