High Efficiency Quantum Well Solar Cells.

N.J.Ekins-Daukes, A.Chan, L.Hirst, K-H. Lee, K.W.J. Barnham, M.Führer, P.Stavrinou, Department of Physics, Imperial College London, SW7 2BZ, U.K. J.Adams, Microlink USA., B.Browne, JDSU, USA.

Abstract

The absorption of a p-i-n solar cell can be extended to lower photon energies by placing quantum wells into the intrinsic region. Photogenerated carriers escape the quantum well via a thermally assisted tunneling process and contribute to the photocurrent of the solar cell. By using alternating compressive and tensile materials, a strain-balanced stack of quantum well and barrier layers can be grown, defect free, providing absorption-edge / lattice parameter combinations that are inaccessible using bulk materials. The high purity of the semiconductor material leads to radiatively dominated recombination enabling further efficiency gain by controlling the optical losses. When using compressively strained quantum well material, a small but fundamental efficiency advantage is realised over conventional bulk semiconductor solar cells on account of suppressed radiative emission from the light hole band. As a result, a strain-balanced GaAsP/InGaAs quantum well solar cell recently attained a power conversion efficiency of 28.3%. In addition, optical coupling between sub-cells enables spectrally tolerant multi-junction solar cells to be made.

The quantum well solar cell has recently gained acceptance as a viable component for multi-junction solar cells. In 2009, a single junction GaAsP/InGaAs quantum well solar cell attained a peak efficiency of 28.3% under solar concentration. Since then InGaP/MQW/Ge quantum well devices have attained efficiencies in excess of 40% under concentration [1] and over 30% under AM0 [2]. The principle motivation for incorporating a quantum well stack into a multi-junction solar cell is to increase the photocurrent delivered by the middle junction over the conventional $In_{0.01}GaAs$ bulk junction. This enables additional current to flow through the top and middle cells, resulting in a sharp rise in efficiency. However, there is also an opportunity to explore the radiative recombination loss in the quantum well solar cell.

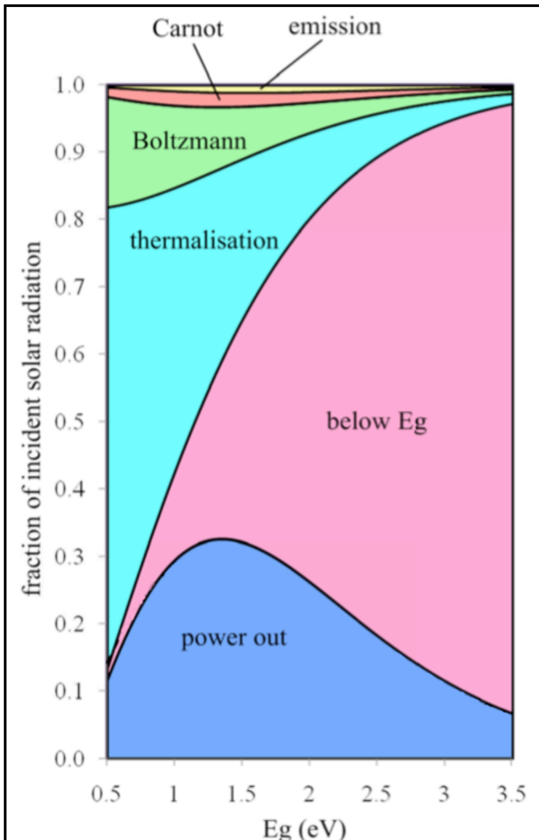

Figure 1: Breakdown of the Shockley Queisser efficiency limit into component losses [3].

All single junction solar cells are ultimately limited by the Shockley-Queisser limit, shown in figure 1 [3]. The well understood trade-off between the transparency of the solar cell (below Eg loss) and heat generation (thermalisation loss) are clearly apparent. A single junction quantum well device can do little to mitigate these two losses. However, there are three further losses, two are thermodynamically inescapable, the Carnot loss and radiative loss, but the third, the Boltzmann loss can be addressed. This Boltzmann loss arises through the generation of entropy upon radiative recombination. Sunlight is received with an étendue of Ω_{abs}, occupying a restricted number of optical modes. In the standard Shockley-Queisser efficiency analysis, radiative recombination proceeds internally over a much larger optical étendue, hence filling a much larger number of optical modes. This expansion of the photon gas in phase-space results in entropy generation and a voltage loss that scales as kT $\ln(\Omega_{emit}/\Omega_{abs})$ [4].

Owing to strain induced splitting of the light and heavy hole valance band in strained quantum wells, it is possible to achieve strongly polarised electroluminescence from the QW device. In strain-balanced GaAsP/InGaAs MQW structures, strongly polarised lateral emission has been observed, with the consequence that the radiative loss from this quantum well device will be lower than that of an otherwise equivalent bulk control cell [5]. It should be emphasised that this result is not due to quantum confinement, but rather the fact that the dominant source of radiative recombination, the InGaAs QW, is biaxially compressively strained. This is only possible on the nanoscale, since growing thick strained layers results in strain relaxation and the loss of valance band-splitting that leads to the anisotropy in emission. A full recovery of the Boltzmann loss will lead to approximately 9% points increase in absolute efficiency. Since the strained quantum well only suppresses one polarisation of laterally propagating light, the effect leads to a modest improvement in single junction devices, estimated at 0.12%. The effect is therefore of minor benefit for single junction devices.

However, in a multi-junction device, to maintain high power conversion efficiency in all sub-cells, it is important to ensure that all junctions remain as closely current matched as possible. Ordinarily the radiative coupling between sub-cells is relatively small under normal operating conditions [6] but in quantum well devices this has been shown to be surprisingly large. Figure 4 shows the observed photon coupling ratio for an InGaP/InGaAsP QW top cell and a GaAsP/InGaAs bottom cell, indicating some remarkably high coupling ratios between the upper and lower sub-cells [7]. This arises since the QW emission is unlikely to be re-absorbed in the thick base layer of the top-cell and the internal emission anisotropy helps direct light into upward and downward propagating modes, rather than propagating laterally. This optical coupling can be exploited to yield a spectrally tolerant multi-junction solar cell. If the upper sub-cell is designed to be current rich under normal operating conditions, it will operate at a marginally higher bias than optimal, resulting in significant radiative recombination. If a large fraction of this radiative emission from the top-cell is coupled into the bottom cell, then the current mismatch between the cells becomes less. If the top-cell suffers a loss in current, that might otherwise result in it becoming current limiting, for example increased aerosol loading of the atmosphere, the top cell current will drop towards the optimum operating point, reducing the radiative loss to the bottom cell and thereby lowering the optimal current that needs to be matched in the device. By enabling radiative coupling between sub-cells, the multi-junction solar cell can adjust dynamically to varying conditions [8].

References

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