ROADMAP: UK III-V COMMUNITY ENGAGEMENT WITH INDUSTRY

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EPSRC Engineering and Physical Sciences Research Council | National Centre for III-V Technologies

Knowledge Transfer Network
Electronics, Sensors, Photonics

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EXECUTIVE SUMMARY

III-V technologies have been key to many major lifestyle-influencing technologies such as the internet (diode lasers), displays (light emitting diodes), optical data storage (lasers for DVD, Blu-ray), and mobile phones (power amplifiers) and continue to play major roles in offering solutions to many of today's societal challenges. In addition, they provide highly novel structures and devices which reveal new fundamental physical phenomena, leading to new device concepts and applications. The UK academic III-V community has an extensive reputation for research excellence in this field. In addition there are a large number of companies either engaged with the technology or able to offer exploitation routes where a strong market pull is identified. Despite the importance of the sector and its significant potential for innovation, no roadmapping exercise specific to potential impacts has previously been carried out. This report describes the outcomes of a wide consultation across academia and industry, involving two workshops held in Sheffield. It aims to inform strategic decision making in TSB and EPSRC, identify the important III-V technologies to be developed and act as a reference to aid formation of new business activities, collaborative clusters and academic proposal writing.

Within the confines of national priorities as articulated by the TSB and EPSRC, UK III-V capability and capacity has been recorded and an evidence-based summary of the high impact technologies and the required underpinning science identified. These application areas have all been identified as having a strong market pull and their high potential for commercial exploitation is proof of the continuing vibrancy of the sector. This exercise is seen as ongoing and this is expected to be 'living' document with future update milestones identified.

Each of the outcome application areas and enabling technologies represent different degrees of opportunity and potential for impact. However, future planning, such as value-chain analysis of each of these areas is left to the formation of smaller groupings. For this to happen, clear pathways to funding must be evident.

A major gap which is preventing rapid exploitation of concepts through to commercial realisation is the lack of centralised infrastructure to produce the required device demonstrators. This gap has long been recognised in many sectors and is being addressed by the establishment of 'Catapult Centres', but none so far cover III-V technologies.

Recommendations to promote and support the sector are made: most important amongst these is the establishment of a Knowledge Transfer (KT) Fellow for the III-V community, which we view as key to keeping the momentum of this exercise going and to work across EPSRC, academia, TSB, and industry to capitalise on a buoyant sector with strong UK capability.

CONTENTS

SECTION 1: CONTEXT AND PURPOSE

1.1 INTRODUCTION

III-V technologies have an all-pervasive impact which has led to revolutionary innovations such as the internet, wireless communications, mobile phones and optical data storage. The discipline provides the basis for numerous newly-developed technologies, such as the injection laser, quantum cascade laser, concentrator solar cells, mid infra-red detectors and modulation doped transistors (MODFETs) to name a few, that impact many of the most important challenges faced by society. These have led to the foundation of major industries on 10-15 year timescales. The UK has been a leader in many of the important developments in III-Vs, and this builds on UK research excellence as measured in reports from EPSRC[1] and BIS[2].

III-V research in UK universities is highly active in applied and fundamental fields. The long range research with potential for major impact over the next 10 years is, as in the past, likely to be very fruitful. This research has been made possible by significant and sustained investment over the last 30 years, predominantly by EPSRC, in a number of institutions throughout the UK.

The provision of state-of-the-art equipment for the growth and characterisation of III-V crystals, and the subsequent fabrication infrastructure needed to demonstrate fundamental effects as well as functional devices, is absolutely crucial to maintaining these world class activities. EPSRC, in partnership with the TSB, is committed to the support and promotion of the UK's excellent research position to maximise the economic and societal impact of their funded academic research and to help drive sustainable economic growth over the long term[1]. As part of this policy, EPSRC encouraged the EPSRC National Centre for III-V Technologies to take a leadership role in consulting the UK III-V community and producing a III-V Semiconductors Roadmap with full engagement from both academia and industry. The diversity of applications emanating from the work of the National Centre contributes significantly to providing impact in the EPSRC priority areas of Manufacturing, Digital Economy, Energy and Healthcare technologies and the similar TSB priority areas. With its strong connections to the wider UK III-V community, the National Centre was well placed to fully engage with that community in carrying out the Roadmap exercise described in this report. The ESP KTN provided valuable resources and experience for the exercise and production of this document. Despite the strategic importance of III-Vs to the UK, as outlined above, no such roadmap had been produced previously.

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[1] *Research Performance and Economic Impact Report 2010/2011*, EPSRC, October 2011, Available at http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/corporate/ResearchPerformanceAndEconomicImpactReport.pdf Accessed 02.04.12

[2] *Innovation and Research Strategy for Growth*, Department for Business Innovation and Skills, December 2011 Available at http://www.bis.gov.uk/assets/biscore/innovation/docs/i/11-1387-innovation-and-research-strategy-for-growth.pdf Accessed 02.04.12

1.2 PURPOSE AND SCOPE

Given the context above, this report attempts to assemble an evidence-based summary of the high impact technologies and underpinning science in III-V Technologies, as related to significant national priorities or commercial markets, with assessment of the whole UK III-V capacity and capability, both commercial and academic. It is recognised that there are many important sectors not mentioned explicitly in this report which are either allied to III-V technologies or which can directly benefit from them. An important outcome from this exercise would be the identification of new, non-traditional collaborations across several sectors.

The authors canvassed the community and have collated a high level roadmap, which shows the consensus opinion of the key technology themes, their likely outcomes in terms of product and services, and the earliest impact these could make on both high-level market opportunities and on national priorities. This was felt to be most appropriate and useful to the main stakeholders. The lessons drawn from recent studies of the UK's international competitors, and the existing UK innovation policy, are considered in making the recommendations.

This document is structured in three sections:

- Section 1 The introduction , setting out the context, target audience and methodology
- Section 2 Current trends and UK positioning in terms of science, commerce or public policy
- Section 3 The key applications and technologies, the UK supply chain positioning, and possible ways forward for the community, with opportunity/gap commentary and recommendations

This report does not encompass a detailed technology or market road-mapping activity, which would require resources and time outside the scope and capability of the NC and ESP KTN; would require the discovery of extensive commercially-sensitive material; and would require the authors to make many assumptions which would be difficult to justify, and might lead to conflict with existing niche roadmaps.

1.3 TARGET AUDIENCE AND IMPACT

The main target audiences for this report are as follows, with some suggestions for the impact it may make.

Audience	Impact
The UK III-V community, including the National III-V Centre and those supported by it.	Provide guidance for those routes to funding which address national priorities and maximise knowledge transfer.
The Research Councils, particularly EPSRC, and other national funding	Validation on impact of support to the III-V community, and input to future policy and strategy.

bodies such as the TSB	
Industry, and Research and Technology organisations	Provide an overview of the III-V community, and the key research directions, to inform engagement and possible collaboration.

1.4 METHODOLOGY

The UK III-V community is highly diverse, varying from large commercial organisations with several points of engagement in technology and markets, to SMEs providing niche capability. Moreover, since the community makes a contribution in a variety of market and application sectors, they are networked in different ways. For example, groups engage via attendance at the NC-run UK Semicon conferences, through membership of groupings like the ESP KTN, through trade bodies like the UK Lighting Association and Association of Laser Users (AILU) and through the normal academic community networks. As a result, to date there has been no attempt to perform an overview survey of the III-V sector's specific interests. The closest recent coverage was probably through the TSB consultation, led by ESP KTN, on the case for a Photonics-based Technology Innovation Centre[3]

In order to consult as widely as practicable, and to capture the required information in a structured roadmap, the NC engaged with the ESP KTN to support it with some best practice tools. The recommended process and structure was informed by the report of the Cambridge University Institute for Manufacturing[4]. A six-stage process was developed as below, culminating in a four-level roadmap with complementary detailed notes:-

1. Early brainstorming by an expert group (from the NC Steering Committee) to identify the likely boundaries of the sectors, both in terms of technology and application.

2. A workshop[5] was held in January 2011, largely for academic institutions but with strong industry representation. Attendees numbered 101, composed of 73% academics and 27% industrialists. The outputs included expert summary talks on each of EPSRC's priority themes and a detailed report on the extent of III-V academic engagement, industrial involvement, strengths and weaknesses and exploitation opportunities.

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[3] *Photonics Innovation Centre Consultation*, ESP KTN (July 2011). Available at https://connect.innovateuk.org/web/photonics Accessed 03.04.12

[4] *Roadmapping for Strategy and Innovation: aligning technology and markets in a dynamic world*, Phaal R. et al, University of Cambridge Institute for Manufacturing, (April 2010), Cambridge University Press.

[5] *First III-V Roadmapping Meeting*, 13 January 2011, EPSRC III-V NC. Available at http://www.epsrciii-vcentre.com/roadmapping%20exercise.aspx Accessed 28.02.12

3. A further, more industry-focussed workshop was held in May 2011, with the aim of identifying, validating and prioritizing a list of III-V technologies and application sectors for future exploration. Registrations numbered 77, composed of 60% academics and 40% industrialists. The outputs were an "applications vs. technology matrix" covering the key applications sectors, prioritised by votes of the participants.

4. Validation and extension of this summary through an email-based survey of about 400 UK individuals with interests in III-V materials, devices, applications and processes. The questionnaire is given at Annexe 1. A total of 34 additional responses were received. The results matrix is further considered in Section 3.

5. Synthesis of all the above by ESP KTN into a summary report and pictorial roadmap with comment on the key four features, namely

    a. The underpinning actions by the community and the NC

    b. Basic science and technology activities

    c. The anticipated impacts for products and services

    d. The earliest possible commercial or societal impact

    This phase particularly makes use of ESP KTN market and technology intelligence and of existing market and technology roadmaps like those of Photonics 21 and ITRS.

6. Review and adoption of the work and its conclusions by the NC and the wider III-V community, in partnership with EPSRC.

The output roadmap is not to be seen as a static document, but more as a live resource which can be updated by disparate users for their own purposes, and may need a formal update every few years in the light of changes in technologies, applications, markets, or the supplier base. Moreover, given the very nature of this road-mapping process, certain strengths and weaknesses of the UK's position will become apparent, so these are discussed briefly.

Figure 1 The first workshop

SECTION 2: CURRENT TRENDS AND UK POSITIONING

2.1 APPLICATION TRENDS ENABLED BY III-V SEMICONDUCTORS

The widespread impact of III-V semiconductors arises from a combination of highly favourable optoelectronic properties (which allow III-Vs to form the basis of lasers, LEDs and detectors, from the mm-range to the ultraviolet), high carrier mobility and, crucially, the existence of highly advanced crystal growth and device fabrication techniques. Epitaxial technologies (MBE and MOVPE) can produce multi-layer nano-scale structures containing controlled compositions of materials within the III-V family, with very high degrees of crystalline quality and interface perfection on an atomic scale. Such structures have provided the basis for hugely important inventions which have led to the foundation of major industries such as in optical communications, high frequency radar, LED lighting, satellite communications, mobile telephones and optical detectors and imaging. The flexibility and width of capability of the materials systems accessible by the III-V community is indicated in Figure 2, which shows some of the achieved device types and their locations on a chart which summarises the available lattice constants and the semiconductor energy gaps available.

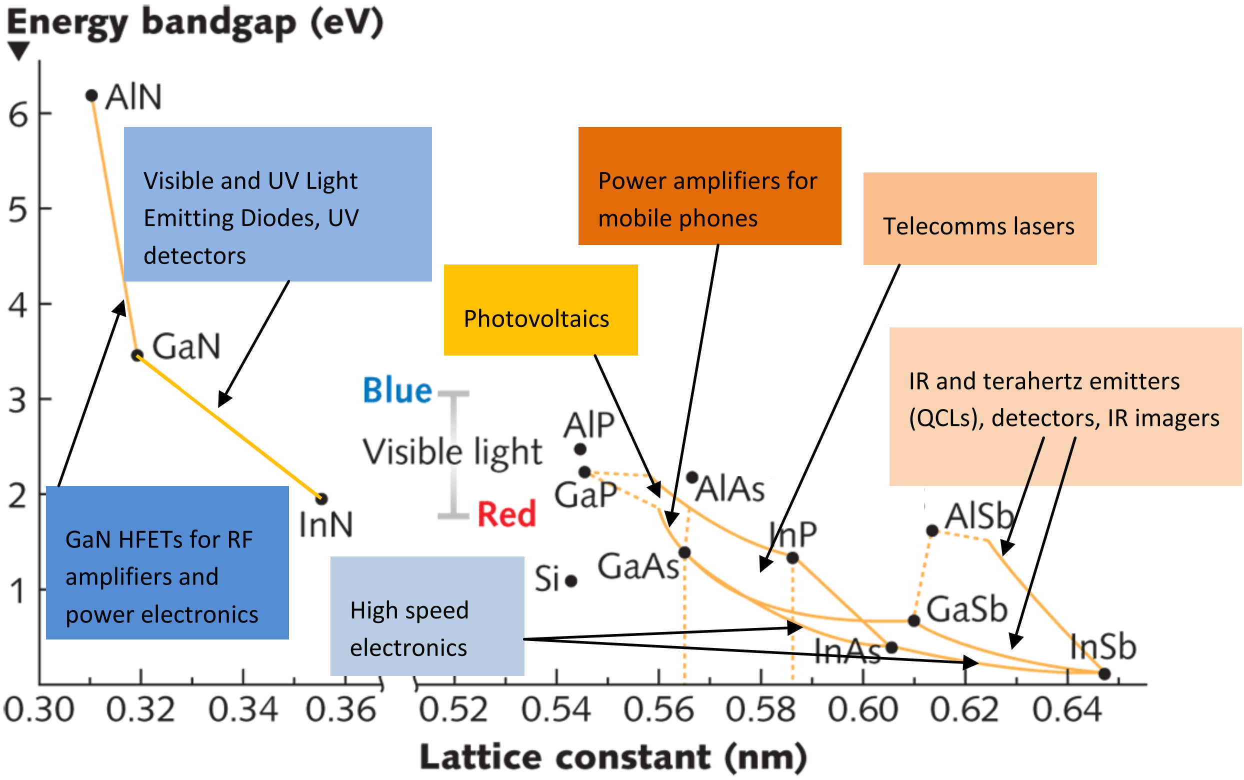

Figure 2- Picture summarising the semiconductor energy gap vs the lattice constant of a few III-V semiconductor applications (modified from Laser Focus World[6])

2.2 SCIENCE TRENDS ENABLED BY III-V SEMICONDUCTORS

The diversity of material properties within the III-V family, combined with the ability to control and manipulate electronic and photonic properties via reduced dimensionality and nano-fabrication, provides almost endless scope to study new areas of fundamental physics and to develop innovative approaches towards new generations of devices with enhanced performance and functionality. Thus, while the field is indisputably well-established, a multitude of opportunities remain for scientific discovery and technological innovation. This is clearly evident from the numerous new areas that have emerged in recent years, such as spintronics, dilute magnetic semiconductors, intersubband optoelectronics, coherent control of quantum states, plasmonics, polaritonics, semiconductor metamaterials and III-V nanowires. Many of these topics have been identified as key enabling technologies within the EU[7]. The continuing development of these and other emerging new areas, in addition to cross-disciplinary activities involving the biological and medical sciences, ensures a vibrant, highly productive and innovative future for III-V research for many years to come and these areas should determine future provision for UK research.

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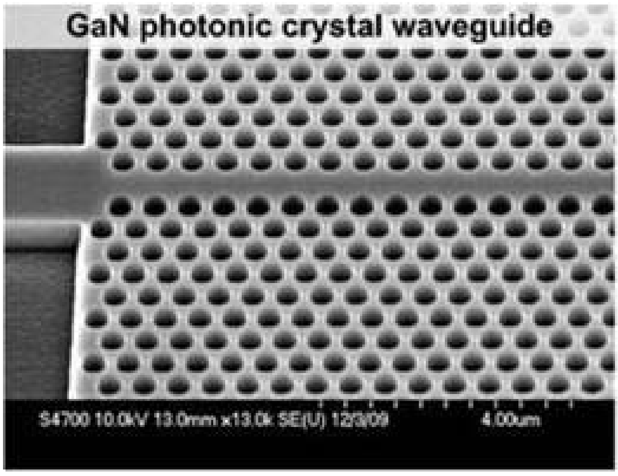
[6] *Photonics frontiers: 50 years of lasers: How laser output spread across the spectrum*, Laser Focus World, (05.01.10). Available at http://www.laserfocusworld.com/articles/print/volume-46/issue-5/features/photonic-frontiers.html Accessed 28.01.12

[7] *Information and communication technologies : Key Enabling Technologies* , EU Commission (2009) http://ec.europa.eu/enterprise/sectors/ict/key_technologies/index_en.htm Accessed 21.06.12

III-V research in UK universities is highly active in applied and fundamental fields. Internationally recognised areas include: quantum transport and tunnelling, ferromagnetic semiconductors, polariton and quantum dot physics, short gate high speed FETs, external cavity surface emitting lasers, quantum dot and quantum cascade lasers, micro-LEDs and wide band gap GaN-based devices. New materials such as, for example, bismides, which have intrinsic properties offering performance improvements for lasers and detectors are also important. Long range research with potential for major impact over the next 10 years is likely to be equally fruitful, including control and coupling of single quantum states, quantum information processing, spintronics, photonic band gap structures, Bose-Einstein condensation, wide band gap materials, III-Vs on silicon and three dimensional growth of nanostructures. This research has been made possible by significant and sustained investment over the last 30 years, predominantly by EPSRC, in a number of institutions including the NC.



(Glasgow University)

2.3 III-V COMMUNITY IMPACT ON NATIONAL AND BUSINESS PRIORITIES

The wide impact of III-V semiconductors is demonstrated convincingly though consideration of Table 1, which lists the TSB's key priority themes and competences, which are potentially (blue) , or currently (green)serviced by just a few III-V technology platforms.

Table 1 How the TSB priority themes are enabled by III-V semiconductor devices

TSB priority theme	III-V technology platform				
	III-V solar cells	Wide band-gap electronic devices	III-V lasers	III-V LEDs	High-speed low- noise electronics
Energy	Concentrator PV, satellite power, H2 generation	High-temperature, and low-loss GaN transistor switches	Efficient sources for communications	Lower power consumption, long-life lighting	
Built Environment	Distributed electricity generation for Smart Grids	Reduced impact (smaller) base stations	Gas analysis for safety and security. Distributed Fibre Optic sensing for civil engineering	"Wraparound" architectural displays and lighting	
Food		Compact microwave sources for cooking	Optical characterisation of "food decay"	UV sterilisation of liquids	
Transport	Battery top-up charging, H2 generation	Efficient power electronics for electric vehicles		High brightness , long-life headlights	GaSb torque sensors
Healthcare	Energy scavenging for wireless body networks		Photodynamic therapy, breath diagnosis, surgery, dermatology, cosmetics, dental decay imaging procedures, benign prostatic hyperplasia	Blood oxygenation monitors, Optical Coherence Tomography for ophthalmic and skin imaging, dental curing	Pre-amplifiers for MRI scanners, THz sources and detectors for cancer scanning
High Value Manufacturing	Volume wafer processing	Volume wafer processing and device and packaging	Diode pumps for solid state lasers and fibre lasers for material processing	Volume wafer processing and device and packaging	Volume wafer processing and device and packaging
Digital services	Remote power supplies	Energy efficient base station electronics	Underpins optical communications infrastructure		Satellite, 3G and 4G cellular phone networks, , high speed optical communications

The TSB has implemented its policy in this sector through the Electronics, Sensors, Photonics (ESP) strategy[8] which highlights the SME-led and fragmented supply-chain, the high costs of development, and picks out the following highly relevant themes and technology areas for focus:-

- Electronic Systems
- Photonics
- Sensor Systems
- Power Electronics

BIS identifies[9] that government has a key role in

- Funding blue skies research as well as new discoveries and inventions - With specific BIS focus on, among others, energy efficient computing, and Energy Harvesting
- Improving the interface between Higher Education Institutions (HEIs) and Business
- Delivering a better environment for commercialising research.

The Wilson Review[10] of relationships between academia and business provides several specific recommendations, of which the most relevant are:

Recommendation 16, paragraph 5.6:	All full-time postdoctoral research staff should have the opportunity to benefit from 8 to 12 weeks' of work experience outside academia every three years during their contract
Reflective recommendation 1, paragraph 3.3	Both business and university leaders should reflect upon their organisational knowledge of the full landscape of business – university collaboration, and on the management of the partnerships that they have. For universities this reflection should extend to strategic decisions concerning the domains that the university wishes to provide; for business it should extend to matching needs to those universities that best meet their requirements within the appropriate domain

[8] *Electronics, Sensors, Photonics* strategy is included in the TSB's Strategy for Technology 2012 -2015 document available at http://www.innovateuk.org/publications/strategy-documents.ashx from July 2012

[9] *Innovation and Research Strategy for Growth* , BIS, (Dec 2011), Available at http://www.bis.gov.uk/assets/biscore/innovation/docs/i/11-1387-innovation-and-research-strategy-for-growth.pdf Accessed 28.02.12

[10] Wilson, T, *A Review of Business–University Collaboration*, (Feb 2012) Available at http://www.wilsonreview.co.uk/wilson-review/wilson-review.pdf Accessed 23.03.12

Reflective recommendation 2, paragraph 3.4	Collaboration between universities in supplying business needs can only benefit the university sector as a whole.
Reflective recommendation 10, paragraph 4.6.1	Universities that work with employers through industry advisory groups should consider including the existence of such a group, its membership and its influence, within the university's enterprise strategy and within the material that it provides to applicants and students.

The activities and success of the UK academic III-V community in meeting these objectives and recommendations is also a valid consideration in this roadmap.

2.4 UK RESEARCH AND COMMERCIAL SUPPLY CHAIN

In Table 2 we have presented a partial list of those companies and academic groups which have a significant position in specific technology sectors.

Table 2 UK R&D and commercial supply-chain membership by technology platform (partial list, based on output from the 2nd workshop)

Technology	Industry/academic capability or interest
III-V epitaxy on Si	Cambridge, RFMD (GaN on Si), IQE, Plessey Semicond, NXP, IR, e2v, Glasgow, Sheffield, UCL ,Warwick (SiGe), Bath (nanorods)
GaN DUV LEDs, lasers	Cambridge, Bath, Sheffield
THz sources	IQE, CST, CIP/Huawei, M2 lasers, Teraview, Cambridge, Leeds, Glasgow, Essex, UCL, QMC, Cardiff, Manchester, Smiths Detection, e2v, St. Andrews.
Crystalline InGaN	Cambridge, Sheffield, Nottingham
VCSELS	Sheffield, Strathclyde
High To, high efficiency lasers (QD)	CIP/Huawei,CST, Oclaro, Cambridge, Cardiff, Surrey, Southampton, Sheffield, Gooch and Housego, Nottingham
GaN UV detectors	Glasgow, Cambridge, Sheffield, Nottingham, IQE

GaN HFETs/ switches	Glasgow, Cambridge, Sheffield, Nottingham, IQE, IR, Plessey Semiconductors, NXP
InGaAs, InSb/AlInS, InAs transistors	Glasgow, Sheffield, Manchester
High speed optical modulators	CIP/Huawei, CST, Oclaro, Cambridge, Cardiff, Surrey, Southampton, Sheffield
IR sources (including QCLs)	Manchester, Sheffield, Glasgow, CIP/Huawei, Lancaster, Strathclyde, Warwick, Oclaro, M2 lasers, CST, QMC, Cardiff, Optocap, Manchester, Teraview, Leeds, IQE , Cambridge, UCL
Monolithic or hybridised opto-electronics on silicon	CIP/Huawei, Oclaro, IQE, CST, Surrey, Southampton, Warwick, Glasgow

SECTION 3: DEVELOPING THE ROADMAP

3.1 APPLICATION AND TECHNOLOGY MATRIX

The top eleven elements of the applications vs. technologies matrix, as identified by the attendees of the 2nd workshop, are presented in Table 3. These technologies were judged to be those where the UK academic III-V community has a strong capability together with a strong market pull. Technologies (columns) with high total scores in Table 3 therefore represent those judged to address a significant number of shortlisted applications and, arguably, are therefore important for the community to pursue. However, the data should be viewed with caution. For example, an application (row) which was highly rated may have only one or two identified applicable technologies and therefore a relatively low score in the matrix (or vica-versa). This should not necessarily lessen its importance and potential for high impact.

One particular "application" should be singled out initially- the "IMRC/TIC/Foundry in III-Vs", which summarises a general desire of many of the academic and commercial players to have an entity similar in scope to one of the "Catapults" that were under discussion and scoping in 2011. In the event, discussions on a "Photonics" and a "Sensors Systems" Catapult revealed significant cross-over into the III-V community, but as neither of these options were progressed by TSB after consultation, the "IMRC/TIC/Foundry in III-Vs" topic is not discussed further.

Table 3 The top 11 elements of the applications vs technology platform matrix

APPLICATION	III-Vs on Si	GaN DUV LEDs, lasers	GaN HFETs/ switches	Enabling equipment	THz sources	InSb/AlInSb, InAs transistors	High speed optical modulators	High T0, high efficiency lasers (QD)	Crystalline InGaN	GaN UV detectors	VCSELS	TOTAL
High data rate telecoms - Photonics Integrated Circuits (PICs) and hybrids	55	13	6	20	6	21	62	49	9	10	47	298
Medical equipment - sensors, monitoring (ie blood etc), lab-on-a chip diagnosis	52	53	12	18	28	8	9	25	19	26	32	282
IMRC/TIC/Foundry in III-Vs	36	20	19	10	18	32	28	25	24	21	29	262
Pollution monitoring and sensing	37	38	11	18	30	13	9	17	15	34	26	248
THz imaging	21	22	5	6	80	10	12	14	6	9	18	203
III-Vs used in manufacturing	29	21	19	20	15	11	7	22	10	12	21	187
Water purification, technologies for food and water	16	60	5	20	2	3	1	10	18	27	7	169
Efficient power electronics	33	8	61	15	2	22	1	5	18	1		166
New PV materials and device concepts, energy harvesting - piezo, PV, Thermoelectric etc	63	6	7	23		7		3	35	5		149

Remote IED detectors	26	12	7	13	27	7	3	10	8	17	6	136
Hydrogen generation and storage	23	8	3	11	2	2	1	2	25	7	1	85
TOTAL	**391**	**261**	**155**	**174**	**210**	**136**	**133**	**182**	**187**	**169**	**187**	

To make the analysis manageable, it was necessary to focus on a limited number of applications and technologies. A list of more-speculative longer term technologies which were not included in Table 3 were selected at the 2nd workshop as worth pursuing on a longer term, more speculative, basis, and are given in Table 4.

Table 4 Technologies selected for speculative development

Speculative Science and Technology area	**Reason to pursue research**
Spintronics	Improved switching transistors (over CMOS), strong UK activity at Nottingham, Leeds, Hitachi and elsewhere
Bismides	Near infrared wavelengths up to 3 µm which are currently inaccessible by standard materials; large spin-orbit splitting for spintronic devices (large spin orbit band offset resulting in significantly reduced Auger recombination, improved temperature stability for emitters and detectors, band offset engineering that offers improvement for hole confinement)
Quantum information devices	Long-term fast computing - very strong world-leading UK physics groups

3.2 MEDIUM TERM COMMERCIALLY-VALUABLE OPPORTUNITIES

To evidence the commercial-advantageous case for the "top 11" activities given in Table 3, we present below a summary of some key commercial and enabling factors that might determine the outcome. For each application, the conclusion is summarised as defined in Table 5 in the form used by TSB for convenience, but the views themselves are those of the authors.

Table 5 Fit against TSB-like investment criteria (the exact criteria are those of the authors)

Criterion	High	Medium	Low
UK Capability	Full academic and commercial supply chain	One or two gaps in academic and commercial supply chain	Many gaps
Market opportunities	Known and existing market size, dynamics, and path to sales of size > £1000m pa	Strong evidence of market size, dynamics, and path to sales of size > £1000m pa	Speculative or no concrete market information, irrespective of size
Timeliness	UK is positioned now to perform appropriate R&D and commercial activities	UK could with investment and skills development respond within 5 years	UK would need longer term investment and skills development

The "Impacts on TSB priorities" tables merely reflect the extent to which the technologies described can impact those priorities listed in Table 1.

High - several impacts of the technologies

Medium - one or two impacts

Low - no impacts

3.2.1 High data rate photonics for telecommunications and storage

Drivers and opportunity

Commercial activity is led by rapidly increasing demand for internet bandwidth and data storage, led by consumer mobile devices, M2M and B2B data, and internet-TV[11]. The global market for photonics components and enabled products in 2006 was worth more than $565 billion, and market forecasts estimate expansion to over $1200 billion by 2017 with 7.7% compound Annual Growth Rate (CAGR). More

[11] Mayer A., *Photonics in Europe : Economic Impact* (2007), Photonics21, Available at http://photonics21.org/downloads/download_brochures.php#3340, Accessed 20.03.12

significantly, the market for optoelectronic components has been put at $3bn in 2010. This sector has been identified by TSB in its 2008 EPES strategy[12] as core to the future of UK economic growth.

(Sheffield University)

III-V technology enablers

This market is technology-led, with the traffic growth being enabled by, amongst others, new capabilities[13] in

- 980nm pump lasers for fibre amplifiers, directly modulated lasers (> 10 Gbps), tunable VCSELs for WDM, optical modulators, semiconductor optical amplifiers
- Temperature-stable (high T_o) diode lasers for reduced system cost and energy saving
- Diode lasers in the read/write head for Heat Assisted Magnetic Recording (HAMR) in hard discs to improve the storage density
- Avalanche photo-detectors, single photon detectors
- VCSELs for chip-to-chip communication, free space communication

[12] *EPES strategy, Electronics, Photonics and Electrical Systems: Key Technology Area 2008-2011*, Technology Strategy Board, p 16. Available at http://www.innovateuk.org/_assets/pdf/Corporate-Publications/EPES%20Strategy.pdf Accessed 20.03.12

[13] Identified at the second NC workshop

UK supply-chain positioning

After the "telecoms crash" of 2000, many international systems integrators, and systems providers such as Agilent, Nortel and Marconi withdrew from the UK. Nevertheless, a significant part of the added-value lies in the material, component and subsystem supply chain. The UK has several companies that are world-class at the component and wafer supply stage: for example:

- IQE provide epiwafers for III-V (and potentially silicon-based photonics) devices
- CST provides volume III-V processing capability based on a foundry business model
- Aixtron (Thomas Swan) provides equipment for growth of III-V based epiwafers for all sectors
- Oclaro provide classical and monolithically integrated optoelectronics and photonics components , and subsystems
- Epichem (now Sigma-Aldritch HiTec) are world leaders in supply of raw materials (metal-organic precursors) for growth of III-V and silicon-based wafers

Each of the component suppliers has existing strong relationships with the system integrator and sub-assembly tiers, led by companies like Ericsson. These are typically based outside the UK, but in the EU there were in 2007 five global players with combined turnover €2.0-2.5bn[14]. There is a general shortage of subsystem and system integrators, except in the cases of the defence electronics groups like Selex, BAE Systems and Thales, all of whom have significant UK operations; and the telecoms company Oclaro. The entire UK supply chain generated turnover of approximately €0.5 billion in 2006. However, close relationships are the norm between industry and academia, as shown by the number of EPSRC and TSB projects in this sector with significant industry backing and support.

Impact opportunities for the III-V community

Three key technology barriers are:-

- The development of telecoms lasers that will operate with high efficiency and with lower temperature dependence, using approaches which include Quantum Dot structures. This would lead to near-term impacts in greatly increased lifetime, lower power consumption, and threshold temperature independence, all of which are important factors in system integration and maintenance. (The NC and its collaborators has critical mass in development of such high efficiency, low lasing threshold devices, and has in the past demonstrated world record threshold current density for InAs/GaAs based QD lasers. Existing programmes like the TSB ETOE II project[15], involving CIP Technologies (CIP), Oclaro, SAFC Hitech, Loughborough Surface

[14] Mayers, op.cit., p 28

[15] TSB project reference TP11/LLD/6/I/AF045L

Analysis , the University of Sheffield and the University of Surrey , position the community well to bring the new designs to TRL 3 by 2015, and to be fed into the normal 10 year cycle of commercialisation. There are also the large number of UK telecommunication companies involved in PIANO+ , an ERANET+ programme.

- Development of high frequency detectors (>40 GHz), for exploitation by companies such as Oclaro and CIP/Huawei
- Development of lasers for Heat Assisted Magnetic Recording (HAMR) in read/write heads, for exploitation by groups such as Seagate

Fit against TSB investment criteria	
UK Capability	Medium
Market opportunities	High
Timeliness	High

Impacts on TSB priorities	
High Value Manufacturing	Medium
Digital Services	High

3.2.2 MEDICAL EQUIPMENT

Drivers and opportunity

A growing elderly population and a rise in chronic diseases results in higher health care costs. Improvements in treatment and cost-effectiveness are prime drivers for the healthcare industries. III-V devices offer a range of new, more effective and cheap diagnosis and treatment options. The predicted market[16] for photonics in healthcare technologies are from \$ 20bn (2010) to\$ 38bn (2015). The UK market for medical technology and supplies is estimated to be £5bn, representing 4.2% of the global market in medical technology.

III-V technology enablers

The principal impacts in healthcare arise from the use of III-V lasers for photodynamic therapy, breath diagnosis, surgery, dermatology treatment, cosmetics, dental decay imaging, instrument UV sterilisation

[16] *Photonics in Health and Wellbeing* (2006) PhotonicRoadSME, Available at http://www.photonicroad.eu/upload/PhotonicRoadSME_Technology%20Roadmap%20on%20Photonics%20in%20Health%20and%20Well%20being.pdf Accessed 03.04.12

and benign prostatic hyperplasia treatment. In addition, non-invasive IR imaging using optical coherence tomography is recognised as important.

(Glasgow University)

UK supply-chain positioning

The Department of Health reported [17] that investment in this area rose from £32m in 2005 to £96m in 2006, while turnover and profits have also increased steadily. The R&D investment in the medical technology sector has increased by ~7% compared to other industrial sector, except pharmaceuticals. The UK medical technology sector contains 2,771 companies with a combined annual turnover based on the latest available company information of £10.6bn. Based on the definitions used by Espicom, UK exports have achieved a total growth of 6.6% over the period 2004-2008 to a total of £4.2bn.

Impact opportunities for the III-V community

- Development of Quantum Dot LEDs for Optical Coherence Tomography imaging
- Sources and subsystems for THz imaging and diagnosis
- Breath diagnosis using QCLs
- Phototherapy requires LEDs at shorter wavelengths than currently available

[17] Strength *and Opportunity: The landscape of the medical technology, medical biotechnology and industrial biotechnology enterprises in the UK,* (2009) The Department of Health, Ministerial Medical Technology Strategy Group (MMTSG) Available at www.dh.gov.uk/ab/HITF/index.htm,p14, p23 Accessed 03.04.12

Fit against TSB investment criteria	
UK Capability	High
Market opportunities	High
Timeliness	High

Impacts on TSB priorities	
High value manufacturing	High
Healthcare	High

3.2.3 GAS SENSING AND MONITORING EQUIPMENT

Drivers and opportunity

Legislation in the developed world, and increasingly in the developing world, has created a focus on measurement of emissions to land, air, and water; on carbon emission to air, and for sensors to support personnel and plant safety.

The global markets for the gas sensing segment at system-level are significant: markets for infrared and NDIR gas sensors and analysers (fixed and portable) are expected to be over $600m in 2016[18], and it is notable that even the simplest infrared gas sensors will have a market value of about $41m in 2016. The water sensing segments, particularly for optical in-situ sensors are also significant but are not pursued here.

III-V technology enablers

The gas sensing market is very conservative, especially as it is often standards-driven, so innovation is slow. The key technology-advances in recent years have included the early stage commercialisation of III-V semiconductor-based infrared light sources, both LEDs and lasers, particularly quantum cascade lasers (QCLs), which have opened up the prospect of low power, robust instrumentation if coupled with suitable wideband detectors.

UK supply-chain positioning

The UK has a very strong community in all parts of the supply chain. These are well connected through networks like the Gas Analysis and Sensing Group (which has about 18 manufacturers, and 12 universities

[18] *World Gas Sensors, Detectors and Analysers Markets* , N6B8-32, (Nov 2009) , Frost and Sullivan

amongst its members) and the trade-body COGDEM. The community has in the past established two roadmaps[19] [20] to highlight the key issues and opportunities for the industry.

Impact opportunities for the III-V community

Key technology barriers are:-

- Room temperature tuneable lasers that operate in the critical mid-infrared region where many "flue-gas" sensors and gas analysers operate are available
- The development of near infrared and far ultraviolet room-temperature LED sources for portable instrumentation, particularly to replace the baseline "pellistor" or "solid-state" sensors much used in the petrochemical and mining industries, and the NDIR sensors which are rapidly becoming a commodity item
- The development of room-temperature infrared detectors

Fit against TSB investment criteria	
UK Capability	High
Market opportunities	Medium
Timeliness	Medium

Impacts on TSB priorities	
Built Environment	Medium
Energy	Medium
Healthcare	Medium

[19] *MNT gas sensor roadmap* (2006), DTI, Available at https://connect.innovateuk.org/c/document_library/get_file?p_l_id=70035&folderId=124339&name=DLFE-2150.pdf Accessed 22.03.12

[20] *Technology Roadmap: optoelectronic gas sensors in the petrochemical, gas and water industries*, (2006), Optochem KTN. Available at http://userweb.eng.gla.ac.uk/charles.ironside/QCSENSEPrivate/GasSensinRoadmap.pdf Accessed 23.03.12

3.2.4 TERAHERTZ IMAGING

Drivers and opportunity

The terahertz (THz) band is that region of the spectrum sitting between microwaves and the far infra-red or in wavelength terms between 30um and 1000um. Radiation in this part of the spectrum has a number of useful properties:-

- Many visually opaque materials, such as clothing, plastics, ceramics and paper are transparent to THz radiation
- THz radiation is non-ionizing and intrinsically safe
- THz radiation provides a means of identification of specific materials, including DNA, because molecular rotations and vibrations occur in this frequency range
- THz can provide important information on the quality of semiconductor materials.

As a result of these properties THz finds applications in a wide range of imaging and diagnostics applications. Opportunities for terahertz imaging are emerging in security, semiconductor inspection, medical imaging and drug development. The ability of terahertz radiation to penetrate deeply into many organic materials without the ionising damage effects associated with X-ray imaging has created potential opportunities for THz imaging in biomedicine. The non-ionising properties of THz radiation and its ability to penetrate clothing has made it an ideal candidate for security screening and explosive detection in environments where public safety is at a premium.

BCC Research[21] reports that the global market for THz radiation devices and systems was worth an estimated $77.2 million in 2008. This is expected to decrease slightly to $63.2 million in 2013, but then to increase to $521.4 million in 2018, with a compound annual growth rate (CAGR) of 52.5%. Imaging systems generated an estimated $71.8 million in 2008. This is expected to decrease in 2013 and reach $206.7 million in 2018, with a CAGR of 37.2%. Spectroscopy systems were worth an estimated $5.4 million in 2008. This should increase to $7.7 million in 2013, for a CAGR of 7.4%.

III-V technology enablers

III-V compound semiconductors are critical to the generation of THz radiation whether through direct emission from quantum cascade lasers or the use of ultrafast lasers converting light to THz frequencies through photo-excitation of a compound semiconductor material. These generation techniques have their merits and demerits but despite the many applications for THz radiation there is no ideal THz system (source + coherent detector).

UK supply chain positioning

[21] BCC Research *Terahertz Radiation Systems: Technologies and Global Markets*, Available at http://www.bccresearch.com/report/terahertz-radiation-systems-ias029a.html

There is a full supply-chain with system, subsystem, component and material suppliers in the UK: Teraview Ltd is one of the world's leading suppliers of commercial equipment for close-in active imaging and spectroscopy at THz frequencies. Thruvision (Oxford) manufacture security screening products which detect passive Terahertz radiation from the surroundings. Other UK companies involved in THz are M-Squared Lasers who manufacture THz laser sources based on ultrafast pulse lasers, QMC Instruments Ltd, which manufactures instrumentation and Teratech Components Ltd (THz electronics). e2v technologies are suppliers of low-THz Gunn diode components and mixer/amplifier subsystems, and the University of Manchester are commercial suppliers of GaAs-based epiwafers through a subsidiary company. There is also a significant tail of specialised microwave sensing groups like Navtech Ltd which integrate systems for defence and security applications at lower frequencies, but are potential entrants at higher frequencies.

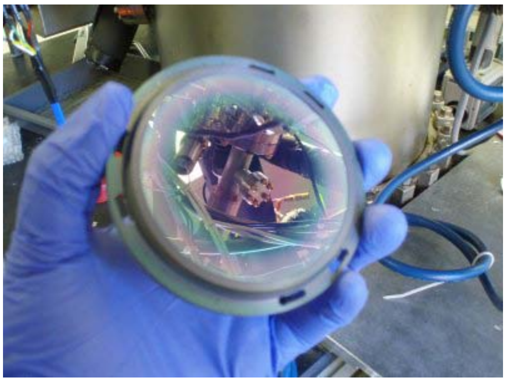
Academic groups like those at Cambridge, St Andrews, Leeds, RAL, Essex, UCL, QMC, Cardiff, and Manchester cover the full range of "optical sources", "solid-state microwave-sources" and detectors for THz, with system integration, whilst the STFC facilities at Daresbury, and associated academic groups provide a full supply chain for "vacuum electronic tube" sources for THz at higher powers.

Impact Opportunities

- Improvement of the current low average powers of solid-state THz systems
- Increased sensitivity of solid state THz detectors

Fit against TSB investment criteria	
UK Capability	High
Market opportunities	Medium
Timeliness	High

Impacts on TSB priorities	
Healthcare	Medium



(Nottingham University)

3.2.5 III-VS USED IN MANUFACTURING

Drivers and opportunity

The use of III-V semiconductors in manufacturing is growing due to the increased usage of diode-pumped solid-state lasers and fibre lasers in manufacturing applications. In these lasers, III-V semiconductor diodes or diode pumps are employed to pump the laser material and achieved the required efficiencies and intensity. Also emerging in manufacturing are diode-pumped ultrafast pulse lasers, and the use of III-V semiconductor laser diodes directly in material processing. In 2011 revenues for lasers used in manufacturing were $2bn and laser system revenues $7bn[22]. The laser type with the fastest growth in 2011 was the fibre laser, achieving annual sales growth of 48%. Applications for growth of solid-state and fibre lasers were in marking and engraving, semiconductor and micro processing and emerging areas such as additive manufacturing. Market sectors that will drive growth in manufacturing are expected to be aerospace, energy (conventional and renewables), electronics and transportation.

III-V technology enablers

The need is for higher power and efficiency, together with maintained robustness and controllability, which strengthens the positions of OEMs as they encroach into existing applications. New technologies, such as pico- and femto-second lasers, fibre lasers, direct diode lasers, plus the extension of available, cost-effective, wavelengths into the UV, visible and mid-IR and further, will open up even more applications[23]. The use of diode lasers directly in manufacturing have been limited due to their low power and poor beam quality. However, these limitations are being overcome by using new approaches to increase the brightness of direct diode lasers such as wavelength beam combining. In February 2012 Oclaro announced the first “15kW” direct diode fibre coupled laser system.

UK supply-chain positioning

There are many laser manufacturers for industrial applications in the UK e.g. Coherent, Rofin-Sinar, SPI Lasers (subsidiary of Trumpf Group), GSI Lumonics, M2 Lasers and a similar number of system integrators specialising in fine- and micro-processing; together with an extremely strong research base in lasers and laser processing. The UK thus has the capability of exploiting the growing world interest in laser sources and applications[24]. In particular, companies like Oclaro have established a business in leading-edge high-power semiconductor lasers, and have developed strong links with the UK III-V academic community. However, the main community of machine tool OEMs is offshore. One UK system integrator of metrology tools is Renishaw, which is active in device and system development.

Impact opportunities for the III-V community

- Near and mid IR lasers

[22] 2012 Laser and Photonics Marketplace seminar, January 2012

[23] EPES strategy, TSB, p 30

[24] EPES strategy, op cit

- Pump lasers
- High power laser structures and packaging

Fit against TSB investment criteria	
UK Capability	High
Market opportunities	Medium
Timeliness	Medium

Impacts on TSB priorities	
High value manufacturing	High
Energy	Medium

3.2.6 UV WATER PURIFICATION

Drivers and opportunity

It is estimated that one third of the world's population, or 2 billion people, lack clean drinking water. As a result diarrhoea, cholera, hepatitis, and other diseases caused by contaminated water kill roughly five million people a year. Many times more than that number become ill, and the growth of 60 million children is stunted because of recurring diarrhoea and other illnesses.

Ultraviolet (UV) disinfection of contaminated water has been attracting a lot of attention as a result of tests confirming the effectiveness of UV to inactivate Cryptosporidium. In addition UV has also proved effective in disinfecting water containing Giardia, E. coli, viruses, spores and other bacteria. Cryptosporidium and Giardia are waterborne pathogenic protozoa implicated in major public health crises throughout the world. Currently the most widely used UV disinfection process is based on fluorescent tube or mercury vapour lamps installed in large scale municipal purification systems. However the fragile nature of fluorescent tubes makes this technology impractical for mobile point of use applications.

LEDs emitting in the UV part of the spectrum have achieved power levels where the irradiation is effective in disinfecting water against bacteria, with the major advantage that UV LED based equipment is considerably more robust and mobile than the incumbent fluorescent tube technology. This has led to the development of water purification systems that takes advantage of the cost, size, robustness and energy saving potential of UV LED technology. The long life of the UV LEDs makes it very suitable for rural applications where maintenance and repair on a frequent basis would be challenging. Given that many water purification problems exist in developing countries and/or remote locations where access to grid electricity may prove difficult such UV water purification systems can be combined with a photovoltaic power source.

UV light is classified into three bands namely A, B and C. The shortest wavelength band is the C region (100 – 280nm) and this is the most effective band in disinfecting water by permanently deactivating bacteria, spores, moulds, viruses and other pathogens, thus destroying their ability to multiply and cause disease. In fact the optimum wavelength for disinfection is 265nm although for particular organisms 271nm and

263nm are important. One of the key advantages of UV disinfection is that unlike chemical disinfectants the organism is unable to develop any immune mechanisms.

The LEDs used in water purification are known as UVC LEDs and in recent years there has been considerable improvement in the power outputs achieved, up to x30 compared to 2008[25] . By 2014 it is anticipated that the challenges of UVC LEDs, namely efficiency, lifetime and cost will have been achieved to make UVC LEDs an effective solution to water purification.

In Europe and the United States, regulatory drivers are already greatly impacting UV market growth. The European Bathing Water Directive, the Water Framework Directive, and Integrated Pollution Prevention Control are just some of the many statutes driving the UV market in Europe. Similarly, in the United States, the Stage 2 Microbials/Disinfection By-products cluster of rules is expected to significantly increase the use of UV technologies.

A recent report by Yole Development stated that the market for UV LEDs would grow to $100m by 2016 at a growth rate of greater than 30%. The current market is dominated by LEDs emitting above 300nm and used in curing applications. However, the UV LED germicidal market (LEDs emitting < 300nm) is considered to be a much larger opportunity given the large number of water disinfectant applications from shower units to portable disinfectant systems for the supply of drinking water in developing countries.

III-V Technology Enablers

The III-V requirement is for higher power LEDs at wavelengths in the region of 255 - 275nm, which defines a wavelength range that is particularly effective in microbial inactivation. Efficient LEDs will also be a requirement in order for mobile water purification devices to operate from solar panels over long periods of time without the need for frequent maintenance.

UK supply-chain positioning

There are no UK companies manufacturing deep UV LEDs or systems. The companies active in this market are a US company Sensor Electronic Technology (SETi) who have recently achieved a 9.8mW UVLED with a wall plug efficiency of 8% emitting at 278nm [26,27]. The SETi LEDs are based on AlGaN on a sapphire substrate. The other significant player in this market is Crystal IS, also based in the US, and their deep UV LED technology is based on aluminum nitride wafers.

The UK does have companies who manufacture UV water purification systems: Hanovia, part of Halma plc, manufacture UV water purification systems and have their own lamp manufacturing plant. Other companies are DaRo UV Systems. There is also a well-networked and very active community in the Sensors

[25] UV LED report by YOLE Development - 2012

[26] Sensor Electronics Technology Inc. press release – April 23 2012

[27] To be reported at the Conference on Lasers and Electro-Optics 2012, San Jose.

for Water Interest Group[28], SWIG, which could facilitate the interactions needed in this sector. The UK water supply utilities are experienced in developing and implementation new technologies.

Impact opportunities for the III-V community

- Develop deep UV LEDs- materials and devices
- Develop relationships with the water treatment industry

Fit against TSB investment criteria	
UK Capability	Low
Market opportunities	High
Timeliness	Medium

Impacts on TSB priorities	
Healthcare	High/Medium

3.2.7 EFFICIENT POWER ELECTRONICS

Drivers and opportunity

The power electronics sector (worth £135bn in 2011, growing at a rate of 10% per annum)[29] is driven largely by the need to reduce the massive loss of energy in motors and actuators (in 2007 representing 50%-60% of all electricity consumption), as well as in electric transport and in PV power conditioning. Currently the sector mainly uses Si-based devices (e.g. MOSFETS, IGBT) but wide band-gap materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) are predicted to take a major share of the silicon market. GaN power management markets are predicted to rise from virtually nil in 2010 to $183.6m by 2013 (iSuppli Corp.) and $350m by 2015 (Yole Development), breaking into markets worth £100m in 2011 (IMS Research[30]) that are currently satisfied by Silicon Carbide .

III-V technology enablers[31]

GaN offers a route to higher breakdown voltages over Si because of the large band-gap and is potentially more versatile than SiC (heterostructures are possible e.g. the HFET). The costs of GaN devices are driven largely by the high substrate costs (silicon carbide, sapphire and native GaN) and the small sizes available.

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[28] SWIG homepage www.swig.org.uk/

[29] Power electronics: a strategy for success: Keeping the UK competitive (Oct 2011), BIS, Available at http://www.bis.gov.uk/assets/biscore/business-sectors/docs/p/11-1073-power-electronics-strategy-for-success Accessed 23.03.12

[30] http://imsresearch.com/blog-template.php?blog_id=48&cat_id=176&type=cat

[31] Identified in the NC road-mapping exercise as key

A change to a lower cost, volume-capable substrate such as Si would make a dramatic difference in commercialisation and capacity. Additionally, designs for 'normally off' operation are required for full system take-up.

UK supply-chain positioning

A 2007 study[32] of the UK companies involved in the manufacture of electrical products and systems identified 19 system companies, 92 product manufacturers, 41 involved with components and materials and 15 in software and services. At least 35 UK universities have specialist groups active in various aspects of electrical technology. Some of these, such as the leading power electronics groups, are highly respected worldwide and, when taken together, represent a higher concentration of resource than in any other EU country.

In particular, there is strength in the academic and industrial precursor and GaN epitaxial growth capability, including GaN on Si (Cambridge), wafer processing and some discrete device packaging. Systems users such as, for example, Rolls-Royce, BAE Systems and Meggitt exert significant pull in this sector, and already International Rectifier, NXP, and Plessey Semiconductors (excellent example of knowledge transfer having acquired MOVPE GaN on Si IP from Cambridge for LED production) have a strong interest in GaN power electronics, particularly on Si substrates. There is also capability in GaAs monolithic microwave integrated circuits (MMICs) within Linwave, Teledyne and Filtronic (now part of RFMD), which are demanded for many high volume or specialist applications, so there are the seeds of capability to exploit the GaN materials platform for MMICs in due course. Finally, the strong UK energy generation and aerospace community have strong relationships with the GaN academic community such as Cambridge, Bath, Sheffield, Glasgow, and Nottingham).

Impact opportunities for the III-V community

To focus on wafer and device-level technologies and capabilities and to carve out an underpinning position in

- Growth on large area Si substrates, and associated Si-compatible wafer processing to reduce cost
- Robust technologies to enable "normally-off" GaN switching devices
- Development of vertical devices for high voltage / high current operation
- Robust, high-temperature packaging & contact metallisation

Fit against TSB investment criteria

[32] UK Capability to Exploit Electrical Technology. REMaCS for Technology Strategy Board. Mar 07

UK Capability	High
Market opportunities	High
Timeliness	High

Impacts on TSB priorities	
Energy	High
High Value Manufacturing	Medium
Transport	High

3.2.8 NEW PHOTOVOLTAIC MATERIALS

Drivers and opportunity

The global opportunity for power generation by PV is well accepted. This has impacts for off-grid power supply, for flexible and reliable grid supply by incorporation in a "Smart Grid" network and to supply a Smart-DC domestic grid, as well as for carbon emission reduction. At present the vast majority of global PV capacity is based on single and multi-crystalline silicon technology, and on amorphous II-VI semiconductors, but the international roadmaps[33] envisage that there is an opportunity for a second round of technology innovation and adoption, associated with niche small-area concentrator PV (CPV) technologies. GTM Research forecasts[34] new CPV installations to grow from under 5MW in 2010 to more than 1,000MW globally by 2015, a CAGR of 82%, although these are normally split between silicon and III-V devices. There are also opportunities for thermo-photovoltaic energy harvesting, using narrow band-gap materials and some of these have been explored in, for example, the automotive industry. In 2011 the market for energy harvesters (of all types) reached US$700 million, and is forecast to reach $1.4bn in 2017[35]. There is also a mature market for space applications.

In common with all III-V products, the substrate cost is a major price driver, so there is a great demand for a route to cheaper substrates and processing routes. However, there are always opportunities for very high-value niche technologies for space applications.

III-V technology Enablers

The next generation PV systems / devices will be based on making better use of the (fundamentally expensive) III-V materials, via device designs that make fuller use of the available solar spectrum, and operate at high solar concentrations. The III-V system has the capability to do this in several ways: building

[33] *Technology Roadmap: Solar photovoltaic energy (2010).* International Energy Agency, p26 Available at http://www.iea.org/papers/2010/pv_roadmap.pdf Accessed 02.04.12

[34] *Concentrating Photovoltaics 2011: Technology, Costs and markets* (2011) , GTM Research, Available at http://www.greentechmedia.com/research/report/concentrating-photovoltaics-2011 Accessed 04.04.12

[35] *Energy harvesting for wireless sensors: 1.6 Million units in 2011. Where next?* IdTechEx, 29.02.12 Available at http://www.idtechex.com/energy-harvesting-europe/article-01.asp Accessed 29.02.12

on both the flexibility of the materials systems, and the capabilities of (especially) MOVPE growth systems to produce abrupt, narrow, and nanostructured layers. Non-crystalline GaAsN (Nottingham) offers the possibility of large areas and full-spectrum coverage. In addition, the growth of III-V on silicon or low-cost substrates like steel or glass will open many commercial opportunities. Finally, there are opportunities to use, for example, narrow band gap materials on the "back" of PV cells to scavenge waste heat.

UK supply-chain positioning

The full UK supply and value chain has recently been reviewed[36]. Even though the UK academic community is very strong, and has spawned several spin-offs, there are no UK III-V PV device manufacturers except Circadian Solar (which focusses on full-system integration), although again, the UK is well-positioned in terms of materials, tools and wafer supply through IQE, CST, and Thomas Swan/Aixtron. The post-epitaxy manufacturing capability for solar cells in this space is currently dominated by non-UK companies with technology credentials and major product portfolios based on the space PV sector: (Emcore (US), Spectrolab (US) and Azur (Germany). There is experience in deposition of thin PV films on steel in Tata/Dyesol using dye sensitised technology, but overall the global commercialisation of PV material, modules and systems has been led by the USA, Japan, Spain and Germany. Therefore it is likely that the UK III-V players would find their best opportunities in provision of new designs and specialised wafer supply to integrators or to groups developing large area or continuous manufacturing methods, especially for systems to be used under concentration or in energy scavenging applications. The III-V community already has close links with this through provision of EPSRC funded R&D that supported the founding of QuantaSol, a spinout from IC and Sheffield, which was acquired by a leading global optoelectronics component manufacturer, JDSU, in 2010.

Impact opportunities for the III-V Community

Develop and demonstrate new designs and materials associated with concentrated solar PV systems and low cost substrates and processing

- Quantum Wells and Dots, and monolithic multi-junction structures
- Narrow band gap PV
- III-V on silicon and silicon/germanium for lower cost
- Non-crystalline GaAsN
- Inter-sub-band devices

[36] *UK solar electricity value chain, Issue 2.0, (2011), ESP KTN Available at* https://connect.innovateuk.org/c/document_library/get_file?uuid=88ba8fbd-1e11-4cf8-b922-8e23e514bd5c&groupId=240498 Accessed 02.04.12

Fit against TSB investment criteria	
UK Capability	Low
Market opportunities	Medium
Timeliness	Low

Impacts on TSB priorities	
Energy	High
High Value Manufacturing	High
Built Environment	Low

3.2.9 HYDROGEN FUEL GENERATION

Drivers and opportunity

The market size of global hydrogen production is estimated at 53m metric tons in 2010. With decreasing sulphur level in petroleum products, lowering crude oil quality and rising demand of hydrogen-operated fuel cell applications, global hydrogen production volume is forecasted to grow at a CAGR of 5.6% during 2011 – 2016. The hydrogen production market in terms of value is estimated to be $83bn in 2010[37] . Underlying constraints on current technologies include high-carbon and non-local production processes.

III-V technology Enablers

The direct generation of hydrogen from solar light (photo-electrolysis) is a promising method of producing molecular hydrogen from water[38]. GaN and GaAsN have been reported to have band-edge potential energies which match the needs well, but the record efficiency for production of hydrogen from sunlight (16%) was achieved with GaInP/GaAs cells. Already, there are research results indicating that the process can produce hydrogen at a cost only a small factor (x4) larger than that of established petrochemical-based processes. However, any approach will require detailed understanding and control of surface chemistry, flammable gas safety and the chemical engineering practice required to develop suitable systems for a variety of applications from major chemical plant to possibly “fuel station” scale.

UK supply-chain positioning

In the long term, this opportunity is likely to require the services of a major chemical-engineering industry- in which the UK is very strong, based on the existing oil and gas and petrochemical industries. The manufacture of GaN or other suitable III-Vs such as GaInP/GaAs itself is likely to involve very large capacity plant, and again the UK is well positioned for precursor and tool suppliers. The links between the process industry and the academic community are not yet well developed, but this is a straightforward

[37] *Hydrogen Generation Market - by Merchant & Captive Type, Distributed & Centralized Generation, Application & Technology - Trends & Global Forecasts (2011 - 2016)*, (2010), MarketsandMarkets. Available at http://www.marketsandmarkets.com/Market-Reports/hydrogen-generation-market-494.html Accessed 03.04.12

[38] *Hydrogen generation from aqueous water using n-GaN by photo-assisted electrolysis* , Fuji K. & Ohkawa K., Phys. Stat. Sol. (c) 3, No. 6, 2270–2273 (2006)

opportunity. The UK government is progressing opportunities through the TSB and other agencies for "the H_2 economy" and this activity imposes a valuable and supportive context for any work in this space.

Impact opportunities for the III-V Community

- Establish studies to fully understand the photo-electrolysis process and develop novel material and structures to improve conversion efficiency and robustness
- Build relationships with the energy and chemical engineering community – possibly mediated by the EG&S KTN
- Develop more capable technology that can provide manufacturing tools for large-scale commercial applications

Fit against TSB investment criteria	
UK Capability	Medium
Market opportunities	High
Timeliness	Medium

Impacts on TSB priorities	
Energy	Medium
High Value Manufacturing	Medium
Built Environment	Medium
Transport	Medium

3.3 SUMMARY OF III-V MARKET OPPORTUNITIES

According to BCC Research[39], the global market for compound semiconductors (which includes III-V semiconductors) was worth $16.0 billion in 2007. This is expected to increase to $33.7 billion in 2012, for a compound annual growth rate (CAGR) of 17.3%. Although the compound semiconductor industry currently represents about 6% of the total semiconductor revenues world-wide, it is also growing about 50% faster than the semiconductor industry overall, and is expected to almost double its share in semiconductor revenues by 2012.

In Table 6, all of the “top 10” application opportunities originating from the current exercise are summarised, although it should be noted that the scope of supply (material, device, subsystem, system) is not always identified explicitly.

Table 6 Summary of current market opportunities for III-V derived technologies from the "top 10"

Application	Market Size	CAGR	Comments
High data rate telecoms - Photonics Integrated Circuits (PICs) and hybrids	Optical components - €3bn (2010)	7.7%	Need to reduce cost through the integration route
Medical equipment - sensors, monitoring	€38bn (2015)	8%	Aging Society leading to increases in healthcare costs
Gas monitoring and sensing	$600m (2016)	4.4%	Gases for environmental and safety sensing
THz imaging	$72m (?)	52%	Key market driver is medical and security.
III-Vs used in manufacturing	$2bn (2011)	7%	Lasers for materials processing
Water purification, technologies for food and water	U.V. global water treatment market - $880M (2010)	10% to 2016	Regulatory drivers in Europe -
Efficient power electronics	GaN components $350m (2015) Global systems market $135bn (2010)	38% 10%	Energy efficiency, reduced size

[39] Semiconductor Manufacturing Report: Compound Semiconductor Materials: Technology, Developments and Markets (July 2008) Available at http://www.bccresearch.com/report/compound-semiconductor-materials-smc032c.html Accessed 29.01.12

Application	Market Size	CAGR	Comments
New PV materials and device concepts, energy harvesting - piezo, PV, Thermoelectric etc	(1000MW)	82%	Low carbon energy
Remote IED detectors	Security segment for equipment using photonic sensing is €15bn.	15%	IED detection systems market - $1.5 Billion[40] Global counter IED market - $6.4 Billion (2011)[41]
Hydrogen generation	$83bn (2010)	5.6% (2011-2016)	Zero emission transport, renewable energy storage

[40] *Homeland Security Research Market report* – August 2010.

[41] *The Counter-IED Market 2011-2021: Systems and Technologies for Force Protection* (Dec 2011) Visiongain

3.4 III-V ACADEMIC-BUSINESS GAPS AND OPPORTUNITIES

So far, this document has presented a picture of a vibrant UK university research base in III-V Technologies with a very strong resonance with national strategic priorities. Review of the discussion in section 3 reveals the following gaps and opportunities in the value and supply-chains, and the enabling activities (leaving aside all the technical gaps), and the authors make some suggestions for paths to mitigation or impact.

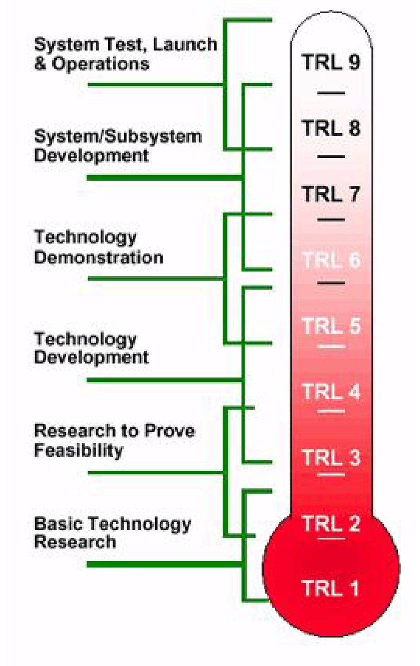
Gaps	Impact	Suggested pathways forward
General shortage of UK subsystem and system integrators in the telecoms and storage sectors	Lack of long-term pull for emerging technologies	Exploit EU-wide networks for systems-level pull (eg via Photonics 21)
Lack of relationships with the water treatment, petrochemical and chemical industries	Lack of pathway to impact for GaN –enabled UV sterilisation of water and hydrogen generation	III-V community to have a “KT Fellow” role to lead engagement with the Chemical, Water and other sectors with which the III-V groups are unfamiliar.
No UK III-V PV device manufacturers except Circadian Solar	Lack of market pull-through for novel III-V PV technologies	III-V community to seek route to inform major non-UK economies (Germany, Spain, USA, China etc) of its capabilities in this space
No UK facility for small scale prototyping and commercialisation, akin to a “Catapult ”	Lack of opportunities for demonstration in realistic environments, and for industry engagement at TRL 4-8.	UK community to seek alternative routes to provide this sort of facility
Very few KT activities (KTPs, KT Fellows , Secondments etc) have been identified during this work	Lack of “people-mediated” KT limits impact of academic work, and limits opportunities for industry feedback and support in the longer term.	UK community to actively target specific sectors for KTP’s, CASE’s etc
Limited “community” coordination at outreach opportunities like trade-shows	Potential duplication and dilution of the key technical and impact messages; lack of clarity of “who	Strengthen the co-ordination of the III-V community presence at conferences and trade shows,

and conferences.	to call"	mediated by the KTN's maybe
This analysis is of necessity only at a high level	More detailed technical analysis is required to support specific science and application roadmaps	The community form subgroups, with some overarching facilitation, to perform and maintain the required detail roadmaps.
Opportunities	**Impact**	**Suggested pathways forward**
The UK community has shown a strong desire to work together to engage with and exploit the strengths of both the NC, and the other III-V and enabling academic centres	Opportunity to build the community to leverage their strengths and relationships	Ensure that groups like the "Photonics Leadership Group", WG6 of Photonics 21, the Horizon 2020 programme directorate etc are actively informed and engaged with this work
Explore longer-term speculative research programmes in three topics: Spintronics, Bismides, and Quantum Information devices	Early-stage engagement possible to gain strategic lead both technically and commercially.	III-V community to work together to shape a joined-up proposal in each area to funding bodies.

3.5 SYNTHESIS

The analysis of the evolution of the III-V activities is founded on the Technology Readiness Level (TRL) scale, as defined by the USA Department of Defence and NASA (see Figure 6, and the more detailed definition given in Annexe 3). It is assumed that the normal extent of an academic project will be TRL3/4, and of a Collaborative R&D project TRL 5/6, whereas a commercial product will be at TRL 8/9.

Figure 6 Illustration of NASA Technology Readiness Levels (source: NASA)



Based on the inputs so far and the referenced roadmaps, the authors have estimated the likely product and service impacts of the key research & technology developments identified in each application area (listed under "III-V community impact opportunities"), making the (unrealistic) assumptions that all these are pursued with appropriate resource levels and no delays, and making reasonable estimates of how long it would take for the science base to take a particular technology from today's status to TRL4, and then for commercial groups to take it to TRL8. Some possible long-term impacts on the TSB's five key thematic areas are picked out, but of course, these depend on many other activities.

These time periods and linkages are then summarised on an image, the roadmap, as summarised in Section 3.6, and given in detail in Annexe 5. This roadmap will be made available as an Excel spreadsheet alongside this report.

This roadmap was then reviewed and amended by the leaders of the various components of the National Centre and external industrial collaborators. It is recognised that this high level roadmap is not a finished article, and requires the full engagement and buy-in from the UK III-V community to realize its full value, so it is likely that follow-on activities of dissemination and scrutiny will be needed to make the impact envisaged.

3.6 THE ROADMAP

	Subsector		2012	2013	2014	2015	2015-2020	2020-2030
Estimated earliest impact on some key TSB priorities	Energy	Internet communications - directly modulated transmitter reduced to 30 fJ/bit						
		Concentrator solar cells with 45% and 50% efficiency				45% eff.		50% eff.
	Built Environment	Real-time in-situ flue gases characterisation to track carbon and VOC emissions						
		Reduced impact base stations using GaN HFETs						
	Food	Real-time process-line characterization of food contamination						
	Transport	Electric or fuel cell cars powered by distributed PV arrays						
		GaN power electronics widely adopted in cars						
	Healthcare	Optical coherence tomography based on QDs and Breath analysis based QCLs adopted in GP surgeries						

		2012	2013	2014	2015	2015-2020	2020-2030
Some enabled products and services	Cost effective fibre to the home						
	Higher density disc drive storage (HAMR)						
	Mid IR optical spectroscopy tools available at primary care level						
	Compact THz stand-off real-time detection systems available						
	Fibre lasers supplanted by diode lasers for majority of laser manufacturing applications						
	Routine 8" growth of III-V devices on silicon or SiGe substrate by foundries						
	Roof-top concentrator PV arrays deployed for microgeneration						
	Water purification systems at all sectors of the supply-line transitioning to GaN UV devices						
	Hydrogen fuel available in PV micro-generation systems						
	GaN power electronics for domestic and automotive						

			2012	2013	2014	2015	2015-2020	2020-2030
Underpinning science and technology impact opportunities	Telecommunications and data storage	980nm pump lasers for fibre amplifiers, directly modulated lasers (> 10 Gbps), tunable VCSELs for WDM, optical modulators, semiconductor optical amplifiers						
		Lasers for Heat Assisted Magnetic Recording						
		Avalanche photo-detectors, single photon detectors						
		VCSELs for chip-to-chip communication, free space communication						
	Medical equipment	Quantum Dot LEDs for Optical Coherence Tomography imaging						
		Sources and subsystems for THz imaging and diagnosis						
		Breath diagnosis using QCLs						
	Gas sensing	RT mid-infrared tunable lasers						
		Near IR and far UV RT LED sources						
		Room temperature IR detectors.						
	THz imaging and spectroscopy	Improvement of the current low average powers of solid-state THz systems						
		Increased sensitivity of solid state THz detectors						
	III-V lasers used in manufacturing	Near and mid IR lasers- based on Quantum Cascade, bismide, antimonide and quantum dot technologies						
		Tunable lasers in the IR						
		High power lasers - structures and packaging						
	UV water purification	Develop deep UV LEDs- materials and devices						
	Efficient power electronics	Growth on large area Si substrates, and associated Si-compatible wafer processing to reduce cost						
		Robust technologies to enable "normally-off" switching device						
		Development of vertical devices for high voltage / high current operation						
		Robust, high-temperature packaging & contact metallisation						
	New PV materials	Quantum Wells and Dots, and monolithic multi-junction structures						
		Narrow band gap PV						
		Non-crystalline InGaN						
		Inter-sub-band devices						
	H2 fuel generation	Photo-electrolysis process , develop novel material and structures to improve conversion efficiency and robustness.						
		Technology for manufacturing-scale tools						

		2012	2013	2014	2015	2015-2020	2020-2030
III-V community enabling actions	Develop relationships with the water treatment industry						
	Build relationships with the energy and chemical engineering community						
	Establish a fabrication facility to prototype devices?						
	Establish CASE students, and KTPs in specific application sectors						
	Review this roadmap every two years			x		x x	x x x x x
	Establish a dedicated KTA for the community						

3.7 CONCLUSIONS

There is very strong UK academic involvement in nearly all of the core technologies that were identified as enablers for the important applications that arose from the two meetings. All of these applications address the societal needs as defined by the TSB priority themes and competences. This publication, with its clear community statements on priority applications, core technologies, and the UK supply-chain, will be extremely valuable in informing both TSB's future strategies for innovation and growth[42] and EPSRC's ongoing development of its Strategic Plan, particularly the goal on 'Shaping Capability'.[43]

The UK III-V academic community has a high level of excellence in research and is in a strong international position. Additionally, there are many UK businesses which have already embraced III-V technologies and others with clear opportunities for exploitation. The strong call from the community for a 'III-V Foundry' illustrates a perceived gap in infrastructure support to advance academic research through TRL4-6 to support, for example, TSB Collaborative R&D projects. This has been recognised and is being addressed in other areas by the 'Catapults' initiative, but no Catapult with significant overlap with III-V technologies is planned. However, following consultation meetings, a 3-year £10M 'Programme in Photonics' R&D support, with strong relevance to III-Vs, has been identified[44]. Although this will not solve the infrastructure gap, there is clear value in linking this document with the planning for this initiative.

It is not for the authors to further prioritise the identified applications and core technologies for future exploitation; rather the community needs to react to this document by the formation of sub-groups or clusters to move forward the themes important to them, ideally with identified funding routes.

[42] *Concept to Commercialisation: A strategy for business innovation, 2011-2015, TSB (2011) op. cit.*

[43] EPSRC Strategic Plan, Available at http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/corporate/EPSRC_strategic_plan_2010.pdf Accessed May 2012

[44] *Catapult update: Shaping the Network of Centres*, TSB, March 2012. Available at http://www.innovateuk.org/_assets/0511/Catapultupdate_final.pdf Accessed May 2012.

3.8 RECOMMENDATIONS

1. The NC to communicate this document to EPSRC and TSB with the aim that they use it to inform their strategic thinking.
2. The III-V academic community to work with the EPSRC to consider the identified application areas and core technologies and identify areas for future research directions, both applied and speculative.
3. The III-V community work together to optimise its outward facing activities to attract investment and research collaboration, especially with industry, possibly through the offices of the KTNs and groups like UK Trade and Industry. In particular to seek to establish CASE students and KTPs in specific applications sectors, and to promote the UK community overseas.
4. The III-V academic community to use this document to enhance EPSRC proposal writing, in particular the section concerning ‘pathways to impact’
5. The whole community to feedback missing information and corrections to this document so that it remains current and has maximum relevance
6. III-V community to seek a joined-up approach to establishment of a device prototyping and demonstration facility
7. The ESP KTN and NC to facilitate the formation of sub-groups or clusters to move forward the important themes, ideally with identified funding routes, including value-chain analysis if possible.
8. ESP KTN and NC to promote this work as contributions to relevant National and EU roadmapping projects (eg ESCO and Photonics21)
9. EPSRC to consider the establishment of an overarching Knowledge Transfer Fellowship position in III-Vs

3.9 ACKNOWLEDGEMENTS

The authors wish to acknowledge the extensive input of all those who attended the workshops and responded to the email survey; the NC management team, and of EPSRC for commentary on the draft report. Any errors of fact or emphasis are ours, and we welcome constructive inputs.

3.10 PRODUCERS OF THE REPORT

EPSRC National Centre for III-V Technologies

The EPSRC National Centre for III-V Technologies (NC) was established in 1979 at Sheffield University with a mission to provide a research service for state-of-the-art III-V epitaxial materials, structures and devices to enable the UK University Community to compete at the highest levels on the world-stage in this highly active field. Currently, the Facility at Sheffield constitutes the core and is partnered by specialist world-class providers at Cambridge (wide band gap nitrides), Glasgow (nanoscale device fabrication) and Nottingham (ferromagnetic semiconductors and metal/semiconductor hybrids). Although the majority of this research supports academic groups funded by EPSRC, there is also significant work funded from BBSRC, MOD, TSB, EU and industrial sources. Visit us at http://www.epsrciii-vcentre.com/Home.aspx

Electronics, Sensors and Photonics Knowledge Transfer Network (ESP KTN)

Electronics, Sensors, Photonics...plastic electronics, embedded systems, displays, lighting, instrumentation, control systems...it's all here at the Electronics, Sensors, Photonics Knowledge Transfer Network. ESP KTN groups all these underpinning technologies together and more, to make a single entity focused on knowledge sharing for growth. We support our technology communities: and we reach out to bring together people that wouldn't usually meet, because sometimes the people you need to reach are not other technical people. Our themes aim to address the Technology Strategy Board's "Challenge Led Agenda" for the key technology area of Electronics, Photonics and Electrical Systems. Visit us at https://connect.innovateuk.org/web/espktn

ANNEXES

1 THE QUESTIONNAIRE

Dear Colleague,

Further to the Sheffield meeting in May and the subsequent consultation by email, we are in a position to indicate the results so far and to seek further input from you. The attached table indicates the priority application areas with technology solutions identified by the community at the May meeting and during the subsequent email consultation.

We would now like you to 'score' these technology areas in the technology fields opposite each application. The score should reflect your view on their potential to enable each priority application by placing a number as follows:

0 or blank - not applicable
1 - may provide a contribution to a solution, but not clear
2 - limited contribution to a solution
3 - partial solution, may require other technology development
4 - good solution, may be in conjunction with others
5 - best technology solution for this application

In this way we will get a collective view of the degree of importance of each technology and reaffirm or otherwise the feasibility of developing the previously identified priority applications in the UK. The results of this, together with a report we will compile, will then be circulated. It is envisaged that the content of the report is likely to form the basis of collaborative bids to the TSB (or FP7/8). This activity resonates strongly with the current consultation by the ESPKTN concerning a possible TIC in Photonics and Sensors

APPLICATION	Road map score	III-Vs on Si	GaN DUV LEDs, lasers	GaN HFETs/ switches	Enabling equipment	High power lasers	High power QCLs	THz sources	InGaAs, InSb/AlInSb, InAs transistors	High speed optical modulators	High To, high efficiency lasers (QD)	Crystalline InGaN	GaN UV detectors	VCSELS
New PV materials and device concepts, energy harvesting - piezo, PV, Thermoelectric etc	29													
IMRC/TIC/Foundry in III-Vs	29													
Efficient power electronics	23													
High data rate telecoms - Photonics Integrated Circuits (PICs) and hybrids	20													
THz sources and imaging	19													
Water purification, technologies for food and water	17													
Hydrogen generation and storage	16													
Medical equipment - sensors, monitoring (ie blood etc), lab-on-a chip diagnosis	15													
Remote IED detectors	6													
III-Vs used in manufacturing	6													
Pollution monitoring and sensing	5													

2 List of participants in workshop and questionnaire

	1st meeting	2nd meeting	Questionnaire response
University of Sheffield	Yes		
University of Bath	Yes	yes	yes
Oxford Instruments Plasma Technology	Yes		yes
Hitachi Cambridge Laboratory			
		yes	yes
University of Sheffield	Yes		
University of Glasgow	Yes	yes	yes
Imperial College London			yes
University of Cambridge			yes
University of Nottingham	Yes	yes	
Whitfield Solar Ltd	Yes		
EPSRC	Yes	yes	
University of Strathclyde			yes
University of Nottingham	Yes		
CIP Technologies	Yes		
e2v technologies (RF power solutions)	Yes	yes	yes
Lancaster University	Yes	yes	
Oclaro		yes	
University of Essex		yes	
Whitfield Solar Ltd	Yes		
University of Sheffield			
Imperial College London	Yes	yes	
Oxford Instruments		yes	
Wafer Technology		yes	
University of Bristol			yes
University of Sheffield	Yes		
University of Strathclyde	Yes		
University of Sheffield	Yes	yes	
Oxford Instruments		yes	
Sheffield Hallam University	Yes		
Cambridge Chemical Co. Ltd	Yes	yes	yes
			yes
Circadian Solar Ltd	Yes	yes	
International Rectifier	Yes	yes	
Imperial College London	Yes	yes	yes
University of Cambridge			yes
University of Sheffield	Yes		yes
University of Nottingham	Yes	yes	
University of Nottingham	Yes	yes	
University of Sheffield	Yes		

Imperial College London	Yes	yes	
ZiNIR Ltd	Yes		
Astrium Satellites		yes	yes
University of Sheffield		yes	
University of Manchester	Yes		
University of Sheffield	Yes	yes	
Lancaster University	Yes	yes	yes
Sharp Laboratories Europe Ltd	Yes	yes	
University of Nottingham	Yes		
University of Sheffield	Yes	yes	
University of Sheffield	Yes	yes	yes
University of Sheffield	Yes	yes	
Photek Ltd	Yes		yes
University of Loughborough			yes
IQE	Yes		
University of Cambridge	Yes		
University of Sheffield	Yes		
University of Hull	Yes	yes	
Selex Galileo		yes	
	Yes		
University of Leeds		yes	
College of Engineering, Swansea		yes	
University of Leeds	Yes		
University of Sheffield	Yes	yes	
St Andrews			yes
Lancaster University	Yes	yes	yes
University of Sheffield	Yes	yes	
Selex Galileo		yes	
University of Leeds	Yes		
University of Glasgow		yes	
University of Sheffield	Yes	yes	
University of Sheffield	Yes		
University of Glasgow	Yes	yes	
Lancaster University	Yes		
University of Strathclyde	Yes		yes
IQE	Yes	yes	
College of Engineering, University of Glasgow		yes	
University of Essex	Yes	yes	
Technology Strategy Board		yes	
University of Nottingham	Yes		
Thales UK			yes
CST Global	Yes		
University of Manchester	Yes	yes	
University of Manchester	Yes		
University of Sheffield	Yes	yes	yes
University of Sheffield	Yes		
IQE		yes	

University of Oxford	Yes		
University of Nottingham	Yes		
Cobham			yes
u2t Photonics UK Ltd	Yes	yes	yes
University of Glasgow	Yes	yes	
University of Manchester	Yes	yes	
Sheffield Hallam University	Yes		
Aixtron Ltd		yes	
University of Sheffield	Yes		
e2v technologies	Yes		
IQE		yes	yes
University of Sheffield	Yes	yes	yes
University of Manchester	Yes	yes	
University of Sheffield	Yes		
University of Cambridge	Yes		
Selex Galileo	Yes		
CIP Technologies		yes	
University of Bristol	Yes	yes	
Jordan Valley Semiconductors UK Ltd	Yes		yes
University of Hull	Yes	yes	yes
University of Sheffield	Yes		yes
Toshiba Research Europe	Yes	yes	
UCL			yes
Toshiba	Yes		yes
Electronics, Sensors and Photonics KTN	Yes	yes	
Cardiff University	Yes		yes
Washington University	Yes	yes	yes
University of Leeds	Yes		
University of Essex	Yes		
University of Surrey	Yes	yes	
University of Sheffield	Yes		
University of Sheffield	Yes		
University of Oxford	Yes	yes	
University of Glasgow	Yes		
Optocap	Yes	yes	
University of Sheffield	Yes	yes	
University of Glasgow		yes	
QuantaSol		yes	
Lancaster University	Yes		
Roke Manor Research Ltd	Yes	yes	
Jordan Valley Semiconductors UK Ltd (roke manor)	Yes		yes
University of Sheffield	Yes		
Oclaro Technology Ltd	Yes	yes	
University of Sheffield		yes	
Toshiba Research Europe Ltd		yes	
University of Strathclyde			yes

ESPKTN		yes	
Oclaro	Yes		yes
Orica	Yes	yes	
University of Sheffield	Yes		
ESPKTN		yes	yes
Lancaster University	Yes		
	Yes		
University of Sheffield		yes	
University of Sheffield		Yes	

Technology Readiness Level	Description
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3. Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an air-craft, in a vehicle, or in space).
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.

Source document: III-V Roadmap (Release 1).xlxs June 2012

			YEAR						Source/comment
	Subsector		2012	2013	2014	2015	2015-2020	2020-2030	References below either have roadmap data or further technical information
Estimated earliest impact on some key TSB priorities	Energy	Internet communications - directly modulated transmitter reduced to 30 fJ/bit							IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 17, NO. 2, MARCH/APRIL 2011
		Concentrator solar cells with 45% and 50% efficiency				45% eff.		50% eff.	Workshop Report: Grand Challenges for Advanced Photovoltaic Technologies and Measurements, p36, Prepared for the National Institute of Standards and Technology 01/08/2010
	Built Environment	Real-time in-situ flue gases characterisation to track carbon and VOC emissions							
		Reduced impact base stations using GaN HFETs							Kikkawa et al, "GaN Devices for Highly Efficient Power Amplifiers" Fujitsu Sci. Tech. J, 48, 1, p45 (2012)
	Food	Real-time process-line characterization of food contamination							
	Transport	Electric or fuel cell cars powered by distributed PV arrays							Kazmerski and Broussard "SOLAR PHOTOVOLTAIC HYDROGEN:THE TECHNOLOGIES AND THEIR PLACE IN OUR ROADMAPS AND ENERGY ECONOMICS"19th European PV Solar Energy Conference and Exhibition Paris, 2004
		GaN power electronics widely adopted in cars							Kikkawa et al, "GaN Devices for Highly Efficient Power Amplifiers" Fujitsu Sci. Tech. J, 48, 1, p45 (2012)
	Healthcare	Optical coherence tomography based on QDs and Breath analysis based QCLs adopted in GP surgeries							PhotonicRoadSME Technology Roadmap on Photonics in Health and Well being FP7, 2010, p47

		2012	2013	2014	2015	2015-2020	2020-2030	Source/comment
Some enabled products and services								
	Cost effective fibre to the home	•						
	Higher density disc drive storage (HAMR)		•					http://www.theregister.co.uk/2012/03/20/seagate_terabit_areal_density/
	Mid IR optical spectroscopy tools available at primary care level				•			Photonics in Health and Well Being , 7th Framewaork Programme, EU, p 47
	Compact THz stand-off real-time detection systems available		•					Cutting-edge terahertz technology, nature photonics, VOL 1, P97, FEBRUARY 2007
	Fibre lasers supplanted by diode lasers for majority of laser manufacturing applications					•		
	Routine 8" growth of III-V devices on silicon or SiGe substrate by foundries		•					http://www.sematech.org/meetings/archives/symposia/9237/Session%202%20Advanced%20CMOS/5%20Richard_Hill_SEMATECH.pdf
	Roof-top concentrator PV arrays deployed for microgeneration		•					http://news.cnet.com/8301-11128_3-10007431-54.html
	Water purification systems at all sectors of the supply-line transitioning to GaN UV devices					•		http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_production_roadmap.pdf
	Hydrogen fuel available in PV micro-generation systems					•		http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_production_roadmap.pdf
	GaN power electronics for domestic and automotive			•				Kikkawa et al, "GaN Devices for Highly Efficient Power Amplifiers" Fujitsu Sci. Tech. J, 48, 1, p45 (2012)

			2012	2013	2014	2015	2015-2020	2020-2030	Source/comment
Underpinning science and technology impact opportunities	Telecommunications and data storage	980nm pump lasers for fibre amplifiers, directly modulated lasers (> 10 Gbps), tunable VCSELs for WDM, optical modulators, semiconductor optical amplifiers	TRL2 to TRL4						
		Lasers for Heat Assisted Magnetic Recording		TRL2 to TRL4					
		Avalanche photo-detectors, single photon detectors	TRL2 to TRL4						
		VCSELs for chip-to-chip communication, free space communication	TRL2 to TRL4						
	Medical equipment	Quantum Dot LEDs for Optical Coherence Tomography imaging	TRL1 to TRL4						
		Sources and subsystems for THz imaging and diagnosis	TRL3 to TRL4						
		Breath diagnosis using QCLs	TRL1 to TRL4						
	Gas sensing	RT mid-infrared tunable lasers	TRL1 to TRL4						
		Near IR and far UV RT LED sources	TRL2 to TRL4						
		Room temperature IR detectors.	TRL2 to TRL4						
	THz imaging and spectroscopy	Improvement of the current low average powers of solid-state THz systems	TRL1 to TRL4						
		Increased sensitivity of solid state THz detectors		TRL3 to TRL4					
	III-V lasers used in manufacturing	Near and mid IR lasers- based on Quantum Cascade, bismide, antimonide and quantum dot technologies	TRL2 to TRL4						
		Tunable lasers in the IR		TRL1 to TRL4					
		High power lasers - structures and packaging		TRL3 to TRL4					
	UV water purification	Develop deep UV LEDs- materials and devices		TRL2 to TRL4					
	Efficient power electronics	Growth on large area Si substrates, and associated Si-compatible wafer processing to reduce cost	TRL2 to TRL4						
		Robust technologies to enable "normally-off" switching device	TRL2 to TRL4						
		Development of vertical devices for high voltage / high current operation	TRL2 to TRL4						
		Robust, high-temperature packaging & contact metallisation	TRL2 to TRL4						

Underpinning science and technology impact opportunities	New PV materials	Quantum Wells and Dots, and monolithic multi-junction structures		■							
		Narrow band gap PV		■							
		Non-crystalline InGaN		■							
		Inter-sub-band devices		■							
	H2 fuel generation	Photo-electrolysis process , develop novel material and structures to improve conversion efficiency and robustness.		■							
		Technology for manufacturing-scale tools			■						

				2012	2013	2014	2015	2015-2020	2020-2030		Source/comment
III-V community enabling actions		Develop relationships with the water treatment industry									
		Build relationships with the energy and chemical engineering community									
		Establish a fabrication facility to prototype devices?									
		Establish CASE students, and KTPs in specific application sectors									
		Review this roadmap every two years				x		x x	x x x x	x	
		Establish a dedicated KTA for the community									
		Promote this work as contributions to relevant National and EU roadmapping projects									
		The III-V community work together to optimise its outward facing activities									