Institution: University of Glasgow (UofG)		
Unit of Assessment: UoA12 Engineering		
Title of case study: High-resolution electron beam lithography tools for the specialist laser gratings industry		
Period when the underpinning research was undertaken: 2006–2017		
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:**
(1) Jonathan Weaver	(1) Professor, Applied Nanofabrication	(1) 1990–present
(2) Douglas Macintyre	(2) Research Technologist and Operations Manager; Honorary Research Fellow	(2) 1989–2015; 2016–2017
(3) Charles Ironside	(3) Professor, Quantum Electronics	(3) 1999–2014
(4) A. Catrina Bryce Coleman	(4) Professor	(4) 1987–2005
(5) John Marsh	(5) Professor, Optoelectronics Systems	(5) 1986–present
(6) Lianping Hou	(6) Senior Lecturer	(6) 2007–present
Period when the claimed impact occurred: 2013–present		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

UofG is a world-leader in Electron beam lithography (EBL) research, resulting in one of the most advanced, large-area, high-resolution capabilities in the world. Data communication is one of the technologies central to modern life. UofG's EBL is now one of the core technologies for creating nanoscale patterns, a key fabrication step in the manufacture of chips used in of novel semiconductor lasers and grating-based devices for data communications (datacomms) products.

This research has enabled UofG-owned Kelvin Nanotechnology (KNT) to expand its business: [text removed for publication]. KNT also manufactures gratings for the cutting-edge quantum markets, enabling customer TMD Technologies Ltd produce the world's first portable grating magneto-optical trap for quantum sensing and timing applications.

2. Underpinning research

<u>The demand for optical gratings</u>

The Internet underpins modern society. With global traffic currently increasing at a compound annual growth rate of 26%, the internet is underpinned by optical fibre communications – for long and short haul data transfer, datacentres, and fibre to the home. Distributed feedback (DFB) lasers are core chip components used in optical fibre communications. These semiconductor lasers emit a single wavelength laser beam enabling data transfer at higher speeds and over longer distances. The single wavelength is achieved through specially designed optical gratings, essential in providing feedback for the laser. Many modern networks, such as those underpinning fibre-optic broadband, require multiple, densely packed wavelengths and high data rates (>25 GHz). Electron beam lithography (EBL), and notably the EBL capability developed at UofG, uniquely offers the precision to develop and process specialist gratings that enable transmission of data at these densely packed wavelengths and high data rates.

<u>The development of EBL at UofG</u>

Researchers at UofG have been at the forefront of advances in nanofabrication since 1978. Integrating research efforts in design, growth of films, modelling and fabrication, UofG has sought to achieve the highest possible level of reproducibility in the fabrication of devices, made possible by its use of EBL. In 1990, UofG became the first UK academic institution to have a commercial EBL system; this capability has been continuously developed and tested ever since.

UofG research in EBL development
Research at UofG has led to the development of its current world leading EBL capability and an understanding of EBL's diverse applications. For example, state-of-the-art EBL systems require a high degree of alignment within the electron beam, the precision of which is critical to fabricating features with nanometre resolution [3.1]. UofG research identified that Penrose tilings can significantly reduce field stitch errors, facilitating the production of large area gratings with minimal misalignments, thus reducing unwanted optical artefacts. These tilings have subsequently been applied to enhance the EBL facility at UofG.

UofG has used EBL to fabricate DFB and Distributed Bragg Reflector (DBR) gratings in several novel laser applications. Of particular note is the demonstration of a single chip containing four lasers, each operating at a different wavelength, where the wavelengths are determined by the pitch of the DFB grating [3.2]. This shows that first-order DFB gratings for lasers operating at different wavelengths used for datacomms can be laid out across a wafer to a desired design. UofG has gone on to use EBL defined gratings in many novel laser-based chips, such as for the fabrication of narrow linewidth lasers [3.3], to generate light modulated at THz frequencies, and for the fabrication of DFB laser arrays whose wavelengths are spaced to match that of the International Telecommunication Union (ITU) grid. UofG has also shown that the in-house EBL tool can create specialist gratings for visible laser diodes [3.4]. UofG's ongoing research programmes in lasers with EBL-defined DFB gratings has demonstrated that the in-house EBL tool can create reproducible, specialist gratings for laser diodes in volume, giving companies the confidence to use KNT to fabricate their gratings.

The advanced resolution of the UofG EBL tool has been essential in facilitating new applications of EBL, driving UofG research in both atomic force microscopy (AFM) and quantum technologies. For example, the in-house UofG EBL tool has been used in the batch-production of scanning electrochemical probes for AFM applications producing probes which are suitable for simultaneous electrochemical constant distance and topographical imaging [3.5]. More recent UofG research has shown the versatility of EBL in atomic cooling applications for quantum technologies [3.6], which are increasingly central to the tool's commercial exploitation.

3. References to the research

3.1. Docherty, K.E., Thoms, S., Dobson, P. and Weaver, J.M.R. (2008) Improvements to the alignment process in a commercial vector scan electron beam lithography tool. *Microelectronic Engineering*, 85(5–6), pp. 761–763. (doi: 10.1016/j.mee.2008.01.081)

3.2. Hou, L., Haji, M., Akbar, J, Marsh, J. H. and Bryce, A. C. (2011) CWDM source based on AlGaInAs/InP monolithically integrated DFB laser array. *Optics Letters* 36, pp. 4188–4190. (doi: 10.1364/OL.36.004188)*

3.3. Hou, L., Haji, M., Akbar, J, Marsh, J. H. (2014) Narrow linewidth laterally coupled 1.55 µm AlGaInAs/InP distributed feedback lasers integrated with a curved tapered semiconductor optical amplifier. *Optics Letters* 37(21), pp. 4525–4527. (doi: 10.1364/OL.37.004525)

3.4. Slight, T. J., Yadav, A., Odedina, O., Meredith, W., Docherty, K. E., Rafailov, E. and Kelly, A. E. (2017) InGaN/GaN laser diodes with high order notched gratings. *IEEE Photonics Technology Letters*, 29(23), pp. 2020–2022. (doi: 10.1109/LPT.2017.2759903)

3.5. Dobson, P., Weaver, J., Burt, D., Holder, M., Wilson, N., Unwin, P. and Macpherson, J. (2006) Electron beam lithographically-defined scanning electrochemical-atomic force microscopy probes: fabrication method and application to high resolution imaging on heterogeneously active surfaces. *Physical Chemistry Chemical Physics*, 8, pp. 3909–3914. (doi: 10.1039/b605828k)

3.6. Nshii, C.C., Vangeleyn, M., Cotter, J.P., Griffin, P.F., Hinds, E.A., Ironside, C.N., See, P., Sinclair, A.G., Riis, E. and Arnold, A.S. (2013). A surface-patterned chip as a strong source of ultracold atoms for quantum technologies. *Nature nanotechnology*, *8*(5), pp.321–324. (doi: 10.1038/nnano.2013.47)*

*=best indicators of quality

4. Details of the impact

Nanofabrication plays a key role in the design and manufacture of the silicon chips that form essential components of modern data communications products, such as smartphones.

KNT was founded in 1997 as a wholly owned University company to provide commercial nanofabrication solutions to industry and academia, delivered through the James Watt Nanofabrication Centre (JWNC) at UofG. UofG research has led to the development of one of the most advanced electron beam lithography (EBL) capabilities in the world, enabling Kelvin Nanotechnology Ltd (KNT) to offer customised EBL services for applications as diverse as laser grating writing, transistor gate writing and nanotextured surfaces. The impacts are primarily economic, creating new jobs, and benefiting its commercial customers around the world.

Economic impacts for KNT

KNT offers fabrication services on a commercial basis, with the EBL capability being central to the company's commercial success [5.1]. [Text removed for publication.]

Economic impacts for KNT's customers

Substantial economic impacts have arisen for KNT's customers in the DFB laser space. [Text removed for publication.] These chips underpin the transceiver industry. Transceivers are a combination of transmitters and receivers in a single package, used in telecomms infrastructure and underpinning mobile phone technology and fibre networking. [Text removed for publication.] Transceiver technology using KNT technology delivers broadband internet to around 2.1 million businesses and homes per year.

KNT are also using grating technology [3.6] to develop future Quantum Technology products. KNT produce the gratings used in an innovative product called gMOT, created in a partnership led by KNT with UofG, the University of Strathclyde and TMD Technologies (London). gMOT is the world's first portable grating magneto-optical trap (MOT) for compact cold atom systems and is used to produce ultracold atoms [5.5]. These ultracold atoms have primary applications in atomic clocks. *"Atomic clocks are an important facet of our everyday lives in this fast-expanding quantum world. [They] have the potential to provide a valuable alternative and back-up to global navigation satellite systems (GNSS) used as either stand-alone timing solutions on a platform or as 'hold-over' clocks should the GNSS signal become unavailable, unreliable or degraded." – Head of Business Development at TMD* [5.5]. The Royal Academy of Engineering estimate that around 6–7% of the GDP of Western countries is dependent on GNSS and the proportion will continue to rise, with accurate timing becoming a ubiquitous requirement for modern technology and business operations [5.6 p3 'Foreword']. gMOT provides a portable solution to back up GNSS and its role in the UK economy.

The unique UofG contribution to gMOT is the grating at the heart of the gMOT cell [5.1]; without it, the system would not work. Thus, there are economic impacts for TMD who market gMOT [5.7]. [Text removed for publication.]

By working with KNT to produce gMOT, TMD have been able to join the UK's National Quantum Technologies Programme (NQTP), contacts from which were the first to buy gMOT [5.7]. The NQTP is a government initiative involving investment of ~GBP800 million over 10 years to accelerate the translation of quantum technologies into the marketplace [5.8 paras 3 and 6]. Joining NQTP has given TMD access to funding and showcase opportunities they would not have had otherwise [5.7]. The NQTP is aligned with investments from the UK Defence, Science and Technology Laboratory and the UK Ministry of Defence to develop demonstrators of quantum timing and navigation devices within 3–5 years [5.9 para 6]; contributing to this network is thus enabling TMD to help the UK government to meet its objectives [5.7].

5. Sources to corroborate the impact

5.1. Testimonial: CEO of KNT
5.2. Presentation: KNT Core Services (2019)
5.3. Presentation: Frost & Sullivan 'Drivers, Opportunities and Developments' (2019)
5.4. Presentation: KNT 'DFB Laser Grating Market' (2020)
5.5. Press release: TMD announces a 'world's first' in portable cold atom technology
5.6. Report: The Royal Academy of Engineering 'Global Navigation Space Systems: reliance and vulnerabilities'
5.7. Testimonial: Head of Business Development at TMD
5.8. Government Response document: Eleventh Special Report – Appendix
5.9. NQTP Overview of programme – UK Quantum Technology