MAKING QUANTUM COMPUTERS FROM OPPOSITE DIRECTIONS

TWO VERY DIFFERENT APPROACHES to realizing quantum computers based on silicon are being investigated under one Japanese programme.

There's never been a more exciting time to be working in quantum computers, according to Hiroyuki Mizuno, a distinguished researcher who manages the Large-Scale Silicon Quantum Computer Project at electronics manufacturer Hitachi, Ltd. in Tokyo, Japan.

"When I was a university student in the early 1990s, quantum computers were a kind of dream; and nobody imagined they would become a real product," he recalls. "But now companies like IBM are developing them. I find that very exciting — a dream come true."

Mizuno is convinced that quantum computers will revolutionize computing. "Many important problems are unsolvable using conventional computers," he says. "Quantum computers will greatly extend the range of problems that can be solved."

As an example of low-hanging fruit, he points to new possibilities for the modelling of enzyme reactions that underpin many life processes. "At the moment, we can generally only calculate the energies of the ground states of electrons in biomolecules," Mizuno says. "But for biochemical reactions, it's vital to grasp the entire energy landscape of the chemical reaction. Quantum computers could be a new tool for such calculations."

RACE TO THE MOON

However, there's still a lot more work to be done before quantum computers become sufficiently large and reliable to become commercially viable on a large scale, Mizuno points out. "While quantum computers are becoming available now, we probably won't have large-scale, fault-tolerant quantum computers until the 2040s or 2050s."

This time frame is reflected in the Japanese government's 'Moonshot Goal 6' — a project with the ambitious target of developing a "fault-tolerant universal quantum computer that will revolutionize the economy, industry and security by 2050." Mizuno and his team are working on one of the dozen projects under this Moonshot goal.

As a manufacturer of conventional computers, Hitachi is seeking to apply its expertise in silicon technologies to develop a quantum computer based on a semiconductor platform.

The attraction of silicon-based quantum technologies, says Mizuno, include a far more compact size, greater qubit stability, better compatibility with advanced fabrication technologies, and higher temperatures operation, than any of the other options.

A big advantage of semiconductor quantum computers is that the technology has already be refined in existing computers, which could prove useful as Hitachi has a lot of experience in combining different conventional-computing technologies into a single system.

"A lot of technologies are needed to make a quantum computer, including operating systems, control systems, implementation techniques and quantum chips," says Mizuno. "Our team specializes in combining these technologies into a single system — it's our strength."

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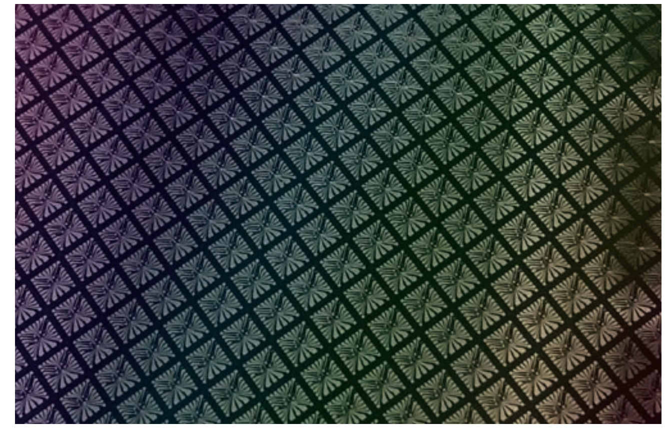
▲ **By harnessing the power of quantum physics, the quantum computers of the future will be able to solve problems that conventional computers are unable to tackle.**



▲ **Left: A quantum computer at Hitachi's research laboratory in Tokyo. Right: A silicon wafer containing qubits made at RIKEN.**

A DIFFERENT APPROACH

While silicon-based technologies are a popular platform for developing quantum computers, Mizuno's team is adopting a different approach to the vast majority of researchers. To create a useful quantum computer, it is vital to increase both the quality (fidelity) of qubits and their number. Almost all other research groups are adopting a bottom-up approach, in which they first focus on improving the quality of qubits and then try to scale up the number of qubits.

But Mizuno is tackling it in the opposite order — initially increasing the number of qubits and then trying to improve their fidelity. "We're adopting a top-down approach in order to take advantage of silicon integrated circuit technology," says Mizuno. "Integration is one of the most important features for semiconductor technologies. To exploit such features, we have to integrate many qubits before improving the quality of the qubits."

Seigo Tarucha, a group director at Japan's national research centre, RIKEN, based in Wako, near Tokyo, shares Mizuno's enthusiasm for quantum computers. "By helping to develop quantum computers, we can benefit society by providing the ability to solve complex problems, such as those involving big data," he says. "That's a huge incentive for me."

STARTING SMALL

While also working with quantum computers based on semiconductor technology, Tarucha is adopting the opposite approach to Mizuno: starting small and scaling up. "We started with just one qubit with high fidelity — more than 99.93% — and are gradually increasing the number," Tarucha says. "We're now at five and hope to achieve ten within a year, and 100 or more by the beginning of 2026."

When they reach the ten-qubit mark, the team will start plans to make the quantum computer publicly available by offering it as a cloud service.

Tarucha's lab is focusing on achieving high-fidelity quantum operations and implementing quantum error correction, both of which are critical for realizing scalable quantum computers. To date, they have achieved one- and two-qubit gates that have sufficient fidelity to implement error correction[1,2] and they have conducted quantum error correction experiments using three high-fidelity qubits — the first demonstration of error correction using silicon qubits[3].

Quantum computers based on superconductors are currently leading the field in terms of qubit number, with IBM boasting a quantum computer of 1,121 qubits in 2023. And Google has demonstrated error correction using 49 superconductor qubits.

But Tarucha is confident that silicon-based quantum computers will overtake superconductor ones within a decade or so. "We still have to develop many technologies," he says. "But I believe we can really start to accelerate development around 2030, and we will catch up or overtake superconductor technologies within about ten years of that."

INDUSTRY COLLABORATION

For Tarucha, the advantages of silicon-based technologies will ensure that they will eventually win out.

"To implement a million qubits, you need an area of 1 square metre for superconductors and a temperature of about 0.1 kelvin, which is almost impractical," says Tarucha. "In contrast, silicon qubits only require 1 square centimetre and can operate at 1 kelvin, which is vastly more feasible."

Tarucha concedes he won't be able to produce quantum computers in his lab. Rather he sees his role as pioneering the technology that commercial manufacturers such as Intel and IMEC can then run with. "We don't have the facilities at RIKEN to produce commercial quantum computers, but we can provide the technology that will underpin the quantum computers of the future," Tarucha says. His team is highly motivated to collaborate with semiconductor industries.

The fact that two very different, but complementary, approaches are being embraced within the same Moonshot project reflects the potential value of a diversity of efforts in the pursuit of fault-tolerant, universal quantum computers, which will no doubt have a profound impact on society. ■

REFERENCES

1. Yoneda, J. *et al. Nat. Nanotechnol.* **13,** 102 (2018).
2. Noiri, A. *et al. Nature* **601**, 338 (2022).
3. Takeda, K. *et al. Nature* **608**, 682 (2022).

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

www8.cao.go.jp/cstp/english/moonshot/top.html