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Hitachi Proposes a New Qubit Control Method Suited to Large-Scale Integration Toward Practical Realization of a Silicon Quantum Computer

Through joint research with the Institute for Molecular Science, accelerate development of a quantum operating system

Tokyo, June 12, 2023 – Hitachi, Ltd. (TSE: 6501) today announced that it has proposed and confirmed the effectiveness of a "shuttling qubit" method for efficiently controlling qubits,[*1] aimed at practical implementation of a silicon quantum computer. The key to practical implementation of a quantum computer is to achieve high integration on a scale of 1 million qubits or more, while implementing error correction[*2] on this scale. A silicon quantum computer, the object of Hitachi's research and development, is seen as more readily scalable compared to the superconducting approach on which research is currently further along. Factors standing in the way of such large-scale integration, however, include the need to connect operation and readout circuits to all qubits, which are normally placed in a fixed location, and the occurrence of crosstalk (error) between adjacent qubits.

In the newly proposed shuttling qubit approach, areas for operation, readout, and other control are assigned in advance and qubits can be freely moved across these areas. This eliminates the need for connecting operation and readout circuits to all qubits, simplifying the silicon device interconnect structure, while also enabling the impact of crosstalk to be minimized by shuttling adjacent qubits aside during operations.

Additionally, Hitachi has begun developing a quantum operating system suited to control of a quantum computer, including one adopting the proposed technology. This development is being carried out jointly with a research group led by Professor Kenji Ohmori of the Institute for Molecular Science in the Inter-University Research Institute Corporation National Institutes of Natural Sciences (hereinafter, "Institute for Molecular Science"). This collaborative research is aimed at accelerating studies on large-scale integration toward early practical implementation of a quantum computer.

*1 Qubit: A qubit (or quantum bit) is the basic unit of information in quantum computing. Making use of the superposition principle of quantum mechanics, a qubit can represent states with both 0 and 1 in any proportion.
*2 Error correction: Technology for correcting errors occurring in the process of quantum calculation. One logical qubit is represented by multiple qubits (redundancy) and the redundant qubits are used to detect/estimate error.

■ Background to the research

In the competition to develop a quantum computer, much of the focus these days is on large-scale integration, which requires increasing the number of qubits. To realize quantum chemistry calculations such as for nitrogenase enzymes,[*3] which is attracting attention in the field of agriculture, and other such ultra-high-speed calculations that are beyond the capability of conventional computers, a quantum computer with a scale of a million qubits or more is said to be necessary. Such a large-scale quantum computer will require implementation of technology capable of efficiently controlling the integrated qubits, along with error correction technology.

While there are various approaches to quantum computing, the silicon quantum computer is able to draw on already mature semiconductor technologies, and is being looked to for its advantage in large-scale integration of qubits. Hitachi earlier developed the two-dimensional silicon qubit array,[*4] enabling silicon qubits to be integrated by arranging them in a lattice shape.[*5]

*3 Nitrogenase enzyme: Found in the root nodules of legumes, this enzyme is known for catalyzing nitrogen fixation, the reduction of nitrogen to ammonia, at room temperature and normal pressure. By clarifying this reaction mechanism, it is hoped to develop an ammonia synthesis process with low environmental load, as an alternative to the Haber-Bosch process that is currently the main industrial method for producing ammonia.
*4 Two-dimensional qubit array: A basic structure arranging qubits in a two-dimensional array.
*5 N. Lee et al., "16 x 8 quantum dot array operation at cryogenic temperatures," Jpn. J. Appl. Phys. 61 SC1040, 2022.

■ Features of the developed technology

In a silicon quantum computer, a single electron is enclosed in a microstructure called a "quantum dot" formed in a silicon device, and its spin[*6] is used as a qubit. The premise up to now has been that this qubit (electron) would not be moved outside its quantum dot. Hitachi, however, noted that in fact an electron can move inside an array, a principle it succeeded in demonstrating experimentally.[*7] Further, being able to move a qubit while maintaining its quantum state (shuttling) would bring new possibilities for operation, readout, and other control. Hitachi therefore proposed the "shuttling qubit" as a new method of control by shuttling of qubits, and verified its effect.

In a conventional silicon device with a fixed qubit location, it was necessary to connect the operation circuits and readout circuits to all qubits; but with the shuttling qubit approach, qubits can be moved to a specific area in an array and perform operation, readout, and other processing within that area. Since this eliminates the need to connect the above circuits to all integrated qubits, the interconnects and circuitry for this purpose can be reduced in the silicon device, achieving a simpler structure.

In a conventional silicon device, there was a problem of crosstalk between adjacent qubits which lowers the qubit performance, however this degradation can be minimized with the shuttling qubit method by moving adjacent qubits aside.

By building a simulator incorporating the above approach, the research group confirmed that in large-scale quantum operations that are severely affected by crosstalk, the shuttling qubit method is able to maintain high quantum calculation accuracy (fidelity) compared to the conventional approach of fixed qubits. Furthermore, since it is possible to perform operations across any qubits by shuttling them, it is expected to become easier to implement error correction functionality.

This technology has been addressed in the keynote address on June 14 at the 2023 Symposium on VLSI Technology and Circuits, held June 11 to 16, 2023.

*6 Spin: A quantum mechanics notion comparable to rotation. Two states are acquired corresponding to right and left rotation, and these are made to correspond to qubit 0 and 1 values.
*7 T. Utsugi et al., "Single-electron pump in a quantum dot array for silicon quantum computers," Jpn. J. Appl. Phys. 62 SC1020, 2023.

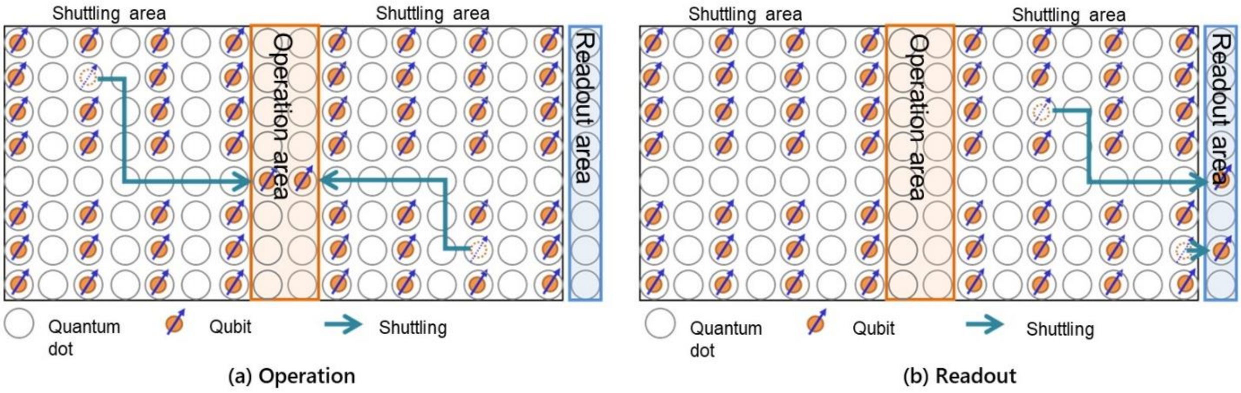

Figure 1. A "shuttling qubit" method for efficient control of qubits

This research was partly supported by a grant under the Japan Science and Technology Agency (JST) Moonshot Research & Development Program Goal 6, "Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050" (Program Director Masahiro Kitagawa), for the R&D Project "Large-scale Silicon Quantum Computer" (Project Manager Hiroyuki Mizuno; grant number JPMJMS2065).

■ Looking ahead

In April 2023, Hitachi launched a collaborative research project with the Kenji Ohmori Group of the Institute for Molecular Science toward development of a quantum operating system suited to control of qubit arrays. Through joint research on a quantum operating system focusing on the points in common with the cold atom quantum computer of the Ohmori Group, Hitachi intends to accelerate practical implementation of a quantum computer, and contribute to innovative business creation by customers making use of vast amounts of data for development of new materials, drugs, and other products.

Based on discussions with international organizations, universities, customers, startups, and others, Hitachi identified as essential issues to be faced by society realizing "an environmentally-neutral society," "a society which supports an active 100-year lifespan of its citizens," and "the co-evolution of digital technologies, people and society." The Research & Development Group is working to create "radical innovation by back-casting from 2050," as set out in the 2024 Mid-term Management Plan. Research and development on the silicon quantum computer will be carried out as one of the priority themes among these.

■ Comment by Prof. Kenji Ohmori of the Institute for Molecular Science in the Inter-University Research Institute Corporation National Institutes of Natural Sciences

The race to develop quantum computers is heating up in industry-academic-government efforts around the world, as a revolutionary technology expected to bring about enormous advances in such areas as materials development, drug discovery, information security, and AI. Among these efforts, the silicon quantum computer being developed by Hitachi, and the quantum computer design using ultra cold atom arrays being developed in our group, are being looked to as next-generation quantum computer hardware for breaking through the scaling limits encountered currently by earlier architectures, such as those based on superconductivity or trapped ions.

Hitachi's accomplishment is highly important for having quantitatively verified the effectiveness of "dynamic" qubits in a silicon quantum computer. Using this technology, it will be possible to achieve the "quantum entanglement" essential to quantum computing, by dynamically converging any random pair of spatially distant qubits during computation. In principle, quantum entanglement of all the qubits making up a quantum computer should also be possible. Such an operation is not possible with hardware in which each qubit is spatially fixed, as in a superconducting design. It raises hopes of dramatic advances in quantum computer calculation accuracy and algorithms.

Meanwhile, we are working on implementation of dynamic qubits also in the cold atom design of the Institute for Molecular Science. Since there are many areas in common between both of these dynamic qubit systems in their control approaches, by carrying out joint development between Hitachi and our Institute, we hope to greatly accelerate practical implementation of Japan's quantum computers.

About Hitachi, Ltd.
Hitachi drives Social Innovation Business, creating a sustainable society through the use of data and technology. We solve customers' and society's challenges with Lumada solutions leveraging IT, OT (Operational Technology) and products. Hitachi operates under the business structure of "Digital Systems & Services" - supporting our customers' digital transformation; "Green Energy & Mobility" - contributing to a decarbonized society through energy and railway systems, and "Connective Industries" - connecting products through digital technology to provide solutions in various industries. Driven by Digital, Green, and Innovation, we aim for growth through co-creation with our customers. The company's consolidated revenues for fiscal year 2022 (ended March 31, 2023) totaled 10,881.1 billion yen, with 696 consolidated subsidiaries and approximately 320,000 employees worldwide. For more information on Hitachi, please visit the company's website at https://www.hitachi.com.

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