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# MULTIPLE QUANTUM WELL TOP CELLS FOR MULTIJUNCTION CONCENTRATOR SOLAR CELLS

K. -H. Lee<sup>1,2</sup>, K. W. J. Barnham<sup>1,2</sup>, B. C. Browne<sup>1</sup>, J. P. Connolly<sup>3</sup>, J. G. J. Adams<sup>1</sup>, R. Airey<sup>4</sup>, N. J. Ekins-Daukes<sup>1</sup>, M. Führer<sup>1</sup>, V. Rees<sup>2</sup>, M. Lumb<sup>2</sup>, A. L. Dobbin<sup>2</sup>, M. Mazzer<sup>2,5</sup>, J. S. Roberts<sup>2,4</sup>, and T. N. D. Tibbits<sup>2</sup>

<sup>1</sup>Experimental Solid State Physics, Physics Department, Imperial College London, London, SW7 2BW, U.K.

<sup>2</sup>QuantaSol Ltd, 14, Kingsmill Business Park, Kingston upon Thames, Surrey, KT1 3GZ, U.K.

<sup>3</sup>Nanophotonics Technology Center, Universidad Politécnica de Valencia, 46022, Valencia, Spain

<sup>4</sup>EPSRC National Centre for III-V Technologies, Sheffield, S3 7HQ, U.K.

<sup>5</sup>CNR-IMEM Parma, 43124 Parma, Italy

## ABSTRACT

High efficiency quantum well GaAs solar cells have been successfully applied in commercial multi-junction concentrator cells to increase the absorption in the infrared and provide variability of the absorption edge to optimise energy harvesting. Multiple quantum well (MQW) top cells can further improve the performance of multi-junction solar cells since the absorption edge of top and middle subcells can be tuned with the MQWs to maximize the efficiency. Our simulations show that photon coupling resulting from the radiative dominance of the MQW top cell can make the multi-junction cell less sensitive to variations in the incoming spectrum, thus further improving energy harvesting. New results on the characterization of a novel MQW top cell will be presented along with electro- and photo-luminescence studies relevant to the photon coupling.

## INTRODUCTION

Strain-balanced quantum well middle cells provide many advantages over conventional bulk middle cells, including the ability to extend the absorption edge further towards infrared region and the flexibility to optimize the absorption edge for different spectrum conditions [1]. QuantaSol Ltd successfully commercializes triple-junction concentrator cells based on strain-balanced quantum well middle cells. Recently, cross-wafer median efficiencies of QuantaSol's production cells have achieved 40%. Theoretical modeling results also show that triple-junction cells with quantum well middle cells have higher energy yields than bulk 3J cells with similar external quantum efficiencies [2].

Top cells with multiple quantum wells can further benefit the efficiency of multiple junction solar cells in a number of ways. They make it possible to independently optimize the absorption edge of both top and middle cell to maximize the efficiency. Furthermore, the radiative dominance of the top cell enhances photon coupling between subcells, which makes the multi-junction cell less sensitive to variations in the incoming spectrum and operating temperature [3].

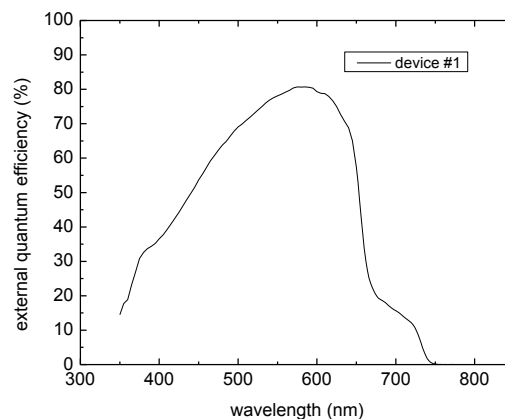
In this paper, we will first present the characterization results of a novel MQW top cell and in particular discuss

its radiative efficiency. We then show the results of simulation results of dual MQW triple-junction solar cell efficiencies by considering photon coupling. Then, we will report experiment results on dual-MQW tandem devices and direct measurements of photon coupling from electro- and photo-luminescence.

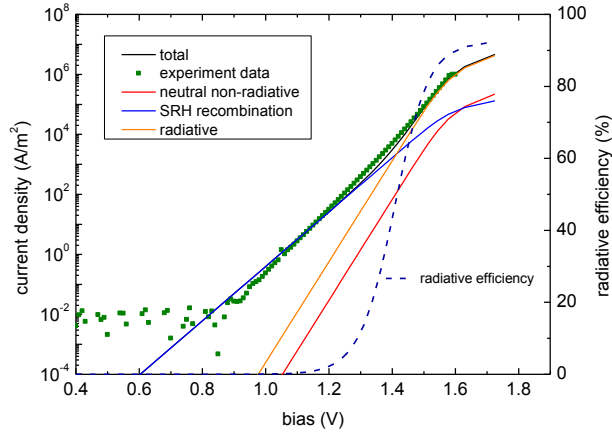
## NOVEL MQW TOP CELL

The MQW top cells in this study are grown at the University of Sheffield and QuantaSol. The bulk regions of the top cell are of a conventional p-on-n GaInP design with a GaInP i-region. The shallow quantum wells are novel, as they consist of quaternary GaInAsP in an essentially lattice matched combination which is immiscible in the bulk. We obtain wells of thickness around 4 nm with high material quality under appropriate growth conditions.

Figure 1 shows the measured and modelled [1] (or reference Escorial paper see email) external quantum efficiency (EQE) and Figure 2 is measured and fitted dark-IV of the same device. This device has 22 shallow wells. As shown in Figure 1, the absorption edge the top cell is extended to around 740nm. In Figure 2, different contributions of modelled dark-IV are plotted. The level of the radiative contribution to the dark-current is a prediction based on the fit to the EQE in the quantum well as explained in Refs. [1] and [3]. The agreement with the data suggests that the device becomes radiatively dominant in the high bias region.



**Figure 1 Measured MQW top cell quantum efficiency**



**Figure 2 Measured and simulated MQW top cell dark current**

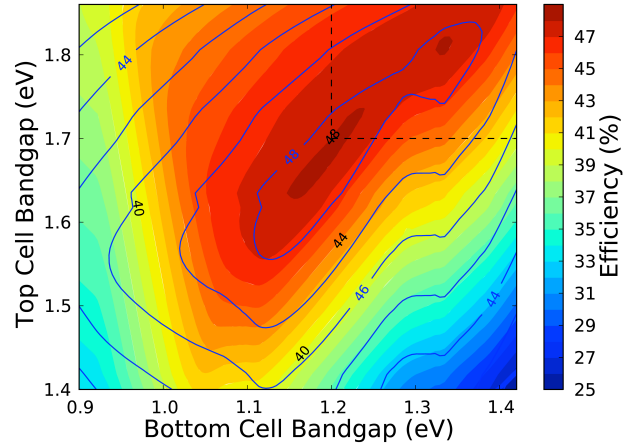
### PHOTON COUPLING IN DUAL-MQW DEVICES

#### MODELING PHOTON COUPLING

Photon coupling between subcells in a multi-junction device has been discussed [4]. However, a MQW top cell can make photon coupling more significant than in conventional bulk multi-junction devices. In a multi-junction cell with an MQW top cell, radiative recombination may dominate over other contributions to the dark current in the top cell as observed in the last section. The top cell emitter, base and tunnel junctions are transparent to the photons radiated by the top cell quantum wells. For this reason, more photons will be absorbed by the bottom cell. As a result, photon coupling needs to be taken into account when predicting the performance of MQW multijunction solar cells.

The calculation of photon coupling is based on the detailed balance approach proposed by Nelson [5]. Figure 3 shows the efficiency contour plot of triple junction GaInP/InGaAs/Ge dual-MQW solar cells. The colored contours assume no photon coupling. To reach the optimum efficiency of bulk triple-junction devices, the band gaps of both the top and middle subcells must be lower than the band gaps in lattice-matched top and middle subcells [6]. One conventional approach to achieving lower band gaps is upright metamorphic growth, which can only be extended further by introducing additional defects and dislocations in the device. However, with MQWs in both top and middle subcells, the absorption edge of these junctions can be independently optimized within the dashed rectangle in Figure 3. The blue lines in Figure 3 are iso-efficiency contours calculated by taking photon coupling into account. It indicates that a radiatively dominated MQW multi-junction solar cell can potentially reach a higher efficiency than bulk metamorphic multi-junction devices. The wide area inside the 48% blue contour line also suggests that dual-MQW solar cells are

less sensitive to variation of the incoming spectrum, which results in more efficient energy harvesting than bulk multi-junction devices.



**Figure 3 Calculated efficiency contours of dual-MQW triple-junction solar cells assuming bulk QE of 100% and MQW quantum efficiency of 60% in the top cell and 40% in the middle cell and an AM1.5-AOD spectrum(?). Color contours are calculated efficiencies without considering photon coupling, while blue lines are efficiencies with the effect of photon coupling considered**

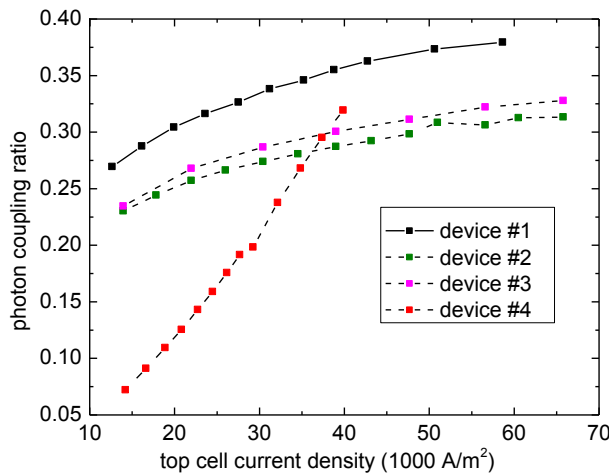
#### PHOTON COUPLING MEASUREMENT

The idea of this photon coupling experiment is producing photoluminescence in the top cell at a given applied bias and subsequently using the bottom cell as a photodetector to measure the photons coupled into it. Three terminal dual-junction devices with additional terminals between top and bottom junction were fabricated allowing subcell to be biased independently. These three-terminal devices are InGaP/GaAs dual junction cells with MQWs in each subcell. The polarity of one junction is inverted and only a highly-doped n-type lateral conduction layer is grown between the top and bottom junction.

In this experiment, we use photoluminescence to generate radiative recombination in the top cell. The bottom cell will then absorb the re-emitted photons from the top cell. The top cell is illuminated by a Spectra Physics Millennia V neodymium vanadate laser capable of producing up to 5.5 W at 532 nm. The intensity of the beam is only  $10^{-11}$  of its original intensity when it reached the surface the bottom cell. Under the same laser intensity, we first measure the short-circuit current of top cell  $I_{TOP}$ , then we keep top cell open and measure the short circuit current of bottom cell. Hence the dark current component coupled into the bottom cell is equal to the ratio  $\eta_{COUP} = I_{BOT}/I_{TOP}$ . This test is repeated with different laser intensity. The radiative efficiency of the top cell can also be obtained from  $\eta_{COUP}$  if the factors of photons collected by the bottom cell and bottom cell quantum efficiency are known. As a result,

$\eta_{\text{COUP}}$  should be proportional to radiative efficiency ideally. This method can also be extended to standard two-terminal dual junction devices. We illuminate the two-terminal devices with the same laser and measure the short-circuit current of the device. In this case, the top cell will be operated at a voltage  $V_{\text{TOP}}$  which is close to its open-circuit voltage because of strong current mismatch between top and bottom cells. The voltage of the bottom junctions becomes  $-V_{\text{TOP}}$ . If the bottom cell is not seriously shunted and has reverse breakdown voltage lower than  $-V_{\text{TOP}}$ , the current at  $-V_{\text{TOP}}$  will be equal to short-circuit current. This can be checked by varying the bias of the dual-junction device under illumination. If the measured current is not constant when the bias is shifted few hundred millivolts from zero point, then the cell is not suitable for this test. The top cell short-circuit current  $I_{\text{TOP}}$  under the same illumination can be estimated by two methods. The first one is measuring  $I_{\text{TOP}}$  with the single junction top cell with same layer structure of the dual-junction top cell. The other one is calculating  $I_{\text{TOP}}$  by measured top cell QE in the dual-junction cell and known laser intensity. This method will slightly underestimate  $\eta_{\text{COUP}}$  because the operating voltage of the top cell is lower than its open-circuit voltage.

Figure 4 shows  $\eta_{\text{COUP}}$  against top cell current density of several different devices. For clarity, the results of two-terminal dual-junction devices are plotted in dashed lines. Some key parameters of these test devices are shown in Table 1. This graph shows that the coupling ratio of device#1, #2 and #3 have very similar trends with the calculated radiative efficiency shown in Figure 2, which is expected. However, the coupling ratio of device#4 has steeper increase in the same range. This may be due to different MQW designs or strong dominance of non-radiative recombination in device#4. This experiment will then be used to calibrate the model described in previous section and optimize multijunction devices by considering photon coupling.



**Figure 4 Photon coupling ratio against top cell current density. The solid line indicates the result of a three**

**terminal device, while the dashed lines shows the result of two-terminal devices.**

device	Terminals	MQW well number	Emitter	Base
			(thickness(nm)/doping density (cm <sup>-3</sup> ))	
#1	3	20	100/1E18	570/1E17
#2	2	40	50/undoped	
#3	2	37	50/undoped	
#4	2	15	100 /5E18	1000/1e17

**Table 1 Details of the dual-junction devices used in the photon coupling experiment. The emitter and base in this table are all InGaP.**

## REFERENCES

- [1] K. W. J. Barnham, I. M. Ballard, B. C. Browne, D. B. Bushnell, J. P. Connolly, N. J. Ekins-Daukes, M. Führer, R. Ginige, G. Hill, A. Ioannides, D. C. Johnson, M. C. Lynch, M. Mazzer, J. S. Roberts, C. Rohr and T.N.D. Tibbitts, Chapter 5, in *Nanotechnology for Photovoltaics*, ed: Loucas Tsakalakos, CRC Press, (2010).
- [2] M. Lumb et al., "Comparing the Energy Yield of (III-V) Multi-Junction Cells with Different Numbers of Sub-Cells", *6<sup>th</sup> International Conference on Concentrating Photovoltaic Systems*.
- [3] K. W. J. Barnham et al., "Photonic Coupling in Multi-Junction Quantum Well Concentrator Cells", *25th European Photovoltaic Solar Energy Conference and Exhibition Proceedings*, p234
- [4] C. Baur et al. "Effects of optical coupling in III-V multilayer systems", *Appl. Phys. Lett.* **90**, 2007, pp. 192109-192109-3
- [5] J. Nelson, "Observation of suppressed radiative recombination in single quantum well p-i-n photodiodes". *Journal of Applied Physics.* **82**, 1997, pp.6240-6246
- [6] R. R. King et al., "40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells" *Appl. Phys. Lett.* **90**, 2007, pp. 83516-183516-3
- [7] M. A. Steiner et al., "A monolithic three-terminal GaInAsP/GaInAs tandem solar cell." *Prog. Photovolt: Res. Appl.* **17**, 2009, pp. 587-593