**Institution:**
University of Cambridge

**Unit of Assessment:**
UoA9

**Title of case study:**
Semiconductor Devices for Quantum Information

**1. Summary of the impact** (indicative maximum 100 words)

The development of Molecular Beam Epitaxial (MBE) growth techniques for self-assembled quantum dots at Cambridge University has led to the creation of electrically driven, compact single-photon and entangled-photon sources, and their demonstration in quantum key distribution (QKD) systems. This highly-cited work has led to significant recent investment in R&D in this area by Toshiba, one of the world's leading microelectronics companies, influencing company policy to the highest levels. It has stimulated world-wide interest in quantum information technology, in government institutions and companies from start-ups and SMEs to multinationals.

**2. Underpinning research** (indicative maximum 500 words)

Researchers from the Semiconductor Physics group at the Cavendish Laboratory, University of Cambridge, led by Professor Sir Michael Pepper until 2008 and since then by Professor David Ritchie, (Assistant Director of Research 1991-1999, Reader 1999-2002, Professor since 2002) have been studying the fabrication and properties of quantum dots formed in semiconductors since the late 1980s.

In 1997-1998 Professor Ritchie developed techniques for the Molecular Beam Epitaxial (MBE) growth of quantum dots [1] formed by the self-assembly of islands of InAs on GaAs. This work enabled the control of the size and density of quantum dots embedded in complex GaAs/AlGaAs semiconductor structures.

Having developed these sample fabrication techniques, Prof Ritchie started collaborating with Dr Andrew Shields of the Toshiba Research Laboratory located in Cambridge to exploit these InAs quantum dots in optical devices, in particular for the development of single- and entangled-photon sources. Previous work had demonstrated single photon generation using atoms, the breakthrough here was to use InAs quantum dots as 'artificial atoms', inside conventional semiconductor devices to realise more compact and robust single photon generators. In 2002 the collaboration made the first single photon source (in any system) driven by an applied voltage, the *Single-Photon Light Emitting Diode* (LED), which removes the complexity and cost of optical pumping with ultra-short laser pulses.[2] In this and the subsequent research, the MBE growth and device fabrication took place at the Cavendish Laboratory with optical measurement taking place at Toshiba.

Another important development was to extend the quantum dot emission wavelength to a transmission band of optical fibre, which was achieved by optimising the size and composition of the quantum dot. This telecom wavelength single-photon source was then applied to quantum key distribution (QKD) demonstrating that a secure key could be transmitted further than with weak coherent pulses from a laser.[3]

Most of the advanced applications in quantum information technology require photons that are indistinguishable from one another and can therefore undergo two-photon interference. However, unlike atoms, quantum dots display a spectrum of emission energies due to unavoidable variations in their size, shape and composition, which prevents interference of photons from different sources. For many years this was thought to be a fundamental barrier to using quantum dot sources in quantum communications and quantum computing schemes. The collaboration showed that a single photon source consisting of an InAs quantum dot situated between AlGaAs barriers can be tuned significantly by an applied electric field, and thereby demonstrated the indistinguishability of photons from different LEDs for the first time.[4]

Long distance quantum communications requires sources of photon pairs which have quantum mechanically entangled properties. In 2006 the collaboration demonstrated for the first time that semiconductor quantum dots can produce polarisation entangled photons. [5]. This was achieved by tailoring the nanostructure of the quantum dot to erase which-path information in the biexciton cascade of the quantum dot. In 2010 the first entangled light emitting diode was demonstrated.[6] This simple semiconductor device could enable the development of applications for quantum

entanglement, in much the same way as the laser diode stimulated today's photonics industry. Most recently the collaboration has shown that entangled LEDs can be used for quantum teleportation, the key protocol for transferring quantum information in a quantum network or quantum computer.
In parallel with this work on quantum light sources, semiconductor technologies have been applied to quantum memories and quantum detectors. It was shown that the photon polarisation can be stored as the spin of an electron in a quantum dot and that field effect transistors gated by a layer of quantum dots can make highly efficient photon detectors. In addition, a second type of single photon detector based on an avalanche photodiode was used to demonstrate Quantum Key Distribution with a secure bit rate in excess of 1 Mbit/sec for the first time, the highest sustained bit rate demonstrated to date.

**3. References to the research** (indicative maximum of six references)

*[1] "Modification of InAs quantum dot structure by the growth of the capping layer ", Lian et al, Appl. Phys. Lett. 73, 49 (1998) [85 cites] DOI: 10.1063/1.121719.

*[2] "Electrically driven single-photon source ", Yuan et al, Science 295, 102 (2002) [665 cites] DOI: 10.1126/science.1066790

[3] "Quantum key distribution using a triggered quantum dot source emitting near 1.3 µm",

Intallura et al, Appl. Phys. Lett. 91, 161103 (2007) [31 cites] DOI: 10.1063/1.2813181

[4] "Two-photon interference of the emission from electrically tunable remote quantum dots ", Patel et al, Nature Photonics 4, 632 (2010) [60 cites] DOI: 10.1038/NPHOTON.2010.161

*[5] "A semiconductor source of triggered entangled photon pairs ", Stevenson et al, Nature 439, 179 (2006) [431 cites]. DOI: 10.1038/nature04446

[6] "An entangled-light-emitting diode" Salter et al, Nature 465, 594 (2010) [83 cites] DOI: 10.1038/nature09078

*References which best represent the quality of the underpinning research.

Citation numbers provided by Web of Science July 2013

**4. Details of the impact** (indicative maximum 750 words)
The development, at the Cavendish Laboratory of the University of Cambridge, of both MBE growth techniques for structures containing quantum dots and suitable device fabrication technology has led to a long-term collaboration between the University and Toshiba Research Europe Ltd based at the Cambridge Science Park. This has been in place since 1999.

As a consequence of the work carried out at the Cavendish, Toshiba has invested heavily in research and development in this area. The Deputy Managing Director, Cambridge Research Laboratory, Toshiba [18], writes, "We have been particularly influenced by research on the growth and fabrication of quantum dot devices, by Professor Ritchie and colleagues in the Semiconductor Physics Group. In collaboration with Professor Ritchie, our researchers have pursued a R&D programme on quantum photonic sources and detectors based on semiconductor quantum dots. This resulted in the creation of the Quantum Information Group at TREL [Toshiba Research Europe Ltd], to explore the applications of quantum devices to IT systems." The programme continues to the current time with the aim of producing small-scale devices using conventional semiconductor technology at a low-cost to fit into quantum information systems.

The demonstration of telecom-wavelength quantum-dot single-photon sources which allow the secure transmission of quantum keys further than attenuated lasers [3] has stimulated the development of Toshiba quantum key distribution systems [8] which although currently using lasers will in the future incorporate quantum dot sources when those sources have been optimised. The Toshiba quantum key distribution system was demonstrated in Vienna in 2008 as part of the SECOQC collaboration of which both the University of Cambridge (Ritchie) and Toshiba were members. [10] The QKD system was also operational in Tokyo in 2010, where secure key generation was demonstrated for a 24 hour period over a 45km link. [11] . The global market for QKD has been predicted as $1B by 2018 in a recent market report [9] which refers to Toshiba as a “Key Player”. By then Quantum LEDs may show a performance advantage over attenuated lasers and allow higher secure bit rates.

Through the work with the Cavendish, Toshiba Research Europe has been able to create a scalable semiconductor device based on quantum dots grown in an optical cavity that emits single photons at a wavelength suitable for optical-fibre transmission. As indicated above, one advantage of quantum dots is that they emit single or entangled photons, in response to an electrical pulse, on demand – unlike nonlinear crystals used to create entangled photon paris, which emit photons probabilistically. The development of such inexpensive chips, hosting millions of such devices, each addressed by an electrical control signal, is intended to be used in linear optical computing schemes. As a consequence of the joint demonstration of entangled-photon LEDs [6] Toshiba are now developing quantum teleportation and quantum repeater technology.

As well as having an impact on Toshiba, this research has had an impact on the wider community through the conventional media such as newspapers, magazines and the BBC as well as an exhibit at the 2013 Royal Society Summer Science Exhibition. [12]

Following on from the SECOQC project the industrial interest in the technology is evidenced by a large consortium of companies working together to produce industrial standards for quantum dot based single-photon sources (such as those developed in [2]) under the auspices of ETSI, the European Telecommunications Standards Institute. [13]. The QKD Industrial Standardisation Group involves 9 private companies and 5 government bodies. [14]. Their work has included the definition of standard measures and test procedures for the single photon devices developed in the collaboration.

This research has stimulated the national measurement Institutes to establish substantial programmes to develop standard tests for quantum light sources and detectors with the National Physical Laboratory involved in one such collaborative project with the University and Toshiba. Similar programmes are underway in the US, Japan, Germany and Italy.

This research has influenced the policy of national science and technology organisations. For example the Institute of Physics have identified Quantum Information Technology as important area of research in the UK, in part due to the work done in the collaboration at Cambridge [15]. Work on single and entangled-photon sources was featured in a publication from 2011 including an illustration on the front cover of an entangled–photon source fabricated at the Cavendish Laboratory and drawn by Robert Young, a University of Cambridge PhD student. [15] The EPSRC have identified quantum technologies as one of their “Grand Challenges” and currently prioritise funding in this area. [16]. Quantum communications has also been a priority in framework programmes of the EU.

This research has also had a considerable impact upon government policy. In Japan there is a large industry-led “Secure Photonic Technology” initiative to promote quantum communication. [17] This initiative is funded by the National Institute of Communication and Information Technology (NICT) and Toshiba’s laboratory in Cambridge is a participant. This initiative involves the development of both single photon quantum cryptography, as well as quantum dot based quantum repeaters and in part builds on collaborative research performed in Cambridge.

**5. Sources to corroborate the impact** (indicative maximum of 10 references)

[7] http://www.toshiba.eu/eu/Cambridge-Research-Laboratory/ http://www.toshiba-europe.com/research/crl/qig/index.html

[8] http://www.toshiba-europe.com/research/crl/qig/quantumkeyserver.html

[9] http://www.prweb.com/releases/quantum_cryptography/quantum_key_distribution/prweb10897723.

htm

[10] http://www.secoqc.net/html/project/

[11]http://www.toshiba.eu/eu/Cambridge-Research-Laboratory/Quantum-Information-Group/Quantum-Key-Distribution/Network-Field-Trials-/

[12] http://sse.royalsociety.org/2013/exhibits/quantum-revolution/

[13] http://www.etsi.org/technologies-clusters/technologies/quantum-key-distribution

[14I http://portal.etsi.org/portal/server.pt/community/QKD/328

[15] http://www.iop.org/publications/iop/2011/file_52078.pdf

[16]
http://www.epsrc.ac.uk/ourportfolio/themes/physicalsciences/introduction/Pages/grandchallenges.aspx

[17] http://www.nict.go.jp/en/press/2010/10/14-1.html

[18] Statement from the Deputy Managing Director, Cambridge Research Laboratory, Toshiba

[19] Assistant Managing Director, Toshiba Research Europe Ltd