Institution: University of Bristol

Unit of Assessment: 9 – Physics

Title of case study: Raman thermography – Enabling semiconductor companies to improve the reliability, performance and lifetimes of their devices

1. Summary of the impact

Raman thermography, a new technique for measuring channel temperature in semiconductor electronic devices developed at the University of Bristol, has been used by many companies to characterise their semiconductor devices. The technology has enabled companies to develop more robust, reliable, higher performing devices and circuits for high-end space, radar, communication and power conversion applications. This is illustrated here in detail on the example of the company, United Monolithic Semiconductor (UMS) (Germany-France), which used the technique to improve the lifetime of its Gallium Nitride (GaN) and Gallium Arsenide (GaAs) semiconductor devices so that they meet customer requirements for product qualification. Corresponding impact resulted for the companies TriQuint (USA), Northrup Grumman (USA), QinetiQ (UK), Selex Galileo (UK & Italy), NXP (UK & Netherlands), Thales Alenia Spaciale (France), Sharp (Japan) and Hitachi Cable (Japan).

2. Underpinning research

Reliable operation of microwave and switching devices made of the semiconductor materials Gallium Nitride (GaN) and Gallium Arsenide (GaAs) is essential for their deployment in space, radar, communication, and power conversion applications, however device lifetime is exponentially inversely related to device temperature.

Detailed knowledge of the device channel temperature resulting from Joule's heating, ie the temperature in the device region that determines its performance and lifetime, is therefore essential for qualifying these technologies for commercial and military standards. As critical device dimensions in this semiconductor technology range from the sub-micron to only a few micron range, accurate temperature measurements with sub-micron resolutions is essential. This, however, has not been achievable with current common thermography techniques such as infra-red thermography with its only many micron spatial resolution.

In 2002 [1] Prof. Kuball's group demonstrated that Raman scattering spectroscopy can be applied to measure channel temperature in these and other semiconductor devices with sub-micron spatial resolution throughout the device structure [2].

The technique of Raman thermography developed in Bristol is fundamentally based on the fact that the energy of atomic lattice vibrations, so-called phonons, in the semiconductor is dependent on the device temperature. Temperature can therefore be determined with 0.5 micron resolution by measuring changes in phonon frequencies between when a device is switched on and off. Such spatial resolution can be achieved using standard microscope objectives, if even smaller dimensions (100-300nm) are required, then solid immersion lenses can be employed.

A key challenge in the development of the Raman thermography technique was the separation of temperature effects and stress/strain effects that influence the phonon energy in the semiconductor devices [3]. This involved gaining a detailed understanding of how temperature and stress/strain affect phonon modes, and how this can be taken advantage of in a semiconductor device context. This understanding was used to develop the technique to accurately quantify channel temperature in semiconductor devices, and also heat transfer across interfaces inside the semiconductor devices, including the impact of material imperfections such as dislocations [4]. This also included the implementation of the ability to measure temperature transients in semiconductor devices with nanosecond time resolution, which is essential both for microwave and for power switching devices [5]. The research was subsequently used to thermally optimize semiconductor structure for optimized devices of high reliability [6].

Apart of **Professor Kuball** (in Bristol from 1997), PhD students and postdoctoral researchers of his research group contributed to this development and subsequent impact: **Dr Hayes** / PhD student 2002-2005, **Dr Pomeroy** / PhD student 2003-2006 & postdoctoral researcher 2006 – present; **Dr Sarua** / postdoctoral researcher & subsequently research fellow and lecturer, 2003 – present; **Dr G. Riedel** / PhD student 2006-2009; **Dr. T Batten** / PhD student 2007-2010; **Dr R. Simms** / PhD student 2007-2010; **Dr N. Killat** / PhD student 2009-2012 & postdoctoral researcher 2012-2013.

3. References to the research

[1] *M. Kuball, J.M. Hayes, M.J. Uren, T. Martin, J.C.H. Birbeck, R.S. Balmer, and B.T. Hughes, *Measurement of temperature in high-power AlGaN/GaN HFETs using Raman scattering* **,** IEEE Electron Dev. Lett. **23**, 7 (2002), doi: 10.1109/55.974795

[2] J.W. Pomeroy, M. Kuball, D. J. Wallis, A. M. Keir, K. P. Hilton, R. S. Balmer, M. J. Uren, T. Martin, and P.J. Heard, *Thermal mapping of defects in AlGaN/GaN heterostructure field-effect transistors using micro-Raman spectroscopy*, Appl. Phys. Lett. **87**, 103508 (2005), doi: 10.1063/1.2041823

[3] A. Sarua, Hangfeng Ji, M. Kuball, M. J. Uren, T. Martin, K. J. Nash, K. P. Hilton, and R. S. Balmer, *Piezoelectric strain in AlGaN/GaN heterostructure field effect transistors under bias*, Appl. Phys. Lett. **88**, 103502 (2006), doi: 10.1063/1.2182011

[4] G.J. Riedel, J.W. Pomeroy, K.P. Hilton, J.O. Maclean, D.J. Wallis, M.J. Uren, T. Martin, U. Forsberg, A. Lundskog, A. Kakanakova-Georgieva, G. Pozina, E. Janzén, R. Lossy, R. Pazirandeh, F. Brunner, J. Würfl, and M. Kuball, *Reducing Thermal Resistance of AlGaN/GaN Electronic Devices Using Novel Nucleation Layers*, IEEE Electron Dev. Lett. **30**, 103 (2009), doi: 10.1109/LED.2008.2010340

[5] *G.J. Riedel, J.W. Pomeroy, K.P. Hilton, J.O. Maclean, D.J. Wallis, M. J. Uren, T. Martin, M. Kuball, *Nanosecond Time-scale Thermal Dynamics of AlGaN/GaN Electronic Devices*, IEEE Electron Dev. Lett. **29**, 416 (2008), doi: 10.1016/j.sse.2010.11.002.

[6] *A. Manoi, J.W. Pomeroy, N. Killat, and M. Kuball, *Benchmarking of Thermal Boundary Resistance in AlGaN/GaN HEMTs on SiC Substrates: Implications of the Nucleation Layer Microstructure*, IEEE Electron Dev. Lett **31**, 1395 (2010), doi: 10.1109/LED.2010.2077730

Grants supporting this research and its application include 11 grants with value in excess of £3M from the UK Technology Strategy Board (TSB) and Engineering and Physical Sciences Research Council (EPSRC), the European Defense Agency (EDA), European Space Agency (ESA), EC Framework Programme 7 (FP7), the US Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA). Highlight grants include:

- *Next Generation GaN-on-Diamond RF Power Amplifier* (PI Kuball, **DARPA (USA)**, $150k, 2011-2013)
- *MANGA (manufacturable GaN): SiC substrates and GaN epi wafers supply chain* (PI Kuball, **EDA (EC)**, £300k, 2010-2014).
- *Design for Reliability of Future Technologies (DRIFT)* (PI Kuball, **ONR (USA)**, $500k, 2008-2013).
- *GaN Reliability and Technology Transfer Initiative* (PI Kuball, **ESA (EC)**, Euro 150k, 2008-2010).
- *Novel time-resolved thermal imaging: AlGaN/GaN heterostructure field effect transistors* (PI Kuball, **EPSRC**, £400k, 2006-2010).
- *Thermal imaging of active AlGaN/GaN field effect transistors using micro-Raman spectroscopy* (PI Kuball, **EPSRC**, 2004-2007, £ 370k).

4. Details of the impact

Linking the research to impact

Raman thermography technology developed at Bristol was made available to UK, European, US and Asian companies to characterize their semiconductor electronic devices, from 2007 onwards. The companies were made aware of the new technique developed at Bristol at European Space

Agency (ESA) – Ministry of Defense (MoD) workshops in Europe, CS-Mantech in the USA and other industry meetings. As result of this, measurements were performed in Bristol on 100s of industry supplied devices, paid by industry (total in excess of £200k), to thermally optimize device structures, determine device lifetime, and ultimately for the qualification of new technology to fulfil industry and/or military standards to generate industrial impact. This work also resulted in a patent [A].

Nature, extent and beneficiaries of the impact

The research enabled companies to develop more robust, reliable, higher performing devices and circuits for high-end space, radar and communication applications, in particular using GaN and GaAs technology. Channel temperatures determined on the devices were correlated against device failure rates, to predict device lifetime. The results were used by the companies to optimize processing and device design for enabling better and more reliable devices. Typically lifetimes of these devices in the early stage of our interaction with the companies were in the 1000s of hours, however, at least 10^6 hours in many cases 10^9 hours are needed for most commercial applications which most companies we work with now achieve.

A typical example of how this technology has been implemented by industry is United Monolithic Semiconductor (UMS), a joint venture between THALES (France) and EADS GmbH (Germany) [B]. UMS is seen by European defence and Space agencies and companies as the European supplier of US International Traffics and Arms Regulation (ITAR) free GaN technology, as the export of GaN technology from the US is heavily restricted.

Dr. H. Blanck from UMS states [B]: "*As a result of these channel temperature measurements we were able to freeze and qualify our GaN technology, in addition support the further development of our current commercial GaAs products, also providing customers with device implementation critical technology information*", ie UMS was able to implement defined new production processes ('freeze') that are now used for providing commercial GaN devices and circuits, which meet the needed reliability criteria, and to support GaAs customer needs. There is no other experimental technique other than Raman thermography available that can achieve the required accuracy in channel temperature information for the qualification of GaN and GaAs technology [C].

Similar work to characterize channel temperature in semiconductor devices was carried out for TriQuint (USA) [D], Selex Galileo (UK & Italy) [E], furthermore for Thales Alenia Spaciale (France), NXP (UK & Netherlands), QinetiQ (UK), Northrop Grumman (USA), Sharp (Japan) and Hitachi Cable (Japan). Raman thermography was for example used by TriQuint USA in 2010 [D] to validate its thermal simulation models to enable accurate channel temperature quantification for its GaN technology, to enable its commercial GaN technology development. It also was used to enable the development of the TriQuint GaN-diamond integrated transistor in 2012/2013 which featured in recent TriQuint and DARPA press releases [F] developed for high end US defense applications.

Due to the uniqueness of the Bristol developed equipment, the measurements were performed in the laboratories of the University of Bristol, with devices sent by the companies or in cases Research & Development engineers of the companies travelled with the devices to Bristol due to their sensitive nature (including from the USA). The University of Bristol is in process of licensing the IP of Raman thermography to the semiconductor equipment manufacturer Quantum Focus Instruments (QFI), San Diego, USA, also to develop a low cost version of the Raman thermography system.

Evidence to corroborate the impact

UMS states [B] "*For reasons of commercial confidentiality it is not possible to give sales figures or any equivalent. However, I can confirm that UMS have invested significantly in commercialising the GaN technology, and that it now forms a strategic part of our business generating significant revenue. In addition, GaAs RF technology already is a large part of our sales figures. The technology developed at the University of Bristol and its use on our technology significantly benefited us financially. In 2009, the headcount at UMS was 255 people, for sales of 47M€.*"

It is clear that the work done at Bristol has enabled the company to enter the GaN market earlier than would otherwise have been possible, giving it a competitive advantage over its rivals.

As due to confidential reasons sales figures can not be disclosed by UMS, the large commercial impact of the Bristol development for UMS is demonstrated by its willingness to directly pay for contract measurements on their devices in Bristol. These measurements were performed on a daily rate charge basis of £1200 + VAT, typically within 3-5 measurement days in each measurement campaign. UMS states [B] "*our direct financial contribution to the University of Bristol for contract measurements well exceeded £50,000, in addition to the direct benefits to us from measurements performed by Bristol on our technology paid to Bristol by ESA under the GREAT^2 contracts, and by the European Defence Agency (EDA) under the MANGA (manufacturable GaN) contract.*" Direct UMS contract measurements were performed 2007 – present. Financial contributions to Bristol for contract measurements from ESA ('High power GaN HFET for ESA applications - GREAT^2 [G]) amounted to Euro 150k (2008-2014), and by the European Defense Agency (MANGA [H]) to £300k (2010-2014).

5. Sources to corroborate the impact

[A] Patent *Measurement of semiconductor temperature by Raman scattering*, M. Kuball and J.M. Hayes, US Patent 6,786,637. Describes the experimental methodology for temperature measurement in semiconductor devices, to measure temperature with submicron spatial resolution which was used for this Impact Study and describes the Bristol IP rights of this development.

[B] Support letter from United Monolithic Semiconductor, dated 15 April 2013, Dr. Herve Blanck, Manager Technology Research and Development, UMS. Dr. H. Blanck verifies that UMS was able to implement new production processes and for the commercial impact of the Bristol work for UMS.

[C] "*Bristol University and Quantum Focus Set to Revolutionise Thermal Imaging*", III-V Review **18** (7), 30 (2005). Describes the joined development of a commercial Raman thermography tool for semiconductor industry, by Quantum Focus Instruments, San Diego, USA and the University of Bristol.

[D] Contact name: Dr. Jose Jimenez, Development Engineering Fellow, TriQuint USA; N. Killat, M. Kuball, T. Chou, U. Chowdury, and J, Jimenez, *Temperature assessment of AlGaN/GaN HEMTs: A comparative study by Raman, electrical and IR thermography*, Proceedings of International Reliability Physics Symposium (IRPS) 2010. Raman thermography has been used by TriQuint to validate its thermal simulation models, for its commercial products.

[E] Contact name: Dr. Graham Morrison, Senior Engineer, Selex Galileo UK; J.W. Pomeroy, M. Bernardoni, D.M. Craig, G.D. Morrison, B. Wilkinson, and M. Kuball, *Comprehensive Thermal Analysis of Pulsed GaAs HPAs for Lifetime Estimation*, Proceedings of International Microwave Symposium (IMS) 2013. Characterization of channel temperature in semiconductor devices to validate Selex Galileo thermal device models to support and enable advanced circuit design for product development.

[F] www.triquint.com/newsroom/news/2013/triquint-achieves-gan-on-diamond-breakthrough & www.darpa.mil/NewsEvents/Releases/2013/04/30a.aspx. Development of the TriQuant GaN-diamond integrated transistor, as part its line of future products, funded as part of the USA Defense Advanced Research Projects Agency (DARPA) project NJTT.

[G] http://www.compoundsemiconductor.net/csc/features-details/19734325/Europe-improves-reliability-of-GaN-microwave-devices-for-space-application.html. Impact of GaN technology for European Space Industry as result of the European Space Agency (ESA) project GREAT2, and therefore Bristol impact as part of this project for European development of US Import and Export Restriction (ITAR) GaN technology.

[H] M. Mikulla, S. Storm, N. Helenius, M. Poisson, E. Janzen, E. Zanoni, and M. Kuball, *Manga: Manufacturable GaN*, Proceedings of Microwave Integrated Circuits Conference 2011. Description of Bristol contributions to the ESA project GREAT2 to develop European ITAR free GaN technology.