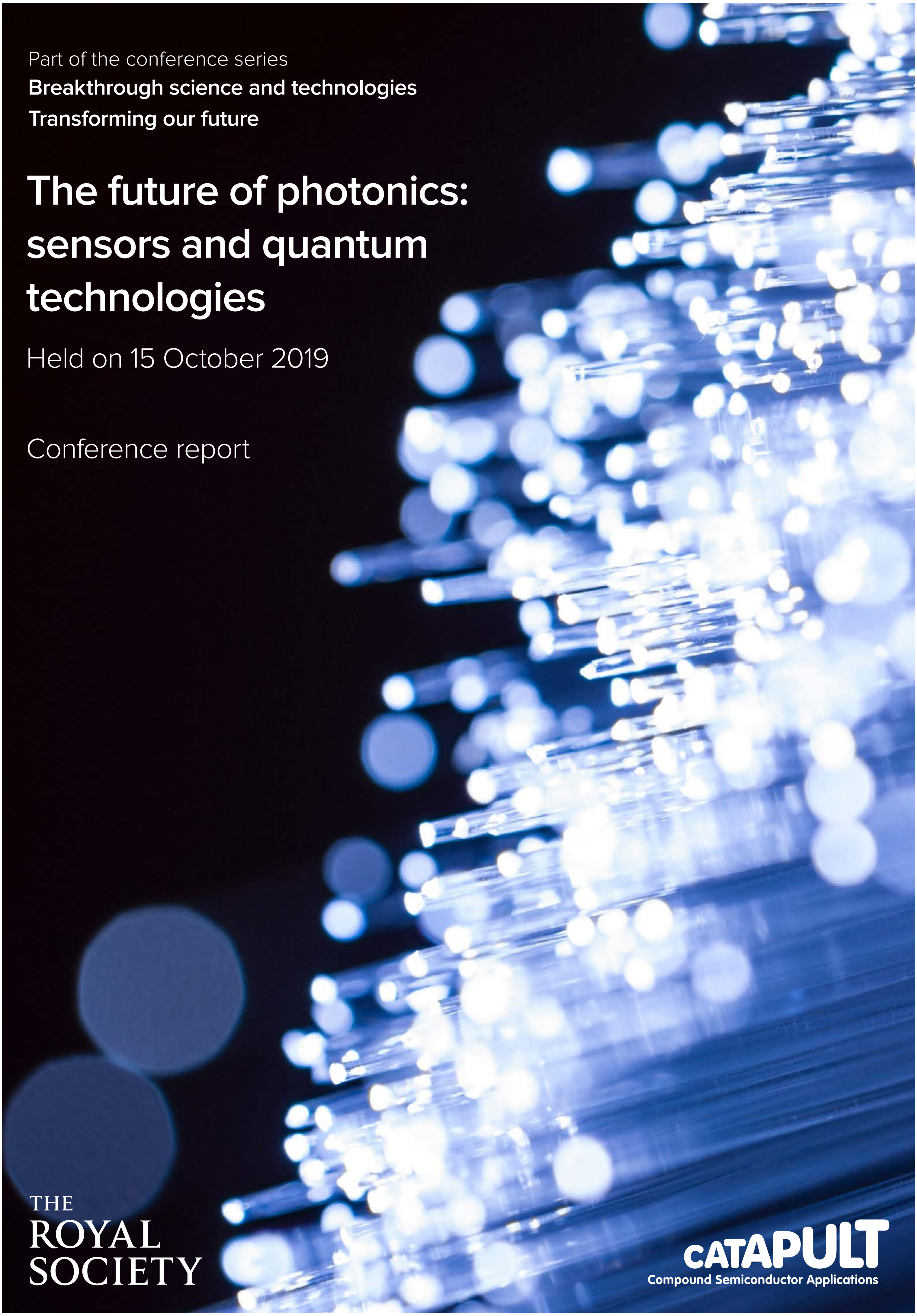
Part of the conference series
Breakthrough science and technologies
Transforming our future

The future of photonics: sensors and quantum technologies

Held on 15 October 2019

Conference report



THE ROYAL SOCIETY

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Compound Semiconductor Applications

Introduction

Photonics is the science of light generation, detection and manipulation and is used to develop technologies spanning sources and sensors to quantum computers. It provides the backbone of the internet and will be used in autonomous vehicles, health diagnosis and treatments, and the 5G network.

Photonics is important for the UK economy as a whole. The industry is worth £13.5 billion per annum to the UK, comparable with the pharmaceutical and fintech industries. The sector employs 69,000[1] people across the UK, and supports all of the Government's first four Grand Challenges of the Industrial Strategy: Artificial intelligence and data, Ageing society, Clean growth and Future of mobility.

On 15 October 2019, the Royal Society held a conference on *The future of photonics* at Cardiff City Hall in collaboration with the Compound Semiconductor Applications (CSA) Catapult. The CSA Catapult hosted a VIP reception at their Innovation Centre in Newport on 14 October, signalling its official opening. The conference aimed to bring to light the vast opportunities of photonics for society and the economy in the broader context of regulation, policy and funding. Experts from industry and academia explored current and potential applications of photonic technologies and the future opportunities and challenges that they present, including assuring the skills pipeline, developing technologies for which there are markets, and funding.

This conference is part of a series organised by the Royal Society entitled Breakthrough science and technologies: Transforming our future, which addresses the major scientific and technical challenges of the next decade. Each conference covers key issues including the current state of the UK industry sector, the future direction of research and the wider social and economic implications.

The conference series is organised through the Royal Society's Science and Industry programme which demonstrates the Society's commitment to integrate science and industry at the Society, promote science and its value, build relationships and foster translation.

This report is not a verbatim record, but a summary of the discussions that took place during the day and the key points raised. Comments and recommendations reflect the views and opinions of the speakers and not necessarily those of the Royal Society.

1. UK Photonics Leadership Group, accessed October 2019, https://photonicsuk.org/revolutionising-our-world/uk-photonics-output

Photonics as a platform for a future economy

The Photonics Industry in the UK goes from strength to strength, growing 8.4% in the last two years. Yet the photonics sector maintains a relatively low profile despite its £13.5 billion contribution to the UK economy and employment of over 69,000 people. Dr Chris Dorman OBE, Coherent Scotland, UK Photonics Leadership Group, explored the Photonics Industry and the main markets, the gap between invention and profit, and the skills needed for industrialisation of photonics technology.

The UK Photonics Industry is hidden, being embedded into everyday technologies; automotive, aeronautical and smartphone manufacture all use many photonic processes, but the public is unfamiliar with the term 'photonics'. The UK is very well-positioned for laser, optics and quantum businesses. Figures from July 2019 show that:

- the Photonics Industry in the UK is worth £13.5 billion, employing 69,000 people (comparable with nuclear (63,000) and fintech (76,000);
- £1 in every £17 of UK engineering output is spent in photonics;
- photonics is well-distributed across the country, and seven regions in the UK have more than £1 billion photonics output;
- The industry has grown by 4.3% per year (2013-2019), a rate four times the average UK manufacturing growth; and
- the laser industry has demonstrated an unusually high compound annual growth rate of 15% per year.

"Photonics is a significant employer and source of income for the UK, but the industry is hidden. We need to bang the drum to show that photonics is a significant industry."

Dr Chris Dorman OBE, Coherent Scotland, UK Photonics Leadership Group.

FIGURE 1

Key figures for the Photonics Industry in the UK as of July 2019.

Credit: UK Photonics Leadership Group.

For the photonics sector to thrive, there is a need not only for technical skills but additionally people who understand operations, business and markets. Developing specific photonics degrees out of engineering would help reduce the burden on photonics businesses to retrain engineers and physicists, and help turn research into products. There is also a need for people trained across all levels from technician to PhD, people with management skills, and product line managers interested in commerce and sales.

The Valley of Death is the concept that academic research is not translated into products, profit and jobs. To create a product, ~10% of funding goes into research and the remaining ~90% into making a product.

As developing a new laser platform costs $5-10 million, researchers should carefully consider where investment in productisation would come from and whether there is customer demand.

Photonics markets are diverse, from multiphoton imaging for neuroscience research to narrow line lasers for detection of gravitational waves. A large area of growth in the photonics sector, for example, has been in production of laser picosecond pulses that cut material without causing heating. This has become a key step in the development of mobile phones, representing a huge hidden part of the photonics market and the application of cutting-edge technology.

Image: (left to right) Dr Chris Dorman OBE, Coherent Scotland, UK Photonics Leadership Group; Dr Andy G Sellars, Compound Semiconductor Applications Catapult; Dame Sue Ion FREng FRS, Chair of the Royal Society Science, Industry and Translation Committee.

Development and applications of photonic sources and sensors

Dr Drew Nelson OBE FREng, IQE, focused on the materials innovations driving the performance and application areas for new photonic devices using VCSELs (vertical cavity surface-emitting lasers), relating these innovations to the UK's ability to compete effectively in the global marketplace for advanced photonic devices supported by industry clusters.

Leading innovation from within the UK

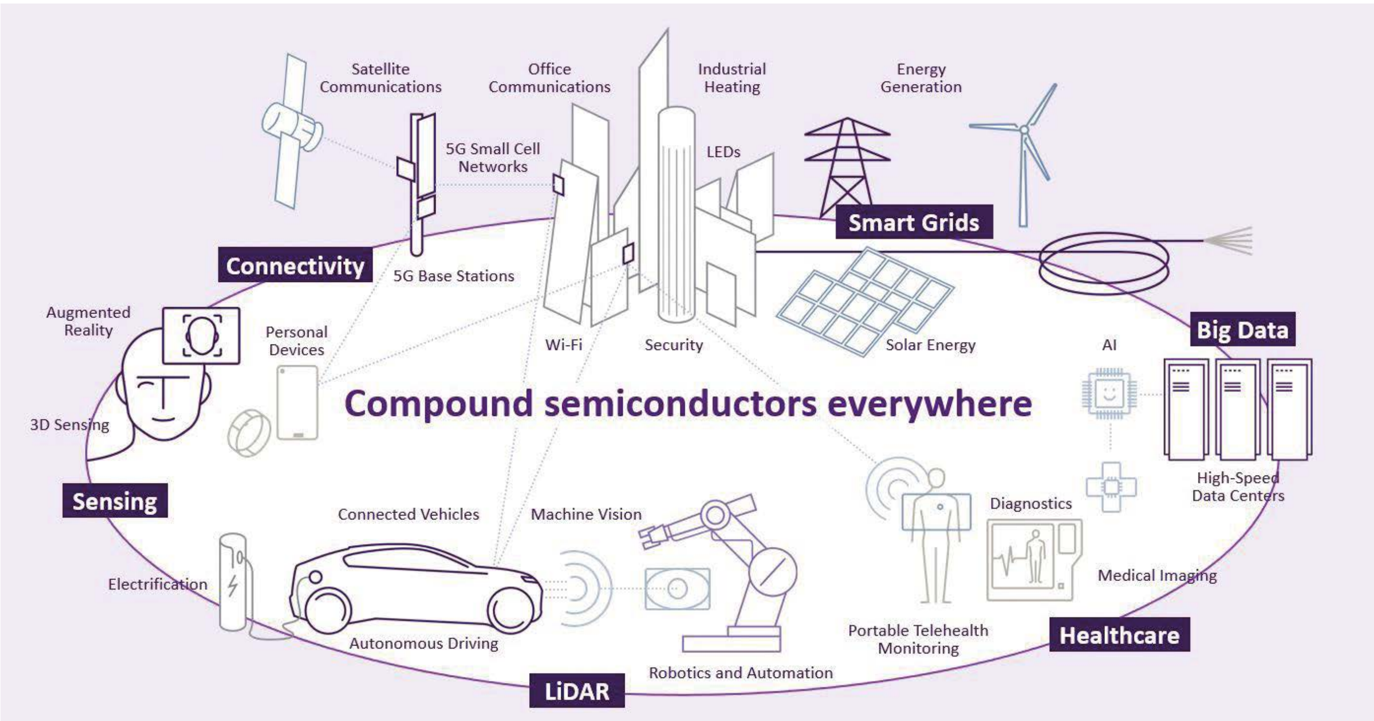
Photonics is at the forefront of numerous new applications spanning almost all industrial sectors from communications and the Internet of Things to autonomous vehicles, aerospace, healthcare, clean energy, lighting, 3D sensing and quantum computing. Meanwhile, everyone has a personal device using photonics to deliver information immediately. Compound semiconductor materials are at the heart of these technologies, and the entire global communications network would not work without them.

One market helping to accelerate photonics adoption is 5G, which allows delivery of large volumes of data. As well as 5G, IQE is focusing on high growth areas across photonics including 3D sensing, infrared imaging and optical communications.

> "The future of photonics is extremely bright."
>
> Dr Drew Nelson OBE FREng, IQE.

FIGURE 2

The applications of compound semiconductors are all-pervasive.



Credit: IQE.

VCSEL markets and 3D sensing

VCSELs have been a key area of development for IQE for 20 years and are one of three basic semiconductor light sources, alongside LEDs (light-emitting diodes) and EELs (edge-emitting lasers). They comprise hundreds of semiconductor layers, with applications ranging from 3D sensing to LIDAR (Light Detection and Ranging), cosmetics and data storage. Manufacture is challenging and achieving 100% reflection of the optical beam in a vertical direction requires extreme precision for the thickness of each layer across the whole 6-inch wafer, particularly as in VCSELs the wavelength is controlled by thickness of each layer.

The VCSEL market is predicted to grow to $4 billion by 2024. VCSEL technology is very market driven, and 3D imaging for facial ID in smartphones using mobile range finders is by far the largest driver of the technology. More VCSELs were made in October 2017 than in entire history of laser production, indicating the effect of developing a consumer application on these devices.

Future challenges in this application include driving the cost down, as this optical package is one of the most expensive parts of a phone, and developing VCSELS that use wavelengths longer than 1.3µm which do not damage the eye.

Compound semiconductors have allowed a revolution in image sensing. The biggest future development for photonics will be putting the technology in healthcare wearables to allow early detection for the onset of illness, with scope to transform how we deliver healthcare globally as they facilitate preventative rather than curative therapies. Further innovations within the photonics sector will be supported by the UK's compound semiconductor technology cluster infrastructure.

Gravitational wave interferometers: very large scale quantum sensors for fundamental physics

Professor Sheila Rowan FRS, University of Glasgow, gave the academic perspective on the state of the art in gravitational wave detection and the future developments in photonic technology needed to advance the field.

Gravitational wave interferometers, such as LIGO (the Laser Interferometer Gravitational-Wave Observatory), detect tiny fluctuations in the curvature of space-time resulting from violent astrophysical events. This enables the study of the massive objects that caused such events. When gravitational waves reach Earth, they stretch and squash the Earth's surface and this change can be detected – if we have sensors sensitive enough.

The detection of gravitational waves in 2015 radically changed our ability to study the Universe. The instruments use laser interferometer systems to sense changes in the relative positions of suspended optics. Typical astronomical sources cause displacements of 10^{-18}m or less, and interferometers having arms several kilometres long are needed to measure this effect. Their performance relies on photonic technologies that push the state of the art - from high power lasers to low absorption optical substrates, mirror coatings of ultra-low optical and mechanical loss, and high efficiency photo-detectors.

Noise is the main limitation to instrument sensitivity for gravitational wave detectors. The effect of photo-electron shot noise, associated with the detection of light with photo-detectors, is improved with increasing laser power. However, radiation pressure, where the suspended optics are shaken every time a photon hits them, worsens with increasing laser power. At any frequency there is an optimum light power to use which results in a measurement limited by the Standard Quantum. Seismic noise from the surrounding area can be isolated against using suspended mirrors. Thermal noise, caused by Brownian motion of test masses and suspensions, can be reduced by careful choice of materials: synthetic fused-silica has the lowest mechanical loss of any silica.

Academics work closely with industry to create instruments at the limit of what is possible. The Advanced LIGO Interferometer has a complex internal setup: two detectors of 4km arm length house 40kg mirrors suspended on glass fibres to reduce various sources of noise. This requires instrument science at the frontiers of fundamental limits in physics, especially in optics. Scientists are looking to next generation technologies to address these issues, each with both advantages and technological challenges, such as;

- longer 10km or 40km arms;
- underground sites;
- larger, heavier optics >100kg;
- cryogenic optics for low thermal noise (eg silicon, sapphire); and
- lower thermal noise coatings (eg highly reflective crystalline coating materials such as AlGaAs, or Czochralski silicon).

"The achievement of detecting gravitational waves was only possible through close work with industry, exploring what is possible and pushing the technology. In the future we will remain a very demanding customer to industry, as well as a technical innovator."

Professor Sheila Rowan FRS, University of Glasgow.

Technological convergence between solid-state lighting, electronic displays and optical communications

Professor Martin Dawson, University of Strathclyde, spoke about the application of compound semiconductors to draw together lighting, displays and optical communications via micro-LEDs (LED pixels a few microns in size) that can interact with and sense the environment. These display and lighting systems may offer combinations of communications, sensing, tracking, ranging and imaging functions.

Solid-state lighting based on gallium nitride is an energy efficient semiconductor technology that interfaces very effectively to electronics. This fosters advances from first-generation 'smart lighting' towards 'digital lighting', with sophisticated capabilities including combined illumination and Li-Fi. Gallium nitride micro-LEDs (LED pixels 1-10s µm in diameter, deployable in high-density arrays) are also rapidly emerging as the basis of new ultra-bright, fast response, high-resolution and scalable displays, that could potentially project their output and interact with their environment. The shared underpinning materials and device technologies, and their compatibility with electronics and solid-state photodetectors, offers the exciting potential for convergence between previously disparate lighting, display and optical wireless communications technologies. Display and lighting systems may be interoperable to some degree, as well as offering combinations of communications, sensing, tracking, ranging and imaging functions.

"LEDs are not just for lighting, they're prospectively a big part of the control system behind the Internet of Things. Lighting is now a semiconductor technology and it is becoming super smart and digital."

Professor Martin Dawson, Institute of Photonics, University of Strathclyde.

LED lighting as a semiconductor technology offers many advantages including;

- energy efficiency and robustness. Pixelated LEDs have low energy requirements (~10mW per pixel) but can project over hundreds of meters. Interfacing with CMOS (complementary metal-oxide-semiconductor) electronics will enable wide applications;
- early stage smart lighting;
- tunable light quality (including colour rendering and health aspects); and
- smart interfacing of semiconductor technology with electronics for super-smart lighting. This enables digital control and aspects including indoor GPS, ranging, 3D imaging, secure data communications and Li-Fi.

Micro-LEDs are being used in high-resolution displays by companies including LG and Samsung, and there is clear investor appetite in this field. These displays are distinctive, self-illuminating devices, with nanosecond response time allowing very high frame rates (potentially up to one million frames per second), high brightness, low energy consumption and very high resolution. Applications range from wearables to big screen displays (millions of pixels). Micro LEDs are mostly gallium nitride based and work at any wavelength including down into extreme deep ultraviolet for other applications. One exciting application is structured illumination, photographing an object in the field at very high frequency with different illuminations to reconstruct its 3D shape.

Silicon core fibres for nonlinear photonics

The nascent field of silicon core fibres is attracting increased interest as a means to exploit the optoelectronic functionality of the semiconductor material directly within the fibre geometry. Professor Anna Peacock, University of Southampton, reviewed progress in the development of nonlinear devices from the silicon optical fibre platform. Wavelengths span the telecoms band up to the mid-infrared regime where there is potential for applications in areas such as medicine, imaging, sensing and spectroscopy.

Silicon clad core fibres resemble normal fibres, yet harness interesting optical and electronic properties owing to their semiconductor core material. Although still under development, silicon fibre technologies are displaying several advantages over their planar wafer counterparts as they retain the flexibility, cylindrical symmetry and long waveguide lengths offered by conventional fibre platforms. Silicon fibres also provide a unique platform for nonlinear optical applications, in which it is possible to use high power light focused in the silicon core to modulate other light signals at very high speeds. Using post-processing techniques, attenuation losses in these fibres are now comparable with on-chip technologies, though future work to reduce the losses to ~1dB/m will open up new applications, especially in quantum technologies. Lastly, silicon is transparent over much longer wavelengths than traditional silica, meaning it can be used for applications in healthcare and environmental sensing.

Fiberising silicon, which is normally in wafers, brings several advantages. It allows;

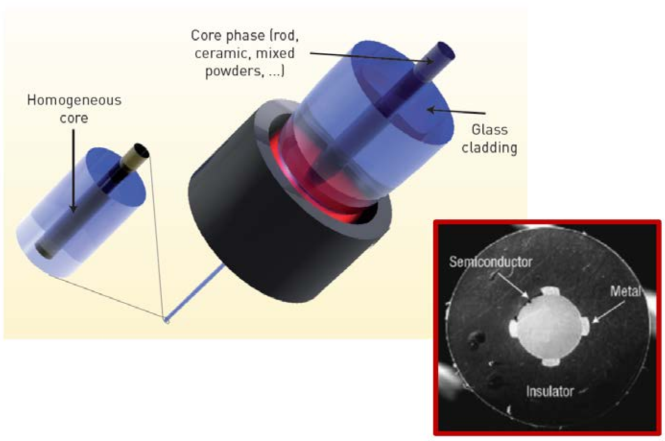
- relaxed constraints on the initial material: the silicon core is heated and drawn down into a fibre, so the starting material can be powder;
- robust all-fibre integrated systems;
- high power operation; and
- novel device designs using fibre geometry.

"The silicon core fibres offer great potential for use in the infrared transmission region, where there are fewer established platforms. However, if we can get the losses down in the telecoms band, their desirable nonlinear properties and ability to be integrated with existing fibre infrastructures could have a significant impact on future communication and even quantum information systems."

Professor Anna Peacock, University of Southampton.

FIGURE 3

Structure of a silicon core fibre and cladding[2].



2. (top left) Peacock, A.C. and Ballato, J., In-fiber silicon photonics. Optics and Photonics News, Vol. 30, Issue 3, (2019). (bottom right) Abouraddy, A. F., Bayindir, M., Benoit, G., Hart, S. D., Kuriki, K., Orf, N., et al., Towards multimaterial multifunctional fibres that see, hear, sense and communicate. Nature Materials, Vol. 6, Issue 5, (2007).

Nonlinearity in silicon

Nonlinear photonics is useful in source generation, where light of a single or narrow band of wavelengths can be converted to new wavelengths spanning a broad spectral region. This facilitates the development of sources where traditional gain materials do not exist and/or the production of sources with much broader or tuneable wavelengths.

Supercontinuum generation uses multiple nonlinear processes to generate a continuum of wavelengths. The fibres can be designed to produce sources at any desired wavelength within the transmission window of the core and with a tuneable source.

The silicon fibres have been engineered to focus on the generation of mid-infrared light owing to silicon's extended transparency and low losses in this region.

Future aims

Much work is currently being done on other semiconductor materials, including germanium and compound semiconductors such as GaSb and GaAs. Future considerations include integrating silicon with other materials for all-fibre coupled semiconductor photonics solutions, particularly for mid-infrared systems.

Image: (left to right) Professor Martin Dawson, Institute of Photonics, University of Strathclyde; Professor Anna Peacock, University of Southampton; Heba Bevan, UtterBerry; Professor Sheila Rowan FRS, University of Glasgow; Sir Colin Humphreys CBE FREng FRS, Queen Mary University of London.

The next generation of sensors for Smart InfraTech

Heba Bevan of UtterBerry™ described the UtterBerry sensor system and its applications in real-time sensing of displacement, strain, seismic activity, crowd movement and the environment for smart city, sport and health applications.

The UtterBerry™ System comprises a collection of miniature, artificially intelligent, ultra-low power sensors. These wireless sensors self-calibrate to form a mesh network via Bluetooth, ZigBee or Thread Mesh networking, relaying data between each other without the need for a line of sight between them. The UtterBerry system is designed to form the core technology required to build Smart Cities and IoT infrastructure. Sensors provide real-time data including displacement, acceleration, temperature, humidity and leak detection. For real-time remote access to the sensor data, the sensors are supported by a base station providing connectivity to the internet or local network. The sensors communicate encrypted data to base stations, which communicate to the cloud via Blockchain technology.

Applications

- Transport – integration with rail transport systems to provide adaptive train scheduling and accurate travel information.
- Construction – ensuring increased efficiency and safety of construction and infrastructure projects via real-time monitoring of movement, vibration and leak detection.
- Infrastructure – monitoring bridge usage by pedestrians, trains or cars.
- Sport – crowd sensing in stadiums with applications in emergency evacuation and athletic performance.
- Smart buildings – real-time monitoring of fire and security systems, as well as energy, water and lighting usage, allows hospitals and businesses to improve safety and reduce operational costs.

Ongoing Utterberry™ monitoring projects include national work with the Thames Tideway Tunnel, such as Tower Bridge, Albert Bridge, Blackfriars Bridge, Greenwich Pumping Station and Chambers Wharf, and international projects such as monitoring the Java Tunnel in Singapore and landslides in Hong Kong.

Market overview

An estimated 75% of the world's population will live in cities by 2050. Smart sensors enable the automated collection of environmental information, facilitating the development of smart cities to enhance quality of life. The global smart sensors market is forecast for 21% compound annual growth rate (2016-2022), reaching $60 billion by 2022. Meanwhile the global smart cities market is estimated to be valued at £900 billion by 2020.

Key market drivers

- Government initiatives to improve infrastructure, reduce congestion and enhance resource deployment.
- The need for urbanisation to be sustainable and resistant to environmental pressures such as climate change.
- Growth of a global urban middle class, with high expectations of public services and infrastructure.
- Rising deployment of smart sensor equipped devices in other sectors, such as healthcare.
- Increasing integration of cloud technology.

> "In today's world, the creation of sensors with radically enhanced performance in artificial intelligence and machine learning requires continuous research into both photonics and the use of recyclable materials."
>
> Heba Bevan, UtterBerry™.

Introduction to photonics for quantum information processing

Quantum technology is making headlines now because of recent discoveries: the ability to isolate single atoms and ions, and trap and cool them to manipulate their states; new sources of single photons; and new efficient photon detectors with very fine timing resolution, leading to new imaging technologies and LIDAR.

Quantum technologies are based on the superposition of states, including energy-levels and photons, in which quantum states can be added together to result in another valid quantum state. A further very important quantum phenomenon is entanglement, where in certain circumstances the properties of multiple particles can be correlated regardless of their separation.

The development of photonics devices and systems remains a critical aspect in quantum technologies. These novel photonic technologies will offer improved reliability and tolerance to environmental conditions, reduced size, weight and power consumption and new levels of performance.

Photonics enabling the commercialisation of quantum technologies

Using photonics effectively for quantum technologies requires the distillation and rapid translation of often esoteric developments in research into robust and cost-effective prototypes. Dr Loyd McKnight, Fraunhofer Centre for Applied Photonics, outlined future challenges and opportunities in this area, as well as centres and industry funding opportunities for quantum technologies.

Applications and challenges

The prospective applications of quantum technologies bring challenges to our traditional technologies but also present new opportunities.

Quantum communication – the ability to encode onto single photons to communicate securely.

- There are huge opportunities for the protection of critical infrastructure including energy, financial services, transport and healthcare, that represent a large risk to public safety and economic activity.
- The 'Quantum Apocalypse' is the risk that one day quantum computing will be able to crack any encryption codes current computers use to protect classified information. Industry will need to pursue new ways of encryption, perhaps using quantum technologies.

Quantum sensing and metrology – using isolated single atoms or ions to create sensors.

- Applications include inertial sensing without reliance on gyroscopes, satellite GPS, ground radar references and the associated security risks. Cold atom technology can be used to build inertial sensors that work over long ranges.
- Gravity gradiometry instruments are being developed which use a cold atom sensor system to investigate underground conditions that could present risks to infrastructure projects. Infrastructure development represents 13% of the world's GDP, and increased investment in technology for surveys has the potential to reduce overspend costs by 25%.

Quantum enhanced imaging – use of single photon detectors to develop new imaging techniques, sensing and LIDAR approaches.

- Quantum enhanced imaging includes environmental monitoring, process control, and monitoring critical infrastructure. Applications include development of precise time of flight systems using single photon detectors (with millimetre depth precision over tens of kilometres) and 100 picosecond laser sources.

Quantum information processing – use of different types of quantum computers in the future.

- Six main architecture options are being explored. The Fraunhofer Centre for Applied Photonics has particular expertise in nitrogen-vacancy centres in diamond. Other technologies include ion traps, superconductors, quantum dots, linear optics and topological.
- Application of quantum computing to develop new drugs, optimise supply chains and offer solutions to financial services.

Funding and research centres

Exploiting quantum technologies is challenging, with obstacles to move ideas from the laboratory environment through to industry. Several substantial new funding schemes and centres for photonics aim to help bridge the gap between academia and industry;

- the UK National Quantum Technologies Programme;
- innovate UK's Innovation Fund;
- the Industrial Strategy Challenge Fund; and
- the Fraunhofer Centre for Applied Photonics.

> "The development of photonics devices and systems remains a critical aspect in quantum technologies."
>
> Dr Loyd McKnight, Fraunhofer Centre for Applied Photonics.

Secure quantum communications

Professor Gerd Leuchs, Max-Planck Institute for the Science of Light, gave an overview of funding for quantum technologies in Germany, and the future application in quantum communication for secure quantum encryption. However, until we have proof that quantum communication works, on either a normal or a quantum computer, its use is risky.

There is currently strong support by the German Government for bringing quantum technologies to industry. QuNET is a joint initiative of the Fraunhofer Society, the German Aerospace Centre and the Max Planck Society, aiming to enable the future of quantum networks by focusing on the underlying engineering challenges. In March 2015, the German Government announced a plan to spend €180 million to secure the digital world and, in 2018, pledged €650 million for 2018 – 2022 to bring quantum technologies to market. The German Government additionally has several published and upcoming calls for work across topics in quantum, including cryptography that is resilient to cracking by quantum, quantum photonics imaging and sensing, innovation in SMEs and enabling start-ups and young scientists' research groups.

Quantum communication, also known as quantum cryptography or quantum key distribution, is a mode of encryption that relies on the idea that there are some problems so difficult that computers take exponential time to solve them. In this way, quantum can ensure security and trustworthiness, for example for quantum voting and signatures. There is no need for a non-classical light source, just for light in a coherent state. Quantum cryptography can be achieved using any two non-orthogonal phase states, using coherent states (continuous variables) or single photons (discrete variables). These two phase states interact to create standing waves.

For quantum key distribution over long distances, the telecom communication must be linked by geostationary satellite rather than optical fibre; attenuation with fibre is exponential, while the attenuation in outer space and the atmosphere is negligible.

> "I believe if there's a new technology it's extremely valuable to push it to its limit to see what you can get out. The initial driver for doing this may not be so important, and I hope by driving this quantum technology further we will be able to find some quantum applications we may not even dream of now."
>
> Professor Gerd Leuchs, Max-Planck Institute for the Science of Light.

A global understanding of quantum technologies: risks and opportunities

Araceli Venegas-Gomez, QURECA (Quantum Resources and Careers), demonstrated how quantum technologies are developing as the emerging technology matures. She outlined clear opportunities across industrial sectors for quantum and future market valuations, potential risks and the importance of narrowing the gap between researchers and those in industry to ensure a society ready for quantum in terms of the technology, market readiness and regulation.

There is a clear opportunity for quantum technologies, with the development of quantum clocks projected within the next five years and quantum computing projected for the next 15 or more years (Figure 4). Meanwhile, markets for Quantum Key Distribution systems and quantum sensors are projected to grow substantially over the next decade (Figure 5).

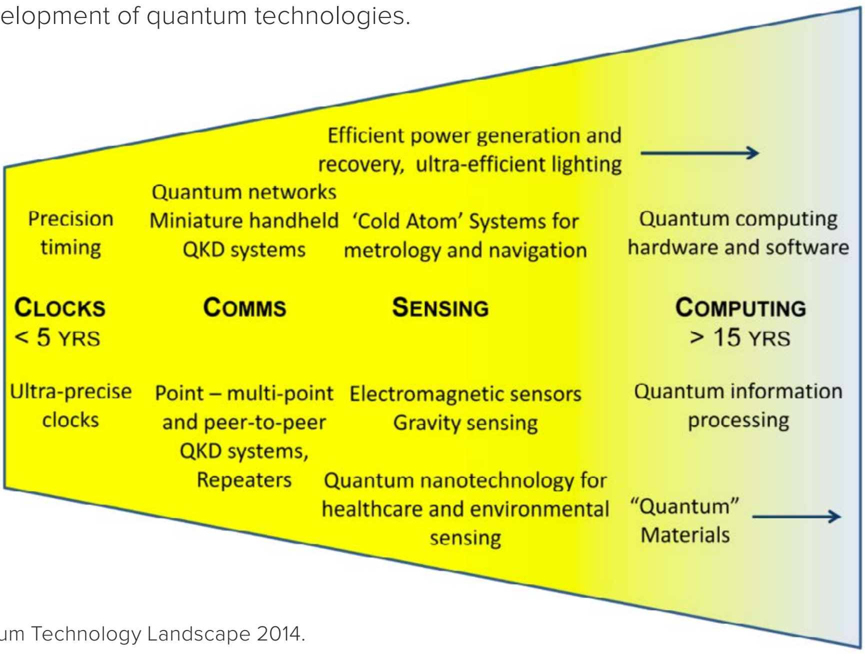
We are seeing a growth in private and public funding in quantum with a race between the US and China, and large multinational companies including IBM, Microsoft and Google investing in order to become the first quantum leader.

To ensure quantum technologies come to fruition, the process required is the same as with any product: to identify the opportunity, then fund research and finally develop the product. Quantum is currently at the basic funding stage. It is not easy to move from research to development, and strategic thinking is required.

QURECA aims to fill the gaps in the community, creating a society ready for quantum through a common language. It offers business development and intelligence, training and resourcing services, helps students find companies and understand the value of their skills for quantum technologies, and *vice versa*.

FIGURE 4

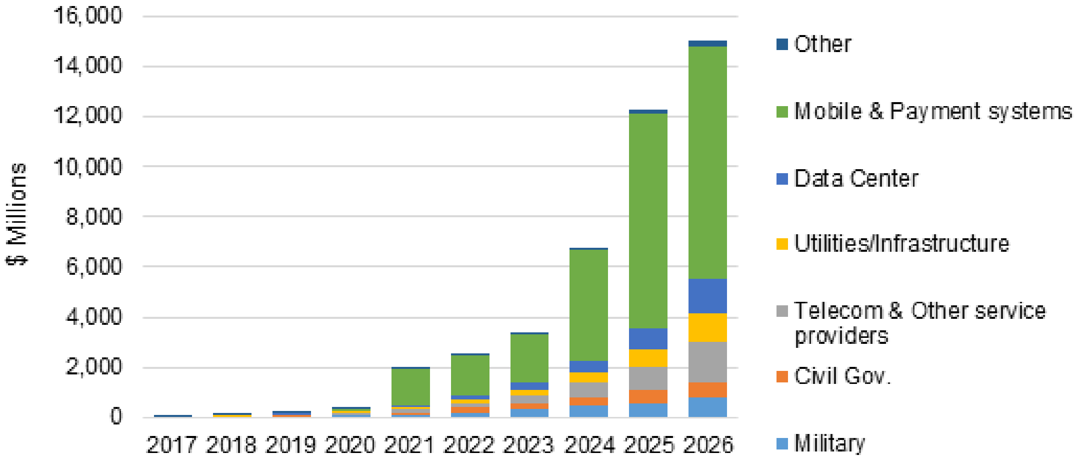
Projected development of quantum technologies.



Credit: UK Quantum Technology Landscape 2014.

FIGURE 5

Projected markets for Quantum Key Distribution Systems by end user ($ millions).



Credit: Communications Industry Researchers, Inc.

Reducing risks to ensure the development of quantum technologies

Quantum technologies, as with all emerging technologies from augmented reality to smart dust, are following the Hype Cycle. Current media has much coverage of both opportunities in quantum and fear of a 'Quantum Apocalypse', in an era of no more secrets as encryption fails.

Like other technologies, the quantum technologies ecosystem comprises government, academia (research), industry (both start-ups and end users) and the general public. The inherent fundamental properties in quantum physics (such as entanglement and superposition) being the basis for quantum technologies makes this emerging field different from any other.

There is a gap between the stakeholders in the quantum technologies community, creating a need to work together to bring a powerful new technology to light, along with appropriate baseline regulatory guidelines to mitigate potential risks including;

- injustice of benefit distribution;
- geopolitical relations.
- cybersecurity and data breach; and
- military use.

"We do not yet know the full picture of this new quantum technology, but we know that revolutions are disruptive and their consequences unpredictable"

Araceli Venegas-Gomez, QURECA.

Quantum technologies: the opportunities and challenges ahead

Dr Richard Murray, Teledyne e2v, summarised the status, opportunities and challenges of the emerging quantum technologies industry. Barriers to commercial viability were also explored.

Quantum Technologies came to the UK in 2013 when a number of pioneering academic, government and industrial figures launched the UK National Quantum Technologies Programme. Five years later, the industrial race is on to deliver high-performance, commercially viable quantum products. The potential performance power will bring significant commercial, economic and societal rewards to the winners of this race, however, it is not a simple feat to get there. Overcoming the underpinning photonics challenges, such as robustness against noise and environment, is central to delivering performance and therefore success of quantum technologies.

Applications and challenges of photonics products in quantum technologies

Quantum devices may provide solutions in global monitoring, cyber security, construction and mapping unknown underground obstacles (the cause of most expense and false starts in construction), and reliance on easily blocked Global Navigation Satellite Systems (GNSS) (Table 1).

To be commercially viable, these quantum solutions must compete with what is already on the market, such as ground penetrating radar, conductivity and seismic. This will require not just technical specialists but experts in business development and market analysis.

"Quantum technologies are both very exciting and very challenging, but if you're developing technology for technology's sake without a strong view of the market and who the customers are, there's a big chance of having to start from the beginning again when you finally solve it."

Dr Richard Murray, Teledyne e2v.

TABLE 1

Application	Solution	Challenges in developing quantum solution	Needs for commercial viability
Construction industry (beneathground investigations)	Ground-based quantum gravity gradient sensor to detect buried massive or very low density underground objects	Performance of gravity sensors	Science: expertise in engineering and manufacture
Global monitoring (eg ice sheet thinning and mass reduction)	Quantum gravity sensor from space	Robustness and space qualification	Testing and assurance
Cybersecurity	Quantum Key Distribution solutions to reduce the frequency and severity of cyber-attacks	Verification of reasonable use and business cases	Business development specialists
Reducing reliance on GNSS (for large systems that need synchronising eg satellite communications, shipping infrastructure)	Very precise quantum clocks: the greater the clock's stability, the longer you can survive without GNSS in an adverse environment	Cost competitiveness	Engineering and manufacturing

There has been great support from government agencies, as well as influential reports including the Economist, Quantum Manifesto and Blackett Review, which outline the broad potential of quantum. Teledyne is taking scientific experiments and concepts through into demonstrators and real products. Areas of development span time, space, gravity, quantum communications and quantum imaging. Teledyne's strategy focuses on creating platform technologies that are customer-focused and contribute to the local and national government and economy, using open innovation. This is a key idea in the quantum technologies landscape, because of the number of customers and supply chain partners.

"As part of the regional compound semiconductor cluster 'CS-Connected', the CSA Catapult supports academics and companies across the UK, helping them develop next generation products in photonics and quantum technologies. We were delighted to see so many of those academics and companies represented at the conference, and to hear their ambitious plans for the future."

Dr Andy G Sellars, CSA Catapult.

Image: Professor Sheila Rowan FRS, University of Glasgow, poses a question from the audience.

Panel session: new directions and applications of photonic technologies

This panel, chaired by Professor Martin Dawson, explored advocacy for photonics and the language surrounding the sector, investment in industry, skills training, movement of people and manufacturing. Panellists were Dr Drew Nelson OBE FREng, IQE; Professor Diana Huffaker, Cardiff University; Professor Sir David Payne CBE FREng FRS; University of Southampton and Sir Peter Knight FRS, Imperial College London.

"We have a very, very distinguished panel here today and it is unusual to have such an eminent group together."

Professor Martin Dawson, Institute of Photonics, University of Strathclyde.

Advocacy and 'photonics' language

- Unlike automotive and pharmaceuticals, photonics is an underlying technology deployed in a wide range of applications and is not recognised as a sector by Government. This makes it challenging to apply for funding and to communicate the strength of the photonics sector to Government and the public.
- It is challenging to maintain political attention on the development of the sector to capitalise on photonics and laser technology (PLT) work and raise the profile of the UK photonics industry. While EPSRC and Innovate UK see the importance of the photonics sector, there is a need to improve marketing to Government as a major potential client of the sector.
- The branding of 'photonics' means little to non-experts, including politicians. Linking photonics to the application (eg banking, communications, automotive) would make it easier to grasp. Microsoft's work in photonics is called 'Optics for the Cloud', for example, while Innovate UK's 'Electech' brings in more technologies. Panellists suggested 'optics for banking', 'optics for security', 'optics for defence' and 'automotive optics' as exemplar applications-focused themes. However, it is then a challenge to then bring these terms back together again to present the sector as a whole.

"Photonics as an enabling and cross-linking technology must be communicated to the Government and reminded to the UKRI entities. The Photonics community would benefit from a cohesive and representative organisation to develop and vocalise a common message."

Professor Diana Huffaker, Cardiff University.

Investment in industry

"What's needed is sustained investment in people and places. I'm beginning to believe that £1 billion is our canonical unit of doing something substantial. If we begin divvying up money we will get nowhere, and the community involved needs to be involved in the planning."

Sir Peter Knight FRS, Imperial College London.

- Sustained investment in people and places to form industry centres is needed, rather than dividing money into smaller packets.
- The UK's investment in university research is comparable to the rest of the world, but there is a gap in long-term investment in industry. The Government is now focusing attention here to meet the goal of investing 2.4% of GDP in R&D by 2027.
- The Government's ambition to invest 2.4% of GDP in R&D by 2027 should consider how investment is distributed across Technology Readiness Level (TRL) stages. The UK closely follows State Aid rules, placing most funding in early TRL stages (academia). However, investing in later TRL stages would increase the chance of research entering commercial production. There is also a need to consider strategically in which technologies we invest.
- As the Eight Great Technologies are revived, those working in the photonics sector should work with BEIS and the Government Office of Science to ensure that photonics is one of the eight. This would highlight the opportunities within the sector, as happened with the Internet of Things.
- It would be helpful to reframe the Eight Great Technologies to focus on the underlying enabling technologies (eg compound semiconductors, silicon manufacturing) instead of the end technologies (eg space, automotive), which have the benefit of being pervasive across all industries.
- Increased focus on underlying technologies would decrease the UK's reliance on imports. Manufacture currently makes up less than 10% of the UK economy, contributing to a considerable payments deficit as we import high-tech goods.

Skills and training

- There is a need for continued investment in photonics in universities to ensure a local supply of skilled people and to attract and retain companies in the area. There is scope to develop photonics-specific degrees and other training in the UK, rather than retraining physicists and engineers.
- The UK produces many high-quality post-graduate scientists who work in the photonics sector. However, there is a need for practical training at advanced technician and apprenticeship level to fill the skill gap in the sector and reduce the burden of retraining for industry.
- Training requires better collaboration between academics and industry. Cardiff University, for example, offers an industrially-driven degree with time in industry and the lab. Additionally, they are developing academic courses for continued training for Newport Wafer Fab. This collaboration is something we should look to expand.
- Funding for training would benefit from restructuring. EPSRC offers £40 million to spend on skills, however, these funds must be spent specifically on research. The funding gap for practical skills training needs to be filled via alternative means to correct the imbalance in the training system.
- The UK Government requires that apprenticeships are defined by industry. However, hiring the staff to develop an apprenticeship programme is beyond budget for most small and medium sized companies, while getting industry to collaborate to develop apprenticeship schemes is difficult.
- One rapidly effective way to fill a skills void is to create client demand: companies are very effective at sourcing skills when given a large order. There is therefore scope for Government to act as a customer, solving the skills gap using a business rather than a government intervention.

"Without a clear idea of how the 2.4% GDP is going to be invested it's kind of an arbitrary number. We should think about where across the Technology Readiness Level stages that money will be spent."

Dr Drew Nelson OBE FREng, IQE.

Image: (left to right) Panellists, Dr Drew Nelson OBE FREng, IQE; Professor Diana Huffaker, Cardiff University; Professor Sir David Payne CBE FREng FRS; University of Southampton; and Sir Peter Knight FRS, Imperial College London.

Brexit and movement of people

- An increase in funding for photonics has been observed following concern about sovereign capability in the face of Brexit.
- Restricting recruitment to the UK will make us less competitive. For example, 25% of Coherent Scotland's engineering team come from Europe, however, movement of their employees from Europe to the UK since the Brexit vote has almost stopped.
- The UK Photonics industry is very export-led, and there is concern about the impact of Brexit on the business and development of the sector.

Manufacture

- UK academic centres, such as Nottingham, Cambridge, Cardiff and Glasgow, have been strong in developing new compound semiconductor technologies over the last 30 years. However, the relationship between industry and academia is in general weaker in the UK than other nations. A closer linkage would allow much sharper focus in getting things done for industry.
- Foundry models, like that being developed at CS Connected, allow rapid manufacture of prototypes developed by universities. Benefits include cheaper manufacture and the ability for companies to have many clients.
- Panellists saw increased opportunities for the UK in technologies including photonic integrated circuits, infinite scalability in lasers (eg used to push spacecraft off the ground), multicore and hollow-core fibres, artificial intelligence and machine learning in photonics.

"I see a huge opportunity for machine learning and artificial intelligence in photonics across the board."

Sir David Payne CBE FREng FRS, University of Southampton.

Conclusions

This meeting provided a discussion platform for photonics as a key part of the UK's innovation and industrial landscape. It explored the very broad technological coverage and wide range of applications of photonics and discussed many of the UK's internationally recognised strengths in the area.

There was support for 'funding at scale' as an effective way to build networks and to develop and implement new technologies. One example is the compound semiconductor cluster in Wales, including the CSA Catapult, with a critical mass of capability to benefit UK companies. There are a number of other examples around the UK of such clusters (localised commercial, academic and independent research and technology organisations) in photonics and related technologies. A very strong research base, coupled with an agile and productive engineering base, can be transformative.

The UK shows clear and longstanding strength in photonics;

- £1 in every £17 spent in UK engineering is spent in photonics;
- The UK is strong across the whole nation: seven separate regions have an output >£1 billion; and
- 15% compound growth has been sustained over 50 years in the sale of lasers: very few manufacturing centres can achieve these numbers.

The Royal Society can help foster linkages between industry and academia to develop this sector.

Acknowledgements

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