Institution: Imperial College London

Unit of Assessment: 9 Physics

Title of case study: P4 – The commercialisation of highly efficient photovoltaic solar cells

1. Summary of the impact (indicative maximum 100 words)

The quantum well solar cell (QWSC) was invented, developed and patented by the Quantum Photovoltaics (QPV) research group at Imperial. QuantaSol was spun out of Imperial college in 2007 and was awarded Guardian CleanTech Top 100 awards in 2008 and 2009. In May 2009 it received £1.35m of funding from a syndicate of investors. In 2011 QuantaSol was bought by JDSU, a leading US semiconductor manufacturer, for US $3.7million. The quantum well (QW) technology developed by the QPV group enabled QuantaSol, and subsequently JDSU, to manufacture QWSCs with efficiencies above those of the then market leaders, Spectrolab and Solar Junction. Uniquely, QWs will allow JDSU to optimise cells for maximum energy harvest in different solar spectra. This will increase world-wide the beneficiaries of concentrator technology and enable other low-carbon applications in building integration and electric transport. The Imperial research has thus had (i) economic impact through the adoption of improved technology and (ii) environmental impact through the take up of QWSCs by JDSU.

2. Underpinning research (indicative maximum 500 words)

The QWSC was invented by Keith Barnham and Geoff Duggan in 1989 (1990, J. Appl. Phys, **67**, 3490). Quantum wells (QWs) enhance efficiency by making it possible to optimise the wavelength at which the cells absorb sunlight. The basic idea was patented [US patent No. 5,496,415] and a number of versions of the cell were developed in over 2 decades of research supported by EPSRC [e.g. G1, G2], the EU and the Greenpeace Trust.

In 1991 the Quantum Photovoltaic (QPV) group at Imperial first demonstrated that incorporating QWs into a cell enhances the efficiency compared to a control cell without wells (1991, Appl. Phys. Lett., 59, 135). From 1990 to 2009 the underpinning device physics of QW solar cells was researched and a simulation programme SOL developed to model QWSC performance [1]. This work was reviewed in an invited chapter in a definitive textbook on the uses of nanotechnology in photovoltaics (Nanotechnology for Photovoltaics, ed. Loucas Tsakalakos, CRC Press, 2010).

A key research insight for the commercialisation of this technology came in 1999 when the strain-balanced QWSC was invented at Imperial and grown successfully by collaborators at the EPSRC National Centre for III-V Technology at the University of Sheffield [2]. This version of the cell is protected by a U.S. patent which is exclusively licensed by Imperial Innovations to JDSU [P1]. The significance of this research is that the band-gap energy of GaAs is higher than optimal. Competitors lower the band-gap by growing an alloy InGaAs which has a bigger atomic separation than GaAs. This introduces dislocations which reduce device performance. The strain-balanced QWSC approach introduces the InGaAs alloy as few nm wide QWs separated by wider barriers formed from the alloy GaAsP which has a narrower atomic spacing. The approach which balances the stress at the well-barrier interfaces was worked out at Imperial and formed the basis of the patent [3, P1].

The complete absence of dislocations in a strain-balanced QWSC means that the recombination of carriers is reduced. The unavoidable radiative recombination back into photons dominates. In a QW cell even this loss can be overcome by reflecting these photons back into the cell. The QPV group demonstrated the advantages of photon-recycling in a solar cell for the first time [4].

A second key research insight for the commercialisation and the breadth of potential beneficiaries was the discovery of a second radiatively efficient QW system suitable for the GaInP top sub-cell of the triple-junction. Experiments at Imperial showed that QWs made from a quaternary alloy GaInAsP in GaInP barriers had much better quality than other options. This was an unexpected research insight as the quaternary alloy has very poor crystal quality in bulk quantities. However, the QPV group demonstrated that nm wide QWs on this alloy had high radiative efficiency. On the basis of the experimental results from Imperial, John Roberts the crystal grower at Sheffield applied for a patent (US 20110180129 A1).

The breadth of the beneficiaries of this research has been greatly extended by this new QW system. QWs in the top and middle sub-cells make it possible to optimise the wavelengths at which both the top and middle cells absorb sunlight. Hence dual-QW cells have the unique advantage of being able to tune the cell for different spectra to be found in different locations and in other low-carbon applications. Another unique advantage of the top sub-cell wells is that the radiative recombination coupled from the top to middle sub-cells cell will reduce sensitivity of the multi-junction cell to spectral and temperature variation, greatly extending the breadth of beneficiaries of this technology [5].

Key researchers at Imperial: Keith Barnham (Senior Lecturer, Reader, Professor, Emeritus Professor), Ian Ballard (RA 2000 – 2007), James Connolly (RA 2000 – 2004, 2006 - 2008), Ned Ekins-Daukes (RA 1999 – 2003, Lecturer 2008 to date), Massimo Mazzer (CNR Fellow, Visiting Professor, 2002 – 2008), Carsten Rohr (RA 2001 - 2006)

3. References to the research (* References that best indicate quality of underpinning research)

[1] *M. Paxman, J. Nelson, B. Braun, J. Connolly, K.W.J. Barnham, C.T. Foxon, and J.S. Roberts., "*Modelling the Spectral Response of the Quantum Well Solar Cell*", J.Appl. Phys., 74, 614, (1993). DOI, **78 citations (on 02/10/13)**

[2] *N.J. Ekins-Daukes, K.W.J. Barnham, J. P. Connolly, et al., "*Strain-balanced GaAsP/InGaAs quantum well solar cells*", Appl. Phys. Letters, 75, 4197, (1999). DOI, **122 citations (on 02/10/13)**

[3] *N.J. Ekins-Daukes, K. Kawaguchi and J. Zhang, "*Strain-balanced criteria for Multiple Quantum Well Structures and its signature in X-ray rocking curves*", Crystal Growth and Design, 2, 287, (2002), DOI, **66 citations (on 02/10/13)**

[4] D.C. Johnson, I.M. Ballard, K.W.J. Barnham, J.P. Connolly, and M. Mazzer et al., "*Observation of photon recycling in strain-balanced quantum well solar cells*", Appl. Phys. Letters, 90, 213505, (2007), DOI, **21 citations (on 02/10/13)**

[5] Kan-Hua Lee, K.W.J. Barnham et al., "*Demonstration of Photon Coupling in Dual Multiple-Quantum-Well Solar Cells*", IEEE Journal of Photovolatics, 2, 68, (2012). DOI, **4 citations (on 02/10/13)**

Patents

[P1] US 7,868,247 B2, "Photovoltaic Device", granted 11-1-2011, Inventors: Ian M. Ballard, Keith W.J. Barnham, James P. Connolly, Nicholas Ekins-Daukes, Massimo Mazzer, Carsten Rohr

Grants:

[G1] EPSRC, EP/F008589/1, 'Proof of Concept for enhancing single-junction and tandem concentrator cells by photon recycling', PI: KWJ Barnham, 01/08/07-31/07/08, £70,003

[G2] EPSRC, EP/D059860/1, 'Development of a Novel Tunnel-junction-free Concentrator Cell and its Evaluation for a Smart Windows Application', PI: KWJ Barnham, 13/03/06-12/03/10, £528,488

4. Details of the impact (indicative maximum 750 words)

The first commercial impact of the research came when the Imperial-spin out QuantaSol was formed in 2007 by Keith Barnham, Massimo Mazzer (a visiting Professor at Imperial) and John Roberts (EPSRC National Centre for III-V Technology). QuantaSol's aim was to exploit QW technology in multi-junction concentrator cells. The company was funded by Imperial Innovations and the Low Carbon Accelerator. It was located in Kingston-upon-Thames and employed between 12-16 people. In May 2009 it was announced that QuantaSol had received £1.35m of investment from a syndicate of investors including the Low Carbon Accelerator, Imperial Innovations, Numis

Securities Ltd and Netscientific Ltd [A]. The first performance impact of the new company came in June 2009. For six months the company broke and held a 21-year-old world record for a single junction concentrator cell with 28.3% efficiency at 534 times concentration, verified by the Fraunhofer ISE [B, C]. This "*new generation of 'nano-structured' millimetre-sized solar cells…could convert the sun's energy to electricity more than twice as efficiently as current technology, [and] can be tuned to the prevailing light conditions of a particular place, to get the most out of the cells wherever they are*" [C]. Commenting on the world record Kevin Arthur, QuantaSol's CEO, said "*Our technology is the industry's best kept secret. This is the first time that anyone has successfully combined high efficiency with ease of manufacture, historically a bug-bear of the solar cell industry*" [C]. The potential commercial and environmental impact of QuantaSol was recognised by the award of the Guardian CleanTech Top 100 company status in both 2008 and 2009 [D, E].

In late 2010 QuantaSol first manufactured triple junction cells with strain-balanced QWSCs in the middle sub-cell. A median efficiency of 39.7% was achieved for 171 cells on a production wafer [F], comparable with the performance of cells from the market leader Spectrolab [G]. It was clear that the strain-balanced QWSC was responsible for this enhanced performance as a control wafer without the quantum wells had a median efficiency of only 36.3% [F].

In 2011 the QuantaSol triple-junction cells passed technical qualification with Amonix, the leading US concentrator manufacturer, who qualified them for "*commercial deployment*" [H] in their high concentration systems. The only other concentrator cell manufacturer to achieve this status by 2011 was Spectrolab. As a result QuantaSol received a substantial order from Amonix of 1MW of concentrator cells (approx. 50,000 cells) [H]. Amonix report that "*the QuantaSol design was better matched to Amonix specifications than any other cell design we have evaluated to date*" [H].

A further significant performance impact of the QuantaSol cells was reported by Amonix in December 2011 [I]. They field tested cells from six suppliers including QuantaSol. The depth of the quantum wells in the QuantaSol cells had been optimised for the Amonix target solar spectrum. Fig. 12 in their paper [I] presents the ratio of currents in top and middle cell for field tests in six locations in the south-west of the US. These ratios were closer to unity in the QuantaSol case (vendor 3) than in the case of the other five vendors. The unity ratio corresponds to the highest efficiency performance, confirming the advantage of the QWSC to optimise for maximum energy harvest in different locations.

QuantaSol was sold to JDSU, a leading US semiconductor manufacturer, in July 2011. The 2012 Annual Report from JDSU reported "*the acquisition of critical product design, patented intellectual property and other assets from QuantaSol, for a cash purchase price consideration of approximately $3.7 million*" [J]. Alan Lowe, President of JDSU's CCOP unit, said of the purchase: "*Incorporating key QuantaSol technology will allow us to further differentiate our products and expand our position in the CPV solar market as popularity for CPV continues to grow*" [K]. All IP generated by Imperial and QuantaSol research passed to the ownership of JDSU. The most important of these for the 40% triple junction cell was licensed by Imperial Innovations exclusively to QuantaSol [P1]. Under the terms of the sale this patent will now be licensed to JDSU with Imperial Innovations to accrue royalties from it.

The next performance milestone of the strain-balanced QWSC came at the 4th International Concentrator Photovoltaic (CPV) Workshop in China in September 2012. Jan-Gustav Werthen of JDSU announced that the company manufacture cells on larger than standard wafers with median efficiency 41.5% [L]. These cells have significantly higher efficiency performance than Spectrolab cells, the market leader in CPV and a Boeing subsidiary. The data sheet on the Spectrolab web-site claim that their CPV cells on standard sized wafers have a "typical efficiency" of 40% [G].

A significant commercial impact of the strain-balanced QWSC is revealed by the current JDSU data sheet [M]. This shows results from 1160 cells nearly all of which had cell efficiency above 40%. The spread in efficiency is remarkably small considering that this was the first report of quantum well cells grown on wafers with more than double the area of the standard wafer. The uniform performance is important as many cells are connected in series in concentrator systems. The larger wafer size will also impact by reducing cell costs.

As reported in Section 3, research by the QPV group in collaboration with Sheffield in the period 2007 – 2011 underpinned another advantage for QuantaSol [Patent US 20110180129 A1]. Quantum wells in the quaternary material GaInAsP lattice matched to the GaInP of the top cell were developed. This QW system turned out to have unexpectedly high radiative efficiencies. The performance impact of this further Imperial research was demonstrated in a JDSU presentation in 2013 where they announced a further 1% absolute efficiency increase in production cells by incorporating quaternary QWs in the top sub-cell [N]. The wafer average of 42.5% makes JDSU the manufacturer of the world's highest efficiency production cells. At the same meeting Solar Junction, who hold the record for research cell efficiency, reported a median efficiency of 41.9% for their production cells [O]. Additionally QWs in both the top and middle cell make it possible to independently optimise both top and middle cell absorption edges, which cannot be done with conventional cells. Hence it will be possible to maximise energy harvest as spectral conditions and cell temperature vary during the day and over the year. This will extend the range of beneficiaries of CPV technology outside the southwest US, potentially world-wide and also enable novel low carbon applications of CPV such as in building integration and powering electric cars [F].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Growing Business article, 'QuantaSol shines through in £1.35m deal', 7/5/09, http://www.growingbusiness.co.uk/quantasol-shines-through-in-1-35m-deal.html (archived at https://www.imperial.ac.uk/ref/webarchive/mpf%20 on 31/7/2013)
[B] Calibration Certificate (serial number 60-420-120-h3), Fraunhofer ISE, Germany, 24/3/09. Confirms 28.3% efficiency of GaAs solar cell (available here)
[C] World Record Academy, 'Most efficient single junction solar cell - QuantaSol sets world record', 4/7/09, http://www.worldrecordacademy.com/technology/most_efficient_single_junction_solar_cell-Quantasol_sets_world_record_90269.htm (Archived at https://www.imperial.ac.uk/ref/webarchive/hpf on 31/7/13)
[D] Guardian CleanTech awards 2008, http://www.guardian.co.uk/environment/table/2008/sep/18/cleantech100fulllist.cleantechnology100 (Archived at https://www.imperial.ac.uk/ref/webarchive/jpf on 31/7/13)
[E] Guardian CleanTech awards 2009, http://www.guardian.co.uk/globalcleantech100/profiles-71-80 (Archived at https://www.imperial.ac.uk/ref/webarchive/kpf on 31/7/13)
[F] Compound Semiconductor Magazine, March 2011, p.32 (available here)
[G] Spectrolab, Inc data sheet: "CPV Point Focus Solar Cells, C4MJ Metamorphic Fourth Generation CPV Technology", Oct 2011 (available here)
[H] Letter from Senior Director of R&D, Amonix, Inc., 30/4/12 (available from Imperial on request)
[I] G.S. Kinsey et al., "Increasing Power and Energy in Amonix CPV Solar Power Plants", IEEE J. of Photovoltaics, 1, 213, (2011). DOI
[J] JDSU 2012 Annual Report and Form 10-K, Acquisitions, page 17, http://yahoo.brand.edgar-online.com/displayfilinginfo.aspx?FilingID=8790066-13893-75735&type=sect&dcn=0001047469-12-008496 (archived at https://www.imperial.ac.uk/ref/webarchive/qpf%20 on 1/8/2013)
[K] JDSU press release, 7/7/11, http://www.jdsu.com/News-and-Events/news-releases/Pages/JDSU-Acquires-Critical-Assets-from-QuantaSol-for-CPV-Solar-Offering.aspx (archived at https://www.imperial.ac.uk/ref/webarchive/spf on 5/8/13)
[L] JDSU Powerpoint presentation at "1st CPC China & 4th International CPV Workshop", Sept 2012. Slide 16 gives the cell efficiency (available here)
[M] JDSU Photovoltaics data sheet: "41% Multiple Quantum Well CPV Cells on 150 mm Wafers", Sept 2012 (available here)
[N] JDSU Powerpoint presentation at CPV9 Miyazaki Japan, Apr 2013, slide 15 (available here)
[O] Solar Junction Powerpoint presentation at CPV9, Miyazaki Japan, Apr 2013, slide 16 (available here)