Institution: University of Glasgow
Unit of Assessment: B15: General Engineering
Title of case study: **Novel Quantum Cascade Laser technology leads to new products, processes and market opportunities**
1. Summary of the impact

The commercialisation of Quantum Cascade Lasers (QCL) and the associated novel fabrication processes developed at the University of Glasgow has provided Compound Semiconductor Technologies Global Ltd (CSTG) with a new foundry product supplying quantum cascade lasers for gas sensing, safety and security, and military applications. This resulted in 40% turnover growth from 2010-2012 and the company is now recognised as a global leader in QCLs and their fabrication. Based on University of Glasgow research, the company has created a manufacturing toolbox for the production of a wide variety of QCL chip designs. CSTG has also achieved a world first, manufacturing QCLs for systems that detect explosives at a safe distance and can counter heat-seeking missile attacks on aircraft.

2. Underpinning research

Quantum cascade lasers (QCLs) were first demonstrated by Federico Capasso's group at Bell Laboratories in the USA in 1994. QCLs are highly compact semiconductor chips, only 1mm long, that emit light in the mid-infrared region of the spectrum enabling many gases of economic and environmental importance to be sensed, e.g. methane and carbon dioxide.

Professor Charles Ironside in the School of Engineering at the University of Glasgow (Senior Lecturer 1992-94, Reader 1994-99, Professor of Quantum Electronics 1999-present) initiated his research into QCLs to diversify the portfolio of applications that could be addressed with this technology.

As QCL devices have important military applications, it was not possible to access US manufactured lasers due to US Government regulations (ITAR) controlling the export of defence-related material and services. No group outside the USA had the ability to manufacture QCLs and so it was necessary to independently discover the experimental means for growing the epitaxial structures and to develop the techniques and processes that would enable their reliable manufacture. This was achieved in 1998 by a consortium comprising epitaxial growth and fabrication at the University of Glasgow, led by Ironside, and device characterisation at the University of Sheffield, led by Prof John Cockburn (Department of Physics and Astronomy). They were the first outside the USA to demonstrate QCLs [1]. The University of Glasgow team included Colin Stanley (Professor 1992-2010), Jane McGill (Research Fellow 1987-88, Lecturer 1988-2000) and PhD student Corrie Farmer.

Key challenges tackled by the consortium were developing the critical etch and lithography processes that define the laser structure. These were overcome by the development of wet and dry etch techniques, including the use of reactive ion etching and inductively coupled reactive ion etching techniques and using hydrogen silsesquioxane for QCL waveguide planarisation.

The research continued with funding from EPSRC for the project "Quantum cascade emission devices for IR optical sensing" (2000-2002, GR/M46983/01). In collaboration with the University of Sheffield, Edinburgh Sensors and GEC Marconi, a successful demonstration of spectroscopy using room temperature QCLs was achieved.

From 1999-2000 Ironside, Dr Farmer (Research Assistant, 2000-present) and PhD student Michel Garcia (2001-2003) collaborated with Dr N Langford and Prof D Duxbury in the Physics

Department at the University of Strathclyde to develop QCLs for gas spectroscopy. The EPSRC funded "Ultra Sensitive Spectroscopy Using QCLs" (GR/M69043/01) led to the discovery of an intra-pulse chirp effect that tuned the laser in a way that made it suitable for detecting gases [2]. Cascade Technologies Ltd was founded, as a University of Strathclyde spin-out, to manufacture sensing systems based on this technique.

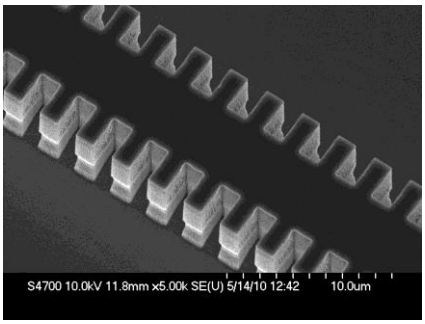

Figure 1. *Lateral grating on the side wall of a QCL.*

The 'QCSENSE' project was funded by the DTI in 2006, in collaboration with Cockburn at the University of Sheffield, Wyn Meredith, Commercial Director, Compound Semiconductor Technologies Global Ltd (CSTG), Erwan Normand, Chief Scientific Officer, Cascade Technologies and Bill Hirst, Shell Global Solutions. Ironside, Miles Padgett (Professor of Physics, 1999-present) and Research Assistant Dr Thomas Slight (2006-2012) worked with the consortium to develop 3.35 micron QCLs, the shortest wavelength QCL at the time, for trace sensing of hydrocarbons such as ethane and methane using the mid-infrared absorption of light by these gases [3]. Deep etched surface grating technology, based on initial work on conventional direct bandgap lasers by John Marsh in 1995 (Lecturer 1986-96, Professor 1996-present), was used to make single-mode lasers. These QCLs were suitable for robust, reliable and compact systems that could be mounted on a mobile platform. Figure 1 illustrates the lateral grating on the side wall of a QCL that ensures the laser operates at a precise single frequency, which is ideal for sensing ethane.

Between 2010 and 2012, CSTG and Ironside collaborated on a Knowledge Transfer Partnership (KTP) project increasing the commercial focus of the research, with Slight as the KTP Associate. The project produced a QCL with a novel laser geometry, giving very high spectral quality for spectroscopy and sensing applications [4], and industrialised the research processes. The project also produced a number of research outputs that have become part of the suite of processes and designs now offered by CSTG. These included an entirely new method for ensuring single mode operation of QCLs with significantly reduced fabrication costs [5] and QCLs with an integrated polarization mode converter which has applications in ellipsometry [6].

3. References to the research

[1] C.D. Farmer, P.T. Keightley, C.N. Ironside, C.R. Stanley, L.R. Wilson and J.W. Cockburn, A quantum cascade laser fabricated using planar native-oxide layers, Appl. Phys.Letts. 77(1), 25-27, 2000. doi: 10.1063/1.126865 *

[2] M. Garcia, E. Normand , C.R. Stanley, C.N. Ironside, C.D. Farmer G. Duxbury and N. Langford, An AlGaAs/GaAs quantum cascade laser operating with a thermoelectric cooler for spectroscopy of NH3, Optics Communications 226 39-43 2003. doi: 10.1016/j.optcom.2003.07.041*

[3] T.J. Slight, G. Tandoi, D. Revin, A. McKee, S. Zhang, W. Meredith, J.W. Cockburn, C. N. Ironside, Lambda =3.35um Distributed Feedback Quantum Cascade Lasers with High Aspect Ratio Lateral Grating, IEEE Photonics Technology Letters, 23(7), 420-422, 2011. doi: 10.1109/LPT.2010.2103358

[4] R. Phelan, T.J. Slight, B. Kelly, J. O'Carroll, A. McKee, D. Revin, S. Zhang, A.B. Krysa, K.L. Kennedy, J.W. Cockburn, C.N. Ironside, W. Meredith, J. O'Gorman, Room-Temperature Operation of Discrete-Mode InGaAs–AlAsSb Quantum-Cascade Laser With Emission at 3.3microns, IEEE Photonics Technology Letters, 22(17), 1273-1275, 2010. doi: 10.1109/LPT.2010.2053529

[5] D. Dhirhe, T.J. Slight, C.C. Nshii and C.N. Ironside, A tunable single-mode double-ring quantum-cascade laser, **(Invited paper)**, Semicond. Sci. Technol. 27, 094007, 2012. doi: 10.1088/0268-1242/27/9/094007 *

[6] D. Dhirhe, T. J. Slight, B. M. Holmes, D. C. Hutchings, and C. N. Ironside, Quantum cascade lasers with an integrated polarization mode converter, Optics Express, 20(23), pp. 25711-25717, 2012. doi: 10.1364/OE.20.025711

* best indicators of research quality

4. Details of the impact

Professor Charles Ironside's research on Quantum Cascade Lasers (QCLs) has created commercial impact through two SMEs – Compound Semiconductor Technologies Global (CSTG) and Cascade Technologies – and the development of new products and processes for gas sensing, safety and security and military applications.

CSTG supplies advanced semiconductor optoelectronic devices to a range of markets including counterterrorism, homeland security, and oil and gas. For example, devices that sense minute quantities of explosive gases are used for the stand-off detection of explosive devices including IEDs, and the detection of hydrogen peroxide is used in combination with infrared counter measures to dazzle heat-seeking missiles. The company serves both fabless and vertically integrated customers in the UK, US, Europe and Japan. In excess of 70% of the company revenues are derived from high-value product exports. CSTG is now recognised as a global leader in QCL fabrication as a direct result of the collaboration with the University of Glasgow and achieved an increase in turnover of ~40% from 2010 to 2012.

Building on his world-leading research, Ironside, together with CSTG, secured a KTP project in 2009 which has had a remarkable impact on CSTG's profitability. This has been achieved through the creation of a manufacturing toolbox, a generic QCL process library that can be used to produce a wide variety of chip designs, hence establishing the company's reputation in new applications and markets. The company has achieved world firsts, in manufacturing QCLs for systems that detect explosives at a safe distance and for countering heat-seeking missile attacks on aircraft.

This project integrated Ironside's knowledge of the design and optical characterisation of QCLs into CSTG business, allowing the company to harness the commercial potential of QCLs as an emerging mid-infrared laser technology. This resulted in CSTG adding a new high-value laser device and manufacturing process to their product range. The project also yielded new fabrication processes and novel laser chip designs, enabling CSTG to address a market need for innovative semiconductor foundry processes for the manufacture of compact, mid-infrared micro-chip laser sources. The Commercial Director at CSTG has stated that at least 60% of the company's increase in turnover (between 2010 and 2012) could be attributed to these mid-infrared products. CSTG's ability to access markets and clients through the introduction of a QCL foundry service has resulted in new contracts, customers, and the recruitment by the company, via a KTP, of Thomas Slight from Ironside's research group. The impact of this collaboration in terms of business profitability and expansion was recognised by the award of Best KTP in Scotland in 2012.

In addition to the impact through CSTG, Ironside's QCLs were used to tune a new intra-pulse spectroscopy technique. This led to a series of successful gas phase molecular fingerprinting experiments. Cascade Technologies was established in 2003 to capitalise on this novel technique. The intra-pulse technology is now used within the spectroscopic systems developed, manufactured and marketed by Cascade Technologies. Their QCL based gas emission monitoring systems and gas analysers are used for industrial emissions monitoring, process optimisation, analytical chemistry and trace level applications. The systems are installed on the production lines of products where integrity is critical, e.g. in the manufacture of aerosol cans and inhalers, guaranteeing their integrity by scanning to sense for escaping gases.

5. Sources to corroborate the impact

- Testimonial from the Commercial Director at Compound Semiconductor Technologies Global (UK) (corroborates the impact created by CSTG from accessing technology developed by Prof Ironside at University of Glasgow)
- Statement from the Chief Scientific Officer at Cascade Technologies (UK) (corroborates the role Prof Ironside's QCL technology had in underpinning the development of the products now offered by Cascade)
- TSB Best of the Best 2012 KTP award brochure – CSTG Page 9
- Video of the KTP project featuring both the company, the associate and Prof Ironside: states the benefits the company has had from the University research