Institution: University of Nottingham (UoN)		
Unit of Assessment: 9		
Title of case study: Teledyne: Manufacture and development of microwave semiconductor devices by the Teledyne Semiconductor Technology Centre, an embedded industrial facility		
Period when the underpinning research was undertaken: 1 Jan 2000 – 31 Dec 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by the submitting HEI:**
Richard Campion	Principal Research Fellow	1997 – present
Laurence Eaves	Research Professor FRS	1976 – present
Tom Foxon	Emeritus Professor FRS	1991 – 2018
Mark Fromhold	Professor	1991 – present
Mohamed Henini	Professor	1986 – present
Tony Kent	Professor	1984 – present
Oleg Makarovskiy	Associate Professor	2003 – present
Christopher Mellor	Associate Professor /Reader	1989 – present
Amalia Patanè	Professor	1998 – present
Period when the impact occurred: 1 August 2013 to 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Our research in semiconductor physics has influenced the strategic direction of Teledyne UK Ltd and underpinned sales (> GBP5.5M) of components fabricated in the Teledyne Semiconductor Technology Centre (TSTC), an embedded facility in the School of Physics and Astronomy (SoPA). The TSTC is part of the microwave business unit of Teledyne UK Ltd (formerly Teledyne e2v Ltd and e2v Technologies Ltd), a leading UK manufacturer of GHz components and equipment that are sold world-wide. The TSTC is engaged in the manufacture, research and development of microwave devices and has drawn heavily on our expertise in semiconductor device physics, including epitaxial growth, fabrication and modelling, as well as access to our facilities, in order to: (i) sustain the on-site manufacture of high frequency (GHz) electronic oscillators with a performance which is unmatched by Teledyne's competitors; (ii) develop and re-shape investment priorities for the company's strategic roadmap for microwave devices. In addition to their direct commercial value, these components add further value to the systems in which they are incorporated; Teledyne UK devices are used in the defence (receivers, receiver protectors and mm-wave sensing) and security (receivers, receiver protectors and superlattice electron devices for sub-THz scanners) sectors, thus realising further societal impact in these areas.

2. Underpinning research

Experimental and theoretical research on the physics of low-dimensional semiconductor devices by the *Experimental Condensed Matter and Nanoscience* (*ECMN*) and *Condensed Matter Theory* (*CMTh*) groups has formed a major part of the SoPA's research portfolio since the early 1980s. The focus is on designing, fabricating (including growth using molecular beam epitaxy (MBE)), measuring and understanding the electronic, magnetic and optical properties of semiconductor devices **[1-7]**. A longstanding theme of our research on carrier transport in semiconductors relates to semiconductor devices which exhibit negative differential conductance, an effect that underpins the generation and detection of high frequency (> 100 GHz) electromagnetic radiation. Our integrated programme of experiment and theory, with complementary device modelling, has enabled us to observe and understand new negative differential conductance phenomena in double-barrier resonant tunnelling diodes (RTDs) and in superlattices. Since 2000, this research activity has been supported through a total investment of more than GBP8.2M from research councils **[i-vi]**. Here we describe examples of specific research activities which have underpinned our interactions with Teledyne UK Ltd.

2.1 Carrier transport in superlattices and quantum well structures We have explored the dynamics of electrons in RTDs and semiconductor superlattices, which exhibit negative differential conductance **[1,2]** and can thus sustain high-frequency (GHz-THz) current oscillations at room temperature. Our experimental studies of individual devices **[6, iv-vi]** have been extended to electromagnetically coupled (synchronised) superlattices **[7]** and complemented by computer simulations of their current-voltage and current-time dependences. The 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 relations **[1]**. We have applied this modelling to a wide range of superlattices and RTDs. Our computer simulations of the spatio-temporal electron dynamics in superlattices enabled us to predict, and confirm experimentally, 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, and that the electromagnetic characteristics of the devices can be tuned by shaping their geometry and array configuration **[6,7]**.

2.2. Growth and fabrication of semiconductor devices The growth by MBE of high-quality quantum-confined semiconductor structures based on III-V semiconductors (*e.g.* quantum wells, RTDs, and superlattices) has provided the foundation for our investigations of quantum phenomena and device physics. Many of these devices require precise control of their doping profile, layer composition and thickness, as well as high-quality heterointerfaces. Epitaxial layers such as the GaAs-based RTDs and superlattices reported in **[1,2]** have required extensive investigation and optimisation of the relevant growth processes. Since the mid-2000s we have undertaken further investigations of growth processes to encompass a much broader range of materials including (GaMn)As magnetic semiconductors **[3]**, nitride semiconductors **[4]** and related spintronic systems **[5]**. These investigations have enhanced our understanding of high doping levels in III-V semiconductors **[5, ii-iii]** and the growth of atomically-precise multi-layered structures (e.g. superlattice- and Schottky-diodes). These advances subsequently proved essential for supplying Teledyne UK Ltd with MBE layers for Gunn diodes and related microwave devices with the required specifications. We have also enhanced our semiconductor processing facilities by developing the deposition of high-quality SiO_2 masking layers by plasma enhanced chemical vapour deposition (PECVD) and have developed reliable inductively-coupled plasma (ICP) dry etching processes during research on wide band-gap nitride semiconductors **[4, i]**. This plasma etching of MBE-grown heterostructures with carefully-controlled doping levels is an integral part of the TSTC manufacturing process.

3. References to the research

Publications:

[1] ***Fromhold, T.M.***, et al. (including ***Patanè, A.***, ***Eaves, L***. and ***Henini, M.***), Chaotic Electron Diffusion through Stochastic Webs Enhances Current Flow in Superlattices, *Nature* **428** (6984) 726-730 (2004). DOI: 10.1038/nature02445.

[2] ***Fromhold, T.M.***, et al. (including ***Eaves, L***.) Effects of Stochastic Webs on Chaotic Electron Transport in Semiconductor Superlattices, *Phys. Rev. Lett.* **87** (4), 046803 (2001). DOI: 10.1103/PhysRevLett.87.046803.

[3] Edmonds, K.W. et al. (including ***Campion, R.P.*** and ***Foxon, C.T.***), Mn Interstitial Diffusion in (GaMn)As, *Phys. Rev. Lett.* **92** (3) 037201 (2004). DOI: 10.1103/PhysRevLett.92.037201.

[4] Zainal, N., Novikov, S.V., ***Mellor, C.J., Foxon, C.T., Kent, A.J.,*** Current-voltage characteristics of zincblende (cubic) $Al_{0.3}Ga_{0.7}N$/GaN double barrier resonant tunneling diodes., *Applied Physics Letters* **97** 112102 (2010). DOI: 10.1063/1.3488819.

[5] Wadley P., et al (including ***Campion RP***), Electrical Switching of an Antiferromagnet, *Science* **351** (6273) 587-590 (2016). DOI: 10.1126/science.aab1031.

[6] Alexeeva, N., et al. (including ***Makarovsky, O., Patanè, A.,*** and ***Fromhold, T.M.***), Controlling High Frequency Collective Electron Dynamics via Single Particle Complexity, *Phys. Rev. Lett.* **109** (2) 024102 (2012). DOI: 10.1103/PhysRevLett.109.024102.

[7] Gaifulin M.B, et al (including ***Fromhold T.M***., ***Patanè A.*** and ***Mellor C.J.***) Microwave Generation in Synchronized Semiconductor Superlattices, *Physical Review Applied* **7** 044024 (2017). DOI: 10.1103/PhysRevApplied.7.044024.

Key Research Grants:
[i] Group III-Nitride Heterostructures for Quantum Tunnelling Devices Grown by MBE, PI: Foxon, EPSRC GR/R46465/01, (Jan 2002 – June 2006) GBP275,306.
[ii] Ferromagnetic Semiconductors: Materials Development and Spintronic Devices, PI: Gallagher, EPSRC GR/S81407/01, (Mar 2004 – July 2007) GBP849,125.
[iii] Development of new CuMn-V epitaxial antiferromagnetic semiconductors for applications in spintronics, PI: Campion, EPSRC EP/K027808/1, (June 2013 – Aug 2015) GBP274,126.
[iv] Quantum Chaos in Semiconductors, PI: Fromhold, EPSRC GR/M35123/01, (Jan 1999 – Jan 2001) GBP 52,410.
[v] Quantum Phenomena in semiconductor heterostructures, PI: Eaves, EPSRC GR/N02863/01, (Apr 2000 – Jul 2003) GBP1,659,906.
[vi] Electron Dynamics and Collective Effects in Semiconductor Quantum Devices, PI: Eaves, EPSRC EP/D500222/1, (Sep 2005 – Feb 2009) GBP1,822,530.
Technology Transfer Grants and Contracts:
[I] GUSTOs for New Quantum Terahertz Technologies, PI: Patanè, Hermes Fellowship, (Sep 2012 – Sep 2013) GBP34,632.
[II] Superlattice Electron Devices for mm Wave Applications, PI: Mellor, EPSRC Impact AA Knowledge Transfer Secondment (KTS), (April 2016 – March 2017) GBP 45,525 (with additional support in-kind from Teledyne UK Ltd worth GBP12,000).
[III] Developing next generation THz sources and detectors, PI: Fromhold, EPSRC Knowledge Transfer Secondment (KTS) (Nov 2010-Oct 2011) GBP38,469.
[IV] TSB Knowledge Transfer Partnership (KTP) with Teledyne UK Ltd, PI: Fromhold, Partnership KTP008964 (Feb 2013 – Feb 2016) GBP 193,574 (UoN income: GBP96,787).
[V] Semiconductor and circuit modelling methods for next generation RF protection devices, EPSRC I-CASE, UoN, DSTL, Teledyne UK Ltd, (Oct 2016 – Sept 2017) GBP27,140.
[VI] Waves in Complex Media, EPSRC thematic programme studentship, University of Nottingham with support from Teledyne UK Ltd, (Oct 2018 – March 2022) GBP66,629.
[VII] Technology transfer and initial supply of MBE grown wafers for superlattice electron devices, e2v technologies, PI: Mellor, (March 2017) GBP32,690.

4. Details of the impact that has occurred

The impact arises from the translation of our semiconductor research and expertise to Teledyne UK Ltd (formerly Teledyne e2v Ltd and e2v Technologies plc prior to March 2017 **[a];** the company is owned by Teledyne Technologies Incorporated) to advance their activities in the design and manufacture of RF/microwave component and subsystems, and digital imaging sensors, primarily serving medical, defence and space markets. Teledyne UK Ltd has global sales of GBP150M per annum and employs approximately 2000 people **[d]**.

Teledyne UK Ltd took a strategic business decision to relocate their semiconductor fabrication facilities from Lincoln to the SoPA (UoN), and in 2010 established the 'The Teledyne Semiconductor Technology Centre' **[b]** (TSTC). This embedded facility is a state-of-the-art cleanroom (102 m^2) for III-V semiconductor manufacturing with a research and development capability. The TSTC is leased, fully staffed and funded by Teledyne UK Ltd **[c]**, and has continued to operate and evolve throughout the assessment period.

Our expertise in the growth and modelling of devices with negative differential conductance was a key factor in their decision to re-locate as confirmed by Teledyne UK Ltd **[d],** and they particularly value the informal interactions between our researchers and company employees which is realised through this co-location '*The Teledyne Semiconductor Technology Centre provides a state-of-the-art semiconductor cleanroom in the University's School of Physics and Astronomy. Placements of our facilities, directly in the School of Physics and Astronomy, allows us access to world leading research facilities in addition to our own, but moreover, the open informal access to the researchers themselves. It is this informal knowledge transfer that we have found particularly beneficial…"* **[d]**.

Teledyne UK Ltd's manufacturing activity draws heavily on our research infrastructure. Our partnership with the company is based on collaboration and service agreements to cover knowledge transfer and intellectual property **[b],** the lease of cleanroom and office space

[c], and access to SoPA facilities (workshops, a nanofabrication cleanroom, and plasma deposition equipment) which are used in their manufacturing processes. Subsequently, we have worked with Teledyne UK to translate our research on new device concepts into their products, thus influencing their investment plans and technology roadmaps **[d]**.

We describe below two types of impact: firstly, how research has supported and sustained the manufacture of commercial microwave devices; and, secondly, collaborative projects which have led Teledyne UK Ltd to re-direct their research strategy.

4.1 Manufacture of microwave oscillators and receiver diodes

Microwave oscillators and receiver devices are a key part of Teledyne UK's portfolio and are now manufactured in the embedded TSTC using III-V semiconductor heterostructures grown by *ECMN* researchers in the SoPA using molecular beam epitaxy, and through access to our clean-room facilities (in addition to those in the TSTC). These devices include cutting-edge Teledyne Gunn diodes with an enhanced AlAs emitter-booster, and Schottky receiver diodes. Both types of device are manufactured from heterostructures which require highly precise levels, and spatial control, of doping and (GaAl)As alloy composition. Building on the expertise gained in the growth of heterostructures used in our experimental studies of negative differential conductance **[1,2,6,7]**, researchers in the SoPA have been able to meet the demanding Teledyne UK specifications; in the REF2021 assessment period we have supplied 2" wafers for the fabrication of Gunn diodes (10 wafers) and Schottky diodes (12 wafers), all of which were grown by *Campion*. The fabrication of Schottky diodes requires additional processing steps (PECVD oxide deposition and ICP dry etching) using our facilities which were established in support of our nitride semiconductor programme **[4]**. Our facilities are also used for a deep etch process step in the fabrication of Gunn diodes. The use of our advanced ICP dry etching has also improved the yield of the beam-lead (a low induction contacting methodology) diode production process.

Teledyne Gunn and Schottky diodes are high frequency (> 100 GHz) sources and receivers and exemplify an industry challenge addressed by our joint research effort; no devices offering the performance levels demanded by Teledyne customers are made anywhere else in the world. Sales of these specialist diodes manufactured in the TSTC amount to GBP5.5M over the REF2021 assessment period [**d**]. The availability of these devices as components of larger systems provides further added value as stated by Teledyne UK Ltd **[d]** '*Recently a major multinational defence company has committed to millimetre wave sensing programmes which will see our Schottky diodes utilised in their new system builds for at least the next ten years, whilst a UK based security system manufacturer has designed our Gunn diodes into all of their current and next generation scanner products'*, and, specifically *'these diode applications directly exploit technology that comes out of the collaboration, and underpin multi-million-pound exports for our customers.'*, thus providing additional impact in the security and defence sectors.

4.2 Technology transfer of new device concepts

The formation of the TSTC has also led to translation of our research, as recognised by Teledyne UK: "*The research at Nottingham has guided strategic thinking at site and national levels, with regard to technology and product road maps including the company's STRategic Action Plan (STRAP). Of particular importance is our joint ability to provide new and novel compound semiconductor technology and components"*. **[d]** Through discussions between their engineers/managers and researchers in the SoPA, Teledyne UK Ltd have also developed a roadmap for several new products. These routes to technology transfer have been enabled through a HERMES Fellowship, Knowledge Transfer Secondments (KTS), and a Knowledge Transfer Partnership (KTP) **[I-IV]**, Industrial-CASE (I-CASE) and EPSRC PhD studentships **[V,VI]**, and research which is fully funded by the company **[VII].** We describe below two examples of translation which have influenced the company's strategic plans.

4.2.1 Superlattice electron devices The negative differential conductance in superlattice heterostructure devices reported by SoPA researchers **[2,6,7]** offers the prospect of high-frequency (THz) oscillators with tailored properties which have the potential to improve and extend Teledyne UK's products. A series of collaborative awards **[I-IV]**, and direct funding from the company **[VII], [d]** supported the development of superlattice electron devices for millimetre wave applications [**II**]. Subsequently, in 2017, Teledyne UK Ltd started to fabricate demonstrator sub-THz devices using heterostructure layer designs developed by Professor Patanè and co-workers **[e]**; two wafers were grown by MBE and supplied to Teledyne UK. These superlattice devices will be used as mm-wave multipliers and sub-harmonic mixers, components for security products such as THz-imaging systems. A key aspect of this project was the "*technology transfer of the device fabrication process and the heterostructure design"* of beam-lead superlattice electron devices from the SoPA team to the Teledyne UK Ltd team **[d]**.

4.2.2 Receiver protectors: Yield improvements and new simulation methods

Receiver protector diodes are a key component in Teledyne UK Ltd's microwave systems. Advanced theoretical modelling techniques (developed by *Fromhold* **[1,6,7]**) and detailed data analysis have been applied to characterise and improve the performance and yield of the PIN diodes used in the receiver protectors with support from two collaborative awards **[III, IV]**. Teledyne UK Ltd state '*The KTP found ways to improve the yield of the production process improving the profitability of the existing receiver protector product line in Teledyne. The market for such systems is worth c.£5 M p.a. to Teledyne Lincoln Microwave, with a predicted financial impact of increase profits by 10-20% per year.'* **[d]**.

In a second phase of this work, which concerns the emerging requirements for next-generation receiver protector products, the need was identified for improved predictive modelling that allows engineers to design microwave systems with performance characteristics significantly beyond the capabilities of current design approaches. This was highlighted by Teledyne as a shortcoming in existing industry standard simulation tools. In 2016, an I-CASE studentship sponsored by the Defence Science and Technology Laboratory (DSTL) in partnership with Teledyne UK Ltd **[V]** was established with the aim of improving the advanced computer simulation of high-frequency electronic components for radar receiver protectors. Researchers **[V, VI]** in the SoPA, and UoN Electronic Engineering, have developed Unstructured Transmission Line Modelling codes to improve the modelling accuracy and speed of receiver protector simulations. Teledyne UK Ltd state '*This novel simulation work has assisted our strategic decision making, giving us the confidence to feature next-generation receiver protectors as a key strand of our technology roadmap*.' **[d]**.

In summary, our research in semiconductor physics has influenced the Teledyne UK roadmap (see discussion of STRAP **[d]**) and underpinned the sales (GBP5.5M) of components fabricated in the TSTC. Teledyne UK Ltd confirm the strategic importance of the link with the SoPA *"When we entered into the partnership with the School of Physics and Astronomy, University of Nottingham, we knew we had started something with great potential. The result is that we now have a well-established, unique capability in the UK which is viewed by many as a model that delivers products for customers and also supports and fosters world-leading complementary research that exploits cutting edge physics for challenging applications in growing markets. The success of the collaboration has exceeded expectations and reinforced Teledyne's position at the forefront of UK discrete compound semiconductor device manufacture."* **[d]**.

5. Sources to corroborate the impact that has occurred

[a] Companies House: Teledyne UK Limited.
[b] Collaboration Agreements Teledyne and School of Physics and Astronomy, 2010, 2017.
[c] Contract between Teledyne UK Ltd and University of Nottingham for lease.
[d] Letter from Teledyne UK Ltd, Technologist, Mr. Gary Stimson (formerly Teledyne e2v).
[e] Sub-THz market projections by Teledyne UK Ltd in Innovate UK proposal 'Superlattice Electron Device (SLED) Frequency Multiplier for mm-Wave Applications', 2017.