Institution: De Montfort University		
Unit of Assessment: 12		
Title of case study: Infra-red micro-thermography for electronic devices		
Period when the underpinning research was undertaken: 2000 to 2017		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Dr C.H. Oxley	**Role(s) (e.g. job title):** Reader Honorary Senior Research Fellow	**Period(s) employed by submitting HEI:** October 1999–October 2016 and 2018–2020
Period when the claimed impact occurred: August 2013 to December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

A DMU team led by Dr C.H. Oxley has undertaken successful research into thermal measurement of electronic devices. In particular, the team has developed a novel microparticle infra-red sensor (MPIRS) technique to increase the accuracy of point infra-red (IR) thermal measurements. During the assessment period, the team's thermal research led to sales worth GBP [text removed for publication] for Teledyne e2v (formerly e2v), [text removed for publication] GBP for Filtronic Broadband Ltd, USD [text removed for publication] /year for MACOM Technology Solutions Ltd, and GBP [text removed for publication] for Silson Ltd. Moreover, Quantum Focus Instruments Corporation was offering the MPIRS technique to its customers, thus giving the company a competitive advantage.

2. Underpinning research

Dr C.H. Oxley has been involved in the research and manufacture of electronic devices in industry and academia for nearly 50 years. At Plessey Research Caswell (between 1970 and 1986), he was chief physicist for gallium arsenide (GaAs) transistors, securing funding from MoD, ESA, INTELSAT and private venture. From 1986 to 1989, he was Semiconductor Manager for Plessey Microwaves. He joined academic staff at DMU in October 1999 and initiated research work on thermal optimisation of microwave semiconductor devices. In 2001, he won an EPSRC grant [G1] in collaboration with GEC Research (Caswell) and the MoD. The project improved understanding of the thermal behaviour of the saturation velocity in gallium nitride (GaN) high electron mobility transistors (HEMT) [R1, R2] and the active thermal impedance in monolithic microwave integrated circuits (MMIC) [R2]. EPSRC rated the work as 'tending towards outstanding'. In parallel, Oxley established an industrial collaboration with e2v Ltd (Lincoln) to improve the thermal performance of millimetric wave (77 GHz) Gunn diodes for adaptive automotive cruise control. The research work comprised computation and thermal measurement techniques to optimise the design of the integrated heatsink and bonding configurations to improve the thermal handling capability of vertical millimetric GaAs Gunn diodes. This work was commercially sensitive so little was published [R3]. The thermal work with e2v, MoD and GEC Research led to an EPSRC award in 2005 [G2]. The research outcomes included making more accurate IR temperature measurements on transparent semiconductors and metal contacts. Both a numerical computation method [R4], as well as a novel high emissivity MPIRS [R5] were developed. The novel MPIRS is very versatile, enabling a more accurate IR surface thermal measurement on materials with low surface emissivity, for example gold metal contacts, and on materials transparent to IR radiation, for example multilayer semiconductor devices [R5]. This approach totally eliminated the conventional method of coating semiconductor devices with a high emissivity paint resulting in lateral heat reducing the thermal spatial resolution and damaging the device. The MPIRS consists of a 3–20 μm diameter sphere fabricated from a high emissivity material placed in iso-thermo contact with the device surface, at the point the temperature is to be measured. By eliminating the high emissivity coating, the thermal spatial resolution is much improved (approximately 0.3 microns) without damaging the

device, thereby adding an element of environmental friendliness. The research on enhancing thermal device design and the novel MPIRS technology secured a number of successful industrial and university collaborations. For example, in 2009, it led to a large collaborative EPSRC project [G3], partnering with Bristol (EP/H011366/1), Glasgow (EP/H011862/1) and Aberdeen (EP/H012532/1) universities. The project initiated groundbreaking research [R6] in the design and performance of GaAs and indium phosphide (InP)-based planar Gunn diodes using novel thermal management technologies, for example aluminium gallium arsenide / gallium arsenide (AlGaAs/GaAs) integrated micro-coolers.

3. References to the research

[R1] Oxley, C.H. and Uren, M.J. (2005) 'Measurements of unity gain cutoff frequency and saturation velocity of a GaN HEMT transistor', *IEEE Transactions on Electron Devices*, 52(2): 165–169; DOI: 10.1109/TED.2004.842719

[R2] De Montfort University (2004), Final Report for EPSRC GR/R21073/01, October 2004 (can be supplied on request).

[R3] Hopper, R.H., Oxley, C.H., Seddon, R., Foulger, R. and Priestley, N. (2008) 'Infrared radiance and temperature measurements on the mesa side of Gunn diodes', *IET Science, Measurement & Technology*, 2(1): 39–41; DOI: 10.1049/iet-smt:20070007

[R4] Oxley, C.H., Hopper, R.H., Hill, G. and Evans, G.A. (2010) 'Improved infrared (IR) microscope measurements and theory for the micro-electronic industry', *Solid-State Electronics*, 54(1): 63–66; https://doi.org/10.1016/j.sse.2009.09.022

[R5] Hopper, R.H., Haneef, I., Ali, S.Z., Udrea, F. and Oxley, C.H. (2010) 'Use of carbon micro-particles for improved infrared temperature measurement of CMOS MEMS devices', *Measurement Science and Technology*, 21 art. 045107; https://doi.org/10.1088/0957-0233/21/4/045107

[R6] Glover, J., Khalid, A., Cumming, D., Dunn, G.M., Kuball, M., Montes Bajo, M. and Oxley, C.H. (2017) 'Thermal profiles within the channel of planar Gunn diodes using micro-particle sensors', *IEEE Electron Device Letters*, 38(9): 1325–1327; DOI: 10.1109/LED.2017.2731961

Grants:

[G1] EPSRC GR/R21073/01, Large signal model including temperature effects for gallium nitride power HEMT, 2001-2004, £60,201. PI C.H. Oxley.

[G2] EPSRC EP/C511085/1, Accurate and repeatable measurement of the thermal profile of RF solid state devices under active operation, 2005-2008, £235,246, PI C.H. Oxley.

[G3] EPSRC EP/H012966/1, Novel thermal management of power electronic devices: High power high frequency planar Gunn diodes, 2010-2013, £184,707, PI C.H. Oxley.

4. Details of the impact

Between August 2013 and December 2020, Oxley's research expertise in semiconductor devices and his innovations in thermal measurement have directly contributed to the economic growth of companies involved in GaAs and GaN device technologies. In addition, the novel MPIRS technology has enabled more specialist thermal measurements to be made where a very accurate thermal mapping is required for optimising the thermal design.

- The joint research work with Teledyne e2v led to the thermal optimisation [R3, R4, R5] of the 77 GHz Gunn diode for automotive cruise control systems by optimising the heatsink, die and wire bonding technologies [C1]. The designed 77 GHz Gunn diodes were superseded in 2008 by an MMIC solution. However, these diodes continued to be supplied for spares and repairs until the end of 2013. The company's repair business for automotive cruise control between August 2013 and December 2013 amounted to a company revenue (pro rota) of approximately GPB [text removed for publication] [C1]. The heatsink and die and wire technologies developed for automotive cruise control systems were also used in the company's Gunn diode

products for Doppler motion detectors, seeker radar for missile guidance systems, and millimetric sources for security imaging systems and non-destructive testing. The sales of these products from August 2013 to December 2019 is estimated to be GBP [text removed for publication] [C1], giving a total revenue of GBP [text removed for publication] over the same period.

- The work with Filtronic Broadband Ltd, a major player in the design and manufacture of micro-wave and mm-wave modules for the point to point backhaul and aerospace markets, included thermal measurement [R2, R5] of GaAs and GaN transistors and MMICs with reference to optimisation of die-attach, packaging and reliability studies [C2]. The MMICs were introduced in 2014 in Filtronic mm-wave products with sales worth [text removed for publication] GBP by August 2019 [C2]. The impact of the unique thermal measurement techniques developed by DMU also manifests itself in terms of the reliability demonstrated by Filtronic's products as the cost of epidemic failures due to inadequate thermal design would be very significant [C2].
- There was significant research collaboration with MACOM Technology Solutions between 2013 and 2017 on thermal optimisation and measurement [R1, R2, R4, R5] of GaAs, GaN, SiC power transistors and MMICs. This included temperature measurements to revise and confirm device models/assumptions to create designs that behave well under extreme temperature [C3] and for product qualification (JEDEC High Temperature Operating Life), as well as lifetime evaluation [C3]. The developed technology for finely manipulating the MPIRS sensor [R6] was used to assess the heat distribution in the channel region of the sub-micron gate structure, which identified complex co-heating problems between the transistor cells, as well as voiding in die-attach methods [C3]. This enabled optimisation in the channel design and die bonding technologies of the transistor structures and led to a new range of power amplifiers, low noise amplifiers, phase shifters and attenuators whose sales were worth USD [text removed for publication] /year between August 2013 and June 2020 and led to a growth in the number of engineers employed by the company [C3].
- Working with Silson Ltd, DMU used the MPIRS [R5, R6] technology to characterise the heating performance of environmental cells used in X-ray scanning and transmission microscopes. The environmental cell consists of a silicon membrane with a micro-heater embedded in it. The micro-heater must be designed to give a uniform high temperature over a small area [C4]. The characterisation of the heating performance enabled Silson Ltd to show customers a usable heating profile, and the company reaped sales (pro rota) of GBP [text removed for publication] between August 2013 and December 2018 on this product [C4].
- Quantum Focus Instruments designs and manufactures advanced failure analysis microscope systems and temperature measurement microscope systems for the semiconductor industry. Quantum Focus also offers temperature mapping services. In 2019, Quantum Focus was offering the MPIRS technology [R5] to its customers, thus giving the company a competitive advantage. The owner of Quantum Focus states that the MPIRS technology avoids the lateral heat spreading, so enabling a more accurate measurement of the peak temperature [C5].

5. Sources to corroborate the impact

[C1] Testimonial from Senior Engineer, Teledyne e2v.

[C2] Testimonial from Chief Scientist, Filtronic Broadband Ltd.

[C3] Testimonial and email from former Engineering Director and site lead at MACOM Technology Solutions. The email confirms that the impact described in the testimonial occurred during the REF 2021 assessment period.

[C4] Testimonial from Managing Director, Silson Ltd.

[C5] Email from Founder and President, Quantum Focus Instruments Corporation.