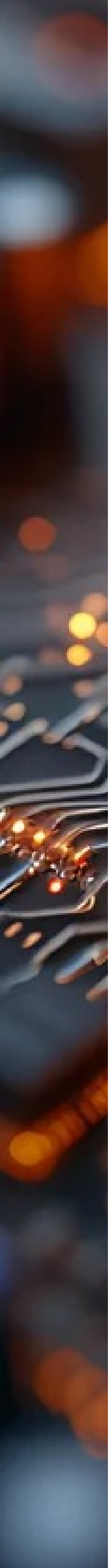
EDITORIAL FOCUS

Quantum Computing

An exclusive collection featuring top-tier articles, visionary experts, and essential industry insights



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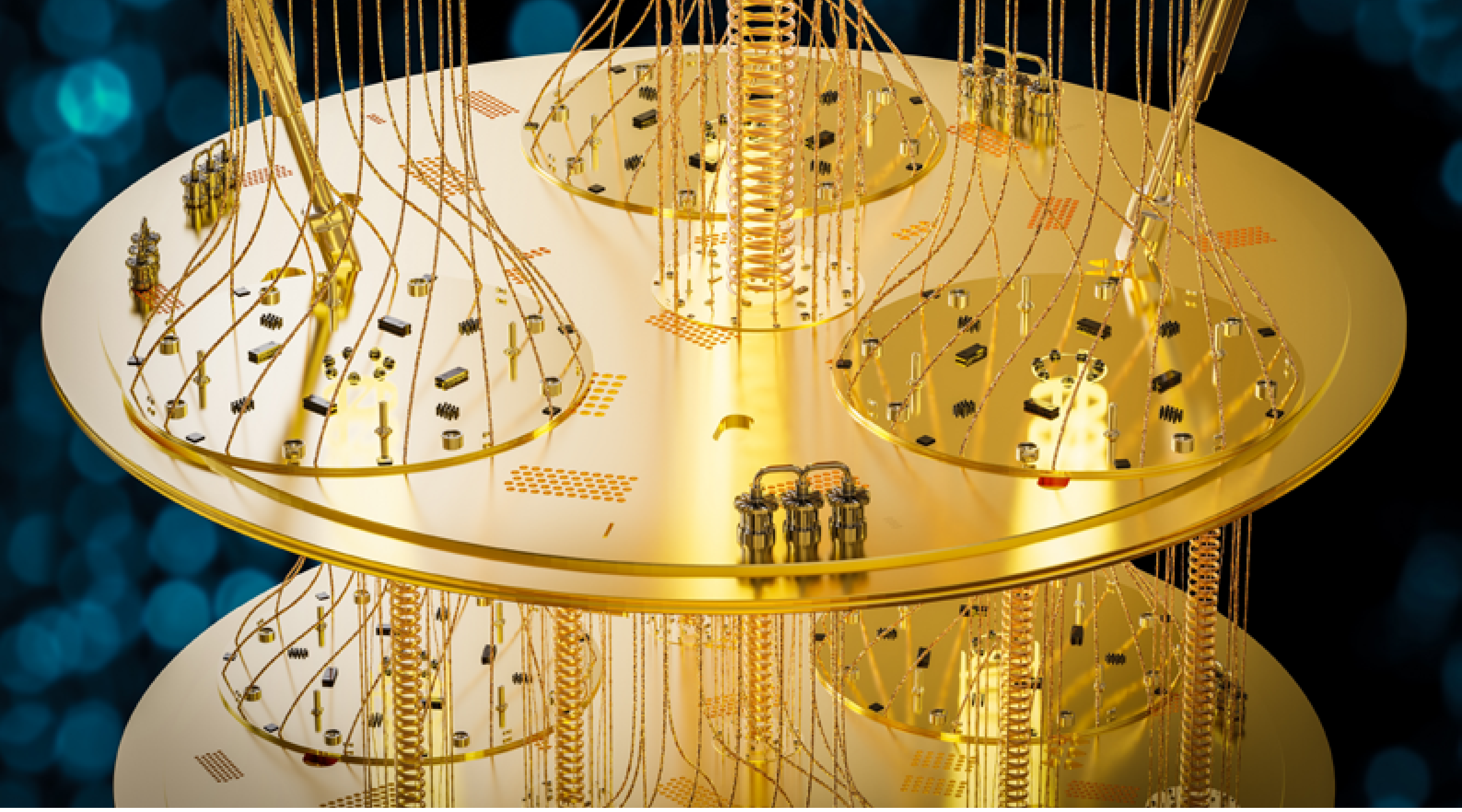


Foreword

Welcome to our new Quantum Computing Industry Focus eBook. Once seen as a far-off scientific concept, quantum computing is steadily advancing toward practical applications, as researchers and technologists tackle long-standing hurdles and unlock powerful new capabilities.

For this edition, AZoQuantum has curated a selection of standout developments propelling the industry forward. From advances in quantum hardware and fault-tolerant architectures to the rise of enterprise-ready, quantum-secure communication systems, the entire ecosystem is moving fast. This selection highlights the technical sophistication involved, but also the creative thinking driving these breakthroughs.

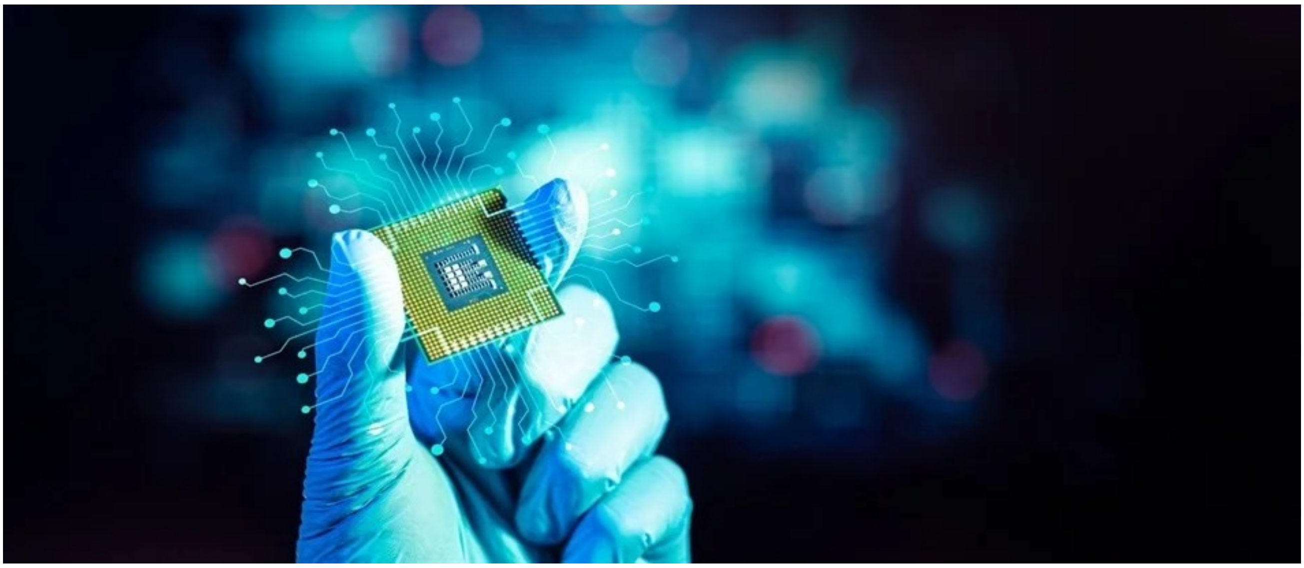
Sustainability is also coming into sharper focus. Scientists are investigating novel quantum materials that could lead to greener, more energy-efficient computing. At the same time, deeper insights into the foundations of physics, such as how gravity subtly impacts qubits or the quantum behavior of semiconductors, are informing the design of tomorrow's technologies.

Meanwhile, quantum computing is beginning to move beyond academic research into real-world impact. Practical use cases are emerging, from optimizing energy-efficient building operations to developing cybersecurity solutions to future threats. These early applications point to a future that's no longer just theoretical.

This eBook provides a concise, engaging snapshot of where quantum computing stands today, and where it's headed next.

Is Quantum Computing Ready-to-Market?

Quantum computing has emerged as a revolutionary inter-disciplinary field paving the way for innovative solutions which were not imaginable using classical physics and computational models.[1] Quantum computing has significantly boosted time savings across healthcare, financial analysis and cryptography, while also optimizing modern digital systems and allowing for better decision-making. However, many experts still feel that this field is in its infancy, with the shift from research centers to industrial settings requiring much more time and effort.



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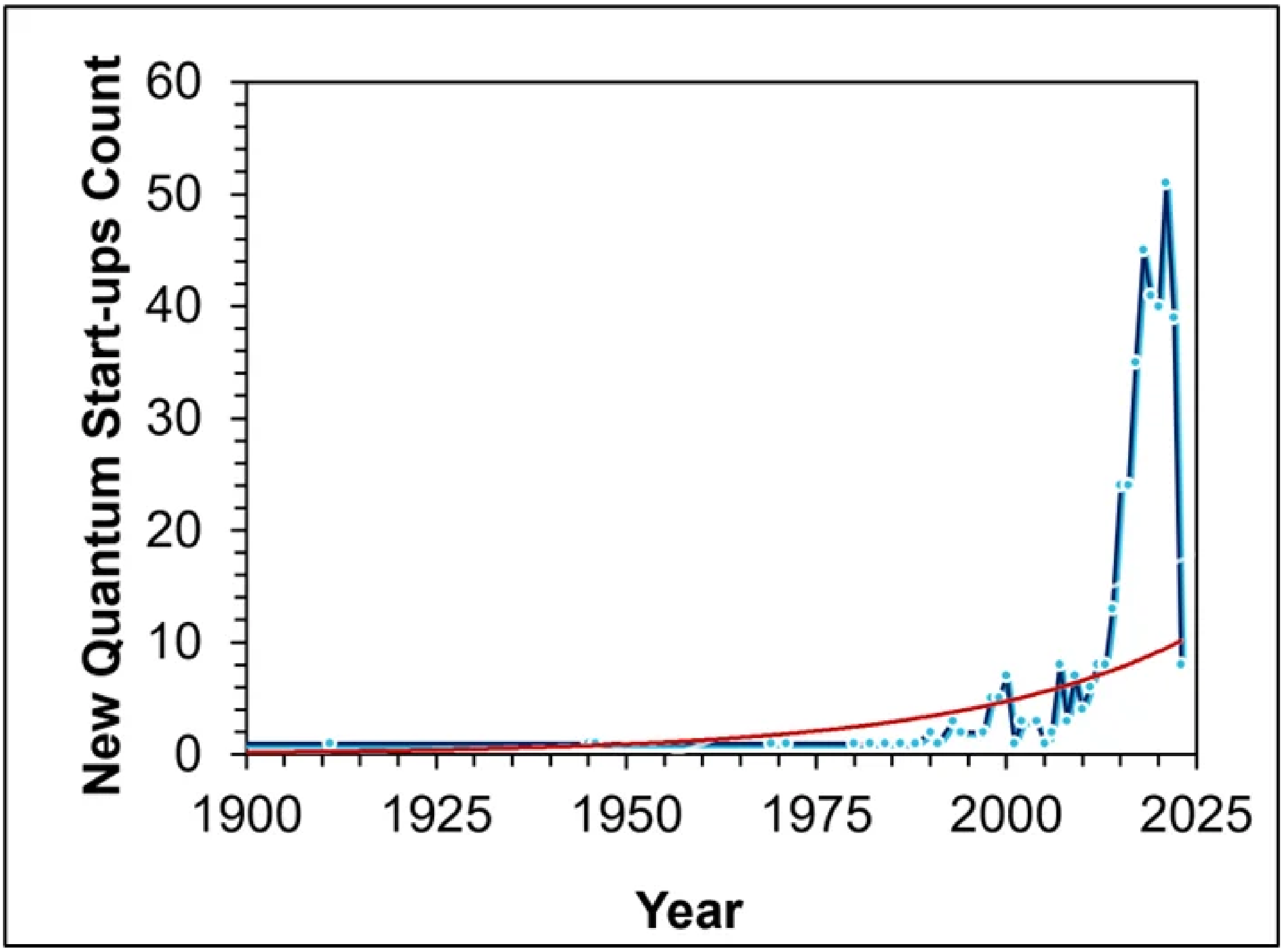
Where is Quantum Computing Up To?

Quantum computing uses qubits, which allows for much faster computation than traditional computers. Experts worldwide are already making the most of this technology for drug discovery in the biomedical and healthcare fields, solving problems related to energy crisis, performing ultrafast aerospace simulations, and manufacturing fast semiconductor chips. Owing to its success in various industries, quantum computing is progressing significantly, and many resources are being invested to develop highly efficient quantum computers and microprocessors.

A detailed study by IDTechEx highlights that the interest by researchers and the rapidly growing number of startups in the domain of quantum computing will transform it into a billion-dollar industry. Experts have predicted that the market valuation of quantum computing technology will reach U.S. 10 Billion dollars in the next 2 decades, with a compound annual growth rate of over 25%.[2]

A Market on the Rise

A research study supported by the National Research Foundation of Korea (NRF) has also highlighted the transformative potential of quantum computing. Experts studied and plotted the yearly growth patterns of emerging quantum computing startups and revealed that in the last 4 years, more than 51 quantum-related startups yielded their maximum profit, and are continuously attracting customers from various fields and industries.[3]



Quantum Startups Growth Trends Plotted by Experts from South Korea in the Research Article.[3]
Picture Credit: Putranto et. al. A Deep Inside Quantum Technology Industry Trends and Future Implications. Available at: https://www.doi.org/10.1109/ACCESS.2024.3444779

Governments are also on the move – nations like the United States, the United Kingdom, China, and Germany are investing millions of dollars, and making significant breakthroughs in the field of quantum computing. This has motivated the governments of other countries like Canada, France, and the Netherlands to allocate funds for researching quantum computing to accelerate scientific advancements.[2, 3]

Major Players Reshaping the Quantum Computing Domain

Major companies and ambitious startups are continuously pushing the boundaries of quantum computing, developing new technologies that exceed the capabilities of earlier processors.

IBM is at the top of the list when it comes to quantum technology advancements. From manufacturing individual quantum processing microchips with over 100 qubits to scaling superconducting quantum processing units (QPUs) beyond the 1000 qubit range, IBM is making remarkable strides in helping quantum computers reach their true potential.[4] Beyond hardware tools, they are also providing several software tools to develop a complete programming framework for users all over the world.[5]

Google is another prominent name when it comes to quantum computing, in particular with the development of a new quantum supercomputing chip called Willow at the end of 2024. Willow is among the fastest quantum chips and boasts superior error correction capabilities. A complex benchmark computation was performed by Willow in under 5 minutes which would take a modern supercomputer more than 10^{25} years.[6]

Rigetti Computing is a California-based company specializing in the development of quantum processing hardware. Their famous product includes The Novera QPU, which is a 9-qubit-based version of a quantum computer developed after 10 years of extensive research.[7]

From a business point of view, D-Wave is the only company demonstrating capabilities in practical quantum computing. They provide tools and support for performing quantum optimization to enhance productivity and lowering costs. D-wave is focused on solving real-world business problems by building quantum apps for various companies and is successfully demonstrating quantum return on investment.[8]

Other companies like IonQ and other emerging startups like PsiQuantum or Universal Quantum are becoming key players in this challenging economy and open up new avenues for fresh talent and chip manufacturers.

Technological Milestones

In the last 2 decades, we have seen breakthroughs in quantum device coherence times and gate fidelity, enabling the utilization of superconducting qubits. Lately, experts have turned to a material-based approach to boost quantum coherence. Niobium (Nb) stands out as the go-to choice for superconducting qubits, thanks to its high critical temperature and the largest superconducting gap among elemental superconductors. This helps minimize thermal quasiparticle-related losses at standard operating temperatures while performing complex computations.

However, surface oxides form on Nb, which leads to microwave losses during quantum operations. Recently, Grassellino et. al. have proposed a novel surface encapsulation strategy that prevents the formation of oxides on the surface of Nb when exposed to air during the operation of quantum devices. This proves to be a key technology in promoting significant systematic improvements in quantum coherence and improving the speed of quantum devices.

The team used different encapsulation materials like titanium, gold, tantalum, aluminum, etc. The experimental results revealed that the quantum devices incorporating encapsulated niobium qubits have much-improved T_1 relaxation times which are about 2 - 5 times superior to the pristine quantum devices with unaltered niobium oxides. The capping of Nb with tantalum significantly improved the quantum coherence, demonstrating qubit lifetimes exceeding 300μs, with maximum values reaching up to 600 μs.[9] This approach provides a solution for developing efficient cutting-edge devices with minimal dielectric loss at the metal/air interface.

Furthermore, companies like IBM and Google have made significant progress in scalability and error correction in modern quantum devices. The experts at IBM have developed a quantum-error correcting framework that is about 10 times more efficient than its counterparts. The experts at IBM have titled it "The Gross Code", which builds remarkable redundancy into the quantum circuits. It involves a systematic circuit using different qubits working in tandem to protect data packets that a single qubit shall lose due to errors and noise.[10] These efficient error mitigation techniques enable users to leverage quantum advantage on real quantum hardware.

An Overview of Technical Challenges

Despite breakthroughs by technological giants and emerging startups, the field of quantum computing still needs to overcome several challenges. The high cost and complexity associated with quantum hardware and software tools are limiting their potential use by the general public. While major companies offer cloud-based quantum computing tools, they're still largely used for research and academia, with commercial applications remaining rare.

Quantum computing is being explored in limited commercial fields such as cryptography, drug discovery, and materials sciences. Additionally, several startups are focusing on using quantum algorithms for Industries with high computational demands, such as finance and pharmaceuticals. However, these efforts are still in the early stages and have yet to be fully optimized. Improving error correction and developing a large number of stable qubits will enhance the performance of quantum algorithms for industrial use and unlock new possibilities in the future.[11]

Future Outlook

The field of quantum computing is ready to take a giant leap toward commercialization, completely changing our thinking in solving complex problems. The advancements in qubit technology, quantum error correction (QEC), and chip design are key milestones in the journey toward building fault-tolerant quantum computers that can address real-world challenges.

Particularly, the integration of quantum and classical computing elements marks the beginning of hybrid systems, which are expected to improve accessibility and versatility across various applications. These systems, along with the progress in quantum networks, are paving the way for secure quantum communication and the potential development of a quantum internet, revolutionizing cybersecurity and global data exchange.[12]

There is no doubt that quantum computing will grow rapidly in the next 5 to 10 years. Strategic investments and interdisciplinary research are the key to unlocking the potential of this billion-dollar industry. A proactive approach involving the development of in-house expertise, laying the foundation of a strategic investment plan, and interdisciplinary collaboration will ensure that commercialization and business opportunities are the core area of focus.

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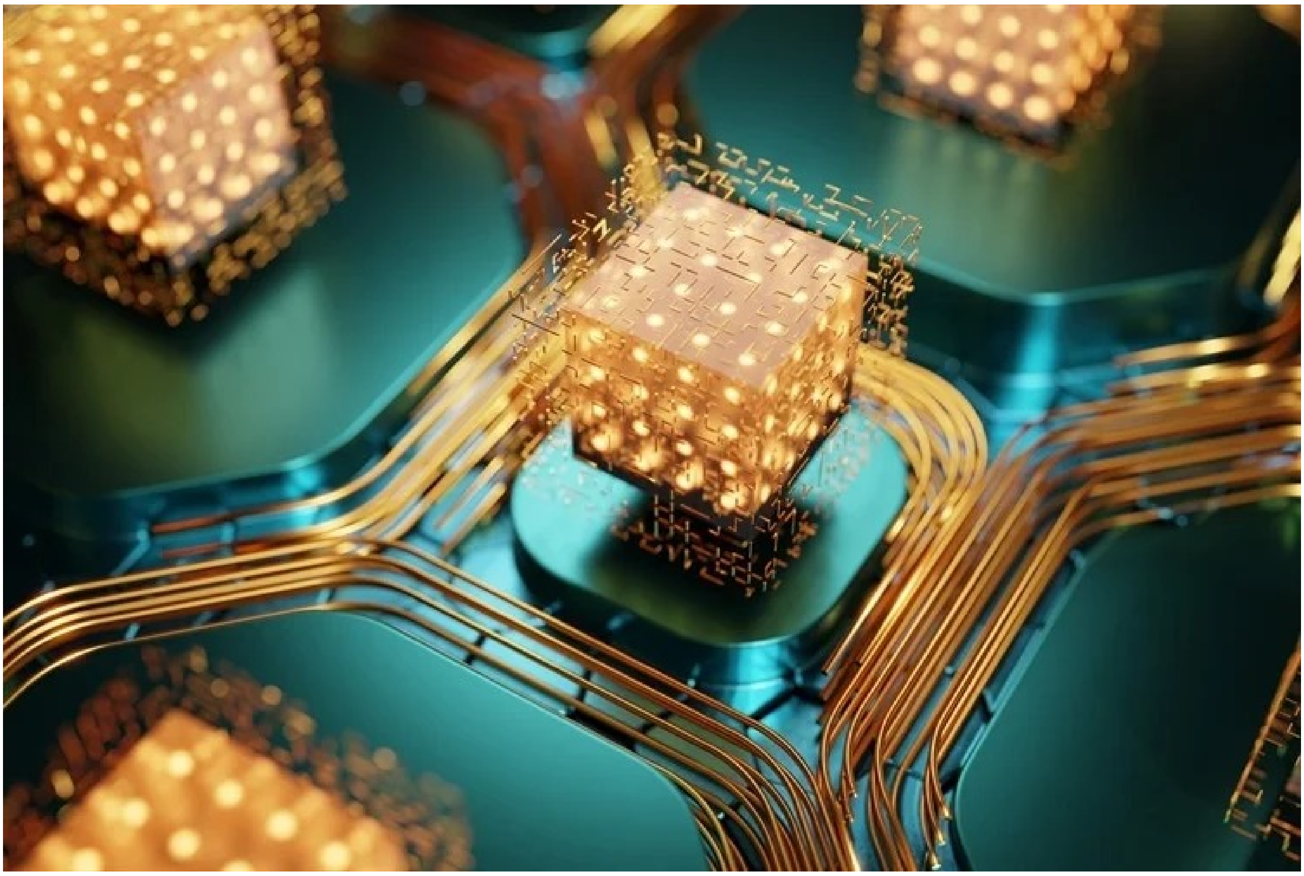
A Fourth State of Matter to Revolutionize Quantum Computing

Quantum computing is faced with a fundamental challenge of scalability. Traditional quantum bits (qubits) have instability issues due to noise and decoherence, making large-scale quantum computations difficult to achieve. This limitation has encouraged scientists and researchers to develop more robust quantum architectures capable of sustaining quantum states for longer durations while maintaining computational accuracy.



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In this context, Microsoft has unveiled its Majorana 1 chip, designed to leverage a fourth state of matter—known as a topological superconductor—to enhance qubit stability. [1]

Understanding the Fourth State of Matter

Topological superconductors are materials that combine the properties of superconductivity with those of topological phases. These materials have potential applications in quantum computing, particularly in the creation of Majorana fermions.

Majorana fermions, theoretical particles first predicted by Italian physicist Ettore Majorana in 1937, are zero-energy excitations that appear at the edges or vortices of topological superconductors. [2] They are unique in the sense that they are their own antiparticles. This peculiar property allows them to act as stable quantum states, resistant to the types of errors that are common in traditional qubits.

The topological nature of these superconductors provides a unique form of protection against environmental noise that arises from the non-local encoding of quantum information. The primary hurdle in building practical quantum computers is decoherence. In topological semiconductors, the information is distributed across multiple Majorana zero modes, making it more resistant to decoherence. This inherent stability distinguishes topological superconductors from conventional materials, placing them in a category of their own fourth state of matter beyond the traditional states. [1, 3, 4]

How Microsoft's Majorana Chip Works

Microsoft has been working on topological quantum computing for some time, aiming to develop qubits that offer greater inherent stability compared to current models. Companies like IBM and Google rely on superconducting circuits that require extensive error correction; conversely, Microsoft's approach is based on Majorana zero modes.

Microsoft's Majorana 1 chip is designed to engineer and manipulate Majorana fermions. This is achieved by combining a superconductor with a semiconductor nanowire in the presence of a strong magnetic field. The interface between these materials under precise conditions gives rise to Majorana zero modes, which can be used as qubits.

One of the key features of Majorana-based qubits is non-Abelian braiding, which is a process where the quantum state is encoded in the way particles are exchanged rather than in a single physical location. This means that information is stored in a topological manner, making it highly resistant to local perturbations. [1, 3]

Implications for Quantum Computing

Microsoft's Majorana 1 chip can significantly reduce error rates, making it possible to build larger, more powerful quantum computers. This chip could realize fault-tolerant quantum computing, where errors are automatically corrected, allowing for complex computations that are currently impossible because of technological limitations. [1, 3]

Scalability is one of the critical barriers to real-world quantum applications due to noise and error rates. The stability of topological qubits could simplify the architecture of quantum computers to make it easier to scale up the number of qubits. This could accelerate the development of quantum computers for practical applications across multiple domains. For instance, in cryptography, quantum-resistant encryption methods could be developed, ensuring secure communication in a post-quantum era. In materials science, they could simulate complex molecules and materials, leading to the discovery of new drugs and advanced materials. Similarly, in artificial intelligence, they could accelerate machine learning algorithms and enable more powerful AI systems.

Majorana-1 Chip Advancing Quantum Computing and Fundamental Physics

In a 2025 study, researchers explored the role of spacetime torsion in influencing topological superconductivity, particularly in Microsoft's Majorana-1 quantum chip. The study examined how Majorana zero modes are stabilized in semiconductor-superconductor hybrid nanowires under specific conditions, forming robust qubits through the Tetron architecture.

A key development highlighted in the study is the potential impact of spacetime torsion, derived from the Unified Field Equations, on shifting critical parameters such as Zeeman fields and superconducting gap energies. These subtle effects, though small, could be experimentally observed through high-precision conductance and quantum capacitance measurements. The findings suggest that beyond enabling fault-tolerant quantum computing, the Majorana-1 chip might serve as an indirect probe into fundamental spacetime geometry, bridging quantum materials research with advanced gravitational theories. [5]

Challenges and Future Prospects

One of the challenges in implementing topological qubits is that the fabrication and manipulation of Majorana zero modes are complex and require extremely precise control. Moreover, while theoretical models and initial experiments support the existence of Majorana fermions, further verification is needed to confirm their utility in practical quantum computing. The experimental conditions required to create and maintain Majorana zero modes are extremely stringent, necessitating temperatures near absolute zero and highly controlled environments.

Building a quantum processor based on topological qubits requires advances in nanofabrication techniques and material engineering. Currently, producing and maintaining these exotic quantum states is difficult and expensive. Microsoft and other research institutions must develop scalable manufacturing processes to make topological quantum computers commercially viable.

Want to know more about quantum computing? It's all here

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Building the World's First Enterprise-Grade Quantum-Proof Communication Platform

AZoQuantum talks to Anurag Lal, CEO and President of NetSfere, about their quantum-resistant communication platform that meets strict compliance and performance standards

Could you provide an overview of what sets NetSfere's new platform apart as the world's first enterprise-ready, quantum-proof secure communication solution?

NetSfere integrated the most advanced NIST-recommended ML-KEM encryption into its enterprise communication platform. This ensures all communications, data, files, etc. are completely secure against the quantum threats we're facing today. Netsfere has a crypto-agile design which allows for us to seamlessly upgrade to future cryptographic standards as they evolve.

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Your platform leverages quantum-resistant algorithms compliant with NIST standards. Can you elaborate on the specific cryptographic technologies implemented and why they were chosen?

NetSfere employs ML-KEM FIPS 203 ML-KEM encryption. It is designed to withstand the capabilities of quantum computers, particularly those that could break conventional public-key cryptographic systems such as RSA and ECC. There are plenty of post-quantum cryptography (PQC) algorithms available worldwide for enterprises to choose from, but this specific one meets the latest U.S. federal agency requirements as well as international security standards, so our worldwide users can be at ease knowing they are protected with the gold standard of security.

Given the unpredictable timeline for quantum computing breakthroughs, how do you evaluate the urgency for enterprises to adopt quantum-safe communication measures today?

We don't have the luxury of taking a wait-and-see approach. We need to act now. When it comes to quantum computing, the timeline isn't just unpredictable, it's accelerating. That's something we all need to recognize. For years, quantum computing felt like a far-off concept, something we had time to prepare for. But that perception is shifting fast. Bad actors are harvesting encrypted data now in anticipation of decrypting it later with quantum technology. These "harvest now, decrypt later" attacks are a quiet but very present danger.

How does the integration of post-quantum cryptography impact the performance, latency, or user experience compared to traditional encrypted platforms?

We were very intentional about ensuring that the added security didn't come at the expense of user experience. We were diligent in the integration process and optimized everything to minimize any impact on latency. For the user, this means the experience stays smooth, responsive, and just as fast as they expect from any modern messaging platform. Our users don't even notice the shift in encryption strength. That's how it should be. The encryption is working hard behind the scenes, and the experience remains intuitive and effortless up front.

Can you speak to the challenges your team faced in developing and deploying a platform that balances compliance, usability, and cutting-edge cryptographic resilience?

Compliance isn't just a box we check, it's foundational, especially for the industries we serve like healthcare, finance, legal. These sectors operate under incredibly strict regulations like HIPAA, GDPR, and now emerging standards around AI and data sovereignty. Integrating PQC introduced another level of complexity. These algorithms are powerful, and they require new key management strategies, new protocols, and above all, they need to run efficiently without degrading performance. Our engineers had to rethink and rearchitect parts of the stack to achieve that balance. We took our time to make sure compatibility, usability, security and compliance remained intact and at optimal performance levels.

Beyond end-to-end encryption, what additional security or privacy features does NetSfere's platform incorporate to support zero-trust architectures in enterprise environments?

End-to-end encryption is just the baseline for NetSfere. The communication platform also puts users at ease with additional security features such as full IT administrative control, strict multi-factor authentication and perhaps most critically, we never collect user data or integrate open-source AI. We can't even access your data - only you can.

How do you envision this platform evolving as quantum computing capabilities mature? Are there mechanisms in place to ensure ongoing cryptographic agility?

This is where crypto agility becomes essential. We've built NetSfere to be a top-tier crypto-agile platform, meaning we can rapidly integrate new algorithms as standards and security threats evolve. Our goal is not to just stay current, it's to stay ahead of the threat. Our PQC integration is just the beginning. We're continually testing and validating next-gen protocols to ensure we're ready for whatever comes next.

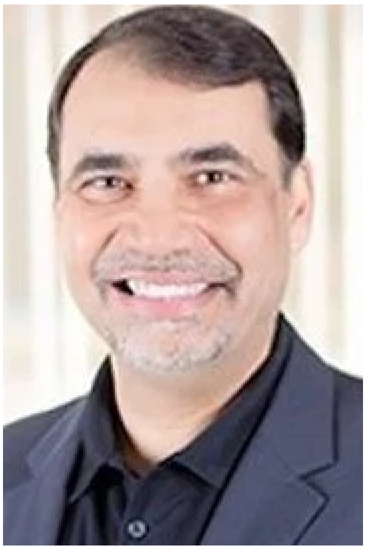
What industries or use cases do you believe will be the earliest adopters of quantum-proof communication, and how is NetSfere engaging with those sectors?

The earliest adopters of PQC will be, and already are, within the government, finance, healthcare and legal sectors. These industries are responsible for mass amounts of highly sensitive data with long-term value. They're the most at risk right now for the "hack now, decrypt later" attacks. A large majority of NetSfere users operate within these sectors and rely on our world-class enterprise security and compliance. Every day we're evaluating looming threats, strengthening the weakest link in a security system and working with our subscribers to ensure they are equipped with the right tools to protect their organization.

Will the Quantum Financial System be safe? Read here to find out

About the Speaker

Anurag Lal is the President and CEO of NetSfere. With more than 25 years of experience in technology, cybersecurity, ransomware, broadband and mobile security services, Anurag leads a team of talented innovators who are creating secure and trusted enterprise-grade workplace communication technology to equip the enterprise with world-class secure communication solutions. Lal is an expert on global cybersecurity innovations, policies, and risks.



Exploring Hematite as a Greener Computing Material

Hematite (Fe_2O_3) is a common iron mineral found in abundance on Earth, and analyses of surface samples have also confirmed its presence on Mars. Hematite plays a key role in the redox cycling of iron and is well-known as a cost-effective semiconductor with the ability to absorb a significant portion of visible light.[1] Hematite is primarily used in the production of steel and iron, but its role as a pigment stands out as one of its most economically significant applications.[2] In recent years, a novel trend has emerged focusing on the use of Hematite in next-generation computational platforms.

Image Credit: mineral vision/Shutterstock.com

Hematite's Magnetic Properties

The magnetic properties of hematite are characterized by three distinct temperatures. These are the Néel temperature, the Morin temperature, and the blocking temperature.

Studies have revealed the Néel temperature of bulk hematite to be around 960 K. Below its Néel temperature, hematite behaves as an antiferromagnetic material, with magnetic moments aligning in opposite directions. This alignment cancels out the net magnetic effect, resulting in a total magnetic moment of zero.

The Morin transition temperature has been estimated to be around 263K, with the magnetic spin being antiparallel below the Morin temperature, leading to the uniaxial antiferromagnetic properties displayed by the hematite. As the temperature exceeds the Morin temperature, a slight magnetic moment is recorded, leading to weak ferromagnetism. If the size of the particles decreases, a decrease is observed in the Morin temperature.

After a certain limit, a further reduction in particle size leads to a fluctuation in the reorientation of the magnetic moment in a single domain. This is due to the thermal agitation, which leads to the hematite behaving like a superparamagnetic material.[3]

Spintronics and Sustainable Computing

Spintronics plays a central role in the development of next-generation computational platforms and nanoelectronic devices. It offers a promising approach to optimizing energy efficiency while significantly enhancing storage capacity and computational speed. These devices utilize the spin degrees of freedom of electrons, where the spin polarization can be regulated by magnetic layers or spin-orbit coupling.[4]

Rare and toxic elements, as well as molecular semiconductors (MSCs), have been used traditionally. However, the effect of physicochemical structures of MSCs on spin relaxation and magnetic properties is very unclear, leading to major challenges in selecting highly efficient materials for spintronics applications.

Furthermore, the conventional materials exhibit shorter lifespan and unfavorable spin-transport efficiency, making it necessary to look for alternatives.[5] In this regard, hematite has emerged as a sustainable and highly abundant material with much higher power efficiency, becoming popular among the experts researching spintronic devices.

Room-Temperature Operation Advantage

The net-zero magnetization and resistance to external magnetic fields make antiferromagnets especially valuable for ultra-fast, energy-efficient spintronic devices. These properties are critical for developing advanced frameworks for next-generation information processing and storage systems. For everyday utilization, efficient operations at room temperature become a necessity.[6]

Hematite, characterized by a corundum crystalline structure, is antiferromagnetic below the high Néel temperature of 675℃. Around room temperature, the spin moments are perpendicular to the basal plane, making it a true antiferromagnet.[7] This makes hematite a highly promising candidate for practical implementation in computing platforms.

The control of spin currents is at the base of spintronics, and the spin current in antiferromagnets can be characterized as having opposite polarization. The ability to control spin currents in hematite at room temperature—without the need for extensive cooling—has already been demonstrated.[8] This capability is helping to open up new possibilities in the emerging field of antiferromagnetic spintronics..

Integration with Existing Technologies

Hematite is easily fabricated by conventional ore processing techniques like hydrothermal synthesis and electrochemical methods. No specialized equipment is required for processing hematite, making the process economical. The current semiconductor manufacturing techniques can be easily used to fabricate hematite-based semiconductor devices used in logic gates and neuromorphic computing platforms. Chemical precipitation techniques have been successfully demonstrated to produce hematite-based nanoparticles, including metal-doped nanoparticles.[9] The compatibility with established manufacturing methods makes hematite an economical choice.

Environmental and Ecological Benefits

Rare earth metals are essential for microelectronics and computing devices. These metals are available in very scarce concentrations, and an individual ore doesn't contain a single rare metal; rather, a complex mixture is present, making specialized separation techniques a requirement.

Rare metals are associated with radioactive substances, making their mining a hazardous process leading to exceptional waste generation, and releasing pollutants responsible for water, soil, and air pollution. These metals severely affect the water quality, disturbing the natural ecosystem as well as causing irreparable damage to the environment and the living organisms [10]

In comparison, hematite is a purely iron oxide ore, not associated with any radioactive pollutants. It is abundantly present and is easily processed using conventional techniques, making it highly economical. Experts have also demonstrated a sustainable, eco-friendly, and highly efficient fabrication method of producing hematite nanoparticles in many studies using organic raw materials.[11] Hematite's potential for reuse and recycling offers a promising path toward accelerating sustainable electronics manufacturing and advancing the carbon-neutral production of semiconducting devices.

Challenges and Research Direction

Experts have recently discovered that hematite photo-electronic devices have a significant limitation and are unable to develop a sufficient Fermi level splitting under light. This is because of the reduction of Fe from Fe^{3+} to Fe^{2+} due to the formation of electron polarons. This is a major issue and will need to be resolved efficiently and economically.[12]

There is much ongoing research focused on developing some modified and/or novel approaches for meticulously controlling the nanostructure and composition of hematite, as these two main factors substantially affect the electronic structure and physicochemical performance of microelectronics.[13] In this regard, interfacial engineering is a popular approach, and the implementation of Machine learning algorithms is expected to boost the process of developing highly optimized functional hematite materials as well as understanding spin injection mechanisms in hematite material.

These key steps will make sure that hematite is at the forefront of the development of next-generation fast and efficient computing frameworks.

Discover how carbon can also help making computing greener

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The Quantum Potential of Carbon Opens the Door to More Sustainable Computing

Carbon holds unique properties at the quantum scale that make it exceptionally well-suited for the next generation of sustainable computing. Unlike traditional semiconductor materials, carbon can exist in highly versatile nanostructures, such as graphene, carbon nanotubes, and fullerenes, that exhibit remarkable electronic and quantum behaviours.[1]

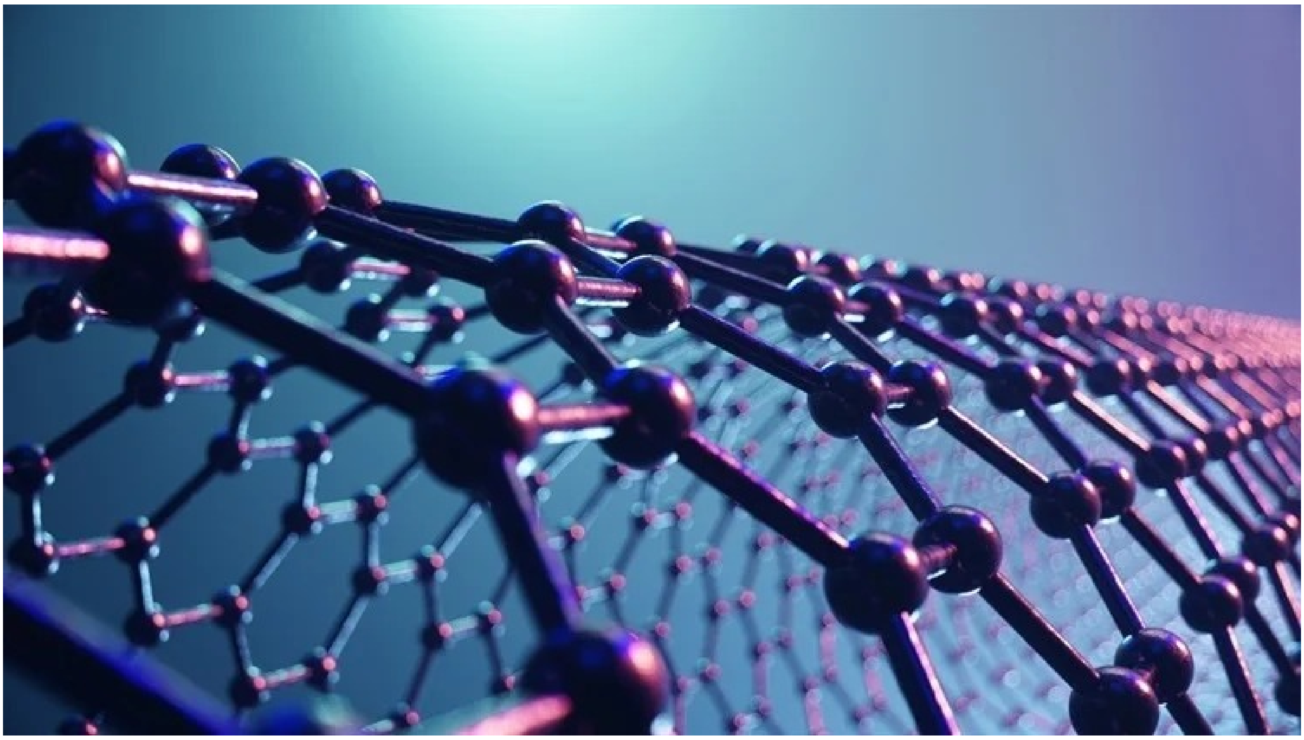

Image Credit: Rost9/Shutterstock.com

These structures allow for phenomena like ballistic electron transport and long qubit coherence times, thanks to low spin-orbit interaction and minimal nuclear spin interference. In quantum computing architectures, such characteristics make carbon an attractive candidate for stable, energy-efficient qubits.[1]

At the same time, the urgency for sustainability in computing is growing. The demand for data processing, driven by AI, cloud services, and IoT, is scaling at an unprecedented rate, with a corresponding spike in the carbon footprint of information and communication technology. Manufacturing contributes significantly to this impact, with embodied carbon from semiconductor production now rivaling or exceeding that of entire industries like aviation. [2]

Why Carbon?

Carbon exists in multiple forms, or allotropes, each with unique properties that make them well-suited to advanced computing. Graphene, a single layer of carbon atoms, is incredibly conductive and flexible, with electrons moving through it with minimal resistance. Carbon nanotubes (CNTs), essentially rolled-up sheets of graphene, are exceptionally strong, thermally stable, and capable of acting as semiconductors or conductors depending on their structure. Fullerenes have shown potential in photonics and quantum dot design. These carbon structures outperform traditional materials in many ways: they conduct heat and electricity better, tolerate stress, and scale more easily to nano sizes.[3]

Silicon has powered the computing industry for decades, but it's reaching physical and performance limits. Compared to silicon, carbon-based materials offer higher energy efficiency, smaller form factors, and superior conductivity.

For example, CNTs transistors can switch faster and operate at lower voltages than their silicon counterparts. Additionally, the ability to stack carbon components in three dimensions makes them more scalable.[4] In quantum computing, where minimizing energy loss and decoherence is crucial, carbon's properties offer a compelling advantage over silicon-based qubit architectures.[2]

Carbon in Quantum Computing

Carbon nanomaterials are well-positioned to support the next generation of quantum computing hardware. For instance, graphene quantum dots can serve as hosts for spin qubits, offering relatively long coherence times due to graphene's low nuclear spin density and minimal spin-orbit interaction.[5]

CNTs can serve as superconducting qubit components or gate materials, offering high mobility and integration potential with classical circuits. Defects in fullerenes and other carbon structures can emit single photons—a key requirement for photonic quantum computing. These features make carbon a flexible foundation for qubit technologies across multiple platforms.[5]

These carbon-based systems offer a set of practical advantages. First, they show potential for lower decoherence, which is a major challenge in maintaining quantum states over time. The stability offered by carbon materials could reduce the overhead required for error correction, improving system efficiency.[6]

Second, the high mobility of charge carriers in carbon materials supports fast gate operations, which are important for executing quantum algorithms within coherence time windows. Finally, some research efforts are evaluating whether certain carbon-based platforms could operate at higher temperatures compared to conventional superconducting systems. While cryogenic environments remain standard, the ability to shift parts of a quantum system closer to room temperature could simplify infrastructure and reduce energy use.[6]

Energy Efficiency & Sustainability

Carbon-based computing technologies offer notable energy efficiency gains over silicon. Their electrical properties allow for lower power use during computation and can be integrated into less energy-intensive fabrication processes. This helps reduce both electricity demand and operational carbon, aligning with carbon-neutral computing goals.[2]

The environmental impact of sourcing and disposal is also lower for carbon-based hardware. Many carbon materials come from abundant or renewable sources, resulting in a smaller embodied carbon footprint. Their modular design also supports easier repair, reuse, and recycling, helping to minimize waste.[5]

Carbon-based components can potentially be made biodegradable or fully recyclable. By using sustainable materials and applying circular economy principles, manufacturers can reduce environmental impact across a device's lifecycle. Policy incentives and growing renewable energy use can further lower total emissions from computing systems.[1, 7]

Cutting-Edge Research & Development

Progress in carbon quantum technologies is accelerating. CNT field-effect transistors (CNT-FETs) are achieving sub-10nm scale, pushing the limits of miniaturization. Meanwhile, hybrid architectures integrating carbon nanotubes with resistive memory (RRAM) have been demonstrated in commercial foundries, indicating growing industry interest.[6]

Another area of focus is the development of single-photon sources using carbon nanomaterials, which offer a compact and potentially lower-cost alternative to more complex rare-earth-based emitters. These devices are being designed to meet performance criteria such as photon indistinguishability, emission rate, and spectral stability—critical factors for quantum networking and photonic computing. Together, these advances highlight how carbon nanostructures can fulfill multiple roles within the quantum technology stack, from computation to communication.[8]

Several research groups and startups are leading the carbon computing movement. Harvard and the University of Pennsylvania's Carbon Connect initiative is working on system-wide carbon-aware computing frameworks. Stanford's Shulaker Lab has made breakthroughs in fully functional carbon nanotube processors. Companies like Carbonics are developing high-frequency CNT-based RF components, and others like Carbon Connect are focused on creating entire computing ecosystems grounded in carbon-aware design principles. These efforts mark a transition from lab demonstrations to practical, scalable hardware.

Challenges & Roadblocks

Despite progress, manufacturing carbon-based hardware at scale remains a challenge. Producing uniform, defect-free CNTs or aligning them precisely on wafers requires new fabrication methods. Variability in the physical properties of carbon materials can lead to inconsistent device behaviour, making mass production difficult.[2]

Integrating carbon-based components into existing silicon-dominated infrastructure is another hurdle. Most current fabrication lines are optimized for silicon, meaning new tooling and workflows are needed. Integrating carbon-based quantum chips with conventional silicon systems will require improvements in packaging technologies, and interface architectures to ensure seamless interoperability.[9]

Achieving fault tolerance and reliable performance with carbon qubits demands new error correction techniques. Additionally, standard benchmarks and lifecycle analysis tools specific to carbon-based quantum systems must be developed to evaluate performance, efficiency, and environmental impact fairly across platforms.[2]

Looking Forward

Widespread use of carbon quantum hardware is still years away but approaching steadily. Early adoption is likely in specialized accelerators and hybrid quantum-classical platforms. Within the next 5 to 10 years, we may see carbon-based qubits used in targeted applications like quantum sensing or secure communication, with broader deployment as fabrication matures.

Carbon is uniquely suited to serve as a bridge between classical and quantum hardware. Its versatility allows it to support both traditional logic and quantum operations on the same chip. This makes carbon an ideal material for integrated systems where classical control logic and quantum processors need to work seamlessly together.[1-2]

Carbon's quantum potential isn't just about speed or power—it's about rethinking computing from the ground up. With its ability to operate efficiently, reduce emissions, and support long-term reuse, carbon offers a path to a greener future. In a world where computing must scale without destroying the climate, carbon may be the material that makes both possible.

Discover how carbon quantum dots can help with wound healing here

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Solving Real-World Problems With Neutral Atoms: The Road to Fault-Tolerance

AZoQuantum speaks to Yuval Boger at QuEra about the exciting advancements in neutral-atom quantum computing and how QuEra is pushing the boundaries of scalable quantum systems. Yuval shares insights into the company's unique approach and the future potential of this rapidly evolving technology.

Can you give us an overview of how this approach differs from other quantum computing paradigms, such as superconducting or trapped-ion qubits?

Neutral-atom quantum computing employs individual atoms as qubits, arranging them with laser-based "optical tweezers" and leveraging the atoms' inherent properties for both storage and processing of quantum information. This approach differs from other paradigms in several key ways:

Interaction on Demand

One major advantage is the ability to bring qubits closer or move them apart as needed. When two atoms are brought into proximity, they can interact with each other. Being able to spatially rearrange qubits on-the-fly is extremely beneficial for implementing more efficient algorithms and new error correction codes.

Perfectly Identical Qubits

Unlike superconducting circuits, which require delicate nanofabrication and can exhibit qubit-to-qubit variability, every neutral atom is identical by nature. This uniformity simplifies calibration and helps maintain consistent performance across all qubits, reducing one of the key sources of error in large-scale quantum systems.

Room-Temperature Operation

Neutral-atom platforms operate at or near room temperature, confined by laser fields within a vacuum chamber. In contrast, superconducting qubits require deep cryogenic cooling and complex infrastructure. This more relaxed thermal requirement makes neutral-atom systems potentially simpler to house and maintain, including in high-performance computing (HPC) environments that often have space and power constraints.

Scalability and Reconfigurability

With neutral-atom arrays, scaling up is mainly a matter of adding more atoms to the trap arrays—no new fabrication runs or specialized chip designs are necessary. Because of this, it's possible to move toward larger numbers of qubits at relatively low incremental cost and effort. Additionally, the layout of atoms can be reshaped in real time, making it feasible to experiment with different topologies or problem mappings without major hardware overhauls.

While trapped-ion systems have also demonstrated high-fidelity quantum operations, neutral-atom platforms excel in scalability and reconfigurability. With neutral atoms, it's straightforward to add more qubits or alter their arrangement for different applications—something significantly more complex in a trapped-ion setup where ions are typically arranged in a linear chain or must be shuttled between multiple zones. Indeed, existing neutral atom systems such as QuEra's 256-qubits include many more qubits than any available trapped ion system.

Overall, neutral-atom technology brings together high scalability, strong controllable interactions, inherent qubit uniformity, and the convenience of near-room-temperature operation. Indeed, given the scientific developments of recent years, many experts believe that neutral atoms moved from being a "dark horse" to becoming a "work horse", the leading quantum modality.

Image Credit: QuEra

What recent advancements has QuEra made in increasing qubit counts and improving coherence times, and how close are we to large-scale, fault-tolerant quantum computation?

Over the last few years, QuEra has made consistent strides in building larger arrays of neutral-atom qubits while preserving—and in many cases, improving—their coherence times. Through advancements in laser systems, vacuum technology, and control electronics, QuEra has been able to extend the time during which qubits remain stable and reduce error rates. Additionally, ongoing improvements in system design and calibration techniques continue to push coherence times higher, enabling more complex algorithms to run reliably.

In addition to scaling our qubit arrays, we're also seeing significant global adoption. Notably, we recently delivered a neutral-atom quantum system to the National Institute of Science and Technology in Japan, underscoring the international traction our platform has gained.

Despite these milestones, the journey to large-scale, fault-tolerant quantum computation is an ongoing endeavor. Achieving fault tolerance will require further breakthroughs, including perfecting advanced error-correction schemes that can handle more qubits and gate operations with extremely low error rates. QuEra's roadmap, like those of other quantum hardware developers, looks toward integrating hardware, software, and algorithmic optimizations in tandem. While it may still take a few more years of research and development to reach fully fault-tolerant machines, the progress so far signals that neutral-atom platforms are particularly well suited for moving up the scale—from today's hundreds of qubits to the thousands or millions needed to tackle the most challenging real-world quantum problems.

Error correction and noise reduction remain major challenges in quantum computing. How is can we tackle these issues, and what innovations in error mitigation are you particularly excited about?

Error correction and noise reduction are at the forefront of quantum computing research, and neutral-atom platforms offer unique ways to approach these challenges. Broadly, we tackle them by improving hardware components to reduce noise, implementing advanced error-correcting codes, and exploiting the flexibility of atomic arrays to shuttle and rearrange qubits when needed. In addition to these foundational efforts, three recent developments underscore the rapid progress being made:

48 Logical Qubit Experiment (December 2023)

This Harvard-led milestone experiment demonstrated a sizable logical qubit array on a neutral-atom platform, effectively pushing error-corrected quantum operations into a regime well beyond small-scale prototypes. Creating and operating 48 logical qubits in such a controlled environment highlights both the scalability of neutral-atom systems and the viability of sophisticated error-correcting strategies at this scale. It offers a crucial proof of concept that neutral-atom architectures can incorporate complex error protection for larger numbers of qubits.

Magic State Distillation Work

Magic state distillation is a pivotal technique for achieving universal fault-tolerant quantum computation because it enables the generation of non-Clifford states, which are essential for implementing a fully universal gate set. By showing how magic state distillation can be efficiently executed on neutral-atom devices, this QuEra-led research team has taken a significant step toward using error correction in universal quantum circuits.

AI Decoding of Quantum Error Correction

A recent collaboration between QuEra and NVIDIA is focused on exploring AI-based decoders for quantum error correction, leveraging NVIDIA's high-performance computing expertise and GPU-based architectures. By applying machine learning techniques to decode quantum error syndromes more efficiently, this partnership aims to accelerate the development of robust fault-tolerant quantum systems.

Together, these breakthroughs illustrate how neutral-atom systems are moving beyond proof-of-principle demonstrations.

One of the unique features of your platform is its ability to reconfigure qubit arrangements dynamically. How does this reconfigurability impact quantum algorithm development, and what kinds of problems does it make more accessible to solve?

Reconfigurability and dynamic qubit shuttling is a game-changer for quantum algorithm development because it allows us to physically rearrange atoms to create more efficient algorithms relative to systems that are constrained by a static hardware layout. Researchers and developers can "dial in" the structure best suited for each step of the problem at hand. This flexibility can significantly shorten circuit depth and reduce overhead in quantum operations, making computations more efficient overall.

In the realm of error correction, reconfigurability also enables the implementation of advanced schemes—such as Quantum Low-Density Parity-Check (QLDPC) codes—that may not be feasible on static architectures with fixed qubit layouts. Because neutral-atom arrays can be rearranged dynamically, it becomes easier to establish and maintain the intricate connectivity patterns that these codes often demand. It can also support parallel operations on multiple qubits at once.

If quantum algorithms become shorter and error correction codes become more efficient, quantum computers with dynamic reconfiguration are likely to be suitable to real-life problems sooner than those with static configuration.

QuEra recently made its quantum computing platform available via the cloud. What does this mean for researchers and businesses looking to experiment with or develop quantum algorithms? Have you seen any interesting use cases emerge from early adopters?

QuEra's integration into the cloud—most notably through Amazon Braket since November 2022—opened the door for researchers and businesses worldwide to experiment with and develop quantum algorithms at will and in a very cost-effective manner. To date, it remains the only publicly-accessible neutral atom platform in the world. By offering on-demand access to 256 neutral-atom qubits, users gain the flexibility to explore various applications, from optimization and machine learning to chemistry simulations, with minimal setup and immediate scalability.

In practice, this cloud accessibility has attracted hundreds of companies and research groups eager to leverage neutral-atom quantum computing. Notable examples include BMW, JPMorgan, Merck, and Deloitte, all of which have actively probed new frontiers in optimization, finance, drug discovery, and strategic use cases. Researchers have also taken advantage of the platform to test out algorithms, explore physical phenomena and generate exciting scientific discoveries. Early adopters are already illustrating the immediate value of near-term access.

What role do you envision for neutral-atom quantum processors in real-world applications?

Neutral-atom quantum processors will excel at simulating the quantum behaviour of atoms and molecules, making them ideal for applications like drug discovery, materials design, battery optimisation and cleaner industrial processes. Beyond physics and chemistry, these systems are also well suited to optimisation problems, AI and financial modelling, where quantum advantages could lead to significant speedups.

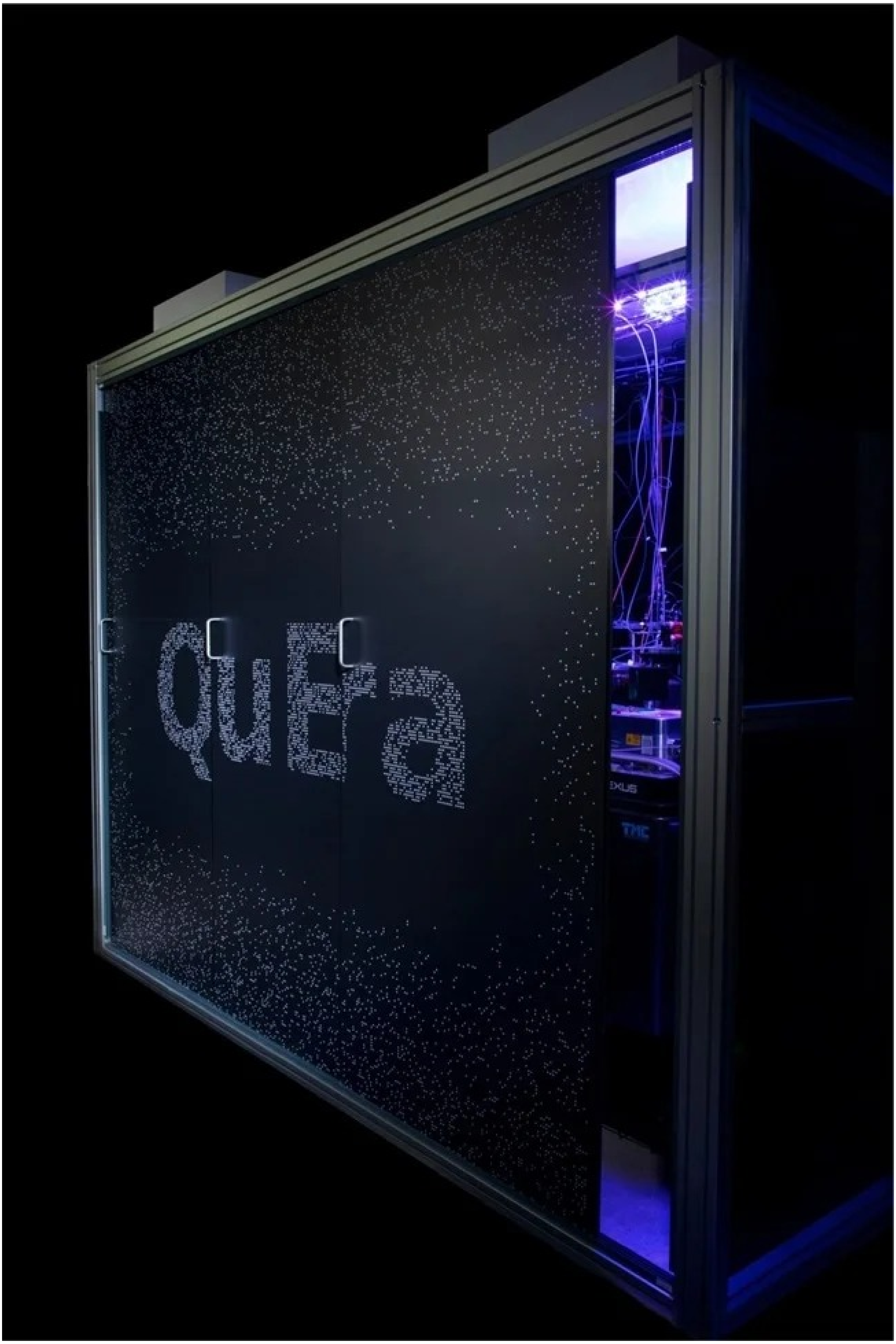

QuEra

Image Credit: QuEra

What are the next major milestones for the industry, both in terms of hardware advancements and software development?

Progress hinges on advancing both hardware scale and software usability. Key milestones include:

- Building larger, error-corrected systems with better logical qubits
- Refining quantum algorithms to solve real-world problems
- Integrating quantum with classical HPC systems for hybrid computing
- Growing the quantum talent pipeline through education and accessibility

QuEra's roadmap is strongly aligned with these goals.

As quantum computing continues to evolve, what do you think will be the defining breakthroughs in the field over the next five to ten years?

From a business perspective, the value of quantum computing lies in its ability to tackle problems that are either beyond the reach of today's classical computers or so resource-intensive that solving them classically becomes prohibitively expensive. In some instances, quantum processors could deliver answers more quickly, or with significantly lower energy consumption, leading to cost savings and more sustainable computational strategies. Among the industries most likely to see breakthroughs first, chemistry and materials science stand out. Within the next three to five years, we may see quantum algorithms that expedite the discovery of new catalysts, streamline drug development, or enable the design of advanced materials with highly tailored properties.

Neutral-atom platforms are particularly well suited to a wide range of algorithmic approaches and computational challenges. QuEra stands at the forefront of both the scientific and commercial development of neutral-atom quantum technology, actively driving the field with larger qubit counts, improved error correction, and novel algorithms. As a result, neutral-atom processors—and QuEra's systems, specifically—are poised to play a central role in delivering real-world breakthroughs.

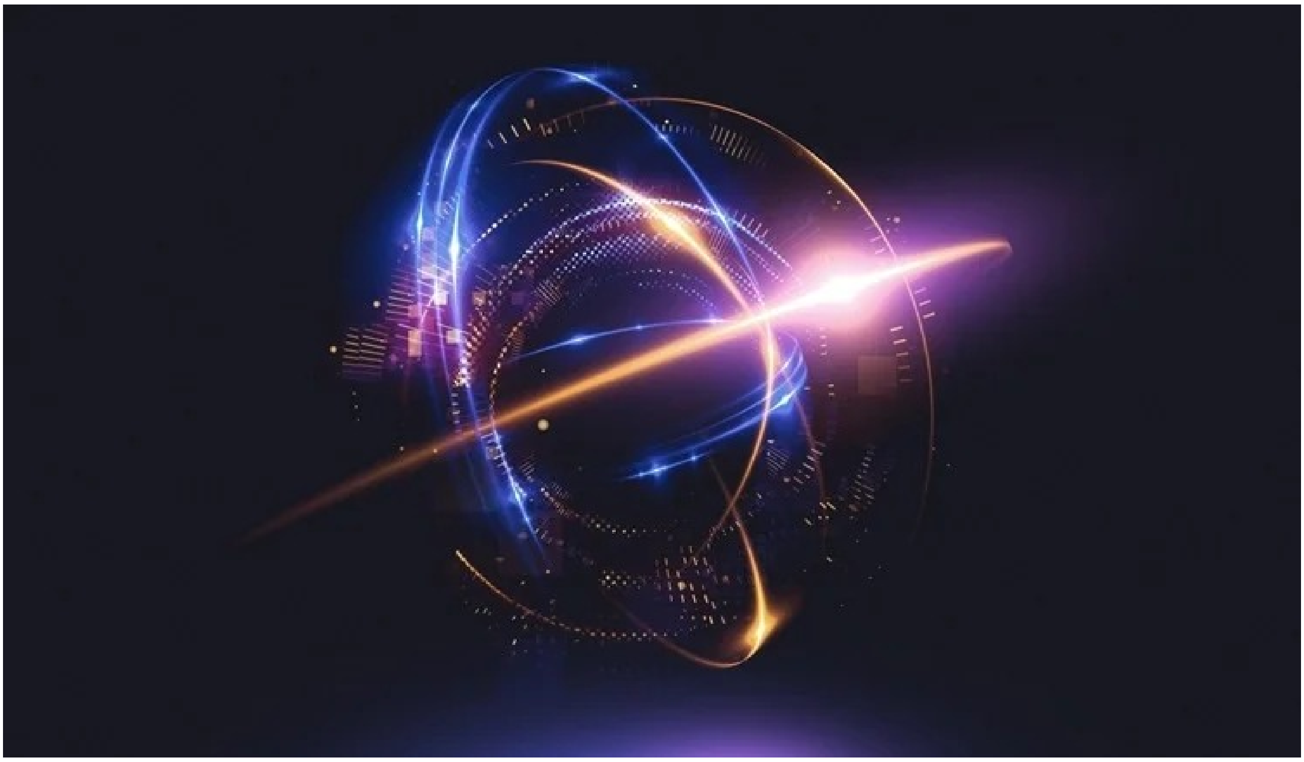
Check how to make quantum computing greener here

About the Speaker

Yuval Boger is the chief commercial officer of QuEra, the leader in neutral atom quantum computers. In his career, he has served as CEO and CMO of frontier-tech companies in markets including quantum computing software, wireless power, and virtual reality. His Superposition Guy's Podcast hosts CEOs and other thought leaders in quantum computing, quantum sensing, and quantum communications to discuss business and technical aspects that impact the quantum ecosystem.

Electron Orbital Angular Momentum and the Rise of Orbitronics

Electron spin has driven quantum technology development for decades, but researchers are now focusing another property: orbital angular momentum (OAM). OAM refers to the wave-like spatial distribution of an electron's motion, offering quantum degrees of freedom that go beyond the binary nature of spin. This article explores recent progress in manipulating electron OAM, its potential applications in quantum computing and spintronics, and how this growing field is beginning to take shape commercially.



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Orbital vs. Spin: Expanding the Quantum Toolkit

Every electron possesses two forms of angular momentum, Spin Angular Momentum (SAM) and Orbital Angular Momentum (OAM), with each having distinct characteristics. Spin Angular Momentum (SAM) is an intrinsic property similar to a top spinning on its axis, typically existing in binary "up" and "down" states. Orbital Angular Momentum (OAM), on the other hand, relates to the spatial distribution of the electron's wave function, characterized by a phase gradient that creates a twisting motion through space.[1,2]

This distinction creates new possibilities for quantum information processing. The binary nature of spin forms the foundation of qubits, but OAM can take on multiple discrete values.

This enables the creation of qudits: quantum units that exist in three, four, or more levels. These multi-level systems can encode more information per particle, thereby boosting efficiency and security in quantum cryptography.[3]

The spatial characteristics of OAM states also provide different noise resilience properties compared to spin states. Combining OAM with spin-orbit coupling produces phenomena like the spin-orbital-Hall effect, where charge currents generate both spin and orbital angular momentum currents in materials.[1]

Recent Advances in OAM Control

Practical control of OAM has progressed mainly through two key approaches: shaping electron beams externally and leveraging the intrinsic properties of materials.

External control methods have achieved notable precision. Researchers have created electron vortex beams carrying OAM values up to $L = 1000\hbar$ using nano-fabricated holograms and phase plates, enabling detailed probing of material electronic and magnetic properties.[4] These high-OAM beams serve as sensitive tools for studying quantum materials and their responses to twisted electron states.

Intrinsic OAM generation represents a parallel track in this development, focusing on materials that naturally induce orbital angular momentum without the need for external beam shaping. Studies of chiral topological semimetals, including platinum gallium (PtGa) and palladium gallium (PdGa), have demonstrated controllable "OAM monopoles". These are essentially localized sources of orbital angular momentum that are embedded directly within the material's electronic structure. Using circular dichroism in angle-resolved photoelectron spectroscopy (CD-ARPES), researchers showed that these monopoles' polarity can be controlled by altering the crystal's structural handedness.[5] This approach eliminates the need for external magnetic fields, simplifying device architectures.

Applications in Quantum Computing and Spintronics

OAM integration into quantum systems addresses several technical challenges. In silicon qubits, spin-orbit coupling effects can extend coherence times to 10 milliseconds, compared with shorter durations in conventional spin-only systems.[6] In superconducting circuits, OAM states could provide additional control mechanisms for qubit manipulation and error correction, though experimental demonstrations remain limited. This improvement arises from OAM's ability to create topologically protected states that resist certain types of environmental decoherence.[7]

Multi-level qudits enabled by OAM offer computational advantages through increased information density and natural error correction mechanisms. Systems with more quantum levels can implement certain algorithms more efficiently and provide redundancy against quantum errors.[3]

The spin-OAM interaction also enables new types of quantum logic gates. Demonstrations of OAM-assisted spin-directional coupling in photonic circuits show potential for on-chip quantum operations that leverage both angular momentum types simultaneously.[8]

Commercial and Industrial Development

Technology companies are beginning to explore OAM applications. IBM and Microsoft Quantum are investigating how OAM properties might enhance quantum system performance, while research institutions like QuTech are studying OAM integration into quantum key distribution networks. Companies such as Riverlane are examining how quantum algorithms and error correction protocols might adapt to hardware that utilizes OAM states.

Hardware development is progressing alongside theoretical work. Photonic integrated circuits designed specifically for OAM mode generation enable parallel quantum communication channels (Zahidy et al., 2021).[9] Vertical-cavity surface-emitting lasers (VCSELs) provide efficient OAM beam generation for optical applications (Li et al., 2015).[10] Patent activity in OAM multiplexing technologies indicates growing commercial interest, with significant patent filings in recent years, though most applications remain in research phases (Liu et al., 2020).[11]

Technical Challenges and Future Directions

Several obstacles limit current OAM implementations. Maintaining coherence of OAM states against environmental noise remains difficult, particularly in solid-state systems.[7] Accurately measuring and distinguishing different OAM states requires precision beyond current detection capabilities, though machine learning approaches show promise for improving state recognition from noisy data.[12]

Research efforts are addressing these limitations through multiple approaches. The HOBBIT system demonstrates rapid, tunable OAM generation for experimental studies (Li et al., 2019).[13] Theoretical work continues to explore fundamental limits of OAM-based quantum communication and computation.

Long-term applications may include OAM-enhanced quantum sensors capable of detecting subtle electromagnetic fields, with applications in medical imaging and navigation. However, significant technical development remains necessary before these applications become practical. As researcher Yen noted in their recent Nature Physics study, "The potential of OAM in enhancing quantum memory and sensor capabilities requires overcoming substantial technical hurdles in coherence and readout precision".[5]

What's Next for Orbitronics?

Research into electron orbital angular momentum is moving beyond fundamental studies and edging closer to practical applications. Recent progress in both externally generated OAM and material-based intrinsic control is opening up new ways to explore quantum systems with expanded degrees of freedom. While challenges remain, such as maintaining coherence, improving readout precision, and scaling devices, ongoing work in materials science, device engineering, and quantum algorithm development is steadily tackling these hurdles.

The field's development will likely determine whether OAM-based systems complement or enhance current quantum technologies, rather than replacing them entirely. Success will depend on overcoming technical hurdles and identifying applications where OAM's unique properties provide clear advantages over existing approaches.

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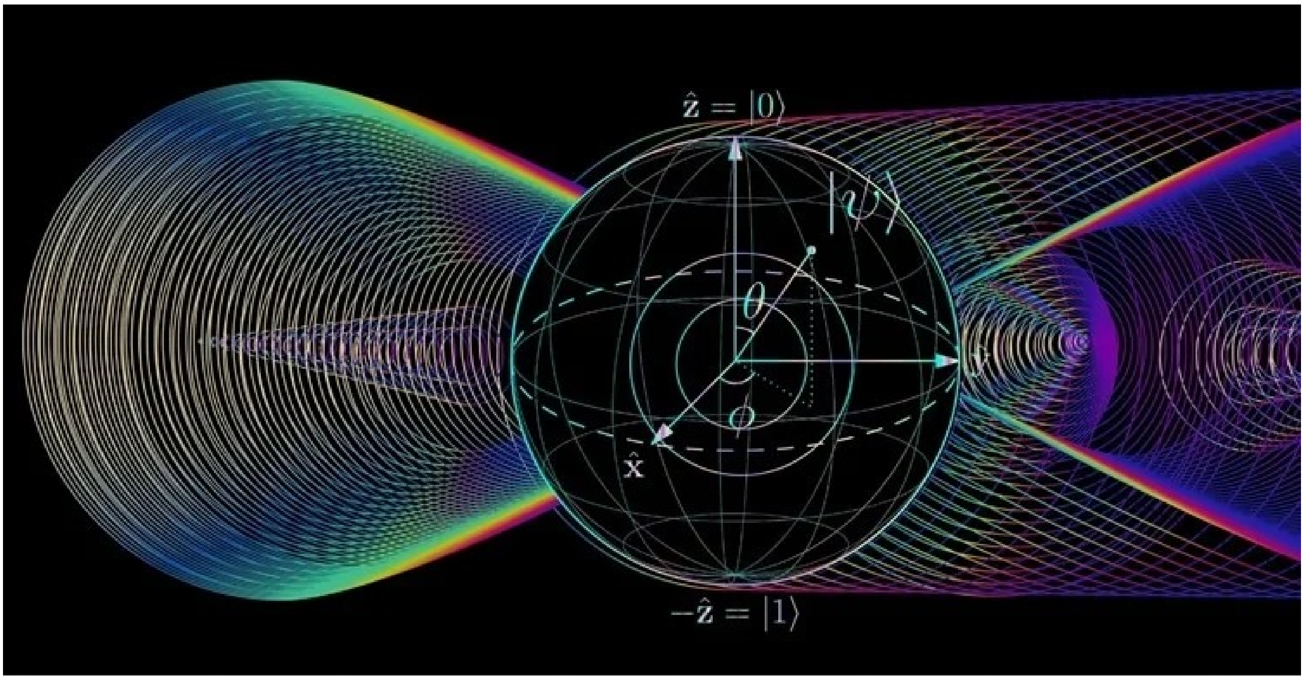
How Gravity Influences Qubits

Quantum computing relies on the precise control of delicate quantum states, such as superposition and entanglement, to achieve computational advantages beyond classical systems. However, maintaining these states is challenging due to environmental interactions that cause decoherence.



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While extensive research has addressed environmental factors like electromagnetic interference and thermal noise, the influence of gravitational fields on qubits has recently gained interest. Unlike other sources of decoherence, gravity cannot be shielded, which raises a critical question: Could gravity serve as a tool rather than a hindrance in quantum computing?

Understanding Qubits and Quantum States

A qubit is the fundamental unit of quantum information, similar to classical bits but capable of processing more complex information. Unlike classical bits, which exist as 0 or 1, qubits can exist in superposition, simultaneously representing multiple states, significantly enhancing computational power. Qubits can also become entangled, establishing correlations between their states regardless of distance, further increasing computational capacity.

However, these advantages come with extreme sensitivity to environmental disturbances, leading to decoherence, where quantum states degrade due to interactions with external factors like temperature fluctuations or electromagnetic interference.

Therefore, quantum systems are typically isolated in environments with extreme cooling or high-vacuum conditions to minimize the effects of noise and preserve coherence.[1,2,3]

Gravitational Effects on Qubits

Once largely overlooked, the gravitational impact on qubits is now recognized as a major factor affecting their phase coherence and stability. According to Einstein's general theory of relativity, gravity manifests as spacetime curvature, altering the evolution of quantum states. This curvature influences time progression and spatial structure, leading to measurable phase shifts in qubits subjected to gravitational fields.[4]

Gravitational fields also induce time dilation and redshift, causing small phase shifts in qubit evolutions leading to decoherence. These shifts occur as variations in proper time within a gravitational field cause qubits at different positions to evolve at different rates, contributing to the loss of coherence and interfering with precise quantum operations. Even in Earth's relatively weak gravitational field, quantum interference experiments have detected measurable deviations in phase evolution, highlighting the challenges gravity poses for maintaining qubit stability.[5]

Experimental Tests of Gravitational Effects on Quantum Entanglement

Researchers are investigating the effects of gravitational fields on quantum entanglement.

In a study published in *Science*, research conducted the first space-based test on the Micius Quantum Satellite for gravity-induced decoherence in entangled states. While no deviations from standard quantum mechanics were observed, future missions at higher altitudes aim to explore stronger gravitational variations.[6]

Similarly, the University of Science and Technology of China researchers probed quantum spin coupling to Earth's gravitational field with 6000 times greater sensitivity than previous studies, refining theoretical models by constraining potential spin-gravity interactions that could affect qubit coherence and entanglement.[7]

These findings highlight the challenges and opportunities gravitational effects pose for quantum technologies.

While gravitational time dilation induces decoherence by coupling internal energy states with center-of-mass motion, disrupting quantum computing, sensing, and metrology, it also offers a unique avenue for probing quantum gravity in low-energy regimes.

This could enable tests of fundamental physics without extreme astrophysical conditions, potentially revealing new aspects of quantum gravity.[6,7,8]

Quantum Computing Hardware in a Gravitational Field

Different qubit technologies exhibit varying sensitivities to gravitational perturbations, necessitating potential shielding or compensation techniques in future quantum devices.

Superconducting qubits experience small gravitationally induced frequency shifts, which if unaccounted for, could impact quantum error correction and computation fidelity. For instance, a 1 cm vertical displacement causes an undetectable single-qubit frequency shift of 10^{-18}, but in multi-qubit systems, accumulated relative shifts make gravitational dephasing a critical factor in large-scale quantum computing.

Trapped-ion qubits may accumulate differential gravitational phases, but their minimal spatial separations likely keep these effects negligible. Photonic qubits may experience gravitational redshift and bending over free-space paths, though their impact in integrated circuits is minimal, while spin qubits may exhibit weak gravitational coupling, as suggested by experimental bounds.

To mitigate these effects, gravitational shielding or compensation techniques—such as adaptive calibration, engineered potential gradients, or algorithmic error correction—may become essential for maintaining qubit stability and enabling high-fidelity quantum operations in next-generation quantum devices.[4,9]

Quantum Computers in Space-Based Environments

Space-based quantum computing presents an alternative environment where minimal gravitational influence could improve qubit coherence. For example, experiments on the International Space Station have shown enhanced atomic clock stability in microgravity, suggesting similar benefits for quantum processors through reduced dephasing and extended coherence times.[10]

Gravity as a Tool for Quantum Sensing

The unique sensitivity of quantum systems to gravitational influences opens an intriguing pathway to a new class of sensing applications that harness rather than avoid these effects.

Quantum gravitational sensors capitalize on this sensitivity by detecting subtle variations in gravitational potential through frequency shifts experienced by qubits under gravitational acceleration.

These sensors utilize atom interferometry, where ultra-cold atoms like rubidium or cesium are cooled to near absolute zero and manipulated with laser pulses to create spatially separated wavefunctions. As these wavefunctions traverse different gravitational potentials, they accumulate phase shifts that encode precise information about local gravitational variations.

Unlike conventional gravimeters, these sensors rely on atomic reference systems, offering long-term precision for applications in geophysics, infrastructure monitoring, and fundamental physics research.[4]

Potential Applications

Quantum gravimeters leverage entangled qubit states to measure gravitational phase shifts with exceptional accuracy, potentially achieving $\delta g/g \sim 10^{-7}$ local gravitational acceleration, while quantum strain sensors detect minute mechanical deformation by measuring interqubit distance variations.[4]

In civil engineering, these sensors passively map subsurface structures, such as tunnels and buried infrastructure, without emitting signals, enhancing safety and efficiency in structural assessments. In military applications, these sensors could provide tools for detecting underground installations, as gravitational fields cannot be shielded. They also show promise for secure navigation systems relying on gravitational mapping instead of external signals, mitigating GPS spoofing risks.[11]

Beyond these applications, quantum gravitational sensors could reveal new insights into the interplay between general relativity and quantum mechanics. The SUPREME-GQ mission exemplifies this potential by using atom interferometry and entanglement to test equivalence principle deviations with unprecedented precision, potentially refining gravitational measurements to 10^{-20} and directly probing quantum gravity models.[12]

Future Prospects and Challenges

Harnessing gravity for quantum computation faces challenges due to the incompatibility between quantum mechanics and general relativity, with gravitational time dilation inducing decoherence and computational errors.

Recent research suggests gravity may emerge from quantum relative entropy, offering potential integration pathways, though practical implementation remains complex.[13] Despite these challenges, gravitationally controlled environments could optimize quantum computing by stabilizing quantum states and mitigating time-dilation-induced decoherence.

Recent research is focused on addressing these challenges and advancing our understanding of quantum-gravitational interactions, potentially bridging the gap between quantum mechanics and general relativity.

For instance, recently, researchers proposed various experiments to detect individual gravitons—the hypothetical quantum particles of gravity—by cooling massive aluminum bars to near absolute zero and employing continuous quantum sensors to observe minuscule vibrations caused by gravitational waves.[14] Additionally, scientists have successfully measured weak gravitational forces acting on tiny particles, bringing us closer to reconciling gravity with quantum mechanics.[15]

These findings suggest that as research progresses, gravitational interactions, long considered obstacles in quantum systems, could instead serve as tools for advancing fundamental physics and quantum technology, potentially unlocking new computational solutions, enhancing precision sensing, and providing crucial insights into the nature of spacetime.

Keep reading about advancing quantum stability here

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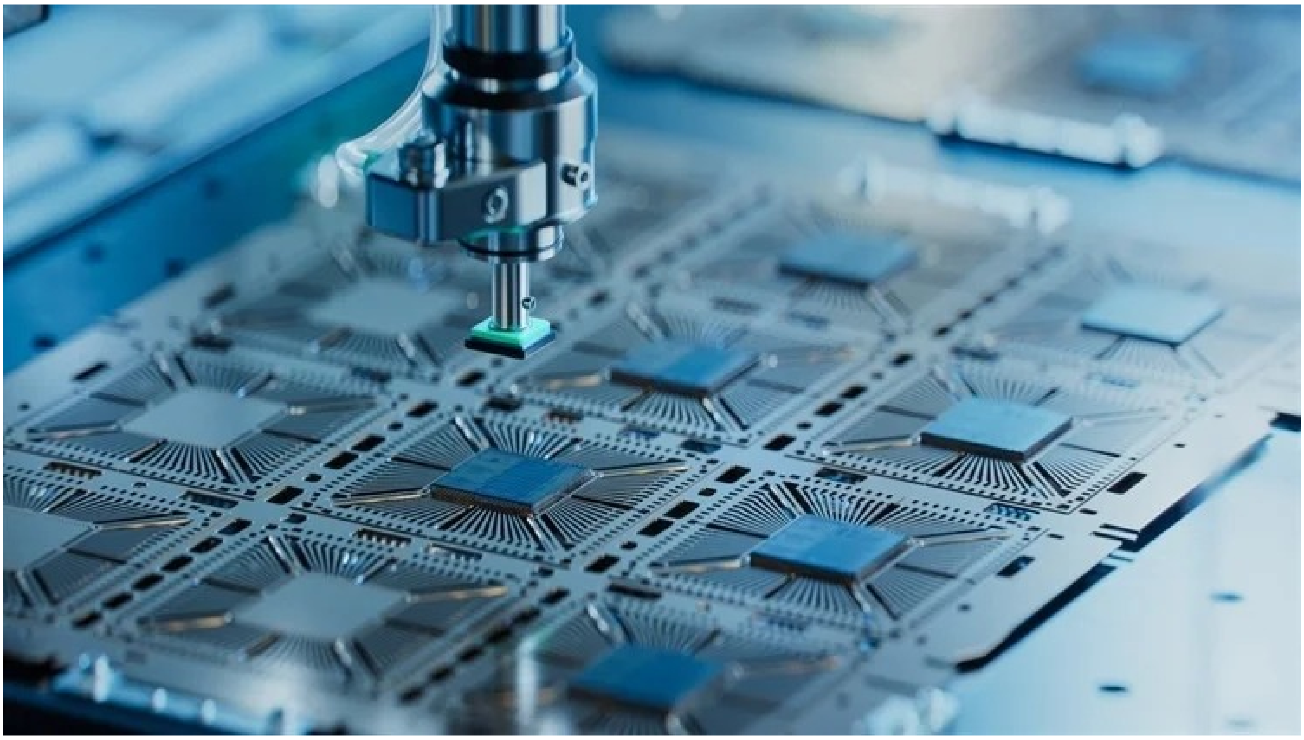
How Do Semiconductors Work? A Quantum Mechanical Perspective

Semiconductors are materials whose electrical conductivity falls between that of conductors and insulators, an essential property that makes them the foundation of modern electronics. Although classical physics describes some aspects of their behavior, it does not fully account for key phenomena such as the formation of energy bands, the controlled conduction under specific conditions, or the mechanisms behind devices like flash memory and LEDs. From a quantum mechanical perspective, these properties are explained by how electrons occupy conduction and valence bands within a crystal lattice, how they can tunnel through potential barriers, and how quantum confinement effects become increasingly important at the nanoscale.



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What Makes a Semiconductor?

Semiconductors are crystalline materials where atoms arrange in regular, repeating patterns called crystal lattices.[1] Silicon, a commonly used semiconductor, forms a diamond cubic structure where each atom bonds covalently with four neighbors. This atomic arrangement creates the specific electronic properties that distinguish semiconductors from other materials.

Understanding semiconductor behavior involves energy bands. In isolated atoms, electrons occupy discrete energy levels, but when atoms combine in a crystal, these levels split and merge into bands. The valence band contains electrons bound to atoms, while the conduction band contains free electrons that can carry electrical current. The energy gap between these bands, the bandgap, determines whether a material behaves as a conductor, semiconductor, or insulator.

Pure semiconductors have bandgaps typically between 0.1 and 4.0 electron volts (eV). When energy is applied through heat or light, electrons can jump across this gap into the conduction band, enabling controlled current flow. In conductors, overlapping bands allow electrons to flow freely, while insulators have large bandgaps that prevent conductivity.[2] This intermediate conductivity between conductors and insulators makes semiconductors useful for electronic devices

Quantum Mechanics behind Semiconductor Behavior

Classical models cannot fully explain electron behavior within semiconductors. Electrons in a crystal behave as waves described by wavefunctions, which define their probable locations and energy states. This wave nature creates the conduction and valence bands shaped by the periodic lattice potential.[3, 4]

The Pauli Exclusion Principle ensures that no two electrons can occupy the same quantum state, determining how electrons fill available energy levels. At any given temperature, electrons arrange themselves according to Fermi-Dirac statistics, which influence a material's conductivity and thermal properties.[3, 4]

Additionally, quantum tunneling represents a particularly important effect where electrons can move through energy barriers they could not overcome classically. This phenomenon is fundamental to flash memory operation and quantum dot devices. As device dimensions shrink to the nanoscale, quantization effects become significant, creating discrete energy levels in nanostructures that enhance optical and electronic functionality.[5, 6]

Doping and Charge Carriers

Pure semiconductors have limited conductivity because few electrons possess sufficient thermal energy to reach the conduction band. Doping involves adding controlled amounts of impurity atoms to create additional charge carriers. Donor atoms like phosphorus in silicon provide additional electrons, resulting in n-type materials with Fermi levels closer to the conduction band. Acceptor atoms like boron create holes, leading to p-type semiconductors with Fermi levels nearer the valence band.[7]

Higher doping concentrations increase charge carriers but can reduce their mobility due to impurity scattering. In nanoscale devices, quantum effects become more prominent as impurity energy levels may become pinned, altering binding energies and affecting carrier dynamics. This precise control of carrier type and concentration enables the development of diverse semiconductor devices.[8]

Semiconductor Devices and Quantum Functionality

The p-n junction forms the basis of most semiconductor devices. When p-type and n-type materials are joined, electrons diffuse from the n-side to the p-side which creates a depletion region with an electric field. Quantum tunneling influences how electrons cross the junction, determining the current-voltage behavior critical to diodes and LEDs. As devices scale down, band-to-band tunneling becomes an essential mechanism in silicon transistors.[9]

Under forward bias, external voltage reduces the barrier height, allowing current to flow. Reverse bias increases the barrier, blocking current flow except for small leakage current. This rectifying behavior enables diodes to convert alternating current to direct current.

Modern transistors rely on band manipulation and quantum effects for operation. Devices like high-electron-mobility transistors (HEMTs) and single-electron transistors leverage quantum confinement to control current more precisely.[10] Tunnel FETs, which operate through tunneling rather than thermal excitation, offer reduced power consumption as traditional MOSFETs approach scaling limits.[11] These advances demonstrate how quantum mechanics both explains semiconductor behavior and drives design innovation.

Real-World Applications and Technologies

Semiconductor physics impacts numerous technologies. Microprocessors containing billions of transistors rely on quantum-aware design to maintain performance. Optoelectronic devices, including laser diodes and solar cells, exploit direct bandgap materials for efficient light emission and absorption.[1]

Quantum computing extends these applications further. IBM explores superconducting qubits and quantum algorithms, while Intel investigates silicon-based spin qubits to integrate quantum devices with established chip manufacturing. TSMC, a major chip foundry, supports this research by exploring scalable quantum processor fabrication. These initiatives demonstrate how quantum mechanics serves both as an explanatory tool and a design driver for future technologies.[12, 13, 14, 15]

Future Developments in Quantum Semiconductor Technology

Emerging technologies aim to harness quantum properties more directly. Quantum dots, nanocrystals with quantized energy levels, are being studied for logic circuits, including quantum dot gate FETs (QDGFETs) that enable multi-valued logic and charge storage. Optical control of these dots shows potential for scalable quantum computing, using exciton or electron spin states as qubits.[16, 17]

Two-dimensional (2D) materials like graphene and molybdenum disulfide (MoS_2) offer distinctive electrical and optical properties, including strong spin-orbit coupling and potential for quantum entanglement. These features make them candidates for next-generation, energy-efficient quantum devices.[18]

However, significant challenges remain. Producing uniform, defect-free quantum dots and 2D materials at scale is technically demanding. Integrating them into dense circuits adds complexity, and for quantum computing, decoherence poses an obstacle. Decoherence occurs when qubits lose their delicate quantum superposition states through interactions with their environment, as vibrations from neighboring atoms, electromagnetic fields, or temperature fluctuations can cause a qubit to collapse from being simultaneously in multiple states to a single classical state within microseconds. This environmental sensitivity makes it extremely difficult to maintain the quantum properties necessary for computation long enough to perform useful calculations.

Outlook

Semiconductors demonstrate the integration of material science and quantum mechanics through electron control in silicon lattices and manipulation of quantum tunneling and spin states. As research addresses challenges like decoherence and defect control, these materials are advancing beyond classical devices toward quantum processors and logic circuits. The connection between quantum theory and engineering applications enables semiconductors to contribute to developments in computing, communication, and technology.

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Quantum Computing Changes the Game for Low-Carbon Building Operations

Decarbonizing the built environment, a major contributor to global carbon emissions, is vital in the push toward net-zero goals. Amongst several emerging and innovative technologies reshaping the construction industry, quantum computing is gaining attention for its potential use in areas such as building operations.

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Quantum computing offers significantly greater processing power compared to conventional binary-based computing systems, presenting promising opportunities to the smart, low-carbon buildings of the future. Quantum optimization and energy modeling, for instance, can significantly impact building operations, opening up new possibilities for design and efficiency.

Why Decarbonizing Building Operations is a Challenge

Decarbonizing the built environment is highly challenging, but essential to reach net zero carbon emissions targets. The construction sector contributes nearly 40% of global CO_2 emissions, according to the United Nations Environment Program and other experts. Concrete and steel use alone, for instance, emits around 18% of global emissions. Moreover, the sector produces significant amounts of waste.[1]

Aside from the carbon emissions caused by the building materials themselves and carbon-intensive construction practises, key challenges include operational inefficiencies and energy management once a building enters its service life. For instance, everyday emissions from areas such as lighting and heating account for around 70% of a building's total emissions.[2] Energy-intensive air conditioning in the summer and heat loss during the winter are also major contributors to a building's carbon footprint.

Current solutions like smart grids and advanced energy modelling, powered by artificial intelligence and machine learning, are already helping to address these challenges and reduce the carbon footprint of buildings. Quantum computing can help to complement these transformative technologies.

The Promise of Quantum Computing in Optimization

Quantum computing offers benefits across a slew of industries and scientific fields, thanks to its super-polynomial processing capabilities that far exceed those of classical computing. Whereas a conventional computer can only perform calculations in binary, quantum computers use superposition to perform calculations using qubits in multiple states at once. Building energy management and optimization systems that incorporate quantum computing will be much more efficient than traditional systems.

Quantum computing holds strong potential for a variety of building management applications. More optimized HVAC systems are possible as quantum computing aids in their design, overcoming issues such a network generation - a task that's computationally intensive for traditional systems. Additionally, building-wide energy management can be enhanced using quantum computing, for instance by integrating of distributed energy resources.

Processes such as quantum annealing, which is an optimization process in quantum computing, are relevant to operation management in smart buildings. By rapidly identifying optimal configurations for energy usage, HVAC scheduling, or lighting control, quantum annealing can help reduce waste and lower carbon emissions, contributing to more sustainable building operations. Hybrid classical-quantum computing systems are also gaining traction, combining the strengths of both approaches to tackle complex problems more efficiently.

Emerging Research and Pilot Projects

Emerging research and pilot projects are exploring how quantum computing can be integrated with energy management and building operations.

Recent research published in *Engineering* demonstrated how quantum computing can be applied to support sustainability goals in energy management and building operations. A team from Cornell University developed a strategy that incorporates model predictive control that can be used in buildings equipped with renewable energy and battery storage.[3]

The project was demonstrated on buildings at Cornell University, achieving a 41.2% carbon emissions reduction. Furthermore, the research team noted that their technology could offer opportunities for commercial scalability, even with limited quantum computing resources.

D-Wave have also employed quantum computing for sustainable building design. In collaboration with partners such as QuantumBasel and VINCI Energies, D-Wave have produced innovative quantum-based solutions for HVAC design optimization, reducing the carbon footprint of buildings.[4] The project helps engineers overcome what is known as the network generation process, which is typically very computational resource-heavy and expensive.

Additionally, companies like IBM are working on innovative near-term applications for quantum computing strategies in this area of research.

Real-World Use Cases and Industry Perspectives

Quantum computing isn't just being explored in research settings: it's also being applied in real-world efforts to tackle sustainability challenges. Quantum sensors and quantum machine learning are increasingly being integrated into new construction projects. Technologies like the Internet of Things (IoT) are enhancing the benefits of quantum and quantum hybrid solutions.

Honeywell have made inroads into this emerging construction industry field with their Advance Control for Buildings platform. Honeywell's quantum solutions have already been applied in the real world, helping to enhance energy efficiency at a smart university in Dubai.[5] Energy of up to 10% were made possible by using the company's expertise and technology.

Current Limitations and Technical Hurdles

Most current solutions rely on hybrid classical-quantum computing technologies. Key technical challenges include scalability, the high cost of emerging quantum technologies (both financially and in terms of computing resources), decoherence, and limited access to hardware

However, as quantum computing continues to advance and becomes more commercially accessible, many of these obstacles could be addressed in the near future. This progress holds promise for broader adoption of quantum technologies in real-world smart building management applications.

Future Prospects for Low-Carbon Innovation

Quantum systems such as algorithms, quantum machine learning, and quantum-enabled sensor networks can have a positive impact on the energy efficiency and carbon footprint of smart buildings by being incorporated into building management systems. This could enable carbon-neutral building ecosystems, both in new builds and by retrofitting existing structures with new quantum capabilities.

Furthermore, emerging quantum-enhanced digital twins and energy simulations can help to design new, more energy and resource-efficient HVAC networks, for example. Quantum-enhanced digital twins could also hold the potential for enhanced predictive maintenance in the smart buildings of the future.

The smart building market is bound to undergo steady growth over the next decade, with the commercial sector driving growth.[6] Energy management systems are seeing growing adoption as part of broader sustainability efforts. The arrival of affordable, commercially scalable quantum computing is likely to make a significant impact on this sector, opening up new possibilities for optimization and efficiency at scale.

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