

The limits to ‘spin-off’: UK defence R & D and the development of gallium arsenide technology

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Abstract. UK defence R & D played a leading role in the development of gallium arsenide and other III–V semiconductor materials. Often touted as the semiconductor of the future because of its potential for high-speed computing, gallium arsenide had unique properties compared to silicon that made it attractive for military applications. Some consumer applications were also developed, and these eventually became significant with its use in mobile phone handsets in the mid-1990s. However, despite the apparent advantage of close links to the defence establishments and early access to expertise in III–V technologies, UK companies had limited success in these civil markets, preferring instead to focus on defence procurement.

One of the most significant industrial developments of the second half of the twentieth century grew out of the development of semiconductors and their application in electronic devices. After some initial use of germanium, this industry came to be primarily based on silicon semiconductors, and it is well documented that the UK failed to become a major player in this technology.¹

The conventional historiography sees this development as partly due to the mid-1950s decision by the UK defence research establishments to focus their electronics work and sponsorship elsewhere, neglecting silicon in favour of III–V semiconductors, and particularly gallium arsenide (GaAs). Whereas elemental semiconductor materials such as silicon or germanium belong to group IV of the periodic table, gallium arsenide is one of a number of compounds formed by combining elements from groups III and V of the periodic table and hence known as III–V semiconductors.²

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1 Peter Robin Morris, ‘The growth and decline of the semiconductor industry within the UK 1950–1985’, Open University PhD, December 1994; Anthony M. Golding, ‘The semiconductor business in Britain and the United States: a case study in innovation, growth and the diffusion of technology’, University of Sussex DPhil thesis, 1971.

2 For general information on gallium arsenide see G. Gibbons, ‘Gallium arsenide electronics’, *Physics in Technology* (1987) 18, pp. 5–10, 16; and Marc H. Brodsky, ‘Progress in gallium arsenide semiconductors’, *Scientific American* (February 1990), pp. 56–63.

The useful properties of III–V materials fall into two main categories: opto-electronic and high-frequency. The opto-electronic properties mean that some III–V materials can be used to build devices that either absorb photons (thus enabling night vision, infrared sensors or solar power cells) or produce photons (enabling lasers or light-emitting diodes). The good high-frequency operation of some III–V materials provides capabilities suitable for radar (microwave) and telecommunications (satellite television, mobile telephones, wireless networks and GPS navigation units) and also offers the potential for ‘chip’ speeds greater than those provided by silicon.³

The decision of the UK defence research establishments to focus on III–V materials stemmed from their judgement that silicon technology was sufficiently mature to be left to the market and they sought instead ‘to leapfrog silicon technology by research into group III–V compounds’.⁴ The initial impetus seems to have stemmed from the view that ‘gallium arsenide was the logical successor to silicon as a base material for transistors and diodes’.⁵ This meant that the ‘research output in silicon technology from the Establishments was almost completely absent during the critical period of integrated circuits development and manufacture’.⁶

Some historians have judged this development harshly because they see the neglect of silicon as responsible (at least in part) for the decline of the UK electronics industry. The focus on III–V materials was undesirable, they argue, because these materials had few commercial uses. Thus Morris claimed in 1994,

Far from any commercial spin-off, the result of research activities within Government establishments led (although no doubt unintentionally) to the restriction of commercial effort. This was because the work was targeted specifically at specialised materials and devices with little commercial application.⁷

However, around the time that Morris wrote this, GaAs was about to take off commercially, thanks to its application in mobile phones. The initial hopes for GaAs as a successor to silicon, offering benefits such as faster chip speeds (and, for the military, radiation hardness), had been frustrated by the practical difficulties and expense of producing such chips. For many years it was possible to sum up the story of gallium

3 The Cray-3 supercomputer, delivered in 1993, is a rare example of the use of gallium arsenide to achieve faster processor speeds. See Andrew Pollack, ‘A speedier chip finally gets a lift’, *New York Times*, 14 October 1987.

4 Morris, *op. cit.* (1), p. 313, see also p. 128. There was concern over the neglect of silicon in the late 1960s. For example, CVD’s Solid State Physics Research Panel complained in 1966, ‘We believe that there remains an imbalance in the programme in that the support for work on silicon is inadequate in relation to the support for work on compound semiconductors. The panel are particularly concerned about the fact that the UK is still behind the US in silicon technology. Of the several (familiar) reasons for this situation we would pick out our failure to spend money on research into silicon technology right up to and including the production stage.’ ‘Solid State Physics Research Panel, Chairman’s Report to CVD Research Advisory Board’, attached to CVD Policy Committee, 1 July 1966. UK National Archives [hereafter NA] ADM 272/244.

5 Golding, *op. cit.* (1), p. 352.

6 Morris, *op. cit.* (1), p. 129. Concerns about the supply of semiconductors for UK weapons systems led the Ministry of Defence to encourage the dominant US manufacturer, Texas Instruments, to set up a UK plant. See Morris, *op. cit.* (1), p. 319.

7 Morris, *op. cit.* (1), pp. 138–139.

arsenide with an aphorism: 'Gallium arsenide is the technology of the future, always has been, always will be'.⁸

Nevertheless, the unique properties of GaAs and other III–V materials meant that they had found some civil uses, first in light-emitting diodes (LEDs) used in displays, then in satellite television receivers and solid-state lasers for CD players, but it was development of mobile phones that led to a huge upsurge in demand for GaAs chips. Although still much smaller than that for silicon, there was no doubt by the mid-1990s that there was a substantial commercial market for GaAs.⁹

Much of the pioneering work on gallium arsenide and other III–V materials was carried out at, or supported by, UK defence research establishments. This meant that the UK was at the forefront of III–V research, and UK industry was apparently well placed to develop commercial spin-offs.¹⁰ One measure of success could be seen in the achievement of four Queen's Awards for Technological Achievement in this area: for crystal growth technology in 1979, GaAs photocathodes in 1987, metal–organic precursors for epitaxy in 1990, and high-precision epitaxial crystal growth for advanced opto-electronic components.¹¹ Consequently, there was 'a hope at one time that III–Vs would be a key technology for the UK to exploit as an aid to future competitiveness'.¹²

This paper describes some of the key developments in III–V technology (particularly GaAs) that came out of UK defence research and development (R & D). These developments fall into three (overlapping) categories: device production, semiconductor material production and epitaxial growth techniques.¹³ After briefly introducing the background to the institutional arrangements for defence funding of UK electronics development, this paper will describe in detail the emergence of III–V semiconductor technology in the UK, drawing on interviews,¹⁴ documents made available by the research establishments, material from the UK National Archives and accounts written by some of the participants.¹⁵

8 Brodsky, *op. cit.* (2), p. 56.

9 Silicon still accounts for almost 99 per cent of the amount of semiconductor substrate produced (although less by cost), with GaAs and sapphire being the largest of the remainder. See 'Compound semiconductor substrates 2010 market report', 16 June 2010. Available at www.prnewswire.co.uk/cgi/news/release?id=289781.

10 On spin-off see Graham Spinardi, 'Civil spin-off from the defence research establishments', in Robert Bud and Philip Gummett (eds.), *Cold War, Hot Science: Applied Research in the UK's Defence Research Laboratories, 1945–90*, Amsterdam: Harwood Academic, 1999, pp. 371–392.

11 'Queens Awards for Technological Achievement, 1979 to 1991'. Leaflet produced by Defence Research Agency, Malvern, 1992.

12 Roy Szweda, 'GaAs the force multiplier—a GaAs Manhattan Project for the UK?', *III–Vs Review* (February 1991) 4(1), p. 4.

13 For a reasonably readable account of how semiconductors work see John Orton, *The Story of Semiconductors*, Oxford: Oxford University Press, 2004.

14 With Roland Ware, formerly of Plessey and Metals Research/Cambridge Instruments, Caswell, MA, 18 June 1999; Fred Myers, Plessey/GEC Marconi Caswell, 15 April 1999; Roy Szweda, Plessey Caswell and then editor of *III–Vs Review*, 27 January 1999; David Wight, SERL and then RSRE, 6 February 1991 and 9 March 1998; Don Hurlle, RSRE, 25 October 1990; Ian Grant, Wafer Technology, 20 February, 1999.

15 Of those cited here, Morris worked at Mullard and Texas Instruments, Hilsum at SERL/RSRE and GEC, Parkinson at RRE/RSRE and then at the MoD (Director General of Establishments), Waldock at SERL and then Metals Research/Cambridge.

The discussion will then address the issue of spin-off from defence R & D—an issue that has typically been framed as dialectic of two extremes. On the one hand, some have seen spin-off as a benefit to the UK economy, albeit one that could have been better exploited. On the other, the effect of military R & D on the UK innovation system, and electronics in particular, is seen as a pervasive and fundamentally detrimental influence, draining resources away from civil innovation and undermining UK competitiveness in commercial manufacturing.¹⁶

Defence R & D and the UK electronics industry

Defence funding played a major part in the development of the UK electronics industry, providing both a market for products and a major source of R & D funding. For many years defence support for electronics R & D was provided through a Ministry of Defence (MoD) organization known as CVD. Originally set up before the Second World War as the Inter-Services Committee for the Coordination of Valve Developments, CVD sought to rationalize the burgeoning number of specialist committees involved in the application of valve technology to warfare.¹⁷

Over the years, CVD's role grew from coordination to active sponsorship of industrial electronics R & D geared towards military objectives. In keeping with the shifting emphasis of technology away from valves and towards semiconductors, the acronym of CVD was retained whilst the organization was formally renamed as the Directorate—Components, Valves and Devices in 1972.¹⁸

CVD's influence on UK electronics R & D was huge. During the 1950s and 1960s, MoD funding of electronics R & D in the UK far exceeded any other external source, and was often greater than the industry's own R & D expenditure.¹⁹ Although CVD support came to be matched by that of the Department of Trade and Industry (and its predecessors), it remained a major source of R & D funding up until the demise of CVD in 1992.

16 For a range of differing viewpoints encompassing these two extremes, see the debate in P.E. Trier, P. Gummatt, J. Richards and A. Wallard, 'The effect of the defence sector on the UK electronics industry', *IEEE Proceedings* (July 1988) 135, Pt. A, No. 6, pp. 419–430; also J.F. Barnes and B.R. Holeman, 'The transfer of defence research on electronic materials to the civil field', in E. Mondros and A. Kelly (eds.), 'Technology in the 1990s: The promise of advanced materials', *Philosophical Transactions of the Royal Society of London* (1987) 322, pp. 335–346; D.H. Parkinson, 'Defence research and civil spin-off', *Physics in Technology* (1987) 18, pp. 244–249; M. Seagram, 'Does relatively high defence spending necessarily degenerate an economy?', *RUSI Journal* (1986) 1, pp. 45–49.

17 See Keith Dickson, 'The influence of Ministry of Defence funding on semiconductor research and development in the United Kingdom', *Research Policy* (1983) 12, pp. 113–120, 114; Stephen Robinson, 'Government management of defence research since the Second World War', in Bud and Gummatt, op. cit. (10), pp. 393–415, 411–413; Peter Robin Morris, 'A review of UK government involvement in the field of semiconductor technology within the research establishments', in Andrew Goldstein and William Aspray (eds.), *Facets: New Perspectives on the History of Semiconductors*, New Brunswick: IEEE Center for the History of Electrical Engineering, 1997, pp. 270–273; Golding, op. cit. (1), pp. 344–350.

18 Dickson, op. cit. (17), p. 114.

19 Dickson, op. cit. (17), p. 114.

Defence-related electronics R & D was carried out at, or in collaboration with, the defence research establishments. The two main establishments involved were the Royal Radar Establishment (RRE) at Malvern and the Services Electronics Research Establishment (SERL) at Baldock, which were amalgamated to form the Royal Radar and Signals Establishment (RSRE) in 1976.²⁰

Although the explicit policies and organizational arrangements regarding civil spin-off have varied over the years, the underlying attitudes of staff working on electronics technology were always supportive of rapid civil uptake. This was especially the case at the Radar Research Establishment at Malvern where research was more basic in orientation, especially during and after the period when it was part of the Ministry of Technology (MinTech) in the late 1960s. The Services Electronic Research Laboratory at Baldock and Harlow, which remained outside MinTech, was more directly geared towards the development of service equipment. Nevertheless, the general view at both establishments was that early civil uptake of new electronics should be encouraged because it was likely to result in the development of more cost-effective manufacturing processes.²¹

Of course, both CVD and the research establishments were primarily motivated by the interests of the armed services, and not explicitly by any broader effects on the UK economy. However, there was recognition that a strong UK microelectronics industry was important for UK defence requirements. For example, a joint meeting of the MoD's Weapons Development and Defence Research Committees on 25 May 1966 to consider the use of microelectronics in defence equipment 'agreed in principle that it was in the interest of Defence to assist in the urgent building up of the British microelectronics industry.'²² The question of broader support for British electronics did of course raise questions about who would pay for this. CVD discussion of the matter concluded that 'the CVD budget was approved fundamentally for expenditure in the defence field. CVD would, however, be perfectly willing to operate on the behalf of the Ministry of Technology if further monies could be supplied for this purpose'. Even then, of course, there was 'also a problem with the definition of "what was a UK firm"', and this remained something which the Ministry of Technology had to define'.²³

CVD contracts, possibly followed by defence procurement, provided one potential channel for industrial exploitation. This was complemented by the work of the National Research Development Corporation (NRDC) that had the formal responsibility for

20 This became part of the Defence Research Agency in 1991, renamed the Defence Evaluation and Research Agency in 1995. In 2001, part of DERA was privatized to form Qinetiq, with part retained under government control as the Defence Science and Technology Laboratories, with both organizations operating side by side at sites such as Malvern. A detailed account of electronics work at the RRE up to 1965 can be found in G.W.A. Dummer, 'A history of microelectronics development at the Royal Radar Establishment', *Microelectronics and Reliability* (1965) 4, pp. 193–219.

21 Barnes and Holeman, *op. cit.* (16), pp. 335–346, 336.

22 CVD Policy Committee, *Integrated Circuits*, Note by the Chairman, 22 June 1966, NA ADM 272/244.

23 'Minutes of the Special Meeting of the Co-ordination of Valve Development Policy Committee to discuss Microelectronics held on the afternoon of Wednesday the 13th July' (1966), NA ADM 272/244.

the exploitation of inventions stemming from UK public-sector R & D from 1950 to 1985.²⁴

In practice this meant that NRDC would take on inventions stemming from the work of the research establishments so long as they were not unsuitable for reasons of national security, nor the result of collaboration in which the industrial contractor would be assigned the intellectual property rights. The relationship between NRDC and the research establishments peaked in the 1960s with the advent of the Ministry of Technology.²⁵ Both the Royal Radar Establishment at Malvern and NRDC came under the jurisdiction of MinTech, which sought to increase civil exploitation of the defence technology base.

Amongst the initiatives promoted by MinTech, the most directly concerned with semiconductor materials was the setting up in 1967 of an Electronic Materials Unit (EMU) within the Royal Radar Establishment. This was intended to supply newly available semiconductor materials to be used by industry, universities or other government research establishments, thus avoiding the necessity for each to produce their own.²⁶

The EMU at Malvern was, like MinTech, short-lived. A longer-lived embodiment of the collaborative spirit underlying defence-funded semiconductor R & D was the Gallium Arsenide Consortium.²⁷ Set up in 1966 under the aegis of CVD, the consortium brought together staff from RRE and SERL with the main CVD contractors – Plessey, STL (Standard Telecommunications Laboratories), BDH (British Drug House) Chemicals, Mullard, and GEC (General Electric Company) – who were active in semiconductor materials work.²⁸ Of these, Mullard, based at Mitcham, was owned by the Dutch Phillips company, and STL, the R & D wing of STC (Standard Telephones and Cables) was owned by the US ITT Corporation.

Because of its potential for radar use, the microwave capability of gallium arsenide gave development of the material high priority at Malvern (although it would be many decades before GaAs could compete with older technologies such as travelling wave tubes,

24 For an account of the origins of the NRDC see S.T. Keith, 'Inventions, patents and commercial development from governmentally financed research in Great Britain: the origins of the National Research Development Corporation', *Minerva* (1981) 19, pp. 92–122; and G.E. Haigh, A.W. Pearson, D.S. Watkins and M. Gibbons, 'NRDC and the environment for innovation', *Nature* (20 August 1971) 232, pp. 527–531. A popular account of NRDC's work is Peter Fairley, *Project X: The Exciting Story of British Invention*, London: Mayflower, 1970.

25 On MinTech see Richard Coopey, 'Restructuring civil and military science and technology: the Ministry of Technology in the 1960s', in Richard Coopey, Graham Spinardi and Matthew Uttley (eds.), *Defence Science and Technology: Adjusting to Change*, Amsterdam: Harwood Academic Press, 1993, pp. 65–84; and David Edgerton, 'The "white heat" revisited: the British government and technology in the 1960s', *Twentieth Century British History* (1996) 7, pp. 53–82.

26 'Electronic materials', *NRDC Bulletin* (April 1971) 37, p. 19. I am grateful to the British Technology Group (as NRDC was renamed) for providing me access to its archive of the NRDC Bulletin at its London headquarters.

27 This was replaced by the Gallium Arsenide Technology Consortium, a joint MoD–DTI body, in the mid-1980s. See Barnes and Holeman, *op. cit.* (16), p. 342.

28 D.T.J. Hurle, 'National collaborative research into gallium arsenide', *Electronic Engineering* (June 1985), pp. 149–153.

magnetrons and klystrons for radar applications that required high power outputs). The other main attribute of III–V materials, their opto-electronic characteristics, was initially investigated mainly at Baldock. The much-publicized advantage of gallium arsenide over silicon – that its operation at higher frequencies meant it was faster – turned out not to find much practical application, although emphasis of this apparent advantage over silicon may have been politically useful.²⁹

Device development

The first useful devices made from III–V materials were light-emitting diodes (LEDs). These can be made by simply connecting leads to a suitable piece of III–V material with the emission of visible radiation occurring when voltage is applied across a p–n junction. A number of materials were found to work as LEDs, including GaAs, gallium phosphide (GaP), gallium arsenide phosphide, and indium phosphide.

SERL was particularly active in LED development and in 1963 claimed the world's first practical application of GaP with an LED array developed to mark positional data on the TSR2 aircraft's reconnaissance film.³⁰ In 1964 Ferranti took over production of the arrays from SERL.³¹ Other arrays were developed at SERL during 1964 for the Atomic Weapons Research Establishment as part of accurate time-recording equipment for nuclear testing and for the joint US/UK re-entry physics experiments using Black Knight rockets.³²

With the technology thus proven, SERL withdrew from LED development, noting, 'Requirements for the present gallium phosphide lamps can now be adequately met by industry and this part of the device programme is terminated.'³³ CVD continued to support LED development (both GaP and GaAs) during the rest of the 1960s with requirements for military systems being met by UK industry.³⁴ In particular, Plessey and Ferranti began work on GaP 'with a view to exploiting the use of semiconductor lamps'.³⁵

²⁹ Szweda interview, *op. cit.* (14).

³⁰ SERL Technical Report No. 59, May 1963, 1.2. I am grateful to the librarian at what was then the Defence Evaluation and Research Agency establishment at Malvern for providing access to these reports. See also 'CVD office report to policy committee, March 1964: Development and device technology programme', attached to 'Co-ordination of Valve Development Policy Committee, Minutes of the 108th Meeting held on Wednesday, 4th March 1964', NA ADM 272/244. This notes, 'The pioneering S.E.R.L. GaP film marker, now being made at Ferranti under Ministry of Aviation contract, was well received by R.A.E. for aircraft cameras.'

³¹ SERL Technical Report No. 60, February 1964, 1.3.

³² SERL Technical Report No. 61, May 1964, 1.2 and 1.3.

³³ SERL Technical Report No. 64, November 1965, 1. SERL did revive its interest in 1967. See 'Minutes of the 8th Meeting of the CVD Special Devices Sub-Committee, 1st November 1967', NA ADM 272/251.

³⁴ See the various Minutes of the CVD Special Devices Sub-Committee between 1965 and 1970 in NA ADM 272/251.

³⁵ 'Solid State Physics Research Panel, Chairman's Report to CVD Research Advisory Board', attached to CVD Policy Committee, 1 July 1966, NA ADM 272/244.

However, SERL's work with Plessey and Ferranti to develop LEDs left little industrial legacy 'largely because neither company was interested in investing in it'.³⁶ CVD's Technical Committee complained in 1974 that it 'had funded GaP research at Ferranti and the work had gone well but the firm was not willing at this time to undertake production'.³⁷ In 1975 CVD reported,

The UK situation on LEDs was grave now that Ferranti had pulled out of the business. This highlighted the inability or unwillingness of UK firms to exploit new devices or technology and is particularly sad in this case as the UK was the first to make GaP lamps.³⁸

The difficulty of establishing a viable indigenous LED manufacturing industry, despite CVD's support and the work of SERL, led to much soul-searching. CVD's Display Devices Research Panel, chaired by Cyril Hilsum, noted,

With the demise of the Ferranti research team we have lost our longest established source of LEDs, and the position of the remaining British suppliers is not very healthy. In this field we made much of the early running and invested considerable intra-mural effort. It would be worth us trying to establish where our policies went wrong.³⁹

Thereafter, Plessey was the sole UK producer of LEDs, although Hilsum noted bitterly that 'to keep them in business, CVD must subsidise them'.⁴⁰ Plessey apparently remained unconvinced that the commercial returns justified a large investment on their part:

Our long term hopes (for GaP devices) now rest exclusively with Plessey. They are experiencing the sort of investment return problem familiar to many component suppliers at present, particularly in the UK. The future is quite uncertain here. We must be vigilant that we do not end up with a materials improvement programme with no UK outlet!⁴¹

In fact, Plessey did remain in LED manufacturing, but mainly supplying markets such as defence and avionics because it was 'not really in that large-volume, low-price business'.⁴² Its LED business was taken over by a management buyout just prior to Plessey's takeover by GEC and Siemens in 1989, and has since operated successfully as PRP Optoelectronics, albeit as a niche producer.⁴³

LEDs were a simple application of the opto-electronic properties of III-V materials, but the ability of these materials to absorb or emit photons also meant that they could be used to build lasers and photocathodes for night vision. Work on these started in the 1960s, but it was developments in epitaxial growth techniques that really brought them to maturity and so they are discussed below.

36 Ware interview, op. cit. (14).

37 'Procurement Executive, Ministry of Defence, Directorate of Components, Valves and Devices, The Technical Committee', Minutes of the 144th Meeting, 20 September 1974, NA ADM 272/263.

38 'Procurement Executive, Ministry of Defence, Directorate of Components, Valves and Devices, The CVD Technical Committee', Minutes of the 146th Meeting, 17 July 1975. NA ADM 272/263.

39 Cyril Hilsum, 'Report of Display Devices Research Panel – July 1975', 30 June 1975, NA ADM 272/263.

40 Cyril Hilsum, 'Report of Display Devices Research Panel – July 1976', RSRE, NA ADM 272/263.

41 'Chairman's Report on Applied Physics Research Panel', CVD, June 1975, P. J. Dean, RRE, Malvern, NA ADM 272/263.

42 Ware interview, op. cit. (14).

43 See www.prpopto.com/about-us.html.

However, although the opto-electronics properties were the first to be exploited, 'the original choice of GaAs was for use as a transistor material, where the higher band gap would allow higher temperature operation and the high mobility higher frequencies of operation than obtainable with silicon'.⁴⁴ These theoretical advantages proved hard to realize, and when CVD's Policy Committee's Research Advisory Panel reviewed the CVD Research Programme on 31 March 1965 it concluded 'that, under normal conditions, GaAs transistors had few advantages over other transistors, but that they might be valuable under conditions of high operating temperature'.⁴⁵

This pessimistic conclusion followed some frustrating work done by a SERL-led consortium involving STC, Marconi Research, Plessey Caswell and RSRE 'under the iron-fisted chairmanship of Cyril Hilsum'.⁴⁶ With little progress to show, this was terminated after two years at the end of 1964.⁴⁷ After being told that the project was to be terminated, the Caswell contingent, while driving home, 'vowed to continue the transistor work in GaAs in some form or other and even before the return journey was complete it was agreed to propose to the MoD that work begin on a gallium arsenide field effect transistor' (FET).⁴⁸

Plessey had the advantage of good-quality in-house material. In the early 1960s Plessey developed a process for producing gallium arsenide in which gallium and arsenic trichloride vapours were combined to grow epitaxial layers on a substrate.⁴⁹ This was acknowledged by CVD's Solid State Physics Research Panel, which reported that 'a process has been developed [at Plessey] to make high purity GaAs of quality superior to that made elsewhere in the world'.⁵⁰ However, the first device to make use of this material was not a transistor, but a microwave-generating oscillator known as the Gunn diode.⁵¹

Although named after J. B. Gunn, an English scientist who had moved to work at IBM in the USA in 1959, the Gunn diode was based on an effect earlier predicted by work at the Mullard Research Laboratories in Surrey and at SERL.⁵² The UK's early emphasis on III-V materials R & D meant that, uniquely in the history of semiconductor developments to that date, the first commercial production of Gunn diodes occurred in the UK, not the USA. In 1965 Associated Semiconductors Manufacturers (ASM),

44 G.P. Wright, *Services Electronics Research Laboratory, 1945–1976*, London: HMSO, 1986, p. 10.

45 Report of Chairman of the CVD Research Advisory Panel to Policy Committee, June 1965, NA ADM 272/244.

46 James Turner, 'History of the GaAs FET at Caswell (1964–1985)', IEEE Colloquium on Modelling, Design, and Applications of MMICs, London, 1994, 1/1–1/3, 1/1.

47 Turner, op. cit. (46), 1/1–1/3; and J.M. Herbert and B.L.H. Wilson, 'Solid-state research at Caswell', *Physics in Technology* (1986) 17, 132–138, 136.

48 Turner, op. cit. (46), 1/1.

49 K.M. Baughan, 'Microwave device development at Plessey', *Physics in Technology* (November 1976) 7 (6), pp. 254–259, 254, has 1965; Herbert and Wilson, op. cit. (47), 136, have 1963.

50 'Solid State Physics Research Panel, Chairman's Report to CVD Research Advisory Board', attached to CVD Policy Committee, 1 July 1966, NA ADM 272/244. See also Baughan, op. cit. (49), pp. 254–259.

51 J.B. Gunn, 'Microwave oscillation of current in III-V semiconductors', *Solid State Communications* (1963) 1(4), pp. 88–91.

52 Orton, op. cit. (13), pp. 195–197.

a subsidiary of Mullard, in conjunction with GEC, began production of gallium arsenide Gunn diodes, and other UK manufacturers followed shortly thereafter.⁵³

The Gunn effect meant that gallium arsenide could provide a cheap, compact, low-power microwave source with potential use in radar and communications technology. Applications based on gallium arsenide Gunn diodes were one of the widely advertised examples of civil spin-off used to promote the work of the Industrial Applications Unit at the RRE, Malvern.⁵⁴ Civil applications in development included burglar alarms and portable 'speed guns'.

Such potential for civil exploitation of the UK's gallium arsenide expertise was a matter of interest to CVD in the mid-1960s:

What is needed is a readiness to back, on a sufficiently large scale, proposals which can be considered likely to lead in the right direction. Significant national economic benefits could arise from research directed towards the early development of all-solid-state communications systems, and there is a likelihood of stimulating a much wider use of microwaves, e.g. in miniature radars. Thus there is justification for putting public money into research in this field, additional to the Defence requirements.⁵⁵

In the meantime, Plessey's work on GaAs FETs during the 1960s eventually paid off with the announcement in February 1970 of the GAT 1, 'the first commercially available GaAs FET.'⁵⁶ Although this particular device 'did not perform as predicted by the theory available at the time', the development of the FET offered the prospect of high-frequency, low-noise amplification.⁵⁷ Caswell continued during the 1970s with work on MESFETs (metal semiconductor field effect transistors) and in July 1977 the chairman of CVD's Power Devices Research Committee noted that Plessey's GaAs work 'continues to extend the performance of microwave FET amplifiers to higher frequencies, higher power and low noise, and the team at Plessey receives world-wide recognition'.⁵⁸ Of particular significance was the demonstration of the first GaAs FET-based monolithic microwave integrated circuit (MMIC) in 1976.⁵⁹

This development of transistors operating at microwave frequencies (and thus usable for amplification in radar systems) really became a practical proposition when good-quality semi-insulating GaAs substrate became available. Plessey's epitaxial growth

53 Golding, *op. cit.* (1), p. 84.

54 Ron Pretty, 'R & D pay-off at the RRE', *Electronics Weekly*, 8 November 1967; 'Diversification in a government laboratory', *Nature*, 11 November 1967, 216; 'Spin-off: to industry from Malvern', *Engineering*, 10 November 1967.

55 'Requirements for future power device research: a report to CVD Policy Committee', Services Electronics Research Laboratory, Microwave Electronics Division, Harlow, Essex, June 1966, by M.O. Bryant, Chairman, CVD Power Devices Research Panel, Attached to CVD Policy Committee, 18 November 1966, NA ADM 272/244.

56 Turner, *op. cit.* (46), 1/1–1/2.

57 Turner, *op. cit.* (46), 1/2.

58 'Power Devices Research Committee – Chairman's Report to CVD Technical Committee – July 1977', K.G. Hambleton, ASWE, Portsmouth, Appendix 2 to 'Procurement Executive, Ministry of Defence, Directorate of Components, Valves and Devices, 150th Meeting of The CVD Technical Committee', 19 July 1977, NA ADM 272/263.

59 R.S. Pengelly and J.A. Turner, 'Monolithic Broadband GaAs FET Amplifiers', *Electronics Letters* (13 May 1976) 12(10), pp. 251–252.

process provided material for their research, but during the 1960s bulk GaAs substrate was typically made by the Bridgman process in which a pressurized, horizontal crucible of polycrystalline GaAs is heated from one end to the other. Seeded with a crystal, this results in virtually all the crucible contents crystallizing so that impurities are in effect moved through the crucible as it is heated so that the final section of the crystal can be discarded with the impurities.

However, the Bridgman process produced semi-conducting GaAs and its low resistivity makes it unsuitable for high-frequency applications because low resistivity GaAs is susceptible to interference within a 'chip'. To make this material semi-insulating requires the Bridgman-produced ingots to be doped heavily with chromium, and 'radial non-uniformity made this material less than satisfactory'.⁶⁰ An important development in materials production was thus the development of crystal 'pullers' (see next section) that could produce good-quality undoped semi-insulating GaAs which then enabled the production of integrated circuits (ICs) using ion implantation: 'High performance FETs fabricated using this technology were first demonstrated in 1977.'⁶¹

With the development of the MMIC and with suitable bulk GaAs becoming available, Caswell was now able to produce devices for military phased-array radars in which each radar element comprises a single transmit/receive device. Other applications also beckoned and during the 1980s Plessey 'took management control of the facility at Caswell' and 'set itself up . . . to have a commercial presence in gallium arsenide . . . not just for in-house specials; it was going to be a commodity supplier'.⁶²

However, the takeover of Caswell by GEC in 1989, and the establishment of GEC-Marconi Materials Technology Ltd in 1991, saw investment in GaAs production facilities, but also an orientation more towards defence-procurement markets.⁶³ Although there was a significant civil market for optical modulators for communications systems, Caswell found itself in the familiar 'dual-use' conundrum of attempting to be effective as both a defence-procurement supplier and a commercial operator.⁶⁴ As noted by one commentator, 'the constant battle between internal defence needs and the external commercial aims is a challenge that few defence operations have successfully pulled off'.⁶⁵ According to one SERL/RSRE scientist, GEC 'maintained a capability to make these devices in the UK, and they are very good, they are world competitive, but they are not commercial'.⁶⁶

60 Hurle, op. cit. (28), p. 149.

61 Hurle, op. cit. (28), p. 152.

62 Myers interview, op. cit. (14).

63 Myers interview, op. cit. (14); Helen Duncan, 'Staff anger at Bookham GaAs line closure', *Microwave Engineering*, 27 May 2004; Jim Turner, 'Europe's premier foundry operation', *III-Vs Review* (October 1991) 4(5), 58–60.

64 Courtaulds had similar problems with its carbon fibre operations. See Graham Spinardi, 'Industrial exploitation of carbon fibre in the UK, USA and Japan', *Technology Analysis & Strategic Management* (2002) 14, 381–398.

65 Stephen Entwistle, vice president of strategic technologies practice at Strategy Analytics, quoted in Duncan, op. cit. (63).

66 Wight 1998 interview, op. cit. (14).

When Marconi demerged, Caswell was taken over by the US-based Bookham Technology in 2002, and in 2004 Caswell's GaAs production line was closed down. This ended over forty years of work on GaAs, said to be the longest continuous such activity anywhere.⁶⁷ This was not the end of GaAs device manufacturing in the UK, however. In 1999, with the help of a £5 million UK government grant, Filtronic took over Fujitsu's silicon foundry at Newton Aycliffe in County Durham and converted it to GaAs production, particularly aimed at the growing market for mobile phone devices. Filtronic's foundry became the largest GaAs device producer in Europe. However, even then Filtronic was not in the top ten GaAs device producers worldwide, a list dominated by US companies.⁶⁸ Moreover, the Newton Aycliffe plant returned to foreign ownership in 2008 when Filtronic sold its compound semiconductor operations to the US RF Micro Devices.⁶⁹

Material production and crystal pullers

One of the biggest successes of UK defence-sponsored work was the development of crystal growth systems that could be used to produce III–V materials such as gallium arsenide, indium phosphide and gallium phosphide. From the mid-1950s materials work at SERL was dominated by efforts to produce gallium arsenide of sufficient quality to investigate its properties. Initially, GaAs ingots were produced by the 'floating zone' technique that involved solidification of a horizontal bath of molten GaAs. In 1960 the *SERL Technical Journal* noted that 'the quality of the average ingot is now better than that available elsewhere. There is still no other British source of high-grade material, but several firms are beginning production on an experimental scale'.⁷⁰

This production method was possible with GaAs, but not with gallium phosphide (GaP) and commercial exploitation of GaP LEDs was held back by the lack of an efficient production process. Instead, the less efficient gallium arsenide phosphide captured most of the initial market for LEDs.⁷¹ GaAsP could be built up on a GaAs substrate by adding phosphorous to a GaAs vapour.

Both SERL and RRE had used Czochralski pullers to produce silicon and germanium and they now applied the technique to GaP.⁷² The Czochralski technique was a proven approach for growing semiconductor crystals by slowly pulling a crystal out of melted liquid. However, gallium phosphide was particularly difficult to grow because it dissociates at its melting point, making the standard approach impractical. To overcome this, RRE developed a modification of the technique in which the surface of the semiconductor melt is covered with a viscous liquid (boric oxide) to suppress loss of

67 Duncan, op. cit. (63).

68 See <http://compoundsemi.com/documents/view/cldoc.php3?id=8724#top>.

69 'Filtronic sale is new dawn for GaAs in Europe', *EE Times*, 17 March 2008, http://eetimes.eu/en/filtronic-sale-is-new-dawn-for-gaas-in-europe?cmp_id=7&news_id=206903961.

70 *SERL Technical Journal* (November 1960) 54, pp. 1–4.

71 G.R. Blackwell, 'Green light for LEDs', *NRDC Bulletin* (Autumn 1975) 43, p. 5.

72 See *SERL Report* (November 1960) 54, pp. 1–9; Parkinson, op. cit. (16), pp. 246–247.

volatile components.⁷³ Known as the liquid-encapsulation Czochralski (LEC) technique, this approach was then adapted to high-pressure vessels and taken up by Metals Research Ltd under licence from the National Research Development Corporation.⁷⁴ NRDC contributed a joint share of development funds in return for a levy on sales.⁷⁵ Metals Research's first puller sale was to Bell Labs in the US, with the second one going to Plessey Caswell.⁷⁶

Known as the 'Malvern', this crystal puller became the standard method for producing GaP crystals, with the pullers themselves selling particularly well in Japan.⁷⁷ Improvements in the Malvern meant that between 1969 and 1975 the size of crystal that could be produced went from fifty grams one kilogram.⁷⁸ However, this was still not enough to make GaP production competitive with that of GaAsP, and the Malvern also suffered from difficulties with its lack of user-friendliness and unevenness of crystal quality.

Metals Research therefore developed a new crystal puller, the Melbourn (named after the village near Cambridge where Metals Research was based), which addressed these problems. Larger than the Malvern, it was designed to produce high-quality crystals weighing up to seven kilograms. Moreover, whereas the Malvern was adapted from RRE's laboratory design, the Melbourn was designed from scratch as a production machine, with ease of operation a main concern. Another improvement stemmed from work at RRE to develop automatic diameter control (ADC). One of the difficulties involved in Czochralski growth is instability that tends to produce a crystal ingot of very uneven diameter. RRE's approach, now widely used in crystal growth of many materials, maintains an even crystal diameter through temperature feedback based on the rate of the increase in the crystal's weight. Working together, RRE and Metals Research produced a world-leading design: 'The result of this pooling of the intellectual resources, experience and expertise of both establishments was a workable system, and a properly engineered version of this has now been incorporated into the new Melbourn puller.'⁷⁹

During the 1970s, Metals Research exported its pullers all over the world, with particularly strong demand in the US and Japan. The pullers were sold on a 'turn-key' basis as a 'technology package' that included setting up the machine and doing enough growth runs to provide guaranteed performance.⁸⁰ As Roger Waldock of Metals Research joked, this could take two weeks to do at Westinghouse in Pittsburgh in the winter, but three months at Hughes in Malibu in the summer.⁸¹ This, of course, meant that at the same time as it was being successful in selling the crystal pullers, Metals

73 Blackwell, *op. cit.* (71), p. 6.

74 'Electronic materials', *NRDC Bulletin* (April 1971) 37, p. 20.

75 Blackwell, *op. cit.* (71), p. 6.

76 Ware interview, *op. cit.* (14).

77 Ware interview, *op. cit.* (14). See also 'Rowland Ware on old and new perspectives in materials science', *III-V Technology Review* (1987) 3, p. 18.

78 Blackwell, *op. cit.* (71), pp. 5–6.

79 Blackwell, *op. cit.* (71), p. 8. See also Barnes and Holeman, *op. cit.* (16), p. 30.

80 'As Cambridge fares, so fares the industry', *III-V Technology Review* (1987) 4, p. 44.

81 Interview with Roger Waldock, in 'As Cambridge fares', *op. cit.* (80), p. 45.

Research was also exporting technology that would enable overseas firms to compete strongly in crystal production.

In fact, Japan very quickly came to dominate the production of GaP, largely based on the use of Metals Research machines:

We also sold a lot of those machines to Japan, and the Japanese sold their GaP for less than the competition, and totally wiped out the U. S. commercial GaP market and, while they were at it, the European market . . . When you look at it, most of the LEDs you see are primarily grown on Japanese substrates, and probably better than 80% of that substrate material is grown using Cambridge [Metals Research merged with Cambridge Instruments] pullers.⁸²

Established as the way to make GaP crystals, Metal Research's pullers then became of interest for GaAs production. Although the LEC approach had been investigated for GaAs production, it was thought unsuitable because of the interaction with the boric oxide encapsulant. In any case, gallium arsenide did not need to be made by the LEC technique because it could be made by the Bridgman process.

Bridgman remains a major source of GaAs crystals because it is cheaper than LEC and generally produces a better crystal structure, which is important for opto-electronic applications. However, the Bridgman process was not ideal for producing GaAs material for microwave applications – Malvern's main interest – because the crucibles are made of silica and the subsequent contamination of the material with silicon complicates the production of semi-insulating properties.⁸³ With concerns over the supply of semi-insulating GaAs, CVD's Applied Physics Panel 'invited Metals Research to submit a proposal for pulled material' in 1975.⁸⁴

The next, very significant, step stemmed from work (both in the US and at Metals Research, which in 1975 took over, and adopted the name of, Cambridge Instruments) that showed that LEC GaAs crystals could be grown with semi-insulating properties without chromium doping if silica was not present.⁸⁵ Initially, this meant using crucibles made of pyrolytic boron nitride, but then Cambridge Instruments discovered that the same effect could be achieved using silica crucibles so long as the moisture content of the boric oxide encapsulating layer was carefully controlled.⁸⁶

This LEC-pulled GaAs also had the added benefit that the cylindrical ingots produced could be cut into cylindrical wafers that 'were highly desirable if the processing technology established for silicon ICs was to be taken over and adapted to gallium arsenide'. As a result the Cambridge 'pullers quickly came to dominate the world market for pressure pullers and the materials base for a gallium arsenide IC technology was founded'.⁸⁷

82 Interview with Roger Waldo, in 'As Cambridge fares', *op. cit.* (80), p. 44.

83 'Rowland Ware on old and new perspectives in materials science', *op. cit.* (77), p. 21.

84 'Procurement Executive, Ministry of Defence, Directorate of Components, Valves and Devices, The CVD Technical Committee', Minutes of the 147th Meeting, 11 December 1975, NA ADM 272/263. See also Hurlle, *op. cit.* (28), p. 149.

85 Ware interview, *op. cit.* (14).

86 Hurlle, *op. cit.* (28), pp. 149–153, 150.

87 Hurlle, *op. cit.* (28), p. 150.

Cambridge Instruments thus repeated the export success that it had first had with its GaP pullers. During the 1980s interest in semi-insulating gallium arsenide led to worldwide sales for Cambridge Instruments pullers (in 1987 it was estimated that 80 per cent of pullers installed for GaAs manufacture in the US had been built by Cambridge⁸⁸). However, by the end of the 1980s the market for pullers had tailed off. Not only had most potential customers already acquired all the pullers they wanted, but limited demand led others to stop gallium arsenide production, leading to the availability of second-hand pullers. In some cases, the initial desire for a puller was to ensure an in-house supply of material for R & D purposes (in, say, device development), a requirement which became unnecessary once satisfactory material became reliably available on the open market.⁸⁹

As well as producing the pullers, Cambridge Instruments also produced and sold some III–V materials, mainly for R & D purposes or for military applications. Ironically, the large number of Metals Research/Cambridge pullers supplied to Japan made it hard to compete. As one of the key figures in the development of pullers at Metals Research/Cambridge noted, 'The Japanese wiped us out as well as everyone else in the GaP business, and we went into GaAs.'⁹⁰ However, although Cambridge Instruments dominated the world market for high-pressure pullers, they were not so successful in producing the final GaAs product themselves, and it was noted that whilst 'the CI pulling technology is in the van of world development, they have been overtaken by several foreign suppliers in wafer finish'.⁹¹

In 1985, the materials production side of the business was sold to ICI Wafer Technology, which set up a new factory at Milton Keynes for the production of gallium arsenide and indium phosphide. Substantial investment by ICI led to improvements in the quality of wafer finishing, but at the end of the 1980s ICI corporate policy was reconsidered, and the move into semiconductors was reversed.

ICI was not the only company to have invested in gallium arsenide production, and production capacity exceeded demand in the late 1980s, leading to several withdrawals from the market. Mining Chemical Products (MCP), the other main UK producer of GaAs and other III–V materials – using a Bridgman method – was also finding market conditions difficult. As a result, in 1990 MCP took over the ICI Milton Keynes plant (and relocated there from its site at Woking) to form Wafer Technology. In 1994 MCP then also decided to move out of electronic materials and a management buyout took control of Wafer Technology (four managers took a majority holding of 80 per cent, with MCP retaining the remaining 20 per cent).

Wafer Technology (now a subsidiary of Cardiff-based IQE plc) continues to make materials using both LEC and vertical gradient freeze techniques. These include LEC-produced indium phosphide, which has become increasingly used in fibre-optic telecommunications applications because it is particularly suitable for making devices

88 Interview with Roger Waldock, in 'As Cambridge fares', *op. cit.* (80), p. 46.

89 Grant interview, *op. cit.* (14).

90 Interview with Roger Waldock in 'As Cambridge fares', *op. cit.* (80), p. 45.

91 'A UK strategy for GaAs', edited by David Colliver and produced by the Royal Signals and Radar Establishment in the mid-1980s (undated), 14. This was provided to me on a visit to RSRE in 1990.

that emit or detect at frequencies (1.3 and 1.55 microns) which provide the best transmission through fibre optics.

Wafer Technology also continues to make LEC GaAs, but mainly for customers who use it for research purposes. The main market for LEC GaAs now involves larger wafer sizes for use in device production, but intense competition for these sizes led to prices that Wafer Technology could not economically match. American investment in this area was driven by the 'Title III' programme that was initiated in 1994 and provided US government support to build up a national gallium arsenide capacity.⁹² According to US Deputy Undersecretary of Defense for International and Commercial Programs,

Prior to the Title III project, U.S. firms accounted for less than 25 percent of sales worldwide and were discouraged from competing more vigorously by the relatively small market for semi-insulating gallium arsenide wafers, and by the high capital cost to be competitive in this market.

However, by 1998 the situation had changed so that 'these companies dominate the U.S. and world markets with nearly 60 percent of the market and world-class product quality'.⁹³ More recently, Japanese companies Sumitomo and Hitachi, alongside the German Freiburger Compound Materials, have taken over as the leading producers. Although Wafer Technology continues to fly the flag for the UK in production of III-V materials, it is now a niche producer.

Epitaxial growth

Semiconductor wafers are the basic building blocks of electronics, but most devices also make use of epitaxy, in which precise layers of semiconductor are laid down on the wafer substrate. This is used to control the semiconductor properties and to develop devices. Initially the most successful approach, liquid-phase epitaxy (LPE) was limited in its potential for high performance because of lack of precise control over both the sharpness of the transition between the epitaxial layers and the evenness of layers across the whole wafer. Two other epitaxial techniques offered better performance: metal organic chemical vapour deposition (MOCVD), also known as metal organic vapour phase epitaxy (MOVPE); and molecular beam epitaxy (MBE).

UK work on MOCVD was pioneered at SERL under Sidney Bass.⁹⁴ Named after its inventor, the Bass reactor allowed thin layers of material to be built up on the semiconductor wafer surface. In particular, the organic-based process (originally conceived by Hal Manasevit in the US) allowed the deposition of materials that could not be carried by the previous chlorine-based process because of their reactive nature. This was crucial because it opened up the potential for mixing aluminium arsenide

⁹² Jo Ann McDonald, 'DoD funds provide timely stimulus for US GaAs producers', *III-Vs Review* (February 1995) 8, pp. 26–28.

⁹³ News Release, 'Department of Defense Program Contributes to Turnaround in a Key Semiconductor Materials Industry', 17 April 1998, at www.defenselink.mil/releases/release.aspx?releaseid=1650, accessed 5 August 2009.

⁹⁴ Barnes and Holeman, op. cit. (16), p. 339.

(which was too reactive for chlorine-based epitaxy) with gallium arsenide to fine-tune semiconductor properties.⁹⁵

SERL's work led to 'the world's first volume production of metal organic gallium arsenide' in the manufacture of an image-intensifying photocathode for military use.⁹⁶ This proved to be 'an unexpectedly difficult development', with the work started at SERL in the mid-1960s not coming to fruition until the 1980s.⁹⁷ Initial development was carried out in collaboration with Mullard at Mitcham and STC at Harlow. Progress at Mullard was considered 'disappointing' by CVD.⁹⁸ Moreover, SERL's expertise was considered to be 'well ahead of that in Industry' and by 1976 had 'shown a definite single route towards the manufacture of satisfactory GaAs photocathodes', and so 'the extramural programme on alternative methods [was] discontinued'.⁹⁹

The situation was reported to the CVD Technical Committee in June 1977: 'Recent success on GaAs photocathode devices at Baldock has led to a review of the likely applications, and a decision will be taken in the near future on whether to proceed to development and if so, on what format.'¹⁰⁰ SERL (which in 1976 merged with RRE to form RSRE) now had 'a preferred manufacturing method using hetero-epitaxial layers of GaAs and GaAlAs bonded in glass, which also gives the required high sensitivity'. This was initially done using liquid phase growth, but work continued on 'vapour phase growth using metal alkyls which offer the possibility of better layers'.¹⁰¹

When the decision was made by the MoD to initiate photocathode production, an industrial contractor was required, but neither Mullard nor STC was prepared to take the step into commercial production.¹⁰² Instead, EEV (English Electric Valve) of Chelmsford won the contract for photocathode production. EEV had experience in producing image-intensifying equipment (they were RRE's main industrial partner in the development of infrared imaging pyroelectric technology¹⁰³), but had no track record in epitaxial growth techniques, which was the key to the photocathode. However, the SERL/RSRE team was confident that it could transfer the technology into EEV in order to meet the MoD's procurement requirements. This led to the development of night goggles that went into service in the mid-1980s and were used in the first Gulf

95 Wight 1998 interview, op. cit. (14).

96 Wight 1998 interview, op. cit. (14).

97 Wright, op. cit. (44), p. 16.

98 'Procurement Executive, Ministry of Defence, Directorate of Components, Valves and Devices, the CVD Technical Committee', Minutes of the 148th Meeting, 15 July 1976, NA ADM 272/263.

99 'Optoelectronic Detector Research Panel—Chairman's Report to CVD Technical Committee, June 1976', NA ADM 272/263.

100 'Optoelectronics Detector Development Committee, Chairman's Report to CVD Technical Committee, June 1977', Appendix 3 to 'Procurement Executive, Ministry of Defence, Directorate of Components, Valves and Devices, 150th Meeting of The CVD Technical Committee', 19 July 1977, NA ADM 272/263.

101 'Electronics Research Council, Department of Industry, Optics and Infra-red Committee, Extracts from Research Programmes of the Procurement Executive, Ministry of Defence', P. J. Holmes, 11 August 1976, NA DEFE 35/5.

102 Wight 1998 interview, op. cit. (14).

103 The role of the UK defence establishments in the development of pyroelectric technology is described in R. Watton, 'Infrared television: thermal imaging with the pyroelectric vidicon', *Physics in Technology* (1980) 11, pp. 62–66; E. Putley, 'Infrared spin-off', *Physics in Technology* (1986) 17, pp. 32–37.

War.¹⁰⁴ This work was carried out so successfully that RSRE and EEV were joint recipients of a Queen's Award in 1987, but this award proved a poor guide to longer-term technological performance. According to one account, changes in EEV's management resulted in a requirement for technical managers to rotate jobs so as to broaden their experience, with the consequence in practice that the specific skills and knowledge base necessary for photocathode production were eroded.¹⁰⁵ EEV (now E²V) continues to be a major producer of image sensors for defence and other specialist applications, but using silicon-based CCD (charge coupled devices) or CMOS (complementary metal oxide semiconductor) technologies.¹⁰⁶

As SERL gained confidence in the MOCVD technique it also sought to apply it to laser production, its other big opto-electronic application of III-Vs. Laser action in GaAs had first been demonstrated in the USA in 1962.¹⁰⁷ CVD funding for research on GaAs lasers was focused at STL where the development of fibre optics for telecommunications was pioneered in the 1960s. Amongst the contracts given to firms and universities to work on this topic was one to develop high-power GaAs lasers placed with STC/STL in 1966.¹⁰⁸ The following year, the availability of devices from STC led SERL to cease its in-house work on GaAs lasers, though SERL continued to monitor and support extramural work at STL through CVD contracts.¹⁰⁹

A familiar complaint of CVD concerned the reluctance of STL (which was owned by the US ITT corporation) to move into production, as the CVD Technical Committee noted in December 1970:

The expertise was concentrated at STL where ITT internal politics were vitiating any attempt to increase the production effort to cope with the work. CVD had pointed out to ITT that research projects in a firm with no production outlet was not a viable proposition.¹¹⁰

However, the following July, CVD were informed that 'STL were setting up a pilot production facility as part of the development programme and this should satisfy demands until it grew to a size that would tempt the ITT organisation to take it into one

104 Wight 1991 interview, op. cit. (14).

105 Wight 1998 interview, op. cit. (14).

106 See, for example, P.R. Jordan, P. Pool and S.M. Tulloch, 'The secrets of E2V technologies CCDs', in Paola Amico, James W. Beletic and Jenna E. Beletic (eds.), *Scientific Detectors for Astronomy*, Dordrecht: Kluwer Academic Publishers, 2004, pp. 115–122.

107 'Minutes of the Fifth Meeting of the CVD Panel on Laser Research', 4 October 1966, 'Appendix II, Notes on Mr Gooch's talk on injection lasers', NA ADM 272/248.

108 *SERL Technical Report* (May 1966) 65, p. 1. Standard Telecommunications Laboratories was the research arm of Standard Telephones and Cables. They had been in receipt of CVD funding to work on GaAs lasers from at least 1963. See 'Minutes of the 4th Meeting of the CVD Optical Maser Working Party held on 25th September, 1963', NA ADM 272/248.

109 Richard Mills, 'Laser research and development, 1960–80', in Bud and Gummert, op. cit. (10), p. 283. See also *idem*, 'British defence expenditure and the growth of technology: a case study of laser technology 1960–1970', University of Lancaster PhD, 1995. For the concentration of CVD on GaAs laser support see 'Report to the CVD Technical Committee from the Chairman of the Laser Panel – 1974', NA ADM 272/263.

110 See 'Ministry of Defence, Department for Co-ordination of Valve Development, Technical Committee', Minutes of the 135th Meeting, 2 December 1970, NA ADM 272/263.

of its production facilities'.¹¹¹ Moreover, it was concluded that the 'policy of concentrating all the CVD funding on semiconductor lasers at STL appears to be paying off with performance data somewhat better than those obtained in the USA'.¹¹² By 1975, 'STL had set up a unit at Paignton for the production of GaAs lasers and were selling mostly in the export market'.¹¹³

RSRE's success with MOCVD-produced photocathodes then led them to apply the same approach to lasers in the late 1970s: 'we said, well, we haven't finished there, this is a generic technology'.¹¹⁴ This required a more complex structure than that used in the photocathode, with more junctions and much more precise control of layer thickness. Once mastered, however, lasers produced by MOCVD offered better performance than previously possible.

The new levels of efficiency achieved in these devices stemmed from the application of 'low-dimensional structures' (LDS) physics.¹¹⁵ LDS takes advantage of the ability to build up precisely (one atomic plain at a time) the epitaxial layers in a crystal structure while mixing gallium arsenide and aluminium arsenide layers without disrupting the structure (because they have the same lattice spacing). This means that the semiconductor properties can be very precisely controlled, and in LDS this manipulation extends to the use of crystal structures with wavelengths shorter than an electron wavelength. This allows electronic activity to be restricted to two dimensions within an epitaxial layer, providing even more precise control over semiconductor properties.

RSRE's collaboration with STC (at both Harlow and Paignton) on MOCVD technology led to a Queen's Award for Technology in 1991. Commercial exploitation was aided by British Telecom support for STC research which led to worldwide application of MOCVD in communications technology. STC Optical Devices at Paignton was first taken over by Nortel (with major job losses following), then by Bookham Technology, which itself merged with Avanex to form Oclaro.¹¹⁶ Paignton now operates as a research facility with MOCVD being used for laser manufacturing being carried out at Caswell, also now owned by Oclaro.¹¹⁷

In addition to companies using the technology in device production, other UK companies became suppliers of the production technology itself. MOCVD reactors

111 'Ministry of Defence, Department for Co-ordination of Valve Development, The Technical Committee', Minutes of the 137th Meeting, 13 July 1971, NA ADM 272/263.

112 'Report for CVD Technical Committee CVD Development Projects – lasers', attached to 'Procurement Executive, Ministry of Defence, Department of Components, Valves and Devices, The Technical Committee', Minutes of the 140th Meeting, 22 November 1972, NA ADM 272/263.

113 'Procurement Executive, Ministry of Defence, Directorate of Components, Valves and Devices, The CVD Technical Committee', Minutes of the 146th Meeting, 17 July 1975, NA ADM 272/263.

114 Wight 1998 interview, op. cit. (14).

115 D.A. Anderson and C.R. Whitehouse, 'Low dimensional structures', in *RSRE Research Review 1985*, London: HMSO, 1985, pp. 136–141.

116 'Global tech firm out of Nortel's ashes', *Herald Express*, 25 February 2010. See www.thisissouthdevon.co.uk/news/Global-tech-firm-Nortel-s-ashes/article-1866351-detail/article.html.

117 Andy Carter, 'Unlocking the value of fab ownership', *Compound Semiconductor* (1 February 2010), available at <http://compoundsemiconductor.net/csc/features-details.php?id=19607287>.

based on Sidney Bass's original design were produced and sold by EEV, Thomas Swann and Cambridge Instruments (although the last of these preferred the term metal organic vapour phase epitaxy or MOVPE).¹¹⁸ RSRE research also led to the development of a reactor sold by EEV that was capable of growing narrow band-gap II–VI materials such as cadmium mercury telluride, used in high-quality infrared vision systems.¹¹⁹

A further spin-off from work at RSRE centred on the source materials used in the MOCVD process, such as trimethyl gallium and trimethyl aluminium. Very high levels of purity (better than one part per million) are required for these precursors if the semiconductor properties are not to be degraded. Two early UK producers of such materials, BDH Chemicals Ltd and Mining and Chemical Products Ltd, both licensed technology via the NRDC.¹²⁰ Other work resulting from collaboration between RSRE and teams at Liverpool University and Queen Mary College in London was taken up by a new company, EPICHEM, founded in 1983 with the help of the Merseyside Development Corporation.¹²¹

The other area of epitaxial technology to which the UK defence establishments made a significant contribution was molecular beam epitaxy (MBE). MBE is carried out in a very high vacuum, providing a very precise process for research purposes, although initially the high expense and low throughput limited its suitability for mass production.¹²² UK work on MBE was stimulated by the formation in 1983 of an MBE Working Party within the Gallium Arsenide Consortium.¹²³ This interest created a market for MBE reactors which was met by Vacuum Generators Ltd (later VG Semicon), which along with collaboration between the company and RSRE led to VG Semicon becoming a major world supplier of MBE equipment.¹²⁴

Discussion

Pioneering in its technical content, UK work on III–V technologies was heavily shaped by its military context. As recalled by one of the key figures at Malvern, the work of the defence research establishments and the support of CVD played a major part in establishing 'the technical and commercial materials base for a UK III–V industry, not historically enjoyed by the UK silicon industry'.¹²⁵ Technology transfer to the industrial partners of the defence establishments was effective, but these were predominantly defence-oriented companies that were content to stick to defence R & D and procurement contracts rather than seeking out opportunities for civil markets.¹²⁶

118 On Cambridge Instruments and MOVPE see 'As Cambridge fares', *op. cit.* (80), p. 43.

119 Barnes and Holeman, *op. cit.* (16), p. 339.

120 'Electronic materials', *NRDC Bulletin* (April 1971) 37, p. 20.

121 Epichem was taken over by the US based Sigma-Aldrich Corporation in February 2007. See www.sigmaaldrich.com/SAFC/Hitech.html, accessed 19 December 2007.

122 Wight 1998 interview, *op. cit.* (14).

123 Hurle, *op. cit.* (28), p. 151.

124 Barnes and Holeman, *op. cit.* (16), p. 339.

125 Hurle, *op. cit.* (28), p. 153.

126 Hurle interview, *op. cit.* (14).

Although potentially dual-use, these technologies were not widely adopted for civil markets by UK industry for two reasons. First, there was initially little market for III–V semiconductors outside defence (with obvious exceptions such as civil radar). Second, even where there was civil potential (for example with LEDs), the UK companies with close ties to the defence establishments were unwilling or unable to realize this potential.

Initially promoted by some as an alternative, higher-speed, material to enable faster chip speeds,¹²⁷ or as a specialist material for military microwave and opto-electronic applications, gallium arsenide would only later prove commercially successful in uses such as mobile phones, digital television, remote controls and laser 'pick-ups' for CD and DVD players.

The high levels of defence support for III–V materials did produce some UK civil success, but many believe that there were missed opportunities for the extension of the technology to mass-market consumer products. By and large, non-UK companies were the ones to 'make millions of dollars out of the chips. And the systems that go in these things, your telephones and radars. They make millions of dollars out of that. Poor little Britain doesn't make any money out of that'.¹²⁸

Instead, most UK exploitation of III–V technology was restricted to three types of market. First, UK companies have had notable successes in the supply of production equipment such as crystal pullers, MOCVD reactors and epitaxial reagents. Second, not surprisingly given the reason for so much defence R & D funding in the first place, UK firms supplied customized III–V products for defence procurement. Third, British industry also found a market for III–V components for use in large civil systems, such as civil radars or communications systems. For example, GEC's (formerly Plessey's) Caswell centre supplied GaAs components for both military and civil radars. Similarly, the success (for a while) of semiconductor laser manufacturing at STC at Paignton (later owned by the Canadian company Northern Telecommunications or Nortel) owed much to supplying the telecommunications market.

The classic explanation put forward for the failure of UK companies – GEC is the example most often cited – to develop commercial markets based on technology stemming from military R & D hinges on their reliance on defence funding, and preference for the high profit margins of procurement contracts.¹²⁹ The widely held view – often mentioned by staff at research establishments such as Malvern – is that UK companies with their main interests in defence procurement had 'a big comfort zone around them'.¹³⁰

127 In the mid-1980s a strategy document produced by the UK Royal Radar and Signals Establishment stated, 'The use of high speed logic for fast computers has until recently been realised exclusively using silicon integrated circuit technology. However, the improvements of Gallium Arsenide devices has been such that they are likely to be used for the next generation of high speed machines.' 'A UK strategy for GaAs', *op. cit.* (91). GaAs's potential for high-speed computing was probably emphasized by proponents of the technology to increase public awareness and political support. Szweda interview, *op. cit.* (14).

128 Szweda interview, *op. cit.* (14).

129 See Morris, *op. cit.* (1), 130.

130 Szweda interview, *op. cit.* (14).

According to D.H. Parkinson, a former director-general of research establishments at the MoD, 'The only way to get firms to take action was to initiate a military project – in general, firms strongly preferred to deal with research projects initiated by the ministry through cost-plus contracts.'¹³¹ In the electronics area, CVD was a promising source of funding, but since CVD typically only supported work that was considered of military importance, and in which the research establishments had some expertise, such an approach was likely to bias industrial R & D away from avenues that might be more commercially advantageous. According to many R & D staff within semiconductor firms, industry thus became too reliant on CVD funding. Some described the relationship of industry to CVD as 'sycophantic'; one R & D manager felt, 'Too much external funding weakened their resolve.'¹³²

Thus the overall structure of government support for electronics, dominated as it was by CVD's defence interests, provided a setting that did not encourage innovation in commercial markets. As one account of the UK government's influence on British electronics development puts it, 'Consistent long-term funding of this nature could well induce a feeling of complacency in the recipients, who would have little incentive to seek alternative sources of profit within the commercial field.'¹³³

In addition, it has also been claimed that UK electronics companies relied on CVD to set their research agendas. The failure of UK companies to pursue R & D on integrated circuits in the 1960s is said to have stemmed from lack of support for this area by CVD. However, CVD's limited support for integrated-circuit work was due to the belief that such an obviously commercially important area could be left to industry to support.¹³⁴ According to Dickson, there was 'a vicious circle that reflected both the power of CVD's influence and the industry's over-reliance on CVD support'.¹³⁵ However, CVD funding was not primarily concerned with establishing a broad industrial base in electronics, but rather was focused 'specifically at satisfying MOD requirements': 'The consequence of this policy was to strengthen the tendency of indigenous semiconductor manufacturers to concentrate on producing microelectronic components for "niche" military requirements and to weaken their incentive to compete within commercial markets.'¹³⁶ As a 1989 report by the UK Government's Advisory Committee on Science and Technology argued, UK industrial reliance on defence funding in the electronics sector 'occurred partly because of a preference to invest in defence rather than civil R & D combined with the fact that the technologies associated with defence work were unlikely to have much potential relevance in the civil sector'.¹³⁷

Although this analysis of complacency due to military support appears plausible, it does not tell the whole story of what some see as UK commercial underachievement in III–V semiconductors. It is significant that the most successful areas of UK exploitation

131 Quoted in Morris, *op. cit.* (17), pp. 291–292.

132 Dickson, *op. cit.* (17), pp. 115 and 118.

133 Morris, *op. cit.* (17), p. 272.

134 Dickson, *op. cit.* (17), p. 118.

135 Dickson, *op. cit.* (17), p. 118.

136 Morris, *op. cit.* (17), p. 282.

137 Advisory Council on Science and Technology (ACOST), *Defence R & D: A National Resource*, 1989.

of III–V technology involve particular types of market. All these markets have one thing in common, distinguishing them from consumer product markets, which is that products are ‘made to order’ rather than ‘made to sell’. Unlike consumer products where buyers are sought after production, made-to-order goods are only produced once a buyer has agreed terms. Investment is therefore far less risky because it can be based on, and costed into, procurement contracts. Indeed, as a former GEC manager, Derek Jackson, noted of defence procurement, ‘You didn’t have to invest. And you got paid for development.’¹³⁸

Herein lies the great challenge to achieving spin-off from defence technology into mass-market civil products. Whereas defence procurement typically emphasizes high performance (product innovation), mass-market products must compete on price and quality and therefore require investment in production technology (process innovation). However, during the period of most importance for the development of III–V materials, from the 1960s onwards, UK industrial investment declined relative to its competitors.¹³⁹ Since the 1970s, with the main exception of pharmaceutical firms, UK industry has had much lower levels of investment in R & D than are found in the UK’s competitors.¹⁴⁰

A financial environment which demands short-term returns on investment – as faced by publicly quoted UK companies – can be very unforgiving on manufacturing industries which must compete in global markets, in some cases against competitors (notably in Germany and Japan) able to operate on longer financial timescales due to less dependence on shareholders. Cyril Hilsum, research director at GEC’s Hirst Centre from 1983 to 1992, described the problem thus:

there is no question that if you had a good idea in GEC and you put it up you have to show a positive cash flow in three or four years... whereas the same question, when it was put to Siemens, was six or seven years.¹⁴¹

The limited ambition of the UK electronics industry can thus be attributed to the ‘prevailing attitude of “short-termism”, typified by GEC under the directorship of Lord Weinstock’.¹⁴²

This UK situation can be contrasted with Japanese companies that typically operate within a financial structure that enables them to be ‘committed and patient

138 Quoted in Stephen Aris, *Arnold Weinstock and the Making of GEC*, London: Aurum Press, 1998, p. 118.

139 See the tables reproduced in David Edgerton, *Science, Technology and the British Industrial ‘Decline’ 1870–1970*, Cambridge: Cambridge University Press, 1996, p. 62.

140 UK pharmaceutical industry’s investment record can be explained, at least in part, by the government drug procurement system that in effect guarantees a certain return on investment. For an analysis of the performance of the British electronics and pharmaceutical industries see G. Owen, ‘National environment and international competitiveness: a comparison of the British pharmaceutical & electronics industries’, Centre for Economic Performance, Working Paper No. 561, March 1994.

141 Oral evidence provided by a delegation chaired by Professor Cyril Hilsum to the House of Lords’ Science and Technology Committee, regarding the inquiry into Innovations in Microprocessing (8 May 2002), available at www.ioppublishing.com/activity/policy/Consultations/Industry_and_Innovation/page_29796.html.

142 Morris, op. cit. (1), p. 325.

innovators'.¹⁴³ Thus, when Dr Akai of Sumitomo was asked whether some of the large number of Japanese GaAs suppliers would drop out of the market because there was oversupply, his response exemplified the Japanese approach: 'They won't drop out.'¹⁴⁴

The strength of patient innovators lies in the ability to continue technology development and production even though the market may initially be small and unprofitable. For example, the advances in low-dimensional structures that originated from work in the 1970s only began to produce significant commercial reward over a decade later:

LDS offered exciting new technology but new devices required not only that but new applications which could benefit from those technologies...[N]o one at that juncture envisaged the massive consumer demand for microwave systems in the guise of personal telephones which was to engulf us all in the 1990s. The high electron mobility transistor was first demonstrated in 1980 and found a niche as the signal amplifier at the front end of every satellite TV receiver, a market which has continued to grow steadily, if not explosively, ever since. (Though, from a chauvinistic British viewpoint, it was unfortunate, perhaps, that most of the profit went to Fujitsu, rather than to GEC!)¹⁴⁵

However, given the financial conditions facing publicly listed UK companies – with shareholders requiring early returns on investment – the choice made by companies such as GEC to increasingly prioritize defence contracts is not unreasonable.¹⁴⁶ Military procurement was 'an area where Whitehall's "cost-plus" method of pricing meant it was impossible not to make a profit, and where the government would finance much of the necessary research'.¹⁴⁷ Moreover, during the period in question, defence procurement was growing more rapidly than overall UK manufacturing, and typically UK suppliers received preferential treatment in obtaining contracts.¹⁴⁸ As management consultants McKinsey noted in a 1988 report apparently focused on GEC: 'Increasing concentration on defence and telecom was, for some companies, a conscious strategy to maintain relatively high financial returns provided by these "protected sectors"'.¹⁴⁹

Although the R & D supported by defence funding and the technology produced by the defence establishments apparently provided companies with technical expertise that could be used in commercial products, this was far from enough to guarantee commercial success in competitive world markets. Even if it was possible to predict that III–V materials would find widespread civil applications, the challenge lay more in predicting the exact timing, and thus, in industry, gauging the correct time to invest. As one of the key figures in this history, Cyril Hilsum – a III–V pioneer at Baldock and then

143 Martin Fransman, 'The Japanese innovation system: how does it work?', in Mark Dodgson and Roy Rothwell (eds.), *The Handbook of Industrial Innovation*, Aldershot: Edward Elgar, 1994, pp. 67–77, 68.

144 'Rowland Ware on old and new perspectives in materials science', op. cit. (77), p. 22.

145 Orton, op. cit. (13), p. 246.

146 GEC was originally a highly diversified company that shifted its emphasis increasingly towards defence work. See Aris, op. cit. (138); also Alex Brummer and Roger Cowe, *Weinstock: The Life and Times of Britain's Premier Industrialist*, London: HarperCollinsBusiness, 1998.

147 David Bowen, 'Too cautious, my Lord', *Independent on Sunday*, 18 June 1995, p. 3.

148 See Aris, op. cit. (138), p. 115.

149 McKinsey & Company, Inc., *Performance and Competitive Success Strengthening Competitiveness in UK Electronics*, 1988, quoted in Aris, op. cit. (138), p. 164.

Malvern – put it, 'It is a story of exploitation, though much of the use came in unforeseen, and probably unforeseeable, ways.'¹⁵⁰

The requirement for short-term returns on investment in the UK means that timing is critical because entering a market too early without demand can be fatal to long-term prospects.¹⁵¹ Thus Morris notes that 'aid from the RRE, along with MOD funding, helped Plessey become a world leader in gallium arsenide technology during the late 1960s and early 1970s, although the devices produced as a result (gallium arsenide FETs) were too advanced for the existing market.'¹⁵²

The period in question, from the 1960s to the 1980s, also marked the rise to dominance of the Japanese innovation system in many of the product areas with which UK electronics manufacturers would have had to compete. Attempting to compete – as another UK company, Courtaulds, discovered with carbon fibre¹⁵³ – may well have been expensive and futile. The USA too proved a difficult competitor as Department of Defense support for gallium arsenide manufacturers through the 1994 Title III programme fostered US competitiveness, no doubt in part because US defence procurement also provides a much larger market than was available to UK companies (which is typically a key explanation given for the dominance that the USA attained in silicon¹⁵⁴). Given the size of the indigenous defence market in the US, it would be unrealistic to have expected UK firms to compete on a sustained basis.

The story of gallium arsenide and other III–V materials is thus one of both success and failure. It can be seen as one of failure to gain the greatest sustained industrial benefits from commercial spin-off from UK defence R & D on III–V materials. Or, one could see the commercial success that was achieved as a bonus, resulting from government support carried out for military purposes. The dominance of defence in the post-war UK innovation system helped provide a technology base with much spin-off potential, but ironically it also engendered industrial conditions that may have limited the capacity of UK industry to make the most of this.

150 Cyril Hilsum, 'The use and abuse of III–V compounds', in *Advances in Imaging and Electron Physics* (1995) 91, pp. 171–188, 171.

151 A similar problem occurred with UK manufacturing of carbon fibre when Courtaulds invested heavily in the late 1980s only to find that demand slumped following the end of the Cold War. See Spinardi, *op. cit.* (64).

152 Morris, *op. cit.* (17), p. 286.

153 Spinardi, *op. cit.* (64).

154 See Morris, *op. cit.* (1).