itution: Cardiff University

Unit of Assessment: Physics (9)

Title of case study: Economic transformation and innovation through the world's first Compound Semiconductor Cluster

Period when the underpinning research was undertaken: 2002 – 2015

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:
Peter Smowton	Professor	1993 – present
Peter Blood	Professor	1990 – 2011
Wolfgang Langbein	Professor	2004 – present
Huw Summers	Senior Lecturer	1996 – 2005
David Westwood	Lecturer	1985 – present

Period when the claimed impact occurred: 2014 – 2020

Is this case study continued from a case study submitted in 2014? No

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

Compound semiconductors underpin the next generation of opto-electronic devices, but the UK lacked an end-to-end compound semiconductor industry. Cardiff researchers developed methods for improved design, production and characterisation of compound semiconductors facilitating more efficient manufacturing processes and quality control. The research encouraged international semiconductor company IQE to expand its manufacturing base and retain its headquarters in South Wales. This strategic partnership laid the foundation for the world's first Compound Semiconductor Cluster. To date, the cluster has led to investments of over £167M, introduced new companies to the South Wales region, and established a new UK manufacturing base that has supported over 1,687 jobs (256 direct, 956 indirect and 545 safeguarded).

2. Underpinning research (indicative maximum 500 words)

The rich functionality afforded by the multitude of ways compound semiconductors can be combined underpins much of our modern electronic technology. Subtle differences in the manufacture of the epitaxial layers and the three-dimensional structuring of compound semiconductors can greatly affect the final application. The Condensed Matter and Photonics (CMP) group in the School of Physics and Astronomy has a sustained record of research and innovation in how compound semiconductor layers are combined and their effect on device performance, particularly for lasers, amplifiers, and applied photonics. This fundamental research has established the CMP as the R&D base for the South Wales Compound Semiconductor Cluster, producing more efficient and accurate methods to assist development of novel compound semiconductor designs. By focusing on novel characterisation techniques, the research improved 1) the design of the epitaxial layers, 2) the fabrication of these into device structures, and 3) the characterisation of resulting materials and devices.

2.1 Design of epitaxial structures

The research investigated the design of the epitaxially grown compound semiconductor layers. Cardiff's analysis showed that saturation of the quantum dot laser gain–current relationship is due to the wetting layer density of states, which slow the movement of the Fermi levels as charge is injected **[3.1]**. Further work demonstrated the limitations and the side-effects of techniques to overcome the problems identified in reference **[3.1]**, including using modulation p-doping, and their impact on the carrier distribution and the temperature dependence of threshold current **[3.2]**. This approach, using device simulation and comprehensive characterisation, was applied across a variety of material systems and device types – for example, by illustrating the importance of dopant density, ionisation energy, and carrier localisation on the performance of GaN based LEDs **[3.3]**. In summary, Cardiff's research demonstrated how direct measurements of the gain, radiative recombination rates,

and Fermi separation allow better understanding of how electrons populate the energy states within the different epitaxial layers and control device performance and enable improvement of the design of compound semiconductor wafers.

2.2 Fabrication

Fabrication of compound semiconductor wafers into useful components requires precision etching methods to define the required circuit pattern. For example, the physical structure of the etch pattern affects compound semiconductor laser quality: deeper cuts with vertical edges create mirrors with maximum reflectivity. Cardiff research developed a new method to produce the deepest vertically etched structures, by careful mix of argon process gas within inductively coupled plasma across AlGaInP and GaAs, on a scale suitable for photonic crystals in AlGaInP **[3.4]**. The research was extended through an Innovate UK project to develop etch processes for VCSELs (vertical-cavity surface-emitting lasers), in collaboration with etch manufacturer and Compound Semiconductor Cluster member, SPTS **[G3.1]**.

2.3 Characterisation of materials and devices

Characterisation is vital to determine the quality and properties of the fabricated compound semiconductors. Although previous approaches required multiple techniques, Cardiff CMP developed a novel and single-method characterisation approach. Through analysis of the edge-emitted amplified spontaneous emission spectra, a full characterisation of the gain medium was produced, known as the segmented contact technique **[3.5]**. In 2015, IQE and Innovate UK funded a Knowledge Transfer Project to transfer the segmented contact technique to IQE for use within their foundry. Additional work at Cardiff developed a heterodyne spectral interferometry technique for non-linear spectroscopy, which measures the spectrally-resolved and time-resolved ultrafast response of individual quantum systems, such as semiconductor quantum dots, with sub-micrometre spatial resolution **[3.6]**.

The advantages that this research provides in manufacturing quality control and in generating designs for future products have established Cardiff at the forefront of compound semiconductor R&D in South Wales. In March 2015 Cardiff secured £17.3M UK Research Partnership Investment Fund (UKRPIF) award to establish the Institute for Compound Semiconductors (ICS) translational research facility **[G3.2]**. The ICS was supported by match-funding from IQE, with an additional £12M investment by the Welsh Government and £13M from the European Regional Development Fund. The ICS was further supported by a £2M grant to purchase equipment **[G3.3]**. The ICS facility is an applied and translational research facility that houses both 4" (research scale) and 8" (industrial scale) equipment.

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

[3.1] Matthews, D. R., et al., *Experimental investigation of the effect of wetting-layer states on the gain-current characteristic of quantum-dot lasers,* Applied Physics Letters 81(26), 4904, 2002. https://doi.org/10.1063/1.1532549 (139 citations)

[3.2] Sandall, I. C. et al., *Temperature dependence of threshold current in p-doped quantum dot lasers,* Applied Physics Letters 89(15), 15111801, 2006. https://doi.org/10.1063/1.2361167 (39 citations)

[3.3] Pope, I., et al., *Carrier leakage in InGaN quantum well light-emitting diodes emitting at 480 nm,* Applied Physics Letters 82(17), 2755, 2003. https://doi.org/10.1063/1.1570515 (118 citations)

[3.4] Edwards, G. T., et al., *Fabrication of high-aspect-ratio, sub-micron gratings in AlGaInP/GaAs laser structures using a BCl3/Cl-2/Ar inductively coupled plasma.* Semiconductor Science and Technology, 22(9), 1010, 2007. https://doi.org/10.1088/0268-1242/22/9/006 (9 citations)

[3.5] Blood, P., et al., *Characterization of semiconductor laser gain media by the segmented contact method,* IEEE Journal of Selected Topics in Quantum Electronics

9(5) 1275, 2003.
10.1109/JSTQE.2003.819472 (147 citations)

[3.6] Langbein, W., et al. *Heterodyne spectral interferometry for multidimensional nonlinear spectroscopy of individual quantum systems, Optics Letters*, 31(8), 1151, 2006. https://doi.org/10.1364/OL.31.001151 (66 citations)

Selected grants:

[G3.1] "HEMAN V: High Efficiency MANufacturing of VCSELs". Innovate UK, 102890, total award £285K.

[G3.2] "Research Foundation in Compound Semiconductor Technology" UK Research Partnership Investment Fund (UKRPIF), total award £17.3M.

[G3.3] "Compound Semiconductor Underpinning Equipment" EPSRC, EP/P030556/1, total award £2M.

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

Cardiff's research laid the foundation for the establishment in South Wales of a major technological cluster for the design, development and commercialisation of compound semiconductors. An initial partnership between Cardiff and IQE encouraged the company to maintain their manufacturing base in South Wales and further develop their presence in the region. The partnership has since 1) established a joint-venture company with £12M private investment and created 70 jobs; 2) attracted external investment and jobs to the cluster, including locating the UK's Compound Semiconductor Catapult and attracting private businesses to the region; and 3) enabled the foundation of the Newport Mega Foundry, directly creating 90 new jobs and safeguarding 545 jobs by preserving a UK manufacturing base.

4.1 Foundation of the Compound Semiconductor Centre

IQE is a 'pure-play' foundry that manufactures semiconductors using generic designs for customers' applications. The designs require independent demonstration of material performance, as well as full device characterisation and failure analysis for new product introductions. IQE partnered with Cardiff's School of Physics and Astronomy to fulfil that role.

Building on the foundation of Cardiff's ICS research facility, in July 2015 IQE and Cardiff University formed a new joint venture company, the Compound Semiconductor Centre (CSC). Described by IQE as a "*a key step in creating the World's first Compound Semiconductor Cluster*", IQE committed £12M investment to establish the company with the aim of developing and commercialising new products based on Cardiff intellectual property **[5.1**, p.26**]**. IQE confirmed that the CSC now has "*more than 70 staff dedicated to compound semiconductor materials technologies*" working across South Wales, closely aligned to the ICS to lead commercialisation of semiconductors **[5.2]**.

CEO and President of IQE, Dr Drew Nelson OBE, highlighted that Cardiff's research enabled a strategic link between the company and Cardiff University, particularly citing the characterisation of semiconductor laser gain media by the segmented contact method **[3.5]**, and heterodyne spectral interferometry **[3.6]**. Dr Nelson noted how Cardiff "*implemented and employed these techniques to support IQE*", and that as a result of this research and development, IQE strengthened its relationship with Cardiff "*ultimately resulting in our strategic decision to maintain and grow our manufacturing base in South Wales as part of an industrial cluster*" **[5.2]**.

4.2 Attracting external investment and jobs to the cluster

The growth of the Compound Semiconductor Cluster has directed millions of pounds of public and private investment to South Wales. In January 2016, Chancellor of the Exchequer George Osborne announced that the UK Government's £53M Semiconductor Catapult would be based in South Wales. Following his tour of Cardiff University, the Chancellor delivered a speech noting that he had "*been to Cardiff Uni to see brilliant work on semiconductors with companies such as IQE. So today I can tell you that we will establish a new UK national centre*

– based here in Wales – that will develop the semiconductors that are at the heart of modern technology" **[5.3]**.

The business case for the Compound Semiconductor Applications Catapult (CSA Catapult) was led by Dr Andy Sellars, now Strategic Development Director of CSA Catapult, who confirmed that Cardiff University's research made South Wales the optimal location for the investment: "*We were attracted to host the Catapult in South Wales because of the emerging cluster of expertise, particularly the strengths of Cardiff University's research in compound semiconductors and their industrial partnership with IQE"* **[5.4].**

The CSA Catapult is based in Newport, South Wales, comprising a 2,500-m^2 site with meeting and conference facilities, and specialist laboratories for the design, testing, integration, and validation of semiconductor designs to encourage commercialisation **[5.4]**. Since its formation, the CSA Catapult has introduced 76 new jobs to South Wales and fostered partnerships with 41 external companies to develop new product lines, including collaborations with Rolls-Royce, BMW, and BP **[5.4]**. Dr Sellars confirmed that the Catapult has "*introduced four high-growth companies valued at over £200M to South Wales, with additional companies developing plans to establish a design and manufacturing presence in the cluster*" **[5.4]**. These agreements are commercially sensitive, but Dr Sellars noted that expansion of companies was "*significantly motivated by the nearby expertise of the CSA Catapult and the South Wales Cluster*" **[5.4]**.

Another company introduced to South Wales is Rockley Photonics, an international fabless developer and designer of photonics-based systems. Dr Andrew Rickman, Chairman and CEO of Rockley Photonics wrote: "*Due to the presence of the expertise and the cluster we decided to make a strategic investment, to start activities and create jobs in the region*" **[5.5]**. The company introduced 21 team members into South Wales to establish its manufacturing capabilities and collaborate with Cardiff researchers to "*help develop the new product designs and manufacturing process innovation required to accelerate our product development plans*". **[5.5]**. Rockley Photonics estimates that, to date: "*we have added over £10M to the local economy through our work with suppliers and new job creation*" with expectation of further jobs and growth, including a £400,000 investment to the Compound Semiconductor Cluster **[5.5]**.

4.3 Launching the IQE Mega Foundry

With the expansion of the South Wales cluster, in May 2017 the Cardiff Capital Region (CCR) announced a £37.9M investment through their City Deal Wider Investment Fund, including provision of a vacant 30,000-m^2 building space for a new semiconductor foundry **[5.6]**. The investment was designed to secure further support for compound semiconductor activity in South Wales, specifically linking "*academic expertise at Cardiff University and a concentration of related firms*" **[5.6**, p.4**]**. Kellie Beirne, Director of the Cardiff Capital Region City Deal, stated that at "*key junctures, the work of [Cardiff University] – both through the Institute and more widely in relation to economic geography – has been critical to investment decisions*" **[5.7]**.

IQE was granted an 11-year lease of the building, with the intention to "*to make South Wales the centre of the worldwide production of Compound Semiconductor epi-wafers and to maintain its headquarters in South Wales*" **[5.2]**. In September 2017 IQE took possession of the building, and by September 2019 the company had invested £63.8M to establish IQE's Mega Foundry, with a commitment to invest a total of £375M **[5.6]**. The revitalised site now features 20 cleanrooms and services for up to 20 Metal Organic Chemical Vapor Phase Deposition (MOCVD) tools **[5.8]**. As of May 2020, the foundry has six MOCVD tools running in full mass production, with another four tools installed and production ready **[5.8]**. Beirne stated that, due to continuing strength in the research base and the Compound Semiconductor Centre joint venture, "*Cardiff University played an instrumental role in creating the conditions necessary in retaining IQE in the region*" **[5.7]**.

Dr Nelson confirmed that the Newport Mega Foundry generated around 90 high-skilled jobs across South Wales and led to multiple benefits by establishing and broadening IQE's product

offering. The Mega Foundry is now "*recognised as a leading global facility*", which has assisted attracting new customers and supplier relationships for IQE and the CSC joint venture **[5.2]**.

The CCR commissioned an independent assessment of its investment in the Newport Mega Foundry, with a report published in April 2020 detailing the outcomes of the Mega Foundry, as well as an overview of the South Wales Semiconductor Cluster **[5.6]**. The report found that alongside jobs located at the site, the Mega Foundry safeguarded a further 545 jobs across South Wales through securing a UK manufacturing base. In addition, as of December 2019 an estimated 956 indirect and induced jobs were secured across South Wales through construction and supply chains for the Mega Foundry **[5.6** p.9**]**.

Taking a wider view, the CCR report specified several key indications of positive growth for the Cluster, namely: the decision to locate the CSA Catapult in South Wales, the growth of an active industry network, and the strength of Cardiff's research capacity in this area **[5.6]**. In particular, the report noted that "*Cardiff University's academic specialisms (for example through the Institute of Compound Semiconductors) are already a key driver of the region's strengths in the sector*" **[5.6]**. The CCR report noted that the Semiconductor Cluster had helped integrate multiple businesses in the region, highlighted by industrial partners who reported that: "*there had been much more joint networking and sharing of ideas and challenges in recent years*" stemming from projects such as the Newport Mega Foundry **[5.6]**, in turn "*igniting supply chains across the region*" **[5.7]**.

4.4 Summary

As the CEO of IQE, Dr Drew Nelson OBE, stated: "*the excellent science base at Cardiff University is a major contributing factor to the success of the cluster in South Wales and IQE's continued location in south Wales*" **[5.2]**. As the R&D base for the Compound Semiconductor Cluster, Cardiff's research enabled a wider process that has attracted private companies, investment, and job creation in the South Wales region.

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

[5.1] IQE Financial Report and Annual Accounts 2015

[5.2] Testimony: Dr Drew Nelson OBE, CEO & President of IQE PLC

[5.3] Chancellor on challenges facing UK economy in 2016. Script of speech by Chancellor of the Exchequer, George Osborne MP. Delivered 7 January 2016

[5.4] Testimony: Dr Andy Sellars, Strategy Development Director, CSA Catapult

[5.5] Testimony: Dr Andrew Rickman, Chairman and CEO, Rockley Photonics

[5.6] Independent Evaluation (National Evaluation Panel) of Local Growth Interventions: Cardiff Capital Region City Deal Director, Gateway Review – One Year Out Report. Cardiff Capital Region Cabinet, 18 May 2020, SQW

[5.7] Testimony: Kellie Beirne, Director of the Cardiff Capital Region City Deal

[5.8] IQE Annual Report and Financial Statements 2019