Institution:
University of Manchester

Unit of Assessment: UoA13b Electrical and Electronic Engineering

Title of case study: Molecular Beam Epitaxy applied to quantum devices for industrial applications

1. Short summary of the case study

This University of Manchester research underpins UK industry's global position in millimetre-wave imaging and ultra-high-precision sensing. These are key technologies in a range of industrial, medical and consumer electronics applications. The devices and methods developed by the research team are now used by a range of companies leading to economic impacts for the UK in strong export markets. In this case study we provide examples of impacts that support commercial sales in excess of £300m by UK SME and FTSE-listed companies in three sectors: automotive radar (e2v), terahertz imaging (TeraView), and linear encoders (Renishaw PLC).

2. Underpinning research

The impact is based on research conducted at The University of Manchester from 1993 to date.

The key researchers were:
Professor M. Missous (1993-date)
Dr Novak Farrington (2007-2009, PDRA)
Dr Nassim Haned (1999-2003: PhD student)
Dr M. Alduraibi (2006-2010: PhD student)
Dr B. Boudejelida (2006-2009: PDRA)
Dr J. Sexton (2001-2005: PhD student, 2006 -2010: PDRA)

The common thread of the underlying research is the ability to synthesize and make devices that emit and detect radiation from direct current (DC) to mm-waves to terahertz frequencies. The main aim of the research has always been to develop high-yielding, high-performance semiconductor components in very high performance but cost-sensitive markets. The key research findings and insights were as follows:

1. Optimizing the growth and anneal temperature steps using Molecular Beam Epitaxy (MBE) produced high-performance devices that could be precisely tailored for specific functions (emitters or detectors) of terahertz radiation. [1,4]

2. MBE was used to grow GaAs devices with graded-gap hot-electron launchers, leading to high-yielding, temperature-stable Gunn diodes which, in turn, led to devices with higher DC to radio-frequency (RF) efficiency at 77GHz.[2,5]

3. The first demonstration of nanoTesla magnetometry in semiconductors materials, produced by MBE growth of highly sensitive 2-Dimensional electron gas (2DEG) Hall sensors. This opened the way to, very high resolution 2-Dimensional arrays for magnetic imaging. [3,6]

3. References to the research

The research was published in leading peer reviewed international journals such as IEEE journal of Quantum Electronics, Applied Physics Letters and Sensors and Actuators. It was also presented at major conferences such as IEEE MTTS and SPIE. Citations are taken from the Scopus database on 24th July 2013.

Key publications

1. "Optimization of photomixers and antennas for continuous-wave terahertz emission" Gregory, IS; Baker, C; Tribe, WR, and Missous M. *IEEE Journal of Quantum Electronics* Volume: 41 Pages: 717-728 (2005) Cited: 48 times DoI 10.1109/JQE.2005.844471

2. "A ruggedly packaged D-B and GaAs Gunn diode with hot electron injection suitable for volume manufacture " Farrington N.E.S.; Norton P; Carr M.; Sly J and Missous, M. *IEEE MTT-S International Microwave Symposium Digest*, art. no. 4633158 , pp. 281-284 (2008) Cited: 3 times DOI: 10.1109/MWSYM.2008.4633158

3. "Nano-tesla magnetic field magnetometry using an InGaAs-AlGaAs-GaAs 2DEG Hall sensor" Haned N and Missous M, *Sensors and Actuators A: Physical* , 102 (3): Article Number 216-222 (January 1 2003) Cited: 12 times DOI 10.1016/S0924-4247(02)00386-2

Other publications

4. "Continuous-wave terahertz system with a 60 dB dynamic range" Gregory, IS; Tribe, WR; Baker, C, M. Missous et al. *Applied Physics Letters*, Volume: 86 Issue: 20 Article Number: 204104 (2005) Cited: 42 times DOI 10.1063/1.1935032

5. "Physical Modelling of a Step-Graded AlGaAs/GaAs Gunn Diode and Investigation of Hot Electron Injector Performance" Amir F.; Farrington N.; Tauqeer T. and Missous M. *7th International Conference on Advanced Semiconductor Devices and Microsystems*, October 12-16, 2008, ASDAM 2008, Conference Proceedings Pages: 51-54 Published: 2008 Cited: 3 Times DOI:10.1109/ASDAM.2008.4743356

6. "Submicron sensors of local electric field with single-electron resolution at room temperature" Barbolina, II; Novoselov, KS; Morozov, SV and M. Missous, .*Applied Physics Letters* Volume: 88 Issue: 1 Article Number: 013901 (2006) DOI:10.1063/1.2159564, Cited: 14 times

4. Details of Impact

Context

Devices for generating and detecting radiation in the DC to THz range are important in a range of applications. The development of new technology by the Manchester team has improved the performance of commercial systems by realising devices with higher sensitivity, better temperature stability and higher signal-to-noise ratio. These improvements have led to more reliable and cost-effective products.

Pathways to impact

The research was presented at major conferences on mm-wave and THz including IEEE MTTS and IRMMWW-THz and published in leading journals. This resulted in significant interest from the sensor and THz communities, including both academic and commercial. Potential routes to market were developed in consultation with the University's IP company (UMIP). This initiative was also supported by a KTP fellowship with the UK SME e2v. Much of the research work was conducted with companies including e2v ltd, Teraview ltd, Selex Galileo, VGSemicon and QinetiQ. This work resulted in the development of high-sensitivity magnetic sensors, broadband terahertz sources and detectors based on Gunn diodes and ultra-high speed photoconductive switches using low temperature grown GaAs. A significant pathway has been supplying wafers on a commercial basis to these companies as detailed in the following.

Reach and Significance of the Impact

The success in developing these technologies is best illustrated by reference to specific industrial outlets that have made direct use of the research:

(i) **Automotive radars:**

The research team designed, produced and delivered to the British company e2v ltd novel epitaxial wafers which had better temperature stability than those used in the industry [from -80 °C in cold start to over +60 °C] and added efficiency at 77GHz. Since 2008 this work led to the delivery of over 100 wafers, each containing up to 10,000 devices for car radars. These high-end products are integrated in the Bosch autonomous cruise control system fitted in BMW and Audi cars.

As a result of the research, e2v has manufactured over 500,000 millimetre-wave Gunn diode devices for Bosch [A] resulting in revenue of approximately £6m, all of which represents UK export income [B]. These Gunn diode devices are incorporated into Bosch ACC1 and ACC2 products that are fitted as the automatic cruise control option on high end Audi and BMW cars. Since this cruise control option became available circa 430,000 vehicles on which this customer option is available have been produced [B].

(ii) **TeraHertz imaging:**

The research developed new epitaxial layers based on low temperature grown GaAs and InGaAs with unprecedented lifetime and resistivity, leading to THz imaging systems with much improved signal-to-noise ratios and which has been supplied to Teraview ltd for over 6 years now. These devices are enablers in the company's pulsed imaging and spectroscopy systems. To date over 30 wafers have been supplied corresponding to over 10,000 devices. Teraview ltd equipment is used in the medical imaging of cancer and industrial inspection. Launched in 2008 [C] around 30 *TPI imaga* and *spectra,* commercial terahertz imaging systems have been sold at a cost of approximately £150k-£200k each. These have been supplied to laboratories in Europe, North America and the Far East with a total UK export value in excess of £6m [D].

(iii) Ultra-high-precision sensing

A spin out company, Advanced Hall Sensors (AHS) ltd, was established in 2008 and this company has been key in producing 2-Dimensional Electron Gas Hall Effect sensors for ultra-high-precision sensing. These sensors have the highest sensitivity of any Hall sensor in the market. Over 3 million sensors have been supplied to Renishaw PLC by AHS since 2008. Renishaw PLC has stated: "The Hall sensors supplied play a vital enabling role in the high performance linear encoders for industrial, photovoltaic and consumer electronics" [E]. The encoder division of Renishaw PLC is a £300m per year business. The supplied Hall sensors play a vital enabling role in the high performance linear encoders for Industrial, Photovoltaic (PV) and consumer electronics [E].

5. References to corroborate the contribution, impact or benefit

A. Letter from Chief Engineer, Microwave and Semiconductor Devices, e2v Ltd confirming the role of the research in solving the industrial problem and the use as a commercial product supplied to Bosch for BMW and Audi

B. Email from Chief Engineer, Microwave and Semiconductor Devices, e2v Ltd confirming the sales value to the company of the work.

C. News release dated March 2008 announcing the launch of the terahertz spectrometer by TeraView based on the Manchester research.

D. Letter from Team Leader, Core Technologies Group, Teraview ltd confirming the number and value of devices produced

E. Letter from Senior Buyer, Supply Chain Development at Renishaw PLC, confirming the size of the encoder division business enabled by this technology