2021/22

PROCESS NEWS

OXFORD INSTRUMENTS

Welcome to the new Process News! Inside you will find all the latest news from Plasma Technology, as well as hearing what our customers are doing. If you want to speak to our experts about anything you read, please contact plasma-experts@oxinst.com and someone will get in touch.

About Oxford Instruments plc

Oxford Instruments designs, supplies, and supports high-technology tools and systems with a focus on research and industrial applications. Innovation has been the driving force behind Oxford Instruments' growth and success for 60 years, supporting its core purpose to address some of the world's most pressing challenges.

The first technology business to be spun out from Oxford University, Oxford Instruments is now a global company and is listed on the FTSE250 index of the London Stock Exchange (OXIG). Its strategy focuses on being a customer-centric, market-focused Group, understanding the technical and commercial challenges faced by its customers. Key market segments include Semiconductor & Communications, Advanced Materials, Healthcare & Life Science, and Quantum Technology.

Their portfolio includes a range of core technologies in areas such as low temperature and high magnetic field environments; Nuclear Magnetic Resonance; X-ray, electron, laser and optical based metrology; atomic force microscopy; optical imaging; and advanced growth, deposition and etching.

Oxford Instruments is helping enable a greener economy, increased connectivity, improved health and leaps in scientific understanding. Their advanced products and services allow the world's leading industrial companies and scientific research communities to image, analyse and manipulate materials down to the atomic and molecular level, helping to accelerate R&D, increase manufacturing productivity and make ground-breaking discoveries.

About Oxford Instruments Plasma Technology

Oxford Instruments Plasma Technology offers flexible, configurable process tools and leading-edge processes for the precise, controllable and repeatable engineering of micro- and nano-structures. Our systems provide process solutions for the etching of nanometre sized features, nanolayer deposition and the controlled growth of nanostructures.

These solutions are based on core technologies in plasma-enhanced deposition and etch, ion-beam deposition and etch, atomic layer deposition, deep silicon etch and physical vapour deposition. Products range from compact stand-alone systems for R&D, through batch tools and up to clustered cassette-to-cassette platforms for high-throughput production processing.

Enabling the Quantum revolution

Note by:

Dr Russ Renzas
Quantum Technologies Market Manager, Oxford Instruments Plasma Technology

Quantum technology will change our lives, enabling faster computational solutions to previously unsolvable problems. Sensitive Quantum magnetic field sensors will enable navigation in GPS-impossible environments and other exciting applications. Quantum is generating public and private investment, with significant development programs reported worldwide.

Continued progress is dependent on improving device performance, because sufficient coherence times are not being achieved to realise the full potential of Quantum technology. Quality materials and interfaces must be engineered for minimal loss to achieve longer coherence times and scale systems to their full capability.

Oxford Instruments Plasma Technology firmly believes atomic layer processing is the key to low loss and high material quality for Quantum technology. Atomic layer deposition (ALD) deposits uniform and conformal superconducting nitrides. Atomic layer etch (ALE) offers low surface damage etches to drastically reduce surface losses.

With our industry and academic partners, Oxford Instruments is deeply invested in the success of quantum technology. Plasma Technology provides the equipment to manufacture Quantum devices, Asylum Research makes market-leading atomic force microscopy (AFMs) for surface characterization, Andor Technology provides state of the art single photon imaging solutions, and NanoScience manufactures the dilution refrigerators used in superconducting Quantum computing. We are active members of the Chicago Quantum Exchange, UCSB's Quantum Foundry, and other industry groups. Oxford Instruments is truly unique within the quantum ecosystem and we are excited to work to develop the technology to its fullest potential.

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Isolating and controlling a quantum state in a qubit and maximizing the duration of its existence before it collapses into a classical state is at the heart of quantum computing research and technology development.

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Webinars in brief

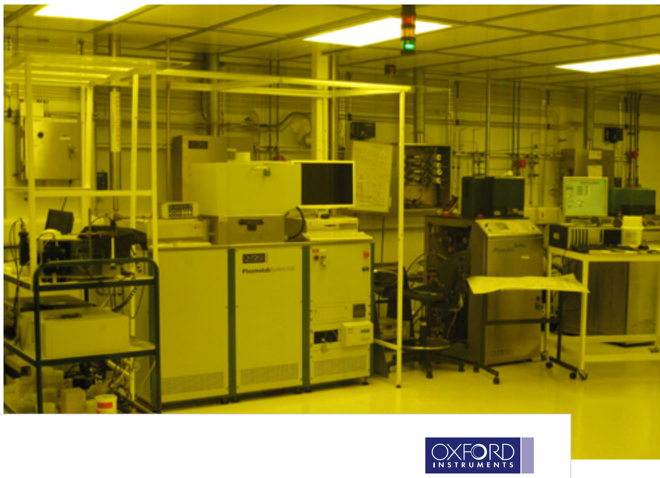
PTIQ

Intelligent Software. Powerful Solutions.

Discover more at: **plasma.oxinst.com/PTIQ**

University of Glasgow case study: Optimising Process Fabrication of Superconducting Qubits

"Once you optimise the process, the ICP system is reliable with repeatable results".



With over 11 years of collaboration with University of Glasgow, we continue to support the innovative fabrication processes for power semiconductor, optoelectronic, quantum and many more devices that take place at the state-of-the-art James Watt Nanofabrication Centre (JWNC) cleanroom within the university.

We had a delightful conversation with two researchers from the University of Glasgow who have shared their innovative projects related to the fabrication of superconducting qubits. Dr Jharna Paul is a Research Associate and Valentino Seferai is a PhD student within the Quantum Circuits Group which is led by Professor Martin Weides. Both researchers use the Oxford Instruments **Plasma**Pro® **100** Cobra ICP RIE system for the fabrication of superconducting qubits.

- Developing Superconducting Qubits
- Process Optimisation is the key for successful research
- Driving the Future of Quantum Industry

Download now >

From Quantum to Optoelectronics: University College London Case Study

"Oxford's RIE system offers high flexibility in the process and excellent control of the gases and the power of plasma".

PlasmaPro® **80** RIE.

We had the privilege to speak with two Senior Research Fellows from UCL who use our **Plasma**Pro® **80** RIE system, presenting their latest research projects related to Quantum and Optoelectronic devices. Reactive Ion Etching offers excellent process control in the fabrication of semiconductor devices and is used in many device manufacturing processes.

- Creating Quantum Memories
- Fabrication Process of Superconducting Circuit
- Optical Networks – The future of Communication
- Requirements for the optimal device performance
- Indium Phosphide (InP) Waveguides Fabrication
- Research and Future Innovations

OXFORD INSTRUMENTS

From Quantum to Optoelectronics:
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UCL

May 2021

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Solutions for Superconducting Qubits and Quantum Circuits

Discover the leading etching & deposition solutions for the fabrication of components for superconducting quantum circuits.

Atomic Layer Deposition of Superconducting NbN

- Superconducting NbN thin films deposited by plasma ALD with RF substrate bias

Atomic Layer Deposition of Superconducting TiN

- Superconducting TiN thin films deposited by plasma ALD with RF substrate bias

Atomic Layer Deposition of Tunnel Barriers

- Conformal, leak-free & low-pinhole tunnel barriers by plasma-enhanced ALD

Plasma Etching of Superconducting Metals and Nitrides

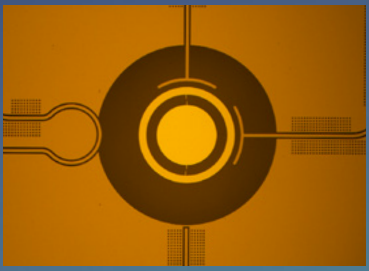
- Superconducting metals and metal nitrides etch: controlling surfaces to minimise noise and signal losses

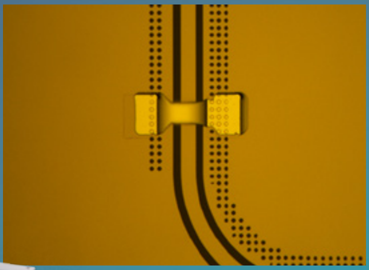
Deep Silicon Etch (DSiE) for TSV

- Through-silicon vias (TSV) for 3D integration

Systems for Superconducting Qubit & Quantum Circuit Applications

Enabling these solutions are the **FlexAL**® and **Plasma**Pro® **100** deposition and etch systems, capable of producing small coupons through to 200 mm wafers, clusterable to increase throughput and avoid vacuum breaks.





For more visit: **plasma.oxinst.com/Quantum**

Oxford Instruments joins Chicago Quantum Exchange (CQE)

Oxford Instruments has announced today that they are partnering with the Chicago Quantum Exchange (CQE), an intellectual hub for quantum information science and engineering.

Oxford Instruments will work with CQE through collaborative research efforts, and joint workshops to identify critical technical challenges and solutions in the quantum space, and student internship opportunities to train the quantum workforce.

The CQE brings together leading academic researchers, national lab facilities, and corporate partners to develop and drive the research underpinning next-generation quantum technology, such as quantum computers, ultra-sensitive magnetometers, quantum repeaters, and single-photon detectors.

"Oxford Instruments is a leader in enabling researchers and industry to harness the power of quantum information science", said David Awschalom, the Liew Family Professor in Molecular Engineering and Physics at the University of Chicago, senior scientist at Argonne, director of the Chicago Quantum Exchange, and director of Q-NEXT, a Department of Energy Quantum Information Science Center. "We look forward to adding their knowledge and expertise to our growing network".

Oxford Instruments plc is a global manufacturer of scientific equipment for device fabrication, cryogenics, and materials characterization.

Several Oxford Instruments' divisions offer leading-edge solutions for quantum applications:

Oxford Instruments NanoScience manufactures market-leading cryogenic refrigerators and wiring solutions to cool and control superconducting quantum devices at the milliKelvin temperatures required for device operation.

Oxford Instruments Plasma Technology provides critical thin film etch, chemical vapor deposition, and atomic layer deposition equipment used to make high-performance quantum processes and sensors in the superconducting, color center (diamond/SiC), and quantum photonic spaces.

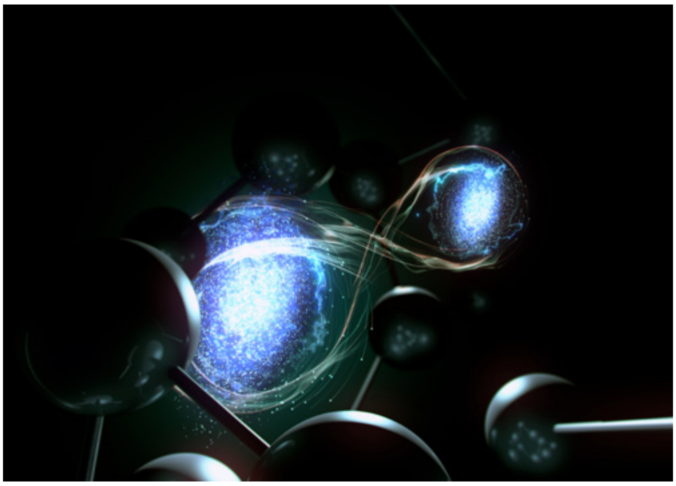
Oxford Instruments Asylum Research manufactures high-performing Atomic Force Microscopes used to characterize quantum device surfaces to better understand and improve their performance.

Oxford Instruments Andor Technology has developed a market-leading portfolio of sCMOS, EMCCD and CCD cameras that are widely used in entangled photon studies, leading to important new capabilities in quantum optics and quantum information science.

"Oxford Instruments is excited to be part of such an impactful and innovative group, and we look forward to working along with all of the Chicago Quantum Exchange member institutions and partners", said Bill Keating, President of Oxford Instruments America. "Oxford Instruments' equipment has been used in countless major quantum computing breakthroughs and is used in some capacity in hundreds of quantum device research labs. The partnership with the Chicago Quantum Exchange furthers Oxford Instruments' deep support for quantum science and engineering".

For more information on Oxford Instruments' Quantum technology solutions please visit:
Plasma.oxinst.com/Quantum

Oxford Instruments Plasma Technology Joins Quantum Foundry at UCSB as Industrial Partner



Oxford Instruments Plasma Technology is pleased to announce they have joined the Quantum Foundry at the University of California Santa Barbara (UCSB) to further develop their Quantum technology solutions.

The Quantum Foundry at UC Santa Barbara is a next generation materials foundry that develops materials and interfaces hosting the coherent quantum states needed to power the coming age of quantum-based electronics. The mission of the Foundry is to develop materials hosting unprecedented quantum coherence, train the next generation quantum workforce, and to partner with industry to accelerate the development of quantum technologies.

Oxford Instruments is proud to be one of the industry partners at the UCSB Quantum Foundry, along with other industry leaders in the Quantum technology ecosystem.

Dr Ravi Sundaram, Head of Strategic R&D Markets, Oxford Instruments, commented "Oxford Instruments is delighted to be part of such a strong consortium at UCSB and to support the development of robust Quantum device fabrication processes for applications in computing, communications. We are committed to providing market leading quantum technology solutions to our customers and partnering with the Quantum Foundry will ensure we continue to be at the forefront of this developing technology."

Dr Tal Margalith, Executive Director of Technology and Industrial Liaison, UCSB Quantum Foundry, said "We are thrilled to have Oxford Instruments on board. Their cutting edge, robust processing solutions tailored for quantum technology device fabrication will help us ensure that there's an executable roadmap from academic discovery to commercial applications."

Oxford Instruments continues to develop and support market-leading nano-fabrication solutions vital to the manufacture of several quantum device platforms including superconducting qubits (ALD, Plasma etch), Diamond NV Centres (Plasma etch, hard mask deposition), and integrated photonics-based qubits (waveguide etch, single photon detector layers etc.).

For more information on Oxford Instruments' Quantum technology solutions please visit: **Plasma.oxinst.com/Quantum**

For more information on the UCSB Quantum Foundry please visit: **https://quantumfoundry.ucsb.edu/**

Oxford Instruments Plasma Technology Joins Cross-Atlantic Quantum Collaboration as the Industry Lead

Global academic and industrial leaders from Canada and the United Kingdom are joining forces to create an advanced manufacturing toolkit for quantum sensing and quantum computing.

Oxford Instruments is proud to be the industry lead in the UK Canada Quantum Technology Programme, a cross-Atlantic collaboration with partners across UK & Canada focussed on furthering quantum device fabrication readiness.

This strengthens Oxford Instruments Plasma Technology's position as a provider of targeted solutions for quantum devices with the capability to deliver unique plasma processing technology for research and scaling up to large wafer sizes and higher volumes. The developments within this project will drive the readiness of the materials processing required for the manufacturing of chips for high performance quantum computers and ultra-sensitive quantum enabled magnetic field sensors. These devices could enable future autonomous vehicles and concealed infrastructure imaging etc.

Funded by Innovate UK-Natural Sciences (UKRI) and Engineering Research Council of Canada (NSERC), the consortium will address the need to produce robust, reliable, and scalable quantum circuits with a view of enabling their commercial exploitation and large-scale deployment. Oxford Instruments will be working on atomic scale processing solutions for thin films of superconducting metals/metal nitrides and defect centres in diamond.

Dr Ravi Sundaram, Head of Strategic R&D Markets, Oxford Instruments Plasma Technology, commented "Oxford Instruments is delighted to be part of this unique trans-Atlantic consortium. Oxford Instruments Plasma Technology is ideally positioned to help develop the technology and scale it up to the next level with a clear roadmap to plasma processing solutions on 200 mm wafers".

Professor Michel Pioro-Ladrière, professor at the Department of Physics and deputy director of the Institut quantique (IQ), Université de Sherbrooke states "The project offers excellent training prospects. Developing a highly skilled workforce is one of the main challenges in our field. The consortium will help train the scientists and engineers of tomorrow who will accelerate the development of quantum technologies."

Professor Martin Weides, Head of the Quantum Circuit Group at the University of Glasgow said: 'This grant is vital to addressing today's new pressing challenges to increase the technological readiness level of superconducting quantum circuits. Our long-standing collaboration with Oxford Instruments will be continued and strengthened by including novel materials and nanofabrication techniques in the UK's leading Nanofabrication Cleanroom, the James Watt Nanofabrication Centre. The University of Glasgow's subsidiary and commercialisation partner Kelvin Nanotechnology will offer access to our nanofabrication portfolio including industrial-grade superconducting processes. We are delighted to advance existing manufacturing

UK Research and Innovation

NSERC CRSNG

UNIVERSITÉ DE SHERBROOKE

University of Glasgow

toolkits to solve issues faced by the quantum technology start-ups, provider and research institutes in the UK and Canada.'

Oxford Instruments continues to develop and support market-leading nano-fabrication solutions vital to the manufacture of several quantum device platforms including superconducting qubits (ALD, Plasma etch), Diamond NV Centres (Plasma etch, Hard mask deposition), and integrated photonics-based qubits (waveguide etch, single photon detector layers etc.).

To read more about Oxford Instruments' Quantum capabilities please visit **https://plasma.oxinst.com/quantum**

To read more about the UK Canada Quantum Technology Programme please visit **https://www.newswire.ca/news-releases/uk-and-canada-collaborate-to-launch-world-first-programme-of-quantum-technologies-896283559.html**

For more information on the UCSB Quantum Foundry please visit **https://quantumfoundry.ucsb.edu/**

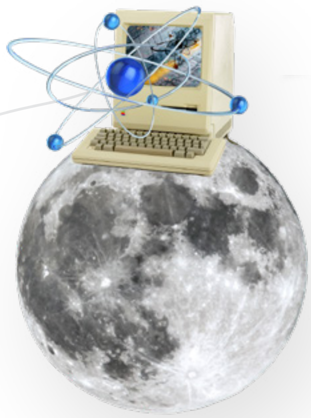
Engineering the Quantum revolution

by: Dr Ravi Sundaram Head of Strategic R&D Markets, Oxford Instruments Plasma Technology

In the early 1980s, a powerful new concept for computing was proposed by Richard Feynman in response to the inadequacy of computers to simulate nature. “Nature isn’t classical dammit”, he contended, “and if you want to make a simulation of nature, you’d better make it quantum mechanical”. The idea was so powerful that intense scientific research ensued in the following decades in an attempt to bring Feynman’s vision to fruition. Over time, with advances in both fundamental understanding and technology, manipulation and control of quantum mechanical phenomena was achieved. The era of quantum technology engineering had begun.

Quantum devices will soon be able to solve problems in minutes that would take classical computers millennia, encrypt data with new quantum encryption schemes for more secure communication, and form the heart of novel sensors that take advantage of quantum phenomena to detect extremely small changes in magnetic fields.

"There are many critical scientific and engineering challenges that must be overcome before quantum devices can reliably solve real-world problems. This presents an attractive opportunity for researchers and technology developers alike"



There is a long way to go yet. While there have been paradigm-shifting advances, especially in the last decade, there are many critical scientific and engineering challenges that must be overcome before quantum devices can reliably solve real-world problems. This presents an attractive opportunity for researchers and technology developers alike:

- Quantum computing is plagued with issues arising from quantum noise, such as decoherence and dephasing due to two-level system defects. These issues increase the overhead required for quantum error correction and pose a strong impediment to the scale up of quantum computing devices to practically-valuable levels.
- Photons are a great carrier of quantum information and could potentially take advantage of the existing datacom infrastructure. However, quantum states decohere at an exponential rate as they propagate through optical fibre, which requires devices such as state-preserving quantum repeaters to reliably operate at scale.
- Solid state quantum sensors have been studied extensively owing to the robust quantum systems afforded by nitrogen vacancy centers in diamond and a wide range of other defect center host materials now under intense investigation. World-class processing is required across this large suite of materials in order to unlock their potential in next-generation sensing applications.

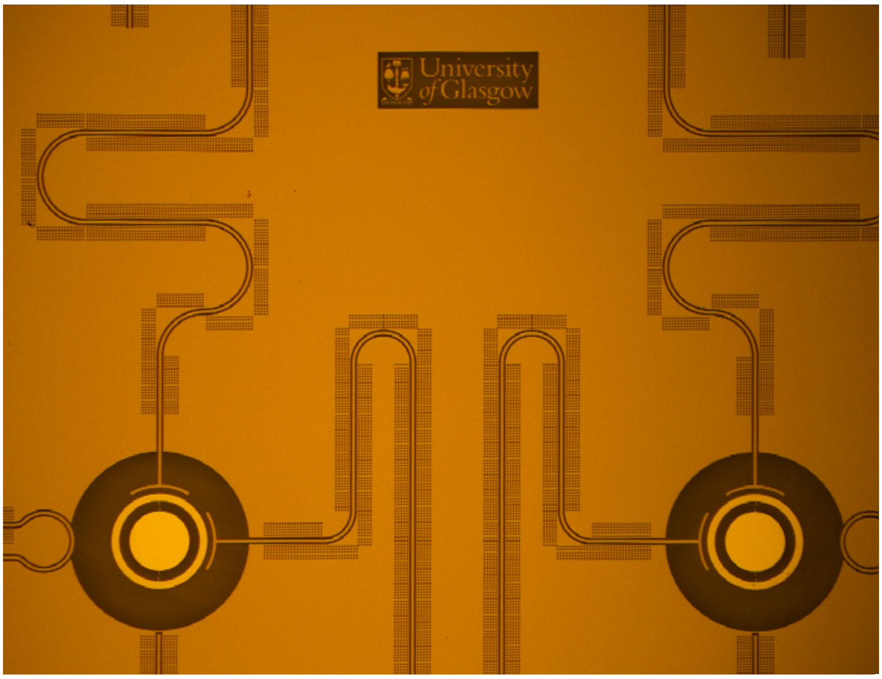
At Oxford Instruments Plasma Technology we are focused on providing state of the art fabrication processing for quantum materials and devices to help solve these challenges. The combination of our strong internal quantum programme and our collaborations with leading universities and companies in this space has enabled the development of our Quantum device fabrication product and process portfolios. We look forward to working with you in this rapidly developing field of technology.

Superconducting Quantum Circuits

by: Alexander Stehli, Karlsruhe Institute of Techology, Germany &
Professor Martin Weides, The University of Glasgow, Scotland

A perspective from the University of Glasgow

Quantum technologies are using the principles of quantum mechanics to revolutionise areas such as communication, sensing or computing. They are based on quantum superposition a physical system may be in many configurations at the same time, and quantum entanglement paired physical systems interact such that the state of each system cannot be described independently of the state of the others. This technology has seen rapid development over the last year. Today, they are at the verge of industrial deployment, for example with demonstrated real-world application in quantum computing.



KIT Karlsruher Institut für Technologie

University of Glasgow

Superconducting Quantum circuits,
The University of Glasgow.

"Superconducting quantum circuits are the leading approach to real-world applications with quantum devices and quantum computers"

Alexander Stehli, Karlsruhe Institute of Techology, Germany & Professor Martin Weides, The University of Glasgow, Scotland.

Why Superconducting Qubits?

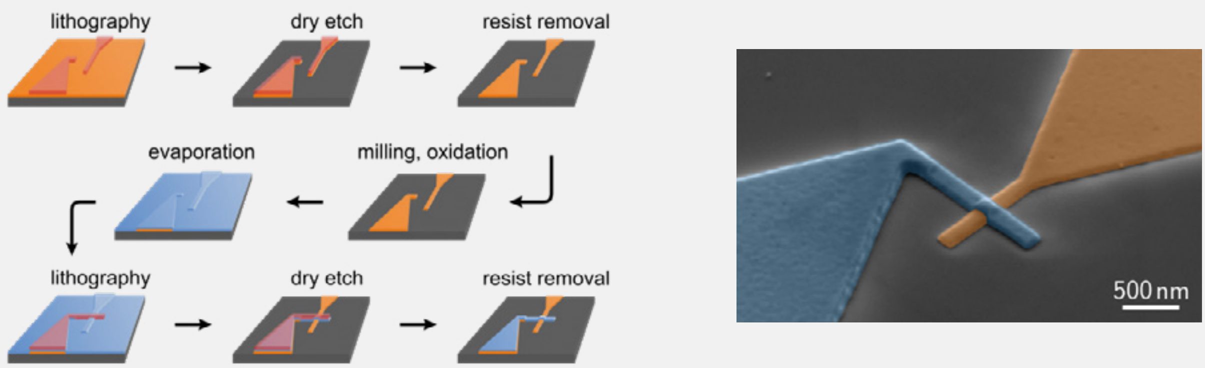
Many different hardware platforms to realize quantum computers exist. The ideal one would feature very long-lived quantum states, a large set of different quantum gates executed in a short time, quantum error correction, scalability to many interacting qubits, and is controlled by widely available microwave electronics and operated at room temperature! Sounds too good? Well, superconducting quantum electronics was already shown to match most criteria! And cooling samples down to 1/100th of the temperature of outer space has become very simple with modern cryostats!

Superconducting Quantum Circuits are...

Superconducting quantum circuits are the leading approach to real-world applications with quantum devices and quantum computers. Their good scalability, controllability and reproducibility make them great building blocks for commercial applications (most IT majors have established research activities), and basic research activities. Globally, increasing the qubit lifetimes as well as enabling manufacturing capabilities toward industry-grade processes with high-yield and high-throughput were pursued over the last couple of years, with increasingly rapid progress. At times it has been challenging to keep an overview!

But how do you make them?

Our circuit fabrication is based on the incredible technology developments for complex integrated semiconducting circuits, such as CMOS microelectronic devices. It requires access to micro and nanofabrication facilities including cleanroom facilities, such as our James Watt Nanofabrication Centre at the University of Glasgow being equipped with shared tools for lithography, etching, deposition, and metrology of chips. Usually, the superconducting quantum circuit fab requires an evaporation tool with a bespoke sample stage to realize the key component of our qubits, the Josephson tunnel junction. Recently, we demonstrated long coherent quantum circuits made with a much simpler approach.



The Josephson junctions are patterned solely by dry etching – enabled by the precise timing and control of the etching plasma on our Oxford Instruments **PlasmaPro® 100** Cobra.

Our junction manufacture technology

Traditionally, Josephson tunnel junctions for superconducting qubits are fabricated using lift-off processes, thus suffer from outgassing of the resist, and parameter spreads across large wafers. The electrode materials are limited to metals with low melting temperatures and point-like evaporation sources. The incorporation of contaminants, and their diffusion, can cause significant drifts in parameters, the junction ages!

Our junction manufacture technology eliminates resist from the evaporation chamber. In contrast to lift-off technologies, the Josephson junctions are patterned solely by dry etching – enabled by the precise timing and control of the etching plasma (on our Oxford Instruments **Plasma**Pro® **100** Cobra). This fabrication platform is fully compatible with deposition at elevated temperatures, as well as homogeneous, or epitaxial material growth. This also opens the door to more exotic junction materials and topologies. Another perk is very low ageing of the Junctions – a result of clean interfaces devoid of resist residues. A great step in quantum circuit fabrication and to enable fundamental research and development in integrated systems and into complex products!

Reference

Coherent superconducting qubits from a subtractive junction fabrication process; Alexander Stehli, Jan David Brehm, Tim Wolz, Paul Baity, Sergey Danilin, Valentino Seferai, Hannes Rotzinger, Alexey V. Ustinov, Martin Weides; https://aip.scitation.org/doi/full/10.1063/5.0023533

If you would like to learn more about Superconducting Qubits and Quantum Circuits, take a look at our Quantum Technology Solutions.

Solutions for Diamond-based Quantum Systems: NV Centers

Discover our expertise in plasma etching solutions for the fabrication of diamond-based quantum devices.

Plasma Etching of Diamond with NV Centres

- Fabrication of thin diamond membranes or surface etch for efficient probing of buried NV Centres

Plasma Etching for Creating Efficient Light Coupling Components

- Photonic crystals and cavities help efficiently extract signals from Diamond

Systems for Diamond Quantum Applications

Our **PlasmaPro® 100** platform enables high precision deposition and etching of a wide range of materials for quantum devices. The **FlexAL®** atomic layer deposition (ALD) system offers a broad range of optimised high-quality ALD processes.

Developed in partnership with leading institutions and companies.

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For more visit: **plasma.oxinst.com/Quantum**

Harnessing Quantum Mechanical Weirdness To Do Computing

Dr. Ravi Sundaram
Head of Strategic R&D Markets, Oxford Instruments Plasma Technology

Quantum Mechanics, Subatomic Particles and Computing

It was during my masters at EPFL Switzerland that I was first able to fully appreciate the mind boggling world of sub atomic particles. Here, classical laws proposed by Newton fail and an entirely different framework of physics called Quantum Mechanics is needed to understand the workings of this fascinating world. This world is full of eerie effects like particles existing in multiple states at the same time, ability to pass through walls etc. As the great Danish physicist, Neils Bohr who laid the foundations of quantum mechanics in the 1920s aptly put it:

> "Anyone who is not shocked by quantum theory has not understood it!"

Fast forward to today and scientists have not only gained a great deal of (note: I did not say complete) understanding of the quantum world but in what is considered one of the greatest examples of human creativity and enterprise, but also beginning to harness this quantum "weirdness" for complex computation.

What are Quantum Gates and Qubits?

Let's take a step back to appreciate its impact. Modern day computation (yes I mean literally every device in proximity to you right now) uses classical bits which have a value of 0 or 1. Using large numbers of bits and a way to control them (logic gates) enables all classic computation. A quantum bit or a qubit allows its state to exist in 0,1 and states that have shades of state 0 and 1, these states are technically called superposition states. Using quantum gates made from qubits one can create a superposition state and encode information in parallel in these states. In order to understand the profound implications and sheer power of this ability to encode information parallel let's consider an example problem. There are four cards on the table. Three of them are identical say king of hearts and one is a queen. Now the cards are shuffled and placed face down on the table and the objective is to find the queen. How would you (and incidentally a classical computer) go about it? It would have to be something like: open card one, then the other etc. Considering the queen can either be found on the first or the fourth attempt, with some simple math you can deduce that it would take around 2.5 attempts on average to do find the queen over many attempts to find it. In contrast using a 2 qubit system this can be done in a single attempt! While this experiment might not sound ground breaking let's look at a more complex problem, say factoring a large prime number 129 digits long, this happens to form the back bone of today's online encryption protocols. A classical computer would take an extremely long time to factor such numbers into its prime components (keys) which is why it is considered secure. In fact it took 8 months and 1,600 internet users to crack RSA129, a quantum computer can do this in seconds!

While internet security is interesting scientists are already working on ways around it (Read about Quantum Key Distribution (QKD) if you would like to know more), its impact will be most seen in its application in drug discovery, financial risk management, AI and most importantly understanding quantum science itself! As Richard Feynman pointed out in his famous Caltech lecture, we need quantum objects to simulate quantum physics.

How Do We Make Qubits?

That's where the challenge lies. A quantum system by its very nature is fickle and changes its state even with very little perturbation. Isolating and controlling a quantum state in a qubit and maximizing the duration of its existence before it collapses into a classical state is at the heart of quantum computing research and technology development. There are several different technologies in play today:

1. Ion traps: Ions or atoms localized by electric field or laser beams. This works well for a few qubits but scaling is difficult and the challenge lies in initialization, control and measurement of large array of trapped ions.

2. Nuclear spin qubits: Here information is coded on to nuclear spin states. This can be achieved by implanting dopants in atoms. While inherently difficult to scale up as it requires deterministic fabrication of coupled spins, progress is being made in this direction.

3. Photonic qubits: Polarization of light in photons is used to carry out computation. This has traditionally required complex instrumentation in controlled environments but progress in silicon photonics based approaches promise a great scale up potential. The main advantage of this technique is a lower level of stochastic noise compared to condensed mater based qubits

Quantum computing technology has arrived but is at an early stage of its evolution.

4. Superconducting qubits: Uses Josephson junctions in superconducting materials to create either phase, charge or flux qubit (other flavours also exist today), this is the most used form of qubit for quantum computing research today.

5. Topologically protected qubits: These are condensed matter versions of qubits currently in early stage research where using certain properties of materials to protect the quantum state in subatomic particles. Some of the popular approaches involve semiconductor-superconductor junctions and topological insulators to create and operate on strange, yet fascinating particles called majorana fermions.

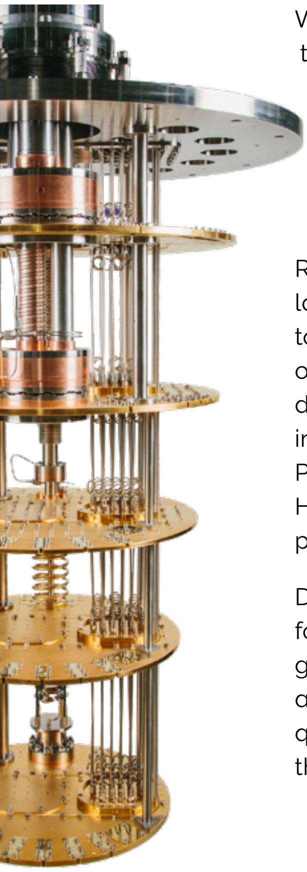
The Future of Quantum Technology

It is clear that quantum computing technology has arrived but is at an early stage of its evolution. At Oxford Instruments we are working on several technologies that are helping with the progress of this mind boggling yet powerful technology. At plasma technology we enable the fabrication of materials like superconducting Niobium Nitride for fabrication of flux qubits as well as single photon detectors. We also have a great deal of expertise in device fabrication processes for on chip photonics, solid state lasers and deposition of low-dielectrics dielectrics for qubit fabrication. Oxford Instruments also enables quantum computing by offering the low temperature environments and measurement technologies necessary along with extremely efficient single photon detectors for photonic routes to quantum computing.

We would be delighted help you with your quantum computing challenges so please get in touch with us at **plasma-experts@oxinst.com** or visit **plasma.oxinst.com**

Diamond Quantum Technology The Beauty In Its Flaws

Oxford Instruments Process Experts



Oxford Instrument NanoScience's Proteox™ dilution refrigerator, a step change in Cryofree® system modularity designed for enhanced adaptability, reliability and increased experimental capacity.

Will diamond enable the scalability and reliability that is necessary to build a Quantum Computer?

That is the $1M question right now. Or should I say $18B as the Market is expected to reach by 2024, according to ResearchAndMarket?

Researchers around the world are investing a lot of time, effort and money to find the answer to this thorny question. Some are placing bets on Superconducting qubits, others are going down the Trapped Ion route, and quite a few are investigating Quantum dots, Topological qubits & Photonic qubits (check out our previous post on Harnessing Quantum for a quick review of each platform)… And let's not forget Diamond!

Diamond is attracting its fair of attention and has found some strong supporters amongst research groups as well as large companies. Why is that and what is so "hard" about making Diamond qubits? Those are the questions we will go through today.

First things first, what makes a qubit a good qubit?

The challenges that the community is facing to build a quantum computer are manifold. On top of the basic properties that quantum memories must exhibit to simply deserve the name of qubits, i.e. superposition, entanglement and interference (view a short explanation of qubits properties), they should also have a long enough coherence time to be able to run any computation and be easy to fabricate in large numbers, and in a reproducible manner so that we can build systems of multiple qubits and thereby unlock the potential of running complex simulations and modelling that are nowadays impossible, even with the most powerful supercomputers. And if that's not too much to ask, ideally, we'd want them to require low power to operate as well.

And what's so interesting about Diamond?

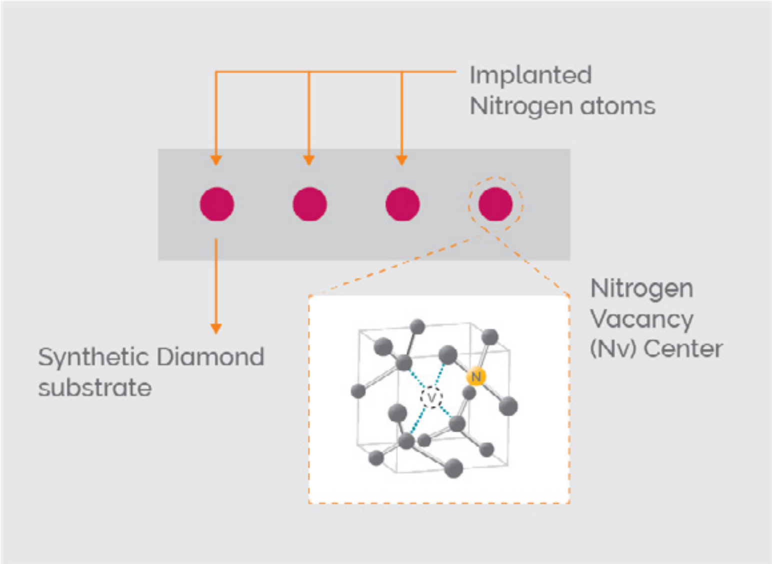
As you can imagine, it is a bit of a headache to find a technology that ticks all the boxes. And so far, none actually does. So no, we don't really expect Diamond to outshine all currently existing platforms, but it does have a lot to offer and that's notably thanks to its unique crystal structure.

As a matter of fact, diamond qubits are essentially defects within an almost perfect crystal structure. First of all there are Nitrogen Vacancies, commonly referred to as NV centres, and artificially created by "knocking off" two neighbour Carbon atoms and only substituting one of them with Nitrogen, thereby leaving behind an unpaired electron (as Nitrogen is trivalent and Carbon is tetravalent) and a vacancy. This unpaired electron transfers to the nearby vacancy, and can then be manipulated, i.e. put into an excited state corresponding to level | 1>, or dropped into a lower energy state corresponding to level | 0>, or a superposition of both, therefore forming a qubit to store information and perform logic operations. And then, there are other types of defects, such as the naturally occurring isotopes 13C, which can also act as qubits.

What's common between all of them and particularly interesting here is that the almost perfect diamond lattice that surrounds those qubits actually provide them with great isolation from external interactions that would otherwise cause them to decohere and lose their quantum states, as they have an irritating tendency to do. The level of isolation, notably associated with the exceptional stiffness of the diamond bond resulting in a very low level of lattice vibration, is such that it enables operation of diamond qubits at room temperature, thereby considerably reducing power consumption in comparison with superconducting qubits or quantum dots which also show good stability but require cooling to cryogenic temperatures.

New records of coherence time have recently been achieved by a team of researchers at Delft University, with entangled qubits retaining their quantum state for up to 10s, thereby placing NV centres as second best qubits for stability, just behind Trapped Ions. But where Trapped Ions require many lasers to operate, the relative simplicity of diamond qubits and their solid-state nature represent a significant advantage for integration into devices.

Finally, NV centres have the very attractive property of being able to couple with light: they can absorb and emit very well-defined wavelengths which is the very principle on which we rely to address those qubits. And as the quantum information is encoded into photons, it opens the exciting opportunity of using existing datacom infrastructures to transport data over long distances.



Seems promising... but how do you get the light out of diamond?

Fair point indeed. The total internal reflection which gives diamonds their shining appearance makes it particularly difficult to extract light from it. And yet, we do need to retrieve the photons from those NV centres as they carry the quantum information. That is the reason why the NV centres need to be very close to the surface of the crystal. One way to form those NV centres consists of doping diamond with nitrogen, by implantation. But it turns out to be very difficult to directly implant Nitrogen just below the surface.

So, at Oxford Instruments, we've developed a process to thin down diamond and bring those NV centres closer to the newly formed surface, while keeping them intact. Our RIE process carried out on the Oxford Instruments **Plasma**Pro® **100** Cobra, allows to rapidly etch through the bulk material while ensuring a controlled and residue/contamination free surface, with very low roughness (typically below 3A) to limit noise and optical losses, and oxygen terminated to provide additional protection to the shallow qubits.

Above, Oxford Instruments' **FlexAL®** system.

To further facilitate light extraction from the NV centres, we also propose solutions to directly nano pattern the diamond surface into photonic crystals, or plasma etch III-V materials (bonded to the diamond substrate) into photonic crystals.

Finally, we do understand that diamond-based quantum technologies, as promising as they may be, are not perfect. And as such, longer-term useful devices are likely to be hybrid structures, incorporating a variety of qubit types, each performing a specific activity for a tailored application.

At Oxford Instruments, we also provide solutions for superconducting qubits and photonic qubits. These include PEALD of NbN and TiN thin films with respective critical temperatures as high as 12.9K and 3K, for interconnects and resonators, PECVD of low loss SiNx for waveguides and Bosch or cryo etch of optical components, with very smooth sidewalls, low etch rates, high selectivity and notch control.

Find out more about our portfolio of Quantum solutions. Visit **plasma.oxinst.com**

Solutions for Photonics Integrated Circuits for Quantum

Discover the leading solutions for the fabrication of integrated quantum photonics.

ALD of Superconducting NbN for Single Photon Detectors

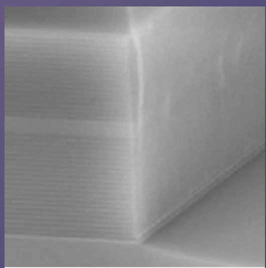
- Thin films of superconducting NbN deposited by plasma ALD using bias for applications as superconducting nanowire single photon detectors (SNSPDs)

Silicon/SiNx Etch for Low-loss Optical Components

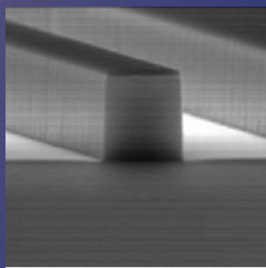
- Cryogenic etch to overcome sidewall roughness issues in Bosch etch

Systems for Superconducting Qubit & Quantum Circuit Applications

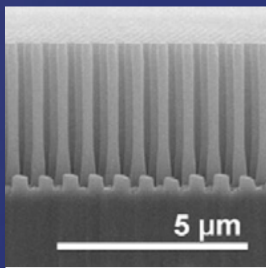
Enabling these solutions are the **FlexAL**® and **Plasma**Pro® **100** deposition and etch systems, capable of producing small coupons through to 200 mm wafers, clusterable to increase throughput and avoid vacuum breaks. Our **Plasma**Pro® **100** platform enables high precision deposition and etching of a wide range of materials for quantum devices.



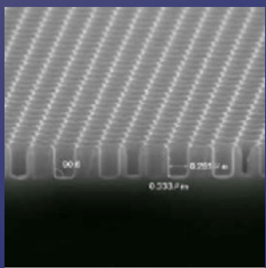
GaAs / AlGaAs Heterostructures.



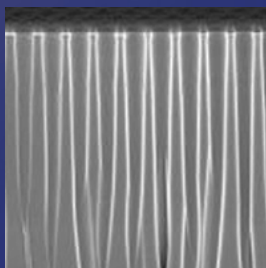
InP Ridge Waveguide.



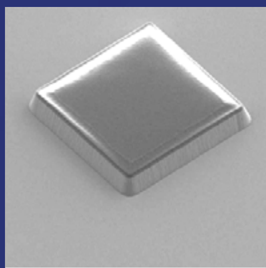
GaN Photonics Crystal.



GaAs / AlGaAs Photonic Crystal.

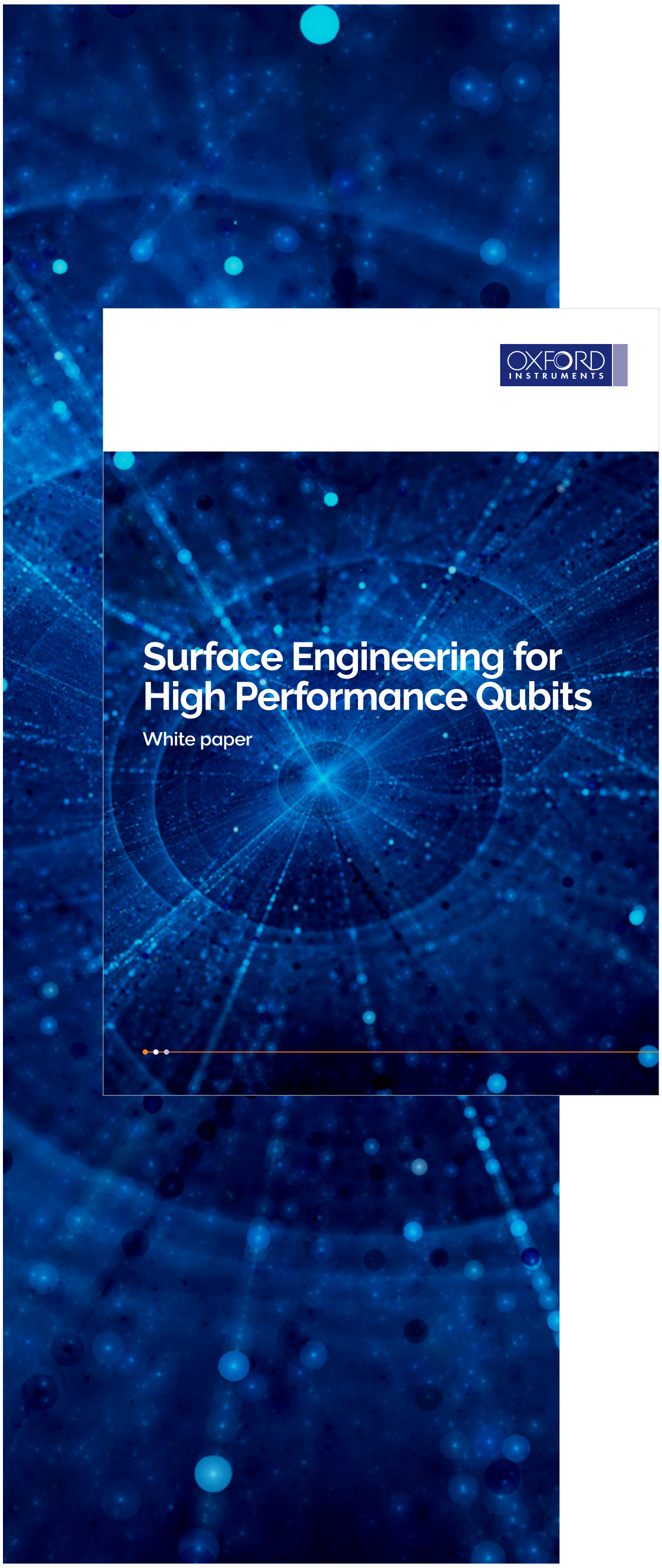


InP Photonic Crystal.



InSb / InSbAs.

For more visit: **plasma.oxinst.com/Quantum**



Surface Engineering for High Performance Qubits

Many of quantum computing's leading researchers and companies have studied the impact of surface engineering on superconducting resonator and qubit performance.

The body of literature in this area shows that the performance of even the simplest element of quantum computers, the superconducting LC resonator, is dramatically impacted by subtle details of device fabrication. Surfaces are known to be critical to the fabrication of high-performance quantum devices of all kinds, including colour centres, ion traps (which can suffer from surface electric field noise), photonics, and quantum dots.

There are three critical surfaces, or interfaces, that must be controlled in order to make high quality superconducting resonators and qubits. These are: the superconducting metal-substrate interface (MS), the superconducting metal-air interface (MA) and the substrate-air interface (SA).

This whitepaper will focus on superconducting quantum devices, but many of the principles and strategies used to optimize interfaces for these systems are also relevant for devices of all kinds, both quantum and classical. Also, we will review how surfaces and interfaces have a strong effect on losses and how plasma processing can be used to control those losses.

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Making Better Diamond and SiC Quantum Devices

Colour centres, also known as solid state defects, and most closely associated with the diamond NV centre, are used for a wide range of quantum applications. Researchers have studied their use for single photon sources, quantum memories, quantum repeaters, and for a variety of quantum sensing applications, including piezometers, electrometers, thermometers, and magnetometers[1].

Colour centres have several advantages as compared to other systems, including relatively long coherence time, operational temperatures up to room temperature, a variety of optical operational frequencies, and all the advantages inherent to any solid-state system, such as compatibility with well-developed tools for lithography, etch, and thin film deposition.

In this whitepaper, we describe:

- The mechanisms by which colour centres can be used as sensors
- Device fabrication requirements and challenges in these systems
- The future of this field, including new material systems and fabrication requirements for the second generation of colour centre-based devices.

1. Zhang, Gang, et al. "Material platforms for defect qubits and single-photon emitters." Applied Physics Reviews 7.3 (2020): 031308.

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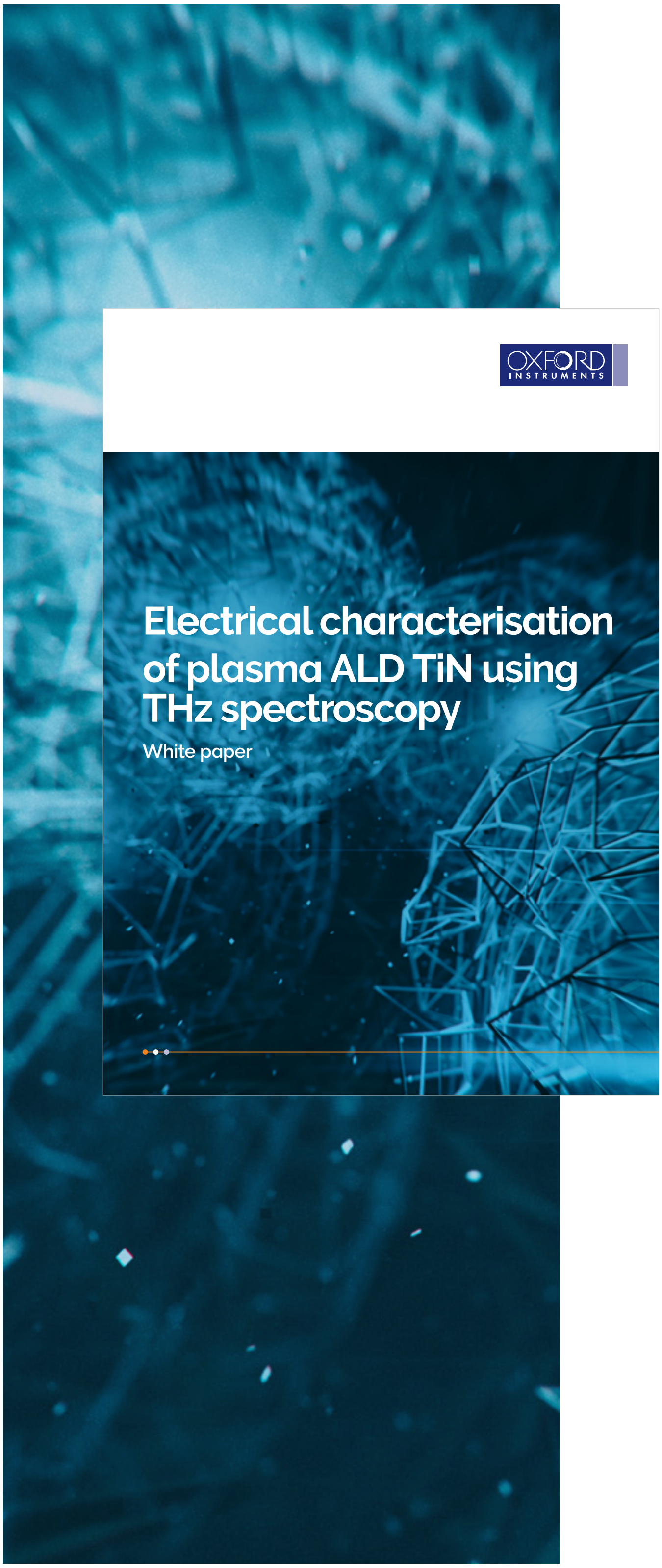

Electrical characterisation of plasma ALD TiN using THz spectroscopy

Titanium nitride (TiN) is used as a metal gate in complementary metal-oxide-semiconductor (CMOS) technology as it has low resistivity and is compatible with gate dielectrics.[1] TiN is also deposited as a wear resistant coating, and barrier layer for copper diffusion due to its chemical and thermal stability.[2] Traditionally TiN was deposited using physical vapour deposition techniques which suffer from a poor step coverage in deep contacts and via trenches due to the shadowing effects especially in high aspect ratio structures.

Atomic layer deposition (ALD) is a thin film deposition technique which allows for Å-level control of the film thickness, excellent uniformity, and conformal coating of high aspect ratio features. The deposition of thin films of TiN by ALD has been reported using various precursors such as titaniumtetrachloride ($TiCl_4$),[3] and tetrakis (dimethylamino) titanium ($Ti(N(CH_3)_2)_4$, TDMAT).[2, 4, 5]

Nevertheless, optimization of film growth and the electrical properties and their uniformities are often required. Ideally, non-destructive characterisation of thickness and electrical uniformity across the entire surface covered by the deposition can be done to ensure the quality of the final film.

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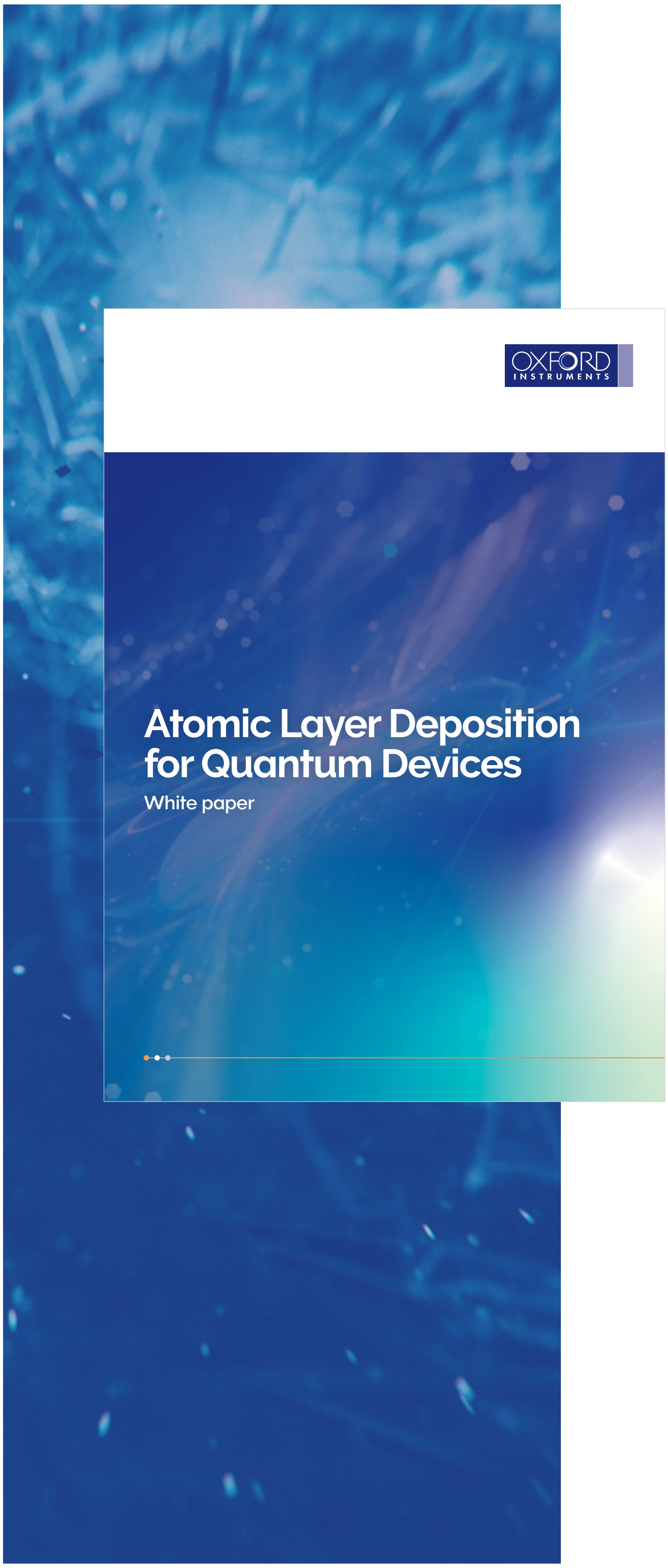
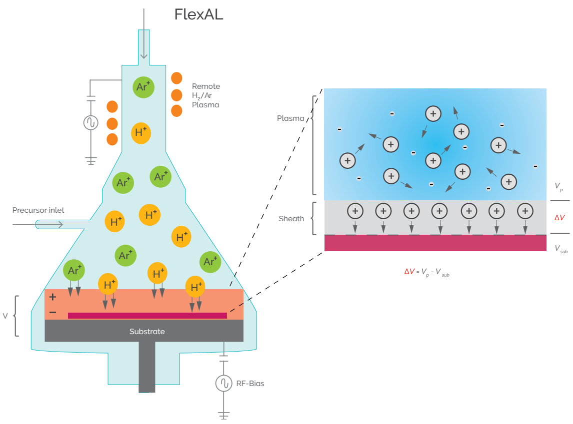


Atomic Layer Deposition for Quantum Devices

As the transistor gave rise to the information age, quantum technology has the potential to be the next great leap forward. Quantum technology is the application of quantum physics for real-world applications, such as quantum computing, sensing, navigation and communication.

Conventional methods for depositing superconductors include sputtering, pulsed laser deposition (PLD), and chemical vapour deposition (CVD). However, these methods can suffer from drawbacks including a lack of thickness control, poor uniformity and high impurity content.

Atomic layer deposition (ALD) is much more beneficial for thin-film deposition due to its ability to produce films with high purity, precise thickness control, conformal coating in high aspect ratio structures, and uniformity over large-area substrates.



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Diamond Quantum Technologies: Advancements in Engineering NV Centre Devices

In this webinar, we will address the key advancements in the optimisation of processes for the fabrication of these powerful quantum devices.

Agenda:

- Optimising Diamond for Quantum Technologies
- Plasma Etching for Diamond-based Quantum Technologies
- Engineering Diamond Devices for Scalable Quantum Networks

Watch recording now >

Fabrication Processes for High Quality Quantum Devices

In this webinar, we will review the uses of the technologies below for creating better superconducting, colour centre (diamond/SiC), and photonic quantum devices:

- Atomic Layer Deposition (ALD) of superconducting materials for Qubits such as NbN and TiN
- Deep Reactive Ion Etching of Silicon (DSiE) for TSV to enable 3D integration of Quantum circuits
- Reactive Ion Etching (RIE) for smooth diamond thinning for NV centres

Watch recording now >

Quantum Technology: Challenges & Solutions for Device Fabrication & Characterisation

In this webinar we will address three aspects of device development for superconducting qubits and quantum circuits:

- Plasma-enhanced ALD of superconductive thin films with RF substrate biasing by Dr Yi Shu, Oxford Instruments Plasma Technology
- Plasma etching of superconducting metals by Colin Welch, Oxford Instruments Plasma Technology
- Qubit characterization and measurement in cryogenic systems by Dr Ziad Melhem, Oxford Instruments NanoScience

Watch recording now >

Careers in Quantum Technology

In this webinar we will talk about the reality of the quantum market, what skills are needed, and how Oxford Instruments fits into this evolving marketplace.

> *"Working in quantum allowed me to solve some of the most interesting and challenging problems in modern engineering, which in turn furthered my interest in innovative technologies."*

(Dr Cat-Vu Bui, Ph.D. Candidate, Brain-Machine Interfaces, ETH Zurich)

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