EPSRC Future Manufacturing Research Hubs

Future Compound Semiconductor Manufacturing Hub

Annual Report 2017

Front cover image:
Future Compound Semiconductor Manufacturing Hub (CS Hub) post-doctoral research associate (PDRA) Dr Zhibo Li performing work in the cleanroom facility at Cardiff University.

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Foreword

"During Year one of the Future Compound Semiconductor Manufacturing Hub (CS Hub) we have put in place strong foundations for our future success.

Our Hub at Cardiff University, together with our spokes at Manchester University, Sheffield University, and University College London are working seamlessly together towards addressing the significant challenges of high volume, high quality and low cost manufacture of compound semiconductors through industry relevant research.

In addition, a core set of our 30+ industrial collaborators are working with us to ensure the relevance and support of our research.

In short after bringing together the resources and structures needed, we have begun our journey towards revolutionising compound semiconductor manufacture. We have exceeded our expected performance, based on our Key Performance Indicators, and have made significant progress towards our strategic objectives.

We look forwards to the next year of success and challenges for the Hub."

Prof Peter Smowton
CS Hub Director
Deputy Head of School
Director of Research
School of Physics & Astronomy, Cardiff University

The Future Compound Semiconductor Manufacturing Hub is funded via EPSRC grant number EP/P006973/1

Key Messages

The EPSRC Manufacturing Hub in Compound Semiconductors addresses the need to integrate CS and Silicon (Si) manufacturing, apply the manufacturing advances made in one type of CS across the different families of CSs and combine these different CSs for optimum functionality.

Compound semiconductor materials are a **Key Enabling Technology** at the heart of modern society.

Next generation technologies will only be achieved with a huge increase in compound semiconductor manufacture.

Key Outcomes:

To radically boost the uptake and application of CS technology by applying the manufacturing approaches of Silicon to CS

To exploit the highly advantageous electronic, magnetic, optical and power handling properties of CS while utilising the cost and scaling advantage of Silicon technology where best suited

To generate novel integrated functionality such as sensing, data processing and communication.

Compound semiconductors are vital for the development of:

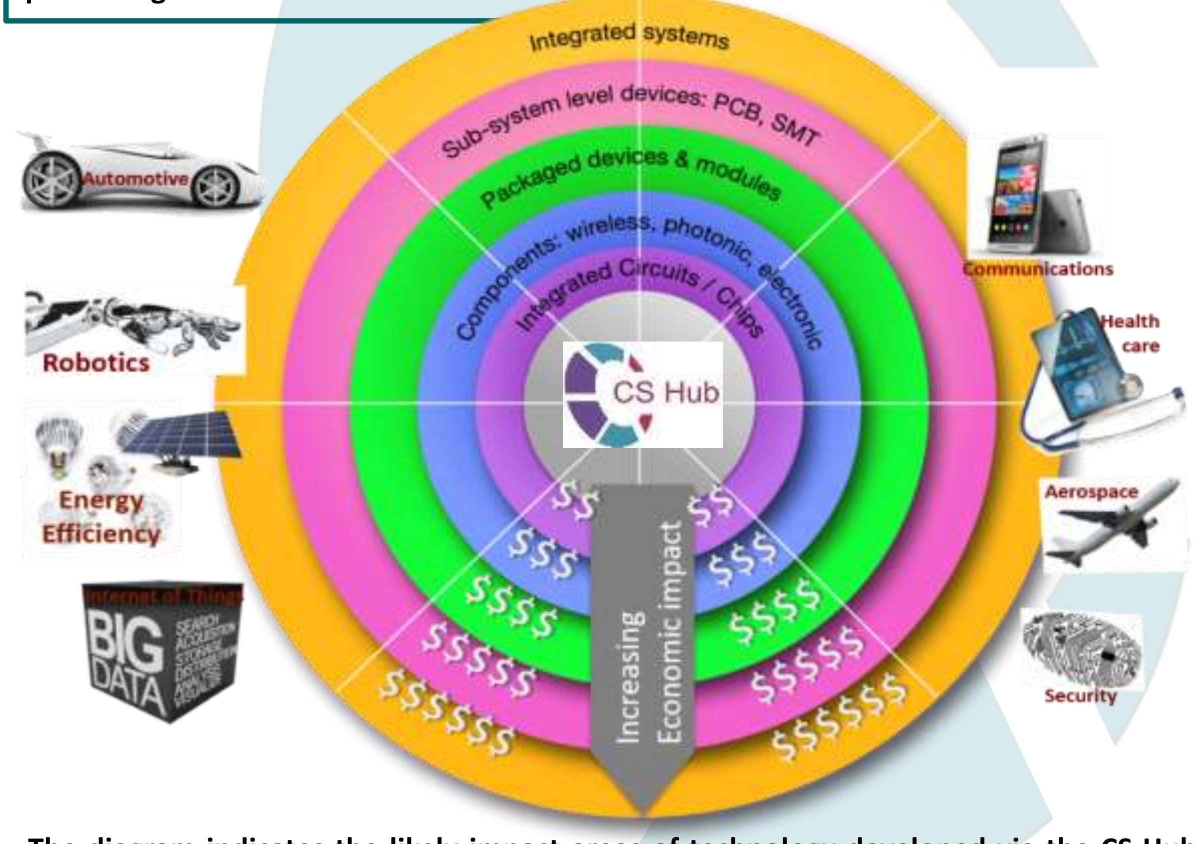
- 5G
- energy efficient lighting
- smart devices
- electric vehicles
- imaging techniques.

Compound semiconductors are vital to development of technologies supporting:

- a connected world
- health
- security
- the environment

The Hub will:

- position the UK at the centre of CS manufacturing research.
- support & promote CS research and systems research in all associated fields.
- apply the manufacturing disciplines and approaches used with Silicon semiconductors
- combine CS with Silicon
- to generate the required increase in CS manufacture.



The diagram indicates the likely impact areas of technology developed via the CS Hub and emphasises the added value at each stage enabled by the CS technology.

Future Manufacturing Hubs Programme

The Context of the Funding used to Develop the CS Hub

To help manufacturing industries respond to future opportunities and drivers and contribute to a prosperous UK, the Engineering and Physical Sciences Research Council (EPSRC), part of Research Councils UK (RCUK), are looking to evolve their critical mass investments in manufacturing, building on the successes of the Innovative Manufacturing Research Centres and the EPSRC Centres for Innovative Manufacturing.

The EPSRCs vision for their critical mass investments is to support UK manufacturing industries by supporting the commercialisation of early stage research opportunities in emerging areas, through a network of Future Manufacturing Research Hubs.

For further information on the EPSRC Manufacturing Research Hubs, please go to:https://www.epsrc.ac.uk/research/centres/manufacturinghubs/

We are one in a network of eight UK-wide Hubs, funded by EPSRC and industry resources.

Uniquely, our Hub researches into large scale Compound Semiconductor manufacturing, and in manufacturing integrated Compound Semiconductors on Silicon. We will provide world-leading facilities that will translate research into large-scale growth and device fabrication.

Our research network includes the newly formed Compound Semiconductor Cluster, the first of it's kind world-wide. We interact with all other cluster members to develop highly translatable and impactful compound semiconductor research with high economic relevance. Cluster members include the CS Hub, Cardiff Universities Institute for Compound Semiconductors, the Compound Semiconductor Centre, the Compound Semiconductors Applications Catapult, and the umbrella organisation CS Connect. Further information on these entities is provided later in this report.

We have made important connections with other Hubs including the Future Advanced Metrology Hub, and the Future Photonics Hub, with whom we are discussing potential collaborations and sharing of resources.

We aim to make huge inroads to the use of compound semiconductors as an alternative to silicon, which will allow other technical areas to flourish, and the Welsh and UK economies to strengthen in these increasingly uncertain times.

Images: EPSRC have provided £10.3m funding for the activities of the CS Hub, one of several Future Manufacturing Hubs, funded to develop research associated with significant manufacturing challenges. The Welsh Government have played an integral role in developing the first compound semiconductor cluster in the world in the South Wales region. Map shows location of the CS Cluster, mainly focused around Cardiff and Newport, South Wales.

Research Landscape

The CS Cluster

Future Compound Semiconductor Manufacturing Hub

The CS Hub will focus on the key scientific challenges in manufacturing, building on fundamental research developed at the Institute for Compound Semiconductors (ICS) and other UK academic centres. The Hub will feed the higher TRL 4+ activity at the Compound Semiconductor Centre (CSC), which links to UK manufacturing industry, and the Compound Semiconductor Catapult. The ICS is a £80M Cardiff University and Welsh Government initiative supporting a strategy to generate a major UK CS cluster and this EPSRC Manufacturing Hub contributes staff and consumables to research and development of new manufacturing processes, leveraging the existing capital investment and completing this strategy.

Compound Semiconductor Centre

The Compound Semiconductor Centre (CSC) was formed in August 2015 as a joint venture between IQE plc, the world leading supplier of advanced compound semiconductor wafer products, and Cardiff University, one of the Britain's leading research universities. The CSC will build on research undertaken at Cardiff University's Institute for Compound Semiconductor to develop innovative new materials technologies that will enable a wide range of new and emerging applications. The aim is to provide a complete capability value chain from high-end, World-class research and development through product and process innovation to high value, large-scale manufacturing. The CSC provides an essential pillar to span the so-called "valley of death" on the Technology Readiness Level (TRL) scale.

Institute for Compound Semiconductors

With state-of-the-art equipment, cutting-edge facilities and highly-skilled people, ICS aims to position Cardiff as the UK and European leader in Compound Semiconductor Technologies. From smartphones and tablets to satellite communications and GPS, compound semiconductors drive the devices and technologies we use today. The ICS enables researchers and industry to work together, meeting consumer demand by progressing academic research to a point where it can be introduced reliably and quickly into the production environment.ICS will also target direct industrial collaboration for product development to prototyping, including advanced device fabrication, measurement and characterisation, and small scale pilot production, incorporating our broad academic expertise to offer innovative business solutions. In addition the Institute will focus on formal and informal specialised training, including new equipment demonstration and housing, outreach, brainstorming and networking events. The Institute has been established as part of the University's £300M capital development plan, including support and investment from the Welsh Government and the UK Research Infrastructure Fund (RPIF). The Institute fills an important niche in today's compound semiconductor sector. While our facilities are new, the ICS builds on existing University strengths in optoelectronics, semiconductor devices and materials, providing infrastructure that industry cannot necessarily accommodate, and that feeds-through to the Compound Semiconductor Centre (CSC) and CS Catapult for post-foundry product realization.

Compound Semiconductor Applications Catapult

Catapults put technology to work to tackle issues and take advantage of opportunities presented to the UK. The CSA Catapult helps UK companies, particularly SME's, to grow by exploiting advancements in compound semiconductor technologies which translate into opportunities for: **Power electronics** e.g. smart grid, electric vehicle powertrain; **RF/microwave** e.g. RADAR, wi-fi and 5G; **Photonics** e.g. security scanning, health diagnostics and high speed communications. The CSA Catapult will provide world-class research facilities with access to independent, trusted expertise to develop capabilities in the above and accelerate the commercialisation of compound semiconductors in key application areas such as healthcare, the digital economy, energy, transport, defence and security, and space.

The CS Cluster continued

CS Connected

The world's first compound semiconductor cluster

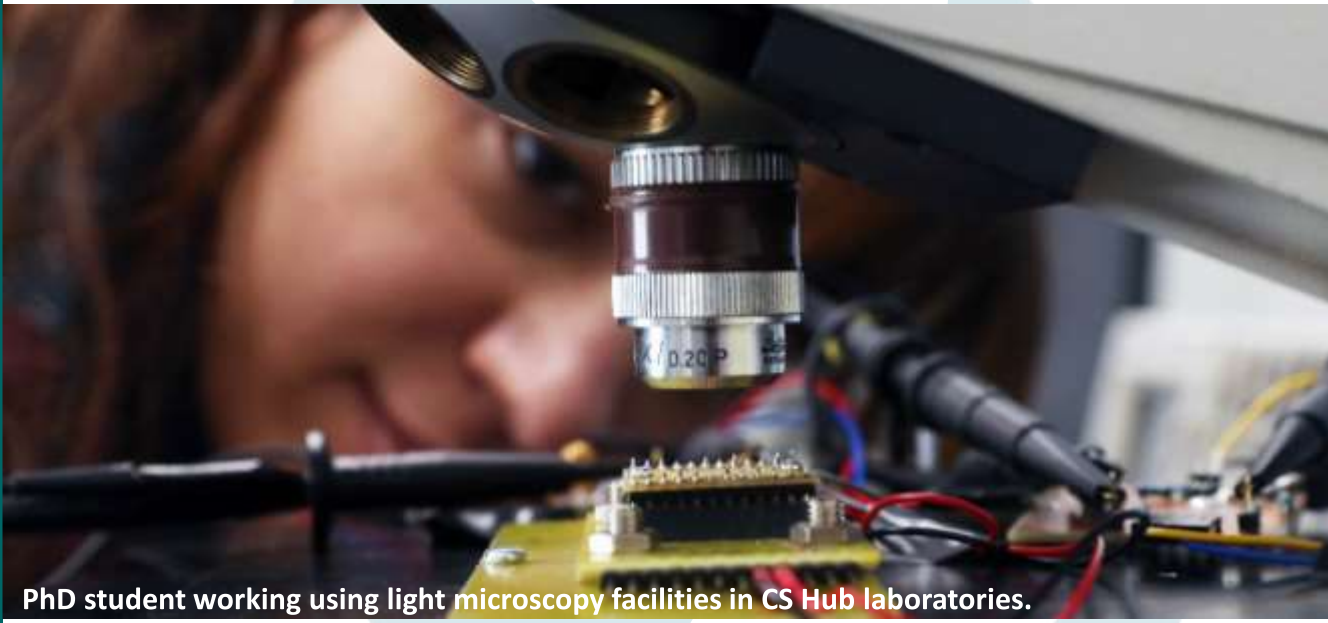
CS-Connected represents organisations who are directly associated with research, development, innovation and manufacturing of compound semiconductor related technologies as well as organisations along the supply chains whose products and services are enabled by compound semiconductors.

The UK, and in particular, Wales, is home to a growing number of organisations and businesses that are active in this increasingly important industry sector. In 2015, Cardiff University announced an investment of around £75M in the Institute for Compound Semiconductors as part of its new £300M Innovation Campus. The announcement for the Institute was quickly followed by the creation of a £24M joint venture between IQE plc and Cardiff University to form the Compound Semiconductor Centre (CSC) for the development and prototyping of compound semiconductor materials. Hot on the heels of the launch of the CSC, came the announcement that the UK Government was to invest £50M in the first Catapult Centre in Wales that would be dedicated to the development of compound semiconductor applications.

In 2016, EPSRC announced a £10M investment in a Compound Semiconductor Hub to be based at Cardiff University.

All in all, the region is gaining global recognition as being a highly active, global centre in the field of compound semiconductors.

All CS Cluster members share a common goal: to position South Wales and the UK as the European leader in compound semiconductors, providing cutting-edge facilities that help researchers and industry work together. To address the industry / user requirement to facilitate new technologies via CS development.



PhD student working using light microscopy facilities in CS Hub laboratories.

Local cluster contacts

***Prof Peter Smowton**: Prof & Deputy Head of School, School of Physics & Astronomy, Cardiff University; CS Hub Director, ICS Managing Director*

***Dr Sarah Taylor**: CS Hub Manager, Cardiff University*

***Dr Wyn Meredith:** CS Hub Innovation lead**,** Compound Semiconductor Centre Director, CS Applications Catapult Board Member*

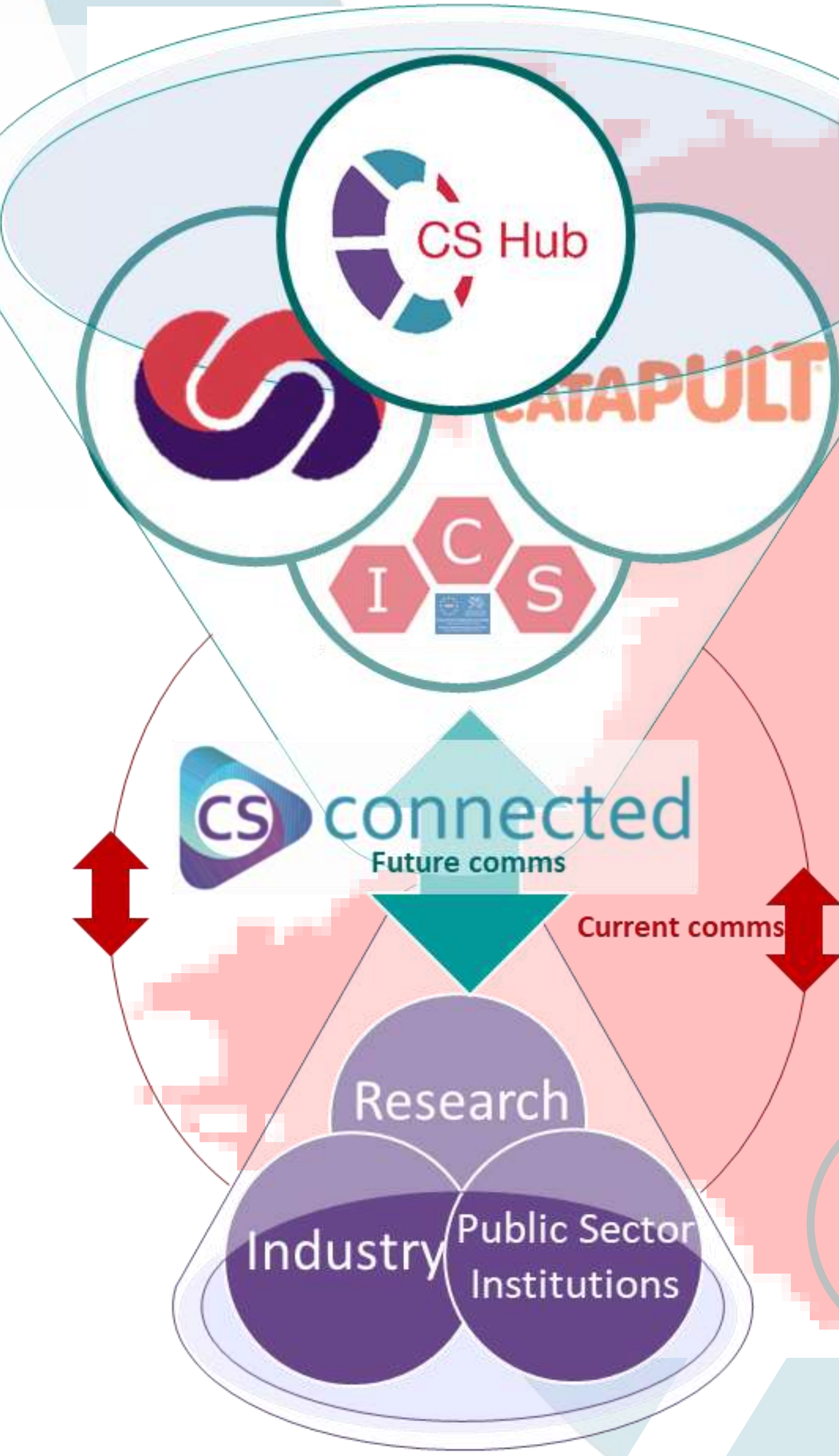
***Steve Sutton:** ICS Business Development Manager, Cardiff University*

***Clive Meaton**: ICS Director of Operations*

***Chris Matthews**: ICS Communications, Cardiff University*

The CS Cluster continued

Driven by scientific excellence the EPSRC Hub will act as the focal point for the creation of Europe's 5th Semiconductor Cluster and the first dedicated to Compound Semiconductors.



Institute for Compound Semiconductors (ICS)

£80m Cardiff University and Welsh Government investment providing CS services to research and industry.

Compound Semiconductor Centre (CSC)

£24m Joint IQE plc and Cardiff University venture to develop and prototype CS materials.

Compound Semiconductor Applications Catapult (Catapult)

£50m UK government investment bridging the gap between developing novel CS materials / topology / devices and developing systems for end-user applications.

Future CS Manufacturing Hub (CS Hub)

£10.3m Research Council UK & industry sponsored full CS research programme.

CS Connected

Umbrella organisation for world's first compound semiconductor cluster.
User interface, represents cluster members.

Image showing the interconnected elements that make up the Compound Semiconductor Cluster in South Wales (UK), the first of it's kind in the world.

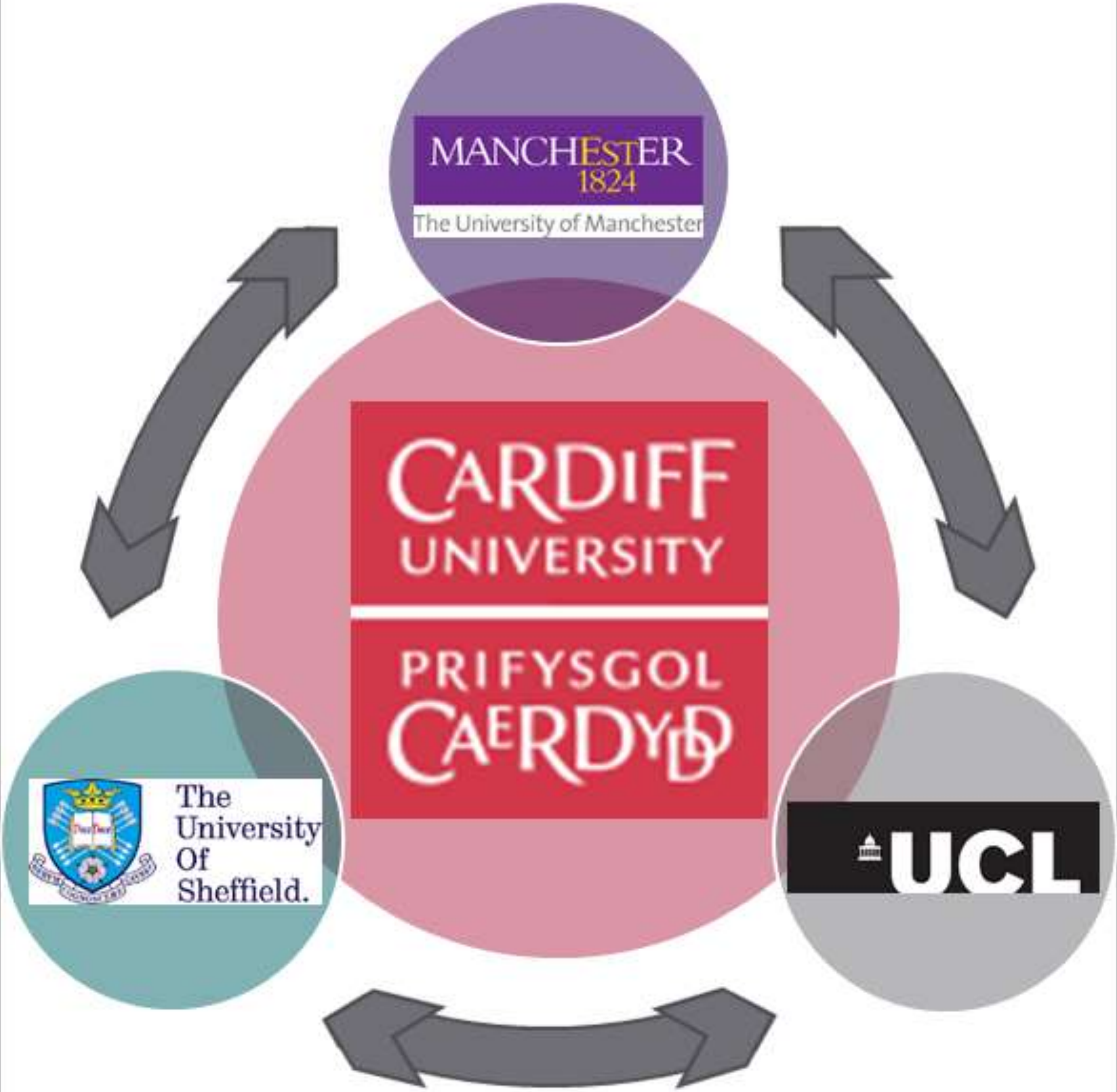
Founding Partners

Academic and Industrial

The CS Hub is led from Cardiff University, with Prof Peter Smowton as Director. Our founding partners bring wide-ranging and essential expertise in all aspects of compound semiconductor technology. This powerful collaboration began as a partnership between the academic institutions of Cardiff University, the University of Manchester, The University of Sheffield, and University College London. In addition we have >30 industry collaborators who have pledged £11,230,160 in support of our activities (see appendix for further partner details). Some of the Hub partners are are shown below.

Many of our industry partners have offered training placements as part of their dedicated contribution to the CS Hub. With a strong ethos of training and communication, the CS Hub is providing a diverse and exciting training programme, and communicating our research to a wide range of individuals. Training and communication come together in our interaction with founding partner, Science Made Simple (SMS). Director of SMS, Wendy Saddler MBE, has a long history of working with communication of concepts in physics and has pledged to provide bespoke training to the CS Hub.

Further engagement with industry is supported by the Compound Semiconductor Cluster (CSC) Director, Dr Wyn Meredith, who acts as engagement officer for the CS Hub. Indeed, our interaction with others in the South Wales landscape, including CSC, the Catapult for Compound Semiconductors, and the Institute for Compound semiconductors (ICS), as well as CS Connected will be critical for service provision, interfacing with end-users, communicating with industry and other essential activities.



Academic Structure

The Choice of Hub and Spokes

Sensors and Communication are essential to the emerging application megatrends, the institutions of choice build on world renowned research excellence. Cardiff is vital for university investment in capital and academic staff excellence. Spokes are complementary to this, with world leading scientific and manufacturing excellence in the following research fields:

- GaN on Silicon (Sheffield), lauded by Nobel Laureate Nakamura,
- in the first practical CS on Si Lasers (UCL) and
- reproducible, high tolerance CS manufacturing and its inclusion in partner supply chains (Manchester).

Mission and Vision

Establishing the UK as the Primary Global CS Research & Manufacturing Hub

Our vision is to establish the UK as the primary global research and manufacturing hub for Compound Semiconductor (CS) Technologies.

We combine and connect the UK's research excellence in compound semiconductors with the very best translational facilities and the CS Applications Catapult to support the UK CS industry and UK industry users of CS.

The Hub aims to make research 'manufacturable.'

Working with spoke universities and other centres of excellence throughout the UK, we will create a path from enabling fundamental research through to wafer, device and integrated chip manufacturing research into final product prototyping, reliability testing and system qualification at the CS Applications Catapult .

CS materials underpin the operation of the internet and enabling emerging 'megatrends' such as Smart Phones, satellite communications/GPS, advanced healthcare and ground-breaking biotechnology.

The Hub integrates CS and Silicon (Si) manufacturing, applies the manufacturing advances made in one type of CS across the different families of CSs, and combines these different CSs for optimum functionality.

Our work aims to radically boost the uptake and application of CS technology by applying the manufacturing approaches of Silicon to CS. It exploits the highly advantageous electronic, magnetic, optical and power-handling properties of CS while utilising the cost and scaling advantage of Silicon technology where suitable. And it generates novel integrated functionality, such as sensing, data processing and communication.

Our researchers have a track record in innovation and impact, complementary technical capability and the individual skill sets that can combine to create new solutions to the identified major scientific challenges in manufacturing.

The ICS houses academic functions and fabrication facilities, and the CSC leads on translation with its growth facilities.

Together as CS Connected, we can exploit the demands of next generation technologies that are driving the integration / replacement of Silicon with advanced CS materials, creating a truly massive market opportunity for CS materials and devices.

Above all, we are geared to changing the UK academic mind-set, turning great research into great applications and future products.

CS Hub PDRA, Dr Dave Hayes working in the dark room laboratory at Cardiff University.

Rational

Why we need the CS Hub

Compound Semiconductor materials are a Key Enabling Technology underpinning the operation of the internet and enabling emerging megatrends such as Smart Phones, Internet of Things (IoT), satellite communications/GPS, energy efficient lighting, efficient solar power generation, advanced healthcare and groundbreaking biotechnology. The demands of next generation technologies are driving the integration / replacement of Silicon with advanced CS materials, creating a truly massive market opportunity for CS materials and devices.

The EPSRC Compound Semiconductor Manufacturing Hub will provide the missing exploitation link for the UK CS Research Community by providing a route to impact and economic leverage for EPSRCs >£30M current CS investment. The hub will capitalise on academic expertise at the hub and spoke universities and the indigenous UK corporate strength in the key advanced materials technologies of CS, in particular GaN, GaAs, InP, InAs and InSb. It will actively encourage new entrants and partners.

The Hub will focus on the key scientific challenges in manufacturing, building on fundamental research developed at the Institute for Compound Semiconductors (ICS) and other UK academic centres. The hub will feed the higher TRL 4+ activity at the Compound Semiconductor Centre (CSC), which links to UK manufacturing industry, and the Compound Semiconductor Catapult.

The hub will provide underpinning platform technologies in manufacturing CS, set up as the capability work packages in the proposal, particularly pushing the boundaries of growth and fabrication on lattice mismatched substrates for high power and RF electronics, magnetics and optoelectronics. The two cross cutting Grand Challenges (GC1 Enabling the Connected Nation and GC2 Sensors) are carefully designed with our partners to meet generic industry pull with specific demonstrations of what these new platform capabilities will provide, taken to a system integration level with our partners.

Driven by scientific excellence the EPSRC Hub will act as the focal point for the creation of Europe's 5th Semiconductor Cluster and the first dedicated to Compound Semiconductors.

CS Hub PDRA, Dr Sam Shutts, working in the clean room facilities, ICS.

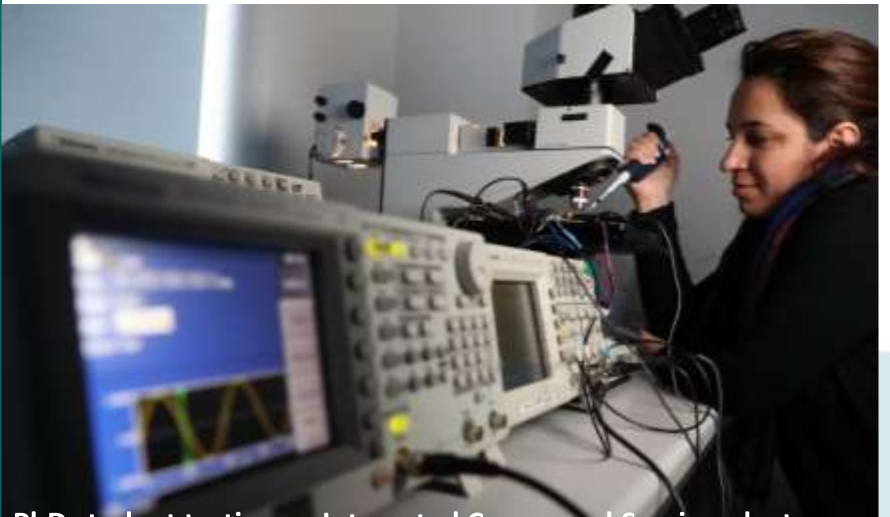
Platform

What the Hub will Help us Achieve

Underpinning funding will be used 1) to develop Silicon like manufacturing processes for CS and 2) to develop the manufacturing of CS grown on silicon for integrated functionality and dramatically reduced cost.

To date the remarkable capabilities (e.g. light emission, higher speed, etc. c.f. Si) of III-As, III-P and III-Sb compound semiconductors have been achieved by growth on small area native substrates and, in almost all cases, bespoke device fabrication processes for particular applications. By contrast the successes of Si electronics have been due to a foundry approach, where devices are created from a suite of common fabrication processes on large area substrates. This facilitates the advantages of mass production even for smaller scale applications, as suitable structures can be developed on a large shared substrate. We will develop a foundry type approach for the other CS on native substrates as well as for CS grown on Si, which is even more challenging because of defect formation due to lattice mismatch and thermal expansion mismatch. In III-Ns, where a native substrate is not available at any suitable scale, progress has been demonstrated using growth on mismatched substrates. A fundamental reason for the success is thought to be Indium segregation and consequent localisation effects preventing carrier diffusion to defects and associated non-radiative centres. Progress in devices using quantum dot active regions in III-As materials grown on Si also relies on carrier localisation to produce excellent performance. This coupled with recent developments in nanowires (which can accommodate the lattice mismatch) and selective area growth make it extremely timely to develop growth of CS on Si. This paves the way for the integration of different CS on the same substrate and the integration of CS functionality with that best obtained using Si. In some applications, e.g. those requiring radiation hardness or operation at high temperature, it is better to integrate on a CS substrate e.g. GaAs, where 150mm growth and Si style fabrication needs developing.

Progress in the growth of CS on Si has proceeded somewhat in isolation and have produced essentially different optimum solutions for the interface between III-Sb, III-As and III-N and silicon. With the scale and expertise in the hub we will develop more effective, combined solutions for III-Vs on Si.



PhD student testing an Integrated Compound Semiconductor Microfluidic chip.

Technology Themes

Structure

In order to achieve our vision of establishing the UK as the primary global research and manufacturing hub for Compound Semiconductor (CS) Technologies, we are working on eight areas within compound semiconductor research, as well as using this research to address two grand challenges for CS manufacturing.

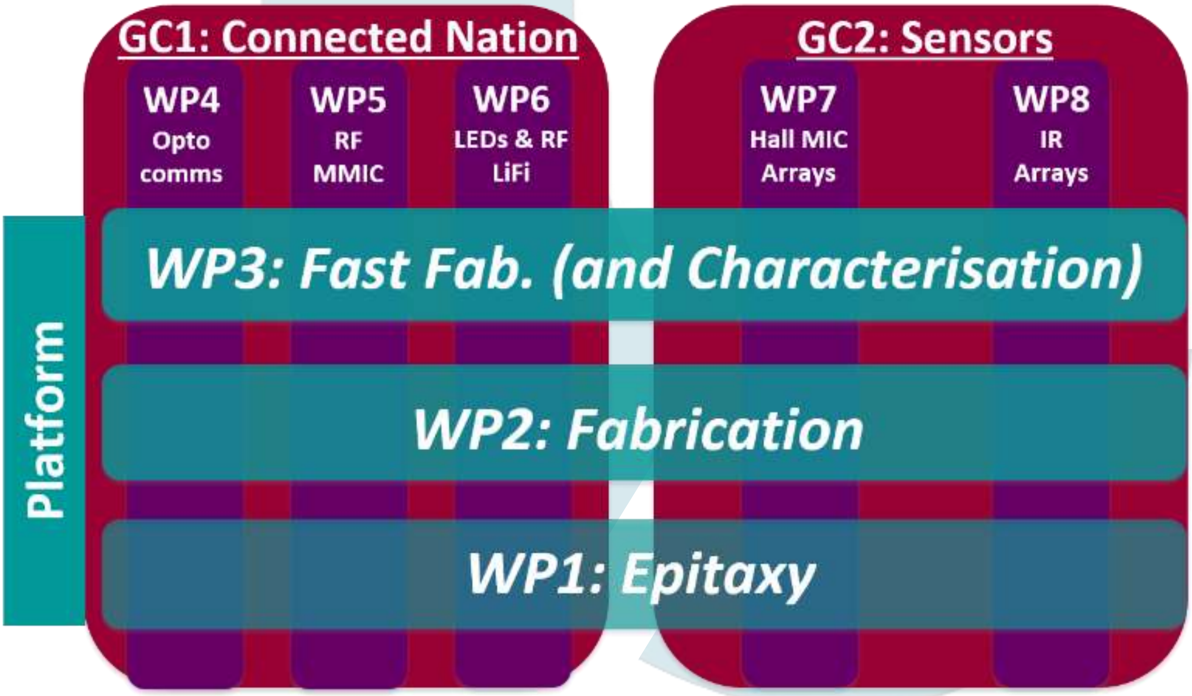
For project delivery, the eight research areas addressed by the Hub are divided into Hub work packages, which can be broadly split into the two Grand Challenges, forming Grand Challenge One: The Connected Nation; and Grand Challenge Two: Sensors. The first three work packages in (1) epitaxy, (2) fabrication and (3) fast fab with characterisation form a platform across both grand challenges. While the remaining five work packages fall separately within either grand challenge.

(4) Opto-communications, (5) RF MMIC and (6) LEDs & RF LiFi involve work towards the connected nation Grand Challenge. (7) Hall MIC arrays and (8) IR arrays focus on development of manufacturing approaches to the sensors Grand Challenge. All work packages are further subdivided into sets of project deliverables.

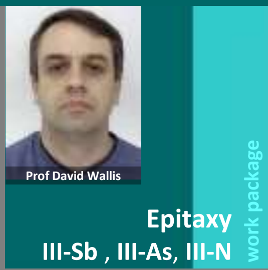
The work packages focus the research of multiple partners, working together to secure the best outcome possible for CS manufacturing research. Further focus is secured by breaking down the research further, into sub-work package deliverables.

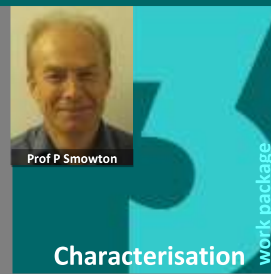
In Cardiff, we are very pleased to welcome Prof David Wallis as the new lead of work package one following the departure of the original work package lead. We are confident that David will bring a wealth of expertise to develop the epitaxy research of the Hub. In addition we are pleased to be able to support the work of Dr Marie Delmas, an early career researcher at Cardiff University. The opportunity to lead a work package under the prestigious EPSRC investment in the hub is an excellent opportunity for Marie, and will prove the Hub's ability to develop young talent in the field of compound semiconductor research.

The structure of the CS Hub Grand Challenges and work packages can be found in the diagram below.



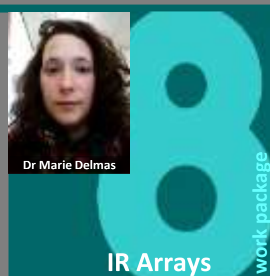
Platform





GC 1: Enabling the Connected Nation

GC 2: Sensing



Technology Themes

Work Packages Represent Technology Themes for the Hub

The work of the Hub is organised into eight different work packages (numbered above), broadly separated by research area, across which all academic partners contribute. In addition, the Hub has two overarching grand challenges (GC) which address the bigger research questions involved in each work package. These work packages can be further subdivided into specific deliverables.

The research of the CS Hub can be broadly split into two grand challenges addressing the connected nation and sensors. WP1, Epitaxy is led by Prof David Wallis at Cardiff University and spans both grand challenges. WP2, Fabrication is led by Dr Phil Buckle at Cardiff University and also spans both grand challenges. WP3, fast fabrication and characterisation is led by Hub Director, Prof Peter Smowton at Cardiff University and also spans both grand challenges. WP4, opto-communications is led by Prof Huiyun Liu at UCL and falls within grand challenge 1. WP5, radio frequency MMICs is led by Prof Paul Tasker at Cardiff University and falls within grand challenge 1. WP6, LEDs and radio frequency LiFi is led by Prof Tao Wang at Sheffield University and falls within grand challenge 1. WP7, Hall MIC arrays is led by Prof Mo Missous at Birmingham University and falls within grand challenge 2. WP8, infrared arrays is led by Dr Marie Delmas at Cardiff University and falls within grand challenge 2.

Grand Challenge 1

Enabling the connected nation

The Connected Nation vision, now an EPSRC priority, requires new *manufacturing concepts that can deliver small integrated communicating systems, at low cost, that have a high degree of functionality*. The first grand challenge agreed with our partners is to provide a Si style manufacturing framework for CS on which to develop systems that can address both wireless and optical connectivity. This will also access lower manufacturing costs due to lower substrate costs and reduced processing costs, partly from the use of the larger substrates. As indicated in the figure below, the manufacturing framework must provide an increased level of integration at all stages, from electronic / optoelectronic materials through device/circuit level fabrication to hybrid assembly. It should also be compatible with the high volume Si manufacturing infrastructure**.** We will focus on the materials integration and the device/circuit integration stages in the figure below. It is in these stages that the highest level of integration is most desirable from both the perspective of cost and functionality. These stages are highly interdependent and must be considered together. Integration that cannot be achieved at these stages will have to be accommodated by hybrid assembly, which is considerably more expensive.

Cisco's visual networking index (VNI) forecast predicts that annual global IP wireless data traffic will exceed 24.3 Exabytes per month by 2019, and will continue to increase at a compound annual growth rate of over 50%. This is driven by the exponential increase in the number of devices such as smart phones and the increased use of interactive video and streaming. In addition, the Internet of Things (IoT), where a wide range of miscellaneous devices are connected to the internet, is expected to grow rapidly from 10.3 million devices in 2014 to more than 29.5 million in 2020. The network will need to support this rapidly growing demand for capacity, which is now considered as a motivation for 5G wireless development. Spectrum scarcity is driving the move to millimetre- wave (mm-wave) band systems and increased base station and device densities. The use of Compound Semiconductor (CS) based lighting to provide optical wireless access (Li-Fi) is also an area of interest to meet the required growth in capacity. Wireless access devices, from Smart phones to the IoT, depend on CS devices for both transmit power amplifiers and low noise receiver pre-amplifiers. Power management is a critical requirement for these distributed systems. For example, the energy efficiency of the transmit CS power amplifier has the potential to limit the development of 5G wireless. Every optical link that enables the internet, from a rack to rack, active optical cable to a trans-oceanic optical fibre system uses CS optical sources because they enable high speed, power efficient data transmission. CS devices are already critical in providing the system connectivity, whether optical or wireless, and future systems will require integration of these functions. Hence the need to *establish a CS manufacturing framework to develop the integrated systems to populate the "Internet of Things"*.

Enabling the connected nation continued

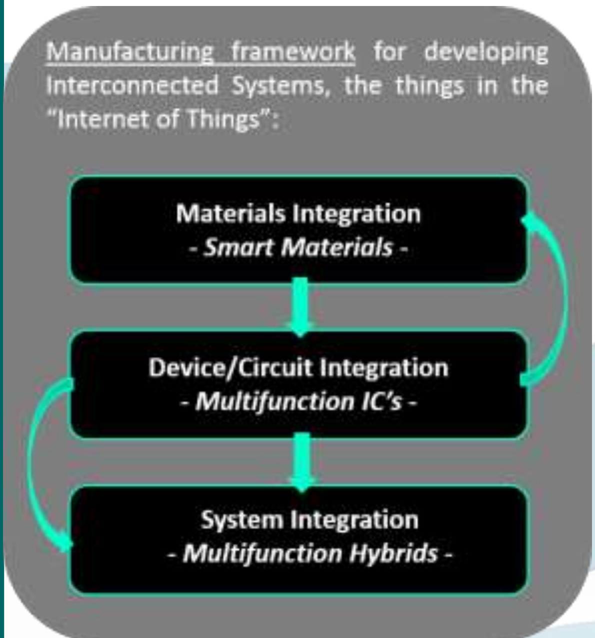


Diagram shows the manufacturing framework for developing Interconnected Systems, the things in the "Internet of Things".

The key enabling manufacturing technologies for meeting this challenge are:

1. the epitaxial growth of CS materials on Si substrates

2. using Foundry like CS process flows to provide the device/circuit integration platform.

Together these solutions, as shown conceptually in the diagram below, must allow for the integration of optoelectronic, power electronic, wireless communications and information processing IC's. Here we will focus on the CS communication elements both optoelectronic and high frequency electronic devices and their integration. It is envisaged that the Si substrate and process flows will also be able to support the integration of other devices/circuit structures being developed under othert EPSRC funded projects.

Aim: We will develop high yield manufacturing of CS on Si technology concepts with a view to integration on a common manufacturing platform and for qualification with partners:

1. GaAs based datacommunications wavelength quantum dot lasers on Si

2. GaAs millimetre-wave frequency multipliers on Si for wireless

3. GaN and GaAsP high speed LEDs on Si for Li-Fi

4. GaN high frequency HEMTs devices on Si

CS Hub PDRA, Dr Zhibo Li, works in the clean room facilities.

Grand Challenge 2

Sensing

We will solve the manufacturing issues in producing integrated sensor arrays and control electronics at scale (including large area substrates) and demonstrate this via 2 different application areas. These have different device technology and are at different stages of maturity, so lessons learnt from the more mature can benefit the other. This GC also underpins the EPSRC *Connected* and *Resilient Nation* priorities by addressing the need for low power, low cost, high sensitivity ubiquitous sensing and imaging.

Semiconductor sensors (electronic, magnetic and optical) are indispensable components in the future Internet of Things (IoT), robotics, industrial non-destructive testing (NDT) of materials and high resolution spectroscopy and imaging. NDT underpins engineering and associated downstream industries in complex in-situ, in-service monitoring (Oil & Gas, Aerospace, Pipe and Rail manufacturing and use and Nuclear Generation), with consequent scientific, commercial and societal benefits. CS will radically improve sensitivity, allow real time data analysis and facilitate disruptive new approaches using e.g. sensor arrays. They will allow inspection in hazardous and remote applications such as deep water oil exploration and in the nuclear industry. According to MarketsandMarkets, the NDT testing equipment market was worth \$3.77bn in 2014 and predicted to reach \$6.88bn by 2020 (growth of 9% pa). Strikingly, the biggest challenge facing this industry is the lack of qualified technicians to understand and use NDT systems. To offset this the introduction of lightweight, low power use, cost effective and above all ease of use (measurement and interpretation) are key features that our partners require to integrate into their instruments.

This vision will be delivered using new modalities in CS devices and circuits for applications where the superior properties of CS (high speed operation, high sensitivity, radiation hardness, infra-red imaging and high temperature operation) are immediately critical.

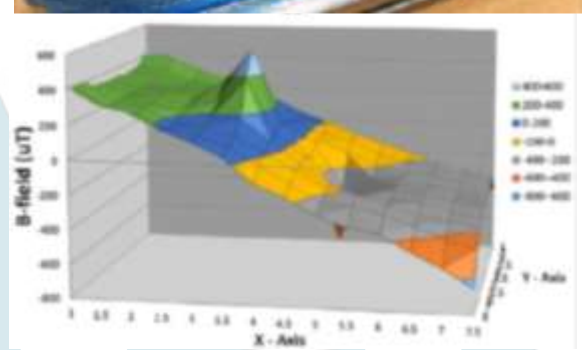
The low cost manufacturing of these sensors will rely both on the use of large GaAs substrates (to 150mm), for lower cost processing, and the medium scale integration of the sensors needed for deployments in a number of harsh environments but also with hybrid or grown directly on Si substrates where operational conditions are more benign. We have already produced all GaAs analogue quantum well Hall Effect (QWHE) circuits for magnetic sensing with superior sensitivity, bandwidth and operating temperature as shown in the figure below, which now require full integration.

Aim: We will develop 1) magnetic arrays and 2) infra-red sensor arrays for separate applications but with common manufacturing issues of:

1a) GaAs QWHE integrated circuits for Metrology;

1b) Metamorphic-GaAs High resolution 3D magnetic sensing and imaging; 2) Infra-red detector arrays

Two dimensional arrays of QWHE **magnetic sensors** with detectivity (≤ 1nT), size (< 10µm) and frequency response down to DC will provide a step change in the capabilities of eddy current inspection and new real time capabilities in inspection and metrology. We will demonstrate prototype magnetic sensors (both linear and 2D) based on advanced QWHE sensor arrays for precision metrology and to analyse 2D microstructures; the proposed techniques include multi-frequency interrogation combined with the unprecedented sensitivity and dynamic range together with signal and data processing and modelling.



Sensing continued

InAs/GaSb IR sensor arrays will form a disruptive technology, far exceeding the performance of bolometers and the current state of the art Mercury Cadmium Telluride (MCT) and GaAs/GaAlAs QWIP (Quantum Well Infrared Photodetector) technologies that are severely limited by uniformity problems and poor quantum efficiency (~10%) respectively. InAs/GaSb Type II Strained Layer Superlattice (SLS) will be pursued as the superior candidate for the next generation of high performance infrared imaging systems (high operating temperature, multispectrality, large focal plane array and, far infrared domain operation). We will transfer recent progress of Sb-based SLS on 3'' GaSb to the challenging and more technologically useful GaAs substrates so that it will be feasible to produce high quality large-format Focal Plane Arrays (FPA). 150mm diameter GaAs wafers could potentially accommodate 16 megapixel imagers. We will demonstrate prototype focal plane arrays based on high performance SLS sensors with low dark current (<10^{-4} A/cm^2 with λ ~12 µm) and high quantum efficiency (~70%) grown on GaAs substrate.

We have put together an entire supply chain for prototyping from wafer growth, with scale up to 150mm wafers, low cost optical lithography processing, device and circuit packaging and system integration with our industrial partners. The established yield and uniformity targets, the associated Foundry Design Rule Manual and the development of the necessary process monitors along with the associated detailed electrical/optical characterization concepts will feed into and depend upon the platform processes.

Magnetic Sensors: To deliver true 2D image capture and 3D image reconstruction the key challenges are:

1. Development of ultra-high sensitivity lattice matched and metamorphic QWHE sensors (including InAs and InGaAs on GaAs) with low 1/f noise, high S/N ratios and temperature stability over large spans (from -1000C to > 2000C), all configured into pixel grid structures.
2. Integrated Sensor array configurations with sufficient sensitivity to detect small variations in induced transverse magnetic fields with increased lift off distances.
3. Integration of sensors and drive electronics on the same die to allow operations at high temperatures (2000C) and in harsh environments (e.g. deep see drilling or nuclear power plants)
4. Translation of all devices and circuits to 150mm (from 100mm) growth and processing.

We will work cooperatively with our industry partners to establish effective configurations for the magnetic sensor geometry, illuminating magnetic field or current, excitation frequency and signal processing for specific targets and determination of effective measurement strategies. While the primary goal is a field imaging camera with high frequency field illuminator for 3D imaging there is also substantial spin-off value to our partners in metrology and ultra-high resolution field mapping where volume reductions and cost advantages of semiconductors apply.

IR Sensors: The key challenges that will be addressed are:

1. Growth of InAs / GaSb based Type II strained layer superlattice SLS on GaAs substrate;
2. Development of Long Wave IR -SLS single pixels with low dark current and specific detectivity;
3. Dual wavelength detector arrays with high operability (fraction of good pixels) and high uniformity;
4.Transfer of the growth and the device processing to larger GaAs wafers (100mm and 150mm);

We will iterate detector array design and the integration into a hybrid FPA as the first stage. Working with our partners we will establish the fundamental limitations of both magnetic and optical technology, i.e. spatial and contrast resolution, image capture and processing rates.

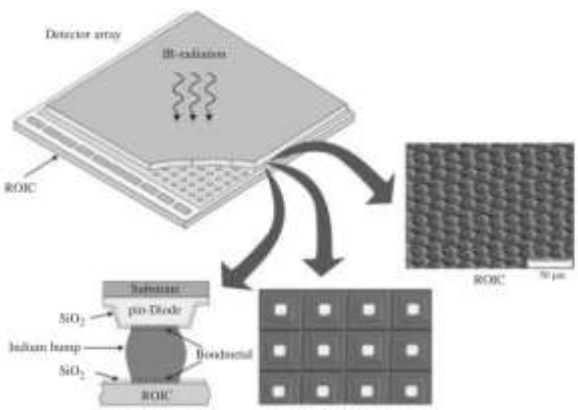


Image shows a schema of processed SL-FPA, flip-chip bonded to a silicon readout integrated circuit using indium solder bump technology.

Work Package 1

Growth

Summary

The main scientific challenges for epitaxial growth involve the formation of high quality compound semiconductor on silicon, including the development of semipolar GaN on Si, and the growth of mismatched InAs / GaSb on GaAs.

Details

Activity involves combining approaches to minimise defect production at the Si to CS interface, the use of nanopillars, and subsequent growth coalescence, and the use of defect filter layers to reduce the number of defects reaching the active region. We are examining the relative benefits of quantum dots for carrier localisation and nanopillar active regions, to exclude defects, as mechanisms to cope with those defects that do reach the active region. We envisage our final approach to integrate different CS on the same substrate will be to fabricate deep trenches in SOI (Si on Insulator), grow a Si buffer to bury contaminants and smooth the surface, and then selectively grow CS materials on the smooth Si in the trenches. Initially we are growing CS on Si over the full wafer for simplicity but does incur some issues with differential thermal expansion.

III-Sb (CF, UCL): Growth of III-Sb is a particular expertise of Prof Huffaker. Challenges include the development of very high uniformity InSb and the development and transfer of InAs / GaSb based Type II strained layer superlattice to growth on GaAs substrates for Grand Challenge 2.

III-As (UCL, CF): The focus will be on developing uniformity and reproducibility, including between multiple areas of selective growth over large substrates, and approaches for defect minimisation shown to work with other materials, such as nanowires for long wavelength (red) emitters for GC1.

III-N (Sheffield, CF): To overcome problems with polar (c-plane) GaN, including long radiative recombination lifetime (10 ns) that limits modulation bandwidth in communications and leads to poor efficiency especially at longer wavelengths, we will use semi- or non -polar GaN. We will develop semi-polar (11-22) GaN, which can accommodate more indium atoms than both polar and non-polar GaN, for longer wavelength emission and facilitate "normally off" devices for RF switching power amplifiers and power convertors. Work will begin on Sapphire substrates and then transfer to Si.

Progress

GaN based optoelectronic materials

Sheffield University – Tao Wang

Despite significant challenges with the MOCVD system, we were able to overcome and make good progress on the growth of semi-polar GaN on Sapphire.

Progress is also being made on growth on (311) Si substrates.

III-As based photonic integration technology

University College London – Huiyun Liu, Qiang Wu

A productive growth campaign has been undertaken with the growth of Q-dot samples with SOA performance completed and samples fabricated and characterised in Cardiff. CEA-Leti have come on board as a collaborator, to work with WP1 for MOCVD template growth.

Cardiff has renovated a dedicated small cleanroom for the installation of a new MOCVD reactor, which is currently being qualified for growth of III-As on Silicon templates.

III-Sb for IR arrays, RF electronics and optical Datacom

Cardiff University – Qiang Li and Diana Huffaker

Cardiff has installed a new MBE reactor for the MBE growth of Sb based materials. These are currently being qualified. In the meantime InAs /GaSb growth development is going on with an external partner.

CS Hub PDRA, Dr Zhibo Li, works in CS Hub clean room facilities.

Work Package 2

Device Fabrication

Summary

Here the emphasis is on developing fabrication processes on up to 200mm wafers, where possible, compatible across the different materials and devices.

Details

Work is underway developing ohmic contacts, gate contacts, via holes, wafer thinning, interconnects, transmission lines and dielectric layers. We aim deliver a suite of fully characterised MIM capacitance structures and Cr-Ni meander resistances to enable the realisation of useful on chip circuits (e.g. MMICs), initially on 150mm before moving to 200mm wafers. The challenge is the need to address optical and electronic devices structures and all the associated passive components using a standard set of well qualified processes.

Ultimately a mixed strategy lithography (wafer scale optical (stepper) and large frame electron beam lithography) will be developed with critical dimension analysis over a large area.

Processing challenges in the GaAs system include the development of multilevel functionality. Here recent work has demonstrated on-chip integrated optoelectronics and capillary fill microfluidics on 2 levels, using standard CS fabrication procedures. The on-chip multilevel functionality must be extended to include control electronics and developed to full wafer size.

A key generic challenge for III-V on Si fabrication is handling thermal stress cycles during growth and processing. These can be beneficial but also can be harmful and determining acceptable parameter space will be an important outcome of this project. Work involves iterative cycles of epitaxial growth and fabrication, hence the need for a strong coupling between WP 1 and WP 2 and WP3 and the use of native as well as Si substrates

Progress

GaN RF devices are being used as a vehicle to develop generic procedures for process flow and robust sample fabrication.

Standard GaN Ohmic process have been implemented with reasonable statistical data to establish process design rules (3 sigma). These are currently wide, and whilst FET development continues using this standard process, it is recommended that process optimisation is now performed for key parameters such as anneal temperature. Cross referencing measurements, both between samples and process, with collaborators is underway.

Progress is steady, mostly due to the speed of data collection, and disruption to infrastructure whilst services are adapted for new equipment.

High level planned outcomes include the development of design rules for GaN MMICs and development of robust process flows for other technologies.

The primary current goal is authoring/production of the first set of basic GaN MMIC design rules. To this end, contacting has been developed, with a small amount of work on gate development.

A new probe card system has been designed to enable greater throughput of sample characterisation.

Peter Smowton and Khalid Eglaid, visit to Newport Wafer Fabrication Facility, 26th January, 2017.

Work Package 3

Characterisation

Summary

The main scientific challenges include the scaling up of characterisation approaches including developing on-wafer testing and the development of fast fab approaches to minimise the growth, fabrication, characterisation development cycle time.

Details

In much research, and even in much of the CS industry, growth and fabrication are separately optimised leading to non-optimum devices and systems. We will optimise the combined process using multiple growth and fabrication runs.

The scale up of on-wafer testing involves developing automated approaches for large area wafer mapping including the development of specific test structures to qualify e.g. material or topological structure over the wafer with respect to a particular application device or structure. We will be examining a range of devices of interest to our industrial partners and have started with VCSELs.

Fast fab is the process of using structures that are representative of the fully fabricated device performance but based on a much quicker, cut down fabrication process. They therefore allow rapid feedback to growth and fabrication eliminating complex fabrication and test procedures yet allowing clear insight into the limiting issues. We will seek generic approaches to widen application and disseminate to the broader research and production community. We will develop protocols for such processes across a range of device types in both a research and an industrial scale foundry. This will also shorten the time for taking basic research to impact.

Another major strand is studying degradation, with the need to develop an understanding of reliability issues and degradation processes and the role of the growth and fabrication sequences. In addition, we will establish and control yield and uniformity targets, both within wafers, from wafer to wafer and from batch to batch across different wafer platforms (from 100mm to 200mm). This is part of developing a viable manufacturing platform and the associated Foundry Design Rules and also includes process monitors and the associated fast fab. characterization concepts, systems and supporting models.

Progress

Procurement of RF testing equipment and reliability apparatus is complete and systems are now being qualified.

Quick fab / characterisation process for VCSELs is on track with automated alignment stages and linewidth measurement apparatus purchased and incorporated into characterisation

We are making substantial progress in the design of generic photonic structures following training / familiarisation of team members with software.

We have assessed both Lumerical and Photon Design software for our purposes.

Samples from UCL grown on GaAs have been fabricated and tested.

Samples from UCL grown on Silicon have been fabricated and results indicate lasing performance achieved.

Going forward we have put in place additional equipment in order to better match characterisation support to growth run frequency.

CS Hub post-doctoral research associate, Dr Sam Shutts, works in CS Hub clean room facilities.

Work Package 4

Manufacturing Technology for Optical Data Communications on Silicon

Summary

Very recently, high-performance silicon-based InAs/GaAs QD lasers have been demonstrated with CW operation at high temperature (>75 °C) and long lifetimes (>100,000 hours). Here we will develop our world leading III-V-on-Si technology to create high performance lasers and semiconductor optical amplifiers (SOAs) for datacommunications applications.

Details

The principal objectives are to optimise gain per unit length (for high frequency) and to increase operation temperature to the required 125 °C maximum, while maintaining low current CW operation at 20mW optical output power. This will be achieved by exploiting p-type modulation doping in lasers and optimizing/combining nucleation layer, dislocation filter layer as well as thermal annealing create offset band-edge waveguides while using strained layers to minimise wafer bow on cool down from growth. We will investigate Sb containing materials for longer telecommunications wavelengths.

Progress

We demonstrated for the first time, an electrically pumped, room temperature, continuous-wave and single-mode distributed feedback (DFB) laser array fabricated in InAs/GaAs quantum-dot gain material epitaxially grown on silicon with a record wavelength coverage range of 100 nm. These results will appear on Optica soon.

EU project – "High Performance and High Yield Hybrid III-V/Si Photonic Integrated Circuits using thin and controllable bonding layers (PICTURE)" was kicked off in January 2018. In this project, UCL is leading the Work Package 3 for develop III-V DFB lasers on silicon platform. In this project, III-V Lab, Cea Leti, IMEC, and Nokia Bell Labs are among the partners in this consortium.

To increase the temperature performance of QD laser on Si, p-type modulation doping into active region would increase the radiative recombination ratio at high temperature. InAs/GaAs QD lasers with different doping density have been examined regarding the density 0, 5, 10, 15, 20 hole/dot. The sample with 10 hole/dot presents the strongest photoluminescence intensity at room temperature.

P-type modulation doped InAs/GaAs QD lasers on GaAs substrates have been grown with different doping density at UCL, and the fabrication and characterisation on these samples are ongoing at Cardiff University. A series of studies of 1.3-µm InAs/GaAs QD laser grown on exact Si (100) substrates have been grown at UCL after optimising quantum dot and DFL growth condition. We are waiting for the results on these silicon-based laser devices.

CS Hub PDRA, Dr Craig Allford, works in the clean room facilities, at Cardiff University.

Work Package 5

Advanced Radio Frequency Devices & MMICs

Summary

Building-on on-going success, in demonstrating a UK III-V-on-Si GaN based HFET technology baseline, this work package aims to ultimately establish a full III-V-on-Si HFET device and MMIC technology platform for high/medium power microwave wave system applications. We will use high-frequency device performance at staged points to allow feedback for optimisation of the epitaxial growth and device technology and encourage industrial engagement.

Details

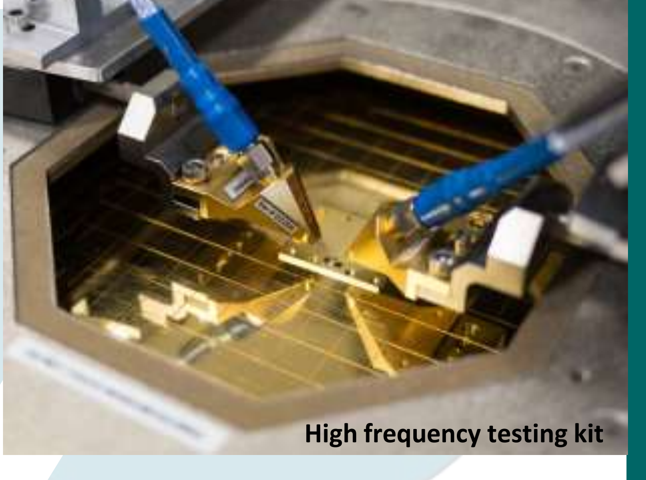
Typical GaN HFETs for these applications are grown on a SiC substrate, which are unfortunately limited in size (<150mm) and are very expensive. An alternative solution would be to use Si substrates, since these can be very large (>300mm) and cheap. To date the RF performance of GaN HFETs on Si is not comparable with those on SiC. There is a larger lattice mismatch when using Si and it also has poorer thermal conductivity. In addition, the conductivity of Si substrates is not compatible with the realization of low loss MMIC passive matching structure

Irrespective of substrate for high speed/frequency electronic devices and circuits there is the need for short gate lengths (L_g < 0.5um) and small source/drain gap (<4µm) to increase intrinsic transistor performance; hence e-beam lithography-based technology. To ensure a corresponding increase in the extrinsic performance requires the appropriate scaling of device parasites and dimensions. For example, a high gate to channel aspect ratio must be maintained. This requires optimization of the epitaxial layer structure and growth. Device layout optimization to minimize capacitive and inductive loading will be undertaking using EM-modelling supported by RF characterization. Minimization of access resistances requires very low contact resistance, processes such as epitaxial re-growth are being consider. A staged approached transitioning from unit-cell RF HFET devices, thru RF HFET power-bars and passive components, to a full HFET MMIC process is envisaged. At each stage an appropriate Process Development Kit (PDK) will be developed and supplied to partners for evaluation and feedback. This will start with 100mm Si substrates and move to 200mm Si substrates.

Progress

Initial activity at Cardiff has focused on defining and acquiring the necessary tool-set for both optical and e-beam fabrication of HFET devices. Primary issues have been related to ensuring that appropriate academic and technical staff are in place and getting equipment installed and operational in the presently available cleanroom at Cardiff. These tasks are now nearing completion and so, following discussions, a master plan involving the coordination of all RF processing projects, under the leadership of Dr Khaled Elgaid, has been proposed with the objective of ensuring that deliverables associated with the development of unit-cell RF devices and RF power-bars can be achieved. However, the MMICs deliverable, at the full wafer scale, will be more of a challenge since to address the Si substrate loss problem alternative passive structures to those previously on SiC or GaAs will need to be developed. Hybrid solutions, utilizing also the Manchester Gas MMIC process are therefor also being considered. Cardiff and Manchester will work together to investigate this hybrid alternative.

Characterisation capability within the High Frequency Characterization Centre at Cardiff University has been upgraded to allow for on-wafer electrical/electrical measurements up to 130GHz and optical/electrical or optical/optical to 67GHz. This addition will insure full device characterization at small signal, high power nonlinear and optical/electrical behaviour.



High frequency testing kit

Work Package 6

Monolithic Integration of RGB LEDs & Integrated RF Electronics for LiFi

Summary

Building on the work in the platform our approach is to use nitrides where they can be efficient and fast enough by using semi-polar or non-polar for green and yellow combined with other CS for longer wavelengths. We will use multiple selective area growth steps to integrate CS/Si structures with several different epitaxy designs on the same substrate.

Details

III-nitride semiconductors have direct bandgaps across their entire composition range, covering the complete visible spectrum and a major part of the ultraviolet (UV).

The large range of bandgap also facilitates high power and RF electronics. The last two decades have seen dramatic advances in the development of III-nitrides (specifically for polar c-plane growth), whose emergence is significantly changing many aspects of our lives, through for example, its application in efficient white light sources and high efficiency cellular radio base station power amplifiers.

However, the main achievements are limited to device types and/or bandgaps where the polar nature of the material has limited effect.

Polar GaN intrinsically poses a number of fundamental issues. The polar orientation generates the quantum confined Stark effect (QCSE) due to the polarisation induced piezoelectric fields, leading to long recombination lifetime and low quantum efficiency. The long lifetime due to polar GaN (typically 10s ns) also limits application in RF applications and in LiFi (simultaneous illumination and visible light communication) due to the limited bandwidth (typically MHz).

These factors become a severe issue for longer wavelength green emitters and still longer wavelengths e.g. yellow are precluded by the challenge of incorporating a large Indium fraction into polar InGaN. Polar nitrides are prone to efficiency droop affecting today's InGaN LEDs, which is a significant reduction in quantum efficiency with increasing current. At the currents required for practical applications the QE falls by up to 50% from its peak. This is again more severe for green and yellow emitters.

Building on the work in the platform our approach is to use nitrides where they can be efficient and fast enough by using semi-polar or non-polar for green and yellow combined with other CS for longer wavelengths. We will use multiple selective area growth steps to integrate CS/Si structures with several different epitaxy designs on the same substrate.

In completing this high level integration, we will consider if all CS on Si devices need to be comparable with their CS alternatives in terms of performance in order to provide an integrated performance advantage and select the best route for overall performance.

Progress

A comprehensive simulation/design of three colours (430 nm, 520 nm and 584nm) white LEDs on semi-polar (11-22) GaN and c-plane GaN have been made, highlighting that semi-polar LEDs exhibit significant enhancement in electron-hole wavefunction overlap under a forward bias (i.e., electro-luminescence) compared with their c-plane counterpart. Our simulation also indicates that the residual polarisation field of semi-polar LEDs is along the same direction as the built-in field, leading to a challenge in forming a good uniformity in hole distribution across MQWs. This situation is different from that in c-plane LED. A proper design can be eliminate this issue. Based on the above simulation, an optimised LEDs with three colours on semi-polar GaN have been grown. The device fabrication is ongoing. A major breakthrough has been made in terms of eliminating Ga melt-back issue. This approach can be extended to the overgrowth of (11-22) semi-polar GaN, (20-21) semi-polar GaN and (11-20) nonpolar GaN on patterned silicon. The growth of (20-21) semi-polar GaN on (114) patterned silicon; (11-20) non-polar on patterned (110) silicon; HEMTs structure on non-polar GaN on sapphire have all begun. UCL will shortly start the growth of GaAs on (113) silicon by MBE.

Growth of GaN on patterned (113) Si

Work Package 7

Magnetic Arrays

Summary

The approach is to integrate high electron mobility 2DEG with the epitaxial layer structures for all of the analogue and some of the digital electronics.

Details

The 2DEG mobility target is at least 16,000 and up to 18,000 cm2/Vs at room temperature while coupled with high gain transistors for the in-built drive electronics. Epitaxial growth will start on 100mm wafers (year 1), will move to 150mm (year 3 onwards).

The Hall Magnetic Integrated Circuits (MIC) will be designed to address two options that are inaccessible to silicon, namely high and low gain circuits for very high sensitivities (nanoTesla detection) and high temperature operation (200 °C). The MIC chip fabrication process will focus on high yielding optical lithography, integrated 2µm gate length transistor technology with capabilities in the 10s of GHz, (traditional technology is limited to a few kHz). We aim for Process Development Kits (PDK) for the fabricated circuits on 150mm wafers. Engineering samples (few 100 to 1000s) will permit ample testing to establish statistical variation.

Magnetic testing will use in-house low and high field magnetic set ups to measure all key characteristics of the fully packaged sensors. This will be vital in the initial trials to align parasitic from the packages into the PDK models. Key deliverables from these tests will include sensitivity and linearity, the most critical parameters of the sensors. We will aim for video rate collection using "camera" arrays instead of the current processes, which are entirely manual and highly operator intensive.

Progress

- GaAs-InGaAs-AlGaAs epitaxy on 4" wafers
- Variable size Hall sensors simulated, designed and measured.
- Mask commissioned and delivered
- First and second iteration sensors fabricated (including first arrays)

Progress is on track, all basic discrete elements simulated and designed and now first fabrication is underway.

All planned activities achieved have been achieved as per original deliverable plan.

Links have been established with TWI, Microsemi, Renishaw and University of Swansea for specific R&D InnovateUK funded projects exploiting and further developing linear arrays and the Magnetic Integrated Circuits. Two Innovate UK grants were awarded, begining on 1st of September 2017 (CSMAGIC (14 months) and QBARKA (18 months)).

- All discrete elements designed and fabricated
- All testing completed but still further ongoing (noise, sensitivity, etc..)
- Equivalent circuits extraction performed for first iteration and in progress for new fabrication runs.
- Design of basic building blocks in second iteration (current sources and amplifiers) all completed and first IC mask commissioned.

CS Hub PDRAs, Dr Sam Shutts and Dr Emmanuel Le Boulbar, work in CS Hub clean room facilities.

Work Package 8

Infra Red Arrays

Summary

The IR sensing epitaxial structures will consist of LWIR-SLS detectors grown on GaAs. WP challenges will be achieving high material quality with high uniformity, and the growth challenges associated with this. Growth conditions will be optimized, and high performance detectors will be designed before model characterisation.

Details

The IR sensing epitaxial structures will consist of LWIR-SLS detectors grown on GaAs. Achieving high material quality (high photoluminescence intensity, low surface roughness) with high uniformity is a growth challenge due to the ~7.8% lattice mismatch between GaSb and GaAs. The growth conditions (growth temperature, As and Sb flux, and shutter sequence) will be optimized, moving from 100 mm wafer to 150 mm.

High performance LWIR-SLS detectors will be designed using accurate simulation tools, based on the k.p model with the Envelope Function Approximation (EFA) for SLS material properties and on Technology Computer Aided Design software for device design. The model developed will be qualified against measured performance.

Fabrication of photodiode arrays, from the epitaxial SLS layers, will use Inductively Coupled Plasma (ICP) deep etching for isotropic profiles. It will first be optimized on single-pixel photodiode and then extended to detector arrays. The required passivation – such as SiO_2 or Si_3N_4 – to reduce/suppress surface leakage currents will have to be compatible with subsequent processing and integration up to the camera level.

Electrical and electro-optical characterizations will be performed on small areas before hybridization. The system will consist of a hybrid infrared FPA interconnecting a detector array and readout integrated circuit (ROIC) using indium bump bonding for the hybrid packaging. This will be mounted on a ceramic leadless chip carrier, wire-bounded and loaded in a cryostat for optical testing to evaluate dark current, quantum efficiency and uniformity.

Progress

• Training of a PhD student (started October 2017);

• Lattice matched SL (mid-IR and long-IR) on GaSb substrate with good material quality – one mid-IR device structure to be processed into single-pixel detectors in Cardiff cleanroom, and performances to be characterized.

• TCAD software has been installed;

Single Pixel Detectors

Growth of T2SL on GaAs substrate & Growth conditions optimization:

In total 6 test samples have been grown on GaSb substrate– they cover wavelength from the mid-IR to the long-IR. XRD and AFM measurements on these samples have been performed during this review period. The long-IR structures have been improved for optical characterization since last time no PL signal was observed, i.e. with a thicker SL region that is sandwiched by AlSb barriers.

Growth of T2SL device structure:

One p-i-n photodiode on GaSb substrate with a wavelength in the mid-IR spectral domain has been grown and is to be processed.

Single-pixel fabrication - Fabrication development:

Further dry etch test by ICP have been done. In particular, the influence of the RF power has been investigated.

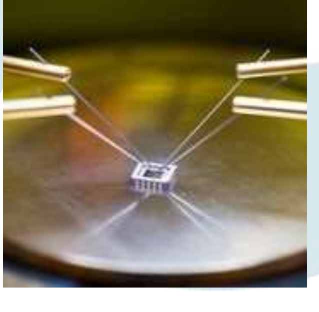
Growth of T2SL on GaAs substrate - Single-pixel fabrication - Device characterization:

Minor delays have occurred due to maintenance on the MBE reactor at UCLA and in running the MBE at Cardiff. Additional time has been dedicated for the development of single-pixel detectors as the transfer on GaAs substrate has to be developed. Cleanroom facilities have been slightly disrupted due to new equipment delivery in Cardiff.

Qualified model

KP modelling - TCAD modelling:

The delivery plan has been adjusted slightly to fit in with the minor delays in single pixel detector delivery. Work will begin in January 2019 on Dual Colour Arrays, Array characterization, IR arrays, and System testing.



Laboratory work undertaken as part of work package 8, CS Hub labs.

Additional Expertise

CS Hub expertise

The CS Hub investigators and associated groups have been carefully selected for their track record in innovation and impact, complementary technical capability and the individual skill sets that can combine to create new solutions to the identified major scientific challenges in manufacturing.

Expertise in epitaxial growth, including growth on non-native substrates is provided by Huffaker, Li, Liu, Missous, Wallis, Wang and Wu. Buckle, Elgaid and Missous bring experience of wafer scale-up and manufacturing uniformity over these larger wafer sizes. Abadia, Beggs, Quaglia, Smowton and Tasker bring world leading expertise in design, integration and characterisation.

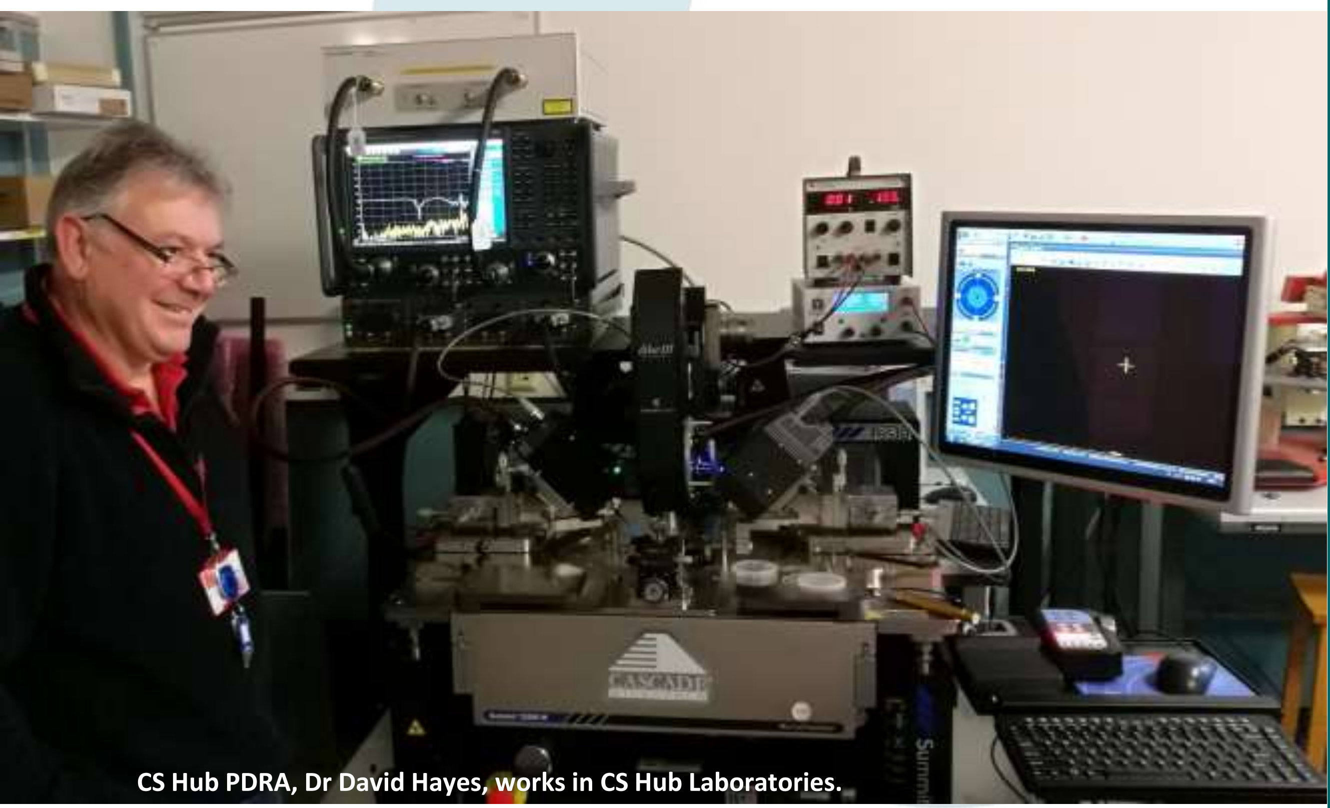
In addition to the Hub's Work Package Leads, we work with a number of world-leading academics to develop the highest impact research possible under the remit of the Hub.

Diana Huffaker (Cardiff University) (h-index 47) is the Welsh Government Ser Cymru Chair in Advanced Materials and Engineering and is a Director of ICS. She has made major contributions in compound semiconductor material and devices and, of particular relevance, in the growth of Compound Semiconductors on mismatched substrates including Silicon. Her current research interests include the directed and self-assembled nanostructure solid state epitaxy and optoelectronic devices including infrared detector arrays, solar cells and III-V/ Si photonics.

Michael Pepper FRS, FREng (UCL) (h-index 55, 8 patents) is Pender Professor of Nanoelectronics and has received the Royal Society's Bakerian Prize Lectureship, Hughes and Royal Medals. He is co-founder and Scientific Director of THz technology spin-off company TeraView. He is a former member of General Board and Council of Cambridge University and Council for Industry and Higher Education.

Alwyn Seeds FREng, FIEEE (UCL) is Professor of Optoelectronics. He pioneered the research area of microwave photonics and was awarded the Gabor Medal and Prize of the Institute of Physics in 2012. He is an inventor on 16 patents and is co-founder of Zinwave Ltd, which is now the third largest supplier of wireless over fibre systems in the world and was acquired by McWane Technologies Inc. in 2014.

These staff are supported by academics Rick Smith & EPSRC Manufacturing Fellow Jon Willmott (Sheffield), Max Migliorato (Manchester), Mokkapati (Cardiff) and Senior Research Fellows Siming Chen (UCL), Marie Delmas and Sang Soon Oh (Cardiff) covering design, nitride fabrication, and characterisation and growth of CS on Si.



CS Hub PDRA, Dr David Hayes, works in CS Hub Laboratories.

Project Governance

CS Hub Internal Structures & Regulation

Summary Statement

Our Hub of CS research activity and operational headquarters is located at Cardiff University, led by CS Hub Director, Prof. Peter Smowton. This central entity interacts highly with three spoke universities: University of Manchester, University of Sheffield and University College London, as well as a large number of industrial partners and collaborators.

The CS Hub structure includes a **Management Board** and **Strategic Advisory Board** as well as support structures for each of **eight work packages** and **two grand challenges**.

Management Board

The Management Board reports to the CS Hub Director and is comprised of a number of senior Hub members who are able to represent fully the research interests of the Hub, and are vital for driving this research Hub forward. All members of the Board meet every three months in a minuted meeting. Meeting documents are stored at the Hub's Wiki pages for all members to access. The Director and Board members are given the opportunity to contribute to agenda items in advance of meetings, and meetings are scheduled at the most convenient time to allow all Board members to attend and contribute. Every Management Board meeting provides an opportunity to discuss project progress at a high level and includes updates on progress from each of the eight Hub Work Package leads (either in person of via a nominee on the Board), from the Hub Director, Manager, and Industrial Engagement Director. These quarterly meetings take place during a half day period and are scheduled to rotate around the four academic partners. When possible, meetings are coordinated with other Hub activities, such as the biannual Strategic Advisory Board meeting, to enable optimal attendance, and value for money.

Strategic Advisory Board

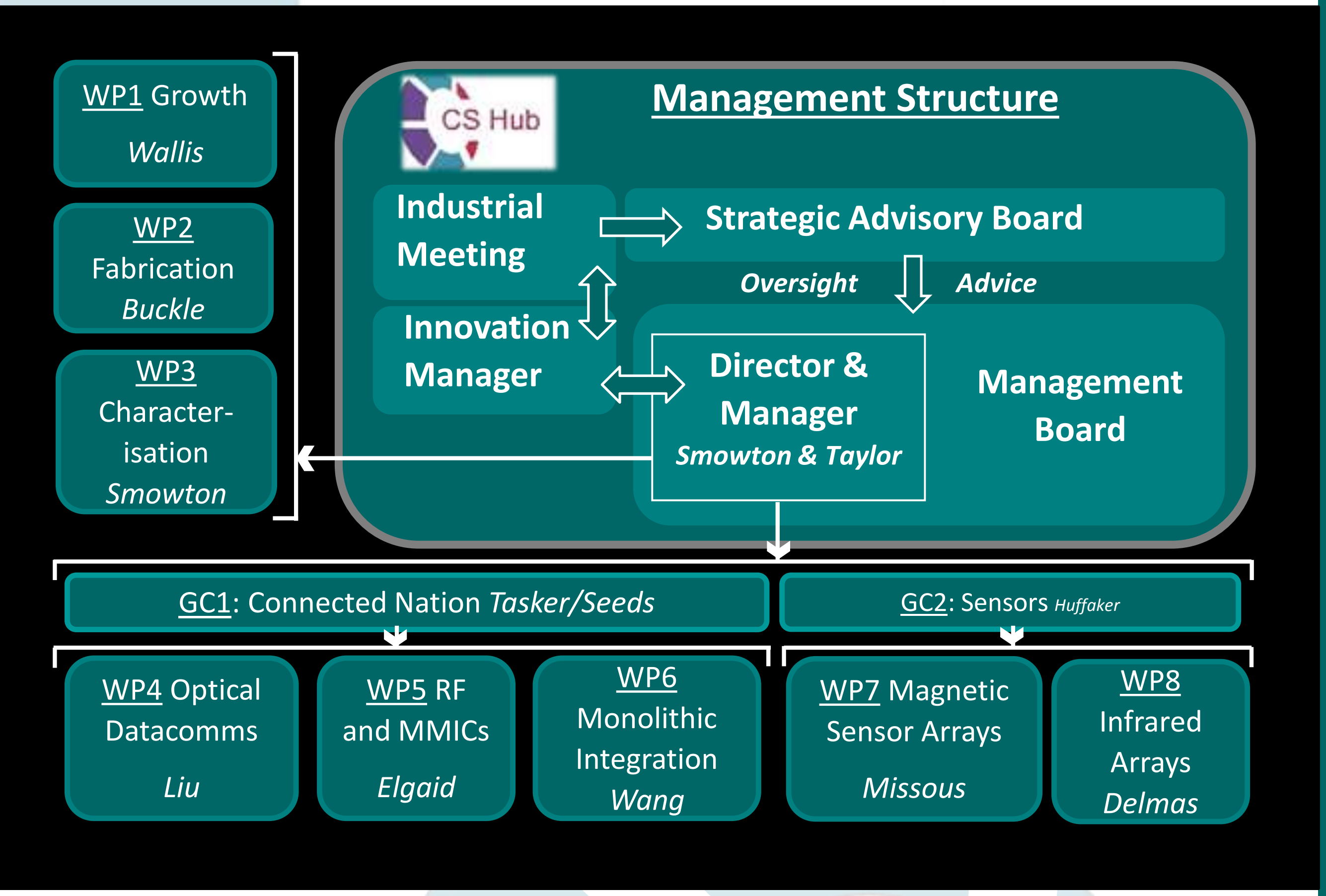
The Strategic Advisory Board provide guidance to the CS Hub Director, the Management Board, the Work Package leads and Hub Management via a biannual meeting held at Cardiff University. All members of the Hub and an EPSRC representative are invited to these important meetings. The meeting is designed to have multi-level appeal, with parallel sessions for different interest groups from the Director to PhD student level. The Board includes a number of world leading research and industry representatives in the field of compound semiconductors. Board members were selected and invited to join the Board on the basis of their vast experience in research and industry, and their significant and successful contribution to these areas. The purpose of the Board is to ensure relevance of the Hub's research to optimise translation and economic impact in changing academic and industrial environments.

Strategic Advisory Board meetings provide an opportunity for Hub members to receive guidance and direction from highly experienced and knowledgeable individuals who are impartial regarding any interest in the Hub. These biannual meetings are run over two days and include agenda and minutes as required. Day one consists of a research overview from the Hub, a closed Strategic Advisory Board session with guidance on relevant and essential discussion topics from the Hub Director, and an open meeting for further discussion and feedback. Day two includes a Management Board meeting with feedback both to and from the Strategic Advisory Board, an opportunity for Hub researchers to present scientific data in the form of a poster display, a tour of any newly acquired or relevant facilities, and a training session for all Hub members. In order to deliver value in terms of delegate time and money spent, meetings are coordinated to coincide with similar meetings of the Institute for Compound Semiconductors (ICS) Strategic Advisory Board. Some Board members are shared between the Hub and ICS.

Work Package Governance

Each of the eight research areas, divided into the CS Hub work packages, are led by an experienced researcher from one of the academic institutions involved in the Hub, is supported by fortnightly conference calls to discuss the research undertaken, any issues or delays, and to coordinate across work packages as necessary. Calls are chaired by the lead academic for the work package, notes are taken and made available on the Wikipedia page for the Hub.

The Hub Manager attends all work package conference calls and coordinates further meetings both between work packages and with other stakeholders as necessary.



Strategic Advisory Board Members

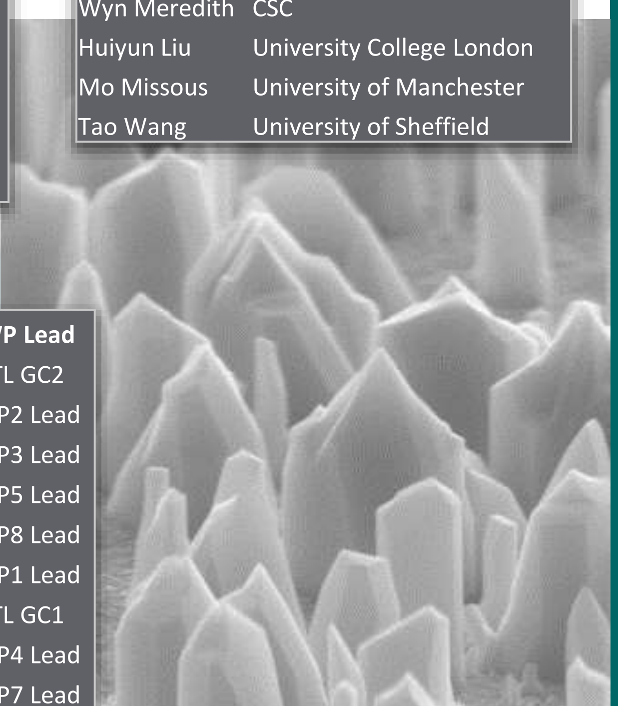
Name	Organisation
Richard Penty	Cambridge University
John Bagshaw	Independent Technology Consultant
Richard Bailey	EPSRC
Gerald Buller	Heriot-Watt University
Lars Samuelson	FTF / LTH
Dominique Schreurs	KU Leuven
Andy Sellers	CSA Catapult
Mike Wale	Oclaro

Management Board Members

Name	Organisation
Diana Huffaker	Cardiff University
Peter Smowton	Cardiff University
Paul Tasker	Cardiff University
Wyn Meredith	CSC
Huiyun Liu	University College London
Mo Missous	University of Manchester
Tao Wang	University of Sheffield

Work Package and Grand Challenge Leads

Name	Organisation	WP Lead
Diana Huffaker	Cardiff University	TL GC2
Philip Buckle	Cardiff University	WP2 Lead
Peter Smowton	Cardiff University	WP3 Lead
Khaled Elgaid	Cardiff University	WP5 Lead
Marie Delmas	Cardiff University	WP8 Lead
David Wallis	Cardiff University	WP1 Lead
Alwyn Seeds	University College London	TL GC1
Huiyun Liu	University College London	WP4 Lead
Mo Missous	University of Manchester	WP7 Lead
Tao Wang	University of Sheffield	WP6 Lead



Wang, WP1, Nanowires on Silicon

Impact

How will the CS Hub Affect the Future of Manufacturing Research

Societal

Compound Semiconductor materials are a Key Enabling Technology underpinning the operation of the Internet and enabling emerging megatrends such as Smart Phone usage, satellite communications/GPS, Direct Broadcast TV, energy efficient lighting, efficient solar power generation, advanced healthcare and ground breaking biotechnology. Simply put these technologies support our connected world and the future health of the planet.

Economic

Our vision is to ensure that the UK's research strength in compound semiconductors will be embedded in manufacturable approaches so the UK can commercially address the opportunities that compound semiconductors will provide. The global market for compound semiconductors is currently worth around $33.7Bn, with a compound annual growth rate of 17.3%, and underpins 100s of billions dollar related industries from telecom to automotive. Expanding commercial activity in the compound semiconductor sector will provide an important boost for the UK economy and maintain UK advanced manufacturing competiveness. A good example of this is Cardiff headquartered IQE Plc, the global leader in supplying compound semiconductor materials (—£155M turnover, 2017 results).

Our aim is to strengthen the relationship between academia and industry and this will be achieved by 1) changing the mind set of researchers to start from solutions that allow rapid translation to production by providing access to production scale and research tools that are functionally similar along with highly skilled support for the tools and processes; 2) Co-location of research and industry staff to maximise cross fertilisation of ideas, techniques and approach in an environment that supports interaction.

The EPSRC Manufacturing Hub funded translation / business developer together with staff from the Compound Semiconductor Centre will support SMEs through product prototyping, IP generation, skills development and training. They will help bid for external grants, coordinate partner forums, form networks and prepare roadmaps.

Skills Base

The cutting edge equipment operated as part of a manufacturing process offers an excellent training opportunity, inculcating a manufacturing mind set in a UK strategically relevant high technology field. We will embed technological excellence and the latest manufacturing approaches in UK industry. PDRAs and students will participate in high level meetings with the commercial organisations and will work alongside R&D staff from industry. There will also be a direct economic impact via the provision of skilled workers to relevant companies, a feature of our previous projects.

Outreach

The Hub funded outreach specialist will promote the reach and importance of compound semiconductors and the strategy and activity of the Hub in manufacturing. The specialist and the team will address audiences from school students to stakeholders to politicians. Resources are available from the Hub to train researchers and staff in media interactions and outreach using a range of innovative formats such as performance and theatre production skills.

Knowledge Dissemination

We are active in dissemination of knowledge via conferences such as UK Semiconductors and Photonics West, the latter providing an excellent mix of science and commercial activity. We will publish in open access peer reviewed journals such as those from both the Nature and IEEE stables.

Our aim throughout is to engage new partners and we will hold workshops, use feasibility funding, actively canvas and make use of our existing partners and contacts, relevant KTNs, the Welsh Optoelectronics Forum and other appropriate bodies to connect as widely as possible.

Dr Zhibo Li, works in CS Hub clean room facilities.

Translation

Industry / User / Innovation Chain Engagement

In 2014 the Sheffield led EPSRC III-V centre CS roadmap identified a concern that the UK CS community was missing an exploitation link to help provide a route to impact and exploitation. Many technological solutions work well in the research environment but fail to succeed commercially. The Hub directly addresses this issue, by working to change the academic community mind set, to inspire researchers, via training and environmental changes, so they begin with solutions that allow rapid translation. The hub is encouraging the Co-location of research and industry staff to maximise interactions. Our Grand Challenges are specifically designed to produce intermediate outputs that can be used to demonstrate the potential for successful translation. In order to promote this activity across the wider UK community the Hub has £1m to invest in new research projects. We have set out our first call for 8x initial short-term <£40k studies, with priority given to those applications including new Hub partners. Funded studies will have a high probability of translatable manufacturable research, and will be expected to cascade into subsequent larger studies with an emphasis on translating technology from research to industry. We recognise that SME engagement is a critical element in promoting rapid exploitation opportunities and interact with a number of these.

CS Connected: User interface, represents cluster members

TRL (+ / -)

Compound Semiconductor Applications Catapult

- Help industry in developing novel CS materials/topology/devices
- Develop systems for end-user applications

Compound Semiconductor Centre

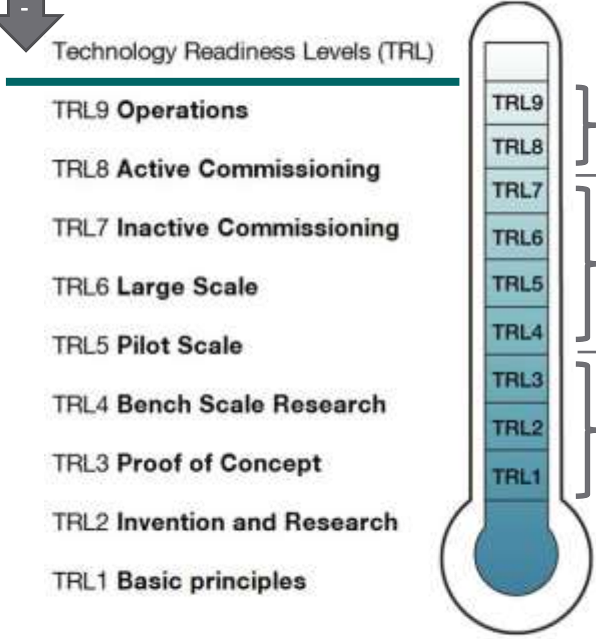
- Develop and prototype CS materials
- Enable a wide range of applications
- Transfer R&D to product & process innovation to high value large scale manufacturing.

Institute for Compound Semiconductors

- Facilities; Equipment; Services (skilled workers)
- Research
- Product development to prototyping
- Industrial collaboration

Future Compound Semiconductor Manufacturing Hub

- CS Manufacturing Research
- Enable high value & productivity in CS manufacturing
- Building on ICS research
- Training; Outreach



Commercial Market: Private

→ **Investor Ready**

Innovation: Public/Private Collaboration

→ **Innovation Ready**

Research & Invention: Mainly Public

Diagram (lower part) shows the TRL scale. The CS Cluster is committed to navigating the "valley of death" on this scale, enabling translation of research into industry solutions. Diagram (upper part) shows simplified potential application of TRL levels to CS Cluster components. Significant overlap between cluster members and TRL levels is essential for successful translation. Images show device development by a Hub PhD student, Cardiff University.

Key Performance Indicators

Annual and long-term targets to measure success

The CS Hub has a number of targets formed of measurable research outputs that are carefully designed to measure the success of the Hub in the context of the CS research environment. Many of these targets are only possible to achieve in the long-term, while others can demonstrate more immediate success for the Hub. Later in this report we will focus on those key performance indicators (KPIs) where we have made some progress in the short time since the Hub began. Meanwhile, the list below indicates the full complement of Hub KPIs.

KPI	Success criteria
New industrial partners, based on exciting manufacturing challenges	5 per annum
New universities joining	5
Close collaborative links with other EPSRC Manufacturing Hubs and the EPSRC Centre for III-V Technology	Joint activities / events
Close collaborative links between the hub and major complementary overseas centres of excellence such as MIT, IMEC or NTU Singapore	2 over duration of Hub
Compound Semiconductor training centre activities to include: a) university and industry funded doctoral level training, b) MSc courses c) on-job and/or apprenticeship training to support industry d) summer schools for postdocs and PhD students	Delivery of a number of training activities per annum
Research and industrial awards per year for associated activity	Average of £5.5M (100% FEC) per annum
Conference presentations per year	Average of 10 per annum
Publications per year	Average of 20 per annum
Commercial impact activity to include: a) Number of IP disclosures/patents filed. b) Number of IP licences granted. c) Amount of VC funding generated, based on Hub technologies. d) New product roll-outs from partners, based upon Hub technologies. e) Sales value enabled by Hub technologies.	This is a late/lagging indicator and can be used later in the project to monitor success.
Outreach activity to include training	Delivery of a number of outreach activities per annum
Career development of Hub staff	Demonstration of staff development via securing fellowships, career training, etc.

The Year in Numbers

Based on our Key Performance Indicators, and some other important measures of success, the last year has generated some impressive numbers for the CS Hub.

25 Publications

Collaborations & partnerships 25

Including ***10*** new industrial partners, and a new university collaborators

16 Further funding

Including new funding from Innovate UK and EPSRC, total

£9,778,782

Engagement Activities 13

Including activities from conference participation (at the inaugural Engineering Wales Conference, CoInnovate Conference, Institute of Physics engagement event and Wales Week in London CS Cluster Showcase and several others), to providing work experience, to providing bespoke communications training to ***18*** Hub affiliates

11 Awards and recognition

Consisting of ***4*** research prizes, and ***7*** invited conference presentations

Award of Fellowships 2

Research Highlight: CS Characterisation

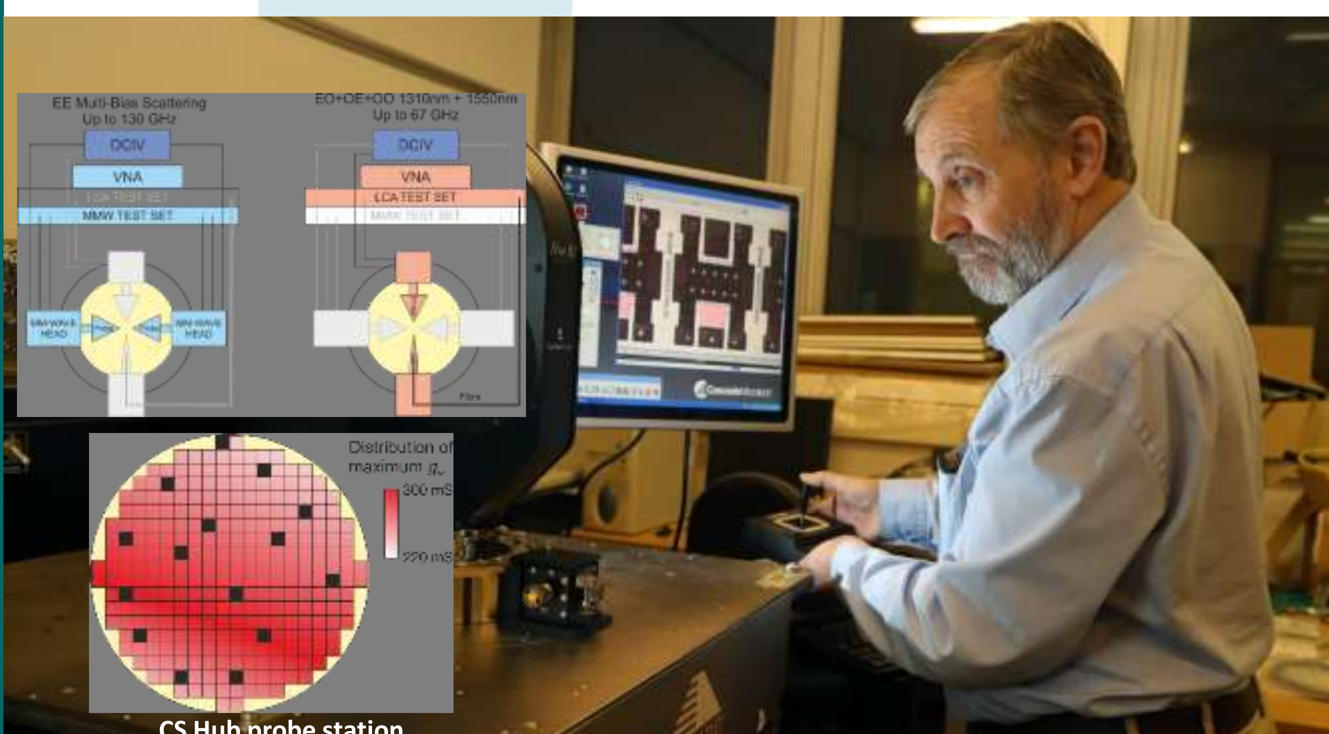
On Wafer Characterisation to Support CS Manufacturing

A measurement system for electronic, optoelectronic and optical devices

Quality control is key in manufacturing: all processes need feedback telling how good and consistent the fabrication has been, to improve products, and sustainability. Manufacturing CS devices is no exception, and the electrical and optical characteristics of transistors, Lasers and photodetectors can tell us much about the potential performance of the systems they will be used in, and the standard of manufacturing.

Large scale CS wafer characterization is normally executed using automated probe stations, where a moving chuck holds the wafer, and probes are used to feed/measure the signals for the characterization while scanning the hundreds/thousands of devices on the wafer. A newly refurbished temperature controlled room within Cardiff School of Engineering has been fitted out with a semi-automatic probe station.

To provide the probe station with a state-of-the-art characterization system with enough flexibility to measure high frequency electronic devices, optoelectronic devices and optical devices, we successfully built a case for an ESPRC equipment bid for a system based on a Vector Network Analyser. Part of the CSHub underpinning equipment grant from EPSRC, £532,648 has been dedicated to acquire this equipment. Following tender, Keysight Technologies were appointed supplier. The turn-key system was delivered and tested in January 2018. It is based on a 4-Port Electrical Vector Network Analyser to 67 GHz. Two ports are connected to 140 GHz mm-wave extenders for Electrical-Electrical characterizations. The remaining two ports are more flexible, and when interfaced with the provided optoelectronic test-bench can perform Optical-Electrical, Electro-Optical and Optical-Optical measurements. To complete the system, a DC-IV Semiconductor Parameter analyser is used to provide and monitor the DC supply for the devices, and hardware/software interfaces link all system components. In this way, from a single PC it will be possible to control measurements, and collect/process characterization data obtaining important information on device characteristics and their statistical spread on a wafer, or among wafers. The system is able to characterize, for example, a wafer containing thousands of high frequency transistors in few hours, returning a map indicating the spread of critical transistor parameters that can be immediately related to the fabrications steps. Or a wafer containing hundreds of lasers, again in few hours, and retrieving information on their behaviour that can be used to improve the manufacturing process.



CS Hub probe station

Research Highlight: Magnetic Arrays (WP7)

Quantum Well Hall Effect Magnetic Field Cameras

Advanced Quantum Well Hall Effect (QWHE) sensors[1] are new types of magnetic field sensors. Compared with search coils or magneto-resistive sensors, QWHE sensors have greater dynamic range, wider frequency response, better amplitude linearity and good temperature coefficient while still demonstrating very high sensitivity capability down to the nano-Tesla range.

A Quantum Well is formed in a heterostructure when a thin layer of a narrow band-gap semiconductor is sandwiched between two identical larger band-gap materials (Figure 1). The free carriers confined within this region (2DEG) have high mobility and low resistance which enhance Hall Effect sensitivity and lowers noise.

Greek cross configuration designs were used to provide best sensor sensitivity. Different sensor sizes from 70 × 70 mm² to 2 × 2 mm² as shown in Figure 2 were tested. The wafer substrates are grown in a (4x4") RIBER VG V100HU Molecular Beam Epitaxy system (Figure 3).

i-line lithography (Figure 4) was employed to fabricate the sensors. 4x4" wafers can be grown and fabricated in one run. Each 4 inch wafer (Figure 5) produces 41,000 QWHE sensors with activate sensing area of 70 × 70 mm².

In the QWHE sensor design, a thin layer of $In_{0.18}Ga_{0.82}As$ is sandwiched between two layers of $Al_{0.35}Ga_{0.65}As$ (Figure 6). Electrons from the high band-gap supply layer are transferred into the Quantum Well as this is energetically favourable for them. These electrons then accumulate at the interface and form a high mobility 2DEG. After fabrication, the QWHE sensors are packaged in a surface mount SOT-143 configuration with typical dimensions 3 mm × 1.5 mm × 1.0 mm.

In non-destructive testing (NDT) inspection, a magnetovision system can be used to improve inspection efficiency substantially and increase tolerance for operations. By using the ultra compact highly sensitivity QWHE sensor, new types of magnetic field camera for NDT inspection can implemented.

A real-time QWHE magnetic field camera[2] was designed and built as shown in Figure 7. This camera contain a 16 x 16 QWHE array which is capable of providing 2-dimensional visualised magnetic field images for materials inspection.

An example of cracks in a weld from the New Nuclear Manufacturing (NNUMAN) group in Manchester was studied (Figure 8). Weld cracks are marked with white dash lines (Figure 8a). The QWHE magnetic field camera was used to inspect the defective sample. Both 2-D and 3-D image inspection results are shown in Figure 9. Magnetic-Flux Leakage (MFL) signal are marked with white dash lines in Figure 9 (a) which match well with the sample optical image. This example shows the great potential of the QWHE sensors in NDT applications.

On-going work is focused on the design and fabrication of an integrated 16 x 1 QWHE sensor array with a sensor activate area of 50 x 50 mm² and a 250 mm sensor pitch. The sensor array die can be directly mounted on PCB for high resolution electromagnetic NDT applications (Figure 10 &11).

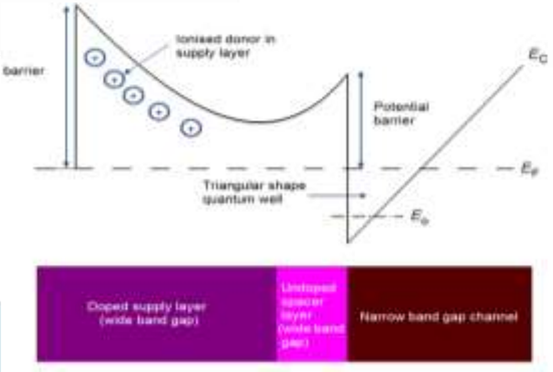


Figure 1: Formation of Quantum Well at an AlGaAs/GaAs heterojunction.

Figure 2: Quantum Well Hall Effect sensor design and layouts.

Figure 3: VG V100HU Molecular Beam Epitaxy system.

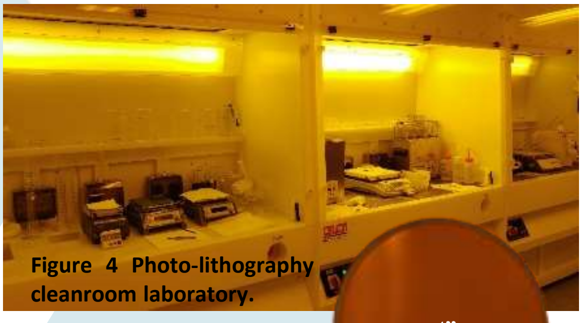


Figure 4 Photo-lithography cleanroom laboratory.

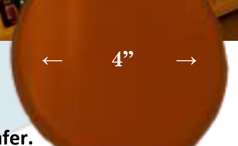


Fig. 5 4-inch wafer.

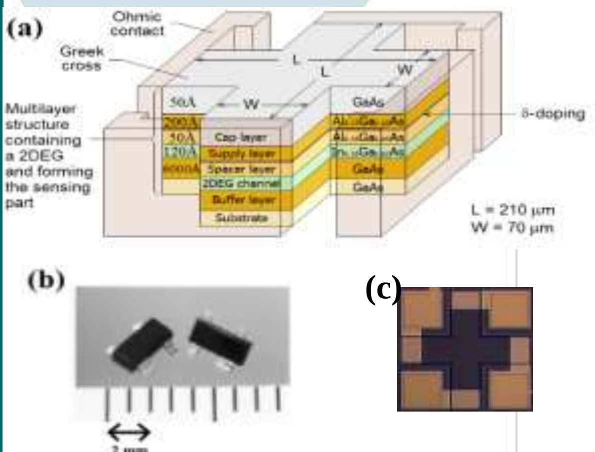


Figure 6: (a) Schematic illustration of 2DEG Quantum Well Hall effect sensor with Quantum Well channel, (b) packaged QWHE sensor in surface mount configuration, and (c) optical picture of QWHE sensor.

Figure 7: Real-time 16 × 16 array Quantum Well Hall effect magnetic-field camera with an LCD touch screen display: (a) top and (b) bottom view.

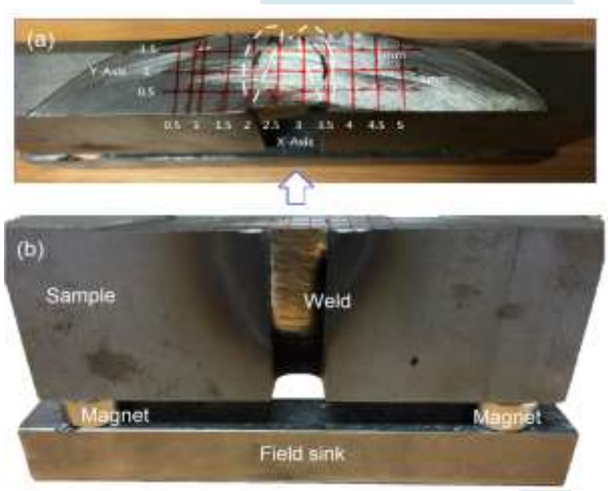


Figure 8: A weld cracked block sample form the New Nuclear Manufacturing (NNUMAN) group, and the coordinate system for manual mapping measurements.

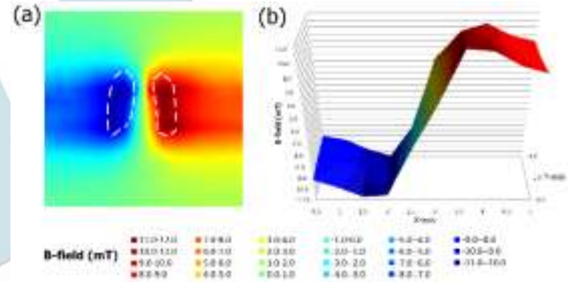


Figure 9: (a) 2D Magnetic field image taken by 16×16 QWHE Magnetic Field Camera. The white dashed lines outline the positions of the cracks; (b) i 3D field images of magnettic flux leakage.

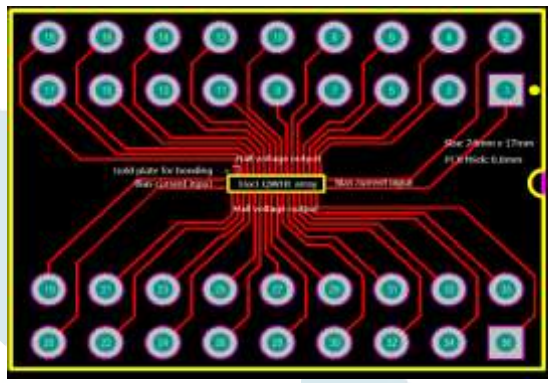


Figure 10: Design of a PCB holder for QWHE 16x1 integrated sensor array.

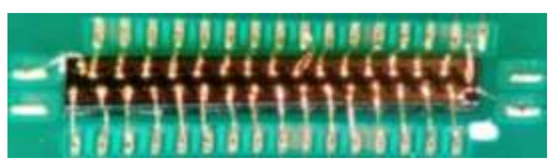


Figure 11: QWHE 16x1 integrated sensor array gold wire mounting on PCB holder.

References:

[1] N. Haned & M. Missous. *Nano-tesla magnetic field magnetometry using an InGaAs-A1GaAs-GaAs 2DEG Hall sensor*. Sensors and Actuators A 102 (2003) 216–222.

[2] C.W. Liang, *et al*. *A Real Time High Sensitivity Quantum Well Hall Effect Magnetovision Camera*. Sensor. Actuat. A-Phys. 265 (2017) 127-137.

Research Highlight: Hub PhD Studentship

The Effects of P-doping on 1.3 µm Quantum Dot Lasers Grown on GaAs & Si Substrates

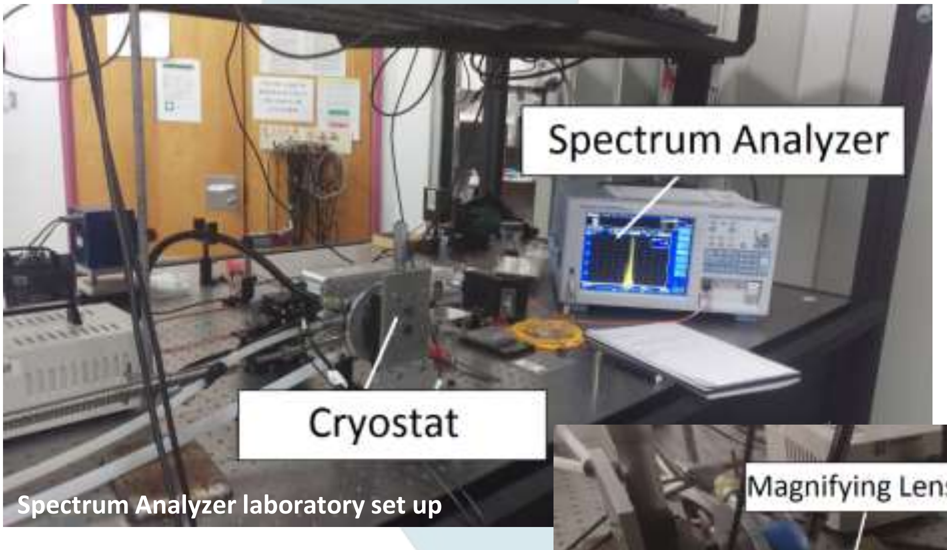
CS Hub PhD student, Lydia Jarvis, began work on her PhD in October 2017 at Cardiff University. Her project is described here as an example of the research performed within the Hub, and also as an example of the training provided.

"The field of Silicon Photonics has attracted much interest in recent years. It aims to use light to process information at a rate which is far faster than that possible using conventional electronics. Quantum Dot lasers for use in Silicon Photonics have been grown directly on Si substrates and have excellent 'threshold' performance, which is how the device operates at the point it begins to lase. So far these devices have achieved lasing at relativity low currents. However to date only devices with low cavity losses have been possible due to the devices having comparatively low gain.

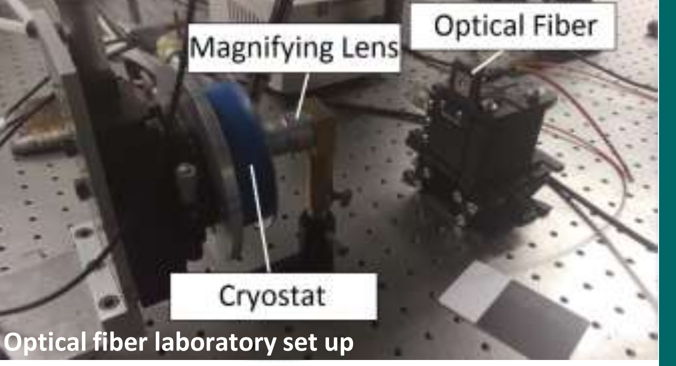
Lasers emit light by the re-combination of an electron and hole. The holes are the absence of an electron in a particular place in an atom. This work examines ways in which Silicon lasers can be improved by a technique called "P-Type Doping," which is the deliberate inclusion of atoms with less electrons than the surrounding atoms, creating extra holes. This enables a greater number of recombination events to take place and enables the device to operate more efficiently and has been demonstrated to improve the available gain in Quantum Dot devices grown on GaAs.

This work examines 1.3µm InAs Quantum Dot lasers with varying levels of p-doping and cavity lengths grown on both GaAs and Si substrates to explore the potential of this approach for increasing the available gain. The lasers are made into ridge waveguide devices of 100µm width with a stripe of 50µm for those grown on GaAs and 100µm width for those grown on Si. To understand the resulting behaviour devices are mounted in a cryostat and several of the characteristics recorded from 200 – 400K. The devices grown on GaAs provide a reference to compare with the performance of the devices grown on Si.

The characteristics that have been examined include the current power-curve, from which the threshold current can be determined. Other measurements that have been taken are the voltage-current curve, the near field profiles and the device's wavelength. Wavelength measurements are taken using a spectrum analyzer. The device is mounted in the cryostat and powered by a pulse generator. The light produced is the focused onto and optical fiber and relayed to the spectrum analyzer which shows the individual wavelengths that make up the beam and their relative intensities."



Spectrum Analyzer laboratory set up



Optical fiber laboratory set up

Key Performance Indicators: FOCUS ON NEW FUNDING

Research & Industrial Awards for Hub Associated Activity

One of the primary goals of the CS Hub is to generate further funding for associated compound semiconductor research and industrial activity. This funding is essential to ensure the Hub produces a sustainable research environment.

Part of this remit will be addressed by the investment of CS Hub funds in up to eight small (£40k maximum award) short term (up to six months) feasibility studies, with work estimated to commence in July 2018. Successful applicants to this first funding round will then be invited to apply for further funding of up to £120k for additional studies, which should then lead to a full application to EPSRC or Innovate UK in an area related to CS manufacturing research.

The table below shows the funding obtained by CS Hub members in association with and complementary to the CS Hub, since October 2016. Total associated new funding is £9,356,747 for the period. Subsequent pages show additional details for selected new awards associated with the CS Hub. These are indicated by * in the table below.

KEY PERFORMANCE INDICATOR:

Research and industrial awards per year for associated activity

Target = £5.5M (100% FEC) pa

Title	Funder	Value
DiLan: Diode Laser using Nano-imprint gratings*	Innovate UK	£1,094,407
MacV: Miniaturised Atomic Clocks using VCSEL pump sources*	Innovate UK	£1,136,000
HEMAN-V: High Efficiency Manufacturing of VCSELs*	Innovate UK	£426,794
SUPER8: A scalable 200G Superthermal CWDM architecture*	Innovate UK	£1,114,197
CS MAG IC: CS Magnetic Integrated Circuits*	Innovate UK	£36,153
QBARKA: Microstructural characterisation using Quantum enabled BARKhausen noise Analysis*	Innovate UK	£488,180
GaNRF: Fast loop fabrication for GaN RF devices	Innovate UK	£206,870
GaN FET fabrication platform	National Research Network (Welsh Government)	£60,000
SC underpinning equipment*	EPSRC	£2,000,000
High performance III-V quantum for photodetectors for low SWaP infrared devices	EPSRC	£100,146
Semiconductor National Epitaxy Facility (Group IV epitaxal activities)	EPSRC	£1,600,000
RAEng Fellowship (5 years, Dr Siming Chen)	EPSRC	£700,000
PICTURE: High Performance and High Yield Heterogeneous III-V/Si Photonic Integrated Circuits using a thin and Uniform Bonding Layer	European Union	£340,000
	Innovate UK	£54,000
Total		**£9,356,747**

Case Study: New Project With Industry Partners

DiLAN: Diode Laser Manufacture Using Nano-Imprint Lithography

Value: £1,088,373
Partners: Compound Semiconductor Centre Ltd, Compound Semiconductor Technologies Ltd, Cardiff University, University of Swansea
Website: http://www.compoundsemiconductorcentre.com/dilan-d...

Project summary: The inexorable growth in broadband communications has created an enormous market (50-100M units per annum) for low cost, single-mode semiconductor lasers emitting around 1.3-1.55um as sources in fibre optic communications to the Premises (FTTP). Current technologies deployed (such as Passive Optical Networking, PON) operate at line rates of 1.25-2.5 Gb/s. However, satisfying the massively expanding bandwidth demand will require implementation of new PON standards that require higher performance, lower cost laser sources. The UK industrial partners in this project are already significant materials and chip scale suppliers to this market.

The project addresses the replacement of a high cost nanometre-scale lithography step in the laser manufacturing process with a low cost, high throughput nano-imprint process to realise a cost saving of 20-30% in the Cost of Manufacture of the laser chip. This has the potential to increase the consortiums value share from ~10% to >30% of the current chip market, which would be worth up to £130M to the UK economy with the first 5 years of introduction into volume manufacturing. However, to our knowledge, the nano-imprint lithography technique has not been implemented in volume semiconductor laser manufacturing, and so there is significant de-risking activity required to establish, qualify and yield engineer a new manufacturing process to unlock the productivity gains.

CS Hub PDRA, Dr Stella Elliot working in the Hub laboratories.

Case Study: New Project With Industry Partners

MacV: Miniaturised Atomic Clocks Using VCSEL Pump Sources

Value: £1,173,079
Partners: Compound Semiconductor Centre Ltd, National Physics Laboratory, Cardiff University, Compound Semiconductor Technologies Ltd
Website: http://www.compoundsemiconductorcentre.com/macv-mi...

Project summary: The findings of the UK Quantum Technology roadmap indicate 'the market for quantum timing devices is expected to become a £100 million in 5-10 years, growing to a multi-£100M market in 10-20 years.' Initial drivers will be durable navigation products for defence and aerospace, followed by 'resilient telecomms infrastructure with increased data capacity (5G), research and for time-stamping of financial transactions'. Coherent population trapping (CPT) based miniature atomic clocks require low power, single mode laser diodes that can be directly modulated at a few gigahertz.

Vertical Cavity Surface Emitting Lasers (VCSELs) are ideal for this application primarily due to their very low power consumption, wide wavelength tuning coefficient, reduced sensitivity to optical feedback, extended device lifetime, and small device footprint. Commercially available VCSELs have linewidths of ~50-100 MHz, and while this can be a problem for many other laser spectroscopy applications, it does not substantially compromise the quality of a CPT resonance. Conversely, due to the circular beam profile, VCSELs are particularly susceptible to polarisation instabilities; however, there are several novel design modifications that can be implemented to address this issue. Currently, there are no UK sources or any supply chain of reliable and robust VCSELs for miniature atomic clocks and a very limited number of commercial manufacturers globally developing VCSELs at the opimium wavelength for the application (CsD1 – 894nm). Our project will establish a UK strategic capability focussed on the development and volume production of VCSEL laser sources, tailored specifically to support the adoption of miniaturised atomic clock applications.

ICS Process Engineeer Saleem Shabbir working on photolithography.

Case Study: New Project With Industry Partners

QBARKA

Value: £488,180
Partners: Compound Semiconductor Centre Ltd, AHS LTD, Microsemi, TWI
Website: http://www.compoundsemiconductorcentre.com/project-award-to-uk-compound-semiconductor-high-resolution-magneto-imaging-consortium

Project award to UK Compound Semiconductor high resolution Magneto-imaging consortium
Cardiff, 14 December 2017. The Compound Semiconductor Centre (CSC) is pleased to announce the award of the project support from Innovate UK's Quantum Technology programme. Project 'QBARKA' will focus on the development of a new technique to enable ultra-high resolution magneto-imaging of metallic microstructure by exploiting the Barkhausen effect in ferromagnetic materials.

Magnetic Barkhausen Noise (BHN) measurements are currently used in non-destructive inspection of stress/strain and microstructures in a range of materials. BHN occurs when a magnetic field is applied to a ferromagnetic material, and is generated by the sudden irreversible motion of magnetic domain walls as they are released from microstructural obstacles such as dislocations and grain boundaries. BHN can provide high resolution microstructure related information, but current detection techniques used do not have the resolution (both spatial and magnetic), to extract the wealth of data available.

The project will leverage core technology based on compound semiconductor Quantum Well Hall Effect (QWHE) magnetic sensing technology developed by Advanced Hall Sensors Ltd in Manchester, UK. Professor Mohamed Missous, inventor of the technology commented *'These sensors have several advantages over incumbent technology: miniaturised size, sensitivities independent of frequency and a very wide dynamic range. The technology offers a novel solution to enable a new paradigm in high resolution microstructural analysis of materials'*.

Wyn Meredith, Director of CSC commented *'Magnetic field sensors are key enabling technologies for a wide range of metrology, imaging, industrial and automotive sensing applications where demand is proliferating rapidly. The consortium (AHS, CSC, Microsemi and TWI) has been constructed to address both the key markets and the development and manufacturing supply chain.'*

About the Compound Semiconductor Centre (CSC)
The Compound Semiconductor Centre was founded in 2015 as a Joint Venture between Cardiff University and IQE Plc, with the mission of accelerating commercialisation of Compound Semiconductor Materials and Device Research, and realising a tangible economic return on the UK investment in this key area of enabling technology. Based in Cardiff, the Centre is a vital milestone towards developing a World-class Compound Semiconductor cluster in South Wales.

About Advanced Hall Sensors (AHS): *Advanced Hall Sensors Ltd specialises in the development and manufacture of high performance magnetic sensor products based on quantum effects in Gallium Arsenide materials, to deliver an unrivalled sensitivity and dynamic range in harsh environments. The company has supplied in excess of 15 million sensors to a range of international customers in industrial, medical, aerospace and the Oil and Gas industries.*

About TWI: *TWI is one of the world's foremost independent research and technology organisations, with expertise in materials joining and engineering processes as applied in industry. TWI specialises in innovation, knowledge transfer and in solving problems across all aspects of manufacturing, fabrication and whole-life integrity management. Established in Cambridge, UK in 1946, the organisation has gained a first-class reputation for service through its teams of respected consultants, scientists, engineers and support staff. With around 800 employees, it works with over 1800 Industrial Member companies in over 70 countries.*

About Microsemi: *Microsemi Corporation (Nasdaq: MSCC), headquartered in Aliso Viejo, California, is focussed on providing solutions where power matters, security is non-negotiable and reliability is vital. Microsemi's advanced packaging business based in South Wales designs and manufactures miniaturised compound semiconductor modules for high reliability, harsh environment data communications, medical implant and aerospace applications. The business has developed novel embedded component technology and wafer scale assembly processes to meet growing needs around complex miniaturised solution.*

Case Study: New Project With Industry Partners

CS MAGIC: Compound Semiconductor MAGnetic Integrated Circuits

Value: £36,153
Partners: Compound Semiconductor Centre Ltd, Advanced Hall Sensors (AHS), TWI, Renishaw, Swansea University
Website: http://www.compoundsemiconductorcentre.com/project...

Project award to UK Compound Semiconductor MAGIC consortium
The Compound Semiconductor Centre (CSC) is pleased to announce the award of a Collaborative R+D project from InnovateUK. Project CS MAGIC: (Compound Semiconductor MAGnetic Integrated Circuits) will focus on the development of new ultra-sensitive magneto-sensors with integrated electronics. The project will leverage core technology based on Gallium Arsenide Quantum Well Hall Effect (QWHE) magnetic sensing technology developed by Professor Mohamed Missous, founder of Advanced Hall Sensors Ltd (AHS), and a novel Gallium Nitride device based on a high electron mobility transistor ('magHEMT') concept developed by Dr Petar Igic at Swansea University. The consortium comprising CSC (Cardiff), AHS ltd (Manchester), TWI (Port Talbot), Renishaw (Edinburgh) and Swansea University will collaborate to deliver commercial grade sensing solutions for a diverse range of challenging applications in automotive current sensing, high resolution metrology, non-destructive inspection and test, and security screening applications.

Professor Missous, inventor of the QWHE technology, commented 'AHS has had considerable success in commercialising the core technology with over 15 million discrete sensors shipped to date, and this project will extend the functionality of sensing platform for harsh environment and ultra-wide dynamic range requirements to service a $3B market in magnetic sensing solutions'. CSC Director, Dr Wyn Meredith commented, 'This project will deliver an 'all UK' developed and manufactured solution which leverages world class compound semiconductor materials and device expertise in the consortium matched with the deep applications understanding of TWI and Renishaw'.

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About Renishaw: Renishaw is one of the world's leading engineering and scientific technology companies, with expertise in precision measurement and healthcare. The company supplies products and services used in applications as diverse as jet engine and wind turbine manufacture, through to dentistry and brain surgery. It is also a world leader in the field of additive manufacturing (also referred to as metal 3D printing), where it is the only UK business that designs and makes industrial machines which 'print' parts from metal powder. The Renishaw Group currently has more than 70 offices in 35 countries, with over 4,000 employees worldwide.

About Swansea University: Swansea University was founded by industry in 1920 to deliver for industry. The University has historically held an excellent reputation in Science and Engineering research, but is now amongst UK leaders for Arts, Humanities and Social Sciences. In the Research Excellence Framework of 2014, Swansea University achieved its ambition to become a UK top 30 research institution, the ranking of 26th was judged as the "biggest leap among research-intensive institutions", according to Times Higher Education.

Case Study: New Project With Industry Partners

A Feasibility Study for the Development of GaN-based High Frequency Devices

Value: £207,176
Partners: Compound Semiconductor Centre Ltd, Glasgow University, Cardiff University

Project summary

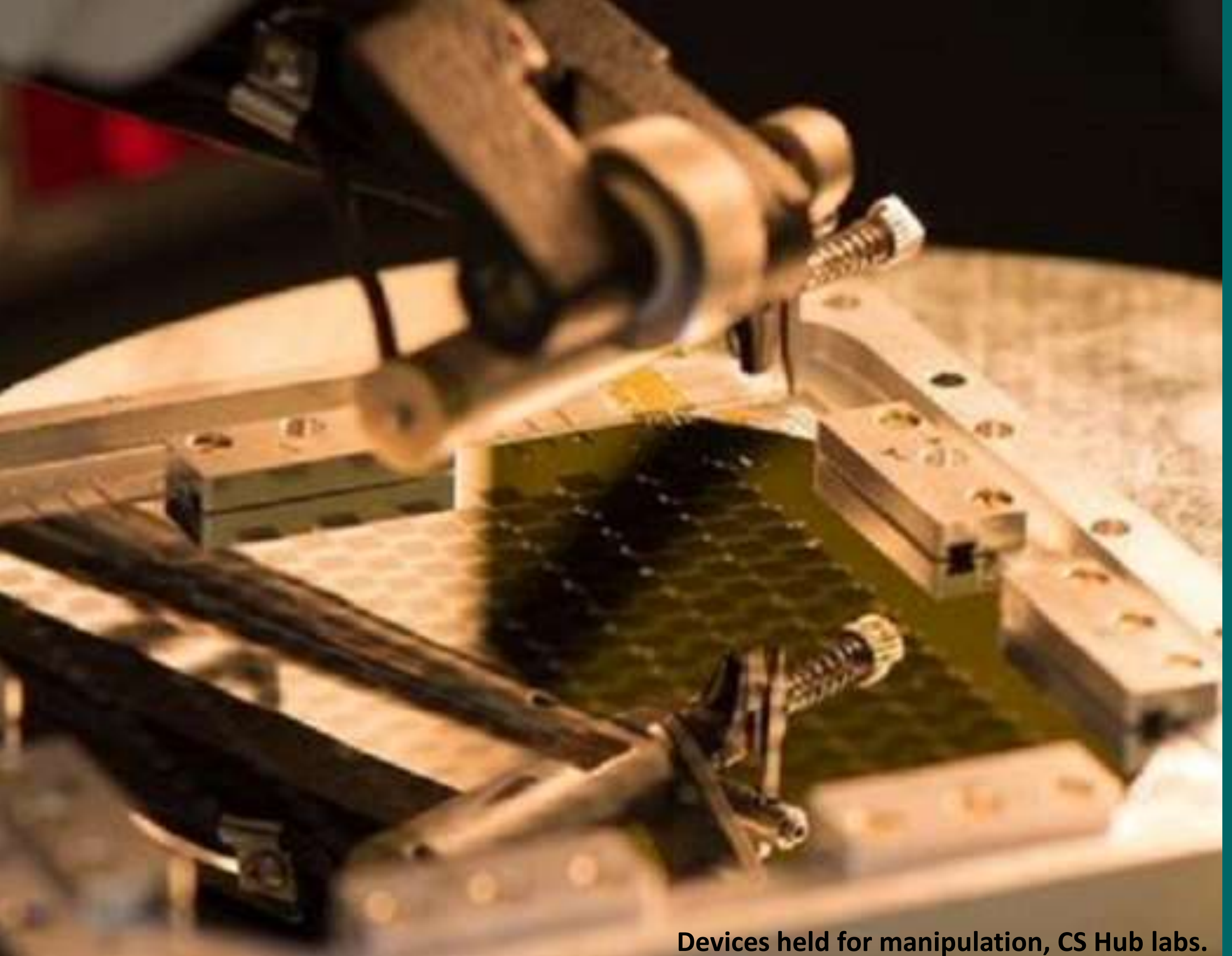
The ambition of this feasibility project is to de-risk a sovereign GaN on SiC process capability and provide UK designers with access to the rapidly growing GaN-based RF market (currently worth $350M and forecast to grow to $750M by 2022).

This capability is strategically important to the development of next generation of high performance RF devices within the UK.

It is especially critical to space and defence applications including military communication and guidance systems where access to best in class technology is now restricted by ITAR (International Traffic in Arms Regulations).

The developed GaN on SiC process will target Ka-band (26.5–40.0GHz) communication frequencies and deliver much higher power density than currently available gallium arsenide or GaN on silicon devices.

This will enable communication at longer range and higher data rate as well as radar systems with higher definition and longer-range detection. This same capability will also be critical in developing device technologies for the imminent "5G" communications revolution.



Devices held for manipulation, CS Hub labs.

Case Study: New Project With Industry Partners

HEMAN V: High Efficiency MANufacturing of VCSELs

Value: £426,794
Partners: Compound Semiconductor Centre Ltd, SPTS Technologies Ltd, University of Swansea, Cardiff University

Project summary
Affordable and reliable laser technologies have revolutionised consumer electronics and telecommunications over the last 30 years, enabling mass market adoption of ICT technology such as fibre optical communications, CD and DVD storage. It is now at the heart of new advances in laser based manufacturing methods, medical diagnosis, surgery, cosmetics and sensing.
The Vertical Cavity Surface Emitting Laser (VCSEL) is an advanced laser device which enables multiple lasers to be integrated for high performance applications whilst leading to further miniaturisation and cost reduction opportunities.

The HEMAN V project will leverage an existing world leading UK capability in VCSEL materials technology to drive the next wave of consumer, industrial and automotive applications such as gesture recognition, high resolution 3D imaging and projection displays.
The project partners offer world-class capabilities in compound semiconductor materials, device fabrication and capital equipment specialists to facilitate the step change in manufacturing methods required to accelerate the adoption of VCSEL solutions in truly mass market products.

100 mm wafer steam oxidation manufacturing tool, ICS at Cardiff University

Case Study: New Project With Industry Partners

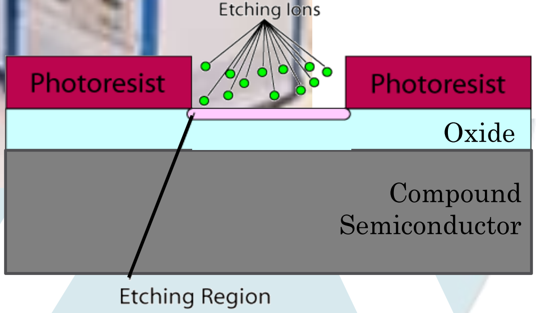
Device Enhanced Performance of Integrated Concentrator Photovoltaics & Thermo-Electrics

Value: £420,122
Partners: IQE PLC, European Thermodynamics Ltd, Cardiff University, Bangor University

Project summary

Concentrator Photovoltaic (CPV) cells offer potentially cost-effective and highly efficiency conversion of solar energy to electricity as much improved alternative to current solar panel technologies.
The small size of standard CPV cells (less than 1cm2) can lead to very low electricity costs but the CPV cell temperature needs to be cooled to optimise power generation. This project will develop optimized theoretical designs and manufactured prototypes of novel CPV-Thermos Electric (TE) receivers, lowering costs of renewable energy generation and building the UK CPV supply chain via technical innovation.

Part of the ICS ICP dry etching capability.



Case Study: New Project With Industry Partners

Process Module Development for GaN RF Power & Sensor Devices

Value: £60,000
Partners: University of Swansea, Cardiff University

Project summary

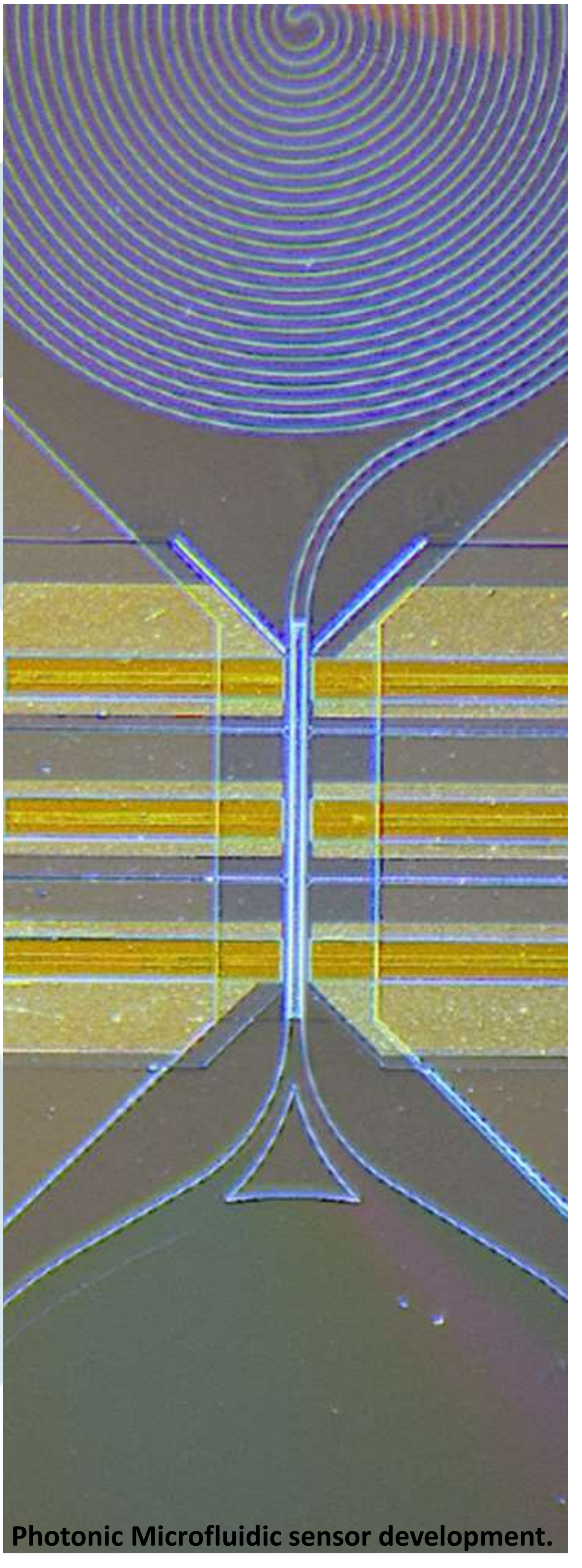
This collaborative project builds on the successful progress of two projects already funded by the National Research Network in Advanced Engineering and Materials.

It utilizes the combined fabrication capabilities of CU and SU in an integrated process flow to extend the existing GaN capabilities into power and sensor applications.

The power control devices being developed exhibit improved conversion efficiency compared to currently available silicon devices and will target the rapidly growing electric vehicle market.

By the end of 2016, over 35,000 plug-in cars had been registered in the UK over the course of the year, the highest number ever.

The new sensors use patented technology from Swansea University and are suited to harsh environment, automotive and aerospace applications by virtue of their improved sensitivity and temperature tolerance.



Photonic Microfluidic sensor development.

Key Performance Indicators: FOCUS ON NEW LINKS

New collaborative links for the CS Hub

The CS Hub aims to generate new collaborative partnerships with a variety of organisations both in academia and industry, in order to facilitate the best ongoing research possible into CS technology.

In recognition of this remit, one of the Hub's key performance indicators is the requirement to instigate a minimum of five new links via collaboration or partnership with five new research organisations per annum.

New links include those with new industrial collaborators, new academic collaborators, and new research centres. In particular, a goal for the Hub over the coming months is to forge collaborations and closer links with the other Future Manufacturing Hubs, and related research centres across the UK and beyond.

Our aim is to strengthen our research, promote the CS Hub, and develop new and productive relationships.

Link Type	Link with	Details
New industrial partner	Airbus	ICase PhD studentship
	SPTS	New Innovate UK project partner
	NPL	
	CyDen	
	PulmonIR	
	Kaiam	
	AHS	
	Cea-Leti	New project partner on UCL EU funded PICTURE grant
New industrial partner / Overseas centre link	IMEC	New project partner on UCL EU funded PICTURE grant
New academic partner	Bangor University	New project partner on Sheffield University EPSRC funded grant to develop electrical nano-lasers in the visible spectrum
	Swansea University	New Innovate UK project partner
Overseas centre link	Chinese Academy of Sciences	Visit by Smowton & Liu, October 2017
	Nanjing University	Joint award with Sheffield for an EPSRC and National Natural Science Foundation of China funded grant on developing semi-polar UV materials

KEY PERFORMANCE INDICATOR:

Links to other research centres

Target = 5 new connections pa

Images show CS Hub trade stand, provided jointly with the Institute for Compound Semiconductors, at the CoInnovate conference, 2018. The conference was held at the Mercure Holland House Hotel, Cardiff.

Case Study: Capability

Institute for Compound Semiconductors
Sefydliad ar gyfer Lled-ddargulyddion Cyfansawdd

Summary

The Institute for Compound Semiconductors (ICS) is in the process of establishing a world class compound semiconductor facility. With state-of-the-art equipment and highly-skilled staff, ICS aims to position Cardiff as the leader in translating Compound Semiconductor Technologies.

Links to the CS Hub

The ICS has close links to the CS Hub. Both are directed by Prof Peter Smowton at Cardiff University. The ICS provides the technical and infrastructure requirements to ensure the success of the CS Hub. The ICS facility houses equipment secured as part of the CS Hub underpinning equipment award, and works intimately with the CS Hub in all aspects of research from public engagement to technical process development and equipment maintenance.

About ICS

From smartphones and tablets to satellite communications and GPS, compound semiconductors drive the devices and technologies we use today. The ICS enables researchers and industry to work together to progress academic research to a point where it can be introduced reliably and quickly into the production environment.

ICS targets direct industrial collaboration for product development to prototyping, including advanced device fabrication, measurement and characterisation, and small scale pilot production, incorporating broad academic expertise to offer innovative business solutions.

In the future the Institute will focus on formal and informal specialised training, including new equipment demonstration and housing, outreach, brainstorming and networking events.

The Institute has been established as part of the University's capital development plan, including support and investment from the Welsh Government and the UK Research Infrastructure Fund (RPIF).

ICS aims to help researchers and industry work together to generate economic impact through commercial and academic exploitation of Compound Semiconductors.

The ICS mission

Over the next five years, ICS will target academic research, industrial productivity and industrial and academic engagement.

Academic research: ICS aim to become the UK facility of choice, with European recognition, for catalysing, facilitating and enabling world-class research. ICS will recruit world-class academics and provide environments that will foster collaborations between staff, including shared laboratory and office space, building space-breakouts, and Institute-centric seminars.

Industrial productivity: ICS will enable high-impact compound semiconductor-based commercially relevant technology, company spin-off and product development. ICS will achieve scientific edge and technical relevance by offering state-of-the-art products and competitive prices, technological expertise, device and system design, process development to prototyping, access to cleanroom infrastructure, and feed through to the Compound Semiconductor Catapult.

Industrial and academic engagement: ICS will work to become a European hub linking industry and academics. We will link industrial partners with top academic researchers to identify and solve mutual problems, and we will develop a culture for knowledge transfer and innovation between these two groups.

ICS forms part of the biggest campus upgrade for a generation at Cardiff University – a £600m investment in the future. The Institute will occupy a key location in the new Translational Research Facility (TRF) within purpose built accommodation at a brand new University site. More information is available at the University web pages for the new facility:

https://www.cardiff.ac.uk/campus-developments/projects/translational-research-facility

The ICS vision

ICS will house the new equipment acquired via the CS Hub underpinning equipment award. In addition, the ICS has available a variety of pre-existing kit, as well as senior technical (process engineers) staff, available. Both the equipment and staff of ICS are available for CS Hub collaborators and partners to access, as well to as others in either the academic or industrial fields.

Access to equipment or staff can be arranged through ICS, and is chargeable.

The diagram below shows details of the equipment available.

Lithography		
Contact	Suss MicroTec MJB3 / MJB4 / MA6	4 µm minimum feature size routinely
		1 µm best over limited area
	MA B8	Resolution: UV 400 1.5-3.5 µm
		Resolution: UV 300 0.5-2.5 µm
		Resolution: UV 250 0.4 µm (vacuum contact)
Projection	ASML PAS 5500/101	0.4 µm
E beam	Raith eline, 30KV	Minimum feature size = 70-90 nm
		Optimal feature size = 50 nm
	Large wafer format e-beam	< 20 nm
Metal / Dielectric PVD		
Edwards 306, 2 Off	Thermal	Max wafer = 50 mm; Typically: Au, Zn , Ge, Cr, Ti
Edwards 306	Thermal, Ebeam	Max wafer = 50 mm; Typically: SiO_2, Al, Ti,Ni, Pt
Kurt Lesker Proline PVD200		Max wafer = 150 mm
Kurt Lesker Proline PVD200 (HV)	Thermal, Ebeam, Sputter	Max wafer = 150 mm; Typically $5x10^{-8}$mBar, Loadlock
Buhler		Max wafer = 150 mm; SiO_2, Si_3N_4
Dielectric CVD		
PECVD	PlasmaLab 180 (Oxford Instruments)	Max wafer = 150 mm; SiO_2 & Si_3N_4 deposition
ALD	ALD System (Beneq)	Max wafer = 200 mm
Dedicated PECVD / LPCVD system (200 mm)		
Dry Etching		
RIE	Oxford Instruments RIE 80	Max wafer = 150 mm; Typically: Cl, Ar, O, CHF3, SF6
ICP-RIE	Oxford Instruments PlasmaLab 180	Max wafer = 200 mm; Typically: Cl, BCl3, Ar, O, C4F8 (Heatable table & LN cooling, loadlock)
	Oxford Instruments Cobra300	Max wafer = 200 mm; O_2, Cl_2, Ar, SF_6, BCl_3, N_2
RTA & Wet Oxidation		
RTA	Jipelec 100	100 mm wafer; Anneal up to 850°C
	Jipelec First	200 mm wafer; Anneal up to 1200°C
Wet Oxidation	AET	100 mm wafer
Characterisation		
SEM	Philips FEI XL30	W source; Resolution = 3.4 nm @ 30 KV
High Resolution SEM	Hitachi SU8320	Resolution typically < 1 nm; Max wafer = 200 mm
Optical microscopes	Zeiss Axio Imager Z2	x 1000
Surface profilometers	Dektak	Max wafer = 200 mm
Spectroscopic ellipsometer	Semilab SE2000	Max wafer = 200 mm
Bonding & Probing		

Key: Black text = Available; Grey text = To be installed

Institute for Compound Semiconductor (ICS) equipment, and CS Hub equipment housed within ICS, can be accessed as a bookable, chargeable service.

Key Performance Indicators: PUBLICATIONS

New Publications & Conference Presentations from the CS Hub

The CS Hub is committed to academic excellence in CS Manufacturing research, and as such, aims to publish as many high impact and high quality publications as possible following consideration of appropriate IP protection. In addition, the CS Hub will aim to be represented at high profile conferences.

During the first year of the CS Hub, we were able to produce a number of scientific abstracts for presentation at conferences across the world. This fledgling research has already produced several papers for the CS Hub. In addition, Hub research scientists have made a number of invited presentations at important events during this first year.

Invited and conference presentations together with published research papers can be found below and in subsequent pages of this report.

The Hub will continue in subsequent years to deliver research excellence in the highest quality publications possible, as we translate our new research activities into substantial and meaningful results for the CS research community.

Examples of keynote or other named speaker to a conference

Prof David Wallis: Invited speaker at Manufacturing 2075, International Conference, 2017
Prof David Wallis was invited to present at the Manufacturing 2075 conference on the future manufacturing challenges to be faced in compound semiconductor research. Successful research and translation of this in the compound semiconductor field will have a significant impact on future technologies. The CS Hub was promoted to others working on future manufacturing challenges who attended the conference.

Prof Tao Wang: Keynote Presentation: Development of semi-polar GaN technology for smart lighting and healthcare, International Conference, 2017
Prof Tao Wang was invited to deliver a keynote presentation at the 2017 International Symposium on Advanced Lighting Science and Technology in Shangyu, China. The keynote was requested due to work undertaken at the CS Hub on semi-polar GaN technology for smart lighting and healthcare. The work of the CS Hub in GaN technology was promoted at an international level.

Prof Tao Wang: Invited speaker APWS, International Conference, 2017
Prof Tao Wang was invited to provide a keynote presentation at APWS 2017 in China. This recognised the world-leading research performed as part of the CS Hub by the University of Sheffield partners. The work of the CS Hub was promoted at an international level.

Prof Huiyun Liu: Invited speaker CLEO-Europe International Conference, 2017
Prof Huiyun Liu has been invited to present cutting edge research on III-V on Si lasers for Si photonics at a number of international conferences including CLEO-Europe.

Prof Tao Wang: Invited speaker ISSLED, International Conference, 2017
Prof Tao Wang, CS Hub CoI, was invited to present on the cutting-edge research performed under the remit of the CS Hub at an international conference in Canada. The cutting-edge research performed under the remit of the CS Hub was recognised and promoted at an international level.

KEY PERFORMANCE INDICATOR:

Publications, conference presentations/abstracts

> 20 / 10 per annum

New Publications & Conference Presentations from the CS Hub continued

Conference Proceeding / Conference Papers

Luminescence and conductivity studies of chevrons in semi-polar (11-22) InGaN/GaN multiple quantum well structures (2017). Brasser C, Bruckbauer J, Li Z, Jiu Z, Bai J, Edwards PR, Wang T, Martin RW.
Optical and structural properties of semipolar GaN on patterned Si substrates (2017). Bruckbauer J, Naresh-Kumar G, Yu X, Pugh J, Cryan MJ, Wang T, Trager-Cowan C, Martin RW.
Manipulable and hybridized, ultralow-threshold lasing in a plasmonic laser using elliptical InGaN/GaN nanorods (2017). Liu B, Tao T, Zhi T, Dai J, Zhuang Z, Xie Z, Chen P, Ren F, Chen D, Zheng Y, *et al*.
Study on the growth mechanism of In(Ga)N (2017). Chen Z, Wang T, Wang P, Zheng X, Schulz T, Albrecht M, Shen B, Wang X.
Novel SEM techniques for rapid structural (2017). Trager-Cowan C, Naresh-Kumar G, Nouf-Allehiani M, Bruckbauer J, Kusch G, Edwards PR, Brasser C, Pascal E, Vespucci S, Kraeusel S, *et al*.
Optical characterization of (11-22) semi-polar (2017). Zhang Y, Athanasiou A, Smith RM, Hou Y, Gong Y, Bai J, Wang T.
Two-dimensional electron gas in InGaN/InN (2017). Wang T, Cheng Z, Wang P, Zheng X, Li J, He X, Zhang X, Yang X, Shen B, Wang X.
2D magnetic field sensing around defects in ferromagnetic and non-ferromagnetic materials using 2DEG quantum well Hall-effect sensor arrays (2017). Biruu FA, Balaban E, Ahmed E, Liang CW, Missous M.
A real time quantum well Hall-effect 2D hand-held magnetovision system for ferromagnetic and non-ferromagnetic materials (2017). Liang CW, Ahmad E, Balaban E, bIRUU fa, Sexton J, Missous M.
Non-destructive detection of metallic objects under AC magnetic field illumination (2017). Ahmad E, Liang CW, Watson JM, Missous M.
Direct growth of III-V quantum dot lasers on silicon (2017). Liu H.
Elecrically driven QD ridge lasers on silicon substrates (2017). Smowton. Photonics West Conference.
Rapid Fabrication and Characterisaion Techniques for VCSELs (2017). Kastein L, Smowton PM. Photonics West Conference.
Development of High Quality Semi-polar GaN for Long Wavelength Emitters (2017). Wang T.
Semi-polar GaN Technology (2016). Wang T.
Semi-polar InGaN/GaN based long wavelength emitters for lighting and display (2016). Wang T.
Development of III-nitride nanostructures for low threshold lasing and semi-polar GaN towards Yellow/Orange lasing
(2016). Wang T.
III-V quantum dot lasers monolithically grown on Si platform (2016). Liu H.
Silicon based III-V quantum dot devices for silicon photonics (2016). Liu H.
Integrating InAs/GaAs quantum-dot laser on silicon photonics (2017). Liu H.
Integrating III-V quantum dot lasers on silicon substrates for silicon photonics (2017). Liu H.
III-V quantum dot lasers monolithically grown on silicon (2017). Liu H.
Silicon based III-V quantum dot devices for silicon photonics (2017). Liu H.
High-performance InAs/GaAs quantum-dot laser diodes monolithically grown on silicon for silicon photonics (2017). Liu H.
Epitaxial growth of III-V quantum dot lasers on silicon substrates for silicon photonics (2017). Liu H.
Non-polar and Semi-polar GaN for Photonics and Electronics (2017). The 11th International symposium on **Semiconductor Light Emitting Devices** (ISSLED 2017), Banff, Alberta, Canada (Sheffield University team).
High Efficiency Emission of InGaN Structures on Overgrown Semi-Polar GaN (2017). E-MRS 2017 Fall Meeting, Warsaw, Poland (Sheffield University team).
Non-polar and Semi-polar GaN for next generation III-nitride devices (2017). The 8th Asia-Pacific Workshop on Widegap Semiconductors, September 24-27, 2017, Qingdao, China (Sheffield University Team).
Keynote presentation, **Development of semi-polar GaN technology for smart lighting and healthcare** (2017). International Symposium on Advanced Lighting Science and Technology, Shangyu, China, 31 May-01 June 2017 (Sheffield University Team).
Development of High Quality Semi-polar GaN for Long Wavelength Emitters (2017). SPIE Photonic West, 28 January – 2 February 2017, San Francisco, California, USA, (Sheffield University team).
Semi-polar GaN Technology (2016). International Conference on Optoelectronics and Microelectronics Technology and Application (OMTA 2016), 10-12 October 2016, Shanghai, China (Sheffield University team).

New Publications & Conference Presentations from the CS Hub continued

Semi-polar InGaN/GaN Based Long Wavelength Emitters for Lighting and Display (2016). IEEE Photonics Conference and Society's Annual Meeting, 2- 6 October 2016, Hawaii, USA (Sheffield University team).

Development of III-nitride nanostructures for low threshold lasing and semi-polar GaN towards Yellow/Orange lasing (2016), IEEE Photonics Conference and Society's Annual Meeting, 2- 6 October 2016, Hawaii, USA (Sheffield University team).

III-V quantum dot lasers monolithically grown on Si platform (2016). SPIE/COS Photonics Asia, Beijing (UCL team)

Silicon-based III-V quantum dot devices for silicon photonics (2016). Asia Communications and Photonics Conference, Wuhan, Hubei China (UCL team).

Integrating InAs/GaAs quantum-dot laser on silicon for silicon photonics (2017). UK Quantum Dot Day Meeting 2017, Edinburgh, UK (UCL team).

Integrating III-V quantum dot lasers on silicon substrates for silicon photonics (2017). Photonics West 2017, San Francisco, USA (UCL team).

III-V quantum-dot lasers monolithically grown on silicon (2017). Compound Semiconductor Week 2017, Berlin, Germany (UCL team).

Silicon-based III-V quantum-dot lasers for silicon photonics (2017). Applied Optics and Photonics China 2017, Beijing China (UCL team).

High-performance InAs/GaAs quantum-dot laser diodes monolithically grown on silicon for silicon photonics (2017). CLEO/Europe – EQEC 2017, Munich Germany (UCL team).

EPITAXIAL GROWTH OF III-V QUANTUM DOT LASERS ON SILICON SUBSTRATES FOR SILICONPHOTONICS (2017). 21st American Conference on Crystal Growth and Epitaxy (ACCGE-21), *and* 18th US Workshop on Organometallic Vapor Phase Epitaxy (OMVPE-18) *and* 3rd Symposium on 2D Electronic Materials *and* Symposium on Epitaxy of Complex Oxides, Santa Fe, USA (UCL team).

Direct growth of III-V quantum-dot lasers on silicon (2017). Group-IV Photonics 2017, Berlin, Germany (UCL team).

Journal Article / Review

Photonic integration platform with pump free microfluidics (2017). Thomas R, Harrison A, Barrow D, Smowton PM. Optics express (V: 25, #: 20, Pg: 23634-23644)

Electrically pumped continuous-wave 1.3 µm InAs/GaAs quantum dot lasers monolithically grown on on-axis Si (001) substrates (2017). Chen S, Liao M, Tang M, Wu J, Martin M, Baron T, Seeds A, Liu H. Optics express (V: 25, #: 5, Pg: 4632-4639).

Electrically Injected Hybrid Organic/Inorganic III-Nitride White Light-Emitting Diodes with Nonradiative Förster Resonance Energy Transfer (2017). Ghataora S, Smith R, Athanasiou M, Wang T. ACS Photonics (#: 2)

Monolithically Integrated Electrically Pumped Continuous-Wave III-V Quantum Dot Light Sources on Silicon (2017). Liao M, Chen S, Huo S, Chen S, Wu J, Tang M, Kennedy K, Li W, Kumar S, Martin M, *et al.* IEEE Journal of Selected Topics in Quantum Electronics (#: 6).

A real time high sensitivity high spatial resolution quantum well hall effect magnetovision camera (2017). Liang C, Balaban E, Ahmad E, Zhang Z, Sexton J, Missous M. Sensors and Actuators A: Physical (V: , #: , Pg:)

Heat-sink free CW operation of injection microdisk lasers grown on Si substrate with emission wavelength beyond 1.3 µm. (2017). Kryzhanovskaya N, Moiseev E, Polubavkina Y, Maximov M, Kulagina M, Troshkov S, Zadiranov Y, Guseva Y, Lipovskii A, Tang M, *et al*. Optics letters (V: 42, #: 17, Pg: 3319-3322).

High Detectivity and Transparent Few-Layer MoS/Glassy-Graphene Heterostructure Photodetectors (2018). Xu H, Han X, Dai X, Liu W, Wu J, Zhu J, Kim D, Zou G, Sablon KA, Sergeev A, *et al*. Advanced materials (Deerfield Beach, Fla.), Publication ID 29380432.

Investigations of Asymmetric Spacer Tunnel Layer Diodes for High-Frequency Applications (2018). Zainul Ariffin K, Wang Y, Abdullah M, Muttlak S, Abdulwahid O, Sexton J, Ian K, Kelly M, Missous M. IEEE Transactions on Electron Devices (#: 1), Publication ID 10.1109/TED.2017.2777803

InGaAs/AlAs Resonant Tunneling Diodes for THz Applications: An Experimental Investigation (2018). Muttlak S, Abdulwahid O, Sexton J, Kelly M, Missous M. IEEE Journal of the Electron Devices Society (#: 1), Publication ID 10.1109/JEDS.2018.2797951

Case Study: Publication relating to Li-Fi

ACS Photonics Publication – A Technological Breakthrough in Fast White Light

The results on fast white light from hybrid III-nitride/organic LEDs for Li-Fi from the Sheffield team were published in the journal, ACS Photonics (http://pubs.acs.org/doi/abs/10.1021/acsphotonics.7b01291).

The technical breakthrough reported in the publication were then immediately highlighted on 1st December 2017 by eeNews Europe, one of the most renowned and popular science and technology media providers (http://www.eenewseurope.com/news/researchers-design-fast-white-light-hybridized-inorganicorganic-led).

The research demonstrated fabrication of an electrically injected hybrid organic/inorganic III-nitride white LED using a 2D microhole array structure.

The hybrid device was characterised, and exhibited high performance electrical properties, ultrafast response and photoluminescent quantum yield of the inorganic and organic materials systems.

This is a significant step forward in the lighting revolution, that is expected to lead to “smart-lighting” in the future.

ACS Photonics
Article
Cite This: ACS Photonics 2018, 5, 642–647

Electrically Injected Hybrid Organic/Inorganic III-Nitride White Light-Emitting Diodes with Nonradiative Förster Resonance Energy Transfer

Suneal Ghataora, Richard M. Smith, Modestos Athanasiou, and Tao Wang*
Department of Electronic and Electrical Engineering, The University of Sheffield, Mappin Street, Sheffield, S1 3JD, United Kingdom

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“LED geometry significantly enhances proximity between the inorganic active-region and the down-converting yellow organic light-emitting polymers (OLEPs), enabling the near-field nonradiative Forster resonance energy transfer (FRET) process with high efficiency while retaining excellent electrical characteristics of an unpatterened planar LED. A reduction in the recombination lifetime in the InGaN/GaN blue active region has been observed with the hybrid device, confirming the nonradiative FRET process occurring between the InGaN/GaN blue active region and the yellow organic polymer. This results in a typical FRET efficiency of 16.7%, where the FRET interaction area accounts for approximately 0.64% of the remaining blue-emitting inorganic LED, but enhancing total device efficiency. An optimised white-light EL emission is achieved with typical CIE colour coordinates at (0.29, 0.32).”

Researchers design fast white light from hybridized inorganic/organic LED

December 04, 2017 // By Julien Happich — 0 Comments

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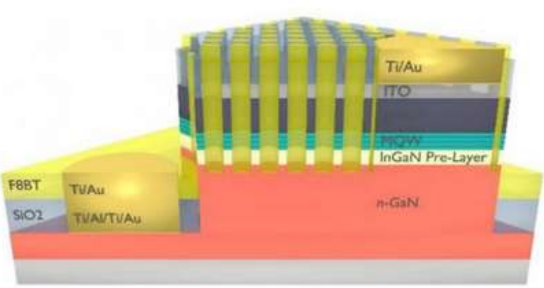


While today's most common approach to creating white light is to cap blue- or ultraviolet-emitting LEDs with down-conversion yellow phosphor materials, such white lights suffer from several inherent limitations, including phosphor inefficiency, stability and a relatively slow response time in the order of microseconds, which restricts their applicability to Li-Fi at bandwidths under 1MHz when unfiltered.

Key Performance Indicator: FOCUS ON TRAINING

The Importance of Training for the CS Hub

The CS Hub has a strong training ethos with an expansive remit. The Hub is committed to delivering high quality and relevant training in many aspects of academic and corporate life. Training has and will have wide relevance to a variety of individuals associated with Hub activity. from associated undergraduate students to high level academics / management (as needed) Training to be delivered includes technical scientific training for Hub members and users, training in engagement and research communication for Hub scientists, as well as novel and bespoke training in line with the remit of the Hub and the commitment of the Hub to research excellence and translation.

The training programme for the Hub involves a high level of input from the outstanding engagement programme run from Cardiff University School of Physics and Astronomy, as well as Hub partner Science Made Simple, and the founder of this partner, Wendy Sadler M.B.E.

Where possible, training activities will be coordinated with other relevant events such as national and international conferences, Hub meetings, and other academic and industrial gatherings. Training will also be provided on an ad hoc basis depending on need and demand.

Images taken at the CS Hub "Creative Engagement" training event. The training was delivered at the CS Hub Strategic Advisory Board meeting in October 2017. A range of Hub members from PhD students to the Hub Director were trained by Wendy Saddler of Science Made Simple via a bespoke training programme. Full details overleaf.

KEY PERFORMANCE INDICATOR:

Training

Case Study: Training in Creative Engagement

Bespoke Training Provided to CS Hub by Award Winning Provider

We are fortunate in Cardiff to benefit from the highly acclaimed "Science Made Simple" programme, founded by Wendy Sadler MBE. This highly acclaimed science communication programme pledged their support for the CS Hub pre-award, and have dedicated a number of free training sessions to aid Hub members in communicating their research.

The first exciting and completely unique training session provided courtesy of Science Made Simple was held at the Hub's Strategic Advisory Board meeting in October 2017. The training, entitled "Creative Engagement", was devised and delivered by Wendy Saddler, specifically for the Hub. Hub members, from PhD students to Strategic Advisory Board Members, were trained in how to communicate their research in an accessible and novel way.

Current ways of thinking regarding communication of research were challenged, as well as traditional engagement strategies.

The training consisted of information sessions, structured group activities incorporating a variety of props and aids, and feedback and summary sessions. The full programme for the session can be found below, photographs taken during the training are on the previous page, including photographic evidence of the novel use of Lego bricks in developing creative technique!

Eighteen Hub members were involved in the highly interactive session. Feedback indicated a high level of satisfaction in the relevance of the training to the individuals involved.

We plan to develop further bespoke training events for the CS Hub with the help of Science Made Simple and other training providers for delivery during the remainder of the Hub project.

Bespoke Creative Engagement Training Programme

Devised by Science Made Simple
Delivered at the CS Hub Strategic Advisory Meeting, October 2017

1. Introduction to creativity:

What is it?
Why is it useful for scientists?
What processes and tools are there for increasing creativity?

Training delivered using a series of creative games based around de Bono's hats, and the creativity spectrum. These tools were used to explore different types of creativity and the requirement for a variety of creativity types for high performing teams.

2. **Introduction to engagement:**

What messages do you have that you want others to know?
Who needs to know / receive these messages?
What are these recipients interested in?
Connections between the message and recipient interest.

Activities were used to facilitate trainees thinking creatively about how to connect research with an audience using the methods learned in the session so far.

3. **Facilitated time** to develop something creative to be used in engagement settings

CS Hub information stand, shared with Institute for Compound Semiconductors. IOP event at Welsh Assembly, Cardiff, January 2018

Key Performance Indicators: FOCUS ON OUTREACH

New Outreach Activity, Including Training, Impact & Career Development

Outreach is a vital component of our CS Hub. During our first reporting period, we have achieved success in this key performance indicator in a number of novel ways.

Most importantly, the CS Hub now has a web presence, with a dedicated website at

http://compoundsemiconductorhub.org/

This is accompanied by the development of other promotional material, including a new Twitter feed, leaflets, and a quarterly newsletter (the first of which can be found overleaf as an example).

The Hub has been represented by a trade stand at several events, and has been key in facilitating the promotion of the CS Cluster across the UK. We intend to expand and build on these opportunities for engaging and reaching out to all stakeholders involved in the project.

Training

Cardiff University has begun providing (2017) an MSc course in Compound Semiconductor Physics.

Apprenticeship training is being set up with Welsh Assembly, Cardiff University and local further education providers and local companies.

3 PhD students funded through Sheffield University started at the end of September on projects related to the Hub. One of the related Sheffield MSc modules is EEE6395 Compound Semiconductor Device Manufacture.

2 PhD students related the Hub and partly funded by UCL will start soon.

18 members of the CS Hub were trained in Creative Engagement, a bespoke course provided specifically for the Hub by Science Made Simple, and delivered at the Hub's Strategic Advisory Meeting, Autumn 2017.

The Cardiff team are creating a continuing professional development offering for local companies and have agreed delivery for Newport Wafer Fab Ltd, a silicon focussed fab looking to expand its CS offering.

Outreach

The Sheffield team accepted 3x A-Level students for one-week of work experience, 1 with Cambridge offer, and 1 with Imperial offer to study Physics.

Tao Wang and colleagues organised & held an Industrial Event on 10 January 2017, CS technologies were highlighted, attracted >10 UK semiconductor company CEOs or Directors.

Attendance and provision of a trade/information stand and/or presentations at various events including: Engineering Wales Conference (2017), CoInnovate Conference (2017), Wales Week in London (CS Cluster Showcase Event, 2018), Institute of Physics in Wales Event (2018).

CS Hub trade stand, CoInnovate Conference, January 2018, Mercure Holland House Hotel, Cardiff

Career Development

Hub staff have been awarded 2 prestigious fellowships for Hub connected activity.

Siming Chen (UCL) was awarded an RAEng Fellowship for Hub related activity.

KEY PERFORMANCE INDICATOR:

New outreach activity to include training, impact and career development

Case Study: Newsletter Example

The First Quarterly Newsletter for the CS Hub

Newsletter One, January 2018

Future Compound Semiconductor Manufacturing Hub

Newsletter

January, 2018

CS Hub

Come and see us in January @

- IoP reception, Welsh Assembly, Cardiff. Jan 18;
- CoInnovate 2018, Mercure Holland House Hotel, Cardiff, Jan 24.

Welcome to 2018 from the CS Hub!

"2017 saw the foundations for the success of the Future Compound Semiconductor Manufacturing Hub (CS Hub) become well established, and we look forwards to a promising and exciting 2018.
Our Cardiff University Hub, is working seamlessly together with our spokes at Manchester University, Sheffield University, and University College London towards addressing the significant challenges of high volume, high quality and low cost manufacture of compound semi-conductors via industry relevant research.
A core set of our 30+ industrial collaborators work with us to support and ensure the relevance of our research.
We have truly begun our journey towards revolutionising compound semiconductor manufacture, exceeding our expected performance and making significant progress towards our strategic objectives."

Prof Peter Smowton
CS Hub Director

New CS Hub website launched

Launched at the end of December 2017, the new CS Hub website is the place to visit for CS Hub related information, news and much more. Take a look at:
http://compoundsemiconductorhub.org/

Feasibility Studies in CS Manufacturing Challenges:

Call for Proposals OPEN NOW for funds to enable the inclusion of new academic and industrial CS Hub partners bringing additional value to key manufacturing challenges in CS research. Funding is for 8x £40k awards for up to 6 months, with follow on funding for 4x £120k awards. Funding is intended to lead to a large scale EPSRC or Innovate UK application with strategic alignment to the CS Hub. See our website for details and to apply.

SIOE Conference Call for Abstracts

The Semiconductor and Integrated Opto-Electronics (SIOE) Conference will take place in Cardiff, Wales, 27-29th March 2018. Deadlines: Abstract submission – 1st Feb. Registration – 27th March.
http://compoundsemiconductorhub.org/2017/12/28/sioe-conference-call-for-abstracts/

CS Hub Studentships Available

We have a number of available PhD studentships available. Details are on our website. Applications are requested from UK and EU nationals with an excellent first degree in Physics, Engineering or Materials Science and a good background in semiconductor physics.

Engineering Wales Conference

The Hub shared a joint trade stand with the Institute for Compound Semiconductors (Cardiff University) at the first "Engineering Wales" conference. Designed to enhance the voice of engineering and promote Welsh activities and scientific achievements, of which, compound semiconductor activity is a significant component, the conference also included a workshop on the South Wales Compound Semiconductor Cluster hosted by Prof Paul Tasker and Dr Wyn Meredith.

Wins at the BEPA Awards 2017

Prof Peter Smowton, CS Hub Director was awarded **Individual Impact**, recognising his leading efforts in compound semiconductor manufacturing research, work with other universities and 30+ businesses, as well as running a KTP with industry leader IQE.
Further recognition was received by the CS Hub host institution, Cardiff University, winning **University of the Year** by virtue of it's plans to create a new innovation campus for industry partnerships and the generation of £13.4m from intellectual property (2017).
The Economic Impact Award was also received in relation to work undertaken by the CS Hub, recognising the collaboration between Cardiff University and IQE for their work in building a compound semiconductor cluster in South Wales.

Cardiff University Prifysgol Caerdydd · The University Of Sheffield. · MANCHESTER 1824 The University of Manchester · UCL · EPSRC Engineering and Physical Sciences Research Council

Highlight: BEPA Award Winners 2017

Prof Peter Smowton Wins "Individual Impact of the Year"

At the same Business and Education Partnership awards 2017, Cardiff University received the Economic Impact Award for it's work with IQE on compound semiconductors. Cardiff University was also named as University of the Year.

Prof Peter Smowton wins "Individual Impact of the Year" continued

CS Hub Director, Prof Peter Smowton played an integral role in winning three significant awards for translational research at the annual *Insider's* Business and Education Partnerships Awards (BEPA) 2017.

Prof Smowton's research as CS Hub Director was recognised in his "Individual Impact Award". The highly translational research of the CS Hub was also pivotal in awards for Cardiff University in the categories "University of the Year" and "Economic Impact". The awards, held at the Marriott Hotel, Cardiff on 2nd November 2017, were a celebration of the integration of work across universities, colleges and companies to achieve world-leading results with huge economic and commercial benefit to Wales.

The **Individual Impact Award** was recognition of Prof Smowton's efforts in translating compound semiconductor research to manufacturable output. The award recognises the vast collaborative networks set up to facilitate this high impact work. For example, the CS Hub alone involves three other academic institutions and 30+ industrial partners which are continually being built on to ensure excellence, reach and relevance. In addition, the Knowledge Transfer Partnership (KTP) between Cardiff University and CS industry leader IQE also directed by Prof Smowton was an important factor.

Cardiff University itself was awarded **University of the Year** thanks to a huge commitment to innovation, partly in the form of a massive investment in the new Innovation Campus at a new University site on Maindy Road, Cardiff. This new Campus will house the facilities for the Institute for Compound Semiconductors, and some staff and equipment from the CS Hub, once it is completed. The Innovation Campus will be ideally situated on a site next to the brand new Cardiff University CUBRIC building, and the University flagship building, Hadyn Ellis. The Campus creates a new dedicated space to develop academic / industry partnerships at the University. In addition to the new campus, the University generated significant funds (£13.4m) from intellectual property during 2017.

A further award for Cardiff University in collaboration with IQE completed the trio. The **Economic Impact award** specifically acknowledged the first compound semiconductor cluster world-wide. The formation of this cluster has been driven by the South Wales research and industry landscape, and reflects the huge amount of work being undertaken in the area to develop manufacturable and economic compound semiconductors to enable next generation technologies. The expected outcome of this work will be the creation of a large number of highly skilled and highly paid jobs, and a vital boost for the local and UK economies.

https://www.insidermedia.com/event/insider-business-and-education-partnerships-awards-2018/coverage

Winner
Economic Impact

Winner
University of the Year

Winner
Individual Impact

Highlight: IEEE Award Won by Hub Co-Investigator

IEEE Microwave Theory & Techniques Society Award

We congratulate Professor Alwyn Seeds, Head of the Photonics Group at UCL, and CS Hub associated member, who has been awarded the 2018 Distinguished Educator Award of the IEEE Microwave Theory and Techniques Society (MTT-S).

Prof Seeds was awarded for: “Outstanding Achievements as an Educator, Mentor, and Role Model for Microwave Engineers and Engineering Students.”

Only the most distinguished educators in the field of microwave engineering and science are honored with this award. Winners must exemplify the special qualities demonstrated by the late Fred J. Rosenbaum, who considered teaching one of the highest callings, and tirelessly served MTT-S, with infallible dedication.

The award winner will be recognized through receipt of a plaque, certificate and honorarium. The award will be made to Prof Seeds at the annual Society Awards Banquet, an event held during the International Microwave Symposium (10 - 15 June 2018) in Philadelphia, Pennsylvania, USA.

Professor Alwyn J. Seeds holds a BSc in Electronics, a PhD in Electronic Engineering and a DSc (Eng.), all from the University of London. From 1980 to 1983 Prof Seeds was a Staff Member at Lincoln Laboratory, Massachusetts Institute of Technology (MIT), before being appointed Lecturer in Telecommunications at Queen Mary University of London (QMUL) in 1983. During 1986 he relocated to UCL where Prof Seeds is currently Professor of Opto-electronics and Head of the Photonics Group.

Prof Seeds is also Chairman of the IEE Photonics Professional Network, a previous chair of the IEEE International Topical Meeting on Microwave Photonics Steering Committee and has served as the Conference Chairman or Technical Programme Committee Chairman for many international conferences. He is a co-founder of ZinWave Inc., a wireless technology company. He was elected an IEEE Fellow in 1997 for his contributions to the development of microwave photonic devices and systems and a Fellow of the Royal Academy of Engineering in 2003.

Professor Seeds is author of over 250 papers on microwave and opto-electronic devices and their systems applications and presenter of the video "Microwave Opto-electronics" in the IEEE Emerging Technologies series.

Prof Seeds research areas of interest include:

- •Photonic generation and detection of THz signals
- •Optical communication systems
- •Wireless over fibre systems
- •Application of optical techniques to microwave systems
- •Optical frequency synthesis
- •Coherent optical detection technology
- •Opto-electronic device technology, especially using quantum effects
- •Tuneable semiconductor lasers, especially fast tuning and athermal operation
- •Optical regeneration and signal processing
- •Optical control of microwave devices

Image shows Professor Alwyn Seeds PhD, DSc(Eng.) FREng, FIEE, FIEEE, Professor of Opto-Electronics, UCL.

ENGINEERING WALES CONFERENCE
CYNHADLEDD PEIRIANNEG CYMRU

http://www.ernw.ac.uk/en/

Case Study: Engineering Wales Conference, 2017

CS Cluster Runs a Highly Successful Workshop & the Hub's First Trade Stand

Prof Peter Smowton, CS Hub Director (left) discusses the latest in compound semiconductor research with Prof Paul Meredith from Swansea University.

Case Study continued

As part of the Welsh Government's Ser Cymru initiative, The National Research Network (NRN) in Advanced Engineering and Materials (AEM) hosted the first "Engineering Wales" conference at the Mercure Holland House Hotel, Cardiff, Wales.

The event was designed to enhance the voice of engineering and promote Welsh activities and scientific achievements during this one day event, via a series of talks, workshops and stands. Compound semiconductor activity in South Wales represents a huge part of this scientific work.

The Hub shared a joint trade stand with the Institute for Compound Semiconductors (Cardiff University), while Prof Paul Tasker and Dr Wyn Meredith hosted a workshop on "South Wales Compound Semiconductor Cluster" with assistance from Prof Peter Smowton.

Images show CS Hub Members taking part during the inaugural Engineering Wales Conference. Wyn Meredith (top) and Prof Paul Tasker (left) took leading roles in the event; Trade stands at the event are shown below.

EW ENGINEERING WALES CONFERENCE CYNHADLEDD PEIRIANNEG CYMRU

http://www.ernw.ac.uk/en/

Case Study: Photonics Industry Event

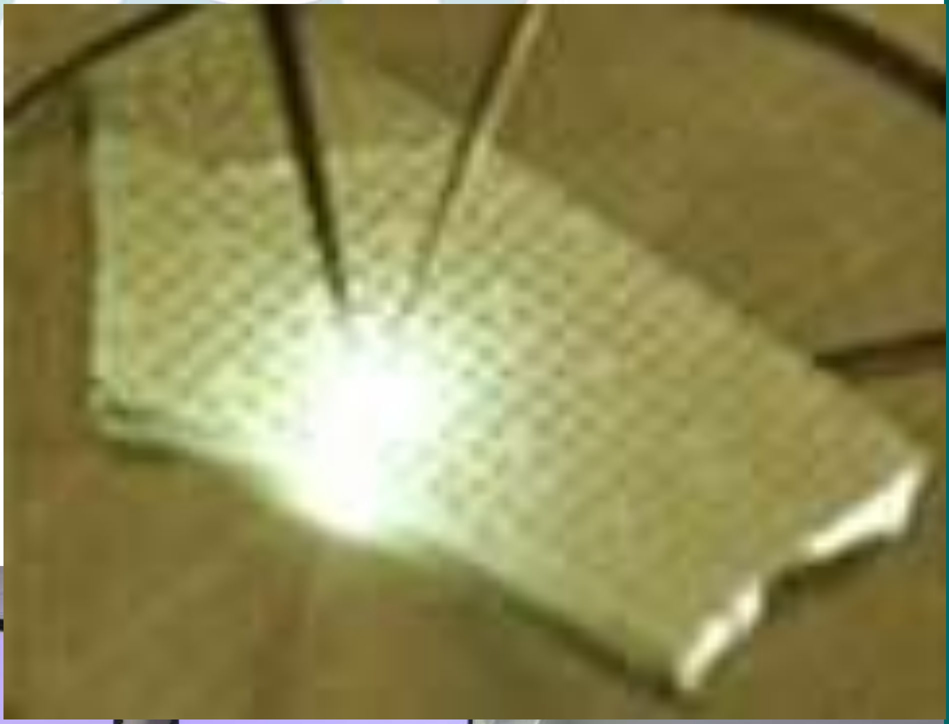
A One-Day Event to Connect Academics with Key Industries

Held on 10th January 2018, and hosted by CS Hub partners, Sheffield, a one day event promoting the interaction between industry and academia proved highly successful. During the event technologies developed as part of CS Hub work packages were showcased by academics to a variety of potential new industrial partners.

The event attracted around 30 participants from across the UK semiconductor industry. This included CEOs or Technical Directors from at least 10 participating companies.

We hope to further cultivate the connections made into new industrial partnerships with a focus on translating the photonics research of the CS Hub into industry relevant manufacturable research.

Images show: Research image from Prof Tao Wang's team, University of Sheffield (right). High magnification picture of monolithic white (B+Y) LEDs on sapphire; Attendees at the photonics industry event held at the University of Sheffield, January 2018 (below).



Case Study: SIOE Conference, 2018

CS Hub Plays a Key Role in the 32nd Annual SIOE Conference

The CS Hub was key in organising and promoting the Semiconductor and Integrated OptoElectronics (SIOE) Conference, 2018.

With strategic alignment to the CS Hub, SIOE is an annual event coordinated by Hub Director Prof Peter Smowton.

The conference provided an opportunity for Hub PhD students, post-doctoral research associates and senior scientists / academics to present and hear about the latest in semiconductor research, as well as network and engage with over 80 individuals within the semiconductor field from across the world.

Relevant research areas included: Growth and fabrication including well / wire / dash and dot materials and devices; Solar cells / photovoltaics; Mid-infra-red semiconductor opto-electronics; Micro-cavity and photonic band-gap effects in semiconductor opto-electronics; Semiconductor lasers and optical sources including organic LEDs and lasers; Gallium Nitride (GaN) based materials and devices; Theory and numerical simulations of semiconductor opto-electronic devices; Optical detectors, modulators, amplifiers and switches; All-optical and opto-electronic integrated circuits.

Contributions from Hub members included oral and poster papers delivered at Cardiff University from 27th to 29th March 2018. In addition, a significant contribution was made by world-renowned guest speakers, Dr Sebastian Schultz (University of St Andrews), and Dr Gregor Kobelmueller (Technical University of Munich). Over 80 delegates attended, with individuals based in USA, Saudi Arabia, Denmark, Germany, France and Iraq making this a truly international event.

The SIOE Conference is held annually at the School of Physical and Astronomy, Cardiff University (top); A special issue of IET Optoelectronics will include additional information on papers presented (left); As part of the conference, an annual banquet at Cardiff Castle (below) provides an excellent opportunity for delegates to network.

Appendix: Contributing Researchers

CS Hub Researchers / Contributors

Work package leads & investigators

Prof Peter Smowton
Prof Diana Huffaker
Prof Alwyn Seeds
Prof David Wallis
Dr Phil Buckle
Prof Huiyun Liu
Dr Khaled Elgaid
Prof Paul Tasker
Prof Tao Wang
Prof Mo Missous
Dr Marie Delmas
Dr Max Migliorato
Prof Sir Michael Pepper
Dr Jiang Wu
Dr Jon Wilmot
Dr Rick Smith

PhD students

Lydia Jarvis
Nicolas Poyiatzis
Ying Lu
Saad Muttlaak
Omar Abdulwahid
Tahani Albiladi

Key associated academic & research staff

Dr Craig Allford
Dr Daryl Beggs
Dr Anthony Bennett
Dr Siming Chen
Dr Stella Elliott
Dr Connie Eng
Dr Rob Harper
Dr David Hayes
Dr Hassan Hirshy
Dr Lewis Kastein
Dr Emmanuel le Boulbar
Dr Qiang Li
Dr Zhibo Li
Dr Chen Wei Liang
Clive Meaton
Dr Wyn Meredith
Dr Sudha Mokkapati
Dr Chris North
Dr Roberto Quaglia
Wendy Sadler MBE
Dr Majid Salhi
Dr Saleem Shabbir
Dr James Sexton
Dr Angela Sobiersierski
Dr Sam Shutts
Dr Mingchu Tang
Dr Sarah Taylor
Dr Xiang Yu

CS Hub PDRAs, Dr Sam Shutts and Dr Emmanuel Le Boulbar, work in clean room facilities.

Appendix: Selected Links

Compound Semiconductor Cluster Member Links

EPSRC Future Compound Semiconductor Manufacturing (CS) Hub:
http://www.compoundsemiconductorhub.org.uk
Institute for Compound Semiconductors (ICS), Cardiff University:
http://www.cardiff.ac.uk/institute-compound-semiconductors
Compound Semiconductor Centre (CSC):
http://www.compoundsemiconductorcentre.com/
Compound Semiconductor Applications (CSA) Catapult:
https://csa.catapult.org.uk/
Compound Semiconductor (CS) Connected:
http://www.csfusion.org/

Funder Links

EPSRC:
https://www.epsrc.ac.uk/

CS Hub Academic Partner Links

Cardiff University:
http://www.cardiff.ac.uk/physics-astronomy
The University of Manchester:
www.manchester.ac.uk/
University of Sheffield:
https://www.sheffield.ac.uk/
University College London:
https://www.ucl.ac.uk/

Selected News Stories Links

http://www.cardiff.ac.uk/news/view/798214-cluster-open-for-business
https://www.cardiff.ac.uk/news/view/992549-cardiff-named-university-of-the-year
http://www.cardiff.ac.uk/news/view/914129-institute-for-compound-semiconductors-gathers-pace
http://www.cardiff.ac.uk/news/view/804532-cs-connected-unites-cluster
http://www.cardiff.ac.uk/news/view/975990-cardiff-partner-iqe-wins-top-aim-award
http://www.cardiff.ac.uk/news/view/926379-signing-seals-worlds-first-compound-semiconductor-cluster
http://www.cardiff.ac.uk/news/view/914129-institute-for-compound-semiconductors-gathers-pace

Images show examples of CS hub engagement activities from year one.