III-V Semiconductor Roadmap

Report on the First Meeting, 13 January 2011

1. Preamble

What is a Roadmap? A Roadmap describes a future environment where the key market opportunities are identified and goals specified, together with a plan on how to achieve these through a series of shorter term objectives within a set timeframe (typically 5-10 years). In our context, it will form a framework linking market needs, industry capability and academic technology push. Market priority decisions are likely to be influenced by the latter two, but a key feature of roadmapping is that major opportunities can also be considered where expertise or infrastructure gaps are identified and addressed. The National Centre (NC) for III-V Technologies will play a coordinating role in realising the goals.

First Meeting (held 13 January 2011): The first meeting, held in Sheffield, outlined UK academic capability and expertise within priority theme areas loosely aligned with those of EPSRC and followed on from the meeting at Birmingham in April 2009 which was convened to provide a ‘statement of need’ to EPSRC as part of its future funding policy on ‘mid-range facilities’. The strong industry presence at the first meeting ensured input to the breakout sessions which was designed to identify applications, level of need and academic and industrial strengths. It was seen as a start to the roadmapping process rather than an end in itself. However, as a stand-alone exercise, it was valuable in bringing the III-V community together where key applications were identified and capabilities outlined, enhancing the possibilities for new academic collaborations. The input from industry was particularly valuable in promoting KT. This document reports on this first meeting.

Second Meeting (proposed 18 May 2011): The second meeting will be strongly industry focussed. It will identify and prioritise market opportunities, set against the background of the data from the first meeting, and lead to a UK roadmap. For credibility, there must be a strong industry consensus to the process and full participation in the outcomes.

2. Background (modified from the statement of need June 2009)

The Importance of III-V Semiconductors: III-V semiconductor materials and devices play a fundamental role in many of the technologies which transform everyday life. In addition to revolutionary innovations such as the internet, wireless communications, mobile phones and optical data storage (eg CD, DVD and blu-ray technologies), III-Vs provide the basis for numerous newly-developed technologies that address many of the most important challenges faced by society. These include renewable energy sources (high efficiency III-V solar cells), control of climate change via reduced energy demand and greenhouse gas emission (III-V solid state lighting and displays, laser emission monitoring and process control), improvements in healthcare (III-V sources for optical coherence tomography, THz imaging and real-time breath analysis) and counter-terrorism measures (mid IR-laser explosives and...
The importance of III-Vs in these areas relies in most cases on highly innovative device physics and technology, illustrating the relevance, diversity and vibrancy of this research field, and its strong alignment with EPSRC, RCUK and TSB priorities.

The all-pervasive impact of III-V semiconductors arises from a combination of high carrier mobility, highly favourable optoelectronic properties (which allow III-Vs to form the basis of lasers and LEDs from the mm-range to the ultraviolet) and, crucially, the existence of highly advanced crystal growth and device fabrication techniques. Epitaxial techniques (MBE and MOCVD) 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 such as the injection laser, quantum cascade laser, and modulation doped transistors (FETs) to name a few. These have led to the foundation of major industries on 10-15 year timescales (e.g. Light Emitting Diodes, diode lasers, high electron mobility transistors etc). In addition to their technological significance, such structures have been the foundation for many ground-breaking advances in fundamental science, such as the integer and fractional quantum Hall effects, Bose-Einstein condensation in solids, and quantum coherence and interference.

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, 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 bandgap GaN-based devices, and new materials such as, for example, bismides, which have intrinsic properties offering performance improvements for lasers and detectors. 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 bandgap 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 25 years, predominantly by EPSRC, in a number of institutions including the NC.

University Research in the III-V Field in the UK: 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 bandgap GaN-based devices, and new materials such as, for example, bismides, which have intrinsic properties offering performance improvements for lasers and detectors. 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 bandgap 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 25 years, predominantly by EPSRC, in a number of institutions including the NC.

Industrial Impact of EPSRC-funded Research: EPSRC-funded III-V research in UK universities has very high industrial relevance in many diverse fields, including lighting (GaN LEDs), displays (LEDs), telecommunications (GaAs microwave circuits, quantum dot lasers), high speed low power transistors beyond silicon (GaAs MOSFETs), automotive and
aero-engine applications (high power, high temperature GaN FETs), environment and healthcare (quantum cascade lasers and quantum dot devices) and energy (multi-quantum well solar cells). Work of this kind has led to several spin-outs and feeds directly into major UK-based companies.

3. First Meeting

The first meeting of the current roadmapping exercise, held in Sheffield on 13 January 2011, was designed to have an academic focus, informed by industrial needs. It was structured to enable all attendees to have an input. Six presentations before lunch set the scene and included an ‘industrial perspective’ plus each of five application themes (Energy, Digital/Nano, Health and Security, Optoelectronics and Fundamental Physics). Breakout sessions, based on the five themes, followed after lunch with brief summaries of the findings given by the breakout leaders. The breakout session leaders were asked to identify applications within their theme and comment on level of need, academic strength and industrial interest for each. The presentations and brief notes from the breakout session can be viewed at http://www.epsrciii-vcentre.com/roadmapping%20exercise.aspx and the following should be read in conjunction with these.

3.1 Energy

The Energy presentation was given by Ned Ekins-Daukes, Imperial College. The three main topics covered were photovoltaics, solid-state lighting and power electronics. These applications are undoubtedly where III-V semiconductors can make the largest contribution towards satisfying the world’s CO₂ emission reduction targets and hence are likely to receive considerable political support within the UK.

3.1.1 Solar cells

Third generation concentrator solar cells involve stacking three semiconductor junctions in series to maximise capture of the solar spectrum. The current record for a triple junction cell is 42.3% (Spire, USA) and is projected to rise above 50% if a fourth junction with a 1eV band-gap can be made with sufficiently high quality. Candidate materials include GaAs containing dilute quantities of nitrogen, bismuth and/or antimony as well as low-dimensional semiconductors such as quantum wells or dots.

Breakout:

There is strong motivation and a capability to develop highly efficient multi-junction solar cells at the materials and fundamental level to feed into the industrial sector. A recent example is the formation of the QuantaSol company, forged from collaborative work between Imperial College London with the University of Sheffield. Companies such as QuantaSol and IQE are well placed to integrate technical III-V material knowhow into a solar cell product. To reduce the solar cell cost, other groups outside the UK are investigating III-V growth on silicon, reusable substrates, polycrystalline substrates and metal foil.

Recognising that the III-Vs have a role to play beyond high-performance concentrator photovoltaics, the development of cheap, thin-film and therefore less efficient PV materials that span the solar spectrum in a single materials system are also under investigation. Amorphous GaAsN alloys developed at Nottingham University have the potential to cover the full solar spectrum, avoiding the present difficulties encountered in finding high-gap
SiGeC materials required to raise the efficiency of present a-Si/a-SiGe thin-film solar cells above 10%. Pilkington glass may have a role in amorphous cell production.

Mechanical stacks for III-V concentrators are an alternative to monolithic 3-4 junction cells. This shifts some of the difficulty in integrating multiple junctions into a single solar cell onto an external optical system that becomes responsible for directing light of different wavelengths towards the appropriate solar cell. Instead, excellent cell processing, mounting and optical design is required, offering an opportunity to engage the strong UK applied optics community.

Non-planar photovoltaic structures were identified to hold advantages for broadband, omni-directional light absorption (e.g. nanowires, plasmonics, photonic dielectric textures). This area extends beyond III-V semiconductor materials, into broader material science and nanophotonics.

Thermophotovoltaics for heat energy harvesting and extension of solar spectrum was identified as another area where the UK’s strength in low-gap semiconductors can be matched to the need for efficient electrical generation from thermal energy. III-V materials systems beyond 1.6 µm such as antimonides are candidates for this.

Packaging and advanced processing of PV devices was identified as an area of weakness for the UK. Few facilities exist for developing stable and low-resistance metallisation of concentrator solar cells and no facilities exist that are capable of full wafer epitaxial lift-off. Most of the supply chain for CPV is represented in the UK, but advanced solar cell processing is the weakest link.

3.1.2 Solid State Lighting
To achieve the target efficiency of 60% (200 lm/W) 3 or 4 colour LED arrays are required. Green diodes remains a problem and more understanding of why InGaN green diodes are inefficient. Additionally work is required to identify the mechanisms for the reduced efficiency at high currents (droop problem). It is clear that growth on inexpensive substrates is required for cheap mass production.

Breakout:
Fundamental studies are required for the understanding of InGaN green diode inefficiencies and the efficiency ‘droop’ at high currents. The use of Si substrates is the key to cheap mass production. There is considerable UK academic expertise in both growth (including on Si substrates at Cambridge) and characterisation. The UK also has the opportunity to address the fundamental issue of internal device efficiency. Industrially, there is strong equipment supply but there is a weakness in partners for manufacturing, although a new venture with Plessey looks promising. To support this effort, it will be desirable to adapt the US DoE Roadmap for UK needs.

3.1.3 Power Electronics
Power electronics for efficient power supplies and control of a range of motor drives, actuators and industrial processes are a key technology for efficient energy usage. GaN-based HFET switching transistors have been identified as the most promising for high efficiency, high speed and high temperature applications in power electronics due to its combination of high mobility, large band-gap and ability to be made into heterojunctions. Although SiC currently has a larger market share, GaN is set to become increasingly important over the
next 5 years or so. The challenges are the development of normally-off devices, reduced cost through the use of Si substrates and robust, high temperature contact metallisation and packaging.

Breakout:
It is recognised that there is strong demand from the large number of UK systems companies and there is also a good industrial device capability (IR, Plessey, SemiFab). A need for communication several stages up and down the supply chain was identified, since those designing power systems are rarely involved in the semiconductor material development and vice versa. There are several universities capable of growth and device fabrication. Hence the UK is in a strong position to fully exploit this opportunity.

3.2 III-V Electronics (Digital/Nano)

Iain Thayne (Glasgow) gave the Digital/Nano presentation which focussed on electronic devices. Roadmapping exercises are deeply engrained in Si industry technological progress where a community or players agree on figures of merit and, through a willingness to share information, achieve a convergence of opinion on industry direction. Experience tells us that products emerge up to 12 years after the first publication describing a particular technology.

III-V electronics have many unique and systems enabling solutions that cannot be met by silicon-based approaches. The specific characteristics (eg gain, bandwidth, noise, power consumption, power handling capability, switching speed etc) of the wide range of devices (Gunn, HBT, HEMT, MOSFET, RTD) built from the various III-V materials (As-based, P-based, N-based, Sb-based…..) demonstrated in the UK need to be catalogued, regularly updated and benchmarked against alternative solutions. These need to be mapped onto systems requirements addressing grand research challenges and societal need.

A quick survey of publications in III-V electronics in the UK academic community revealed that in the area of three terminal devices, there was activity with critical mass in GaAs/InP MOSFETs, GaN HEMTs, GaAs mHEMTs and InP HEMTs, but no academic outputs in Sb-based FETs. There is little or no activity in bipolars. Two terminal electronic devices being explored include GaAs and InP RTDs and Gunn diodes for THz generation and mm-wave sources.

Assuming an economic impact agenda is the primary research driver, engagement with systems integrators e.g. Selex, BAE, Thales etc will be vital. Components alone will not address societal need - routes to embedding high performance III-V electronics in systems solutions are required. Collectively, the UK has the full supply chain from epitaxial growth, wafer fab and packaging through to system insertion, but it is not coordinated or properly supported at key levels to maximise exploitation.

Breakout:
There is a need to find a “basket” of applications which will be enabled by a portfolio of III-V electronics since there is likely not one application or device type sufficiently large to motivate a prototype foundry with stable, repeatable processes, which realistically will be required if emerging research devices are to make it into systems. It is suggested that the community identify potential applications and map these onto the most promising Grand
Challenges (one or two at most). We should generate IP based on these new markets and solutions. A strong need to form a strategic partnership with foundries for higher volume manufacture was identified.

In terms of potential applications it was recognised that III-Vs need to live where silicon cannot reach. Examples include high speed D/A, A/D, synthesisers etc, room temperature THz sources and detectors, ultra low power (narrow bandgap materials) and high breakdown (large bandgap materials) electronics.

### 3.3 Optoelectronics

Stephen Sweeney (Surrey) presented this section. Optoelectronics involving III-Vs covers a large part of the spectrum and addresses a very wide range of applications including Energy, Healthcare, Security and Communications. The principal features of a road-mapping exercise should consider science/technology push versus market pull, the need to match opportunities with funding priorities, developing and maintaining excellence and maximising resources through effective collaboration.

The UK has a strong presence in optoelectronics covering the wavelength range from GaN-based LEDs (e.g. Cambridge and IoP), through visible/near IR (e.g. Surrey, Cardiff, Southampton) to Mid IR (e.g. Sheffield, Lancaster). Applications with a strong market need include UV lasers, closing the ‘green gap’ for lighting and displays, photovoltaics, integration of III-V lasers with Si and high efficiency Mid-IR RT inter-band and intra-band sources and detectors. The main challenges within many of these applications are efficient operation under ambient conditions, integration with electronics and cost reduction. In terms of market push, industry sees their future needs in terms of speed, lower cost, new markets and higher volumes. There is also an industrial demand for materials for higher temperature operation and techniques for monolithic integration. Technology push is coming from full exploitation of quantum dots, further exploitation of GaN, investigation of the properties of highly mismatched alloys, methods for producing silicon-based lasers, and how to develop a practical optical meta-material.

Photonics technologies for the manipulation of light have yet to be fully exploited and there is a strong need for high speed, efficient all-optical components for future internet. It is integral to almost every aspect of modern society (e.g. ICT, sensing, healthcare etc.). In communications applications, the current issues are low efficiency of lasers (require active cooling) and heat generation in computer systems and integration. Possible solutions are new materials and Si-based lasers, respectively, which require developing and understanding new optoelectronic materials. Emerging new materials beyond quantum dot lasers (which are becoming a commercial reality), could involve highly mismatched III-V alloys with N and Bi which are potentially important for loss suppression in near-IR lasers. Integration and efficiency drive the need to develop new III-V semiconductors.

There is a drive towards electronic/photonic integration involving III-Vs on Si where the UK has (separately) strong III-V and Si-photonics bases. This application presents many new III-V materials challenges and Ga(NAsP) lasers lattice matched to Si is an example. This also provides an opportunity to pull together UK expertise in III-V and silicon photonics/electronics.
The EU MONA (Merging Optics and Nanotechnologies) roadmap provides some useful input to a UK III-V roadmap. The ICT objectives of Framework 7 identify scalable core networks up to 100 Gb/s and beyond and energy efficient optical interconnects for short range (chip-to-chip and board-to-board) communications. Biophotonics for medical point-of-care diagnosis is another important area and where III-Vs can offer solutions. There are many III-V photonic disruptive technologies on the horizon such as plasmonics, photonic crystals, nano-photonics and manipulation of quantum states all of which are appearing as European priority themes.

There are several elements of EPSRC’s 2011-2015 delivery plan which are well supported by the current roadmapping exercise in III-Vs. Emphasis is being increasingly placed on maximising resources through collaboration. This is something that the III-V community is already doing but could be more structured.

**Breakout:**
Several applications in optoelectronics were discussed and reported. Highly efficient telecoms lasers with high T_R and stable wavelength are required for telecoms. Al quaternaries and QDs were identified as solutions together with new materials such as bismides, but a question remains as to how this would be aligned with funding priorities. For shorter range (e.g. board-to-board) communications the integration of III-V lasers on Si is important. There are strong academic III-V materials science and Si photonics activities in the UK to exploit this and these communities need to be brought together. Currently there is little work on this in the UK.

In terms of sensor applications, there is a requirement for novel pump lasers (e.g. nano-lasers) and device arrays (e.g. InGaN LEDs) where III-Vs can offer new materials or device structures. Current academic expertise in single devices could be further developed for array applications. Ultra short pulse generation using QDs has UK pockets of expertise (direct modulation of lasers, SESAMs) but end users need to be identified and better exploitation and collaboration is required.

Hybrid materials and devices were discussed where there are various potential applications in medicine, chemical sensing etc. This is another example of materials integration which is currently a relatively small UK activity.

Further general comments indicated that it was not always clear what companies/sectors need or want and that the technological Roadmap should be driven or strongly influenced by end users. There is a need to develop from component level through to systems. This is typically expected in European projects. In addition to EPSRC/TSB etc. the community should consider other funding sources that are available e.g. health. However, it was not clear whether the III-V community have a high enough profile which is clearly something that should be addressed. Scenario planning was identified as important in Roadmapping. Inviting experts from other fields (e.g. from defence, automotive, petrochemical, medicine) would help the community to develop activities more closely with end-users and increase exposure of the importance of III-Vs. Looking ahead, a perceived lack of training and future lack of PhD studentships on grants was deemed to be problematic and something which should be addressed further with EPSRC.
3.4 Health and Security

This section was presented by Edmund Linfield (Leeds – THz) and John Cockburn (Sheffield – Mid-IR). Applications in mid-IR include clinical diagnostics, medical imaging (e.g. Optical Coherence Tomography (OCT), species-specific mapping), stand-off explosives and weapons detection and IR countermeasures. THz sits between the IR and the microwave parts of the spectrum and spectral fingerprints from polycrystalline samples can be obtained. Additionally, many plastics and packaging materials are relatively transparent to THz, allowing probing through envelopes and clothing.

Mid-IR emission is realised through inter-band transitions in Quantum Cascade Lasers (QCLs) in a range of III-V materials. Molecular mid-IR ‘fingerprint’ detection of a wide range of gases is possible through molecular roto-vibration absorption in the range 3-12 µm. These include many pollutant and dangerous (poisonous and/or explosive) gases. Compact breath analysis units are possible which can produce indicators of a wide range of abnormal conditions in humans. In Mid-IR imaging it is possible to map out chemical differences from the well known fingerprints of species, leading to images, for example, of skin cancer. The specific signatures of explosives can be detected in the range 6-9 µm and a prototype screening system is in operation at Glasgow Airport (Cascade Technologies).

In terms of UK strengths and weaknesses in mid-IR, although there is a relatively small academic community, it does have a range of comprehensive capabilities (sources, detectors, materials, theory, device physics and technology). The National Centre III-V capability in this area has been significantly enhanced in recent years and there are also several highly active and flourishing SMEs (e.g. Cascade Technologies, CST, M Squared) able to exploit the academic activity. Interaction between groups/technologies and universities/industry could be much improved (Mid-IR Network is missed). More multi-partner, multi-disciplinary collaboration is essential for international success (see MIRTHE network as exemplar (http://www.mirthecenter.org/)). There is also a lack of major industrial involvement.

As well as its usefulness in explosives detection, THz radiation can detect the inter-molecular modes in drugs which are subject to abuse. Terahertz in vivo measurements of patients can successfully image tumours, revealing both surface and depth information, which match well with histology. III-V devices contribute to THz generation through frequency doubling in superlattice diodes, Gunn diodes and directly, using QCLs in the 1-5 THz range. As with mid-IR QCLs, the epitaxial structures are extremely complex with up to 1000 separate hetero interfaces with a total thickness up to 10 µm. In summary, terahertz frequencies have a broad range of potential applications in security, pharmaceuticals and dermatology. Applications of III-V semiconductors include high frequency microwave devices, terahertz quantum cascade lasers and photoconductive emitters and detectors.

Breakout:

Additional applications identified included surgical treatment, IED detection and thermal imaging. All require extensive use of III-Vs. The group considered sources only but consideration of detectors etc need to be tackled elsewhere. It was appreciated that there were companies across the sectors, both start-up and large (GE, Smiths, BAE, Thales), which are well able to exploit the academic research. It was recognised that more direct company input is needed to define road maps and take-up opportunities (requirements, costing strategies, yields, etc) and there is a role for NC to arrange this.
In terms of sources, in the near-IR there should be a focus on integration, broadband, and driving down costs, size, etc. InP QCLs are good for mid-infrared (3.5 – 15 μm) sources but there is a need to focus on defining characteristics (beam profiles, tuning, etc) required for applications. Higher power lasers are still needed in the shorter wavelength range. For terahertz, there is a need for high power and high operating temperature sources. There is still much to be done at the research level with different materials. Future focus should be on integrated technologies for cheaper technology and biomedical devices. Example applications in healthcare (and detection of illicit substances) through implant or ingestible electronics is important when packaged III-V systems need to be developed.

3.5 Fundamental Research Enabled by III-V Semiconductors

This presentation was given by Maurice Skolnick (Sheffield).

III-V semiconductors are an excellent vehicle to study fundamental physics. They have a very well developed growth and fabrication technology to enable top class fundamental research, very high quality hetero-interfaces and an ability to engineer heterostructures. Additionally, III-Vs are capable of a variety of small-dimensioned structures prepared with very high precision (quantum wells, wires and dots), excellent control on the nanometre scale, and highly favourable properties for new physics. Many of these technological developments enabling the new physics are driven by industrial applications (and vice versa) and which have led for example to two Nobel prizes in the field (1998 and 2000). A strong recent theme is control at the level of single quantum states.

The very high purity and electron mobilities achievable in the GaAs/AlGaAs system have prompted many transport studies such as coupled carrier gases (Bose-Einstein condensation, excitonic superfluidity, half-filled Landau levels), coupled e-h gases (Cambridge - Excitons, charge density waves, Wigner crystals, condensation) and resonant tunnelling (Nottingham). The main UK transport activities are at Cambridge (also NPL, Bath) and Nottingham. Electrostatic dots for spin control (Harvard, Tokyo, Delft, Weizmann) is a large general area which is under-represented in UK.

Optics is an area of UK strength, particularly in (at least) two prominent areas, quantum dot physics and polariton physics, enabled by strong interaction of III-V nanostructures with optical fields. Self-assembled quantum dots, mostly InGaAs/GaAs but also InP/GaInP (below ~50K), reveal atom-like properties in a solid state system. Studies on ultrafast control of single quantum states, nuclear spins, memory resources and dephasing are possible. Quantum dots are studied as components for quantum information systems e.g. electrically driven entangled photon pair source (Toshiba, Cambridge). Quantum dots in optical cavities have demonstrated strong coupling between the solid state two-level system and a confined photon mode (Cardiff) where the novelty is a two photon state coupled to a dot. There is unpublished work from Bristol on phase shifts from single dots and related work on Mollow triplet exciton-photon coupled states (more than one photon) and real time readout of single spins (Atature group, Cambridge).

Exciton-polaritons in GaAs-based microcavities (quantum well exciton-photon coupled modes) can achieve strong coupling with Rabi splitting of up to 15meV. Polaritons are robust quasi-particles which exhibit properties found in cold atom systems, such as Bose-Einstein condensation, vortices and 'superfluid' flow (c.f. transport). These systems may be
electrically driven, resulting in the possibility of a polariton laser. Activities are centred around Sheffield, Southampton (experiment and theory) and Cambridge. Polariton solitons (superfluid behaviour) hold out the possibility of polariton circuits at room temperature where GaN may play a role. This is also an alternative approach to exciton based circuits using coupled quantum wells (UCSD).

Overall, there is diverse activity in fundamental optics in the UK with significant achievements.

In the field of spintronics, III-V ferromagnetic semiconductors, (Ga,Al,In)(MnP,As,Sb) (Nottingham), have the highest Curie temperature (~187 K) and there are on-going efforts to increase this using new materials. Sensors are based on tunnelling anisotropic magneto-resistance and coulomb blockade anisotropic magneto-resistance. Spin-Hall effect studies have demonstrated spin polarised currents and Hall voltages without magnetic elements (Hitachi Cambridge) in GaAs/AlGaAs structures with optical injection.

In summary, many of the important developments of semiconductor physics in the last twenty years have taken place in III-V systems. The UK is making significant contributions and there are high expectations of new developments such as in control and interaction of quantum states, light-matter particles, spintronics, nanowires and opto/nano-mechanical systems. Physics research in III-Vs will impact on future technologies (e.g. QCLs, QD lasers, quantum information technologies). It is also notable that fundamental growth and physics research in the 1980s led to foundation for a major industry e.g. IQE, QW solar cells (QuantaSol).

Breakout:
The breakout session identified the need for investment in new hardware across UK universities (much is at least 10 years old, some 20); an inventory of capability would inform this process. The future for quantum nanostructure research requires innovation in growth and fabrication such as position, composition and size control. Scale-up, integration and manufacturability all need to be addressed. Skilled people are a major output (applies across all III-V topics). III/V hybrids (III-Vs on Si, metal hybrids, in situ deposition e.g. spin injection) are another area of future study. Finally, it was recognised that deep centres in GaN remain unexplored.

4. Related Roadmaps/Reports

- MONA (Merging Optics and Nanotechnologies) European roadmap for photonics and nanotechnologies (2008)
  http://www.ist-mona.org/roadmaps/default.asp

- Joint IeMRC-EEPKTN Power Electronics Roadmap (2007)
  http://www.lboro.ac.uk/research/iemrc/documents/DownloadDocuments/IeMRC_EEPKTN_Roadmap_as_published_080219.pdf

- INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS (2009 EDITION) - EXECUTIVE SUMMARY
• UK Photovoltaic Solar Energy Road Map (2009)
  https://ktn.innovateuk.org/c/document_library/get_file?uuid=539d9b42-7ea4-4571-9050-c0f4920bddd1&groupId=240498

• Photonics21 - Lighting the way ahead (Second Strategic Research Agenda in Photonics) (2010)

• PhotonicRoadSME (FP7 Project)