Institution:
University of Cambridge

Unit of Assessment:
UoA9

Title of case study:
The development and exploitation of Terahertz technology

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

The development by Cambridge University staff of compact semiconductor sources and detectors of Terahertz radiation has opened up this part of the electromagnetic spectrum to commercial use for the first time, enabling many applications. In medicine these applications include the analysis of drugs and the detection and imaging of cancer; in security applications the detection and imaging of explosives; and in the semiconductor industry the detection and imaging of buried defects in semiconductor wafers. High power Terahertz lasers are used in gas sensors, for imaging and as local oscillators. This technology has been exploited by a spin-off company TeraView which has 25 employees, has raised £16M in funding, £3.5M since 2008, and has sold 70 imaging systems, half since 2008 at an average cost of $300K each.

2. Underpinning research (indicative maximum 500 words)

Terahertz radiation research in the Cavendish Laboratory originated with the University of Cambridge Department of Physics' long-standing interest in semiconductor physics. The Semiconductor Physics Research Group started to develop molecular beam epitaxy (MBE) growth methods for III-V semiconductors in 1986 and work over the next 15 years provided the basis for the subsequent THz technology. Within the relevant period, the Group, in partnership with Toshiba Research Europe Ltd. based at the Science Park in Cambridge, pioneered the emission and detection of Terahertz radiation using semiconductor devices. The importance of the technology was clear from the start, and so spin-off company TeraView was founded in 2000 concurrently with the key research work, done from then onwards. Professor Sir Michael Pepper, co-founder of TeraView and Professor at the Department throughout the period until 2008, led the Semiconductor Physics Group and was supported by Dr E H Linfield (Research Associate from 1991, Assistant Director of Research 1997 to 2004) and Dr A G Davies (Research Fellow 1995 to 2002) working on Terahertz device design and testing with Dr H E Beere (Research Associate from 1999, Senior Research Associate from 2004) working on MBE growth of materials for devices.

In 2001 concepts and simulation of terahertz generation in GaAs devices irradiated with very short laser pulses were developed at the Cavendish Laboratory [1]. This work led to the development of the MBE growth of suitable GaAs and the fabrication of devices for broadband sources and detectors of terahertz radiation [2]. This research was undertaken entirely at the Cavendish Laboratory and published in 2003.

The results of the research stimulated collaboration with TeraView. Low-temperature MBE growth of GaAs and sample annealing were carried out in the Department of Physics and carrier lifetime measurements were carried out at TeraView. This study allowed the development of GaAs with very short carrier lifetimes in 2003 [3]. This material was then used in devices to generate and detect terahertz radiation, again in collaboration with TeraView in 2004 [4].

The Semiconductor Physics Group's research in conjunction with TeraView resulted in the development of broadband terahertz sources and detectors based on photoconductive effects. The time-resolved nature of these devices enabled the TeraView imaging systems to be developed. This patented terahertz technology created spectroscopic information and 3D image maps with unique spectroscopic signatures not found at other wavelengths. It thus resolved many of the questions left unanswered by complementary techniques, such as optical imaging, Raman and infrared spectroscopy.

Using technology of this type, in a collaboration between the Cavendish Laboratory and TeraView, investigations were undertaken into the imaging of skin cancer in 2002 [5], and the imaging of teeth as well as drug analysis [6] in 2003. This research enabled the development of applications for THz imaging systems of interest to the medical profession as well as drug companies.

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

*[1] "**Simulation of terahertz generation at semiconductor surfaces**", M. B. Johnston, D. M. Whittaker, A. Corchia, A. G. Davies and E. H. Linfield, *Phys. Rev. B*, **65**, 165301–1 – 165301–8 (2002) DOI: 10.1103/PhysRevB.65.165301. [145 cites].

*[2] "**Ultrabroadband terahertz radiation from low-temperature-grown GaAs photconductive emitters**", Y. C. Shen, P. C. Upadhya, E. H. Linfield, H. E. Beere and A. G. Davies, , *Appl. Phys. Lett.*, **83**, 3117–3119 (2003), DOI: 10.1063/1.1619223.[85 cites].

[3] "**High Resitivity Annealed Low-Temperature GaAs with 100fs Lifetimes**" I. S. Gregory, C. Baker, W. R. Tribe, M. J. Evans, H. E. Beere, E. H. Linfield, A. G. Davies and M. Missous, *Appl. Phys. Lett.*, **83**, 4199–4201 (2003) DOI: 10.1063/1.1628389. [67 cites].

[4] "**Generation and detection of ultrabroadband THz radiation using photoconductive emitters and receivers**" Y. C. Shen, P. C. Upadhya, A. G. Davies, I. S. Gregory, C. Baker, W. R. Tribe, M. J. Evans, H. E. Beere and E. H. Linfield, , *Appl. Phys. Lett.*, **85**, 164–165 (2004). DOI: 10.1063/1.1768313 [56 cites].

[5] "**Terahertz pulse imaging in reflection geometry of human skin cancer and skin tissue**", R. M. Woodward, B. E. Cole, V. P. Wallace, R. J. Pye, D. D. Arnone, E. H. Linfield and M. Pepper, *Phys. Med. Biol.*, **47**, 3853–3863 (2002), DOI: 10.1088/0031-9155/47/21/325. [197 cites].

[6] "**Using Terahertz Pulse Spectroscopy to Study the Crystalline Structure of a Drug: A Case Study of the Polymorphs of Ranitidine Hydrochloride**", P. Taday, I. V. Bradley, D. D. Arnone and M. Pepper, *J. Pharm. Sci.*, **92**, 831–838 (2003), DOI: 10.1002/jps.10358. [158 cites].

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*Research references which best indicate the quality of the underpinning research.

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

Tetrahertz radiation encompasses frequencies invisible to the naked eye in the electromagnetic spectrum, lying between microwaves and the infrared. Frequencies in this region offer many applications and are intrinsically safe, non-invasive and non-destructive. The success of the Semiconductor Physics Group in developing this unique technology to emit and detect terahertz light, and to harness its remarkable diagnostic and inspection properties to provide unique 3D image and spectroscopic measurements, has facilitated solutions for a number of industries.

TeraView developed the TPI imaga systems, the first commercial terahertz imaging systems for material characterization. A total of 70 of these systems have been sold to date, half within the impact period at a cost of approximately $300k each. These have been supplied to laboratories in Europe, North America and the Far East. Roughly half of these are industrial laboratories. TeraView has received £16M investment so far, £3.5M within the impact period, and has 25 employees with two key appointments since 2008 (Heads of Semiconductor and Industrial Businesses). TeraView is the largest supplier of terahertz imagining systems by a factor of 5-10x in terms of installed base.

The main industrial area to have benefitted initially was in the pharmaceutical sector where two main applications have been developed:

- Detection of polymorphic changes of active ingredients in tablets.
- Non-invasive imaging of the coatings and internal structure of tablets to provide a quantitative assessment of the character of the internal interfaces separating different chemical constituents. This is emerging as a technique of first choice.

Both of the above applications have resulted in projects with Big Pharma and equipment sales. In

2013 Takeda Pharmaceutical Company conducted ground-breaking quality control research of layer separation of pharmaceutical tablets, comparing use of TPI to use of other analytical methods and determined that "TPI can aid in quality control by providing a precise estimate of the layer separation risk and robust quality of bilayer tablet development with better understanding of layer separation".

In the area of healthcare, the high quality of the generation and detection of the radiation has resulted in joint projects with medical groups as terahertz can distinguish healthy and cancerous tissue. Evidence is the joint publications with the clinical community. Studies of skin cancer have shown that the growth of a tumour below the skin surface can be detected and now a joint project with Guys Hospital is investigating the applicability of a hand held probe for assessing tumour margin during surgery for removal of breast cancer. Late in 2012, TeraView and its collaborators at Guys performed the first set of in-vivo (in-patient) pre-clinical trials on a subject undergoing breast conservation surgery to remove a tumour; this is a world-first for the technology, and will hopefully lead to more in-depth clinical trials. Results of the pre-clinical trials were extremely positive, with several patients measured in the theatre and promising results for breast conservation procedures.

Other recent applications of this technology are described below:

- The detection and identification of explosives where the absorption of THz at several specific frequencies allows the type of explosive to be identified and distinguished from clothing or other inert materials. Teraview market a system specifically for the stand-off detection and identification of explosives.
- TeraView have a range of applications for the photovoltaic (PV) industry having delivered terahertz inspection systems to major solar manufacturers. Applications include the detection and imaging of cracks and defects buried in silicon, as well as inspection and quality control of coatings used on crucibles for production.
- Semiconductor fault analysis and quality control of integrated circuits. A system has been developed by Teraview, in collaboration with Intel, to use Time Domain Reflectometry to non-destructively discover faults in integrated circuits. This system can locate faults such as short circuits and open circuits to 10µm, dramatically reducing the time for failure analysis in production. This techniques has applications to a wide range of devices including smartphones and tablet PCs.

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

[1] http://www.teraview.com/ (products and applications)
[2] Chief Executive Officer, TeraView Ltd
Examples of joint publications with the clinical community:
[3] "**Using Terahertz Pulse Spectroscopy to Study the Crystalline Structure of a Drug: A Case Study of the Polymorphs of Ranitidine Hydrochloride**", P. Taday, I. V. Bradley, D. D. Arnone and M. Pepper, *J. Pharm. Sci.*, **92**, 831–838 (2003). DOI: 10.1002/jps.10358 [130 cites].
[4] "**Terahertz pulsed spectroscopy and imaging in the pharmaceutical setting**", J. A. Zeitler, P. F. Taday, D. A. Newnham, M. Pepper, K. C. Gordon and T. Rades, *Journal of Pharmacy and Pharmacology*, **59 (2)**, 209–223 (2007). DOI: 10.1211/jpp.59.2.0008. [69 cites]
[5] **"Terahertz pulsed imaging of human breast tumors"** Fitzgerald A.J., Wallace V.P., Jimenez-Linan M., Bobrow L., Pye R.J., Purushotham A.D., Arnone D.D., *Radiology*, **239,** 533-540 (2006). DOI: 10.1148/radiol.2392041315. [83 cites].

[6] **"Quantitative analysis of the layer separation risk in bilayer tablets using terahertz pulsed imaging",** Masahiro Niwaa, Yasuhiro Hiraishia, Norio Iwasakia, Katsuhide Teradab, *Int. J. Pharm,* **452**, 249–256 (2013). DOI: 10.1016/j.ijpharm.2013.05.010. Takeda Pharmaceutical Company research comparing TPI to other analytical methods