Institution: University of Surrey

Unit of Assessment: UOA 9 Physics

Title of case study:

Commercial exploitation of strained semiconductor alloys in communications, energy efficiency and consumer electronics

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

Surrey's Photonics Group has played a pivotal role in understanding and developing compound semiconductors for use in photonic devices. The strained-layer quantum well technology proposed and developed in their research is now incorporated in the vast majority of CD, DVD and blu-ray systems, in telecommunications and the internet, in computer mice, and in LEDs for solid-state lighting. Strained-layer quantum well lasers are manufactured by industry in their millions annually with a market value estimated in 2009 to be €15bn. Compared to the alternatives; these lasers offer greater efficiency, which has opened up new applications.

The Group's research has expanded to develop semiconductors for use in energy generation and combatting climate change, and in novel photovoltaics, low energy internet communications, and greenhouse gas detection. The research has led to engagement with the UK government's energy minister and has stimulated public discussion around the world.

2. Underpinning research (indicative maximum 500 words)

One of the key achievements of the underlying research can be traced back to the mid-1990s when the idea of Prof. Alf Adams, FRS, for using strained layers in quantum well lasers was verified theoretically and experimentally [1]. Prof. Adams and Prof. Eoin O'Reilly (who left the University in 2000) showed that by deliberately incorporating a thin semiconductor layer (*i.e*. a quantum well) with different lattice constant to the host crystal substrate, the resulting strain would bring a number of enhanced optical properties. These properties make lasers, optical amplifiers and other optoelectronic components more efficient and faster in operation. Strained-layer devices were demonstrated commercially by Philips, working with Surrey researchers, and extended to applications in high power laser diodes for manufacturing and printing. Adams extended the idea of using strain from lattice mismatch to create non-absorbing mirrors in high power lasers, as was described in a patent [2].

More recently, under the direction of Prof. Stephen Sweeney, the Photonics Group has made large inroads into developing alternative III-V material approaches for high efficiency lasers. They demonstrated that 1550 nm InGaAlAs quantum well buried heterostructure lasers offer superior high temperature performance [3]. Other research, in collaboration with Dr Andreev (senior lecturer in the Photonics Group), described how p-doping in InAs/GaAs quantum dots imparts improved temperature stability in semiconductor lasers [4].

Research on quantum well lasers, published by the Group in 1999, showed that even in the best strained-layer quantum well lasers, the efficiency is governed by non-radiative Auger processes involving the spin-orbit band [5]. This finding led to work on new materials where the spin-orbit splitting energy could be increased to remove the Auger processes. Recently, another patent has been published by the Group [6] on an entirely new class of III-V semiconductor (based on bismuth alloys), which provides an optimised band structure offering power savings of 80% due to loss suppression. The inclusion of bismuth in a III-V material increases the spin-orbit splitting energy whilst reducing the band gap. When the spin-orbit splitting energy exceeds the band gap energy, the major Auger processes are inhibited, thus reducing the sensitivity of lasers to changes in ambient temperature. Initial experimental evidence that this concept can be achieved in practice was recently reported [7].

In parallel, the Photonics Group has been working closely with EADS-Astrium to develop new semiconductor materials for photovoltaics to capture solar energy in space. Highly efficient (>43%) photovoltaic cells have been designed and tested at Surrey and are part of a pilot programme to develop space-based solar power. This collaborative research has formed the basis of a European Space Agency pilot study involving Surrey to develop a fully working prototype.

3. References to the research

1. E. P. O'Reilly and A. R. Adams, "Band-structure engineering in strained semiconductor lasers", *IEEE Jour. Quant. Electr*. **30**, pp 366-379 (1994) **DOI**: http://dx.doi.org/10.1109/3.283784.

   This is one of the first papers theoretically and experimentally verifying Surrey's strained-layer concept which now appears in almost every semiconductor laser and LED produced in the world today.

2. A. R. Adams et al."Semiconductor diode laser and method of manufacturing same", US Patent 5,956,359 (1999). See: http://www.google.com/patents/US5956359.

   This patent describes a method for using strain to create non-absorbing mirrors. This method is now implemented in high power pump lasers for telecommunications.

3. S. A. Sayid, *et al.* "Thermal Characteristics of 1.55 μm InGaAlAs Quantum Well Buried Heterostructure Lasers", *IEEE Jour. Quant. Electr.*, 5, pp 700-705 (2010). **DOI:** http://dx.doi.org/10.1109/JQE.2009.2039117

4. I. P. Marko, et al. "Carrier Transport and recombination in p-doped and intrinsic 1.3 μm InAs/GaAs quantum dot lasers", *Applied Physics Letters* (2005) **87**, 211114 (3 pages) **DOI**: http://dx.doi.org/10.1063/1.2135204 (51 citations)

5. A. F. Phillips, S. J. Sweeney, A. R. Adams and P. J. A. Thijs, "The temperature dependence of 1.3- and 1.5μm compressively strained InGaAs(P) MQW semiconductor lasers", *IEEE Jour. Sel. Top. Quant. Electr*., 5, pp 401-412 (1999). **DOI**: http://dx.doi.org/10.1109/2944.788398 (127 citations)

6. S. J. Sweeney, "Light emitting semiconductor device," GB patent WO/2010/149978 and US patent 20,120,168,816. Available from: http://goo.gl/mHgBg

   This patent application describes how bismuth may be used to develop high efficiency photonic devices.

7. Ludewig *et al*., "Electrical injection Ga(AsBi)/(AlGa)As single quantum well laser," *Applied Physics Letters,* **102** (24), 242115 (2013). **DOI**: http://dx.doi.org/+10.1063/1.4811736

Funding

Prof. Adams and his collaborators held 14 EPSRC grants within the impact period starting in 1993. An EPSRC LINK grant "Strained Layer Semiconductor Materials" GR/G36142/01 (1991-94; valued at £207k) funded the research leading to ref. 1. Research on quantum wells and quantum dots has attracted significant investment through two Technology Strategy Board programmes (totalling £3.7M) from 2003 to 2011 and led to outputs in [4]. Other funding: €3M EU BIANCHO project (July 2011 - July 2014; see www.biancho.org) and £2M NSF/EPSRC/CRC/DPG Bismide Materials World Network project (Jan. 2011- April 2013; see www.bismides.net). Bismides research is also central to a £1M EPSRC Leadership Fellowship held by Prof. Sweeney (2010-2015).

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

Surrey research on the concepts of strained-layer devices has made a major economic impact. This impact was first achieved via close interaction with the electronics firm, Philips N.V. They were prepared to take the risk with what was considered at the time to be an unusual approach, and in 2000 they licensed the Surrey patent (ref. 2) on using strain to create non-absorbing mirrors. The technology proved to be superior to other approaches existing at the time for telecommunications applications. Philips (and later JDS) subsequently used the non-absorbing mirror concept in the development of high power pump lasers, which are used for optical amplification in telecommunications systems and to pump high-power fibre lasers, such as those used in manufacturing.

The disruptive nature of the strained-layer technology forced all of the other semiconductor laser manufacturers to adopt it. Dr. Andrew Carter, the Chief Technology Officer at Oclaro, one of the world's largest telecommunications companies, has stated that the Surrey research has "revolutionised aspects of the design" of optoelectronic devices [Source S1].

The majority of semiconductor-based photonics components now use strained-layer quantum wells as embedded technology, which represents a major economic impact of the research. According to Photonics21, the European task force for photonics, the global market for these components was around €15bn in 2009 and is expected to grow to >€30bn by 2015 [S2]. Furthermore, the component market levers much larger industries, *e.g*. telecoms services worth more than €2 trillion at current estimates [S2]. As evidence of the reach of the economic impact of the research, it is notable that almost all of the current known semiconductor laser technology incorporates the strained-layer concept developed at Surrey. Peter Selway, formerly the Director of Operations at Nortel, has explained: "The use of appropriately strained layers gives benefits in almost all aspects of the performance of semiconductor lasers, so much so that laser engineers routinely use strain to fine-tune the performance of virtually all lasers for all applications." [S3]

The strained-layer quantum well concept is now being employed in InGaN based solid-state lighting, which is starting to become the core for all future lighting technology. In this application, the ability to incorporate strain provides a method of optimising the emission wavelength of the InGaN LEDs used in solid-state lighting luminaires. The current market for lighting is worth €50bn and is expected to grow to €100bn by 2020. Strained-layer quantum well LEDs are expected to form a core aspect of this technology [S2]. The recently commercialised Philips LED lamp, which was the recipient of the U.S.A. Department of Energy's first-ever "L Prize" [S4], utilises strained quantum wells.

The new material reported in ref. 3 (Section 3) is now being implemented in distributed feedback (DFB) and tunable lasers for telecommunications by UK-based CIP and global telecoms giant, Oclaro, and is directly derived from Surrey's research in the TSB-sponsored ETOE and ETOE2 projects.

Prof. Sugawara (Fujitsu, Japan) made use of the results of Surrey research (ref. 4 in Section 3) when he set-up QD Laser Inc. to commercialise the technology of quantum dot lasers. Their 1.3 μm quantum dot lasers, which are currently commercialised, rely on p-doping to provide temperature insensitivity. The mechanism by which this insensitivity occurs and can be utilised was described in the Surrey research.

The Photonics Group's research in developing new semiconductor materials and devices for renewable energy has made an impact on society by capturing the public's attention and stimulating discussion. The research has received wide exposure in international publications for general audiences, such as *The Economist* [S5] (receiving >760 Facebook likes, >100 re-tweets on Twitter, and >30 direct comments from the public) and *National Geographic* [S6] (receiving >350 Facebook likes, >130 re-tweets on Twitter, >100 Google+ recommendations and 10 direct comments from the public). The research was also highlighted in national newspaper articles in *The Independent*, *The Observer* [S7] (>70 direct comments from the public), *The Sunday Times* [S8], the *Times of India* [S9], and more than ten trade journals in the solar cell community. A television feature was produced by RAI (Italy) for their Superquark popular science programme [S10], and a radio programme was broadcast by ORF Radio (Austria). The potential of Surrey's recent research on bismide materials to reduce the energy demands of the internet was featured in the *Financial Times* [S11].

The *Sunday Times* article led to a direct request by the UK's Energy Minister (Charles Hendry, MP) to visit the University to learn more about the emerging field of research on using solar energy from space. Mr Hendry commented: "The work that Prof. Sweeney of the ATI and his colleagues are doing makes us realise that the way we'll be generating electricity in 20 years' time is radically different to the way in which it's being done today" [S12]. This ministerial visit and statement attest the extent to which the Surrey activities are having an influence on policy-makers. In addition, impact on industrial policy is made via Sweeney's membership on Astrium's Photonics Strategy Group and contributions to the UK Roadmap in Optoelectronics.

5. Sources to corroborate the impact

[S1] Video of Dr. Carter available at: http://bit.ly/1cGUFSI

[S2] "Photonics – Our vision for a key enabling technology of Europe", European Technology Platform Photonics21, 2nd Edition, May 2011.

[S3] Former Director of Operations at Nortel. Contact details provided.

[S4] U.S.A. Department of Energy L Prize: http://www.lightingprize.org/

[S5] "Solar Power from Space: Beam it down Scotty", *The Economist*, 25th June 2011 (http://econ.st/1izbpQu).

[S6] "Beam it down, a drive to launch space-based solar power", *National Geographic Daily News*, 5th December 2011 (http://bit.ly/1fWbL1s).

[S7] "How Britain can rejoin the space race", *The Observer*, 3rd July 2011 (http://bit.ly/1h5VSZo).

[S8] "2021: a space power odyssey", *The Sunday Times*, 28th August 2011 (http://thetim.es/1bGA6UB).

[S9] "Solar Harvest", *Times of India*, 7th November 2011.

[S10] Superquark "Centrali Solari Orbitanti", RAI TV, July 2010. Available here: http://bit.ly/19HVNCr

[S11] "Laser redesign takes the heat off the internet", *Financial Times Magazine*, 13th July 2012 (http://on.ft.com/1ivAhIS)

[S12] "The Next Generation", *Total Politics Magazine*, Jan 2012 (http://bit.ly/1eiFMYW)