

Coherent Coupling between a Superconducting Qubit and a Spin Ensemble

Shiro Saito, Xiaobo Zhu, William John Munro, and Kouichi Semba

Abstract

This article reviews an experiment that demonstrated the principle of quantum memory operation in a superconductor-diamond hybrid system. Superconducting qubits have excellent controllability and scalability but short memory (coherence) time because they are artificial structures; on the other hand, electron spins in diamond are natural structures and have the opposite characteristics: they show extremely long memory times (seconds or greater) but are hard to control and manipulate. A superconductor-diamond hybrid system could offer the best properties of these systems without the associated disadvantages.

1. Introduction

The coherent control of quantum two-level systems, which are applicable to quantum bits (qubits), has attracted significant interest in the context of quantum computing and quantum information processing. Among the various candidates for quantum bits, superconducting qubits based on Josephson junctions have gained in importance because of their controllability and scalability. Their coherence time has reached a few tens of microseconds [1], compared with several nanoseconds at first in 1999 [2]. A few qubit gates have been demonstrated in superconducting circuits [3]. To execute larger and more useful quantum algorithms in the future though, it will be necessary to achieve a long coherence time. However, we are unsure whether this can be achieved solely with superconducting circuits.

The key components of a conventional computer are the central processing unit (CPU) and the random access memory (RAM) (**Fig. 1**). Each component plays its own unique role. The CPU processes the information while the RAM stores it. On the other hand, superconducting qubits have played the roles of both a processor and memory. In view of the above-

mentioned issues, NTT has aimed to create a hybrid of superconducting qubits and another suitable system that can store quantum information for longer times [4] (**Fig. 2**).

2. NV⁻ centers in diamond

Nitrogen-vacancy (NV⁻) centers in diamond have attracted significant attention as a potential candidate for a quantum memory for superconducting qubits. The NV⁻ center is a complex defect in a diamond crystal, formed of (1) a nitrogen (N) atom substituting for a carbon atom and (2) an adjacent vacancy (V) (**Fig. 3(a)**). As shown in **Fig. 3(b)**, its electron state is spin 1 with a zero field splitting of 2.88 GHz between the $m_s = 0$ and $m_s = \pm 1$ states at zero magnetic field, where m_s is the magnetic quantum number. The electron spin is known for its long room-temperature coherence time of 2 ms [5], so it seems to be suitable for a quantum memory. We can perform a memory operation under low magnetic fields because the zero field splitting of 2.88 GHz is compatible with the transition frequency of superconducting qubits. Furthermore, there is an optical transition in addition to the microwave one, so we may be able to create a

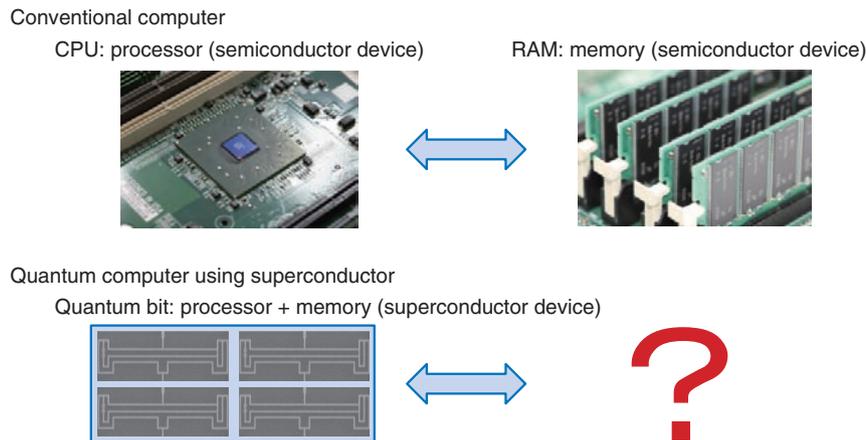


Fig. 1. Components of a computer.

	Controllability, scalability	Memory time (coherence time)
Superconducting qubits	Good (various circuit designs)	Poor (coupling to noise environment)
NV⁻ centers in diamond	Poor (weak coupling between spins)	Good (isolated from external noise)

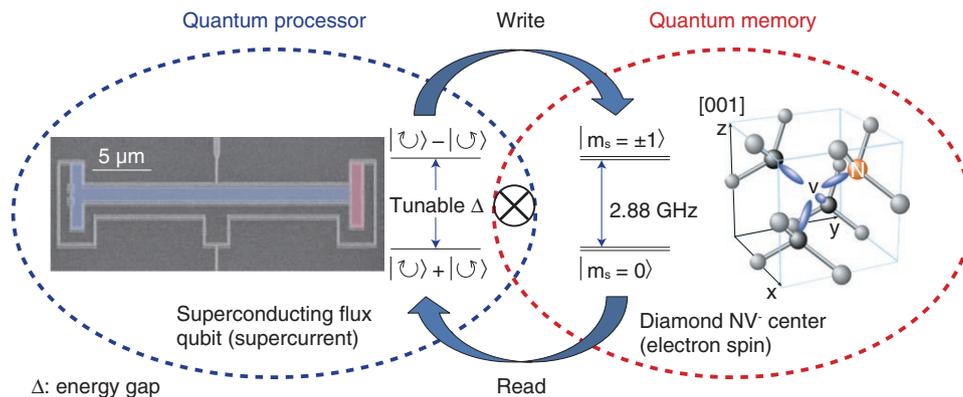


Fig. 2. Superconductor-diamond hybrid system.

quantum transducer—a microwave-to-optical frequency converter. This would be a key technology for quantum repeaters, quantum networks, and quantum computers.

3. Gap-tunable superconducting flux qubit

A superconducting flux qubit consists of a superconducting aluminium loop with three Josephson junctions. One of them is $\alpha \sim 0.8$ times smaller than the other two, which makes its Josephson energy proportionally smaller, i.e., equal to $\alpha \times E_J$ (see Fig. 4(a)).

The system works as a quantum two-level system, that is, a qubit, when we apply an external magnetic field $\Phi_{\text{ex}} \sim (m+1/2) \Phi_0$ through the qubit loop (here, m is an integer and Φ_0 is the magnetic flux quantum). Figure 4(a) shows the lowest two energy levels of the system when $\Phi_{\text{ex}} \sim 1.5 \Phi_0$. The clockwise circulating current state $|R\rangle$ and the anticlockwise one $|L\rangle$ are the energy eigenstates when Φ_{ex} is far away from $1.5 \Phi_0$. These states are composed of persistent currents $I_p \sim 300$ nA. The equal superposition states between $|L\rangle$ and $|R\rangle$ are realized at the degeneracy point where $\Phi_{\text{ex}} = 1.5 \Phi_0$ because of tunneling due to the

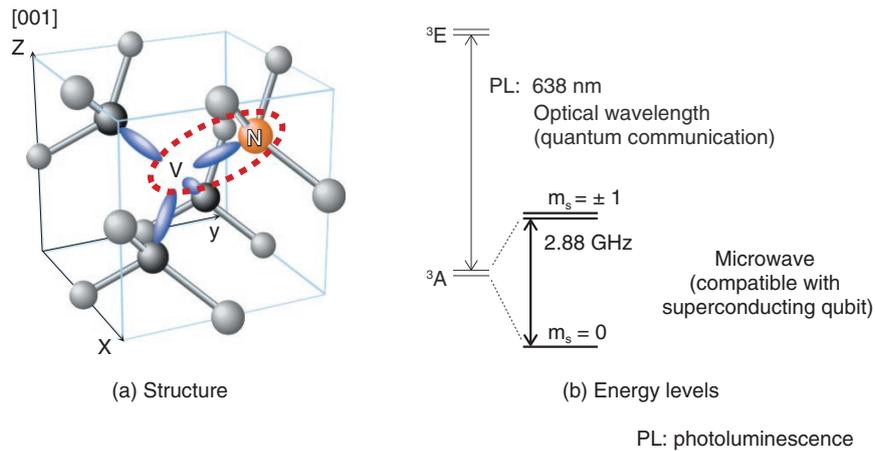


Fig. 3. NV center in diamond.

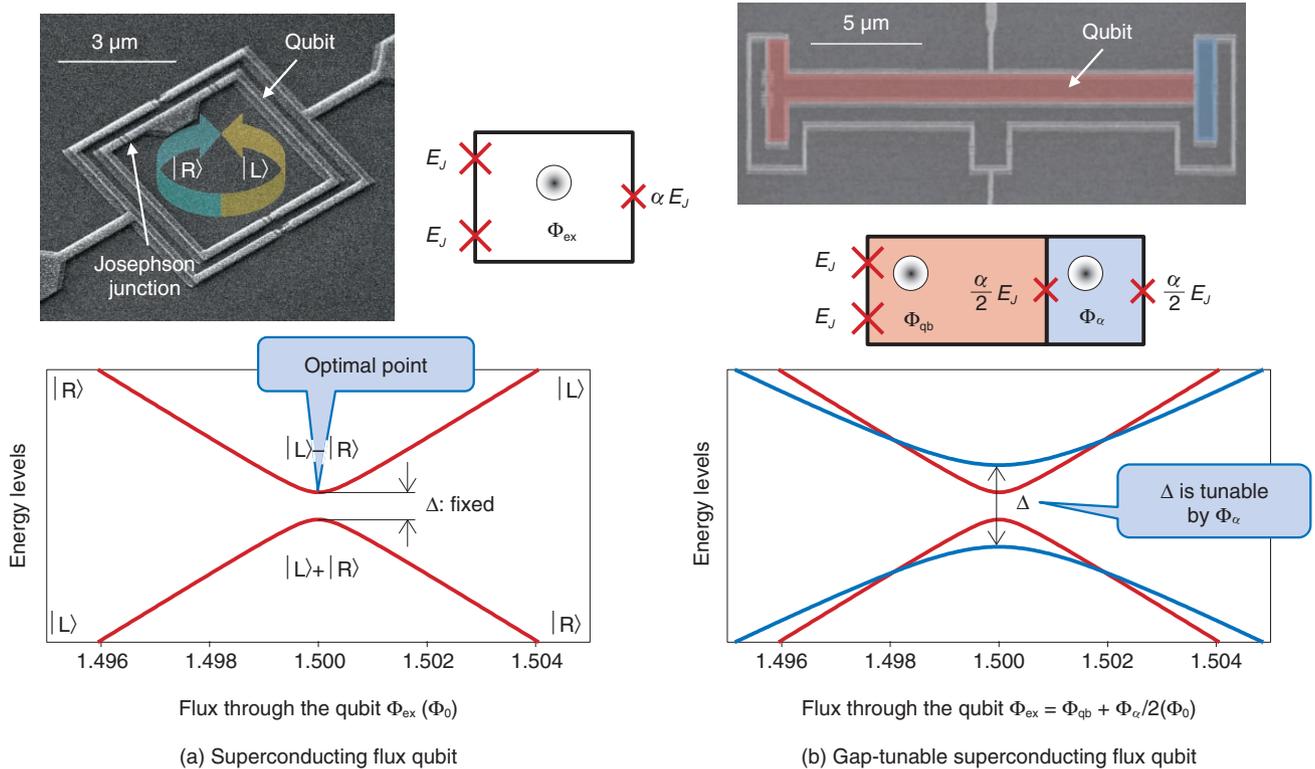


Fig. 4. Superconducting flux qubits and their energy levels.

charging energy of the junctions. The tunneling causes energy anticrossing between $|L\rangle$ and $|R\rangle$, so the transition energy between the ground state and the excited state of the qubit is a minimum at this degeneracy point, which is called the *optimal point* because

it is where the qubit is immune to external flux noise and exhibits its longest coherence time.

We can control the energy gap Δ of the standard flux qubit at this optimal point by an appropriate design of the junction area ratio α ; however, we

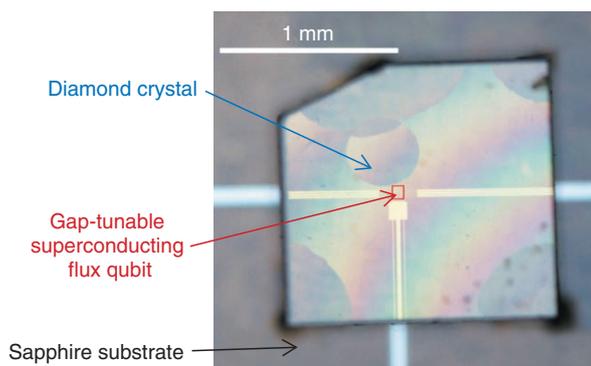


Fig. 5. Superconductor-diamond hybrid system.

cannot change it after sample fabrication. For our purposes, we need a gap-tunable superconducting flux qubit (**Fig. 4(b)**) in order to tune our qubit in resonance with other quantum systems, for example, an NV^- spin ensemble, while keeping it at the optimal point. We therefore need to replace the smallest junction (α junction) by a dc-superconducting quantum interference device (SQUID), whose E_J can be controlled by the external flux through it. The energy gap Δ can then be tuned in-situ by several gigahertz within a few nanoseconds [6]. The fact that a typical gap is between 1 GHz and 10 GHz thus indicates excellent compatibility with an NV^- spin ensemble in diamond.

4. Superconductor-diamond hybrid quantum system

The coupling strength between two physical systems is the key factor necessary for quantum memory operation in hybrid systems because the time taken to transfer information between the systems is inversely proportional to the coupling strength, so faster operation within its coherence time leads to high-fidelity operation. In the case of the coupling between a flux qubit and the NV^- spin ensemble, reducing the spatial distance between them increases the coupling strength because the spin ensemble couples to the qubit through the magnetic field induced by the qubit's persistent current I_p . Moreover, increasing the density of the NV^- spin leads to a stronger coupling because the coupling is enhanced by a factor \sqrt{N} owing to a collective effect when the qubit couples to N electron spins. Therefore, it is important to prepare a diamond crystal that contains a high density of NV^- centers.

To achieve this, we injected carbon ions into a high-pressure high-temperature (HPHT) synthesized diamond crystal and annealed it in vacuum. We estimated the density of NV^- centers to be $N \sim 1.1 \times 10^{18} \text{ cm}^{-3}$ by comparing the photoluminescence spectroscopy from a single center with that of our ensemble.

We fabricated our superconducting flux qubit on a sapphire substrate by using electron beam lithography and a shadow evaporation technique. The diamond crystal was then glued on top of it, achieving a spatial separation of less than $1 \mu\text{m}$. The hybrid sample after mounting of the diamond crystal is shown in **Fig. 5**. We estimated the coupling g_i between a single NV^- spin and the flux qubit to be approximately 8.8 kHz from the geometrical configuration. This gave the estimated collective coupling $g_{\text{ens}}^{\text{(estimated)}}$ as about 50 MHz for the NV^- center density.

5. Spectroscopy

We performed microwave spectroscopy measurements at 12 mK using a dilution refrigerator. The spectrum of the flux qubit with the diamond crystal shows a clear energy anticrossing at 2.88 GHz (**Fig. 6(a)**) corresponding to the transition frequency of NV^- spins. On the other hand, the spectrum taken before the diamond was mounted (**Fig. 6(b)**) does not show an anticrossing. From the above results, we can conclude that the splitting at 2.88 GHz comes from the strong coupling g_{ens} between the flux qubit and the spin ensemble. The coupling g_{ens} of 70 MHz is in good agreement with the coupling $g_{\text{ens}}^{\text{(estimated)}}$ estimated using the NV^- center density.

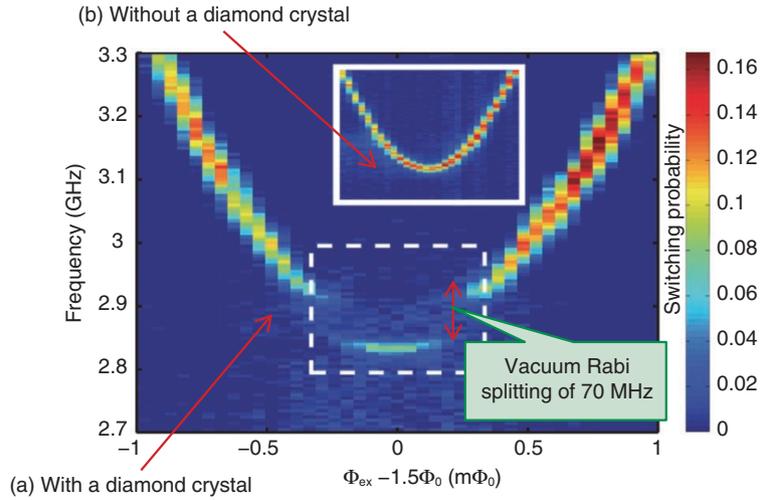


Fig. 6. Spectra of a superconducting flux qubit.

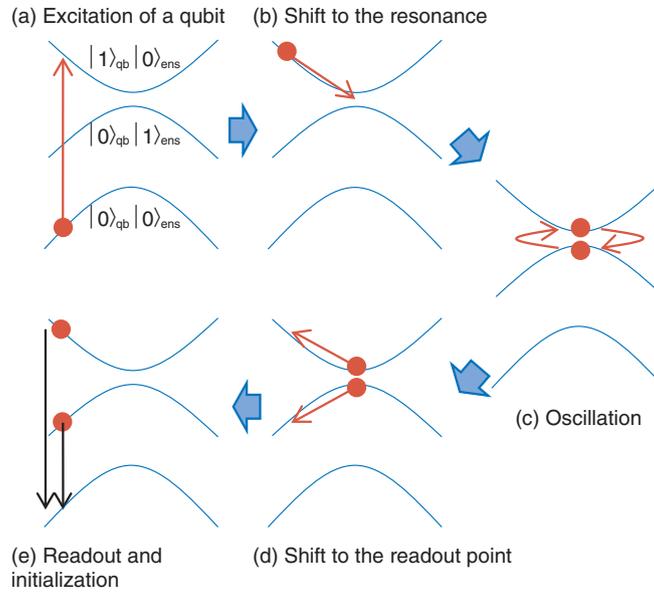


Fig. 7. Measurement sequence for observing vacuum Rabi oscillation.

6. Time domain measurement

We performed time domain measurements according to the sequence depicted in **Fig. 7** to demonstrate memory operations, that is writing to the spin ensemble and reading from it. First, we excited only the flux qubit by applying a microwave π -pulse to it when the qubit and the spin ensemble were well detuned (Fig. 7(a)). The qubit was quickly tuned by Φ_{ex} into reso-

nance with the spin ensemble (Fig. 7(b)). This tuning (much faster than the coupling strength g_{ens}) causes a non-adiabatic transition, and the flux qubit can then start coherently exchanging a single quantum of energy with the spin ensemble as follows (Fig. 7(c)): $|1\rangle_{\text{qb}}|0\rangle_{\text{ens}} \leftrightarrow |0\rangle_{\text{qb}}|1\rangle_{\text{ens}}$, where qb and ens indicate the flux qubit and the spin ensemble, respectively. The 0 (1) represents the ground (excited) state of each part of the hybrid

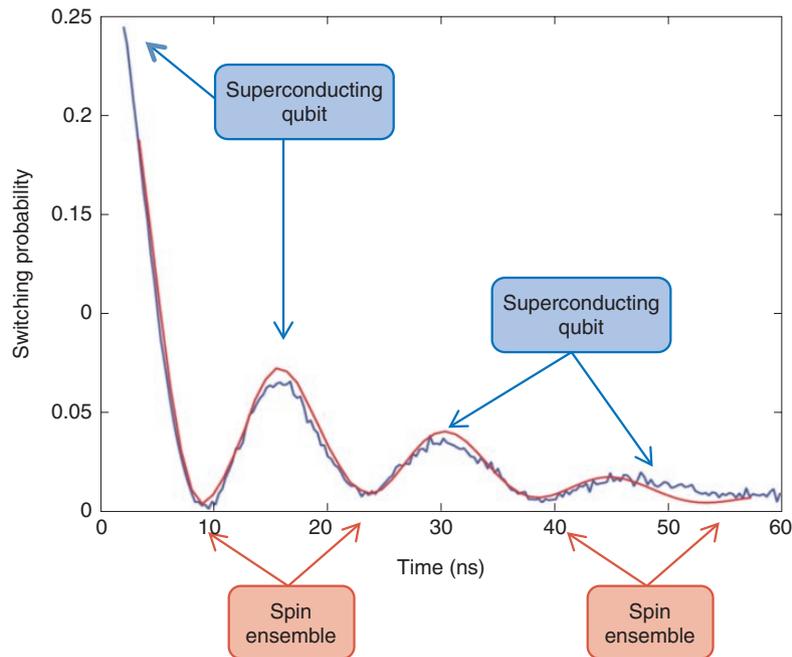


Fig. 8. Vacuum Rabi oscillations between a flux qubit and an NV spin ensemble.

system. The resulting oscillation with frequency g_{ens} is called a vacuum Rabi oscillation. Finally, to finish the memory operation, we detuned the qubit non-adiabatically away from the spin ensemble (Fig. 7(d)) and read out the qubit state with a dc-SQUID (Fig. 7(e)). The vacuum Rabi oscillations that we observed are shown in Fig. 8. The blue (red) curve represents experimental data (simulation). These results indicate that quantum information in the flux qubit was transferred to and then retrieved from the spin ensemble.

7. Concluding remarks

The vacuum Rabi oscillations shown in Fig. 8 continued for only 40 ns, which is much shorter than the decay times of the flux qubit ($T_{2,\text{qb}} \sim 150$ ns) and the NV spin ensemble ($T_{1,\text{NV}} \gg 10$ μs). This indicates an unexpectedly short coherence time for the spin ensemble. There are several likely sources of this dephasing. The most probable is a large electron spin $-1/2$ bath derived from the 100 ppm (parts per million) P1 centers (a nitrogen atom substituting for a carbon atom) present in our diamond crystal. The degeneracy of the $m_s = \pm 1$ states could also be a source of decoherence. Hence, the future challenges are to apply an in-plane magnetic field to remove this degeneracy and to prepare a diamond sample with fewer P1 cen-

ters.

In summary, we have experimentally demonstrated strong coherent coupling between a flux qubit and a spin ensemble in a diamond crystal. Furthermore, we have observed the coherent exchange (transfer) of a single quantum of energy between them. This is the first step towards a long-lived quantum memory for a superconducting qubit. It could also lead to an interface between the microwave and optical domains.

References

- [1] H. Paik, D. I. Schuster, L. S. Bishop, G. Kirchmair, G. Catelani, A. P. Sears, B. R. Johnson, M. J. Reagor, L. Frunzio, L. Glazman, S. M. Girvin, M. H. Devoret, and R. J. Schoelkopf, "Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture," *Phys. Rev. Lett.*, Vol. 107, No. 24, 240501, 2011.
- [2] Y. Nakamura, Y. A. Pashkin, and J. S. Tsai, "Coherent Control of Macroscopic Quantum States in a Single-Cooper-pair box," *Nature*, Vol. 398, No. 6730, pp. 786–788, 1999.
- [3] M. D. Reed, L. DiCarlo, S. E. Nigg, L. Sun, L. Frunzio, S. M. Girvin, and R. J. Schoelkopf, "Realization of Three-qubit Quantum Error Correction with Superconducting Circuits," *Nature*, Vol. 482, No. 7385, pp. 382–385, 2012.
- [4] X. Zhu, S. Saito, A. Kemp, K. Kakuyanagi, S. Karimoto, H. Nakano, W. J. Munro, Y. Tokura, M. S. Everitt, K. Nemoto, M. Kasu, N. Mizuochi, and K. Semba, "Coherent Coupling of a Superconducting Flux Qubit to an Electron Spin Ensemble in Diamond," *Nature*, Vol. 478, No. 7368, pp. 221–224, 2011.
- [5] G. Balasubramanian, P. Neumann, D. Twitchen, M. Markham, R. Kolesov, N. Mizuochi, J. Isoya, J. Achard, J. Beck, J. Tissler, V.

Jacques, P. R. Hemmer, F. Jelezko, and J. Wrachtrup, "Ultralong Spin Coherence Time in Isotopically Engineered Diamond," *Nature Mater.*, Vol. 8, No. 5, pp. 383–387, 2009.

[6] X. Zhu, A. Kemp, S. Saito, and K. Semba, "Coherent Operation of a Gap-tunable Flux Qubit," *Appl. Phys. Lett.*, Vol. 97, No. 10, 102503, 2010.



Shiro Saito

Distinguished Researcher, Senior Research Scientist, Superconducting Quantum Physics Research Group, Physical Science Laboratory, NTT Basic Research Laboratories.

He received the B.S., M.S., and Dr.Eng. degrees in applied physics from the University of Tokyo in 1995, 1997, and 2000, respectively. Since joining NTT Basic Research Laboratories in 2000, he has been engaged in quantum information processing research using superconducting circuits. He was a guest researcher at Delft University of Technology, the Netherlands, during 2005–2006. He received the Young Scientist Award from the Japan Society of Applied Physics (JSAP) at the spring meeting in 2004. He is a member of JSAP and the Physical Society of Japan.



Xiaobo Zhu

Senior Research Associate, Superconducting Quantum Physics Research Group, Physical Science Laboratory, NTT Basic Research Laboratories.

He received the Ph.D. degree from the Institute of Physics at the Chinese Academy of Sciences in 2003. During 2003–2008, he worked as an assistant/associate professor in the Institute of Physics at the Chinese Academy of Sciences. He moved to NTT Basic Research Laboratories in Japan in 2008. His research interests include superconducting qubits and circuits and their application in hybrid systems.



William John Munro

Research Specialist Quantum Optical State Control Research Group, Optical Science Laboratory, NTT Basic Research Laboratories.

He received the B.Sc. degree in chemistry and physics in 1989, M.Sc. degree in physics in 1991, and D.Phil. degree in quantum optics in 1994 from the University of Waikato, New Zealand. He entered the computer industry in 1995, where he worked on various projects. In July 1997, he accepted an Australian Research Council Fellowship at the Department of Physics in the University of Queensland. During this fellowship, he developed an interest in entanglement, methods to characterize it, and its practical use in quantum information processing. In 2000, he became a senior researcher in the Australian Special Centre for Quantum Information Processing. In late 2000, he joined HP Labs as a research scientist. In early 2010, he moved to NTT Basic Research Laboratories as a research specialist, where he is working on hybrid-system approaches to both quantum computation and communication. He is currently a visiting professor at the National Institute of Informatics in Japan, the University of Queensland in Australia, and Leeds University in the UK.



Kouichi Semba

Research Professor, Research Support Coordinator, Global Research Center for Quantum Information Science, National Institute of Informatics.

He received the B.S., M.S., and Dr.Eng. degrees from the University of Tokyo in 1983, 1985, and 2002, respectively. He joined the NTT Electrical Communications Laboratories in 1985 and moved to NTT Basic Research Laboratories in 1987. From 2003 to 2012, including the period when the research described in this article was conducted, he was the leader of the superconducting quantum physics research group. He was a visiting researcher in the Department of Nanoscience at Delft University of Technology, the Netherlands, during 2002–2003. He was a lecturer at Waseda University in 2005 and a guest professor at Tokyo University of Science during 2008–2012; he has been a guest professor at the National Institute of Informatics since 2010. His achievements include being the first to characterize the electronic state of Penrose's non-periodic tiling as an ideal 2D-quasicrystal; the first to reveal the relevant elemental composition of the high-Tc cuprate superconductor YBCO (Tc = 90 K); the first to demonstrate entanglement in a solid device, namely vacuum Rabi oscillation in a macroscopic superconducting Josephson-qubit LC-resonator system; and the first to demonstrate the coherent coupling of a superconducting flux qubit and NV spins in diamond.