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High Efficiency Quantum Well Solar Cells.

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1. Introduction

The ultimate efficiency for solar power conversion sits at 87%, yet conventional solar cells with a single semiconductor absorber typically have efficiencies between 10-20%. This loss in efficiency arrises primarily through incomplete absorption and internal heat generation as photogenerated carriers equilibrate with the lattice [1], but can be overcome by using multiple semiconductor absorbers to form a multi-junction solar cell. The III-V semiconductor material system has direct-gap alloys that span the solar spectrum and enable multi-junction solar cells to be fabricated. The combination of InGaP/$In_{0.01}$GaAs/Ge forms a lattice matched triple junction solar cell combination that is presently achieves efficiencies in excess of 30% under extraterrestial illumination (AM0) [2] and in excess of 40% under concentrated terrestrial sunlight (AM1.5D) [3]. The solar cell can be grown at industrial scale using metal organic vapour phase epitaxy (MOVPE) and presently represents the commercial state of the art. However, this semiconductor system does not yield the highest triple-junction solar cell efficiencies. Figure 1 shows projected solar cell efficiencies assuming an InGaP top-cell and variable solar cell absorption thresholds for the middle and bottom sub cells under both the AM0. The present InGaP/$In_{0.01}$GaAs/Ge triple junction solar cell is marked by a cross on the contour map.

It is clear that the solar cell could be improved by lowering the band-gap of the middle cell and raising that of the bottom cell. However, there is no high-quality lattice matched bulk semiconductor alloy that can be grown by MOVPE, although sufficiently high quality InGaAsN has been demonstrated using molecular beam epitaxy [4].

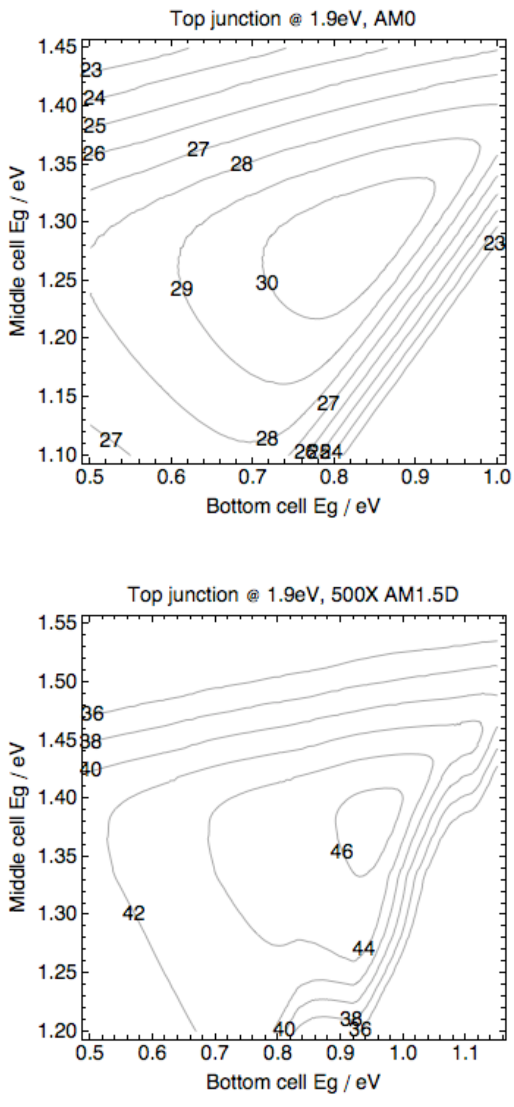

Figure 1. Contour maps with fixed 1.9eV InGaP top-cell & variable middle and bottom cell band-gaps, under AM0 and 500X AM1.5D spectra

2. Engineering the absorption threshold using quantum well heterostructures

One means of adjusting the absorption threshold of a semiconductor is to grow thin strained layers of semiconductor of alternating compressive and tensile strain, resulting in a strain-balanced stack [5], [6]. This enables effective absorption thresholds to be achieved using high-quality ternary alloys, yet avoiding introduction of dislocations associated with strain-relaxation. The concept has been demonstrated in GaAsP/InGaAs quantum wells where an absorption threshold at 965nm was achieved with a recombination current only marginally higher than that of a GaAs control cell [7]. The band-structure for this solar cell is shown in figure 2 below.

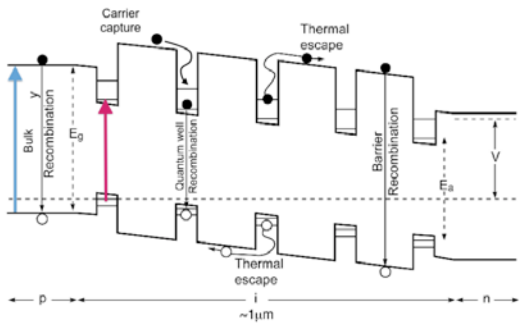

Figure 2. Band-structure for a quantum well solar cell.

As it is necessary for carriers photogenerated in the quantum wells to escape, it is important to place the quantum wells in the intrinsic region of a p-i-n diode, where a combination of thermal and tunneling processes ensure efficient carrier escape [8]. If the well depth is too great, or there is insufficient electric field across the quantum well, carrier escape will be impaired, together with the solar cell performance [9]. Some of these constraints can be lifted by growing a coupled quantum well superlattice structure [10]

A typical quantum efficiency for a MQW GaAsP/InGaAs solar cell is shown in figure 3 with and without a distributed Bragg reflector. The external quantum efficiency (EQE) beyond 900nm is due to photogeneration in the quantum well region and is increased in the cell the DBR owing to the second pass that the light makes through the MQW region.

The high purity of the semiconductor material leads to radiatively dominated recombination when the solar cell is operated at a concentration in excess of 200 suns. In this regime, further improvement in voltage depends only upon control of the optical loss. The compressive strain in the quantum wells leads to anisotropic emission in the direction normal to the quantum well (TE) and leads to a small but fundamental efficiency advantage over conventional bulk semiconductor solar cells [11].

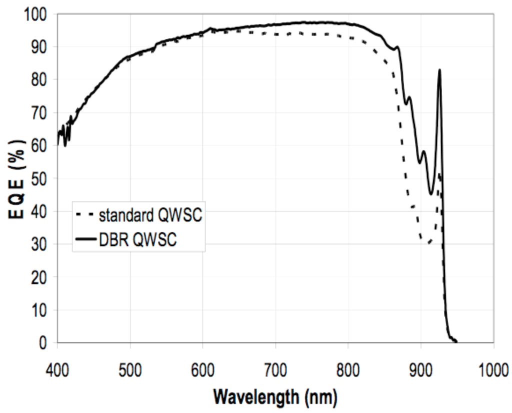

Figure 3. External quantum efficiency for a 50 MQW GaAsP/InGaAs solar cell.

Combining these effects a strain-balanced GaAsP/InGaAs quantum well solar cell was demonstrated in 2009 by the Quantasol company with a power conversion efficiency of 28.3% at 300 suns.

3. Conclusions

Inserting quantum well sub-cells provides an effective means to control the absorption threshold of a solar cell. It has particular application in series connected multi-junction solar cells where specific absorption thresholds can be obtained yet remaining lattice matched to the host lattice constant.

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