Institution: University of Strathclyde

Unit of Assessment: 13

Title of case study: Economic benefit from improved processes and sales of new products in diamond photonics market

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

Commercialisation of high optical quality diamond by ***Element Six Ltd*** (2010 on) and of diamond-enabled lasers by ***M Squared Lasers Ltd*** (2012 on) has been made possible by underpinning research on laser engineering and optical characterisation at the University of Strathclyde. [Text removed for publication.] Markets for this material include thermal management of lasers to enable higher powers and high-performance laser output windows. [Text removed for publication.]

2. Underpinning research (indicative maximum 500 words)

Context:

Market requirements for developments in solid-state lasers focus on improved functionality – for example, by increasing wavelength coverage, while increasing the output power. This requires a step change in thermal engineering to manage greater heat deposition in the laser material when operated at higher powers. To achieve this, Strathclyde has pioneered the use of high optical quality synthetic diamond, which has a thermal conductivity almost 100 times that of current optical materials. This required improvements in the optical quality of synthetic diamond and the development of laser architectures that enable diamond to efficiently extract heat from a conventional laser material or to be used as a laser material in its own right.

Key Findings:

- **Identifying and Proving Key Opportunities (2003-present):** The Strathclyde team was the first to demonstrate (2004 [1]) and then fully analyse (2005 [2]) the use of diamond as a heat spreader within the cavity of a semiconductor disk laser. This reduced the temperature rise within the laser material and enabled the team to demonstrate watt-level output powers at 0.67µm (2005), 1.05µm (2006), 1.32µm (2004), 2.0µm (2009) and 2.35µm (2007). Prior to this, semiconductor disk lasers with output powers in excess of a few hundred milliwatts had only been demonstrated between 0.9 and 1.1µm. This work was undertaken with a range of partners, both industrial (e.g. ***Samsung***, ***Osram***, ***FujiFilm***) and academic (e.g. Fraunhofer IAF, Tampere, Sheffield, whose expertise was in III-V semiconductor growth, not diamond and its use), helping seed the growth of a world-wide semiconductor disk laser community. The Strathclyde team demonstrated that these lasers are ideal for nonlinear frequency conversion to address an even wider range of wavelengths and hence applications, demonstrating an ultra-violet system (2006) [3] and their first use to pump optical parametric oscillators (2009) and Raman lasers (2011). The team's Raman lasers were the first demonstrations of diamond as a laser material in its own right in a continuously operating laser – a route by which diamond's exceptional thermal properties can be more fully exploited to improve the output power of lasers in the future [6].
- **Developing and Proving Enabling Material (2006-present):** The Strathclyde team identified deficiencies that severely limited the market potential of existing diamond: birefringence (2006) and loss (2011). They then worked closely with the manufacturer (***Element Six Ltd***) on an iterative process of diagnostic assessment (Strathclyde), growth development (Element Six Ltd) and demonstration of critical function (Strathclyde) in disk (2008) [5] and Raman lasers (2011) [6]. This process resulted in >100-fold reductions in the levels of loss and birefringence achievable simultaneously, which in turn enabled the demonstrations of critical function.
- **Demonstrating Vital Micro-fabrication Capability (2003-present):** Having identified the potential of diamond for integrated photonics and electronics, the team developed (2006) a precise argon-chlorine inductively coupled plasma etch giving unprecedentedly low surface roughness (<0.2nm) [3], which was then patented (WO/2008/090511). This was used to fabricate high-quality micro-lenses (2006) [3], transistors (2008), and waveguides (2011).

Key Researchers at University of Strathclyde: At the time of the research (2003-2013), the team was led by Professor Martin Dawson (Chair) with key contributions from Drs David Burns (2003-2012), Erdan Gu, Jennifer Hastie, Stephane Calvez (2003-2012), Alan Kemp, and John-

Mark Hopkins (2003-2012). All were University of Strathclyde employees at Professorial or Research Fellow level.

3. References to the research (indicative maximum of six references)

The three references that best exemplify the quality of this work are [1], [2], and [5].

[1] J. M. Hopkins, S. A. Smith, C. W. Jeon, H. D. Sun, D. Burns, S. Calvez, M. D. Dawson, T. Jouhti, and M. Pessa, "0.6 W CW GaInNAs vertical external-cavity surface emitting laser operating at 1.32 µm," *Electronics Letters*, vol. 40, pp. 30-31, 2004. DOI: 10.1049/el:20040049
The first use of an intracavity diamond heatspreader in a semiconductor disk laser.

[2] A. J. Kemp, G. J. Valentine, J. M. Hopkins, J. E. Hastie, S. A. Smith, S. Calvez, M. D. Dawson, and D. Burns, "Thermal management in vertical-external-cavity surface-emitting lasers: Finite-element analysis of a heatspreader approach," *IEEE Journal of Quantum Electronics*, vol. 41, pp. 148-155, 2005. DOI: 10.1109/JQE.2004.839706
Modelling showing how intracavity diamond heatspreaders can enable watt-level operation of semiconductor disk lasers over a much wider range of wavelengths.

[3] C. L. Lee, H. W. Choi, E. Gu, M. D. Dawson, and H. Murphy, "Fabrication and characterization of diamond micro-optics," *Diamond and Related Materials*, vol. 15, pp. 725-728, 2006. DOI: 10.1016/j.diamond.2005.09.033
A precision inductively coupled plasma-etching technique for diamond. Patent granted (WO/2008/090511).

[4] J. E. Hastie, L. G. Morton, A. J. Kemp, M. D. Dawson, A. B. Krysa, and J. S. Roberts, "Tunable ultraviolet output from an intracavity frequency-doubled red vertical-external-cavity surface-emitting laser," *Applied Physics Letters*, vol. 89, 061114, 2006. DOI: 10.1063/1.2236108
Watt-level output power from a red semiconductor disk laser cooled using a diamond heatspreader and the first frequency doubling of such a laser into the UV.

[5] P. Millar, R. B. Birch, A. J. Kemp, and D. Burns, "Synthetic Diamond for Intracavity Thermal Management in Compact Solid-State Lasers," *IEEE Journal of Quantum Electronics* vol. 44, pp. 709-717, 2008. DOI: 10.1109/JQE.2008.923424. Included in REF2.
*First demonstration of the intracavity use of low-birefringence synthetic diamond in lasers. The result of collaboration with the leading manufacturer (**Element Six Ltd**).*

[6] W. Lubeigt, V. G. Savitski, G. M. Bonner, S. L. Geoghegan, I. Friel, J. E. Hastie, M. D. Dawson, D. Burns, and A. J. Kemp, "1.6W continuous-wave Raman laser using low-loss synthetic diamond," *Optics Express*, vol. 19, pp. 6938-6944, 2011.
DOI: 10.1364/OE.19.006938. Included in REF2.
*The first continuous-wave diamond Raman laser with an output power above the watt level (joint paper with **Element Six**: Geoghegan and Friel). An eight-fold improvement in power over the state of the art was achieved by using low loss and low birefringence diamond.*

Other evidence for quality of research

Grants: The work was funded by 8 EPSRC grants (including 4 platform grants), two EU programmes (‘NATAL’ and ‘VERTIGO’) and two DTI-LINK programmes (‘ALFONSO’ and ‘MIDDI’), an ERC grant (‘DiaL’), 3 industrially funded projects (***Element 6***; ***Samsung***; ***Fujifilm***), and two research fellowships (Royal Academy of Engineering and Royal Society of Edinburgh). Total value of grants approximately £6M.

[Text removed for publication.]

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

Process from research to impact:

The Strathclyde team maximised the economic impact resulting from its research through a series of coordinated steps:

1. *Instigating and then collaborating on the development and commercialisation of new diamond product lines, by iterative diagnostic assessment and proving the material in key applications.*
2. *Pioneering a diamond-enabled laser technology that was subsequently commercialised.*
3. *Developing a diamond etch process [text removed for publication].*

4. *Identifying and developing the novel laser architectures needed to enable new markets for diamond in photonics, for example as heatspreaders in semiconductor disk lasers.*

This impact was developed in partnership with ***Element Six Ltd***, drawing on their world-leading diamond growth capability. The Strathclyde team stimulated interest in, and then contributed to the development of new diamond product lines by proactively taking to Element Six the requirement for lower birefringence and absorption along with an appreciation of the markets such material would address. Strathclyde and Element Six then worked together on an iterative process of diagnostic assessment and growth development. The Strathclyde team proved the efficacy of the resulting new material in disk (2008) and Raman lasers (2011), effectively completing a major design cycle and directly enabling new product lines for the company. (Sources A2 and D1)

The team was instrumental in building four substantial academic/industrial collaborative projects: 'NATAL' and 'VERTIGO' (EU-funded); 'ALFONSO' and 'MIDDI' (DTI-funded). These involved working with companies such as ***Osram***, ***Toptica***, ***LISA-LASER***, ***Cablefree***, and ***Element Six*** to transfer to industry the technology that was subsequently commercialised.

In parallel, the Strathclyde team identified the barriers to the commercial uptake of diamond in photonics and the need for laser designs that fully exploited the exceptional properties of diamond, putting in place research programmes to overcome these hurdles. The Strathclyde team postulated and then proved the efficacy of high optical quality diamond in advanced laser applications, and scoped the markets for diamond-enabled laser technologies. This included consultancy to scope the technological challenges and market potential for diamond Raman lasers, influencing Element Six's investment in this area. The Strathclyde team was also the academic partner on the DTI-funded 'MIDDI' project (with Element Six) that developed a precise etching technique [Reference 3]. [Text removed for publication.]

Reach and Significance of the Impact:

a **Sales Growth:** [Text removed for publication] head of the optical business unit at Element Six, notes that *"we have had a number of experiences in recent years of existing and potential new customers approaching us quoting results from Strathclyde"*. This growth is driven by the world leading optical quality of Element Six's single crystal material, where the material and markets (for example semiconductor disk lasers) were developed with support from the Strathclyde team (Source D1).

b **Improved Products – Diamond:** Collaborative research with Strathclyde has enabled ***Element Six*** to introduce new CVD diamond product lines (2010-2012) to address markets in 1) Raman crystals for frequency shifting of established laser systems, 2) intracavity cooling elements for solid state disk lasers to enable higher power systems, and 3) intracavity coolers for semiconductor disk lasers, improving longevity and efficiency. [Text removed for publication.] Element Six's website notes the importance to these markets of reductions in loss and birefringence (areas worked on with Strathclyde - References 5, 6), since this material is *"particularly suited for the most demanding optical applications"*, and that key markets include areas pioneered by Strathclyde: *"novel laser technologies, including semiconductor and doped dielectric disk lasers"* [References 1,2,4,6] and *"Raman laser applications"* [Ref 6]. Photonics is the fastest growing sector of the CVD diamond business according to Adrian Wilson, Head of Technologies at Element Six (quoted in Electro-optics magazine, July 2012). (Sources: D1, A2 and C).

c **Improved Products – Lasers:** ***M Squared Lasers Ltd*** entered the marketplace for diamond-enabled lasers in 2012 with the purchase of ***Solus Technologies Ltd***. These lasers utilise the intracavity diamond heat spreader technology pioneered at Strathclyde [References 1,2,4,5] for markets including high volume printing, semiconductor metrology and scientific instrumentation. [Text removed for publication.] Business Development Manager at M Squared Lasers Ltd, notes that *"the pioneering research at Strathclyde on diamond-enabled lasers has been influential in opening up a valuable new market for M Squared Lasers Ltd"* (Source D2).

d **Improved Processes:** [Text removed for publication.]

e **Securing company viability:** [Text removed for publication.]

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

A. Press releases from *Element Six* relating to collaboration with Strathclyde and supporting the importance of the Strathclyde etch process (A1 and A3) and laser engineering research (A2):

1. http://www.e6.com/wps/wcm/connect/e6_content_en/home/about+us/news/news+2008/successful+conclusion+to+research+programme+into+next+generation+technologies+for+synthetic+diamond+device+fabrication

2. http://www.e6.com/wps/wcm/connect/e6_content_en/home/about+us/news/news+2008/novel+solid-state+laser+design+based+on+synthetic+diamond+from+element+six+opens+up+new+applications

3. http://www.e6.com/wps/wcm/connect/e6_content_en/home/about+us/news/news+2007/micromachined+diamond+device+initiative+(middi)+project+on+target+to+fulfil+research+goals

B. http://www.leedsinnovationcentre.co.uk/news/diamond-microwave-devices-clsoes-1-3m-commercialisation-round/ Press release from *Diamond Microwave Devices Ltd* confirming £1.3M of equity investment in 2009

C. Article in Electro-Optics Magazine (July 2012, pp 8-9) http://www.electrooptics.com/features/ stating the importance of the photonics market to *Element Six Ltd*.

D. The following beneficiaries can be contacted for corroborating information:
   1. Principal Research Scientist, *Element Six Ltd*. will confirm evidence on the importance and value of sales of high optical quality diamond.
   2. Business Development Manager, *M-Squared Lasers Ltd.* will confirm evidence on the importance and value of sales of diamond-enabled lasers.
   3. Principal Research Scientist, *Element Six Ltd*. will confirm evidence [text removed for publication].

E. Statement from the Commercial Business Manager at Element Six.