Institution: Lancaster University		
Unit of Assessment: 9, Physics		
Title of case study: Supporting the establishment and rapid growth of Quantum Base Ltd through innovative research on the application of quantum physics to information security		
Period when the underpinning research was undertaken: 2013 to 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof. Robert Young	Professor and Royal Society Research Fellow at Lancaster University. Co-Founder of Quantum Base Ltd.	01/09/2009 to present
Period when the claimed impact occurred: 2014 to 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

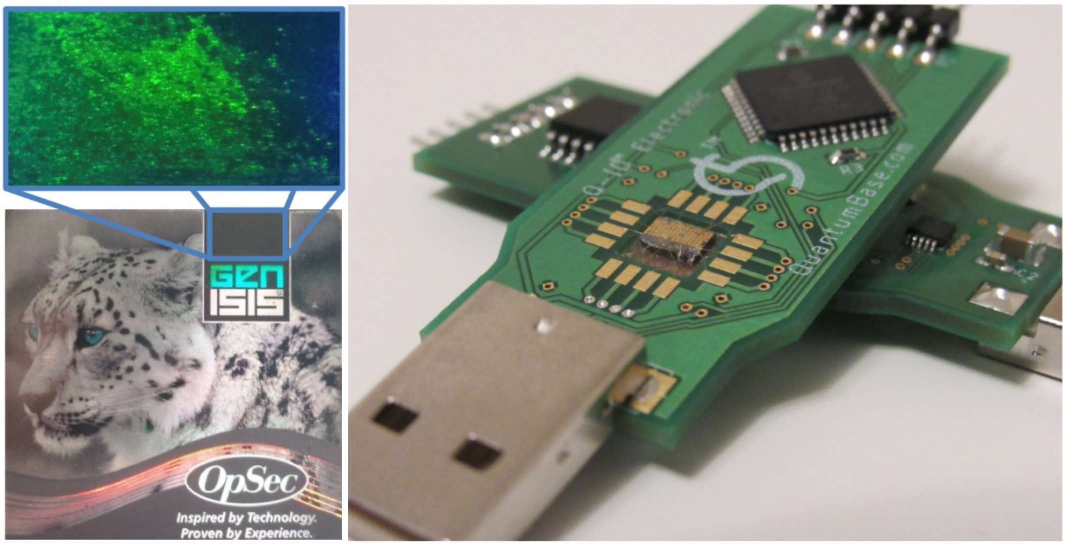
Research from the Department of Physics at Lancaster University has pioneered the use of quantum effects in semiconductor nanostructures in hardware security devices. These include a tag incorporating quantum materials, from which a unique fingerprint can be read optically; a device for electronic authentication, where an identity is generated from process variations in semiconductor diodes; and an electronic random number generator, whose output is based on quantum tunnelling. A spin-out company, Quantum Base Ltd. (QBL), was incorporated in April 2013 and officially began co-development and commercialisation activities in conjunction with Lancaster University in August 2014, when the two parties co-signed master licensing and commercialisation agreements. QBL, which is located in rented office space within the Physics building at Lancaster University, has grown from being a new company at the start of the current REF period, into a pioneer of the nascent field of quantum security, with a value defined by private investment in excess of GBP10.0 million. QBL is responsible for creating 15 jobs and holds 15 patents (granted in a variety of territories), with 32 patents pending. QBL has engaged the anti-counterfeiting industry through features in three industry publications, and developed mass-market fabrication processes at OpSec Security Ltd. (OSL), a major hologram manufacturer. Commercialisation agreements have been made with two significant manufacturers of anti-counterfeiting tags, and licenses to produce 10 million security tags have been sold.

2. Underpinning research

The research underpinning the impacts in this case study was conducted at Lancaster University in projects led by Young, who is listed as an inventor on 45 of the 47 granted and pending patents held by QBL. Young's research focuses on devices containing semiconductor nanostructures for applications in information security.

2.1 Q-ID®

The concept of using imperfections in electronic and optical devices to specify their identities, known as physical unclonable functions (PUFs), gained popularity in the early 2000s. The appeal of these devices is striking; randomness inherent in a structure, or introduced during fabrication, is more complex than deterministically programmed or manufactured uniqueness. In 2014, Young's research, funded through a University Research Fellowship from the Royal Society [QI1] developed the first PUFs that derive their identity from atomic imperfections, known as quantum PUFs. These were later trademarked as Q-ID®s. Compared to previous technologies, this innovation boasts several key advantages. Fingerprinting at the atomic scale makes the engineering challenge of producing counterfeits as difficult as possible, while utilising quantum effects that grow as feature sizes reduce makes it easier to read individual signatures. Additionally, by measuring additional physical properties, the dimensionality of the physics underlying fingerprint generation can be verified, and thus cloning-based attacks can be prevented. The technology was developed by Young in two distinct variants: Q-ID® Electronic [3.1] and Q-ID® Optical [3.2]. The electronic Q-ID® device, shown on the right in the figure below, is connected to a USB interface, but the final implementation will be fully integrated. The optical Q-ID® tag on the top left-hand side of the figure is embedded within a surface coating on a hologram, which is shown below it.



In a seminal 2015 paper [3.1], the first use of quantum confinement to uniquely identify a simple electronic device was demonstrated. In this work, it was shown that unique identities can be extracted from current peaks in resonant tunnelling diodes. Despite being fabricated using ultra-high-precision epitaxial processes, small variations in the width and composition of the quantum well in these devices lead to variations in their physical properties that are effectively magnified by the quantum physics governing their behaviour. A patent broadly covering the concept of using quantum confinement for authentication, first filed in 2014, has been granted in the UK, China, Japan and the US [3.3]. Additional patent applications were filed in 2016 (also granted) to cover the use of networked Q-ID's for communication security, and as a hardware lock for integrated circuits to physically enable/disable logical elements. This later work was supported by grants from the US Air Force Office of Scientific Research [QI2 and QI3].

Research led by Young demonstrated an optical analogue of this technology in 2017, where variations in the band gap of quantum materials on a surface, or locked in a polymer, were used to generate unique fingerprints [3.2]. A patent for this concept filed in 2015 [3.4] has now been granted in the UK and US, and additional method and device patents have been filed and granted since, to protect IP relating to its practical implementation. A PhD student developing the technology with Young at Lancaster University won a prestigious award from EPSRC for his work [QI4]. In 2020, it was also demonstrated that similar concepts can be employed with materials that are biocompatible and food-safe, paving the way for directly utilising the technology on products that are ingested, such as pills.

2.2 Q-RAND®

Random number generators (RNGs) are important in diverse applications such as cryptography, simulations, testing (*e.g.* selecting samples from a population for assessing drug efficacy), digital address generation and gaming. Limits in the way current digital systems choose random numbers leaves everyone vulnerable to hacking, causing large-scale information breaches. It has been demonstrated that truly random numbers can be obtained from different sources such as noise, chaotic systems and quantum phenomena. The main advantage of using a quantum noise source is its intrinsic uncertainty, as opposed to the predictability of classical sources of noise, and Young's team proposed and demonstrated that quantum tunnelling in a simple semiconductor structure could be used as an RNG in 2017 [3.5]. These devices are practical, scalable sources of randomness whose behaviour is governed by quantum physics at room temperature. The semiconductor nature of RTDs and the simple system proposed to read random numbers from them, make them a promising candidate for integration into microelectronic systems. The potential to integrate single-element RNGs into current technologies makes them resistant to frequency injection and biasing attacks, as tampering with them is prohibitively difficult. The output of these devices can be directly used as a random stream of bits, or can be further distilled using randomness extraction algorithms, depending on the application. Two patents were filed in 2016 to protect these concepts [3.6], both of which have since been granted in the UK. Prototype devices were produced with support from Impact Acceleration Awards made to Lancaster University by EPSRC and a peer-reviewed grant from the Royal Society [QI5].

3. References to the research

Due to the innovative nature and commercial value of the research, patents were filed prior to publishing scientific articles to ensure the protection of intellectual property.

[3.1] J. Roberts, I. E. Bagci, M. A. M. Zawawi, J. Sexton, N. Hulbert, Y. J. Noori, M. P. Young, C. S. Woodhead, M. Missous, M. A. Migliorato, U. Roedig and **R. J. Young**. "Using Quantum Confinement to Uniquely Identify Devices" Sci. Rep. 5, 16456 (2015). Altmetric – 471**.**

[3.2] Y. Cao, A. J. Robson, A. Alharbi, J. Roberts, C. S. Woodhead, Y. J. Noori, R. Bernardo-Gavito, D. Shahrjerdi, U. Roedig, V. I. Fal'ko and **R. J. Young**. "Optical identification using imperfections in 2D materials" 2D Mater. 4, 045021 (2017). Altmetric – 265**.**

[3.3] U. Roedig, J. Roberts and **R. J. Young**, "Unique identifier", ZL 2015 8 00249144, GB2537543, JP6581107, US10148435 (priority date 3rd April 2014). [patent]

[3.4] V. Falko and **R. J. Young**, "Improvements relating to the authentication of physical entities", GB2538181, US10475271 (priority date 27th January 2015). [patent]

[3.5] R. Bernardo-Gavito, I. E. Bagci, J. Roberts, J. Sexton, B. Astbury, H. Shokeir, T. McGrath, Y. J. Noori, C. S. Woodhead, M. Missous, U. Roedig, **R. J. Young**. "Extracting random numbers from quantum tunnelling through a single diode" Sci. Rep. 7, 17879 (2017).

[3.6] (a) R. Bernardo-Gavito and **R. J. Young**, "Nondeterministic Response To A Challenge", GB2548428 (priority date 8th August 2016). (b) J. Roberts, R. Bernardo Gavito, **R. J. Young** "Generating A Nondeterministic Response To A Challenge", GB2543126 (priority date 27th July 2016). [patent]

Quality indicators:

[QI1] PI: R. Young, University Research Fellowship, Royal Society, between October 2012 and present (renewed in 2017), GBP897,000 (UF11055 and UF160721).

[QI2] PI: R. Young, Co-I U. Roedig, Atomically unique physically unclonable functions, US Air Force Office of Scientific Research, between 2016 and 2019, USD885,673 (FA9550-16-1-0276).

[QI3] PI: R. Young, Split Quantum Physical Unclonable Functions, US Air Force Office of Scientific Research, between 2019 and 2022, USD893,008 (FA9550-19-1-0397).

[QI4] 2015 EPSRC ICT Pioneers Award 'overall winner' for J. Roberts.

[QI5] PI: R. Young, Ultra-fast quantum random number generators, Royal Society, between 2018 and 2021, GBP95,396 (RGF\EA\180146).

4. Details of the impact

To date, the primary impact of the research is on the Lancaster spin-out, QBL, which is currently located in office space rented from the Physics Department at Lancaster University [5.1]. Co-founded by Young (Chief Scientific Officer) and Philip Speed (Chief Executive Officer), QBL was incorporated in April 2013, but commercialisation and licensing agreements with Lancaster were not signed until 2014, meaning that all the value (impact) generated by QBL occurred during the current REF period. During this time, working in very close cooperation with Young's research team in the Physics Department at Lancaster University, QBL has developed novel, low-cost quantum security solutions suitable for mass-market applications in areas such as authentication and secure communication. QBL has established itself as a pioneer in the nascent quantum security market, founded on the novel and robust underpinning research described in Section 2. The company's commercial success is built on the fact that current security devices on the market base their signatures on classical macroscopic physics; whereas technologies developed by QBL are dominated by quantum mechanics. The difference: due to the quantum nature of the device and no reliance on keys, attacks such as cloning and copying are not practically feasible. QBL is now directly engaged in product development with global Tier 1 companies, as described in sections 4.1 and 4.2 below, though some cannot be named in this document due to strict confidentiality agreements that are in place.

As a result of this activity, and following several rounds of private investment, the company is now estimated to be worth more than GBP10.0 million [5.1, 5.2]. This valuation was derived from a combination of factors including the market potential for QBL's solutions, agreements made between QBL and its production partners, licenses sold, and the successful completion of a contract and external trial with a US West Coast-based multinational technology company. Additionally, the valuation is validated by the investment rate at which experienced technology investors have bought into QBL. QBL recently sold 10 million licenses to a multi-national security label manufacturer for them to create tags based on QBL's intellectual property [5.1]. Independent patent landscaping analyses, focusing on the nascent field of quantum technologies, have ranked QBL's portfolio highly (top 20) with respect to some major world-leading companies [5.3, 5.4]. As QBL has expanded since its inception, 15 jobs have been created.

4.1 Impact of Q-ID®
Counterfeiting and forgery of digital identities are two of the costliest crimes in the world today. Counterfeiting is a problem that is ubiquitous to almost all products. The Organisation for Economic Co-operation and Development (OECD) estimates that the global trade for counterfeit goods cost industry USD200.0 billion in 2005 and has grown to an estimated USD461.0 billion today [OECD website]. Digital identity counterfeiting and device spoofing are rapidly becoming more acute problems. As the Internet of Things (IoT) expands, the need to trust the identity of smart systems, such as the brake systems in connected cars, becomes vital. The specific impacts of QBL's two families of Q-ID® products, Q-ID® Optical and Q-ID® Electronic, are given below.

Q-ID® Optical: QBL and Lancaster University are working with OSL to integrate Q-ID® Optical into mass-market security holograms and QR codes [5.5], based on research conducted at Lancaster University since 2017 [3.2]. OSL is the market leader in fighting counterfeits for brands, transaction cards, and government documents and currency, supplying thousands of companies across different industry sectors and 50 governments worldwide. Three rounds of in-factory trials with OSL have been successfully completed and a final product development stage is underway. The final product, a tag with a surface coating containing quantum materials, has a target cost of less than GBP0.01 per unit, which is between 10 and 100 times less than existing RFID-based solutions with which it competes.

Verification of authenticity with Q-ID® Optical will be with a smartphone; using its flash to excite emission from the tag and its camera to collect an identity and signature of quantum emission. This enables a mass-market uptake and the power to confirm products are genuine by anyone in possession of a smartphone. QBL is currently working with a leading smartphone manufacturer to facilitate this solution. The importance of this anti-counterfeiting solution to the general consumer base is demonstrated by broad media coverage of Young's publications by Sky, The Times, New Scientist and BBC's Tomorrow's World [5.6], which has reached over 8 million people. Important niche publications targeting policymakers and industry members have also published articles on this technology, including Trading Standards Review, Trading Standards Today and Semiconductor Engineering [5.7].

Q-ID® Electronic: QBL is pursuing the application of its electronic variant of Q-ID® to increase the security of electronic devices, to prevent problems such as device spoofing. The first demonstrators of this technology were made using III-V semiconductors in 2015 [3.1], which are typically used for optoelectronics and in more niche applications, such as, *e.g.*, high-speed filters. For III-V implementation, QBL is working with one of the largest semiconductor fabrication companies in the world to develop a product. However, as silicon dominates electronics, they are also translating the technology to devices that can be readily implemented into standard silicon (complementary metal-oxide-semiconductor, CMOS) processing, working in conjunction with a major semiconductor foundry.

4.2 Impact of Q-RAND®

To realise commercially ready technology from Lancaster University research [3.5], QBL is pursuing a strategy to embed Q-RAND® within new devices. In particular, small embedded systems, such as IoT devices, vastly outnumber conventional computers. Cisco estimated the number of IP connected devices to be over 18 billion in 2018, and forecast it to rise 50% by 2023 [from Cisco's Annual Internet Report 'Cisco Annual Internet Report (2018–2023) White Paper, 2020']. Every IoT device requires an RNG to communicate securely, to generate cryptographic keys for specific sessions, and for operational efficiently, to schedule windows in which to transmit data, minimising clashes with other devices. A prototype of a CMOS-compatible structure has been implemented in silicon, and work is currently underway to integrate the technology in existing semiconductor fabrication processes for next-generation IoT devices.

5. Sources to corroborate the impact

[5.1] Statement from QBL's CEO confirming the company's heritage, relationship to Lancaster University and external partner, valuation and other details. Dated 19th October 2020.

[5.2] Financial Statements, Companies House (company no. 08501521). Dated 2018 and 2019 to evidence value of QBL.

[5.3] In 2018 an Institute of Physics production, Physics World, published an article mapping the commercial landscape of quantum technologies. Young was interviewed, indicating the significance of his contribution to this field, and QBL featured prominently in the article.

[5.4] An independent patent landscaping report produced by Patent Seekers in 2018 mapping the growth of patents in the quantum technology sector. It concludes on page 16 that '*Quantum Base appear to be accelerating the most in the UK over the last 5 years*'.

[5.5] Statement from OSL, dated 19th October 2020. Corroborates the incorporation of this research into holograms – modification of manufacturing, R&D time/resource investment, numbers manufactured, and geographical reach.

[5.6] Archived media coverage from 2017 tracing exposure numbers. Highlights include:

- Page 2: A live TV interview on Sky News in 2017, in which Young was interviewed about Optical Q-ID and its anticipated impact on counterfeiting. The station has a reach of approximately 1 million viewers for the timeslot this program was aired.
- Pages 4 to 6: A long-form article published by New Scientist on PUFs. It focuses on how Prof. Young's research has advanced the field and how QBL is leveraging this to disrupt the hologram market with OSL.
- Page 21: The BBC produced a video that was featured on their 'Tomorrow's World' website, illustrating how the optical Q-ID variant works and the problems it solves.

[5.7] Copies of articles published by policy-making industry bodies relating to the technology: Trading Standards Review, dated October 2017 and Semiconductor Engineering, dated October 2018 (pdf provided), and Trading Standards Today, dated October 2017 (available online only).