Tyndall
National Institute
Institiúid Náisiúnta

Position paper

Positioning Ireland for the quantum opportunity

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

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Executive summary

At Tyndall National Institute, we are investing in growth areas where Quantum Technologies feature prominently. The fundamentals of quantum science offer solutions to challenging problems using novel engineering solutions. They offer uncharted fertile territory for innovation that has sparked an international arms race to attain quantum advantage.

At Tyndall, we have pioneered Irish efforts in the field, specifically on the actual realisation of Quantum Technologies. Tyndall's strategy is to foster the development of new programmes around novel quantum materials and nanostructures and their translation into disruptive devices for Quantum Technologies. This activity is complemented by University College Cork's recent appointment of leading quantum physicist, Prof. Séamus Davis.

Given this opportunity, we want to work with national and global stakeholders to embark on a programme for Quantum Technologies. Ireland is in a unique position to become internationally competitive and attractive, thanks to long-term investments in materials and engineering science for digital technologies and the strong footprint of technology giants with significant investments in the field. To prepare Ireland for the quantum opportunity, we and our partners see the opportunity to:

- Establish Quantum Technologies as a key driver in Ireland's innovation strategy
- Develop Quantum Technology hardware utilising Ireland's strengths, for example in photonics and nano-electronics
- Establish infrastructure for Quantum Technologies, for example, a National Quantum Institute
- Invest in educating quantum scientists and engineers.

State-of-play on Quantum Technologies

Quantum mechanics is more than one hundred years old. Its fundamental equations were established in the early twentieth century and have developed to yield quantitative predictions of our physical world with incredible precision. Modern era technology has been built on our understanding of quantum effects: semiconductors, transistors, lasers, organic chemistry, magnetic resonance, etc. However, quantum mechanics is full of oddities and surprises. One can simply understand and exploit most of quantum mechanics by thinking of particles as waves. But the underlying concepts are so unfamiliar to humankind that we have barely scratched the surface.

A fundamental turning point occurred in 1964 when John Bell, a Northern Irish physicist, discovered what is now known as Bell's inequalities. Bell's set of equations definitively prove not only the full wave nature of fundamental particles but also that there is mutual dependence (so-called entanglement) which appears to violate causality. In simple terms, the rules of quantum physics state that an unobserved particle exists in all possible states simultaneously but, when observed or measured, exhibits only one state. When two particles are prepared in such a superposition (entangled) state, they remain connected; therefore, observing the state of one immediately affects the other, even when separated by great distances. This is what Albert Einstein called "spooky action at a distance."

As an increasing number of experiments have been devised to test such oddities, the new discoveries are allowing us to embark on a second quantum technological revolution and exploit the laws of quantum mechanics to increase performance in computation, communication and sensing. Quantum advantage would allow outperformance of classical computers in problems of increased complexity, guarantee secure communication and achieve the highest possible sensitivities in sensor technologies.[1]

The growing realisation of the emerging opportunities has already kick-started an international race to turn the recent excellent achievements of quantum science into a national competitive advantage in Quantum Technologies.[2] Countries such as the United States of America (USA), the United Kingdom (UK), Germany, the Netherlands, Australia, Japan, Singapore and Canada have been heavily investing in strong Quantum Technology research programmes amounting to several billions. China has also commenced in this direction with huge strides, including a strong space programme for secure quantum-based communications.[3,4] China dominates the field of quantum communication,

1 European Commission Quantum Technologies Flagship (2016) Quantum Technologies Roadmap. Available online from: https://qt.eu/app/uploads/2018/04/QT-Roadmap-2016.pdf

2 European Commission (2016) Quantum Technologies: Implications for European Policy. Issues for Debate. Brussels: European Union. Available online from: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC101632/lbna28103enn.pdf

3 Hsu J (2019) The race to develop the world's best quantum tech. IEEE Spectrum, 9 January. Available online from: https://spectrum.ieee.org/tech-talk/computing/hardware/race-for-the-quantum-prize-rises-to-national-priority

4 Wallace N (2018) EU runs to catch up as governments pledge more cash for quantum computing, Science|Business, 8 November. Available online from: https://sciencebusiness.net/news/eu-runs-catch-governments-pledge-more-cash-quantum-computing

whereas US firms lead in the development of quantum computation. To ensure strategic and economic sovereignty, the European Union (EU) has responded by committing to invest in excess of €1bn over the next 10 years to support a variety of Quantum Technology platforms.[5] The wealth of business opportunities existing in quantum computing, cryptography, communication, simulation and sensing has also triggered investments from major private companies. Quantum Technologies are now major research topics for IBM, Google, Microsoft, Intel and other technology giants. Quantum computers promise to considerably speed up solutions to a number of computational tasks, realising the only known model that could offer exponentially faster computing over today's conventional processors.

Besides, we are at a pivotal time where traditional scaling, as encompassed by Moore's Law, is coming to an end.[6,7,8] While the amount of data to be handled and analysed is constantly exponentially growing, next generation Information and Communication Technologies (ICTs) will demand scientific and technological paradigm shifts. Radical advances will require new concepts to be invented, new materials and their fundamental properties to be understood, and new fundamental principles to be explored.[9]

5 European Commission (2018) Quantum Technologies Flagship (October 2018). Available online from: https://ec.europa.eu/digital-single-market/en/quantum-technologies

6 Tyler, N. (2016) Is the semiconductor industry entering a new phase when it comes to scaling? Newelectronics, 28 June. Available online from: http://www.newelectronics.co.uk/electronics-technology/is-the-semiconductor-industry-entering-a-new-phase-when-it-comes-to-scaling/142714/

7 DARPA News (2017) Beyond scaling: An electronics resurgence initiative. Power Electronics, 9 June. Available online from: https://www.powerelectronics.com/power-electronics-systems/beyond-scaling-electronics-resurgence-initiative

8 Merritt, R. (2017) Roadmap says CMOS ends ~2024, EE|Times, 23 March. Available online from: https://www.eetimes.com/document.asp?doc_id=1331517#

9 Ahopelto, J., Ardila, G., Baldi, L., Balestra, F., Belot, D., Fagas, G., et al. (2019) NanoElectronics roadmap for Europe: From nanodevices and innovative materials to system integration. Solid-State Electronics, 155: 7–9. Available online from: https://doi.org/10.1016/j.sse.2019.03.014

Irish context

Despite the growing significance of Quantum Technologies and their importance for international competitiveness, Ireland lags considerably behind leader and follower countries alike.

However, the Irish Government does recognise the impact of digitalisation and has re-emphasised their commitment to embracing ICT innovation and technological change under Pillar one of the recently published policy Future Jobs Ireland 2019. Given the potential impact Quantum Technologies will have on the ICT sector, in which Ireland already holds a strong position, establishing a quantum ecosystem in Ireland will represent a great opportunity.

In Technology Skills 2022, co-signed by the Department of Education and Skills (DES), there is significant emphasis on high-level ICT skills, such as computing and electrical and electronic engineering skillsets. This is recognisably instrumental in delivering in the short term on the high industry demand for skills in the design, building and maintenance of ICT systems. A new generation of scientists and engineers, with substantial knowledge in both quantum mechanics and its technological applications, will ensure future ICT innovations and add to the success of Project Ireland 2040. Besides the commercial potential of the sector itself, there are significant gains to be earned by applying Quantum Technologies in Ireland's foremost industries. Examples include digital (machine learning, artificial intelligence, cybersecurity); pharmaceutical (drug design); finance (pricing, risk optimisation); industrial goods and energy (materials chemistry, compound selection); manufacturing (highly AI-efficient processes). Not investing now in such a disruptive technology and complementary skills will result in Ireland missing the window of opportunity in order to utilise the current baseline to attract and stimulate substantial business growth.

The underlying quantum research and enterprise community, given the right conditions, can gain momentum and thrive internationally as an attractor for investment and growth. First, there is a growing number of high-profile experimental outputs complementing theoretical studies of academic groups around Ireland on the fundamentals of quantum mechanics and how these may apply to computation. All seven constituent universities of Ireland have research groups which are either directly involved in research in Quantum Technologies or their research has the potential to converge with Quantum Technologies in the foreseeable future. For example, quantum computation theory is strongly represented at Maynooth University, with complementary research emerging at Trinity College Dublin and National University of Ireland Galway. Moreover, an ambitious effort has recently been undertaken at University College Dublin to address issues from the electronic engineering perspective. Second, most of the key technology firms which have been investing in quantum technologies have a strong Irish footprint. Notably, IBM, which has been running one of the most comprehensive quantum computing programmes, is conducting research in Ireland on the applications of quantum algorithms for optimisation, executed on quantum computing hardware and simulators, over the cloud.[10]

10 See for example Simonetta, A., Mareček, J., and Mevissen, M. (? Year) Qiskit Aqua: Vehicle routing. GitHub. Available online from: https://github.com/Qiskit/qiskit tutorials/blob/master/qiskit/optimization/vehicle_routing.ipynb; Simonetta, A., Mareček, J., and Mevissen, M. (? Year) Qiskit Finance: Portfolio diversification. GitHub. Available online from: https://github.com/Qiskit/qiskit-tutorials/blob/master/qiskit/finance/optimization/portfolio_diversification.ipynb

Tyndall position

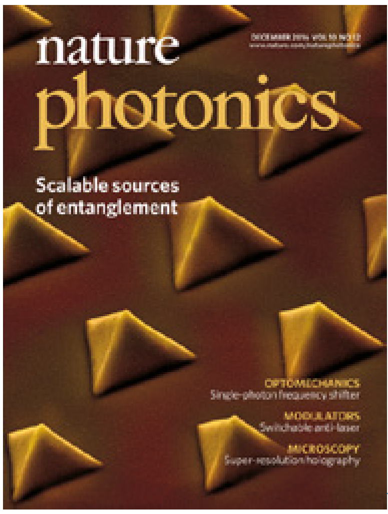
At Tyndall, we have pioneered Irish efforts in the field, specifically on the actual realisation of Quantum Technologies. Quantum cryptography for secure communications and sources of quantum light for quantum information (quantum internet and quantum computation) have been at the core of our work. Our photonics research centre is led by a founder of the field of experimental Quantum Key Distribution (QKD)[11], our research teams have been investing in quantum materials and quantum-effect devices for over 15 years, and this activity is finally paying off. [12]

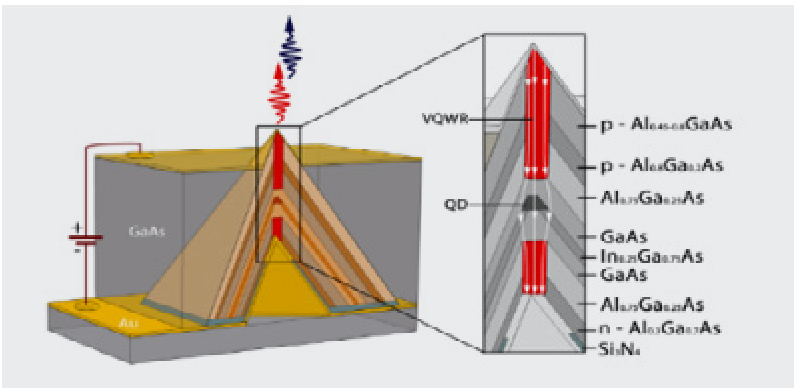
An optical quantum platform, based on site-controlled III-V quantum dots, has been uniquely developed by our Epitaxy and Physics of Nanostructures Group. This platform has demonstrated the only site-controlled quantum dot system capable of high-fidelity entangled light emission, making it a most promising scalable platform for solid-state quantum computation and [12]communication. Among the particles investigated to date for quantum information technologies, photons are the least prone to decoherence due to weak interaction with their environment.

The Tyndall nanostructures represent a deterministic source of on-demand non-classical light, a fundamental pre-requisite for any optical quantum information protocol. Quite remarkably, sources based on quantum dots do not have any fundamental physical limitation in their potential to deliver quantum signals deterministically and on-demand. In addition, Tyndall and Cork Institute of Technology researchers are exploiting their expertise in quantum modelling and integration of nanophotonics to deliver single photon sources for quantum cryptography as core partners in CUSPIDOR,[13] the sole project with Irish participation funded under the Quantum European Research Area Network (QuantERA). Tyndall is also very active in European forums, coordinating the Quantum in Space network and contributing to the Strategic Research Agenda of the Quantum Technology Flagship.

In the context of our ambition and growth, we are committed to fostering the development of new programmes on novel quantum materials and nanostructures and their translation into disruptive devices for Quantum Technologies. We have recently launched a CMOS++ programme to enable Deep Tech innovation for the next generation of computing technologies by bringing together frontier research in:

- Modelling
- Metrology and characterisation
- Materials processing
- Device fabrication.





Site controlled quantum dot based quantum light emitters (QLEDs).

Selective injection mechanism into QLEDs: electrons and holes run through the self-assembled nanowire structure in the middle of the pyramidal ensemble.

11 See for example C. Marad and PD Towsend (1995) Quantum key distribution over distances as long as 30km. Optics Letters, 20, 1695-1697.

12 See for example Juska, G., Dimastrodonato, V., Mereni, L.O., Gocalinska, A. and Pelucchi, E. (2013) Towards quantum-dot arrays of entangled photon emitters. Nature Photonics, 7: 527–31; Chung, T.H., Juska, G., Moroni, S.T., Pescaglini, A., Gocalinska, A. and Pelucchi, E. (2016) Selective carrier injection into patterned arrays of pyramidal quantum dots for entangled photon light-emitting diodes. Nature Photonics, 10: 782–87.

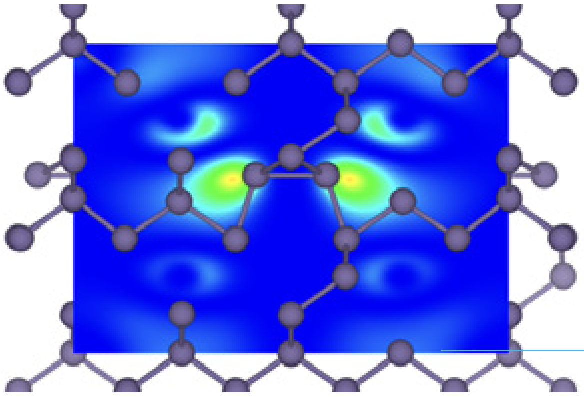
13 Compatible Single Photon Sources based on SiGe Quantum Dots (www.cuspidor-quantera.eu)

One of the key deliverables of the programme is to demonstrate quantum advantage using solid-state platforms that are Complementary Metal–Oxide–Semiconductor (CMOS) compatible. As Ireland's flagship ICT hardware research infrastructure, Tyndall is in a unique position to realise such quantum platforms and engage with industry to accelerate innovation path-finding as a first step towards commercialisation. We operate a number of cleanrooms with fabrication lines in nanoelectronics, compound semiconductors, and Micro-Electronic-Mechanical Systems (MEMS). These are fully supported by on-site expertise with an extensive suite of equipment on test, characterisation and packaging (photonic and electronic).

In the period 2006–2010, the Irish Government, through its Programme for Research in Third-Level Institutions, invested in the development of FlexiFab at Tyndall to complement the infrastructure that had been in place since 2004. Further investment is foreseen under the Irish Government's National Development Plan (NDP) 2018–2027, which includes an objective to upgrade and expand Tyndall in response to evolving ICT-related technology opportunities and also to strengthen our successful industry engagement model.

As part of the NDP Tyndall development, we are planning to support our CMOS++ programme with specialised cryo-magneto-probe infrastructure that will provide the world's first electronic and optical characterisation suite for quantum materials and devices. At the end of this implementation phase, we will be in the distinct position to build our own on-chip quantum computing platform and address a range of important issues in solid-state qubit technologies.

Our strength will be enhanced by partnering with distinguished quantum physicist Prof. Séamus Davis, who will lead a pioneering research programme on direct, atomic-scale visualisation of electronic states in quantum materials.



Visualisation of quantum state in a defect engineered quantum dot.

Actions to succeed

Demonstrating technologies where quantum mechanics yields an advantage is the holy grail for the next generation of physicists and engineers. This idea is also widely acknowledged by established top-tech players and newly formed companies in Ireland. At Tyndall, we recognise that there are demanding scientific and technological challenges to be overcome, and short-term expectations are idealistic. Nevertheless, the progress in the past 20 years has been truly exceptional, and Quantum Technologies have already moved beyond the academic environment and into the real world. For example:

- Quantum cryptographic systems are commercially available.
- Magnetic sensors based on diamond Nitrogen-Vacancy (NV) centres are in an advanced development state for biomedical applications.
- Atomic traps to map the Earth's gravitational field non-uniformities, or more profitably discover new oil fields, have been tested.

One of our key objectives is to strengthen the link with industry to nurture the growth of Quantum Technologies through translating science to innovation and attracting talent with quantum expertise to Ireland. This effort requires a coordinated and synergetic engagement nationally with actions supported by all stakeholders including research partners, industry, application end-users, the Government and its agencies.

At Tyndall, we are prepared to lead and work with all parties to establish Quantum Technologies as a key driver in Ireland's next innovation strategy; develop on-chip quantum computers; establish infrastructure for quantum technologies; and invest in educating quantum scientists and engineers.

Establish Quantum Technologies as a key driver in Ireland's innovation strategy

Intensify support for fundamental research and disruptive technologies delivering quantum advantage, in alignment with Ireland's ambitious goals in increasing investment in Research, Development and Innovation (RD&I) and promoting strong links between industry and the research community. Such an endorsement would create momentum within the Irish quantum community.

Develop on-chip quantum computers

Designs based on solid-state nanostructures and advanced materials are most promising, as they are scalable and would be easier to integrate with conventional semiconductor technologies. Ireland's strengths in nanoelecronics and quantum materials can be utilised to drive CMOS-based quantum computing architectures. Ireland is in a unique position to leverage existing expertise and mobilise the currently forming critical mass to become world pioneers through building the first quantum computer on an optical quantum platform, thereby fostering enterprise growth.

Commit infrastructure for Quantum Technologies

Following Tyndall's initial investment, acquire the necessary equipment and build dedicated facilities to support the establishment of a National Quantum Institute (e.g., using the organisational structure of an SFI research centre or equivalent). Embedding in an already established institute will allow existing infrastructure to be utilised and ensure the development of a decision centre with national remit and authority to represent the Irish quantum research and industry community in Europe and globally.

Invest in educating quantum scientists and engineers

Prioritise the establishment of a national postgraduate school on quantum science and engineering and use funding opportunities available (e.g. DES Human Capital Iniative; SFI CRT Programme).

No postgraduate programme dedicated to Quantum Science and Technology currently exists to prepare the next generation of scientists and engineers to develop and exploit the counterintuitive results of quantum research either in academia or industrial settings. The famous physicist Richard Feynman once said 'if you think you understand quantum mechanics then you don't understand quantum mechanics'.

About Tyndall

Tyndall National Institute is a leading European research centre in integrated ICT hardware and systems. Central to our mission is delivering economic impact through research excellence. We work with industry and academia to transform research into products in our core market areas of communications, agri-tech, energy, environment, and health.

As the national institute for micro/nanoelectronics and photonics, and a research flagship of University College Cork, we employ more than 500 researchers, engineers and support staff, with a cohort of 120 full-time postgraduate students. Together we generate more than 300 peer-reviewed publications annually. With a network of 200 industry partners and customers worldwide, we generate 85% of our €40m income each year from competitively won contracts.

We are home to a high-tech national research infrastructure unique in Ireland and is a national research asset. Hosting the only full CMOS, MEMS and III-V wafer semiconductor fabrication facilities and services in Ireland, we are capable of creating opportunities and prototyping new products for our target industries.

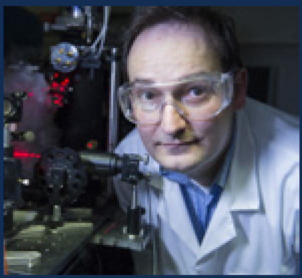
In recent years, we have received international recognition for designing, miniaturising and prototyping products to drive connectivity. Our researchers have won numerous awards for their ground-breaking research on new materials, devices and systems across micro/nanoelectronics and photonics, including in the areas of ICT for Health, Virtual Reality/Augmented Reality (AR/VR), wearables and the Internet of Things (IoT).

We are also a lead partner in European research programmes in electronics and photonics and their integration into smart systems with applications in communications, agri-tech, energy, environment and health. In Horizon 2020, we have delivered value to European research in 79 projects thus far (12 as coordinator).

At Tyndall, we host a number of industry-led research centres, including IPIC (Irish Photonic Integration Centre); CONNECT (Research Centre for Future Networks and Communications); and MCCI (Microelectronic Circuits Centre Ireland). These centres fully encompass the mission of the Institute, that is of representing a critical link between academia and industry, in order to expedite the development of new technologies and their market exploitation. The Tyndall community are important actors at European level, with key representation at high-level groups, scientific councils and European technology platforms. We have been contributing to the development and implementation of the strategic agendas of ESTHER (Emerging and Strategic Technologies for Healthcare), AIOTI (Alliance for Internet of Things Innovation), AENEAS (Association for European NanoElectronics Activities), EPoSS (European Platform on Smart Systems Integration) and Photonics21.

Cleanroom facility at Tyndall National Institute.

About the authors



Dr Emanuele Pelucchi

Dr Giorgos Fagas

Dr Emanuele Pelucchi

Dr Emanuele Pelucchi is the Head of Group at Tyndall National Institute, responsible for the MOVPE national facility activities, SFI principal investigator, and co-principal investigator in a number of projects, including at SFI-funded IPIC. He holds a PhD in Physics from the University of Bremen (2001), and subsequently joined École Polytechnique Fédérale de Lausanne (EPFL) as research assistant. In May 2006, Dr Pelucchi was awarded a SFI Principal Investigator Grant and moved to Tyndall in January 2007, where he set up a new research group in the field of III-V epitaxy for device applications, semiconductor (site-controlled) quantum dots and their applications to quantum optics and information. Dr Pelucchi has very broad interests, spanning surface science and epitaxy to quantum optics. He has developed world-leading III-V material quality (especially in the field of photonic integration) and growth process understanding, while uniquely developing and demonstrating arrays of site-controlled quantum dots and entangled photon emitters.

Dr Giorgos Fagas

Dr Giorgos Fagas MBA is the Head of EU Programmes at Tyndall National Institute. Since late 2013, he has been leading Tyndall's EU Programmes to engage with academia, industry, other research and technology organisations, and policy stakeholders to develop technology roadmaps, shape EU research and innovation policies, and establish strategic partnerships for collaborative research in Europe and internationally. Dr Fagas is a member of the Digital Innovation Hubs Working Group, the ESFRI Physical Sciences and Engineering Working Group, the Quantum Community Network of the Quantum Flagship, and the AENEAS Scientific Council as well as a regular delegate to the EPoSS Executive Committee, where he chairs the Working Group for Smart Systems in Natural Resources. Dr Fagas was also elected to the executive committee of MIDAS, the Irish industry association for micro and nanoelectronics-based 'system solutions' to represent their interests in European affairs. Previously, Dr Fagas has led activities in nanoelectronics and energy-efficient electronics as a senior researcher at Tyndall. His research has been published in more than 70 peer-reviewed articles; he is also editor of one reference book on Molecular Electronics and two books on ICT Energy Concepts.

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