Research team demonstrates modular, scalable hardware architecture for a quantum computer

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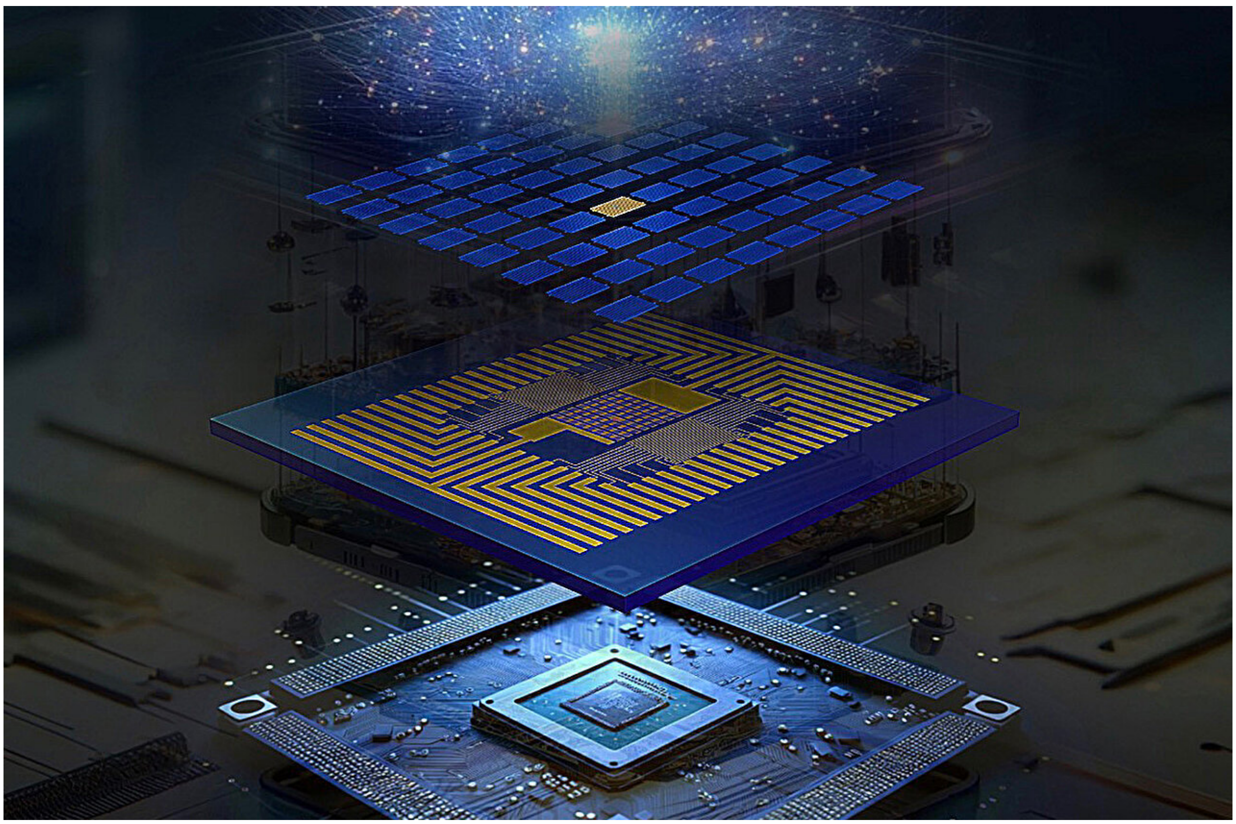

Researchers developed a modular fabrication process to produce a quantum system-on-chip which integrates an array of artificial atom qubits onto a semiconductor chip. Credit: Sampson Wilcox and Linsen Li, RLE.

Quantum computers hold the promise of being able to quickly solve extremely complex problems that might take the world's most powerful supercomputer decades to crack.

But achieving that performance involves building a system with millions of interconnected building blocks called qubits. Making and controlling so many qubits in a hardware architecture is an enormous challenge that scientists around the world are striving to meet.

Toward this goal, researchers at MIT and MITRE have demonstrated a scalable, modular hardware platform that integrates thousands of interconnected qubits onto a customized integrated circuit. This "quantum-system-on-chip" (QSoC) architecture enables the researchers to precisely tune and control a dense array of qubits. Multiple chips could be connected using optical networking to create a large-scale quantum communication network.

By tuning qubits across 11 frequency channels, this QSoC architecture allows for a new proposed protocol of "entanglement multiplexing" for large-scale quantum computing.

The team spent years perfecting an intricate process for manufacturing two-dimensional arrays of atom-sized qubit microchiplets and transferring thousands of them onto a carefully prepared complementary metal-oxide semiconductor (CMOS) chip. This transfer can be performed in a single step.

"We will need a large number of qubits, and great control over them, to really leverage the power of a quantum system and make it useful. We are proposing a brand new architecture and a fabrication technology that can support the scalability requirements of a hardware system for a quantum computer," says Linsen Li, an electrical engineering and computer science (EECS) graduate student and lead author of a paper on this architecture.

Li's co-authors include Ruonan Han, an associate professor in EECS, leader of the Terahertz Integrated Electronics Group, and member of the Research Laboratory of Electronics (RLE); senior author Dirk Englund, professor of EECS, principal investigator of the Quantum Photonics and Artificial Intelligence Group and of RLE; as well as others at MIT, Cornell University, the Delft Institute of Technology, the Army Research Laboratory, and the MITRE Corporation. The paper appears in *Nature*.

Diamond microchiplets

While there are many types of qubits, the researchers chose to use diamond color centers because of their scalability advantages. They previously used such qubits to produce integrated quantum chips with photonic circuitry.

Qubits made from diamond color centers are "artificial atoms" that carry quantum information. Because diamond color centers are solid-state systems, the qubit manufacturing is compatible with modern semiconductor fabrication processes. They are also compact and have relatively long coherence times, which refers to the amount of time a qubit's state remains stable, due to the clean environment provided by the diamond material.

In addition, diamond color centers have photonic interfaces which allow them to be remotely entangled, or connected, with other qubits that aren't adjacent to them.

"The conventional assumption in the field is that the inhomogeneity of the diamond color center is a drawback compared to identical quantum memory like ions and neutral atoms. However, we turn this challenge into an advantage by embracing the diversity of the artificial atoms: Each atom has its own spectral frequency. This allows us to communicate with individual atoms by voltage tuning them into resonance with a laser, much like tuning the dial on a tiny radio," says Englund.

This is especially difficult because the researchers must achieve this at a large scale to compensate for the qubit inhomogeneity in a large system.

To communicate across qubits, they need to have multiple such "quantum radios" dialed into the same channel. Achieving this condition becomes near-certain when scaling to thousands of qubits.

To this end, the researchers surmounted that challenge by integrating a large array of diamond color center qubits onto a CMOS chip which provides the control dials. The chip can be incorporated with built-in digital logic that rapidly and automatically reconfigures the voltages, enabling the qubits to reach full connectivity.

"This compensates for the in-homogenous nature of the system. With the CMOS platform, we can quickly and dynamically tune all the qubit frequencies," Li explains.

Lock-and-release fabrication

To build this QSoC, the researchers developed a fabrication process to transfer diamond color center "microchiplets" onto a CMOS backplane at a large scale.

They started by fabricating an array of diamond color center microchiplets from a solid block of diamond. They also designed and fabricated nanoscale optical antennas that enable more efficient collection of the photons emitted by these color center qubits in free space.

Then, they designed and mapped out the chip from the semiconductor foundry. Working in the MIT.nano cleanroom, they post-processed a CMOS chip to add microscale sockets that match up with the diamond microchiplet array.

They built an in-house transfer setup in the lab and applied a lock-and-release process to integrate the two layers by locking the diamond microchiplets into the sockets on the CMOS chip. Since the diamond microchiplets are weakly bonded to the diamond surface, when they release the bulk diamond horizontally, the microchiplets stay in the sockets.

"Because we can control the fabrication of both the diamond and the CMOS chip, we can make a complementary pattern. In this way, we can transfer thousands of diamond chiplets into their corresponding sockets all at the same time," Li says.

The researchers demonstrated a 500-micron by 500-micron area transfer for an array with 1,024 diamond nanoantennas, but they could use larger diamond arrays and a larger CMOS chip to further scale up the system. In fact, they found that with more qubits, tuning the frequencies actually requires less voltage for this architecture.

"In this case, if you have more qubits, our architecture will work even better," Li says.

The team tested many nanostructures before they determined the ideal microchiplet array for the lock-and-release process. However, making quantum microchiplets is no easy task, and the process took years to perfect.

"We have iterated and developed the recipe to fabricate these diamond nanostructures in MIT cleanroom, but it is a very complicated process. It took 19 steps of nanofabrication to get the diamond quantum microchiplets, and the steps were not straightforward," he adds.

Alongside their QSoC, the researchers developed an approach to characterize the system and measure its performance on a large scale. To do this, they built a custom cryo-optical metrology setup.

Using this technique, they demonstrated an entire chip with over 4,000 qubits that could be tuned to the same frequency while maintaining their spin and optical properties. They also built a digital twin simulation that connects the experiment with digitized modeling, which helps them understand the root causes of the observed phenomenon and determine how to efficiently implement the architecture.

In the future, the researchers could boost the performance of their system by refining the materials they used to make qubits or developing more precise control processes. They could also apply this architecture to other solid-state quantum systems.

More information: Dirk Englund, Heterogeneous integration of spin–photon interfaces with a CMOS platform, *Nature* (2024). DOI: 10.1038/s41586-024-07371-7.
www.nature.com/articles/s41586-024-07371-7