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BUSINESS AND INNOVATION   ANALYSIS

Mapping the commercial landscape for quantum technologies

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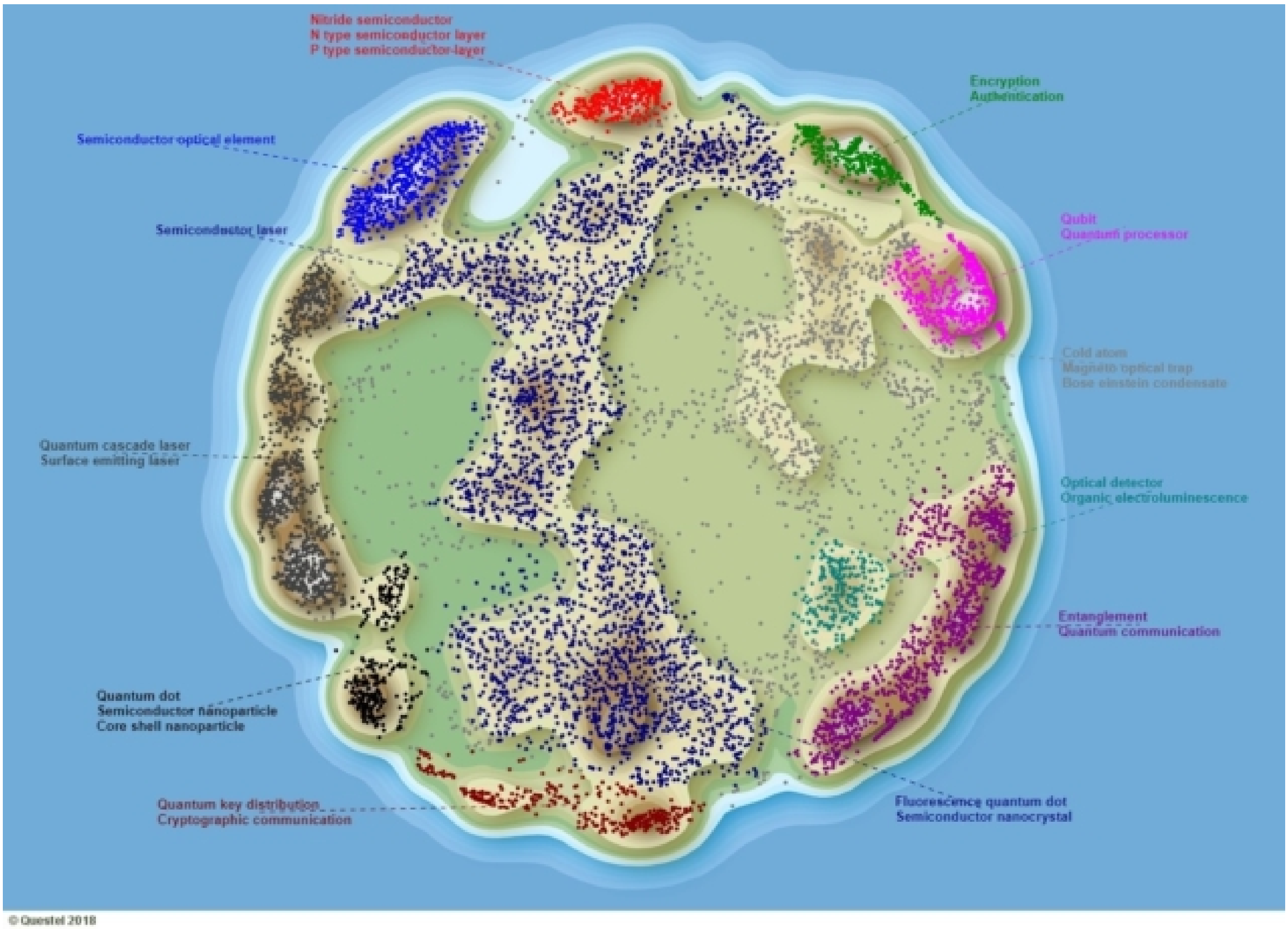
As a second generation of quantum devices begins to move out of physics labs and into the marketplace, patent attorney Andrew Fearnside offers a tour through the developing commercial landscape, with a particular focus on how this landscape compares to funding programmes currently under way in the UK and beyond



Mapping the patent landscape (Image copyright: Questel 2018 and Patent Seekers Limited 2018)

Albert Einstein never really reconciled himself to a quantum-mechanical world. “The more success the quantum theory has, the sillier it looks,” he grumbled in 1912. Since then, the theory has nevertheless proved fabulously good as a framework for explaining how the world works at the microscopic level. However, until quite recently there has been a notable absence of mass-produced consumer technology based on uniquely quantum effects. Whereas past advances in, for example, electromagnetic theory underpinned revolutions in communication technology and power generation — revolutions that have dramatically changed the way we organize our lives and run our societies — we have not yet seen quantum theory do the same.

Of course, one could argue that semiconductor technologies, quantum dots, nuclear magnetic resonance (NMR) devices, electron microscopes and lasers are all examples of mass-produced quantum technologies. To some extent, that may be true. However, as others have noted (see *Physics World* May 2012 pp16–17), these "first generation" technologies do not directly harness uniquely quantum phenomena such as superposition, uncertainty or entanglement within individual quantum states to perform a task or achieve a result. Such effects lie, instead, in the realm of so-called "second generation" quantum technologies.

This second generation promises to take us into a new era far beyond today's familiar digital technology landscape. While quantum technology can encode information into the familiar 0s and 1s of the binary world, it can also encode information as mixed combinations of both a 0 and a 1 simultaneously. This is the *qubit*, the quantum analogue of the digital bit, and if its counter-intuitive properties can be harnessed, the results will lead to advances in technologies as varied as computing, artificial intelligence, measurement, sensing, timing and imaging — to name just a few. Such advances have the potential to disrupt many sectors of the economy, including not only IT, computing and telecommunications but also engineering, transport, navigation, finance, defence and aerospace.

Not so silly

In 2013 the UK government announced a plan to invest £270 million to develop and commercialize quantum technologies, with the aim of placing the UK in a leading position within the global quantum technology marketplace. As a first step in this plan, a national funding body, the Engineering and Physical Sciences Research Council (EPSRC), established a programme for quantum technologies – a programme implemented, in the main, through several "hubs". Each hub consists of a network of academic and industrial partnerships, focused on one of five core areas: time-keeping; sensing and measurement; imaging; communications security; or computing. The hubs' goals are not only to develop a quantum technology manufacturing capability in each sector, but also to develop services around various core technologies.

Of course, industry at large is not unaware of the potential opportunities associated with second-generation quantum technologies, either in these sectors or elsewhere. The extent to which these opportunities, as seen from the industry perspective, align with the goals of the EPSRC's national programme is an open question, and one worth examining in some detail. Perfect alignment was always unlikely, as industry researchers have different priorities and pressures to those in academia. Businesses are typically cautious in planning research and development (R&D) investments and may not have the freedom to invest in the sorts of "blue skies" research that government-funded projects enjoy. Nevertheless, where alignment does occur, this could indicate a strong market for the types of quantum technology prioritized by the EPSRC. Conversely, in areas where there is no alignment, there may be opportunities for the national, government-funded research programme to push the technology forward, to the point where it begins to attract commercial interest. To get a better sense of how this works (or might work in the future), let's look at each hub area individually.

Time-keeping

The UK has long been a world leader in time-keeping technology, and its scientists have twice produced revolutions in the field. In the mid-18th century, John Harrison's model H4 marine chronometer made it possible to reliably and effectively measure longitude at sea from anywhere on the globe. Almost 200 years later, scientists at the UK's National Physical Laboratory created the world's first caesium atomic clock. In their own way, both inventions drove an expansion of commerce: Harrison's chronometer by enabling reliable navigation to support global trading routes, and the atomic clock by underpinning the "trading route" of global digital communications.

The two inventions are also linked in another way. Modern global navigation relies on satellite systems such as the US-operated Global Positioning System (GPS), which in turn rely on precise time-keeping signals transmitted from space-borne atomic clocks. These time-keeping signals are also widely used by telecommunications operators and power generation companies to coordinate the operation of infrastructure. Even international financial institutions routinely use GPS time-keeping signals to "time-stamp" rapid automated-trading transactions, making it possible to trace and co-ordinate individual trades.

The GPS system is, however, vulnerable to interference or failure. This raises the risk of disruption to telecommunications, critical power supply infrastructure and financial markets. Accordingly, one goal of the UK's national quantum technology programme is to make highly accurate, terrestrial atomic clocks that can be used as a reliable and routine back-up against disruption of space-borne timing signals. To this end, the programme aims to develop a new generation of atomic clocks that are much more accurate than existing systems. The best atomic clocks currently available hold their accuracy to within a few nanoseconds per century, but these devices are big enough to fill a room. Researchers within this hub are therefore working on atomic clocks that are smaller, more robust and portable than today's state-of-the-art systems.

Sensing and measurement

Superpositions of quantum states are highly delicate things. The wave-like nature of quantum particles makes them extremely sensitive to the extended environment around them. For some applications, particularly quantum computing, this is a problem, as the fragility of qubit states makes it difficult to maintain them long enough to perform quantum operations. In sensing and measurement, however, the very delicacy of quantum superpositions makes them ideal as the basis for precise sensors.

This new generation of sensors aims to exploit the quantum nature of atoms by using lasers to trap them in minute clouds, at very low temperatures. Low temperature means a low average atomic velocity, and that means the de Broglie wavelengths of the atoms will overlap and interfere. The pattern made by this interference is very sensitive to influences from the local environment. Hence, quantum sensors may be used to measure electric, magnetic or gravitational fields, as well as other properties such as temperature, acceleration, rotation or pressure.

Quantum gravitational sensors have attracted particular interest as potential tools for subterranean surveying. Because they sense gravity very precisely, such “quantum gravimeters” could be used in civil engineering applications, or to detect groundwater reserves and deposits of minerals, oil or gas. They work underground or underwater where satellite navigation fails, and could in theory be deployed from space, rather than in local ground-based units. To investigate these possibilities (and more), NASA recently placed a cold-atom device on the International Space Station (ISS). Dubbed “the coolest experiment in space”, the Cold Atom Laboratory (CAL) uses cold atoms to make precision measurements of gravity.

The underlying technology for the CAL was developed by ColdQuanta, a spin-out of the University of Colorado in the US that recently raised $6.75m in venture funding. The company has also established an office in Oxford, UK, and they hope to develop cold-atom quantum technologies for quantum computing as well as sensing and measurement. According to ColdQuanta CEO Dana Anderson, commercial interest in this area is “exploding”, despite factors that have, in the past, prevented it from being operated outside specialist labs. “We took a critical look at what technological gap is preventing rapid forward progress,” he says. “It’s in the progression from laboratory settings into commercial settings. We aim to fill that gap and enable practical quantum tech systems.” As an example, Anderson mentions a recent customer who got a system similar to the one on the ISS running within six hours of taking it out of the box.

Imaging

Cameras that can take pictures around corners might seem like the stuff of science fiction, but they are a key area of development for the UK’s quantum imaging hub. These specialized cameras send out laser pulses that illuminate a point on the ground in front of them. The resulting scattered light then hits an object lurking unseen around the corner, bounces off it, and re-enters the camera’s field of view, where it is detected. The ability to build up detailed images via this indirect method is down to the cameras’ exquisite sensitivity, which enables them to detect single photons efficiently with short exposure times, and thus to “see” around corners.

Another focus for the quantum imaging hub is known as “ghost imaging”. While not involving spectres as such, the technology is certainly spectral in the physics sense of the word. Conventional cameras capture the same wavelength of light used to illuminate the imaged object. Not so with a quantum "ghost" camera. Instead, the object is illuminated with one wavelength of light, but imaged with a different one. To do this, experimenters must generate beams of entangled photons: one beam to illuminate the object while the other beam separately illuminates the camera, forming an image of the object. Entanglement allows the first beam to influence the image formed by the second.

Secure communications

Clearly, both around-the-corner imaging and ghost imaging would not work without single-photon detectors and sources of entangled photons. These technologies are also key enablers for quantum cryptography. Cryptographic keys are ubiquitous in modern-day communications, allowing data to be encrypted before transmission and decrypted after reception. In one widely-used encryption method, known as public-key cryptography, the public key typically consists of large, randomly-generated numbers, while the private key is the (also very large) prime factors of those random numbers. As long as it remains difficult to calculate the prime factors, this method remains safe. However, prime factorization is one of a handful of problems that a (so far hypothetical) large-scale quantum computer could do with ease. Hence, come the day when such computers exist, come the "crypto-apocalypse" or "quantum Y2K moment" when current cryptographic key distribution will fail spectacularly. A more subtle point is that encrypted communications can be recorded and saved for a later date. Some communications, from government agencies for example, could still be sensitive a decade after first being sent. This means that we need secure our data now from attack by quantum computers that may exist in the future.

Quantum key distribution (QKD) offers a potential solution to this problem. This method encodes the key not in large random numbers, but in the states of quantum particles – for example, in the polarization state of a photon. Communications are sent from the transmitting party (Alice) to the receiving party (Bob) using these encoded quanta. Quantum theory tells us that if a third party (an eavesdropper, or Eve) should intercept and read any of the data in the quantum channel, then the states of the hacked quantum particles will be altered. This alteration can be detected by Bob, who warns Alice about Eve. Alice may then send a new key or use a different communications channel.

For QKD to work properly, would-be quantum communicators will need reliable sources of quantum light for Alice to encode; effective detectors for Bob; and reliable random number generators for both of them. QKD was first introduced with single photons acting as information carrier, sometimes referred to as "discrete-variable" QKD. This requires the use of single-photon sources and detectors. Later, QKD with continuous variables was introduced as a promising alternative using coherent states of light. The advantage of continuous-variable QKD lies in the efficient, high-rate and cost-effective detection using homodyne receivers as opposed to single-photon counters.

"The promise of quantum communications is incredibly exciting, as it represents a new means to share information that is fundamentally secure," says Robert Young, who co-founded Quantum Base, a spin-out of the UK's Lancaster University that specializes in quantum security technology. The challenge, Young explains, is to bring this new technology to the masses, which will require simple, low-cost devices that can be produced in bulk and integrated into the next generation of electronics. “At Quantum Base we don’t want to limit the potential of QKD to the few with deep pockets, so we’re focused on developing scalable, practical products,” he says.

Computing and artificial intelligence

A number of different systems have been proposed as the basis for a powerful, universal quantum computer. The UK is among the world leaders in photonic quantum computing. The core elements necessary for photon-based computers include single-photon sources to provide qubits; optical logic circuits for executing operations on them; photon detectors to read computational outputs; and memories for storing the qubits. An alternative approach – the focus of efforts by several companies, including D-Wave Systems, Google, IBM and Intel – uses superconducting qubits, while arrays of cold ions or neutral atoms also offer certain advantages.

In the last of these approaches, researchers use lasers to trap and cool the atoms until they are virtually motionless – the same basic starting point as the quantum gravimeters discussed earlier. Then, after lining up the atoms in single file, electrons in neighbouring cold atoms are promoted into highly excited states (known as Rydberg states) with energies just shy of the atoms’ ionization energy. This process, in effect, inflates the atoms so that they are big enough to interact with each other. In principle, these highly excited (but still neutral) atoms could provide the superposition and entanglement needed to create the qubits for performing quantum calculations.

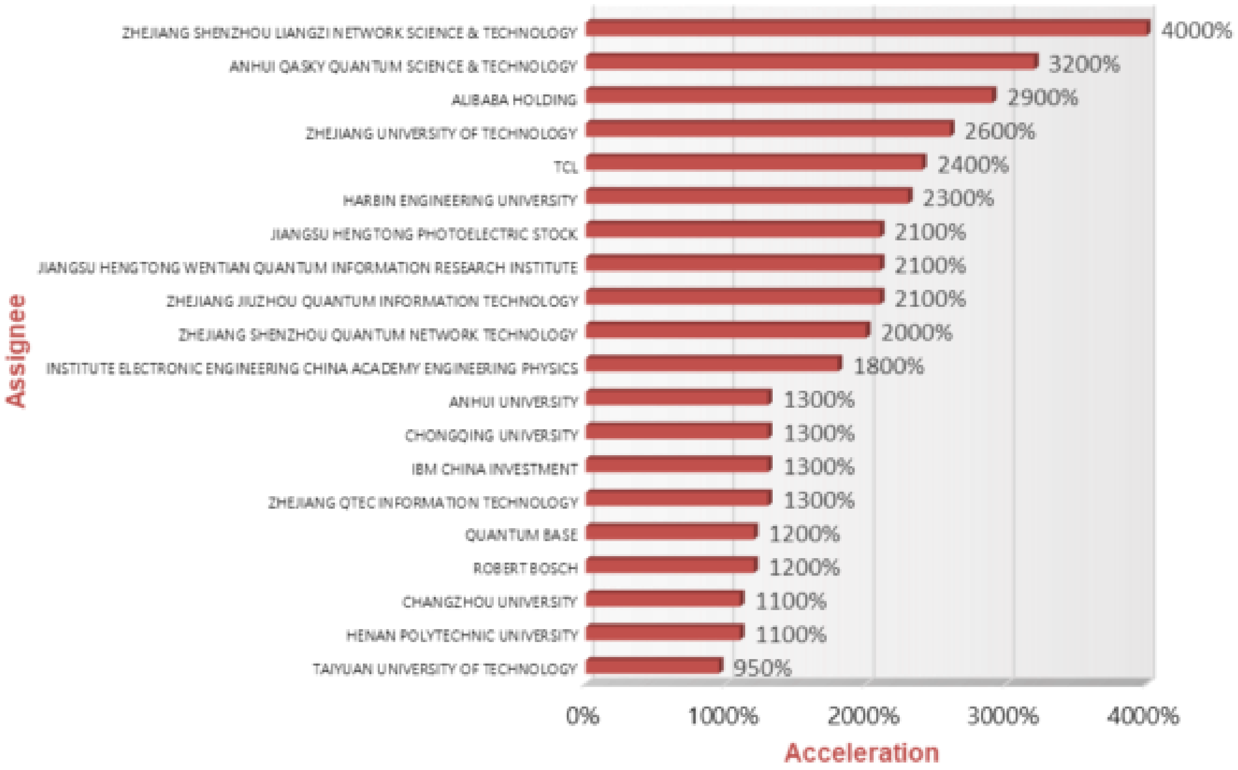
While a universal quantum computer is still an indeterminate number of years away, there is a growing (though not universal) consensus that the so-called “quantum annealer” developed by D-Wave is indeed directly exploiting quantum effects. Interestingly, the structure of the quantum annealer is not dissimilar to that formed by the connections in a neural network. This has spawned development of so-called quantum neutral networks formed by coupling a classical neural network to a quantum annealer. The annealer “trains” the classical neural network using data obtained by processing qubits to solve problems that would be intractable with classical processors.

The speed and efficiency of the D-Wave processor opens up new possibilities in artificial intelligence – and particularly in machine learning, where huge volumes of data must be rapidly processed in order to train computers to perform tasks such as object recognition and classification. Machine learning has already been applied to problems in numerous sectors, including robotics, driverless vehicles and medical diagnostics, and the potential to add quantum capabilities to the mix has not gone unnoticed.

What lies ahead

The 20th century saw the rise of technologies underpinned by electromagnetics and materials science. Electronics, computing and communications grew into vast new industries, providing devices that have changed the way we live our lives and organize our society. Second-generation quantum technologies have the potential do the same again, and if commercial indicators (such as patent applications and other features of the intellectual-property landscape) are anything to go by, we may already be seeing the beginnings of this process.

While the UK's £270 million quantum technologies programme was among the first and largest globally, other counties are also committing a lot of money and energy to developing quantum technology. Following the passage of the National Quantum Initiative Act in summer 2018, the US plans to increase the size of its quantum technology programme significantly. The European Union's "Quantum Manifesto", which calls for a €1 billion investment in quantum technology, was launched in October 2018 as part of the EU's Horizon 2020 research and innovation programme. China's quantum technologies programme is well-advanced, with notable successes such as the Quantum Experiments at Space Scale (QUESS) satellite that test (and of course showcase) technologies developed by researchers there. In addition, Chinese companies and institutions are patenting aggressively (see figure). The governments of Canada, Australia and Japan have also invested in quantum technology programmes.



Distribution of Search Results by Acceleration

Who's active in quantum patents?

Ultimately, however, the speed at which these quantum technology programmes translate into commercially successful enterprises will depend on solving practical business problems such as the scalability and cost of product manufacture. The easier an established technology business is able to adapt to a new quantum technology – by, for example, limiting disruption to its existing manufacturing principles and product portfolio – the quicker the uptake of that technology is likely to be. This seems to be reflected in today's patent landscape (see heat map below), which is dominated by large technology companies that appear to be investing in quantum technologies that are, at face value, sympathetic to the company's existing technology base.

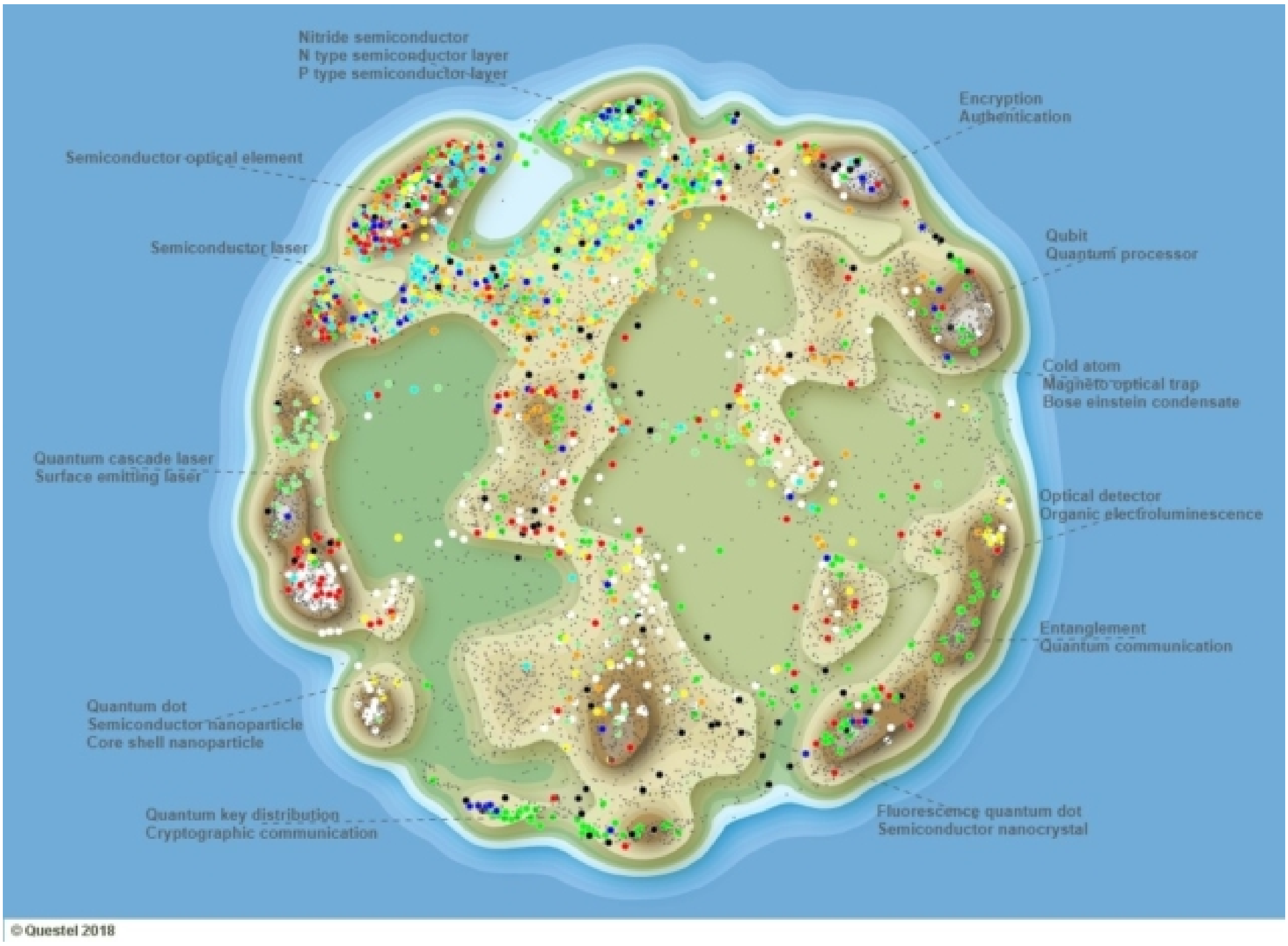
Assignee	B82Y10/00	B82Y20/00	B82Y40/00	G06N99/00	H01L21/20	H01L21/205	H01L29/06	H01L33/00	H01L33/06	H01L33/32	H01S5/00	H01S5/042	H01S5/10	H01S5/183	H01S5/20	H01S5/22	H01S5/323	H01S5/34	H01S5/343	H04L9/08
CANON	10	60	5	5	9	18	14	13	16	8	128	54	47	70	21	7	23	80	103	1
FUJITSU	8	45	10	8	41	53	157	19	69	21	306	50	32	33	34	42	59	92	203	4
FURUKAWA ELECTRIC		7			2	8	5	2	11	7	68	19	23	32	37	39	22	55	142	
HITACHI	8	19	3	38	9	32	24	15	38	28	116	20	10	21	16	13	65	55	146	10
IBM	21	3	7	46	9	4	27	16	10	2	12	11	11	6	5	3	4	12	17	14
INSTITUTE OF SEMICONDUCTORS	3		2		5			15	4	1	28	5	11	7	15	31	10	40	122	1
INTEL	18	2	6	7	11	2	33	3	2	1	3	2	7	3	5	4		6	3	8
MICROSOFT TECHNOLOGY LICENSING	18	1		60	1		9	1												3
MITSUBISHI	7	25	5	6	28	32	27	23	42	42	200	46	30	7	67	86	78	89	259	26
NEC	6	18	6	8	20	36	39	13	50	31	215	42	21	24	31	32	66	83	229	61
NICHIA		17	1		16	79	12	31	144	176	176	55	21	13	50	95	294	34	397	
NIPPON TELEGRAPH & TELEPHONE	2	8	4	36	8	19	33	3	22	12	76	11	6	13	8	12	19	23	134	27
PANASONIC	2	23	2	9	42	85	44	66	92	157	188	55	25	17	56	129	224	40	433	5
SAMSUNG	25	137	32	8	23	12	48	94	80	57	56	11	10	25	18	20	33	27	81	6
SANYO ELECTRIC		1			8	32	8	17	52	69	82	28	14		12	66	127	8	205	
SHARP	7	48	14	1	41	122	29	70	160	186	200	61	22	14	59	130	270	62	548	1
SONY	10	38	3	5	32	85	37	48	91	117	149	80	28	31	47	118	199	28	350	9
SUMITOMO	9	57	7		49	112	21	79	73	123	104	35	21	16	41	81	108	48	384	
TOSHIBA	13	22	5	29	24	57	84	76	148	175	188	54	24	29	26	57	131	57	267	82
UNIVERSITY OF CALIFORNIA	9	30	7	4	27	18	24	35	17	29	23	8	17	17	15	9	17	20	51	1

IPC Code

MIN 0 55 110 164 219 274 329 384 438 493 548 MAX

Hot topics.

For example, several giant Korean and Japanese electronics firms appear to be focusing on semiconductor-based quantum well lasers, quantum optics and QKD (see top figure and below). Similarly, computer and software giants such as Microsoft, Samsung and IBM have concentrated on quantum computers and quantum optics, potentially including various "enabling technologies" that make it possible to manipulate single photons for quantum-state control, entanglement and superposition.



Top patent filers. (Image copyright Questel 2018 and Patent Seekers Limited 2018)

However, the patent landscape appears to be relatively sparse in several of the development areas targeted by the UK's national programme. In particular, we have seen relatively low patent activity in fields related to atomic clocks, cold-atom technology, quantum optics or quantum processors as applied to neural networks. While the field of quantum computers shows a few hot-spots in terms of patent-filing activity, it, too, lags far behind areas like quantum-well lasers and other semiconductor-based quantum-confinement light sources, such as quantum dots.

Our conclusion, therefore, is that the UK's quantum technology programme has identified gaps in the quantum technology marketplace that are not being filled by the existing big technology providers – or at least, not yet. Government funding, coupled with the academic freedom to pursue new and disruptive innovations, is surely key to accelerating developments in these fields. But will this translate into successful new industries and businesses in the UK? Anderson, of ColdQuanta, thinks it will. "I deeply applaud the UK government for realizing that quantum technology has a commercial advantage," he says, adding that his company has developed a UK base for that reason. "Quantum is here to stay. Hype is present, but tools really are available to perform at the quantum limit. You must work at that limit to be competitive."

Andrew Fearnside gained a PhD in theoretical atomic physics from the University of Durham, UK, and is now a UK and European patent attorney, specializing in quantum technologies, at the Manchester, UK-based intellectual property firm Appleyard Lees, e-mail andrew.fearnside@appleyardlees.com