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Progress in quantum well solar cells

M. Mazzer [a,*], K.W.J. Barnham [b], I.M. Ballard [b], A. Bessiere [b], A. Ioannides [b], D.C. Johnson [b], M.C. Lynch [b], T.N.D. Tibbits [b], J.S. Roberts [c], G. Hill [c], C. Calder [c]

[a] *CNR-IMM, University Campus Lecce, Italy and Experimental Solid State Physics, Blackett Laboratory, Imperial College of Science, Technology and Medicine, London SW7 2BW, UK*

[b] *Experimental Solid State Physics, Blackett Laboratory, Imperial College of Science, Technology and Medicine, London SW7 2BW, UK*

[c] *EPSRC III-V Facility, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK*

Abstract

A quantum well solar cell is a special multiple-band gap device with intermediate properties between heterojunction cells (sum of the currents generated in the different materials but voltage controlled by the lowest of the two band gaps) and tandem cells (sum of the voltages but current determined by the worst of the two sub-cells).

Strain-balanced GaAsP/InGaAs multi-quantum wells move the absorption edge of GaAs solar cells closer to the optimum value for single junction cells with no need for any partially relaxed buffer layer to accommodate lattice mismatch between the absorbing layers and the substrate. Covering a large spectral range in a single-junction cell has the benefit that the cell remains close to optimal efficiency in the varying spectral conditions of a typical terrestrial concentrator. Though monolithic multi-junction cells have significantly higher efficiency, the series-current constraint means that some of this advantage is lost as the illuminating spectra and the cell temperature change from the values at which the tandem was optimised.

The good material quality which can be achieved with these structures makes the cell dark current at the typical operating conditions expected under moderate sunlight concentration (~200×), increasingly dominated by radiative processes the deeper the quantum wells.

We will report on high concentration measurements of strain-balanced quantum well solar cells with and without Bragg-stack reflectors and discuss the "additivity" between the short-circuit current and the dark-current. We discuss a 50 shallow well cell with measured AM1.5d efficiency of (26±1)% at around 200× concentration. This is approximately 2% higher than a comparable p–n cell with comparable material quality.

The good material quality is also responsible for another effect previously observed in single quantum wells becoming measurable in structures with 5 and 10 wells, that is the suppression of carrier recombination in quantum wells with respect to expectations assuming that the quasi-Fermi level separation in the depletion region is equal to the cell output voltage throughout the active region. The latest results are presented together with possible explanations for this effect both in the dark and under illumination.

Finally a brief discussion about the potential applications of quantum well solar cells completes the paper.

Keywords: Photovoltaic; Quantum well; III-V semiconductors; Solar concentrators

1. Introduction

The Quantum Photovoltaic Group (QPV) at Imperial has pioneered the application of low-dimensional systems [1] such as quantum wells [2] and quantum dots [3] in photovoltaics (PV). The strain-balanced quantum well solar cell (SB-QWSC) was introduced as a way to extend the spectral range of high efficiency GaAs cells. We have demonstrated that the extended spectral range can be achieved and the SB-QWSCs can be grown with zero dislocations in the active region, in contrast to the alternative approach using virtual substrates [2].

The SB-QWSC can achieve optimal band-gaps for the highest single-junction efficiencies due to the tunability of the quantum well thickness and composition. Moreover, although tandem cells can achieve significantly higher efficiencies under standard AM 1.5 solar spectra, the series current constraint of a

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[*] Corresponding author.
E-mail address: m.mazzer@imperial.ac.uk (M. Mazzer).

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monolithic, multi-junction cell results in some of this advantage being lost in the varying spectral conditions of a typical urban environment. This spectral sensitivity is also likely to mean the efficiency of multi-junction cell is more dependent on cell temperature, which is particularly important under high concentration. Furthermore, tunnel junction performance is more problematic at concentrator current levels.

The absence of dislocations and radiative dominance at high current levels in the SB-QWSC means that the dark-current is minimal at the optimum band-gap [4]. Furthermore radiative recombination dominance means that photon recycling can be used to reduce the dark-current further [5].

We report on our latest measurements of SB-QWSC performance under concentrated light and in particular the test of additivity up to 200× concentration. Finally, the most recent data on the behaviour of the quasi-Fermi level separation in multiple-quantum well solar cells are reviewed and discussed with reference to our earlier results in single quantum well devices.

2. The strain-balanced quantum well solar cell

The AM1.5d efficiency variation with band-gap of a single junction cell in a concentrator system is well known to peak below the band-gap of GaAs.

It is also well known that there is no binary or ternary III–V alloy lattice matched to GaAs with lower band-gap. Hence, to achieve optimum efficiencies, tandem cells are often grown on relaxed or "virtual-substrates" which necessarily involve dislocations [6,7]. The GaInNAs quaternary alloy is being considered for multi-junction cells though its bulk and QW material properties are currently poor.

The band-gap of the SB-QWSC is represented schematically in Fig. 1. It consists of a *p*–*i*–*n* diode with an *i*-region containing a number (up to 65) of approximately 7 nm wide quantum wells (QWs) of compressively strained $In_xGa_{1-x}As$ inserted into tensile strained $GaAs_{1-y}P_y$ barrier regions. The crystal structure is represented in Fig. 2. The alloy compositions and well and barrier thicknesses are adjusted to minimise the formation of dislocations. The stress–balance condition ensures that when the structure in Fig. 2 is grown epitaxially with the same lattice constant as the substrate, there is essential zero stress between the thin alloy layers. The critical thickness of the overall structure is well above 1 μm. This constraint means that the $GaAs_{1-y}P_y$ barriers have higher band-gap than the bulk GaAs in the p and n regions and this helps to reduce the dark-current.

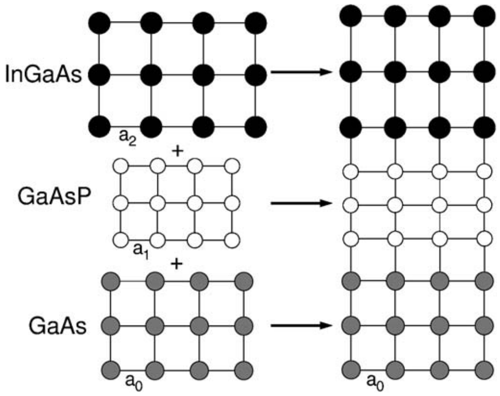

Fig. 2. Schematic of the crystal structure of the strain-balanced quantum well solar cell.

The QWs extend absorption from bulk band-gap E_g to threshold energy E_a determined by the confinement energy as in Fig. 1. For 7 nm wells and $GaAs_{1-y}P_y$ barrier alloys with $y \sim 0.1$ (barrier band-gap ~1.5 eV) the threshold energies that can be achieved are $E_a \sim 1.34$ eV for In fractions $x \sim 0.1$ and $E_a \sim 1.28$ eV for $x \sim 0.17$. The extra absorption is demonstrated for a 50 well sample in Fig. 3, which shows the experimental spectral response (external quantum efficiency at zero bias) and the fit described in Ref. [4]. Fig. 3 also demonstrates a sharp exciton feature in the QW which is a good indication of material quality.

3. Dark current behaviour at concentrator current levels

A range of SB-QWSCs has been grown by metal-organic vapour phase epitaxy (MOVPE). Further growth details can be found in Ref. [1]. These include a series of structures with P fraction $y = 0.08$ and a varying number (10 to 65) of shallow

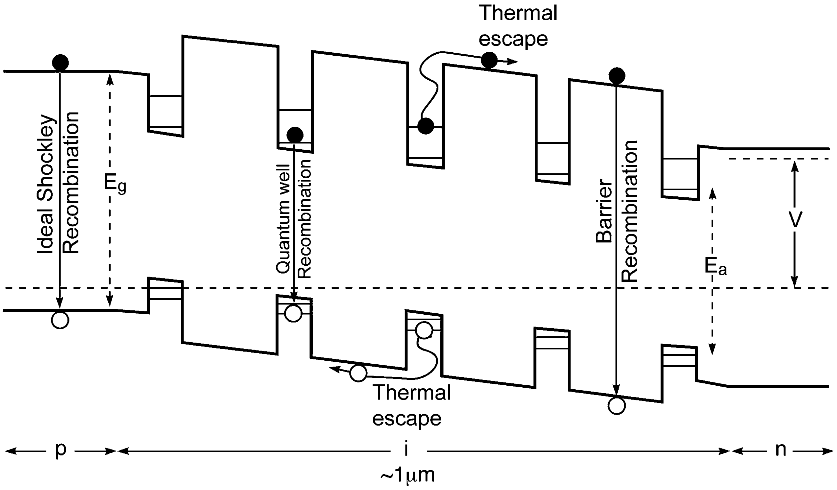

Fig. 1. Schematic of a SB-QWSC with compressively strained $In_xGa_{1-x}As$ wells and tensile strained $GaAs_{1-y}P_y$ barriers higher than the bulk GaAs in *p* and *n* regions.