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| **Institution:** University of Strathclyde | | |
| **Unit of Assessment:** B9 - Physics | | |
| **Title of case study:** Diamond in photonics: economic impacts from new products, strategic industrial R&D investment and inter-company innovation | | |
| **Period when the underpinning research was undertaken:** 2003-2020 | | |
| **Details of staff conducting the underpinning research from the submitting unit:** | | |
| **Name(s):** | **Role(s) (e.g. job title):** | **Period(s) employed by submitting HEI:** |
| Prof Martin Dawson | Professor | 01/03/1996 – present |
| Dr David Burns | Senior Research Fellow | 01/03/1996 – 09/11/2012 |
| Dr Erdan Gu | Senior Research Fellow | 16/07/2002 – present |
| Dr Jennifer Hastie | Reader | 01/10/2003 – present |
| Prof Alan Kemp | Professor | 05/08/2002 – present |
| Dr Stephanie Calvez | Research Fellow | 01/12/2000 – 31/01/2012 |
| **Period when the claimed impact occurred:** August 2013 – December 2020 | | |
| **Is this case study continued from a case study submitted in 2014?** No | | |

## 1. Summary of the impact

University of Strathclyde research has contributed to synthetic diamond manufacturer Element Six delivering economic impact on three fronts. First, it has underpinned new products, in turn opening up new markets [Text removed for publication]. Second, as a significant component of a wider UK research effort in diamond, it contributed to Element Six's decision to invest [Text removed for publication] in its new UK-based Global Innovation Centre (GIC), which, since its establishment in July 2013, has created or secured jobs for [Text removed for publication] scientists and technologists. Third, GIC facilities, in combination with Strathclyde underpinning research, have allowed Element Six to partner with companies to pioneer new products for markets including tools for computer chip manufacture and quantum technologies.

## 2. Underpinning research

### Context: understanding how to process and use diamond for photonics

Photonics, an enabling technology that underpins much of modern manufacturing and communications, is itself underpinned by high performance materials. In addition to optical transparency at the relevant wavelengths, these materials must, particularly for high power applications, handle considerable thermal, optical and mechanical loads. In principle, diamond excels in all these regards, but in practice, it was, until recently, too difficult to manufacture with sufficient quality and to process into device-ready products. Since 2004, research by Strathclyde's Institute of Photonics team, led by Prof Martin Dawson, has made significant contributions to Element Six's product and market development by demonstrating the critical function of diamond in high performance lasers [R1-R5], by developing a novel etch for preparation of advanced diamond products [R6], and by helping to improve the base material via iterative measurements and tests [R3-R4].

### Key findings and proof-of-principle demonstrations

In 2004, the Strathclyde team demonstrated that diamond can be used as a very effective heat spreader in semiconductor disk lasers, enabling a considerable boost in output power at a previously challenging wavelength region for these lasers (1.3μm) [R1]. Significantly, this demonstration pioneered the use of diamond within the laser cavity, an innovation which required diamond with excellent optical properties. The benefit of this approach, as the team went on to show [R2], is that it provides efficient thermal management regardless of semiconductor materials system, which together with diamond's optical transparency across a wide spectral band, opened the way for high power operation of semiconductor disk lasers over a much wider range of wavelengths than had previously been possible.

Through this work, the Strathclyde team uncovered issues with first-generation synthetic single crystal diamond in terms of its optical loss (absorption and scatter) and its spatially varying birefringence. These were significant obstacles to efficient laser operation [R3]. Working with Element Six, the Strathclyde team characterised the problem, contributing to the development of material with at least an order of magnitude better characteristics in terms of loss and birefringence, which was in turn proven in Strathclyde demonstrations of improved laser performance [R3-R5]. This enabled not only a wide range of high-power semiconductor disk laser research at Strathclyde, but also the demonstration of the effective use of diamond for thermal management in doped-dielectric lasers [R3] and, as part of collaborations between Element Six, Strathclyde and Macquaire University in Australia, in Raman lasers. The Strathclyde work on diamond for Raman lasers included the first full characterisation of the Raman gain coefficient [R4] and the first demonstration of a robust and fully monolithic diamond Raman laser [R5].

This latter demonstration took advantage of a parallel but highly complementary strand of Strathclyde research: the development of an advanced argon-chlorine inductively coupled plasma etch capable of producing smoother, lower defect diamond surfaces and devices [R6]. Since the initial work at Strathclyde from around 2003, this etch has not only been used in laser devices (e.g. R5) but has also gone on to enable the production of high-power laser and quantum technology components as discussed in section 4.

**3. References to the research** (Strathclyde affiliated authors in **bold**)


**R1** **J.M. Hopkins**, **S.A. Smith**, **C.W. Jeon**, **H.D. Sun**, **D. Burns**, **S. Calvez**, **M.D. Dawson**, T. Jouhti, and M. Pessa, "0.6W 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 [FWCI: 14.37]

**R2** **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 [FWCI: 6.79]

**R3** **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 [FWCI: 2.53; REF2 in 2014]

**R4** **V.G. Savitski**, I. Friel, **J.E. Hastie**, **M.D. Dawson**, **D. Burns**, and **A.J. Kemp**, "Characterization of Single-Crystal Synthetic Diamond for Multi-Watt Continuous-Wave Raman Lasers," *IEEE Journal of Quantum Electronics,* vol. 48, pp. 328-337, 2011. DOI: 10.1109/JQE.2011.2179917 [FWCI: 4.31; REF2 in 2014]

**R5** **S. Reilly**, **V.G. Savitski**, **H. Liu**, **E. Gu**, **M.D. Dawson**, and **A.J. Kemp**, "Monolithic diamond Raman laser," *Optics Letters,* vol. 40, pp. 930-933, 2015. DOI: 10.1364/OL.40.000930 [FWCI: 2.74, REF2]

**R6** **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 [FWCI: 2.42]


**Notes on the quality of research:** The field-weighted citation impact (FWCI) at 02/02/2021 for each of the above publications is noted alongside each reference. These demonstrate that the publications, representative of an extensive body of research since 2004, have had significantly higher than average influence on the academic field. The work has been supported by some GBP5,500,000 of competitively won research funding in the same period, including EPSRC, European and DTI awards, the latter led by Element Six. Early work was supported by a prestigious EPSRC Platform Grant won by Dawson, with more recent prestigious awards including a European Research Council (ERC) Starting Grant on Diamond Lasers won by Kemp, an EPSRC Challenging Engineering Fellowship for Hastie and a Royal Academy of Engineering research chair for Kemp. The research group has also contributed diamond expertise to the EPSRC Quantum Technology Hubs on Networked Quantum Information Technology and on Sensors and Metrology. Dawson was awarded the 2015 Dennis Gabor Medal and Prize from the Institute of Physics and the 2016 Aron Kressel Award from the IEEE Photonics Society; diamond photonics was mentioned in the citations for both awards.

## 4. Details of the impact

### Route to impact: 16 years of strategic interaction

Founded in 1946, Element Six is a global leader in the design, development and production of synthetic diamond and tungsten carbide supermaterials. It comprises two businesses, Technologies and Abrasives, with the synthetic diamond business forming part of Element Six Technologies, which operates production and technical facilities in Santa Clara, California and in Ascot, UK. The company is acknowledged as a major player in the synthetic diamond market, which was valued at around USD17,000,000,000 in 2016 and expected to grow at a compound annual growth rate (CAGR) of 7% between 2016 and 2021 [**S1**].

Since 2004, when Strathclyde researchers contacted Element Six to discuss diamond quality and laser performance, Strathclyde research has underpinned impact realised by Element Six and its customers through active collaboration with the company on diamond product lines, and by developing new technologies and processes subsequently used and commercialised by Element Six. This collaboration is confirmed by the Chief Technologist at Element Six, who notes that:

> *'Element Six have worked closely with Strathclyde for over a decade on optimising the optical properties of single crystal diamond. This joint research effort has been very important to Element Six in increasing our interactions with photonics and related companies in the UK and world-wide. These interactions have in turn driven sales and investment at Element Six.'* [**S2**]

Strathclyde research has contributed to impact in three areas:

- The development of diamond products for photonics as well as the markets for these products, leading to commercial benefits for Element Six;
- The enabling of strategic investment in commercial R&D, leading to job creation and commercial benefits;
- The underpinning of product development between commercial partners, leading to new collaborations and markets for Element Six.

### Impact 1: Commercial benefits from new products and markets

***New products for new markets***

Collaborative research with Strathclyde has enabled Element Six to introduce new chemical vapour deposition (CVD) diamond product lines to address markets in areas including:

- Intracavity cooling elements for solid state disk lasers to enable higher power systems [**R3**];
- Intracavity coolers for semiconductor disk lasers, improving longevity and efficiency [**R1**-**R3**];
- Raman crystals for frequency shifting of established laser systems [**R4**, **R5**].

[Text removed for publication] This has contributed to a 95% growth in Element Six Technologies' annual turnover between 2016 and 2019 [**S3**]. Overall, Element Six Technologies' sales are approximately 30% to the UK, 50% to Europe and 20% to the rest of the world [**S3**]. Much of the material has been sold for incorporation into advanced devices for the lasers, spectroscopy, semiconductor processing, biomedical optics and defence/ aerospace markets [**S4**]. This, in turn, has raised Element Six's industry reputation. As the Chief Technologist at Element Six notes:

> *'Element Six have gained a globally leading understanding of the impact and role diamond can have in the field of semiconductor and Raman lasers from collaborating with Strathclyde. This has helped us increase our interactions with a range of significant companies in the UK and worldwide. Customers often point to the joint*

*Element Six/Strathclyde research as a key reason why they are switching to diamond in their photonic products.'* [**S2**]

Diamond Pure Optics is a product line launched by Element Six in 2015. In an innovative approach that allows these components to operate at 10 times the laser power density of their predecessors, Element Six use an innovative antireflection structure etched onto the diamond surface [**S5**] using an etch based on that pioneered at Strathclyde [**R6**]. Element Six are working with manufacturers in the high-power lasers market to incorporate these diamond components into high-power laser products aimed at extreme ultraviolet (EUV) lithography, materials processing, directed energy and imaging applications [**S5**].

M Squared Lasers Ltd, a Glasgow-based company with a longstanding heritage in the development of semiconductor disk laser systems, is one company utilising Element Six diamond components in their products. M Squared's CEO notes that:

'*The presence of Element Six in our supply chain represents a valuable commercial partner. One of the outcomes of our extensive collective discussions with them has been continued improvement in the absorption and birefringence specifications of their material, ultimately outperforming the best available competing transparent heatspreader devices.*' [**S6**]

M Squared has two semiconductor disk lasers product lines that use intracavity diamond. The Dragonfly, a compact modelocked ultrashort pulse laser optimised as a source for multiphoton microscopy, and the Infinite, a continuous wave narrow linewidth laser, targeted towards applications in cold atom physics. These products, directed towards the important and growing life science and quantum technology markets respectively, both have the potential to be marketed at scale [**S6**].

**Impact 2: Strategic investment in commercialisation infrastructure**

In July 2013, Element Six opened the [Text removed for publication] Global Innovation Centre (GIC) at Harwell, Oxfordshire, the '*world's largest and most sophisticated synthetic diamond research and development facility*' [**S7**]. This 5000m$^2$ facility now employs over 100 scientists and technologists, bringing together and expanding Element Six's global R&D capability in one integrated site [**S2**]. The GIC allows Element Six to partner with customers to rapidly design, manufacture and test market-ready diamond components, improving performance, increasing productivity, and reducing cost for the customer company. Strathclyde was the lead partner in bringing laser applications expertise to Element Six, and thereby played an important role in the decision to establish the GIC, as explained by the Chief Technologist at Element Six:

*'one of the key reasons Element Six [Text removed for publication] set up the GIC in the UK was the quality of the UK research base in diamond science. Strathclyde is one of a core of five UK universities with whom Element Six has cultivated long term relationships that enabled and continue to support our GIC investment. Strathclyde research has supported the expansion of our optics and photonics business and helped underpin our GIC investments in this area, including a team of [Text removed for publication] scientists and technologists working on CVD diamond.'* [**S2**]

Strathclyde has continued to contribute to GIC activities through the Centre for Doctoral Training (CDT) in Diamond Science and Technology, as one of eight university partners. The CDT has been a key source of both research support for Element Six and of highly skilled staff once its students graduate. [Text removed for publication]

**Impact 3: Product development and collaboration between industry partners**

The ability that the GIC gives Element Six to rapidly prototype new diamond technologies – working with both prime manufacturers and SMEs in the relevant applications areas to drive both the technology and the market – is exemplified in two areas that build on Strathclyde diamond etch research [**R6**]: the development of diamond components for cutting-edge systems for EUV lithography in computer chip manufacture [S8], and the nurturing of the nascent quantum technologies industry [S9]. In both cases, Element Six are actively working with companies in the relevant areas on product development.

***EUV lithography systems***

Element Six have built on the successful Diamond Pure Optics range of components for high power lasers [Text removed for publication].

***Quantum technologies***

The precision diamond etching capability has also contributed to Element Six's role in underpinning the creation of SMEs and products from those SMEs in the quantum technology sector [S9]. Precision etching is vital to the manufacture of diamond devices for quantum technology. [Text removed for publication] This has put Element Six at the centre of the commercialisation of diamond quantum technologies, developing products with, and selling material to, companies including start-ups like Qnami and NVision, as well as manufacturers like Lockhead-Martin, Bosch and Thales [S9].

As the Chief Technologist at Element Six notes: '*these are exciting new commercial partnerships and new markets for Element Six in EUV lithography and quantum technology. They are driven by the interaction of our in-house expertise and university research, with the Strathclyde diamond etch research being a vital part of that*' [S2].

## 5. Sources to corroborate the impact


**S1** Business Wire. *Global $23.8 Billion Synthetic Diamond Market, 2021*. https://bwnews.pr/3bYxPwx (accessed 15/02/2021).

**S2** Corroborating statements from Product Manager, CVD Diamond Optics, Element Six and Chief Technologist, Element Six (dated 26/02/2021).

**S3** Element Six Technologies' annual accounts 2016-2019.

**S4** Element Six CVD Diamond Optics Product Information Page 4 https://bit.ly/2Y282go (accessed 15/02/2021).

**S5** Element Six Diamond PureOptics Product Information Pages 2-3 https://bit.ly/3c0AMOv (accessed 15/02/2021).

**S6** Corroborating statement from CEO M Squared Lasers Ltd (dated 17/03/2021).

**S7** The Business Magazine. *Oxford: Element Six opens world's most advanced synthetic diamond Innovation Centre*. 3rd July 2013. https://bit.ly/3p9kIOu (accessed 28/10/2020).

**S8** Element Six. *Using Meta-surfaces Etched into Diamond Eliminates the Need for Thin Film Coatings, Enabling More Than 10 Times Increase in Damage Thresholds for Applications Including EUV Lithography*. 5th November 2015. https://bit.ly/39275uA (accessed 1/12/2020).

**S9** Physics World Magazine. *The diamond quantum revolution. 23 Apr 2020*. https://bit.ly/2LINgzV (accessed 25/11/2020).