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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Transfer of Defence Research on Electronic Materials to the Civil Field [and Discussion]

J. F. Barnes, B. R. Holeman and E. I. Young

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The transfer of defence research on electronic materials to the civil field

By J. F. Barnes[1] and B. R. Holeman[2]

[1] *R & D Establishments and Research, Ministry of Defence, Whitehall, London SW1A 2HB, U.K.*

[2] *Royal Signals and Radar Establishment, St Andrews Road, Malvern, Worcestershire WR14 3PS, U.K.*

The Royal Signals and Radar Establishment (RSRE) has for many years been the focus within the Ministry of Defence for research on electronic materials and devices. This research has led to a number of successful transfers of technology to industry with tangible benefits accruing to the economy of the U.K. Specific examples are described, covering liquid crystals, semiconductors, pyroelectrics and materials processing, together with an example outside the field of electronic materials: photon-correlation spectroscopy. The route followed for commercial exploitation is outlined in each case, and an attempt made to quantify the benefits of the impact of this research originally paid for by the U.K. defence budget.

The paper concludes with a brief description of an initiative that has been taken recently to foster commercial exploitation of the research work done in defence R & D establishments.

Role of a research establishment in the Ministry of Defence

The primary role of the defence research establishments within the Ministry of Defence (MoD) is to make advances in technologies relevant to defence. They range from basic technologies such as materials, devices, electromagnetic propagation, aerodynamics, through to research into complete systems such as warships, air defence, air-traffic control, and land warfare. Although any one topic within this wide range can produce spinoff, it is more likely to come from the basic technologies where the sensitivity to defence issues is less, and where there is likely to be greater commonality between defence and civil use. Given the long-standing predominant emphasis on defence research, the extent to which civil exploitation has been actively pursued has tended to vary over the years and has depended on a number of factors; particularly upon the research objectives given to the establishments. As the time from original research to successful commercial exploitation is typically 5–10 years, civil spinoff that is detailed now reflects research programmes that were in existence 10–20 years ago, and likewise the research programme now in establishments will influence industrial exploitation through the 1990s.

A defence research establishment is not necessarily wholly funded from the defence budget. The extent to which alternative funding is available varies with time and circumstances. Many programmes now are partly funded by other organizations such as the Department of Trade and Industry (DTI), the Civil Aviation Authority (CAA) and industrial firms. Where there is joint funding with a civil partner the route to subsequent exploitation is eased.

Recent history of the Royal Signals and Radar Establishment (RSRE)

This paper concentrates on the contribution of RSRE, which has existed in its present form since the mid-1970s, with its main site at Malvern. Because of the time taken to exploit an invention, the case histories that are described in this paper must of necessity depend on work undertaken in other locations. RSRE was formed in 1976 by the amalgamation of three establishments: RRE (Royal Radar Establishment) at Malvern, SRDE (Signals Research and Development Establishment) at Christchurch and SERL (Services Electronics Research Laboratory) at Baldock. Only RRE and SERL were active in the field of electronic materials research. Whereas SERL has always been a defence establishment, this was not so for RRE, which had at various times had assigned to it a specifically civil role, notably in the late 1960s when it was part of the Ministry of Technology. In consequence, the emphasis placed on spinoff into industry has varied, but throughout the natural inclination of the staff concerned engaged on research into electronic materials has been to ensure, as far as possible, that civil spinoff did, in fact, occur. One of the driving forces behind this is the fact that a new manufacturing process for electronic materials is more likely to be cost-effective if there are civil as well as military applications.

For a number of years the research programmes of RSRE have been predominantly defence-orientated, with only a limited fraction of its work supported by civil organizations such as, currently, DTI and CAA. In addition, it has been accepted practice for industry to place research fellows or other staff on attachment to RSRE to work on topics of mutual interest. Some of its work on electronic materials figures in the Alvey programme, a joint initiative supported by Her Majesty's Government (HMG) and Industry. HMG participants are MoD, DTI and the Science and Engineering Research Council (SERC).

Transfer mechanisms

There have been three prime methods for transferring technology from RSRE to the civil field. A patent may be taken out as a result of an invention at RSRE primarily to protect the MoD interest. It will ensure that should a particular invention be required for a military system, then it will be available to an MoD contractor without the need to pay royalties. A patent can be the first step in a more aggressive exploitation route where it is used as a means of easing the transfer of technology to the industrial sector. A secondary use of patents is to ensure some financial return to the MoD for money spent on innovation. Royalty returns on patents tend to be low and they represent only a small fraction of the impact of RSRE innovation on the U.K. economy.

The second method of transfer is brought about by attachments of staff from industry to RSRE. A new or emergent research topic may be regarded as of mutual benefit to both an industrial partner and the establishment, and, as a result, the company attaches one or more of its research workers to RSRE as a member of the team. This method has proved to be very fruitful, and is the best way of ensuring that there is no barrier to the subsequent transfer of technology into a commercial production environment.

A similar but often less efficient way is the third method, where a new technology is developed at RSRE and then an industrial partner is sought. Although it has the attraction of delaying the choice of industrial partner compared with the second method, and hence allows more than one firm to bid, experience shows that it is usually more difficult to transfer technology efficiently at this relatively late stage. However, in some cases it is unavoidable, particularly where a completely new technology is developed for which there is no existing base in industry.

Case histories

Displays

In the early 1970s RSRE recognized that there were many obvious military applications of low-power displays to enhance the interface between man and machine, and that civil spinoff could be considerable.

RSRE identified the potential of liquid-crystal technology for such future displays. The vital first step, which made the large-scale production of reliable displays viable, was the invention and subsequent development of the world's first stable liquid crystals for devices, the cyanobiphenyls, as part of a collaborative programme with Hull University paid for by the MoD. The cyanobiphenyls comprise clear, stable liquid crystals with low viscosity and the research programme included the derivation (principally at RSRE) of theoretical and practical techniques to allow the various homologues to be combined into mixtures with optimized properties for display purposes. These materials were licensed to BDH Chemicals (a subsidiary of British Drug Houses plc)†, and worldwide sales now run at a few millions of pounds sterling per year with annual royalties to the MoD of about £0.5×10^6. This work earned the three partners a Queen's Award for Technology in 1979. Research has continued at RSRE, Hull University and BDH Chemicals into better compounds, particularly for complex displays, capable of operating over a wider temperature range. These are the fluorobiphenyls, which have improved low-temperature properties and have been exploited by BDH Chemicals. In addition, RSRE has made other major advances in complex liquid-crystal displays and has actively promoted the establishment of a viable manufacturing capability for liquid-crystal displays in the U.K. This industry has now achieved significant and rapidly growing sales in the face of strong foreign competition. One of several possible examples is the work on a dyed display to give colour, described below.

Dyed liquid-crystal displays are being exploited in the area of liquid-crystal sign-board displays. Although this is a relatively new area for the application of liquid-crystal displays, it is one very much in the public gaze; although the public doesn't usually realize that what it is looking at is, in fact, a liquid crystal display. Two U.K. companies, STC and Racal, have pioneered this field, with Racal achieving particular success with a display 18.3 m long by 2.1 m high that has operated at Paddington Railway Station since December 1985. This very large display is constructed from standard modules now in full production by Racal. They allow great flexibility in size and format of the final display. The display technology being used is not the familiar twisted nematic technology used in watches and calculators, but instead relies on the combination of specially formulated dichroic dyes disolved in liquid crystals together with a single external polarizer to produce an electronically controlled shutter, which is placed in front of a large-area light source. The special dyes used are a result of an extensive research programme between RSRE and the Organics Division of ICI in which dyes suitable for liquid-crystal shutters were invented with several joint patents being filed in the period 1980–1982.

† A full list of the names and addresses of the firms quoted in this paper is given in Appendix A.

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Although the main impact to date has been the sale of liquid-crystal display materials rather than devices, there is now a steadily growing industry in the U.K., which is supported by two display projects that stand a good chance of achieving worth-while success for U.K. companies in the field of large-area (A4: 210 mm × 300 mm) flat-panel information displays. Both of these projects form part of the Alvey programme. RSRE has also contributed substantially to the field of DC electroluminescence. This technique produces flat-panel light-emitting displays and for many years research has been carried out under collaboration between RSRE and Phosphor Products.

Annual sales of U.K. manufactured materials and displays by these two techniques now amount to about £7M and are expected to double again next year. The Exchequer receives annual royalties of about £0.8M from licences on RSRE inventions, approximately half of this sum coming from overseas. Collaboration with British industry was established at an early stage to assist U.K. companies, both large and small, to make use of these new technologies in the products. It is difficult to quantify accurately the financial impact in this area, but a conservative estimate of the annual sales volume involved is £75M.

III–V *Semiconductor bulk growth*

At a time when silicon was beginning to replace germanium as the semiconductor device material used in industry, RRE and SERL were working on a new family of semiconductors, the III–V series. The most important of these, gallium arsenide, indium phosphide and gallium phosphide, are difficult materials to grow because they dissociate at their melting points. RRE pioneered the growth of these crystals by using a modification of the Czochralski technique. By using liquid encapsulation, i.e. by covering the surface of the semiconductor melt with a viscous liquid, the loss of the volatile component could be effectively suppressed and normal Czochralski growth achieved. The encapsulant used was boric oxide, and this process is now known as the liquid-encapsulation Czochralski technique (LEC). By the late 1960s this technique had been transferred to a pressure vessel to give the high-pressure LEC technique, which was subsequently licensed to Metals Research (now part of Cambridge Instruments). They marketed the original RSRE high-pressure LEC puller and proceeded to develop scaled-up versions, which now result in the current '354' and '358' pullers for 4 and 8 kg loads of III–V materials. These pullers are used throughout Europe, the U.S.A. and Japan for the growth of gallium phosphide, gallium arsenide and indium phosphide. RSRE holds a Queen's Award for Technology for this work.

The continued development of the technology has progressed since this original transfer to industry first with the development of automatic diameter control (ADC). Growth of a semiconductor from the melt by Czochralski is a fundamentally unstable process and requires feedback to grow a crystal of uniform diameter. The solution adopted at RSRE, crucible weighing, proved to be satisfactory and is now marketed with application to semiconductor crystals and a wide range of other materials grown by this technology, such as oxide crystals for solid-state lasers. Subsequently, the growth of semi-insulating gallium arsenide from undoped melts has been pioneered at RSRE, and this technique is now the world standard for production of gallium arsenide wafers for use in digital and microwave applications.

Until recently the U.K. commercial source of gallium arsenide wafers was Cambridge Instruments, who also made the pullers. In 1985 the production of wafers was bought by ICI Wafer Technology, thus separating the production of pullers from their exploitation, a move which is evidence of the increasing commercial importance of this technology. ICI Wafer Technology have set up a new factory at Milton Keynes for full-scale production of gallium arsenide and indium phosphide wafers. Royalties to MoD have only recently been agreed for the technology used by Cambridge Instruments, but in the meantime very substantial commercial sales of pullers have been realized. It represents a multi-million-pound business with almost 100% exported.

Epitaxy

Most semiconductor devices require thin layers of material with accurately controlled composition and doping. This is readily achieved by using epitaxy, and RSRE has worked on a variety of appropriate technologies. Two technologies where a particular input has been made are metalorganic chemical vapour deposition (MOCVD) and molecular beam epitaxy (MBE).

RSRE pioneered MOCVD of semiconductors in the 1960s applying it particularly to gallium arsenide and gallium aluminium arsenide. The original research cell (or reactor) that was developed at that time is still in use in research laboratories today and is known after its inventor, Dr S. J. Bass (RSRE). The technology was exploited for defence purposes primarily in the production of image intensifiers at the English Electric Valve Company (EEV), and semiconductor lasers at Standard Telephones and Cables (STC). A number of U.K. firms sell reactors based on the RSRE design, including EEV, Thomas Swann and Cambridge Instruments. Recent work at RSRE on fast switching of gas flows for MOCVD reactors has been licenced to Thomas Swann at Consett, and RSRE sponsored work at Liverpool University on the relevant source materials, e.g. trimethyl gallium and trimethyl aluminium, has led to the establishment of a new company, Epichem, in Merseyside. Work at RSRE on the extension of the range of materials that can be grown by this technique has, for example, resulted in growth of the narrow band-gap II–VI materials such as cadmium–mercury telluride, $Cd_xHg_{(1-x)}Te$. As a result of this work EEV are already selling reactors capable of growing this important material for infrared detectors to the U.S.A.

MBE growth of semiconductors takes place in ultra-high vacuum. It is a high-technology and expensive technique that is capable of producing the type of structures required for research such as the low-dimensional solids programme (e.g. quantum wells, multiple quantum wells). For some years the principal source of suitable equipment was in the U.S.A., but the purchase by RSRE of a prototype reactor from VG Semicon in the U.K., and subsequent collaboration between RSRE and that firm, have resulted in very substantial sales to many companies with over 80% of sales exported. VG Semicon is now regarded as a world leading supplier of state-of-the-art high-technology equipment in this field.

Semiconductor processing

Expertise in electronic materials requires more than just the ability to grow the material in the required chemical purity. The material must be prepared in the right physical state for end-use, and nowhere is this more critical than in the field of semiconductor processing technology. Semiconductor wafers must have structures written on them comprising insulators, doping patterns, metallization, etc., with extremely high uniformity and reproducibility on a scale down to fractions of a micrometre.

Commercial device and integrated circuit processing uses optical lithography as a means of generating these complex structures on a semiconductor chip. This approach has inherent limits to the resolution obtainable and very early (in the 1960s) RSRE realized the implications of this limit and initiated a collaborative study with Cambridge Instruments on the use of electron beams for lithography. This led to a specification for the U.K.'s first computer-controlled electron-beam lithography machine, which was then constructed and further developed in collaboration with Cambridge Instruments. This early start and the continuing interaction in the 1970s and 1980s has enabled Cambridge Instruments to establish a series of state-of-the-art instruments costing up to £1M. The export markets for such advanced technology are large. Cambridge Instruments has achieved a significant performance in this area and is recognized as a world leading supplier. This collaboration is continuing as part of the Alvey programme.

Recent research at RSRE has demonstrated that lithography with focused ion beams has the potential to overcome the limitations evident in the electron-beam approach and also to give specific enhancements. This new method is likely to be important for future generations of chip-processing technologies. A machine, the IBL-100, has been developed in collaboration with VG Semicon to RSRE's specification. Already a similar basic machine has been ordered for a cooperative industrial–university advanced research programme in the U.S.A.

New silicon-processing technologies such as silicon molecular-beam epitaxy (RSRE, VG Semicon, Ferranti) and low-temperature chemical-vapour deposition (RSRE, VG Semicon) are currently the subject of collaboration as part of the Alvey programme.

Pyroelectrics

Infrared detectors have for many years been a predominantly military topic. The main driving forces have been the requirements of the British Armed Forces coupled with defence sales to foreign governments of equipments such as airborne infrared line scan, thermal imaging or as components in complete systems such as aircraft, missiles or tanks. Civilian uses now include clinical medical studies, inspection of thermal insulation, inspection of power lines by the Central Electricity Generating Board, deployment by the emergency services, and identification of faulty electronic components on circuit boards. Although semiconductor infrared detectors have had little impact on the civil field because of their relatively high cost and their requirements for logistic support, pyroelectric detectors have enjoyed significant civilian sales and represent a medium-performance, lower-cost technology.

The heart of a pyroelectric detector is the sensing material. Optimization of the detector requires detailed engineering of the properties of the material, notably the pyroelectric coefficient, but also the dielectric constant, thermal capacity and thermal conductivity. The material must be fabricated in an acceptable form, and sophisticated techniques are available for fabricating the material in shapes that alleviate problems such as excessive thermal conductivity with attendant degradation of the thermal image.

The application of pyroelectric technology to the civilian area continues to grow: devices have been developed with the joint aim of low cost and ease of operation. These features are particularly important in civil use. The pyroelectric vidicon camera, which has been developed as a fire-fighting aid by EEV after collaborative research with RSRE, is an example. From television news coverage, the public has seen these cameras in use by fire brigades for detection and rescue during emergencies such as the gas explosion in Putney in 1985. EEV are finding a ready market for this product with over 800 cameras in operation in civil and military fire services. EEV and RSRE have also completed the development of a high-resolution pyroelectric vidicon, which will encourage the growing interest in industrial thermography. A camera funded by the Rank Prize Fund is at present being assessed for medical thermography in hospitals in Bath and London.

A second collaborative programme, between Plessey and RSRE, provides a further illustration of the civil interest in pyroelectric technologies. Here pyroelectric materials are being interfaced with the latest developments in silicon integrated circuit technology to produce a range of compact and rugged detector arrays. Very-low-cost single or dual element devices have, in the past, made an impact in the intruder-detection field, but recently a significant market is opening for sophisticated arrays in industrial and laboratory instrumentation. The annual current market for professional and military pyroelectric products is assessed at £1.5M, growing to £15M over the next five to six years, as new array developments are introduced in the product range. Uncooled, low-cost rugged thermal detectors will find more applications as these sophisticated products make their impact. They are expected to lay claim to a significant part of the accumulated annual European market for far-infrared detectors, which is estimated to rise to £500M–£800M by early next century. As the pyroelectric array size has grown, in line with defence programmes, an emphasis in the technology remains that of keeping device costs at a level where they will continue to satisfy commercial requirements.

Photon correlation spectroscopy

The technique of photon correlation spectroscopy (PCS) was invented and developed at RSRE. The technique consists of the analysis of temporal fluctuations in scattered light, and it can be applied in two main areas: laser Doppler velocimetry (LDV), where the bulk motion in solids, liquids or gases is measured in terms of the local velocity of small scattering particles, and dynamic light scattering (DLS), which is the study of the natural random brownian motions of small particles in quiescent liquid suspensions.

The study of the motion of small particles by analysing fluctuations in the intensity of scattered light was suggested by Raman as early as 1943. However, it was not until 20 years later, when lasers became available to provide an intense source of coherent light, that the method could be developed experimentally. Towards the end of the 1960s, digital electronics had progressed to the point where efficient digital temporal signal analysis was both feasible and economic. The effective match between this technology and the digital (quantum) nature of optical signals was recognized by a team at RSRE and was the starting point for a series of photon-counting experiments, leading to the build of the first multichannel digital photon correlators. The success of this first instrument lead to the development, in conjunction with Malvern Instruments and with NRDC assistance, of a commercial product first marketed in 1971. Since then, these photon correlators have sold well throughout the world and RSRE has been actively involved in advising on their use in an increasing range of LDV and DLS applications. This work has been recognized by a number of awards to the originating team and to the firms involved, culminating in a Queen's Award for technology in 1978.

The economic benefits of LDV to the U.K. are very substantial, but do not arise specifically from the use of electronic materials. LDV has been used to improve the design of both commercial-vehicle diesel engines and aircraft jet engines, where relatively small savings in fuel consumption equate to enormous savings in operating costs.

For DLS, the economic benefit accruing from the use of these methods is mainly in the chemical and oil industries, and it is very difficult to obtain any figures because much of the work is commercially confidential. However, when one realizes that the technique is capable of obtaining size distributions of particles in suspension, and also information on the shape of these particles, applications as diverse as the manufacture of paints and pharmaceuticals indicate a wide range of application.

Surface-acoustic-wave devices

Surface-acoustic-wave (SAW) devices exploit the properties of mechanical-wave propagation in the surface region of piezoelectric materials. These devices offer three important properties. First they operate in the frequency range 10 MHz to 1 GHz or greater, and therefore fill an awkward gap between the lumped-component and microwave technologies. Second, in an SAW device, the signal (in its acoustic form) is confined to the surface and is readily available to be tapped, guided, reflected, focused, absorbed, etc. This leads to an extremely wide flexibility in the design of devices. Third, device fabrication can exploit photolithography developed for the semiconductor industry, resulting in cheap production of SAW devices in mass production. The most important bulk materials for fabrication of SAW devices are quartz, lithium niobate and lithium tantalate. Layer structures based on zinc oxide on glass are also feasible. RSRE had a major programme on SAW devices that has had substantial spinoff into U.K. industry. On the materials side, a wide range of materials were investigated before quartz and lithium niobate were selected as the optimum substrate materials. The growth of lithium niobate is now undertaken at Barr and Stroud in the U.K. who are substantial suppliers of this refractory mixed oxide. Lithium borate was explored in this country, and is now grown by the Japanese, who pay royalties to the U.K. The Japanese also have been successful in the growth of zinc oxide on glass, and lithium tantalate, both technologies not available commercially in the U.K.

The main civil spinoff has been in television filters, where Mullard and Signal Technology (Plessey) have a substantial business with significant export content. There have been also substantial sales of professional components by these companies and others, principally MESL-Racal, GEC-MEDL and STL. The total SAW industrial activity in the U.K. is now estimated at some 200 jobs and £10M annually in sales.

Gallium arsenide devices

Research on gallium arsenide and related materials started in RRE and SERL over 25 years ago. For many years these establishments and associated sponsored work provided the main U.K. research effort in this area. As early as 1966 RRE and SERL recognized the potential of this new material and formed the GaAs Consortium to promote cooperative U.K. research in the field. This cooperation between Government, Industry and Universities has grown to cover virtually the whole U.K. activity in the base technology of gallium arsenide material and devices. More recently the Department of Trade and Industry has taken an active role in the support of the British gallium arsenide industry, and the GaAs Consortium has now been replaced by an MoD–DTI body, the GaAs Technology Consortium. Real benefits are now accruing with annual commercial-device sales in the U.K. estimated at £3M–£4M. They are predicted to rise tenfold by 1990. This family of devices is essential for many high-technology products in the fields of optoelectronics, microwaves and logic.

Semiconductor lasers are vital to fibre-optic communications and the U.K. base was laid by RSRE in the early 1970s. Exploitation in the U.K. has been mainly at STC, where some 350 jobs are involved. Civil funding is now dominant in this area, led by British Telecom, although there are military interests to replace wiring in aircraft, ships, etc., and for optical interconnections in computers.

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Solid-state microwave sources resulted from RSRE research, and the simpler devices find wide application in intruder alarms and other object-sensing uses such as traffic lights. More sophisticated microwave components are not yet fully exploited, but microwave integrated circuits based on gallium arsenide will be used in applications such as direct broadcast satellite (DBS) television. This is an expanding area with at least 100 jobs involved at present.

Gallium arsenide logic integrated circuits are becoming available with a speed of operation that silicon cannot match. RSRE support has established the base technology for gallium arsenide and U.K. industry is now poised to exploit this in the production of integrated circuits for microwave and digital applications. The international competition is fierce, the Japanese already have a 4K random access memory, and major research and development programmes have been launched in the U.S.A. and France.

The current annual production of gallium arsenide components in the U.K. is estimated at 360000 devices worth £3M–£4M. The associated product value is at least £30M–£40M. A recent market survey predicts an annual world market for gallium-arsenide devices of £3 $\times 10^9$ by 1990 and a recent U.S. survey predicts a market of \$4 $\times 10^9$ world wide by 1992.

X-ray scintillators

Computed axial tomography (CAT) scanners produce television-like images of the internal structure of the human body by measuring variations in the transmission of X-rays. A key component is the detector, which converts the X-rays into light and then into an electrical signal. The detailed pictures provided by such body-scanning systems are now an integral part of advanced medical diagnostics and surgery throughout the world. The X-ray crystal detector is the key element because the scanner performance is largely determined by the properties of the detector crystal.

At RSRE, research proceeded for some time on a range of materials with phosphor properties. This research was aimed at a number of end-uses including, for example, solid-state laser materials and phosphors for use in cathode-ray tubes. In 1979 Rank Hilger (now Hilger Analytical) approached RSRE to set up a collaborative research-and-development programme aimed at improved X-ray-scintillator materials. The initial work of a small team in the Electronic Materials Division concentrated on the family of complex tungstates, and this study showed that the very demanding CAT detector application could be met by the growth of perfect, single crystals of zinc tungstate free from strains, defects and impurities. The research study proceeded to establish a growth process for large-diameter optically perfect crystals of zinc tungstate by the Czochalski or vertical pulling technique. This growth process was developed for large-scale production by Hilger Analytical during 1981–2. Hilger Analytical market these scintillators under an agreement with RSRE with export sales exceeding £1M, earning RSRE and Hilger Analytical the Queen's Award for Technology in 1983.

Measures of impact

A traditional measure of the impact of a piece of technological research is the royalties that arise as a result of sales of licences. For electronic-materials research this licence revenue is, as we have said, modest, being predominantly that arising from the liquid-crystal technology and amounting, in this area, to several hundred thousand pounds per year.

Royalties from other areas of electronic materials amount to about the same again. It must

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be remembered that for many years the aim of the programme in RSRE and the predecessor establishments was to support British industry while exploring technologies of relevance to defence. As a result, many technological developments were passed freely to British industry, an example being the technology of MOCVD deposition of III–V semiconductors. As royalties now being received arise from research that was carried out 10–15 years ago, the benefits of the commercial attitude more recently adopted by the MoD are only slowly beginning to filter through in terms of patents, royalties and licences.

A better measure of the impact is the sales volume generated as a result of the research carried out at RSRE or actively sponsored by RSRE. Most of the areas covered by the case studies have generated annual sales running at an average of £10M, although accurate figures are almost impossible to obtain because of the natural commercial reticence of the companies about their marketing plans and successes. A conservative figure for total sales would be about £70M. Associated with this is the market that has been generated by exploiting these technologies. A typical case is liquid crystals and displays, where the annual generated market of devices and systems exploiting those displays is estimated as at least £75M, and for gallium arsenide devices the figure is £30M–£40M. The direct sales markets and the generated market sales would not have been available to U.K. manufacturers unless the research carried out under MoD auspices had taken place years ago.

A further measure of the impact on the U.K. economy is the technological capability that has been generated. Important components of the advanced-technology field are optoelectronics, microwave devices and high-speed digital components, all of which rely on III–V semiconductors, which themselves stem, as we have seen, from research at RSRE. Although one can never argue that a particular technology would not have arisen if a specific action had not been carried out in the past, a large number of key developments in electronic-materials technology have arisen as a result of work carried out at RSRE, or sponsored by RSRE under MoD contracts. As a result of this capability, the U.K. is better placed to compete with other countries such as the U.S.A. and Japan in products and in advanced research collaborative fields such as ESPRIT (European Scientific Programme for Research into Information Technology).

Current thrusts

It is clear from the foregoing that research carried out at an establishment such as RSRE is relevant to more than purely defence needs. In recognition of this, DTI supports specific research topics at RSRE. One of the criteria for selecting such a topic is the perceived ability at the outset to generate exploitable research and, in fact, it may involve specific industrial interaction to facilitate subsequent exploitation. The electronic materials field has received significant support from this source, and continues to do so.

Silicon technology is covered by the Alvey programme. Alvey projects are interactive between a group of partners and therefore have an inbuilt mechanism for subsequent exploitation of results.

Although significant transfer of technology from MoD research establishments to industry has taken place, it is important to ensure as far as possible that ideas that appear capable of exploitation are followed through to a successful conclusion. It is seldom easy (or appropriate) for the research worker to identify commercial spinoff because his expertise lies in research and technology rather than in the field of market opportunities. To enhance exploitation a new organization was launched last year as a result of a joint initiative by the MoD and the City.

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This is Defence Technology Enterprises (DTE), which is specifically tasked with identifying and disseminating to industry exploitable technology within government establishments. DTE has eight founder share-holders: Barclays Bank, BASE International, British Technology Group, Citicorp Venture Capital, Electra Investment Trust, Lazard Brothers, Prutec and Robert Fleming Ltd. This organization brings together a range of technological, commercial and financial skills as well as the good will of the MoD. DTE operates by placing at selected research Establishments a research executive tasked with identifying ideas with prospective commercial potential, arranging, if necessary, for their development, and acting as a bridge between the establishment and commercial entrepreneurs. So far, more than 100 companies have taken out associate membership and there are already 400 items on the DTE database of potential commercially exploitable ideas. The scope is, of course, much wider than electronic materials. Several potential areas for exploitation have been identified in the few months that the organization has been in operation. At the time of writing one has already been licensed, in the field of computer software.

Appendix A. Firms quoted in the paper

Barclays Bank Ltd, London EC3V 0BA
Barr and Stroud Ltd, Glasgow G13 1HZ
BASE International Ltd, Milton Keynes MK9 3BN
BDH Chemicals Ltd, Poole, Dorset BH12 4NN
British Drug Houses plc, Poole, Dorset BH12 4NL
British Technology Group, London SE1 6BU
British Telecom plc, London EC1A 7AJ
Cambridge Instruments Ltd, Cambridge CB3 8EL
Citicorp Venture Capital Ltd, London WC2R 1LS
Defence Technology Enterprises Ltd, Milton Keynes MK9 2HN
Electra Investment Trust plc, London WC2R 3HP
English Electric Valve Company Ltd, Chelmsford, Essex CM1 2QU
Epichem Ltd, The Wirral, Merseyside L62 3QF
Ferranti plc, Cheadle, Greater Manchester SK8 4HZ
GEC-MEDL Ltd, Lincoln LN6 3LF
Hilger Analytical Ltd, Margate, Kent CT9 4JL
ICI plc, Organics Division, Manchester M9 3DA
ICI Wafer Technology, Tungwell, Milton Keynes MK15 8HJ
Lazard Brothers & Co. Ltd, London EC2 HT
Malvern Instruments Ltd, Malvern, Worcestershire WR14 1AQ
MESL-Racal Ltd, Newbridge, Lothian EH28 8LP
Mullard Ltd, London WC1E 7HD
Phosphor Products Ltd, Poole, Dorset BH15 4JP
Plessey plc, Ilford, Essex 1GI 4AQ
Prutec International Ltd, Edinburgh EH30 9HT
Racal Electronics plc, Bracknell RG12 1RG
Robert Flemming Ltd, London EC3A 6AN
Signal Technology Ltd, Swindon, Wiltshire SN2 5AY

Standard Telephones and Cables plc, London WC2R 1DU
STL Ltd, Harlow, Essex CM17 9NA
Thomas Swan & Co Ltd, Consett, County Durham DH8 6NG
VG Semicon Ltd, East Grinstead, West Sussex RH19 1XZ

Discussion

E. I. Young (*Rushpond Cottage, School Lane, Dorchester, U.K.*). Could Mr Barnes say which types of research on electronic materials have been transferred to the civil field; could he comment especially on optical fibres for cable television?

J. F. Barnes. The materials transferred to the civil field are those described in the paper. The lead in the U.K. on research into optical fibres for cable television and similar applications resides with laboratories other than RSRE, notably the British Telecom laboratories at Martlesham.

E. I. Young. Have any papers on this been transferred to 'Mercury', which has legal permission to be the only competitor with British Telecom for fifteen years?

J. F. Barnes. Mercury has made no approach, so far as I am aware, to the MoD. I believe their priorities are in areas other than R & D.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES