Approaching Quantum Error Correction Using Bosonic Qubits While Looking Beyond the Red Ocean of a Research Field

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Abstract

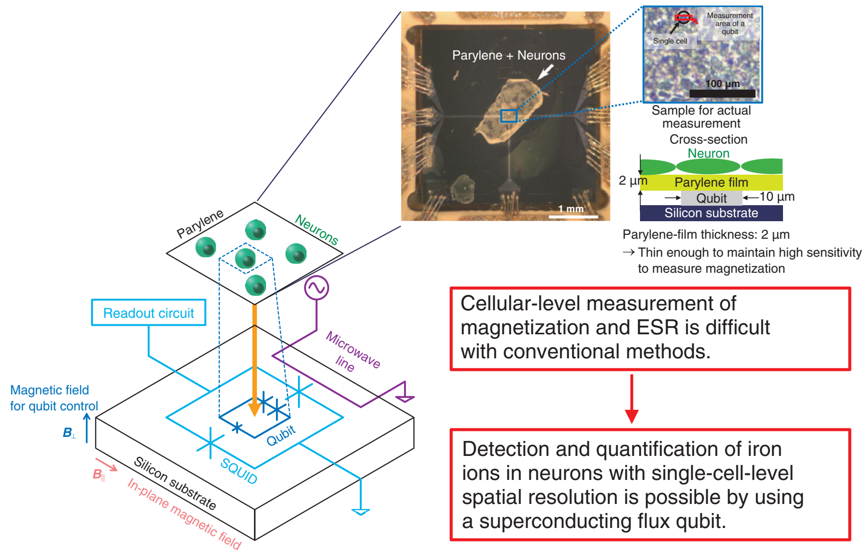
A challenge with a superconducting quantum bit (qubit)—the basic element of a quantum computer—is its short lifetime. To overcome this challenge for developing a quantum computer, approaches, such as elucidating the mechanisms that affect the lifetime of a qubit and extending its lifetime by correcting errors that occur when it reaches the end of its life, have been taken. Extending the lifetime of a qubit is expected to improve the accuracy of quantum sensing. A superconducting flux qubit has two quantum states, which correspond to the direction of the superconducting current, and by controlling these states with a magnetic field, the qubit can be used as a highly sensitive magnetometer. We interviewed Shiro Saito, a senior distinguished researcher at NTT Basic Research Laboratories, who aims to apply a hybrid combination of high-performance magnetometers and biological samples to pathological diagnosis. He talked about the detection of iron ions in neurons by using superconducting flux qubits and shared his research approach that looks beyond the red ocean of a research field.

Keywords: superconducting flux qubit, two-level-system defect, bosonic qubit

Clarifying the mechanisms behind the characteristics of a superconducting quantum bit through experiments and progressing toward its application

—Would you tell us about the research you are currently conducting?

Our group is researching superconducting quantum bits (qubits), focusing on three themes: “detecting iron ions in neurons by using superconducting flux qubits,” “detecting and identifying defects that limit the lifetime of superconducting qubits,” and “studying superconducting bosonic qubits.” As a fundamental element of a quantum computer, a superconducting qubit exploits quantum states that emerge in a superconducting environment. Among the several types of superconducting qubits, a superconducting flux qubit is a superconducting circuit consisting of a superconducting loop. The qubit can be controlled by



SQUID: superconducting quantum interference device

Fig. 1. Experimental setup for detecting electron spins in neurons by measuring the spectrum shift of a qubit.

the magnetic field penetrating the loop and functions as a highly sensitive magnetometer. In my previous interview (November 2021 issue), I explained that we have demonstrated electron-spin resonance (ESR) by using this magnetometer to detect electron spins, which have the properties of a tiny magnet, and developed an ESR method based on this principle for analyzing material samples containing a small number of electron spins in a small volume.

For our first theme, "detecting iron ions in neurons by using superconducting flux qubits," when conventional measurement methods are used, for example, when electron spins of cells in the brain are measured by biopsy, only the average value of the spins of all cells can be measured. In contrast, sensors using superconducting flux qubits achieve high spatial resolution, which enables us to detect the property of electron spins of individual cells. We began research on the detection of iron, which is the most-abundant trace metallic element in the human body. We chose iron because knowing the redox state of iron is key to understanding oxygen transport and the electron-transport chain. Iron also plays an important role from a pathological perspective, for example, the deposition of iron in cells is related to diseases such as Alzheimer's disease. In an experiment, we attached a biological sample of neurons cultured on parylene (i.e., a paraxylylene polymer with a linear crystal structure) to a chip consisting of a superconducting flux qubit and measured the spectrum of the superconducting flux qubit to detect the electron spins in the neurons (**Fig. 1**).

The magnetic field generated by the electron spins changes to reflect the difference in the orientation of the electron spins in the biological sample, which are disoriented at high temperatures but aligned at low temperatures. By detecting the change in the magnetic field in the form of a shift in the spectrum (**Fig. 2**), we succeeded in detecting the electron spins caused by the iron ions contained in the neurons at single-cell-level spatial resolution.

These results indicate that detection of electron spins using superconducting flux qubits is highly sensitive and has the advantage that even small amounts of sample can be detected. I therefore believe that it can be applied to pathological diagnosis or to the measurement of extremely valuable samples such as milligram-sized samples of sand collected from the asteroid Itokawa. Going forward, we intend to obtain spectra by using the ESR method and from those spectra, identify which ions an electron spin is caused by, for example, iron or copper ions.

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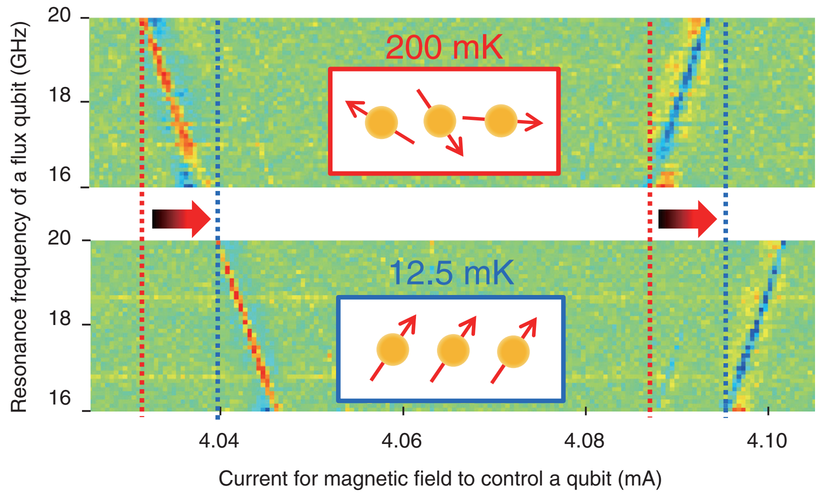

Fig. 2. Spectrum of a qubit.

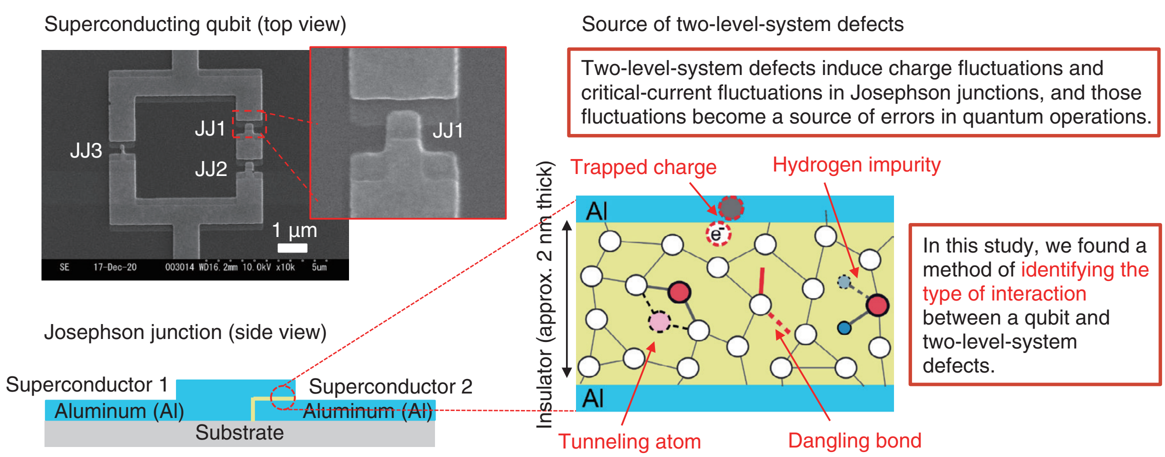

Fig. 3. Two-level-system defects.

Science and Technology (CREST) program "Creation of Innovative Quantum Technology Platform Based on Advanced Control of Quantum States" (Research Supervisor: Yasuhiko Arakawa) and was published in the British scientific journal *Communications Physics* on February 6, 2023.

—What kind of research is "detecting and identifying defects that limit the lifetime of superconducting qubits"?

It is a research theme to extend the short lifetime of qubits by detecting and identifying defects that limit the lifetime. In the aforementioned research on electron-spin sensing using a superconducting flux qubit, we attempted to narrow the linewidth of the qubit's spectrum by extending the lifetime of the qubit to improve sensing sensitivity. However, while sensing electron spins, we discovered a phenomenon that slightly differed from what we expected and began investigating it as a separate theme.

A major noise source that limits the lifetime of qubits is two-level-system defects that cause charge fluctuations in the Josephson junction contained in the qubit (**Fig. 3**). The superconducting loop of a superconducting flux qubit contains three Josephson junctions (JJ1 to 3 in the figure), and as shown in the enlarged view of JJ1, each Josephson junction is composed of two superconductors joined via an insulating film. If the insulating film is grown epitaxially, and the atoms are regularly aligned, the Josephson junction will be free of defects, and the qubit will have a very long lifetime; however, an aluminum-oxide insulating film is currently grown in an amorphous state in which atoms are irregularly aligned. Trapped charges, atomic tunneling, and dangling bonds are considered the causes of two-level-system defects. Although well-known studies have attempted to theoretically explain two-level-system defects, and the existence of two-level-system defects is clear, it is currently impossible to prevent them.

There are two main types of interaction between superconducting qubits and two-level-system defects: charge and critical current. For a charge-type interaction, charge fluctuations of a two-level-system defect displace the charge in the Josephson junction, thus coupling the two-level-system defect to the qubit. For a critical-current-type interaction, charge fluctuations of a two-level-system defect cause a change in the critical current in the Josephson junction, thus coupling the two-level-system defect to the qubit. A charge-type-interaction two-level-system defect is detected when there is a resonance transfer between a single excitation of a qubit and a single excitation of a two-level-system defect. On the contrary, a critical-current-type-interaction two-level-system defect is detected when there is a resonance transfer between two excitations of the qubit and one excitation of the two-level-system defect. By finding the differences between these detection conditions through experiments, it has become possible to distinguish between the two types of interaction between superconducting qubits and two-level-system defects.

By measuring the spectrum of two-level-system defects while controlling the transition frequency of superconducting qubits, we succeeded in visualizing the difference between the two types of interaction between a qubit and a two-level-system defect on the spectrum. Therefore, it has become possible to distinguish between the two types of two-level-system defects by sweeping the transition frequency of a qubit.

By advancing this research, we intend to elucidate the properties of defects in superconducting qubits, the result of which will provide feedback for the sample-fabrication process to optimize the fabrication process and materials and create defect-free, long-lifetime superconducting qubits. As a short-term application, it became possible to model noise due to two-level-system defects, which can be applied to the optimization of gate operations of qubits, improving the performance of currently available quantum computers.

This research was partly supported by the following research and development (R&D) projects: “Quantum sensing using superconducting flux qubits” (Research Director: Shiro Saito)” (No. JPMJCR1774) in the CREST program “Creation of Innovative Quantum Technology Platform Based on Advanced Control of Quantum States” (Research Supervisor: Yasuhiko Arakawa) as well as “Research and development of bosonic codes using superconducting resonators” (Performer: Shiro Saito) (No. JPMJMS2067) in the “Development of Integration Technologies for Superconducting Quantum Circuits” (Project Manager: Tsuyoshi Yamamoto) project, which is the national Moonshot R&D Program Goal 6: Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050 (Program Director: Masahiro Kitagawa) promoted by JST. The above result of this research was published online in the American Scientific Journal *PRX Quantum* on December 21, 2022.

—You recently started investigating superconducting bosonic qubits, right?

Our third theme, “studying superconducting bosonic qubits” was started as the aforementioned research topic “Research and development of bosonic codes using superconducting resonators” (Performer: Shiro Saito) (No. JPMJMS2067), and we have obtained new results.

One of the most important applications of superconducting quantum circuits is quantum computers. To improve the performance of a quantum computer, it is necessary to increase the number of qubits that it uses; thus far, a quantum computer with up to around 1000 qubits has been achieved. A qubit has a short lifetime, and external disturbances can change its state and cause errors. To ensure the operation of a quantum computer, quantum errors must be corrected. The currently mainstream error-correction method implements a surface code using qubits called “transmons” in a manner that increases the number of qubits so that their redundancy can be used for error correction. In the case of a typical error rate of 0.1%, about 1000 physical qubits per logical bit are needed to correct errors; in other words, 1 to 100 million qubits are needed for a meaningful quantum computation

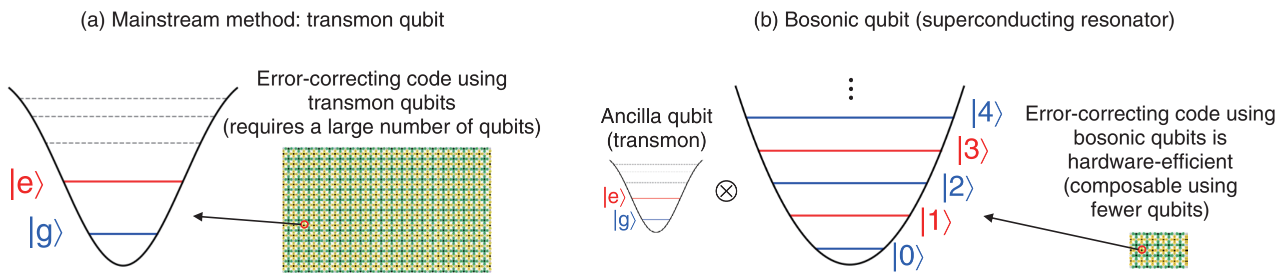

Fig. 4. Hardware-efficient bosonic qubit.

(**Fig. 4(a)**).

In contrast, a bosonic qubit is created by combining a storage cavity called a resonator and ancilla qubit (transmon) to form a single qubit, and errors are corrected by the redundancy and degrees of freedom of the theoretically infinite number of energy levels within the resonator (**Fig. 4(b)**). Compared with the conventional error-correction method using transmon qubits, the method using bosonic qubits requires fewer qubits (so less hardware) by one to two orders of magnitude. However, bosonic qubits have many energy levels, so it is extremely difficult to control them. Therefore, controlling quantum states in those energy levels is a challenge with bosonic qubits.

Thus far, we have prototyped a three-dimensional coaxial cavity made of aluminum and achieved a Q value (an index that represents the quality of a resonant circuit in terms of the low level of its loss) of over 10^8, which is equal to or better than that achieved in previous research. We have also optimized the design of the bosonic qubit and improved the properties of the ancilla qubit, creating an environment in which bosonic qubits can be implemented. As a first step of this research theme, we have successfully observed the spectral splitting of ancilla qubits in accordance with the photon number states in the storage cavity.

We are beginning to see results such as the encoding of bosonic codes. By refining technology of these results, we intend to implement binomial codes in the resonator and, in parallel, build a prototype niobium resonator to achieve an even higher Q value.

Looking beyond the red ocean of a research field and cherishing human connections

—What do you keep in mind as a researcher?

Research on superconducting quantum computers is a “red ocean,” where a growing number of researchers are actively investigating it. At its core, mainstream research in related technologies is conducted by researchers supported by global corporations or national governments with a wealth of resources. Facing an overwhelming difference in resources, we would find it extremely difficult to compete with them head on. Accordingly, I’m trying to take a slightly different approach from those researchers by looking ahead to the future, i.e., targeting research areas that are still new, interesting, and promising and have the potential to turn the tables in the future such as bosonic qubits. In my previous interview, I talked about analyzing the current situation and selecting a theme that would enable me to use my strengths to create novelty, and I have been updating this approach.

Regarding the two-level-system defects that I mentioned, our initial goal was to increase the spin sensitivity to enable us to detect electron spins; however, we were unable to detect electron spins due to insufficient sensitivity but detected an unexpected phenomenon. At that time, a postdoctoral researcher and I thought about what we could detect with our method and found that we could detect two-level-system defects at high frequencies. Using one of our strengths, namely, a variable-frequency superconducting flux qubit to measure the spectrum of two-level-system defects, we also discovered two spectra: a spectrum with the same shape as the qubit and spectrum with a shape twice the frequency of the qubit. We then went back to the starting point and calculated the Hamiltonian of the qubit coupled with two-level-system defects and were able to detect and identify the types of the defects. I believe that even when the results differed from what we expected, pursuing our goal while changing our perspective and digging deeper led to new discoveries.

After I presented these results during an invited talk at a conference called "Superconducting Qubits and Algorithms," a researcher working on the theory of two-level-system defects approached me and said he was highly impressed by our results because he had been repeatedly conducting experiments to distinguish between the two types of two-level-system defects but could not produce results. I'm delighted that the efforts we've been making have led to these results and that opportunities for future collaboration and joint research were created, which will be valuable when this research progresses further and we need theoretical support.

—What is your message for younger researchers?

I hope you will cherish your connections with others. In detecting iron ions in neurons by using superconducting flux qubits, we were able to achieve results by combining superconducting qubits with biological samples. NTT Basic Research Laboratories has recently produced a variety of achievements through hybrid combinations of different fields such as mechatronics and photonics. These achievements are the result of collaborations between professional researchers by harnessing human connections. If we look beyond NTT, we will find many excellent professors at universities and other institutions in Japan who are researching topics that NTT does not handle. If we keep our eyes open and find teams with which we could conduct collaborative research, or if we look overseas, the opportunities will be even greater. To take advantage of such opportunities and expand your research, it is important to build connections with those researchers.

I also think you should be proactive and challenge yourself in everything you do. For example, it might be a good idea to try your hand at large projects such as the Moonshot programs or JST's CREST. Although the application process for these projects is time-consuming, it helps you clarify the purpose and plan of your research, and if your proposal is accepted, it will attract people to the project. It is thus a good opportunity to make connections.

Finally, I encourage you to participate in research abroad, because you will be exposed to research cultures that differ from that of Japan and will also be able to make connections with outstanding international researchers.

■ Interviewee profile

Shiro Saito received a B.E., M.E., and Dr. Eng. in applied physics from the University of Tokyo in 1995, 1997, and 2000. He joined NTT Basic Research Laboratories in 2000. Since then he has been engaged in quantum information processing using superconducting circuits. He was appointed as distinguished researcher of NTT in 2012 and senior distinguished researcher in 2021. He was a guest researcher at Delft University of Technology from 2005 to 2006. He was a guest associate professor at Tokyo University of Science from 2012 to 2020 and promoted to a guest professor in 2020. He is a member of the Physical Society of Japan and the Japan Society of Applied Physics.