Quantum Heterostructure Solar Cells

N.J. Ekins-Daukes, D.Alonso Alvarez, O.Hess, N.Hylton, A.Mellor, P.Stavrinou, T.Thomas, C.Phillips, A.Pusch, A.Vaquero, T.Wilson, M.Yoshida

Imperial College London, U.K.
www.imperial.ac.uk/qpv

Quantum heterostructures provide a remarkable ability to control the energetic distribution of electronic states in a semiconductor and are routinely applied to a wide range of optoelectronic devices. In photovoltaic devices they provide an means for adjusting the absorption threshold of a solar cell. In a conventional InGaP/GaAs/Ge multi-junction solar cell, it is desirable to marginally extend the absorption threshold of the GaAs sub-cell to 930nm. While quantum confinement serves to increase the energy of confined states, the ability to grow strain-balanced bi-layers provides a means to engineer the absorption threshold of strained, ternary semiconductors into a composite structure that can be grown free of dislocations onto a lattice constant of choice. This was achieved using a strain-balanced GaAsP/InGaAs quantum well structure that achieved an efficiency of 28.3% as a single junction device and 42.5% in a multi-junction configuration [1].

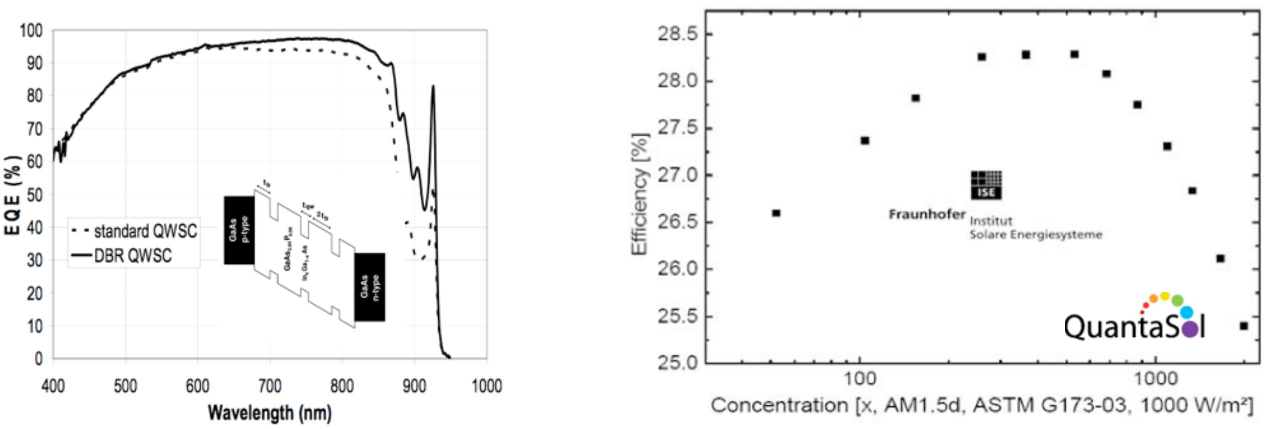

Figure 1. External quantum efficiency for a single junction GaAsP/InGaAs quantum well solar cell and efficiency measured under concentrated sunlight.

The next technological milestone is to develop a monolithic 4J solar cell, with the potential to reach efficiencies in excess of 50%. This requires a semiconductor materials with an absorption threshold around 1eV but which can be grown lattice matched to GaAs. The most promising bulk semiconductor, lattice matched approach is to grow a dilute nitride alloy of InGaAsSbN which has been successfully employed in 3J solar cells. However, a very aggressively strain-balanced GaAsP/InGaAs quantum well structure has been demonstrated with an absorption threshold at 1.15eV which could provide an alternative approach. Since each component layer is so close to the critical thickness, in-situ wafer curvature monitoring is used to measure the strain of each layer and ensure that the overall structure remains strain-balanced. Depending upon the growth conditions, planar quantum well and modulated `wire in well' structures can be formed. Working sub-cell devices have been fabricated using this approach with a 1.15eV absorption threshold that meet the voltage requirement for a 50% efficient cell and achieve close to the target current value. However, the fill factor remains problematic since carriers increasingly become trapped in confined states under forward bias conditions. Studies to date have shown evidence for the accumulation of space-charge under illuminated conditions in the quantum well region and a stark difference in carrier dynamics between planar quantum well and `wire in well` structures [2].

The ability to control electronic states using quantum heterostructures has also led to proposals for their use in intermediate band devices. Much research in this area has concerned the application of quantum dot materials that are proposed as a means for introducing intermediate states to promote sequential absorption. While proof of principle devices have been demonstrated, there remain two key and related problems, namely the strength of the intermediate optical transitions and the lifetime of the intermediate state. We have recently suggested that a relaxation stage is beneficial and possibly required for the efficient operation of an intermediate band solar cell. The situation is illustrated in Figure 2, where the limiting efficiency of a three level intermediate band cell (Fig. 2a) is compared against one with a relaxation stage (Fig. 2b) into a band that is both optically and electronically decoupled from the valance band. We find that the overall efficiency of a solar cell with a relaxation stage is increased under 1-sun illumination (Fig 2c) [3].

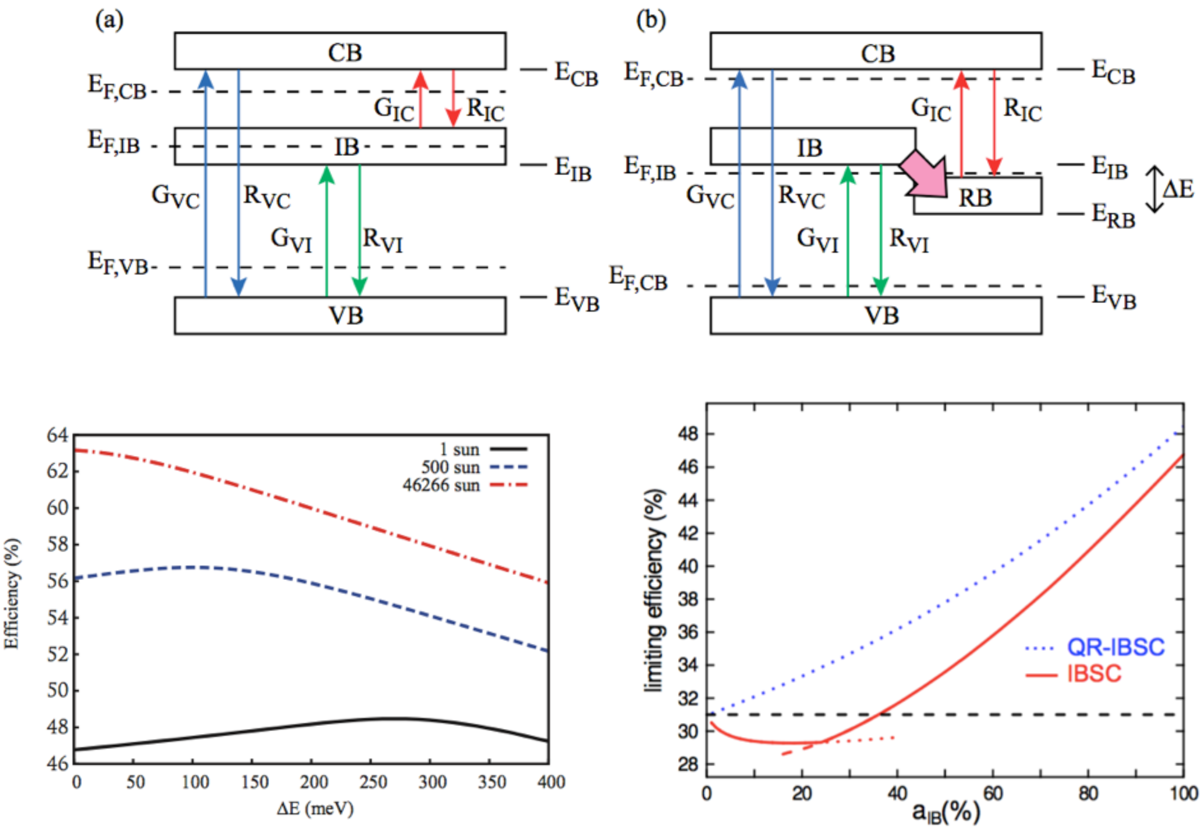

Figure 2. Comparison between (a) standard 3-level intermediate band solar cell and (b) device with a relaxation stage from IB to RB. (c) shows the limiting efficiency as a function of relaxation energy ΔE for a fully absorbing device (a=1) and (d) shows the effect of non-unity absorptivity for both cell architectures.

It is further demonstrated that non-unity absorptivity for the intermediate levels leads to a loss in efficiency when a_{IB}<38%, while with a relaxation stage any introduction of intermediate absorption increases the efficiency of the solar cell [4].

[1] J.Nelson & N.Ekins-Daukes, 2014. "Quantum Well Solar Cells" in 'Clean Electricity from Photovoltaics', Eds. M.Archer & M.Green, Imperial College Press.
[2] Alonso-Alvarez, D. et al., 2014. InGaAs/GaAsP strain balanced multi-quantum wires grown on misoriented GaAs substrates for high efficiency solar cells. Applied Physics Letters, 105(8), p. 083124.
[3] Yoshida, M. et al., 2012. Photon ratchet intermediate band solar cells. Applied Physics Letters, 100(26), p.263902.
[4] Pusch, A. et al., 2016. Limiting efficiencies for intermediate band solar cells with partial absorptivity: the case for a quantum ratchet, Progress in Photovoltaics, in press.