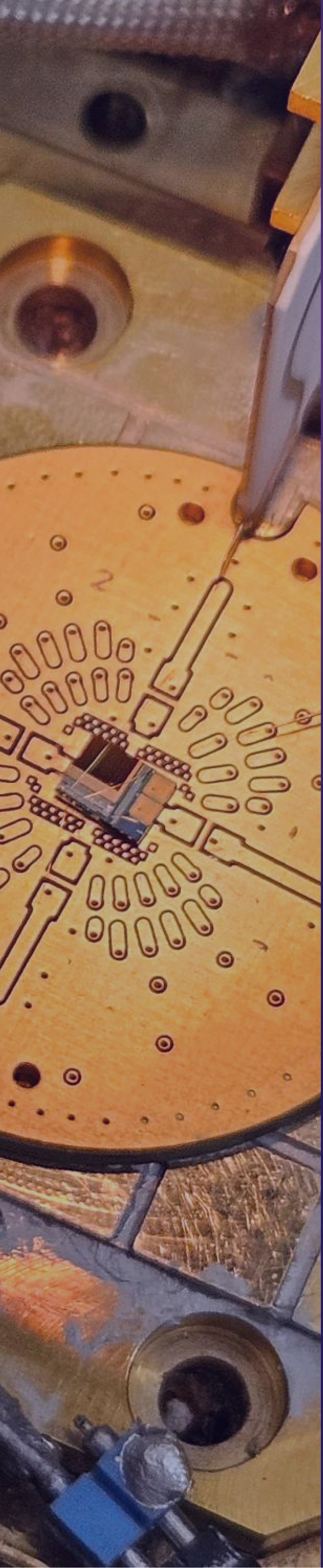

quobly

The future of quantum
starts with silicon.

THE MOST EFFICIENT PATH TO SCALING QUANTUM

WHY QUOBLY BELIEVES IN SILICON SPIN QUBITS

MAUD VINET, CEO & TRISTAN MEUNIER, CTO

At Quobly, we have charted an achievable path toward a scalable quantum computer based on our silicon spin qubit technology. Based on our own research, our conviction is that the same very-large-scale integration (VLSI) processes used to manufacture classical processors can be used to build large-scale quantum integrated circuits efficiently and cost-effectively in existing semiconductor fabs.

August 2024

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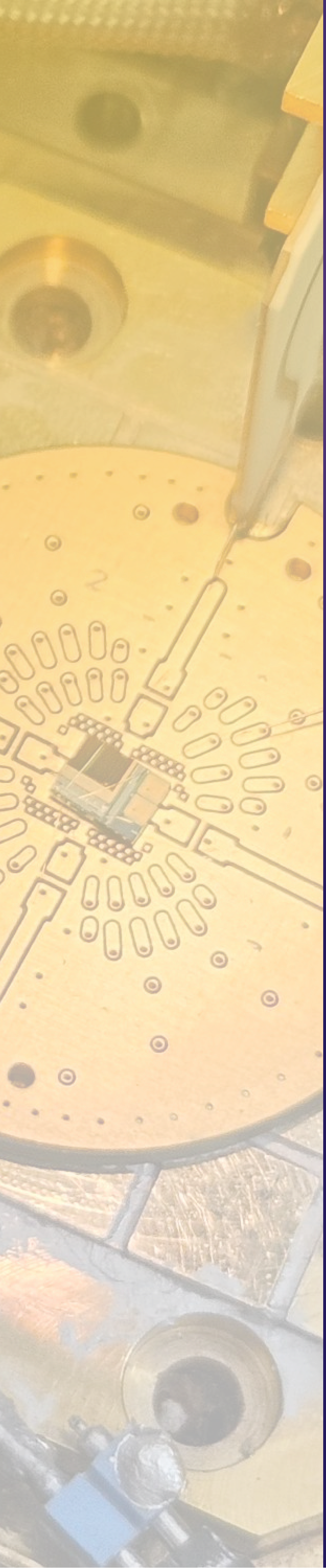

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VLSI: our path to scaling up silicon spin qubits

At Quobly, we have charted an achievable path toward a scalable quantum computer based on our silicon spin qubit technology. We are committed to explaining our technological choices simply, clearly, and realistically to all quantum computing stakeholders. Based on our own research, our conviction is that the same very-large-scale integration (VLSI) processes used to manufacture classical processors can be used to build large-scale quantum integrated circuits efficiently and cost-effectively in existing semiconductor fabs. Here's why.

A brief history

Quantum computing is not a new idea. With decades of research on individual qubits behind it, the concept of using quantum bits to encode and compute information has been proven possible. Today, the research has shifted toward how to scale up quantum computers. In practical terms, scaling up quantum means having enough good-quality qubits to achieve what is known as quantum advantage (the demonstrated ability to solve a given real-world problem faster than a classical computer). The main hurdles to scalability are variability, noise, errors, and how to connect the many qubits within the system.

In terms of quantum computing hardware, at the time this article was written, the state-of-the-art stands at devices with 1,000-plus physical qubits—still very far from the estimated million or more that would be required to achieve quantum advantage for specific problems. Qubit and/or connectivity-intensive error correction protocols are the main reason so many qubits will be needed. The quantum hardware is only part of the future quantum stack, however.

Software will also be needed, and very substantial resources are already being invested in development across the software stack, from the lowest and intermediary levels (pulse-level gate implementations, how to decompose quantum circuits into native gates) to the highest level (integrating quantum computation into existing classical workflows seamlessly, providing computational advantage).

The million-qubit question(s)

Two fundamental questions underpin quantum scalability. The first is whether it is actually feasible to control million-qubit machines; the second is whether coherence can be maintained in machines at this scale while millions of operations are being performed. The scientific and technological challenges to building a quantum machine of this size are not to be underestimated.

However, as we will explain, at Quobly, we believe that silicon spin qubits, which are small (with a footprint under 1 μm²) and can operate at relatively high temperatures (around 500 mK and up to 1.5 K), offer significant advantages over other qubit platforms.

One of these is that conventional industrial nanofabrication capabilities—already proven for manufacturing many, many more than a million identical objects for everyday chips like those used in our smartphones and computers—would offer a faster, more cost-effective, and resource-efficient path to manufacturing a large-scale quantum machine.

An added benefit would be the co-integration of classical control circuits with quantum circuits on the same die. This would put manufacturable quantum processors with large-scale control capabilities and, eventually, embedded quantum error correction within reach.

Combined, these advantages could result in a highly competitive cost per qubit.

Things are never that simple, especially in quantum

At Quobly, we know the semiconductor industry well enough to understand how long putting a new concept into production can take. In the case of innovative CMOS modules, it is more than a decade. To scale up our technology efficiently, i.e., within a reasonable timeframe and without the billions of dollars in investments that go into scaling up new CMOS technologies, we are convinced that silicon spin qubits would need to be fabricated using only marginally modified existing semiconductor manufacturing processes. The alternative would essentially be the capital-intensive development of a whole new industry and new resource-heavy fabs to manufacture quantum devices, duplicating decades of work that have gone into achieving the massive repetition of identical processes that has led to the kinds of advances we have seen in semiconductor manufacturing.

When it comes to quantum, there is one other major difference, and that is market size. The semiconductor industry, which generated around $600 billion in revenue in 2022, is driven by huge demand for chips for consumer electronics, telecommunications, and data processing. Conservatively, quantum computing may stay a niche market, not generating enough demand, in terms of units sold, to justify investment on such a massive scale.

At Quobly, our strategy is to leverage existing manufacturing infrastructure as much as possible while addressing the fundamental differences between classical and quantum computing. The main one being that, while CMOS technologies have been optimized to deliver high current, i.e., large amounts of charges at room temperature, silicon qubits require the manipulation of single charges at low temperature. All around the globe, strategies for adapting existing CMOS technologies to the specificities of quantum are currently being explored.

Semiconductor qubits are all about tradeoffs

In silicon spin qubits, quantum information is encoded in the spin degree of freedom of a single charge (electron or hole) trapped in a quantum well (also called a quantum dot) defined by external electrostatic potential applied to gates. Therefore, most of today's research on silicon spin qubits points to the necessity for quantum dots to be defined solely by their electrostatic potential. But what is currently observed is that, sometimes, electrostatic disorder interferes with the definition of the electrostatic potential solely by gate voltage. The disorder potential can be induced either by charges in dielectrics or at the interfaces, or by defects in the semiconductor materials. Currently, the disorder can be too high to ensure precise control of the charge position. In practical terms, controlling charge position and, therefore, the deterministic position of the quantum bits, means reducing the amplitude of the disorder potential compared to the potential induced by the gate voltage. This tradeoff is a major figure of merit in semiconductor quantum devices.

In terms of the number of qubits, the most advanced developments are currently happening in academic research labs and are based on Si/Ge heterostructures to ensure robust quantum dot definition. While these systems, which open a very effective window for electrostatic charge manipulation in quantum dot arrays, are of high interest for initial scientific demonstrations, they bump up against some very real limitations in terms of scalability. The main issue is that they are not directly derived from existing CMOS technology, creating the need for significant development work (defect-free epitaxial growth of the heterostructures, gate stack development, ohmic contact optimization, etc.). Overall, the sensitivity of these systems to temperatures above 750 °C, for example, where significant interdiffusion between layers occurs, would make the high-temperature annealing used in conventional CMOS processes (at more than 800 °C) impossible, or would require drastic changes to the usual process flows.

Nonetheless, these systems are effective for small numbers of qubits, and adjustments do not impact yields at this scale. It also explains why advanced CMOS R&D centers are investigating how to adapt current processes to these temperature needs. Although a 12-qubit quantum processor was recently demonstrated on an industrial pilot line, implementation at a large scale still remains impractical.

At Quobly, we believe that, despite the current performance of the approaches being explored in academic labs, a roadmap compatible with advanced CMOS technologies will get us to a scalable quantum computer fastest.

We are starting from qubit manufacturing processes that follow VLSI flows as closely as possible, and have already demonstrated that we can fabricate and operate good-quality one- and two-qubit gates. In our research, for example, we have also demonstrated that we can lower the impact of the gate dielectric interface when the back gate is used to pull the charges away from the interfaces. This has proven to be effective to reduce the amplitude of the disorder potential.

MAUD VINET, CEO

Maud Vinet is the visionary CEO of Quobly, the France-based quantum startup founded in 2022. Maud is leading the development and market launch of an operable silicon quantum processor that will leverage Europe's existing semiconductor fabs.

Her scientific career began with a PhD in Physics from Université Grenoble Alpes. Shortly thereafter, she began her tenure at CEA-Leti, a world-leading RTO specializing in semiconductor devices. While at CEA-Leti she held various positions, including a role at the helm of the advanced CMOS integration team and, starting in 2019, the leadership of the pioneering quantum computing R&D program, laying the foundation for a large-scale quantum computer based on silicon qubits.

An intellectual powerhouse, Maud has published some 300 much-cited papers and owns more than 70 patents. She was admitted into the Order of the French Legion of Honor in 2019.

A silicon spin qubit primer for the deeptech curious

To run useful quantum algorithms in a fault-tolerant manner, several ingredients will be necessary, not least of which are robust quantum gates that are not too sensitive to environmental changes and control electronics that are suitable for large-scale systems.

A closer look at quantum gates

The Loss-di Vincenzo qubit, one of the most prominent spin qubits being used in semiconductor quantum circuits, relies on a single charge trapped in a quantum dot. The underlying semiconductor band structure plays a key role in defining the qubit's spin properties and the quantum system's energy spectrum.

Because this qubit is a "spin-1/2" object (which means, in its most basic sense, that the qubit needs two full rotations, or 720°, to arrive back in its original position), the application of a magnetic field creates a canonical two-level system. This is the way we define the individual qubit.

Once this magnetic field is applied, the energy of the qubit as compared with the system's other energy levels (valley, orbital excited energy, etc.) is quite different. This means that leakage outside of the qubit space is negligible during the manipulation of the qubit.

For quantum gates to be truly functional, the minimum requirements for silicon spin qubits are:

- The existence of quantum dot arrays
- A means of controlling the dot potential and tunneling between dots
- Charge detection to probe the qubits
- Excitation antennae to enable radiofrequency magnetic manipulation of the spin

These are the "tools" used to engineer the three main quantum gates—measurement, one-qubit, and two-qubit—that form the universal set of gates. These gates are underpinned by two fundamental principles:

- Radiofrequency-driven quantum systems, which leverage techniques borrowed from nanomagnetic resonance (NMR) to write quantum information on qubits using one-qubit gates.
- The Pauli exclusion principle, which enables the strong spin-spin interaction needed for quantum entanglement and two-qubit gates.

Semiconductor spin qubits offer the added functionality of displacing qubits in a controlled manner. This is where the coherent displacement gate comes in. It makes transferring qubits between distant quantum cores possible, which could open the door to new manipulation schemes and scaling opportunities.

At Quobly, we are currently working with research partners to measure the quality of the different gate implementation methods with the goal of refining our plan for large-scale architectures.

Singularity of decoherence in spin qubits

Like with any qubit, in silicon spin qubits, decoherence is the enemy of high-fidelity quantum gates. In this kind of qubit, the choice has been made to encode quantum information in the spin degree of freedom of the charge carriers. This is because spin is largely separated from the charge properties and, therefore, protected from the strong electrical disturbances present in semiconductor devices. In addition, by using Silicon 28, a nuclear-free silicon isotope, a quasi-noiseless environment well-suited to preserving the fragile quantum information manipulated during a quantum calculation can be created. And, due to the microscopic nature of the qubit, this solid-state environment also enables exceptional coherence times. Coherence time is ultimately limited by spin relaxation time, or the time it takes for the particle's spin to decay.

The spin relaxation time has been proven to take up to several tenths of seconds for individually-isolated spin qubits. This exceptionally "long" coherence time is closely related to the relative protection of the spin degree of freedom from electrical disturbances.

Decoherence is characterized by significant asymmetry between bit flips and phase flips. Bit flips are related to the aforementioned spin relaxation processes. As stated, they have been proven to take up to several seconds. Phase flip coherence times have only been measured up to a few ms. This asymmetry is intimately related to the different processes induced by the semiconductor environment.

At Quobly, we are investigating the factors that limit spin qubit coherence from a technological point of view, and the consequences of the spin qubit noise properties on fault-tolerant quantum computing in order to optimize the complete architecture of our quantum processor.

The cryocontrol unit

The spin qubit research and development community has now demonstrated the ability to fulfill all the basic gate requirements for quantum computing. The focus has now shifted to increasing the number of qubits and engineering spin-based quantum processors at the intermediate and large scales.

Whether it is for spin qubits or for other quantum computing technologies, the question of scalability is also one that must be answered. The level of control that can be achieved and maintained at this scale is a major challenge.

The ability to engineer a control unit and a quantum system on the same chip and qubit tolerance to operating temperatures where strong cooling capabilities are available (above 100 mW) are two of semiconductor spin qubits' main differentiators. In addition, the ability to tightly integrate classical transistors and qubits reduces control and readout overhead and keeps the size of a qubit with all quantum functionalities to a minimum.

At Quobly, we are exploring ways to engineer the qubit unit with all the functionalities while keeping overall chip size down.

Bringing it all together

As stated earlier, silicon spin qubits present a unique opportunity to engineer the quantum system and the control unit on the same chip. They also offer potential tolerance for higher operating temperatures—a major differentiator considered an enabler for large-scale quantum computing and error correction implementation. While the final system architecture still needs further investigation, Quobly has devised an initial plan to scale to a 100-logical-qubit quantum processor unit.

For the time being, we are measuring the performance of the individual modules to refine their specifications. Our overall focus remains on the quantum unit itself and the potential of existing VLSI processes in Tier 1 foundries for scaling up semiconductor quantum circuits.

TRISTAN MEUNIER, CTO

Tristan Meunier is the CTO at Quobly, where his job is to make sure that the company's future quantum computer works.

An accomplished experimental physicist internationally known for his groundbreaking research on the coherent transport and manipulation of spins in quantum dot arrays, Tristan did his PhD at the Laboratoire Kastler Brossel (LKB) of the École Normale Supérieure (ENS) in Paris under the tutelage of Nobel Laureate Serge Haroche, followed by a postdoctoral fellowship at TU Delft—a pioneering center for experimental research on spin qubits. Tristan also led Grenoble's quantum spin qubit community at the French National Center for Scientific Research (CNRS) before joining Quobly as CTO full-time.

Tristan has authored or co-authored over 100 papers and owns more than 10 patents related to quantum computing with semiconductors. His Google H-index is 35, with more than 6,000 citations.

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starts with silicon.

The scalable quantum technology

The semiconductor industry perfected its manufacturing processes over decades to get to where it is today.

At Quobly, we believe that borrowing the tried and tested processes that have been used to make billions of high-performance semiconductor devices is the fastest, most efficient way to scale a quantum processor in years, not decades.

At a glance

2022

FOUNDED IN GRENOBLE, FRANCE

€21.5M

IN CAPITAL RAISED IN 2023

42+

PATENTS

Why Quobly believes in silicon spin qubits