Institution: University of Bristol		
Unit of Assessment: 9) Physics		
Title of case study: Bristol's research has spawned a vibrant ecosystem of quantum technology start-ups, building jobs and investment in a new technology sector in the UK and USA		
Period when the underpinning research was undertaken: 2006 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period employed by submitting HEI:**
Jeremy O'Brien	Professor	04/2006 – 01/2019
Anthony Laing	Associate Professor	10/2010 – present
Mark Thompson	Professor	09/2008 – present
Jonathan Matthews	Associate Professor	07/2011 – present
John Rarity	Professor	Pre 2000 – present
Martin Cryan	Professor	Pre 2000 – present
Phillip Sibson	Postdoctoral researcher	08/2016 – 08/2018
Neciah Dorh	Postdoctoral researcher	11/2016 – 10/2018
Xiao Ai	Postdoctoral researcher	01/2016 – 01/2018
Mateusz Piekarek	Postdoctoral researcher	10/2016 – 03/2019
Period when the claimed impact occurred: 2015 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

University of Bristol (UoB) research has produced a diverse cluster of companies exploiting quantum photonic technologies, including the world's most highly funded start-up quantum computing company, which has raised USD215M and created over 100 jobs. Companies exploiting UoB research are enabling secure telecommunications; reducing diagnostic time and reliance on broad-spectrum antibiotics in healthcare; and combating climate change by preventing leakage of natural gas from production facilities. The research has led to the founding of a skills and training centre for quantum entrepreneurs from which 31 new businesses have been developed, attracting a combined investment of GBP44.8M and creating 126 new highly skilled jobs. To grow this vibrant technology ecosystem, we have attracted GBP91M for a business incubator which will further enhance Bristol's position as a world leading centre for the commercialisation of quantum technologies.

2. Underpinning research

Before the advent of integrated quantum photonics, state-of-the-art photonics involved bulky apparatus and unwieldy table-top interferometers the stabilisation of which was challenging. In 2008, UoB researchers from the Quantum Engineering Technology Laboratories (QET Labs) combined their interdisciplinary strengths in quantum photonics and microfabrication to demonstrate the first integrated photonic quantum logic gate on a chip [1]. These first quantum photonic chips were fabricated in silica (glass). At only a few square centimetres in size, they had the advantage of being two orders of magnitude smaller than their bulk optics predecessors, but more importantly they were completely interferometrically stable.

A further development showed how the platform could be fabricated from silicon [2] which allowed the UoB team to exploit mature fabrication tools from the microelectronics industry. This permitted much greater numbers of photonic components to be combined on a single chip, leading to the development of a multidimensional integrated quantum photonic platform

able to generate, control, and analyse high-dimensional quantum entanglement. This platform marked a major step towards the creation of a quantum computer based on silicon photonics.

A further large body of work has demonstrated that techniques for generating single photons, controlling their interaction with nanoscale structures, precision time-of-flight measurements and sensitive photodetection techniques, together provide a versatile platform for a wide variety of photonic quantum technologies, including secure communications [3], metrology [4], sensing [5] and imaging [6]. Seven UoB patents have underpinned a drive towards applications. The combined body of work on integrated quantum photonics from the UoB group comprises over 100 publications, with 20 in Nature, Science, and the Nature journal family.

3. References to the research

[1] Politi A, Cryan MJ, Rarity JG, Yu S, O'Brien JL. (2008). Silica-on-silicon waveguide quantum circuits. *Science,* 320, 646. https://doi.org/10.1126/science.1155441

[2] Silverstone JW, *et al.* (2014). On-chip quantum interference between silicon photon-pair sources. *Nature Photonics,* 8, 104. https://doi.org/10.1038/nphoton.2013.339

[3] Sibson P, *et al.* (2017). Chip-based quantum key distribution. *Nature Communications,* 8, 13984. https://doi.org/10.1038/ncomms13984

[4] Ai X, *et al.* (2016), Analysis of a random modulation single photon counting differential absorption lidar system for space-borne atmospheric CO_2 sensing, *Optics express 24* (18), 21119. https://doi.org/10.1364/OE.24.021119

[5] Dorh N, Sarua A, Ajmal T, Okache J, Rega C, Müller GM, Cryan MJ. (2017). Nanoantenna arrays combining enhancement and beam control for fluorescence-based sensing applications. *Appl. Opt.* 56, 8252–8256. https://doi.org/10.1364/AO.56.008252

[6] J. Sabines-Chesterking, *et al*. Sub-Shot-Noise Transmission Measurement Enabled by Active Feed-Forward of Heralded Single Photons. *Phys. Rev. Applied* 8, 014016 (2017). https://doi.org/10.1103/PhysRevApplied.8.014016

4. Details of the impact

UoB's ground-breaking research in quantum photonics provides opportunities for a host of innovative applications. Supported by a strong entrepreneurial culture, academics have leveraged their interdisciplinary skillsets to found a series of new companies. They have also established a world-leading skills and training centre (QTEC) for budding entrepreneurs in quantum inspired technologies. These initiatives have spawned a vibrant local ecosystem in quantum technologies. From our diverse portfolio, we highlight several companies that have developed directly out of UoB's research.

1) PsiQuantum – photonic quantum computing

Quantum computing is the most ambitious and far-reaching quantum technology, with applications including new methods for drug discovery and dramatic speed ups in data searching and image recognition. In 2016, QET Labs academics co-founded the world's most highly funded quantum computing start-up company, PsiQuantum in Silicon Valley [A] to exploit UoB research in quantum photonics.

The basic unit of information in a quantum computer is the qubit and it is widely accepted that the first useful computer will require at least 1 million physical qubits. A highly promising way to achieve this is via photonics and the technological innovations at the heart of PsiQuantum were invented at UoB [1,2]. Specifically, PsiQuantum exploits QET Labs' development of silicon photonic quantum circuit chip technology which allows operations on qubits at room temperature. These chips can be fabricated in standard microchip foundries. Silicon photonics

greatly enhances the scalability at which a quantum computer can be designed and ameliorates several of the engineering issues that plague other computing architectures such as ion-traps and superconductors. In the words of PsiQuantum's CTO: "*Rather than take a quantum system and make it scalable, we have taken a scalable process - silicon manufacturing - and made it quantum*".

Four UoB patents have been transferred to PsiQuantum [B]. Since 2016 the company has raised USD215M including investment from Microsoft's venture capital arm and Blackrock [A]. They operate from their own premises in Palo Alto where they employ over 100 people [C]. PsiQuantum have formed a strategic alliance with *Global Foundries*, a top tier semiconductor fabrication company, to produce the hardware for their quantum computer [A,C].

2) KETS Quantum Security – increased encryption security for UK industry

KETS uses quantum key distribution (QKD) protocols to realize cost-effective encryption for secure communications. Their chip based QKD technology [3], protected by a UoB patent, enables applications that call for ultra-low size, weight and power, without compromising performance. KETS are working with multinational companies across diverse sectors, including Airbus, BT and Thales. The Head of Optical Research at BT stated that *"The KETS solution solves that problem* [of high cost of equipment] *through integration and this puts them in a very strong position to capitalise on the current world ambition towards quantum secured communication"* [D]. R&D work with Airbus on an Innovate-UK funded project has developed secure communications for unmanned aerial vehicles [D]. Investor Quantonation states "We *opted to invest in KETS due to their potential to become a global leader in quantum secure communications and as a result of their technological advantage gained from nearly 10 years of world class research in quantum technologies"* [E]. KETS employs 12.5 FTE staff and has raised investment of over GBP2M [C].

3) FluoretiQ – point of care diagnostics for health services and patients

Annually 700,000 people die due to drug-resistant infections. Using UoB discoveries to resolve fluorescence emissions at the single-photon level [5,F], FluoretiQ, has developed a rapid (15 minutes) diagnostic platform to identify specific bacterial pathogens. This technology reduces the time to diagnosis and obviates the need to prescribe broad-spectrum antibiotics that encourage the global threat of bacterial resistance [C]. A prototype analyser for identifying *E. coli* (which accounts for 80% of urinary tract infections) has been trialled in an NHS lab [F]. FluoretiQ employs 7 FTE and has raised over GBP1M investment [C].

4) QLM Technology – preventing gas losses for the natural gas industry

Leakage of natural gas to the atmosphere constitutes more than 10% of global greenhouse gas emissions and costs industry more than USD30 billion annually [G]. QLM (Quantum Light Metrology) produce a tuneable diode laser gas detection and imaging system based on Light Detection and Ranging technology the sensitivity of which is enhanced via UoB discovered techniques for single photon quantum optics and detection techniques [4]. This low power detector underwent field trials in 2020 and is at the centre of the GBP2.7M SPLICE project in which QLM is collaborating with the National Physical Laboratory BP, National Grid and Ametek among others [C]. QLM has revenue of GBP200K and employs 7 FTE [C].

5) RayCal – correlated photon pair source

RayCal in collaboration with Thorlabs have developed a commercial version of a correlated photon pair source, the SPDC810. This is based on UoB research on the suppression of the

quantum fluctuations that cause errors in optical metrology [6]. The director of Thorlabs' Laser Division said *"This is an exciting addition to Thorlabs' line up of products for the Quantum Photonics community. The project started when a UoB researcher asked if we could expedite the efforts of those working in quantum optics labs by offering a compact, reliable single photon source. Prompted by that need, we engaged in a collaborative effort that led to the development of the SPDC source"* [H]. The product went to market in August 2020 and in the first 4 months has accumulated sales of GBP 80K [C].

6) Duality Quantum Photonics – photonic chips to simulate molecular dynamics

DQP was founded in early 2020 to design and fabricate photonic chips that can simulate the quantum dynamical behaviour of molecules to assist drug design in the pharmaceutical industry. DQP are collaborating with Hitachi Europe and ARM on a novel quantum operating system and have secured GBP900K of investment and sales revenue of GBP325K (contract with BT). They employ 3 FTE [C].

7) Qontrol – instrumentation for the global integrated photonics community

Founded in 2016, Qontrol develops and markets state-of-the-art electronic instrumentation for the global integrated photonics community. The company's products make controlling complex photonic and quantum photonic devices easy and economical. The CEO says [C] "*Qontrol now boasts more than a hundred customers worldwide, including many of the largest companies in the global ICT space…Our success has only been possible because of the research and ecosystem developing around the University and City of Bristol".* It has an annual turnover of around GBP200K and supports 4 FTE [C].

QTEC – An enterprise ecosystem for commercialising quantum technologies

Seeking to capitalise more widely on the potential for ground-breaking applications arising from their research, in 2015 QET Labs secured GBP4.4M of EPSRC funding to establish the Quantum Technologies Enterprise Centre (QTEC). This innovative skills and training centre is producing the next generation of entrepreneurs in quantum technologies.

The 12-month QTEC fellowship programme provides training and mentoring by academics and entrepreneurs with experience of commercialisation. Fellows gain new knowledge in quantum technologies, skills to develop a viable business plan, management expertise, and access to dedicated incubator space. They also forge connections to the investor community, the National Quantum Technology Hubs and relevant industry partners.

QTEC has trained 33 Quantum Enterprise Fellows across four cohorts [I]. According to the Chair of Innovate UK's Special Interest Group in Quantum Technologies "*The QTEC fellowship program provides scientists with invaluable entrepreneurial skills which allows their companies to be successful. This in turn gives investors confidence in the companies"* … "*The vibrant Bristol quantum technologies ecosystem that has grown up around UoB and QTEC is unique and world leading, making it a very important centre for quantum industries in the UK with global significance.*" [J].

The first cohort of four Fellows were all QET Labs alumni and have founded the four thriving companies (2)-(5) above. Subsequent cohorts have been attracted from further afield, both nationally and internationally. These have founded a further 27 companies, 20 of which remain active [I], including *Nu Quantum* who have raised GBP2.75M to produce quantum photonic components, and *SeeQC* based in New York and employing 16 people, which has raised

USD22.4M to develop a quantum computing processing system. SeeQC's Managing Director said "*I returned to the UK [from the US] and joined the QTEC fellowship program at the University of Bristol. If QTEC had not provided me with these opportunities and skills, investment may not have been forthcoming, and my business success might never have happened.*" [C].

QTEC's Director of Enterprise notes that, "a*n independent report … found that a third of the UK's funded Quantum Start-ups originated through the QTEC fellowship programme*" [I]. By the end of 2020, QTEC alumni companies raised over GBP44.8M of funding from grants, revenue, and equity, generating 126 new highly skilled jobs [I].

QTIC+ Local economic growth and capacity building

Building on these successes, in 2019 UoB established the Quantum Technologies Innovation Centre (QTIC+), as Europe's first incubator providing specialist facilities and expertise for quantum businesses. Currently operating as a pilot facility, QTIC+ is already making an impact, KETS's CEO states "*QTIC+ provides us affordable access to the high-tech equipment we need to develop our product. Without it we would have needed to raise a huge amount of capital to get started, while now we can, on a modest budget, produce our technology demonstrators*" [C].

GBP91M has been invested in QTIC+ as part of the Temple Quarter Enterprise Campus. Investment comes from West of England Combined Authority (WECA) and the Local Enterprise Partnership (LEP) GBP35M, UoB GBP35M, and GBP21M from industry. Commenting on the impact of QTIC+ on Bristol, WECA's Director of Business and Skills states that QTIC+ will *"position the West of England as a global leader in deep tech innovation…This local strength has already attracted four global businesses with an existing presence in the region (Boeing, Airbus Group, BAE Systems and Raytheon) to establish their own quantum activities … WECA are excited about the potential of QTIC+ to help propel fledgling quantum companies to success. Indeed, without it, there would be a high risk of losing these companies to other countries which are also investing heavily in quantum technologies"* [K].

5. Sources to corroborate the impact

[A] Bloomberg Businessweek (2020). Quantum Computing Startup Raises $215 Million for Faster Device.

[B] UoB (2019). Patent Assignment

[C] Compilation of letters (2020). CEO/CTO/CPO/Director of 22 companies *(corroborating investment, sales and employment figures)*

[D] i) Innovate (2020). KETS Quantum Security
ii) KETS (2018). News KETS and Airbus partner on Innovate UK grant to secure UAVs with quantum encryption

[E] Quantonation (2020). Corroborating statement – Managing Partner.

[F] McEntee (2019). Nanoparticles home in on infectious diseases, Physics World, 32(5), 39.

[G] Rhodium Group (2015). Untapped Potential: Reducing Global Methane Emissions from Oil and Natural Gas Systems

[H] QuantIC (2020). UK Quantum Technology Hub press release on RayCal and Thorlabs

[I] QTEC (2021). Supporting Letter - Director *(confirming statistics for companies)*

[J] KTN & Innovate UK (2020). Supporting Letter - Chair of Quantum Technologies Industry Group

[K] WECA (2020). Supporting Letter - Director of Business and Skills