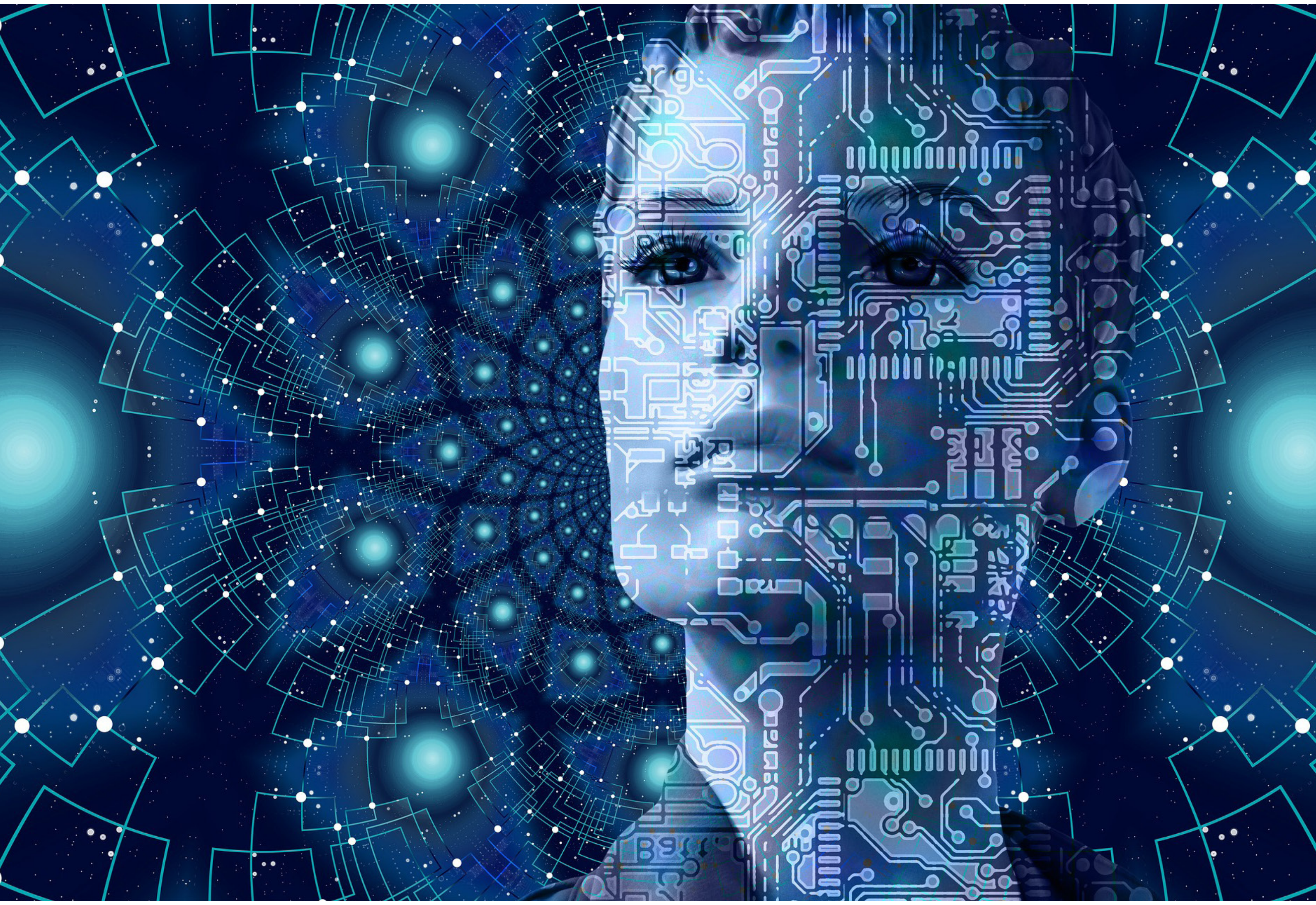
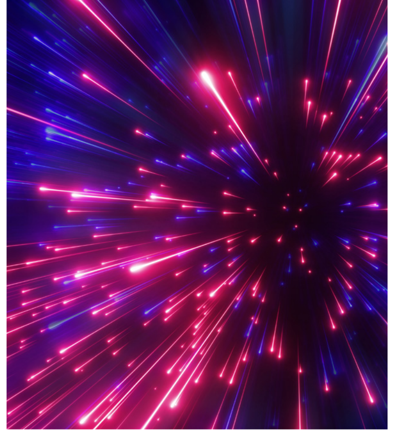
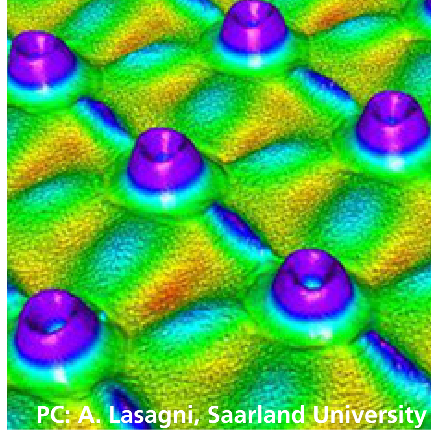
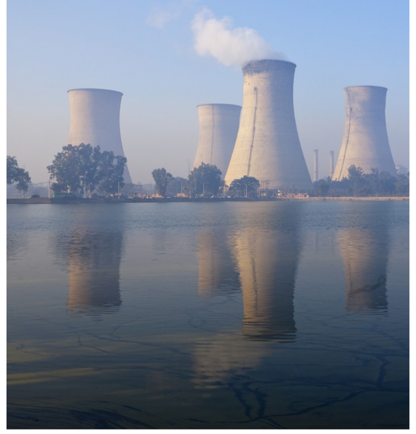
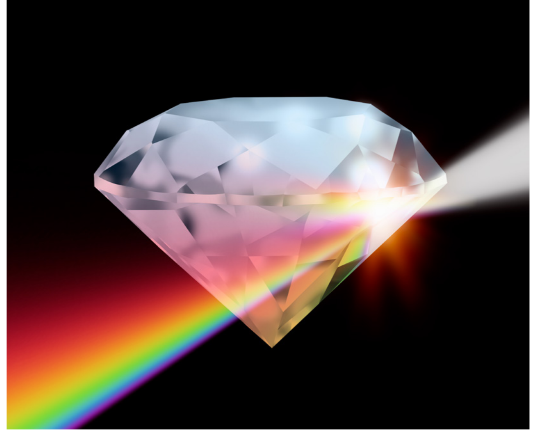
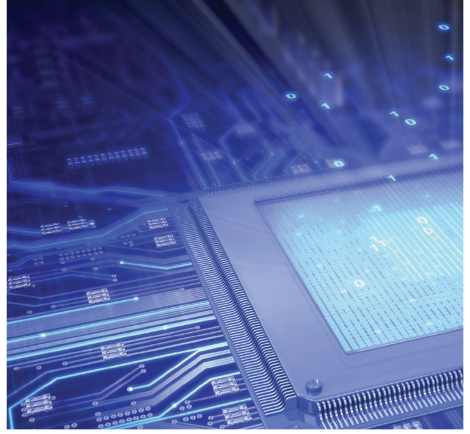
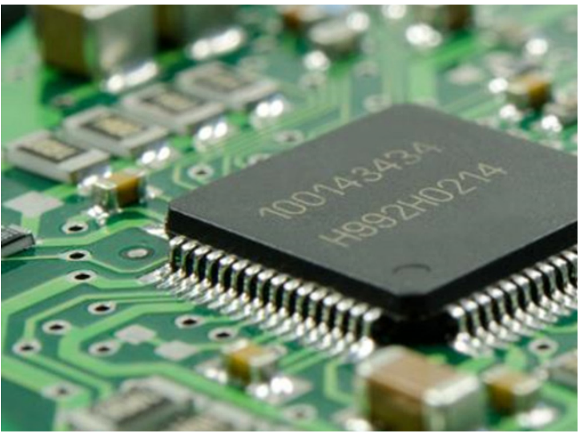
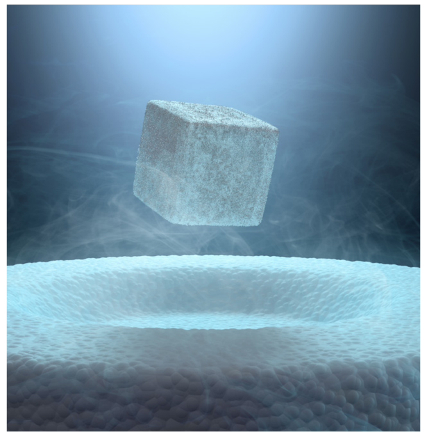
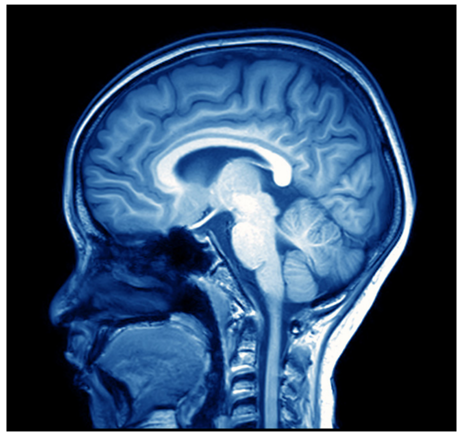
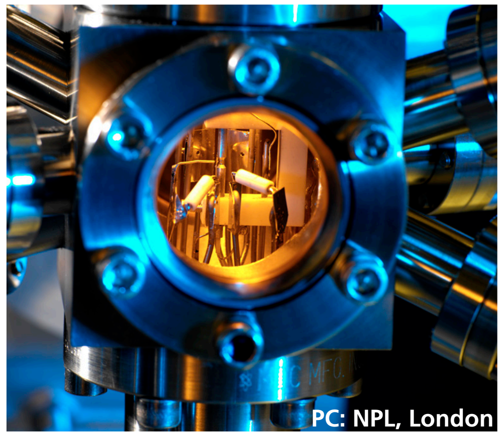
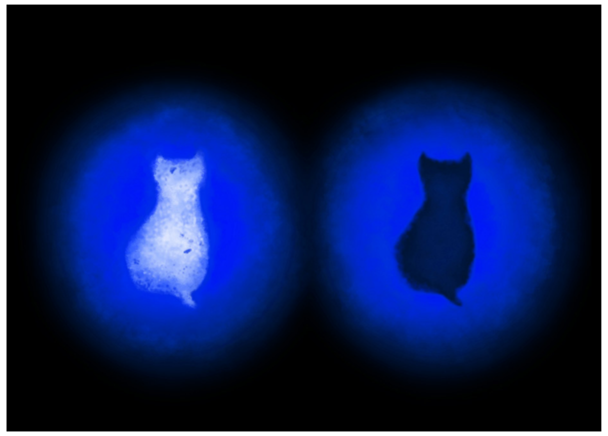
Quantum Technologies

Changing the art of the possible





Quantum Technologies

Founded in 1959, Oxford Instruments has grown and flourished, exploiting technologies developed in the first quantum revolution.

In our first 60 years, our technologies have harnessed the quantum phenomena of ‘coherence’ and ‘localization’. This includes superconducting materials cooled to liquid helium temperatures used to generate high magnetic fields for medical imaging; lasers and cameras for optical spectroscopy; X-ray detectors used for chemical fingerprinting in electron microscopy; superfluids and the generation of ultra-low temperatures; single atoms imaged through atomic force microscopy; and graphene nanostructures deposited atom by atom.

In our next 60 years, the second quantum revolution exploiting ‘entanglement’ and ‘superposition’ will open new possibilities in timing; sensing; imaging; computing; and cryptography. Oxford Instruments is committed to playing a key role in driving quantum technology development and creating societal impact through improved healthcare, energy generation and storage, biosciences and informatics, functional materials, advanced computing and global security.

The world we live and work in will be revolutionized through quantum technologies and, Oxford Instruments want to be your partner on that journey.

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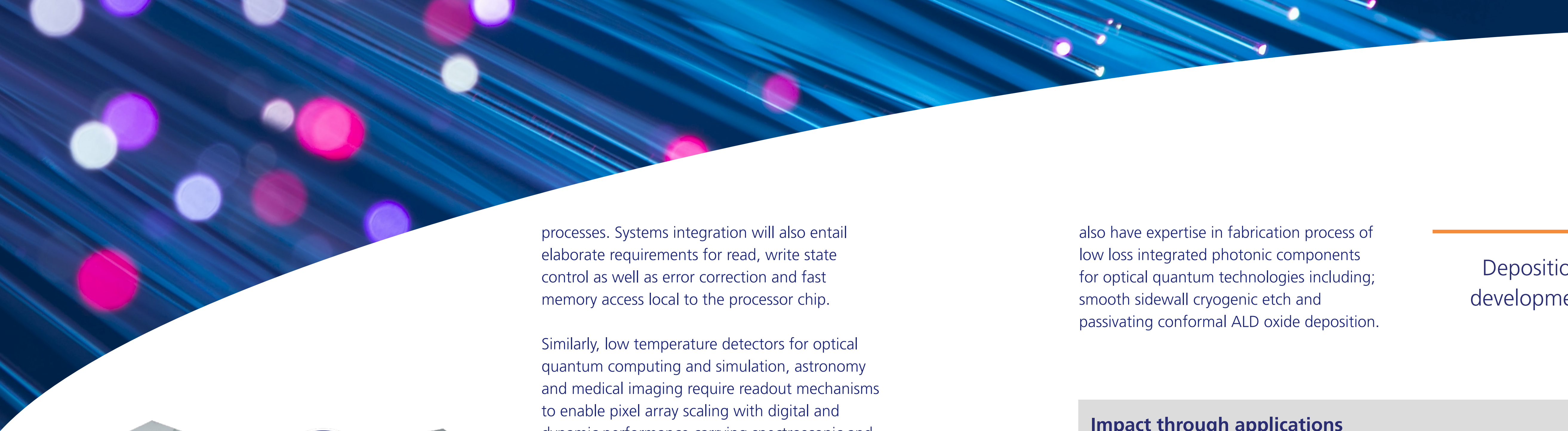


Quantum Materials

Deposition and etch tools enabling development of functional materials

New classes of materials have emerged in recent years with unique and often surprising properties. Examples being single atomic layer graphene and its derivatives, and the edge conduction states in topological insulators and nanowires.

Furthermore, as quantum computing has developed as a potential disruptive technology in the high-performance computing sector, so a number of material classes have emerged as qubit candidates.

Candidate devices have been developed using both superconducting and semiconducting materials. However, in the longer-term useful devices are likely to be hybrid structures requiring complex fabrication processes. Systems integration will also entail elaborate requirements for read, write state control as well as error correction and fast memory access local to the processor chip.

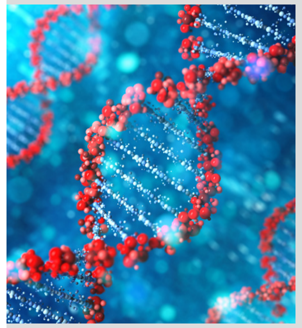
Similarly, low temperature detectors for optical quantum computing and simulation, astronomy and medical imaging require readout mechanisms to enable pixel array scaling with digital and dynamic performance carrying spectroscopic and spatially resolved data sets.

Across these classes of materials there are overarching requirements for atomic purity, stoichiometric accuracy, depth and verticality of etch, feature size and density of surface element. Chip packaging and bonding is a crucial aspect of system integration made challenging by the high bandwidth of signals used and the need to pass signals on and off chip, to and from superconducting devices without loss of phase coherence.

The base element of superconducting electronics are Josephson junctions. These are typically formed creating normal metal or insulating layers between two superconducting elements, often with an oxide of the superconducting film as the bilayer.

Oxford Instruments Plasma Technology have developed over 7000 process solutions across a range of materials using cutting edge atomic layer, plasma and ion beam etching and deposition technology. For quantum technologies, we specialize in tailored processing solutions for both quantum information processing and quantum sensing. These include leading edge processes such as; precision Si, metals and III-V semiconductor etch, deposition of superconducting NbN, TiN and diamond etch. We also have expertise in fabrication process of low loss integrated photonic components for optical quantum technologies including; smooth sidewall cryogenic etch and passivating conformal ALD oxide deposition.

Impact through applications

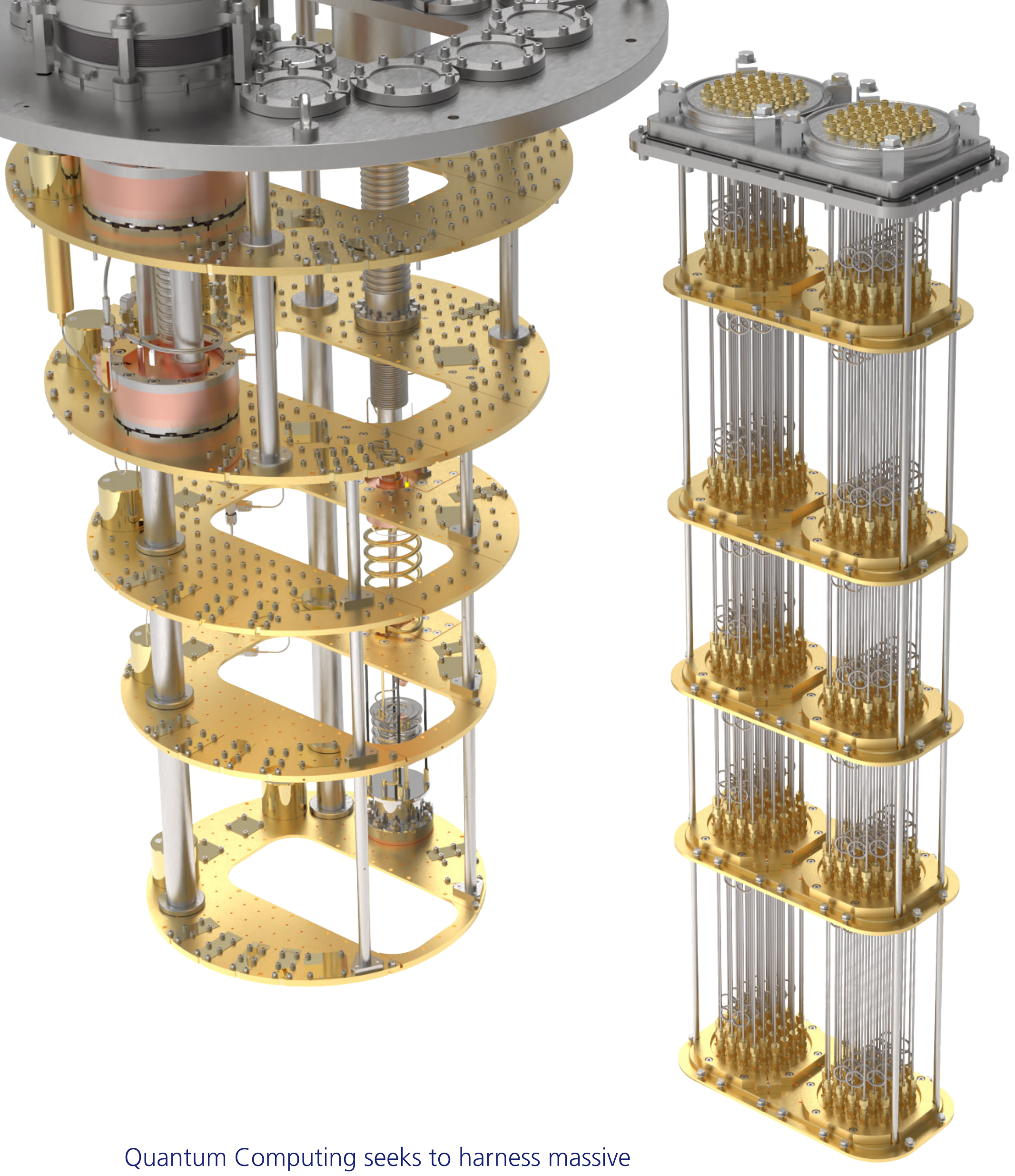


Simulation
First described by Richard Feynman, qubits can be used to simulate molecules as they are quantum entities just like the atoms they would seek to mimic. Drug discovery, protein folding, catalysis and battery modelling are likely candidate problems to be tackled using quantum computing. Photon fields using Ti Sapphire lasers show early promise. Companies are already experimenting with quantum simulation to accelerate lengthy and costly processes.

Cryptography
At the heart of cryptographic systems are random number generators. To ensure true randomness, seed numbers and algorithms can be replaced by a quantum physical process. InP lasers and InGaAs avalanche photodiodes are used to generate and detect random photon streams. Telecoms and financial services organizations have established programs for disaster recovery and secure communications in place today using quantum key distribution.

Photonics
The use of light to transfer and store information has revolutionized our world. Chip scale photonic circuits are enabling quantum computing, optical switching, memory and light field qubit arrays to perform computation and simulation. Miniaturization of components, systems integration and reduction in power consumption play a critical role when designing photonic architectures impacting in quantum technologies.

Healthcare
Semiconductor technology has a growing role in global healthcare enabling understanding, discovery and treatment of disease, making healthcare more affordable and efficient, in and out of the clinic. Biosensors transform biochemical signals into physical ones that can correlate with the concentration of target species. These active components are fabricated using processes for electronic, photonic or MEMS based sensors combined with surface functionalization.



High performance closed-cycle coolers enable cryogen free mK temperatures to be readily achieved with large sample volumes, high cooling powers and significant wiring assemblies for high line count applications such as quantum computing.

Quantum Computing seeks to harness massive parallelism in computation by examining many entangled quantum states **simultaneously** rather than individual classical states **sequentially**.

It is anticipated there are a diverse range of applications particularly in previously unsolvable or lengthy computational problems. This is of particular importance for optimization, unstructured search, materials simulation and logistics.

In the near future quantum annealers, simulators and so called Noisy Intermediate Scale Quantum machines (NISQ) with fifty to a few hundred qubits are likely to prove both useful and commercially viable. Whether they will demonstrate quantum supremacy as a general-purpose machine or specific application functionality compared to classical equivalents is yet to be determined.

Many of the leading candidate qubit contenders require a low temperature environment for operation and to screen out noise sources. These noise sources both on and off chip cause decoherence and increased error rates. Fully fault tolerant quantum computers are expected to require a million qubits or more and this remains some decades in the future. In the meantime, low temperature performance and error avoidance is critical to deliver a useful and usable NISQ machine.

Full stack architecture

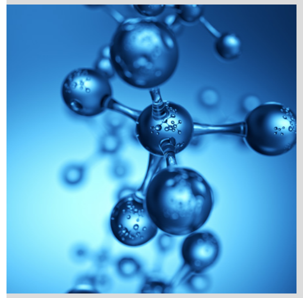
The energy level separation of the qubit 1's and 0's at the low temperatures required for operation are typically in the GHz frequency range, with carefully shaped nano second pulses required to control the computational operations.

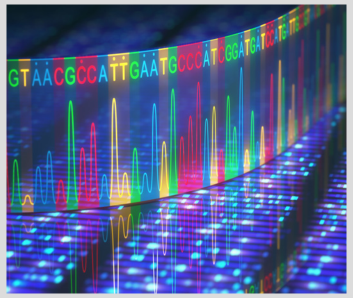
Maintaining precision and accuracy of pulse shape is challenging. Scaling engineering solutions to ensure low noise, wide band attenuated input lines and low impedance, low noise amplified output lines is required. Low noise performance, modularity and long-term reliability are features of Oxford Instruments NanoScience's enhanced cabling solutions for quantum computation.

Quantum Computing

High performance low temperature systems for NISQ type computation and simulation

Impact through applications





Materials Modelling
As with materials simulation; drug discovery, protein folding, catalysis and battery modelling are likely candidate problems to be tackled using quantum computing. Rather than simulating materials using qubits, modelling utilises computational techniques that lend themselves to quantum computing over classical computing to extend the range of species that can be investigated for both the speed and accuracy of the computation.

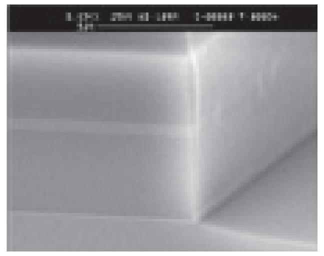
Optimization
Many classes of problems cannot be solved analytically. These classes of problems are widespread in logistics, medicine and finance. As the number of variables in a problem grows, the serial nature of classical computing stalls. A 270 variable problem already outstrips the number of atoms in the universe. The parallelism of quantum computing allows multi-variable optimization that could impact applications such as flight scheduling, traffic flow and cancer radiotherapy treatment.

Database Search
Relational database searching with structured datasets is a requirement of Big Data applications from the high street to CERN. Unstructured datasets such as text, multi-media and language can prove difficult to search or impossible depending on its size. Quantum computing offers the possibility of optimal unstructured search techniques using Grover's Algorithm. Security and drug discovery are candidate areas for development.

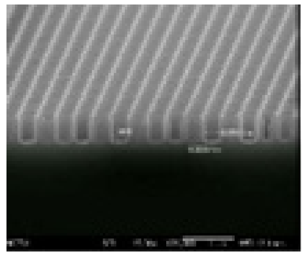
Security
In the absence of quantum cryptography, quantum computers could pose a threat to encryption mechanisms. RSA-2048 encryption would go from many millions of years to break on a classical machine to days on a quantum computer with 2000 qubits and GHz clocking speed. To counter this threat, quantum technologies are also being employed to establish non-computational security protocols, that will remain secure despite progress in quantum computation.

Quantum Sensing

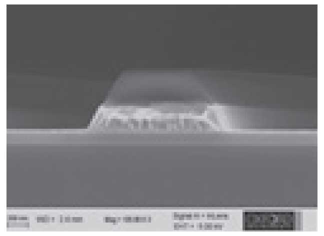
Sensors and devices enabling navigation, healthcare and the digital economy



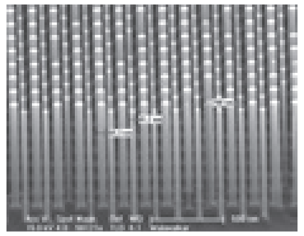
GaAs/AlGaAs layer interface on 2DEG



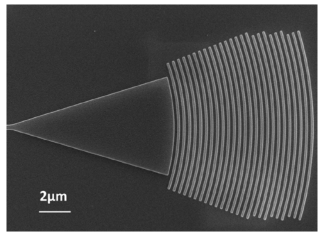
GaAs/AlGaAs photonic cavity etch



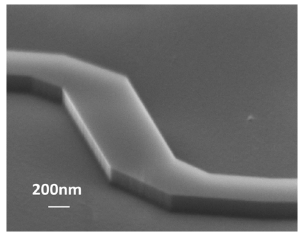
300 nm Nb etched to SiO_2 for superconducting electronics



Deep Si etch nanowires formed from dense 40 & 60 nm pillars



Etched grating coupler and taper waveguide on SOI



Etched strip waveguide on SOI with clean and smooth sidewall for low propagation loss

As sensors become smaller, quantum effects have a greater influence over the behaviour of the device, its properties and sensitivity. Moreover, systems with discrete energy levels may be used to enhance sensitivity beyond conventional methods.

Precision measurements have importance across all areas of research and industry. Metrology and measurements are of critical importance in nano-fabrication and other industrial manufacturing processes where the suitability, calibration and quality of the measurements is critical to the success of the operation. Poor quality measurements impact on form, fit and function as well as scrap and rework costs. Dynamic range, resolution, precision and accuracy are the cornerstones of quality measurements.

Quantum sensors offer enhanced performance beyond the classical shot noise limit. This may be through squeezed light in plasmonic sensors or by coupling to spin states in qubits such as NV centres in diamond. Better known quantum sensors include superconducting thin film devices such as SQUIDS, SQUIPS, nanowires, kinetic inductance detectors and bolometers.

Oxford Instruments Plasma Technology provides underpinning technology in deposition and etch tools employed to create the quantum sensors of the future. Andor Technologies, an Oxford Instruments company, offers integration of sensors operating at the quantum limit for photonic and quantum optics applications.

Impact through applications

Battery Technology

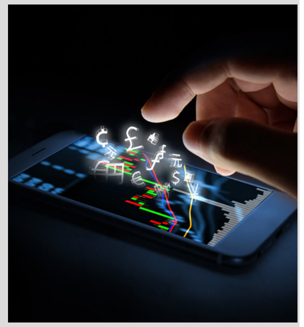
Hydrogen has the potential to be an exceptional green fuel produced in a carbon-free cycle. However, storage capacity limits implementation, range and usability for electric vehicles. Organo-metallic compounds can aid the absorption and release of hydrogen within a fuel cell. Oxford Instruments' optical cryostats, cameras and spectrographs are used to understand the thermodynamic processes underpinning this technology.

Life Science

Genomics, bioinformatics and medical imaging are examples wherever larger datasets are generated from increasingly complex workflows. Quantum imaging is enhancing the data collected and the inspection techniques employed, while quantum computing and machine learning are at the forefront of data search, analysis and computation across the life sciences.

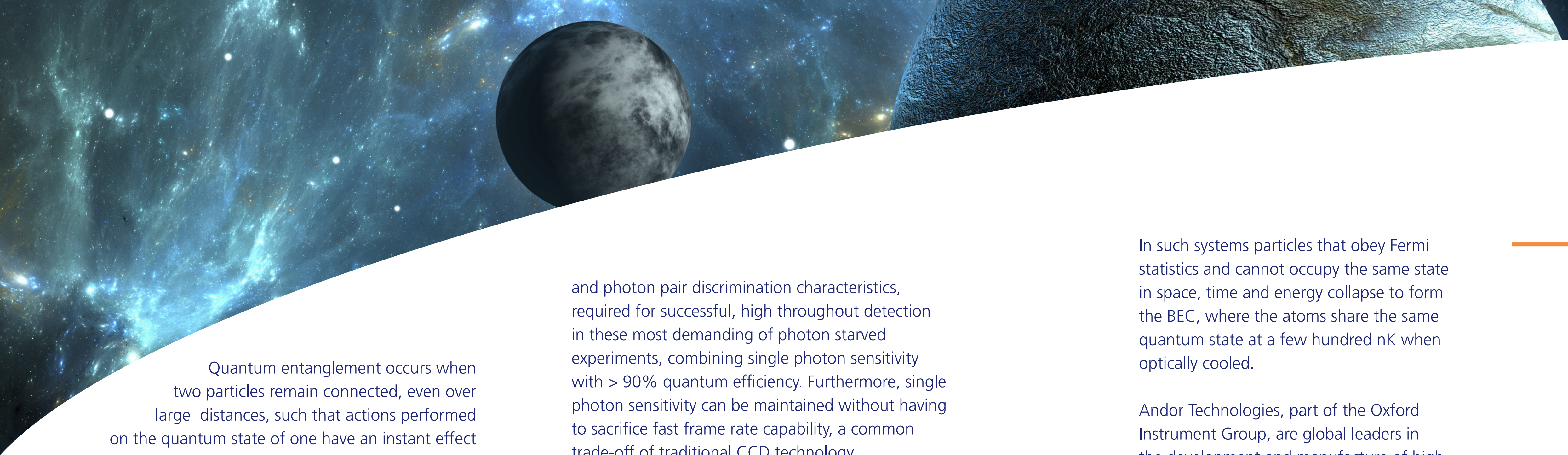
Brain Imaging

Multi-modal imaging techniques such as MEG, EEG, CT and fMRI are uncovering greater understanding of the brain and conditions such as epilepsy, concussion, dementia and Alzheimers. Quantum sensors, ultra-sensitive to brain function through magnetic field measurement and mapping across a range of frequencies and timescales, are enabling non-invasive medical research into localized brain function.



Digital Economy

Micro/Nano Electromechanical Systems (M/NEMS) and Sensors have become well established with multiple devices being used in consumer and commercial products. This includes smartphones, automotive, game consoles, navigation aids, drones, and biomedical devices. This is set to increase, as the Internet of Things (IoT) matures beyond its current capabilities.



Quantum Imaging

Seeing the invisible using low photon count cameras

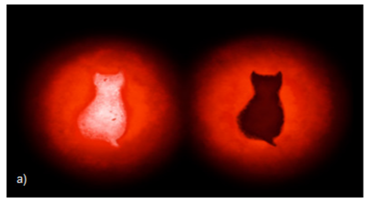
Quantum entanglement occurs when two particles remain connected, even over large distances, such that actions performed on the quantum state of one have an instant effect on the other; the quantum state must be described for the system as a whole, which is at the root of the growing fields of quantum communications, cryptography, computation and microscopy.

Imaging studies of entangled photon systems require ultrasensitive array detectors capable of registering and counting single photon events and photon pairs with superb discrimination from background noise events. Experimental workflow is furthermore enhanced through the ability to image with a rapid frame rate, thus accelerating the rate of image construction through photon counting.

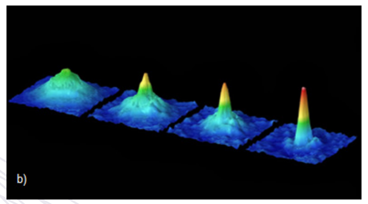
The cooled EMCCD with back illumination minimizes spurious noise sources. It provides the single photon and photon pair discrimination characteristics, required for successful, high throughout detection in these most demanding of photon starved experiments, combining single photon sensitivity with > 90% quantum efficiency. Furthermore, single photon sensitivity can be maintained without having to sacrifice fast frame rate capability, a common trade-off of traditional CCD technology.

Entangled photon pairs used in quantum imaging are enabling us to see the invisible. One photon is used to image an object, the other is detected by the EMCCD camera (a). This 'spooky action at a distance' allows irradiation in a frequency domain aligned to the object of interest, whilst imaging with a frequency best suited to the sensitivity of the detector.

EMCCD cameras have also been widely used by the Bose Einstein Condensate (BEC) and Cold Atom community for more than two decades for measuring absorption signal of Rubidium BECs using 785 nm lasers (b).



a) Ghost imaging using entangled photons



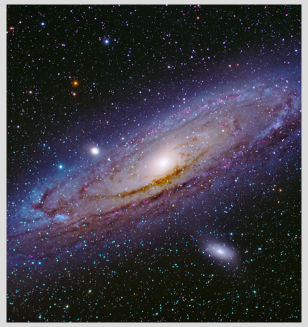
b) BEC developing out of cold atom cluster

In such systems particles that obey Fermi statistics and cannot occupy the same state in space, time and energy collapse to form the BEC, where the atoms share the same quantum state at a few hundred nK when optically cooled.

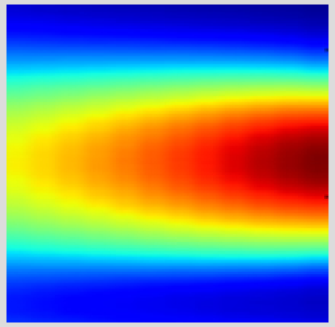
Andor Technologies, part of the Oxford Instrument Group, are global leaders in the development and manufacture of high performance scientific digital cameras for quantum imaging.

Impact through applications

Autonomous Vehicles
Object detection, analysis and validation for AV is challenging. Training imaging systems to recognize hazards in bad weather, with wide field of view, across uncharted terrain and changing road conditions presents further problems. Quantum enhanced imaging techniques and AI control networks could enable lidar, GPS and optical detection improvements in cost effective ways to make AV a reality.



Astronomy
Since 2000 over 3,800 diverse types of exoplanets have been discovered. Across large fields of view in the sky, detection requires significant photometric variability and precision with an ultra-low noise floor. Furthermore, distortions caused by atmospheric turbulence can be mitigated using adaptive optics where a deformable mirror and high-speed camera are used to provide rapid feedback minimizing image distortion.



Research
Structural and chemical spectral analysis along with microscopy imaging of biomaterials, polymers and semiconductors are commonplace in the research market. Large field of view, high resolution and excellent dynamic range are necessary to ensure optimal low light photon counts. Furthermore, nanosecond time resolution and superior acquisition rates deliver sensitivity down to a single photon.

Communications
Quantum Key Distribution (QKD) is a significant development topic within the cryptography landscape. However, QKD suffers from distance limitations with quantum amplifier and repeater units necessary within any future network architecture and protocol design to enable long range communications without loss of coherence and for 'over the hill' ranging for mobile and secure networks.

Supply Chain, Solutions and Services for quantum applications and collaborative development

Through a series of collaborative R&D programs with leading academic and industry partners, Oxford Instruments has, and continues to, engage in a number of early market prototyping projects. These have ranged from rapid qubit screening tools to early adoption of graphene for table-top metrology.

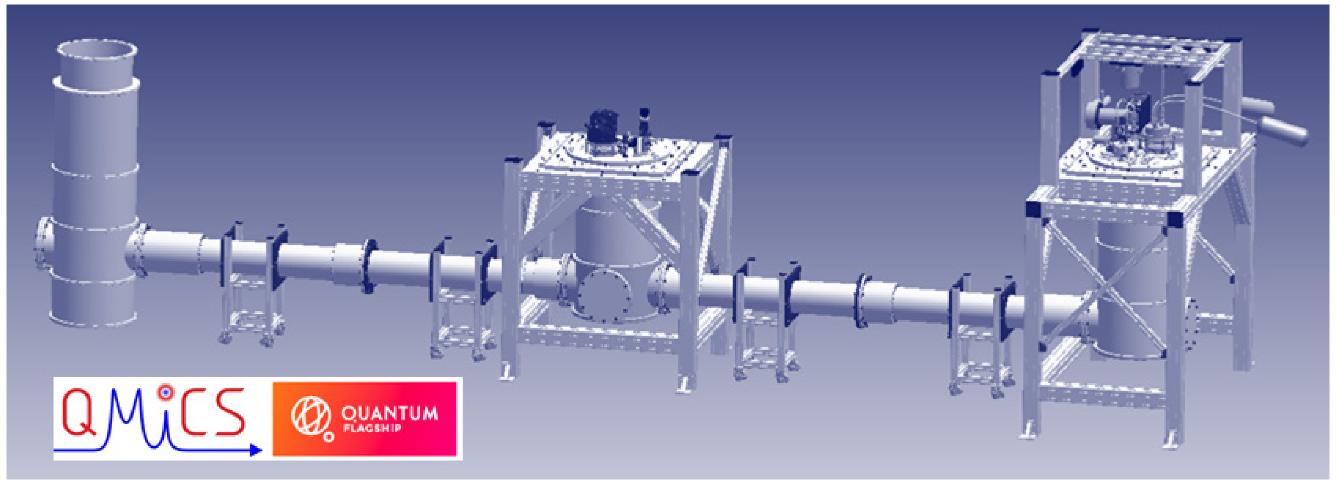
Case Study – rapid qubit screening

Coupled spin states in quantum dot nano-structures in 2DEG GaAs showed early promise as a scalable qubit candidate. Gate deposition and QD tuning were challenging with many devices requiring screening, before long term measurements were undertaken.

Working closely with research teams from Copenhagen, New York, San Diego, Tokyo, Sydney and Delft as part of the MQCO IARPA project, a new concept sample exchange mechanism was developed integrating GHz control lines, thermal management and qubit control circuitry for mK operation.

Case Study – graphene for metrology

Graphene, a single layer of carbon atoms, has a very strong quantization of the Hall resistance at 5 T and 4 K. Using specially-designed graphene devices, NPL, Graphensic and Oxford Instruments partnered to develop a turn-key table-top quantum Hall system for high-accuracy resistance metrology combining simple, reliable operation with low running costs.

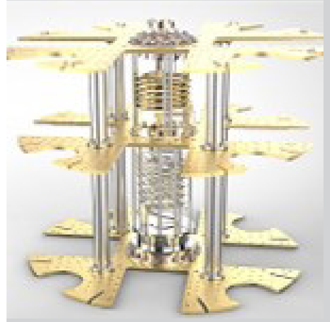


Design model of quantum teleportation system between two superconducting quantum devices operating below 50 mK with inter-fridge communication circuit also held at mK temperatures along its length.

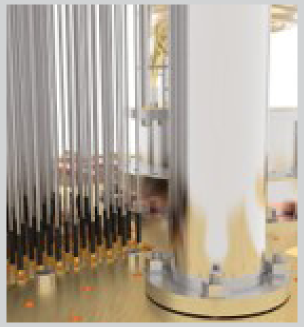
Case Study – teleportation and quantum communications

As part of the European Quantum Flagship QMiCS programme, Oxford Instruments is a key partner supporting the development of a quantum microwave local area network. This architecture will enable quantum communication protocols such as teleportation between two superconducting quantum nodes. This approach has future applications for distributed quantum computing and radar-style quantum sensing with microwaves.

Impact through applications

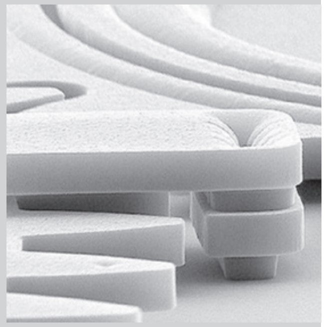


Cryogenics
Millikelvin temperatures without the use of liquid helium and with intermediate cooling at multiple temperature stages are routine across the physical sciences. For many of the leading qubit candidates, operation at mK temperatures is a must. For qubit and detector readout, as well as single photon detection, quantum limited cryo-electronics are essential. Low power, compact footprint and reliable components are key to successful systems integration.



Qubit Control
As NISQ machines grow and qubit scaling evolves both in numbers and cross qubit coupling, so the challenge of system integration and control grows. Low temperature qubits require GHz frequency pulse sequences to control their operation. Scalable engineering solutions to ensure low-noise, wide-band attenuated input lines and low-impedance, low-noise amplified output lines, are offered by Oxford Instruments' dilution refrigeration cabling solutions.

Energy
Ever increasing environmental demands are being placed on energy generation, which is leading to diversification of energy sources, building a low carbon economy. This is driving interest in battery technology and alternative energy sources, such as wind and solar. Photovoltaic (PV) and thermoelectric devices are developing rapidly, and branching into many varying fields including PV polymers and traditional semiconductor based PV devices.



MEMS and Sensors
Nano-mechanical and superconducting phase slip quantum devices as well as more conventional SQUID devices have been readily adopted when developing sensitive readout architectures. With the increased demands for energy efficient, smaller and cost-effective devices, a comprehensive selection of fabrication tools and process solutions such as ICP, PECVD and Ion Beam Etch is essential.

Quantum Technologies

The Quantum Technologies landscape has evolved and grown rapidly in recent years on the back of significant public and private funding. Fundamental technologies, skills and training, market feasibility, industry readiness and end user applications have been developed as a result of this investment. Governments and global corporations have flagship projects, start-up ventures have been established and new research groups have been formed through academic and industrial partnership.

Oxford Instruments recognise the impact Quantum Technologies will have on society and through our footprint in both research and industrial markets seek to play a significant role in the commercialization of these tools and techniques.

By engaging with our customers, partners and suppliers we seek to create value through our solutions and demonstrate thought leadership across the quantum sector. Our long-established expertise in materials fabrication, characterisation, optics and cryogenics gives us a unique insight into this growing landscape.

For our employees, this makes Oxford Instruments an exciting and challenging place to work, and our best brains are focused on solutions that will change the art of the possible.

Quantum Community

Customers, partners, suppliers and employees developing a quantum technologies ecosystem

Quantum Technologies

Building on our 60 years knowledge and experience to develop new capabilities for the quantum era

Quantum Materials

Deposition and etch tools enabling development of functional materials

Quantum Computing

High performance ultra-low temperature systems for NISQ type computation and simulation

Quantum Sensing

Sensors and devices enabling navigation, healthcare and the digital economy

Quantum Imaging

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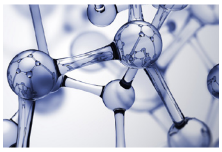

Quantum Solutions

Supply Chain, Solutions and Services for quantum applications and collaborative development

Quantum Community

Customers, partners, suppliers and employees developing a quantum technologies ecosystem

Visit **www.oxinst.com/quantum** or email **info.oiplc@oxinst.com**

Main service locations: UK, USA, Germany, China, Japan and India

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