Institution: The University of Nottingham

Unit of Assessment: 9

Title of case study: A New Manufacturing, Research and Development Centre for e2v

1. Summary of the impact

Our research on semiconductor materials and devices has led to the establishment by e2v Technologies of a combined manufacturing, research and development facility within the School of Physics and Astronomy. We have adapted and transferred device simulation software to e2v, and have provided epitaxially-grown semiconductors and access to fabrication facilities which have been used in their manufacturing processes. Devices fabricated within the facility, which was opened in 2011, have generated sales of £7M for e2v. This initiative has also led to shifts in the investment priorities of e2v, and mitigated risks to the company arising from import restrictions associated with the US International Traffic in Arms Regulations (ITAR).

2. Underpinning research

Experimental and theoretical research on the physics of low-dimensional semiconductor devices has formed a major part of the School research portfolio dating back to the 1980s. Since 1993 there have been wide-ranging fundamental and applied studies of the electronic and optoelectronic properties of GaAs/(AlGa)As heterostructures [1], magnetic semiconductors such as (GaMn)As [2] and wide band-gap nitride semiconductors [3]. Our materials research encompasses the growth of new materials using molecular beam epitaxy (MBE) and also nanofabrication technologies, such as electron beam lithography, plasma etching and plasma-enhanced chemical vapour deposition (PECVD). These facilities are used to grow customised semiconductor heterostructures, which may be processed into prototype devices that are investigated both within the School, and also by external collaborators. The focus is on measuring and understanding the electronic, magnetic and optical properties of the devices. Condensed matter theorists within the School work in collaboration with experimentalists to develop models and theories to explain newly-observed phenomena in quantum transport, optics and device physics. Since 1993 this activity has been supported through an overall investment of ~£50M from the research councils, the University and HEFCE infrastructure funding. We include selected grants in Section 3.

A longstanding theme of our research on carrier transport in semiconductors relates to devices which exhibit negative differential conductance, an effect that underpins the operation of high-frequency (>100 GHz) oscillators. Our integrated programmes of experiment and theory, with complementary device modelling, enabled us to observe and understand these phenomena in both double-barrier resonant tunnelling diodes and superlattices. Our expertise in the growth and modelling of devices with negative differential conductance was a key factor in the decision of e2v to relocate their high-frequency research, development and manufacturing facility to the School and we describe below two sub-areas of particular relevance:

- **Simulations of carrier transport in superlattices and quantum well structures**

We have explored the dynamics of electrons in resonant tunnelling diodes and semiconductor superlattices which exhibit negative differential conductance and, hence, can sustain high-frequency current oscillations [4,5]. Our experimental studies were complemented by computer simulations of the current-voltage and current-time dependences of these devices. These calculations provide self-consistent solutions of the drift-diffusion equations, which must be treated numerically in this regime since the engineered band structure gives rise to complex energy-momentum carrier dispersion. We have applied this modelling to a wide range of superlattices and resonant tunnelling diodes, and found that a full treatment of contacts, often neglected in quantum transport studies, is necessary to understand our experimental results, and relate them to the composition of the structures, including the layer parameters, materials, and doping profiles.

Our computer simulations of the spatio-temporal electron dynamics in superlattices enabled us to predict, and confirm in experiment, that both the amplitude and frequency of the current oscillations can be enhanced by applying electromagnetic signals to tailor the dependence of electron drift-velocity on electric field [4,5]. This area of research is of particular relevance to e2v.

- **Growth and processing of semiconductor devices**

The growth and processing of semiconductor devices form an integral part of our semiconductor activity. Since 1993 we have developed many processes to optimise device design to enable the investigation of device physics. A relevant example involved the development of a high degree of control in the doping of MBE-grown GaAs heterostructures, which enabled the study of single donor impurities and their influence on device characteristics [6]. This work started in the mid-1990s and was subsequently extended to include the transport [1] and optical properties of single self-assembled quantum dots. In a second, more recent, example, we have grown high-quality SiO_2 layers which are deposited by PECVD and have been used in our research programme as etch masks for the fabrication of wide band-gap nitride semiconductors [3]. Both these processes have been used to grow and process materials for e2v as part of their Nottingham-based manufacturing process, as we describe in Section 4.

The staff involved in this research are listed below together with their area of expertise:

Novikov, Foxon	MBE growth of nitride semiconductors
Henini, Campion	MBE growth of GaAs/(AlGa)As structures
Eaves, Patanè, Makarovsky	Low temperature magnetotransport
Mellor	Nanofabrication
Fromhold	Theory and modelling of device physics
Kent, Akimov	Ultrafast optical measurements

3. References to the research (*denotes paper which best highlights the quality of research)

1) *E.E. Vdovin, A. Levin, A. Patanè, L. Eaves, P.C. Main, Y.N. Khanin, Y.V. Dubrovskii, M. Henini, G.Hill, *'Imaging the electron wave function in self-assembled quantum dots', Science* **290**, 122 (2000).
DOI: 10.1126/science.290.5489.122

2) K.W. Edmonds, P. Boguslawski, K.Y. Wang, R.P. Campion, S.N. Novikov, N.R.S. Farley, B.L. Gallagher, C.T. Foxon, M. Sawicki, T. Dietl, M.B. Nardelli, J. Bernholc, *'Mn interstitial diffusion in (Ga,Mn)As'*, *Phys.Rev.Lett.* **92**, 037201 (2004).
DOI: 10.1103/PhysRevLett.92.037201

3) *N. Zainal, S.V. Novikov, C.J. Mellor, C.T. Foxon, A.J. Kent, '*Current-voltage characteristics of zinc-blende (cubic) Al(0.3)Ga(0.7)N/GaN double barrier resonant tunneling diodes*', *Appl. Phys. Lett*. **97**, 112102 (2010).
DOI: 10.1063/1.3488819

4) M.T. Greenaway, A.G. Balanov, E. Schöll, T.M. Fromhold, '*Controlling and enhancing terahertz collective electron dynamics in superlattices by chaos-assisted miniband transport*', *Phys. Rev. B* **80**, 205318 (2009).
DOI: 10.1103/PhysRevB.80.205318

5) ***N. Alexeeva, M.T. Greenaway, A.G. Balanov, O. Makarovsky, A. Patanè, M.B. Gaifullin, F. Kusmartsev, T.M. Fromhold,** '*Controlling high-frequency collective electron dynamics via single-particle complexity*', *Phys. Rev. Lett.* **109**, 024102 (2012).
Listed in REF2; DOI: 10.1103/PhysRevLett.109.024102

6) J.W. Sakai, P.C. Main, P.H. Beton, N. La Scala Jr, A.K. Geim, L. Eaves, M. Henini, *'Zero-dimensional states in macroscopic resonant tunnelling diodes', Appl.Phys.Lett.* **64**, 2563 (1994).
URL http://dx.doi.org/10.1063/1.111574

Funding

i. '*KTP8964 Technology Strategy Board (TSB) with e2v (UK) Technologies Ltd',* PI: Fromhold, (10/08/2012) £193,574.
ii. '*Gunn superlattice terahertz oscillators for new quantum terahertz technologies*', Hermes Fellowship awarded to A. Patanè, (Oct 2012-Sep 2013) £35,000.
iii. *'Electron dynamics and collective effects in semiconductor quantum devices'*, PI: L. Eaves, EPSRC EP/D500222/1, (Sept 2005-Feb 2009), £1,822,530.
iv. *'Free-standing zinc-blende (cubic) GaN, AlN and AlGaN layers grown by molecular beam epitaxy'*, PI: S. Novikov, EPSRC EP/G046867/1, (Sep 2009-Aug 2012), £356,350
v. *'Group III-Nitride heterostructures for quantum tunnelling devices grown by molecular beam epitaxy'*, PI: C.T. Foxon, EPSRC GR/R46465/01, (Jan 2002-Jun 2005), £275,306.
vi. '*Quantum phenomena in III-V semiconductor heterostructures'*, PI: L. Eaves, EPSRC GR/N02863/01, (Apr 2000-Jul 2003), £1,659,906.

4. Details of the impact

In early 2009, semiconductor researchers working within the School held the first of a series of meetings with senior technologists at the e2v facility in Lincoln to explore the strengthening of informal links between the two groups, which date back over 20 years. e2v, a company with over 1500 employees and a turnover, in 2013, of £200M, manufacture a wide range of electronic devices including high-frequency oscillators, which exploit the negative differential resistance arising from the Gunn effect in III-V semiconductors. These devices, which are grown by MBE and fabricated using semiconductor processing techniques in cleanrooms, are supplied to the aerospace, military and automobile industrial sectors, mainly for use in radar systems.

The interest within the School in strengthening links with e2v arose from the growing research portfolio of theoretical and experimental studies of high-frequency (>100GHz) oscillators, which had been identified by our semiconductor researchers as having the potential for commercial exploitation. Within e2v, the motivating factors were: their common interest in enhanced high-frequency devices; their strategic aim to develop closer interactions with leading semiconductor research groups with complementary interests; the new opportunities for collaboration between Nottingham and e2v in the areas of nitride semiconductors, resonant tunnelling, THz acoustics and device modelling.

The initial discussions subsequently expanded in scope to encompass not only research collaborations, but also the relocation of the company's microwave semiconductor facility from a site in Lincoln; the company were at that time exploring options to re-locate their activity to a site with higher-quality clean-room infrastructure. The infrastructure for nanofabrication which the School has built up over the last 25 years (MBE growth, nanofabrication, our extensive capability for electronic and optoelectronic characterisation, and access to clean rooms and the associated technical and research personnel) provided strong motivation for e2v to move to Nottingham.

The discussions with e2v then followed a dual-track process, encompassing both research collaboration and relocation. The initial focus of collaborative research was on the adaption of the numerical techniques described in Section 2, which were developed by *Fromhold*, to the modelling of silicon p-i-n diodes. In our approach the whole device - including the contacts, energy bands, and scattering processes - was included in the model. This was of particular interest to e2v, and proved crucial for obtaining quantitative agreement between the calculated and measured device characteristics. In collaboration with e2v, *Fromhold* modified his model so that it could be used to calculate electrical characteristics of devices that are used by e2v in receiver-protection systems.

This activity was initially supported through a successful application to the EPSRC Knowledge Transfer Secondment (KTS) scheme (£40k: 01/11/2010-30/10/2011) and, by the end of the funded period, software for calculations of the static characteristics of the diodes had been transferred to e2v who now use the package as part of their component testing and quality control procedures. In a follow-up study supported by a TSB Knowledge Transfer Partnership (KTP) (£194k: 36 months from autumn 2012; 50% funding from e2v) the simulation software is being extended to include coupling to the electromagnetic environment (to model high-frequency characteristics) and variation of material properties. The market for systems which includes these components is worth close to £3M per year to e2v, and our collaborative work has promoted a shift of e2v's investment priorities to include the development of in-house software to simulate device characteristics.

In parallel, discussions on the relocation of e2v progressed to involve their Board of Directors, and the University of Nottingham Management Board, leading to the establishment of a formal collaboration. The collaboration is based on three contracts spanning a 5-year period from October 2010 with a commitment of £1M from e2v [A], including an initial capital investment of £0.35M. These contracts cover: the construction of a 90 m^2 purpose-built ISO Class 7 (Class 10000) manufacturing and research cleanroom [B]; the lease of the cleanroom and additional office space to e2v [C]; service and collaboration agreements [D] with the School (Nottingham PI *Mellor*, Associate Professor in Physics). The latter covers protection of intellectual property, access by e2v to School facilities (workshops, another nanofabrication cleanroom, and plasma deposition equipment, which e2v now use in their manufacturing processes), and commits the partners to knowledge transfer collaboration. The commitment of the School to this joint venture is evident through our appointment of an Experimental Officer with expertise in commercial semiconductor device manufacture to work with the e2v staff and build the collaboration. In addition, a Hermes fellowship (a University-administered scheme funded by the Higher Education Innovation Fund

(HEIF) to support innovation and business engagement) was awarded to *Patanè* to work with e2v on new sources and detectors of high-frequency (GHz-THz) radiation based on semiconductor superlattices (see Grant (ii) in Section 3).

The e2v facility was completed in 2011 and has since been operated by two senior e2v engineers. The physical relocation of e2v has led to an acceleration of knowledge transfer to the company. In addition to the general support provided through our infrastructure and expertise, we highlight the growth of SiO_2 layers by PECVD (as described in Section 2) on 3-inch wafers. These wafers are used by e2v to manufacture high-frequency oscillators, and the high quality of the oxide layers that we developed for etch masks (see Section 2) proved critical in this fabrication process. In addition we have used our experience in the control of doping profiles to grow GaAs layers using MBE for e2v. These layers were processed into varactor diodes used by e2v to tune high-frequency circuitry. The e2v manufacturing activity, which draws heavily on our research infrastructure, has been successfully embedded in the School; sales of components manufactured in the facility since its launch in 2011 amount to approximately £7M (£3M/annum) [A].

The Group Chief Technology Officer of e2v has stated [E]:

'e2v made the decision to relocate our microwave semiconductor device manufacturing facility to the School of Physics & Astronomy at Nottingham primarily because of the facilities, skills base and closely aligned research interests. We were also attracted by the School's excellent track record of research and its world leading expertise and the synergy with e2v's long term ambitions. The success of this initiative has already been demonstrated through the transfer of modelling and processing techniques originally applied to fundamental aspects of device physics to e2v's design and manufacturing processes. Notably amongst these; the device simulation of p-i-n diodes, the deposition of oxides used in our commercial production and the supply of semiconductor layers grown by molecular beam epitaxy (MBE).'

The e2v-Nottingham activities are supported by the Nottingham Steering Group in Microwave Semiconductor Devices, established in 2010, with a membership including senior e2v staff. At knowledge transfer meetings, held 3 times a year, semiconductor researchers within the School present their research and identify, in discussion with e2v, pathways to exploitation. These meetings have led to changes, at Board level, of the company strategy for high-frequency device manufacture and development. To this end, e2v have identified and prioritised routes for translating our research into new and improved products, as articulated in their Strategic Action Plan (STRAP). The first priority of this road map was to develop better sources and detectors of GHz and THz radiation, building on our expertise in modelling and the growth of nitride semiconductors.

A further significant benefit to e2v of the new facility is the mitigation of risk from import restrictions arising from the US International Traffic in Arms Regulations (ITAR). The company is vulnerable to changes in these regulations and the new, Nottingham-based facility provides additional flexibility for the company to access and manufacture components from an ITAR free source [A].

e2v's Chief Engineer, Microwave Semiconductor Devices confirms the strategic importance of their link with Nottingham,

'I'm glad to report that the research at Nottingham has further guided strategic thinking at board level, with regard to technology and product road maps (including the company's STRAP). These collaborative activities will open new markets and opportunities for us and importantly will enable us to move up the supply chain and provide our customers with solutions for systems. Of particular increasing importance is our joint ability to provide new and novel compound semiconductor technology and components from an ITAR free source.' [A].

5. Sources to corroborate the impact (available on request)

A. Letter from Chief Engineer, Microwave Semiconductor Devices, e2v Technologies.
B. Contract between e2v and University of Nottingham for cleanroom construction.
C. Contract between e2v and University of Nottingham for lease.
D. Contract between e2v and University of Nottingham for Service and Intellectual Property.
E. Letter from Group Chief Technology Officer, e2v Technologies.