Reading Out Qubit States with a SQUID

Hideaki Takayanagi†

Abstract

The readout process of a superconducting flux-qubit is an interesting topic from the viewpoints of both quantum computing and quantum measurement of macroscopic quantum states. We recently succeeded in performing a single-shot detection of the qubit state with an under-damped DC-SQUID. Here I describe some experimental results and discuss them.

1. Introduction

1.1 Quantum computers and quantum bits

Quantum computers are expected to be overwhelmingly faster than conventional classical computers mainly because of quantum parallelism. The most fundamental element of quantum computers is the qubit (quantum bit). The qubit is physically a two-state quantum system. For a two-state system to be used as a qubit, however, it must have the potential to satisfy the following conditions. (i) The quantum coherence should remain stable in the environment for a long period of time. (ii) Its state must be controllable in accordance with a given purpose. (iii) The measurement of the state can be carried out with sufficient precision. (iv) Many qubits can be implemented in a small space.

Several physical implementations of qubits have been theoretically proposed and experiments are currently in progress [1]-[4]. Of these, qubits implemented in superconducting circuits (a superconducting network with Josephson junctions) are promising. A superconducting gap excludes quasiparticle motion, which often causes decoherence. Each Josephson junction has two degrees of freedom: charge and phase. This gives a wide range of potential controllability. Superconducting circuits can be designed to have appropriate parameters by present microfabrication techniques. Moreover, superconducting qubits can be integrated in a small chip.

In this paper, I introduce one type of superconducting qubit, the superconducting flux-qubit. Experiments on flux-qubits are being carried out by only a few groups around the world. One of them is the Superconducting Quantum Physics Research Group in NTT Basic Research Laboratories, which is the only one in Japan. Recently, we obtained an advanced result in relation to the qubit measurement process [4]. Here, I describe the significance of this result in terms of quantum computers and quantum physics.

1.2 Superconducting flux-qubit

Consider a superconducting ring. We apply an external magnetic field which corresponds to half a flux quantum $\Phi_0/2$ piercing the ring. Then, the ring has two stable states: one in which the circulating supercurrent flows clockwise around the ring and one in which it flows counterclockwise. We call the former the "$|L\rangle$" state and the latter the "$|R\rangle$" state. In our usual "classical" world, we only find the ring is in either $|L\rangle$ "or" $|R\rangle$ probabilistically. In the quantum world, however, the ring can be in a superposition state $|\psi\rangle = a|L\rangle + b|R\rangle$, where a and b are complex-number coefficients, satisfying $|a|^2 + |b|^2 = 1$. The current flows clockwise and counterclockwise at the same time! If we measure the current we obtain $|L\rangle$ and $|R\rangle$ with probabilities $|a|^2$ and $|b|^2$, respectively, and the direction of the current gets determined. However, before the measurement, the direction is not determined. It might be easier to imagine a superposition state of a microscopic object, for example, electronic motion, or electronic spin. In the supercon-

† NTT Basic Research Laboratories
Atsugi-shi, 243-0198 Japan
E-mail: takayan@will.brl.ntt.co.jp

ducting ring mentioned above, there are millions of electrons (Cooper-pairs). All the electrons (Cooper-pairs) in the ring are traveling in opposite directions in $|L\rangle$ and $|R\rangle$.

This type of quantum superposition state is called macroscopic quantum coherence (MQC). The question of whether MQC is actually possible was originally introduced by A. J. Leggett, in the 1980s [5]. Recently MQC in a superconducting ring with Josephson junctions has been experimentally observed [1]. This MQC can also be used as a qubit because it is a typical two-state quantum system with parameters that can be controlled as we wish. A qubit based on MQC in a superconducting ring is called a superconducting flux-qubit.

1.3 Single-shot measurement

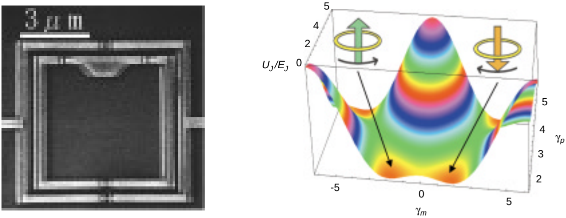
The single-shot measurement of a single quantum system is interesting especially as regards macroscopic quantum objects. If the macroscopic extrapolation of quantum physics were justified, then orthogonal quantum states would certainly be distinguished by a single measurement regardless of the size of the objects. However, due to the vulnerability of macroscopic superposition and the sensitivity of the measuring device, we must usually perform an enormous number of measurements over the same states to obtain sufficient readout resolution for the MQC state even though the two states are orthogonal. A measurement technique that gives us information from a single measurement is called a "single-shot measurement". Therefore, it is interesting to find out whether or not the simple single-shot measurement procedure used in thought experiments can be realized in real experiments and described with quantum mechanical correctness.

Single-shot measurement also plays an important role in quantum computation, which has been demonstrated with liquid nuclear magnetic resonance, showing the operations of quantum algorithms. Several Josephson junction systems exhibit Rabi oscillations as a simple 1-qubit gate operation [1], [2]. These systems use either time or spatial ensemble readout. The possibility of a single-shot readout of a charge-based qubit by superconductor phase measurement has been reported by Vion *et al*. [3]. Another interesting feature of single-shot measurement is related to entanglement. An example is two qubits or two particles, entangled with each other, such as, $|01\rangle + |10\rangle$, $|00\rangle + |11\rangle$. It is well known that the average readout of an entangled state provides insufficient information about the non-classical correlation between the two particles. A single-shot measurement is able to extract information on individual quantum events in the system. Therefore, the single-shot measurement of a single quantum system is of interest in terms of both pure quantum mechanics and quantum computation.

2. Experimental configurations

2.1 Three-Josephson-junction qubit

The real flux-qubit used in our experiments has three Josephson junctions. Figure 1(a) is a scanning electron micrograph of a superconducting ring (inside) and a DC-SQUID (outside) as a readout device. The inner ring (qubit) contains three Josephson junctions, which appear as narrow constrictions.



(a) (b)

Fig. 1. (a) A scanning electron microscope photograph of a superconducting ring and a DC-SQUID as a readout device. (b) 3D plot of the potential energy of the qubit.

The DC-SQUID with two Josephson junctions has two leads extending up and down. The ring and the DC-SQUID are coupled magnetically via mutual inductance M. This structure was first proposed by Professor Mooij's group at the Technical University of Delft [6]. The Josephson and charging energies of the two identical junctions are E_J and E_C. Those of the third junction are αE_J and E_C/α with $\alpha = 0.8$. Here E_C is defined as $E_C = e^2/(2C)$ with the junction capacitance C. For our sample, $E_C = 6.17$ GHz and $E_J = 308$ GHz. The junction areas of the DC-SQUID are both 100×100 nm^2. The inner ring is 5.1×5.3 μm^2 and the DC- SQUID is 7.3×7.7 μm^2.

The Josephson potential $U_J = E_J(2 + \alpha - \cos[\gamma_1] - \alpha\cos[2\pi f - \gamma_1 + \gamma_2])$ of the qubit is shown in Fig. 1(b), where γ_1 and γ_2 are the phase differences at two identical Josephson junctions and f is the filling factor of the external magnetic field, $f \equiv \Phi_{\rm ext}/\Phi_0$. The coefficient α, which determines the barrier height, is fixed at $\alpha = 0.8$. The f dependence of the Josephson potential is periodic with period of 1. Most of our qubit measurements were carried out in the vicinity of $f = 1.5$, where we obtain better DC-SQUID sensitivity compared with $f \approx 0.5$. The energy plot is shown as a function of $\gamma_{\rm p} \equiv (\gamma_1 + \gamma_2)/2$ and $\gamma_{\rm m} \equiv (\gamma_1 + \gamma_2)/2$ with $f = 1.5$. We can see that a symmetrical double well is formed along the axis $\gamma_{\rm m}$.

In this double well system at $f \approx 1.5$ the ground $|0\rangle$ and first excited $|1\rangle$ states become bonding and anti-bonding states, respectively due to macroscopic tunneling through the potential barrier. The relative energy difference between the wells is controlled by f. When f deviates from 1.5, the double well potential becomes asymmetric and the wave-function of the ground (excited) state becomes localized in the lower (higher) well. These two localized states, $|L\rangle$ and $|R\rangle$, are classically stable states and are robust against decoherence. This constitutes a macroscopic two-level system and should exhibit superposition if quantum mechanics is to be extrapolated to a macroscopic scale of several micrometers.

We can treat the states of the ring as a pseudo two-level system and obtain a reduced two-level-system Hamiltonian with a $\{|L\rangle, |R\rangle\}$ basis:

$$H_{\rm q} = \varepsilon\sigma_z - \Delta\sigma_x, \tag{1}$$

where is the energy difference between the localized states in the left and right wells and can be controlled by f. Here Δ represents the macroscopic quantum tunneling between the wells, and

$$\begin{aligned} \sigma_z &= |L\rangle\langle L| - |R\rangle\langle R| \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \\ \sigma_x &= |L\rangle\langle R| + |R\rangle\langle L| \equiv \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \end{aligned} \tag{2}$$

The eigenenergy of the ground (excited) states becomes $E_{0(1)} = -(+)\sqrt{\varepsilon^2 + \Delta^2}$. The eigenstates are

$$\begin{aligned} |0\rangle &= \sin(\theta/2)|L\rangle + \cos(\theta/2)|R\rangle, \\ |1\rangle &= -\cos(\theta/2)|L\rangle + \sin(\theta/2)|R\rangle \end{aligned} \tag{3}$$

Figure 2(a) shows the energy levels of the ground and first excited states E_0 and E_1, as a function of the filling factor of the external magnetic flux f. The energy levels exhibit anti-crossing at $f = 1.5$ due to macros ically predicted quantum mechanically averaged values of the qubit circulation current $I_{cir} = I_{co}\langle i|\sigma_z|i\rangle$ ($i = 0,1$), for the ground $|0\rangle$ and the first excited states $|1\rangle$, obtained using $\langle 0|\sigma_z|0\rangle = -\cos(\theta)$ and $\langle 1|\sigma_z|1\rangle = \cos(\theta)$, where I_{co} is the maximum supercurrent around the qubit ring.

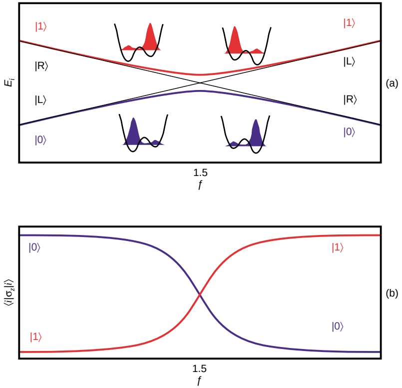


Fig. 2. (a) Energy diagram of the qubit.
(b) Quantum mechanical average of the qubit circulating current.

2.2 Measurement with DC-SQUID

The observable difference between the states $|L\rangle$ and $|R\rangle$ is the orientation of the flux induced by the qubit circulation current because the direction of the current is opposite for $|L\rangle$ and $|R\rangle$. The induced flux $\phi_q \approx 10^{-3}\Phi_0$ is very small. Therefore, in order to measure it we utilize the current-voltage (*I-V*) characteristics of the DC-SQUID, which works as a highly sensitive flux detector. The sample was cooled by using a dilution refrigerator. Since our DC-SQUID is under-damped, the *I-V* characteristics have hysteresis. The switching current, where the voltage across the DC-SQUID jumps from zero to a finite value, depends on the magnetic flux piercing the DC-SQUID. We ramped up the bias current while monitoring the voltage across the DC-SQUID and measured the switching current.

The Hamiltonian of the DC-SQUID when there is no flux induced by the qubit is

$$H_{SQ} = \left(\frac{\hbar}{2e}\right)^2 C_S \gamma_+^2 - 2E_{SJ}\cos[\gamma_+]\cos[\pi\Phi_e/\Phi_0] - I_s\left(\frac{\hbar}{2e}\right)\gamma_+, \qquad (4)$$

where C_S is the capacitance of the two Josephson junctions in the SQUID, $\gamma_+ \equiv (\gamma_{S1} + \gamma_{S2})/2$, γ_{S1} and γ_{S2} are the phase differences of two Josephson junctions in the SQUID, E_{SJ} is the Josephson energy of the junctions, and Φ_e is the magnetic flux piercing the SQUID ring. The switching current I_{sw} is the bias current I_S value at which γ_+ escapes from the Josephson potential well. Disregarding thermal effects or other renormalization, the switching current is roughly given by

$$I_{sw} = (2e)/\hbar E_{SJ}\cos[\pi\Phi_e/\Phi_0], \qquad (5)$$

which changes with the magnetic flux Φ_e. When the qubit is placed in the SQUID ring, the magnetic flux ϕ_q induced by the qubit circulating current is added to Φ_e. So, we expect to be able to measure ϕ_q by measuring the switching current. When the qubit is in a superposition state $|\psi\rangle = a|L\rangle + b|R\rangle$, however, it is not so trivial what property of the qubit we measure with the DC-SQUID switching current. This is discussed in section 3.2.

The maximum switching current of the DC-SQUID is around 260 nA. The switching at the Josephson junction is essentially a stochastic process. In addition to the classical thermal effect, quantum tunneling makes a major contribution to switching events at lower temperatures. We fabricated rings and DC-SQUIDs with several different sizes of junctions and loops and measured them to find a system that satisfied both single-shot measurement and coherent superposition. As the result, we found the system that enables us to observe macroscopic coherence with high readout resolution.

3. Experimental results and discussion

3.1 Switching current behavior

Figure 3(a) shows normalized DC-SQUID switching currents modulated by the inner ring (qubit) state as a function of the external magnetic field at different temperatures. Each curve is shifted vertically for clarity. The single small points correspond to single-shot measurements. No averaging was performed. There is a χ-shape cross structure around f = 1.5, where the wavefunction is expected to be a superposition of macroscopically distinct states, $|L\rangle$ and $|R\rangle$. The presence of the cross region suggests that the macroscopic superposition states are formed as ground and excited states.

The solid curves are the expected switching currents estimated from the average qubit circulation current $\langle I_{cir}\rangle$ for the ground state and the first excited state. These are shown in Fig. 2(b). The dense stripe corresponds to the ground state $|0\rangle$ and the other stripe crossing at $f \approx 1.5$ corresponds to the excited state $|1\rangle$. The normalization of the vertical axis from

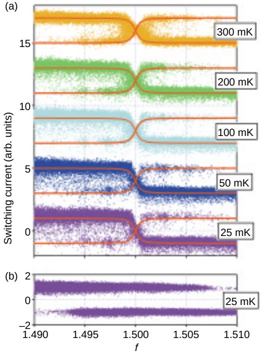


Fig. 3. (a) DC-SQUID switching current modulated by the qubit.
(b) "classical" sample without χ-shape.

-1 to $+1$ is based on two fully localized states, one on either side of the well as wavefunctions of $|L\rangle$ or $|R\rangle$, where the current flows clockwise and counterclockwise, respectively. When we repeated the measurement in a fixed external magnetic field f, the measurement results were random on either stripe and there were only a few points in between. We set the repetition period for successive single-shot measurements at $\tau_{\mathrm{rep}} \approx 3.5$ ms, which is much longer than the relaxation time of the ring. Therefore, the states were well initialized in thermal equilibrium before the measurements.

For comparison, the readout data of a sample without coherent superposition at 25 mK is shown in Fig. 3(b). Hereafter, we call this a "classical" sample. In this sample, the Josephson and charging energies of the two junctions are 578 and 3.12 GHz, respectively. There is no cross region. The state in this system is localized either in $|L\rangle$ or $|R\rangle$. All the readout data are completely separated, and there is no superposed region. In this measurement we completed the single-shot measurement of a localized state but not that of a superposed state.

In Fig. 3(a), the ground and excited states, $|0\rangle$ and $|1\rangle$ are read out well and separately except at exactly $f \approx 1.5$. Measurements in the cross region become single-shot measurements of $|0\rangle$ or $|1\rangle$, which are superpositions of $|L\rangle$ and $|R\rangle$. This means that the measurement provided the information on whether the state was a ground or excited state.

Each stripe has its own distribution, which originates from the external magnetic noise and intrinsic fluctuation of the switching current at the DC-SQUID, since the DC-SQUID has no shunt resistor to achieve single-shot measurement. The standard deviation of the switching current has an equivalent flux fluctuation of $2.7 \times 10^{-3}\Phi_0$ at $f = 1.5$, where the residual distribution originates with the DC-SQUID itself, because the readout switching currents of the $|0\rangle$ and $|1\rangle$ states become identical. This distribution is smaller than the difference between two macroscopically distinct quantum states. This indicates that there is sufficient distinguishability between the two states. Even in the χ cross region, the χ shape is clearly visible. This illustrates the successful single-shot measurement of a macroscopic quantum superposition state.

3.2 What do we measure with a DC-SQUID?

The behavior of the switching current versus the external flux f in Fig. 3(a) is very similar to that of the quantum mechanically averaged value of the qubit circulating current I_{cir} in Fig. 2(b). At first glance, this is very strange.

Since the circulation current I_{cir} is proportional to the z-component of the qubit spin, it should be written as $I_{cir} = I_{co}\sigma_z$, under the two-state approximation for the qubit. According to quantum mechanics, when the spin is in a superposition state $|\psi\rangle = a|L\rangle + b|R\rangle$, each measurement of σ_z provides the discrete result -1 or 1 probabilistically, and never provides an intermediate value. Although the quantum-mechanically averaged value of the circulating current for the superposition state $|\psi\rangle = a|L\rangle + b|R\rangle$ is given by $\langle I_{cir}\rangle = I_{c\,0}(2|a|^2 - 1)$, this value is obtained after we measure the I_{cir} of the state $|\psi\rangle$ many times and calculate the average. Why did each of our switching currents exhibit the "average" value?

To answer this question requires the aid of a theory based on the Hamiltonian of the qubit-SQUID composite system. By integrating out an invisible variable, we obtain the effective total Hamiltonian of the qubit-SQUID composite system as $H'_{\mathrm{tot}} = H_{\mathrm{SQ}} + H_{\mathrm{int}} + H_{\mathrm{q}}$, where H_{SQ} and H_{q} are already given in Eqs. (1) and (4) and

$$H_{\mathrm{int}} = \frac{L}{2}\left(\frac{2e}{\hbar}\right)^2 \Big(E_{\mathrm{SJ}}\sin[2\pi\Phi_e/\Phi_0]\cos[\gamma_+(t)] - \frac{MI_{\mathrm{c}0}}{L}\left(\frac{\hbar}{2e}\right)\sigma_z\Big)^2, \tag{6}$$

where L is the self-inductance of the SQUID ring. The switching current is the bias current at which γ_+ escapes from the Josephson potential well $V_{\mathrm{SQ}}(\gamma_+;\sigma_z) \equiv -2E_{\mathrm{SJ}}\cos[\gamma_+]\cos[\pi\Phi_e/\Phi_0] - I_s\,(h/2e)\gamma_+ + H_{\mathrm{int}}$. Through the interaction H_{int}, the qubit state σ_z affects the SQUID wavefunction $\psi(\gamma_+)$, so the switching current varies with the change in the qubit state. If the qubit were a classical system, which takes only the two states $|L\rangle$ and $|R\rangle$, the switching current would show only two values corresponding to the SQUID potential $V_{\mathrm{SQ}}(\gamma_+;\sigma_z = \pm 1)$. However, in order to discuss the switching current when the qubit is in a superposition state $|\psi\rangle = a|L\rangle + b|R\rangle$, we have to determine the wavefunction of the total system according to the total Hamiltonian H'_{tot}, and find the bias current at which γ_+ escapes from the potential well. The wavefunction of the total system can be written schematically as

$$|\psi_{tot}\rangle = \int d\gamma_+\{\psi_L(\gamma_+)|\gamma_+\rangle \otimes |L\rangle + \psi_R(\gamma_+)|\gamma_+\rangle \otimes |R\rangle\}, \tag{7}$$

where $|\gamma_+\rangle$ is the γ_+ eigenstate, and $\psi_L(\gamma_+)$ and $\psi_R(\gamma_+)$ are the coefficients including the amplitude (*i.e.*, not normalized). The quantity $E[\psi_L, \psi_R] \equiv |\int\psi_L^*(\gamma_+)\,\psi_R(\gamma_+)d\gamma_+|^2/\{|\int\psi_L^*(\gamma_+)\psi_L(\gamma_+)\,d\gamma_+||\int\psi_R^*(\gamma_+)\psi_R(\gamma_+)d\gamma_+|\}$ indicates the entity of the entanglement between the qubit and the SQUID. $E[\psi_L, \psi_R]$ =1,0 means no entanglement (separable) and maximum entanglement, respectively.

If the measurement with the SQUID were a σ_z measurement as introduced above, the observed switching current would appear at a value corresponding to $\psi_L(\gamma_+)$ or $\psi_R(\gamma_+)$, probabilistically. Therefore, if $\psi_L(\gamma_+)$ were not proportional to $\psi_R(\gamma_+)$ and $E[\psi_L, \psi_R] \approx 1$, the switching current would split into two values even for a one qubit state at absolute zero temperature. However, when we carried out numerical calculations on the time evolution of the density operator of the total system [7], we found that total system wavefunctions with low energies are not entangled states but separable states, that is, $E[\psi_L, \psi_R] \approx 1$ ($\psi_L(\gamma_+) \propto \psi_L(\gamma_+) \equiv \psi(\gamma_+)$). Only the position in the γ_+ coordinate of the wavepacket $\psi(\gamma_+)$ depends on the qubit state. And the obtained switching current corresponds to that of $\psi(\gamma_+)$, which is a single value, in contrast to the case of the entangled state mentioned above. In addition, the numerical calculation showed that the switching current has a two-value distribution in the presence of strong decoherence, which destroys the qubit superposition [7]. This explains the classical case in Fig. 3(b).

We find that the center position of the wavepacket $\psi(\gamma_+)$ is approximately the bottom of the potential $V_{SQ}(\gamma_+;\sigma_z = 2|a|^2 - 1)$ by variational calculation. The resulting switching current becomes that for a usual SQUID with this potential. This value coincides with the quantum-mechanical average I_{sw} of the switching current for the qubit $|\psi\rangle = a|L\rangle + b|R\rangle$. The fact that the switching current behaves as the average value, which may at first seem strange, is explained as described above. Moreover, this indicates a very important fact about the DC-SQUID measurement of flux-qubit states. The measurement is not a projection measurement that determines whether the qubit is $|L\rangle$ or $|R\rangle$. It is a simple measurement of the weight $|a|^2(= 1 - |b|^2)$ of the qubit.

The flux ϕ_q induced by the qubit ring current has a large quantum fluctuation when the qubit is in a superposition state. The fluctuation of the measured switching current, however, has almost nothing to do with the fluctuation. The switching current fluctuation is caused mainly by fluctuations of the SQUID itself. This may give us important clues for improving the measurement resolution.

3.3 Microwave irradiation

External driving by microwaves that invoke a transition between two states is important if we are to employ this superconducting ring as a qubit, because it is a typical way of controlling qubits. Therefore, we applied continuous microwaves to both samples to induce Rabi oscillation. The sample in Fig. 3(b) (without χ) did not respond to the microwaves while a resonant transition was observed for the sample in Fig. 3(a) (with χ). The readout is still well separated into the $|0\rangle$ and $|1\rangle$ states, even though the states are within continuous transitions between $|0\rangle$ and $|1\rangle$ via the superposition. This indicates that projective single-shot measurement is also achieved against the superposition state as $|\psi\rangle = a|L\rangle + b|R\rangle$. The dephasing time of the ring is estimated from the resonant width of the averaged resonance curve as $T_2^* \approx 5$ ns. This means that during this time scale, the coherence of the ring is sustained because the measurement is effectively switched off even if the DC-SQUID is permanently aligned close to the ring. However once switching occurs, the DC-SQUID will provide a measurement result with sufficient resolution. This is mainly a contribution of the under-damped characteristics of the DC-SQUID.

4. Conclusion

I described our experiments on superconducting flux-qubits and the successful measurement of the qubit state with a DC-SQUID, in a single-shot manner. We achieved MQC in a small superconducting ring, which is the superposition of two macroscopically distinct states $|L\rangle$ and $|R\rangle$. And we detected the existence of this superposition using an under-damped DC-SQUID, which is a very sensitive magnetic-flux probe with high resolution.

In previously reported superconducting qubit experiments, an extremely large number of results had to be averaged to detect the qubit state. We succeeded in obtaining sufficient resolution to distinguish the qubit state with only one measurement. This single-shot measurement result posed a new question regarding what is observed as the SQUID switching current, especially when the qubit is in a superposition state $|\psi\rangle = a|L\rangle + b|R\rangle$. Theoretical analysis with numerical calculations provided the answer that the switching current reflects $2|a|^2 - 1$, which is a continuous value for a superposition state between two localized states $|L\rangle$ and $|R\rangle$. This explains why the switching current behaves almost identically to the quantum-mechanically averaged value $\langle I_{cir}\rangle$ of the qubit circulating current. The result reported here is a direct observation of macroscopic superposition, while identifying each measurement event separately. I believe that single-shot/single-system quantum measurement will further aid our understanding of the quantum measurement process, which is interesting as regards both pure science and engineering, in conjunction with the recent rapid development of nano-technology.

Acknowledgments

I thank my co-workers, Dr. H. Tanaka, Dr. S. Saito, Dr. H. Nakano, and Professor M. Ueda. I also acknowledge Professor J. E. Mooij, Professor C. J. P. M. Harmans, Dr. C. van der Wal, Dr. Y. Nakamura, and Professor M. Devoret for useful discussions, and Dr. Y. Sekine, K. Shan Kivong, M. Golden, S. Kohlar, and E. Laffose for sample fabrication. The measurement system was partly developed by Professor P. Delsing and Professor T. Claeson. I also thank Dr. S. Ishihara for his warm encouragement throughout the course of this work.

References

[1] J. R. Friedman, V. Patel, W. Chen, S. K. Tolpygo, and J. E. Lukens, "Quantum superposition of distinct macroscopic states," Nature, Vol. 406, pp. 43-46, 2000; C. van der Wal, *et al.*, "Quantum Superposition of Macroscopic Persistent-Current States," Science, Vol. 290, pp. 773-777, 2000; John M. Martinis, S. Nam J. Aumentado, and C. Urbina, "Rabi Oscillations in a Large Josephson-Junction Qubit," Phys. Rev. Lett., Vol. 89, pp. 117901-117904, 2002; C. van der Wal, "Quantum superpositions of persistent Josephson currents," Ph. D. thesis, Delft Univ. Press, 2001.

[2] Y. Nakamura, Yu. A. Pashkin, and J. S. Tsai, "Coherent control of macroscopic quantum states in a single-Cooper-pair box," Nature, Vol. 398, pp. 786-788, 1999; Y. Yu, S. Han, X. Chu, S. Chu, and Z. Wang, "Coherent Temporal Oscillations of Macroscopic Quantum States in a Josephson Junction," Science, Vol. 296, pp. 889-892, 2002.

[3] D. Vion, *et al.*, "Manipulating the Quantum State of an Electrical Circuit," Science, Vol. 296, pp. 886-889, 2002.

[4] H. Tanaka, Y. Sekine, S. Saito, and H. Takayanagi, "DC-SQUID readout for qubit," Physica C, Vol. 368, pp. 300-304, 2002; H. Takayanagi, H. Tanaka, S. Saito, and H. Nakano, "Observation of qubit state with a DC-SQUID and dissipation effect in the SQUID," Physica Scripta, Vol. T102, pp. 95-102, 2002; H. Tanaka, S. Saito, and H. Takayanagi, "Quantum Classical Crossover with Superconducting Ring," pp. 366-372 in Toward the Controllable Quantum States, edited by H.Takayanagi and J.Nitta (World Scientific Pub., Singapore, 2003).

[5] A. O. Caldeira and A. J. Leggett, "Influence of Dissipation on Quantum Tunneling in Macroscopic Systems," Phys. Rev. Lett., Vol. 46, pp. 211-214, 1981; A. J. Leggett and A. Garg, "Quantum mechanics versus macroscopic realism: Is the flux there when nobody looks?" Phys. Rev. Lett., Vol. 54, pp. 857-860, 1985.

[6] J. E. Mooij, *et al.*, "Josephson Persistent-Current Qubit," Science, Vol. 285, pp. 1036-1039, 1999.

[7] H. Nakano and H. Takayanagi, "Dynamics in the read-out process of the superconducting flux-qubit," J. of Phys. Soc. Jpn, Suppl. A, Vol. 72, pp. 1-2, 2003; H. Nakano and H. Takayanagi, "Dynamics of Superconducting Flux-qubit Measurements by DC-SQUID," pp. 359-365 in Toward the Controllable Quantum States, edited by H. Takayanagi and J. Nitta (World Scientific Pub., Singapore, 2003).

Hideaki Takayanagi
NTT R&D Fellow, Director, NTT Basic Research Laboratories.

He received the B.S., M.S., and Ph.D. degrees in science from the University of Tokyo in 1975, 1977, and 1987, respectively. In 1977, he joined the Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation (now NTT), Tokyo, Japan. Since 1985 he has been working on superconducting quantum device physics. In 2000 he was awarded the Nissan Science Prize. He also works as a visiting professor in the University of Tokyo and Tokyo University of Science. Dr. Takayanagi is a member of Physical Society of Japan, the Japan Society of Applied Physics, and the American Physical Society.