Review

Toward a superconducting quantum computer
Harnessing macroscopic quantum coherence

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Abstract: Intensive research on the construction of superconducting quantum computers has produced numerous important achievements. The quantum bit (qubit), based on the Josephson junction, is at the heart of this research. This macroscopic system has the ability to control quantum coherence. This article reviews the current state of quantum computing as well as its history, and discusses its future. Although progress has been rapid, the field remains beset with unsolved issues, and there are still many new research opportunities open to physicists and engineers.

Keywords: Josephson junction, quantum coherence, quantum computing, superconductivity, qubit, macroscopic quantum state

1. Introduction

Quantum information science, on which the idea of the quantum computer is based, rests on the fusion of two pinnacles of 20th century scientific achievements: quantum mechanics and information science. The fusion of these two breakthroughs has resulted in a new paradigm in the science of information and control that has the potential to start a revolution in many branches of science and technology in the 21st century, just as its direct predecessors did in the past century.

The ability to process, record and transmit information is one of the very foundations of civilization. Quantum information technology, which makes use of coherent quantum states, has shown promise as a next-generation technology that could offer groundbreaking performance in computing and communications. ‘Coherence’ in the quantum sense refers to the ability of quantum states to interfere with one another. Quantum computing is a totally new computing paradigm that could efficiently solve some of the important problems that cannot be addressed by existing computers. The sequence of advances in information-processing technology that have sustained the march of modern civilization will soon run into a number of limits, including the limits of Moore’s Law, the limits of energy resources for information processing and the theoretical limits on the information processing power of classical computers. Quantum information is a remarkable technology that will provide an exponential acceleration of computing speed and reduce the amount of energy required for computation by several orders of magnitude, thus relaxing the constraints of these limits.

Initially developed in the 1930s to explain the behavior of atoms, quantum mechanics is a milestone of modern science. Research on semiconductors based on quantum theory led to the development of the transistor in 1948 and the first transistor-based computers in the mid-1950s. However, semiconductor-based electronic devices and computers operate via the control of classical physical states. By contrast, the probabilistic interpretation of quantum theory, the coherence of quantum states, quantum superposition, quantum non-locality and quantum entanglement deviate radically from classical theory and reject classical realism, and are thus much less intuitive to understand.

Quantum states had long been considered for their applications to limited microscopic systems, including atoms, molecules and photons. In 1995, a team of scientists created a microscopic qubit logic gate that controlled the states of two atoms (ions). More recently, advances in experimental techniques have led to the generation, manipulation and obser-
vation of quantum coherence in macroscopic physical systems such as superconducting circuits and semiconductor quantum dots that realize qubits. Nearly 50 years since the realization of a transistor based on quantum mechanics, scientists have finally created a solid-state device that allows the control of quantum states.

Electronic states in a superconducting circuit are associated with macroscopic numbers of electrons. There was a theoretical prediction that such a huge population of electrons would produce a coherent quantum state, a ‘quantum superposition’. The practical realization of the quantum state was nevertheless a surprise, and an important discovery that stimulated new perspectives on physics. Moreover, this particular achievement provided a deeper understanding of the decoherence phenomenon that exists at the boundary between classical theory and quantum theory, opening the way to a microscopic understanding of the incompleteness of the materials that enhance this phenomenon. From an engineering perspective, the control of quantum coherent states by a solid-state device is an important field of research that should advance to applications in quantum computers in the future, and has already had significant impacts on research in quantum information processing, an innovative area of research currently in the making.

The quantum bit is the building block of quantum computing. A solid-state qubit offers relatively easy integration, which is generally difficult in microscopic systems, and has a degree of freedom in the design of the qubit energy and other circuit parameters that was previously impossible in microscopic systems. In addition, the solid-state qubit has the major advantage of allowing the coupling of qubits to be switched on and off by external control.

Few scientific discoveries usually give rise to new technologies that, in turn, nurture further advances in science. Science and engineering thus progress through a complementary and synergistic relationship. Advances in each respective field occur alternately in the manner of a swinging pendulum, continuing the progress of civilization. Quantum coherence in macroscopic systems is an important scientific discovery that has finally been achieved by a deeper understanding of basic physics as well as advancements in engineering, including technologies such as cryogenic cooling, nano-micro circuit production, integrated microwave circuits, low noise electrical characterization and other composite technologies. On the basis of the vast array of knowledge in physics that has been gained through these recent advances, intense research efforts are now being devoted to swinging the pendulum all the way back to the engineering side in order to take the next revolutionary step in information technology.

This article describes a range of research efforts that have been made toward realizing the superconducting quantum computer, including a brief introduction to quantum computing as well as a review of the physics of macroscopic quantum coherence and Josephson-junction qubits.

2. Quantum coherence in macroscopic systems

Is an object with macroscopic scale capable of quantum-mechanical behaviors, including quantum coherence? Where is the boundary between the scales where classical theory holds and where quantum theory is required? These are the important questions, exemplified by the paradox of Schrödinger’s cat, that were raised in the very early days of quantum mechanics. The definition of the term ‘macroscopic’ is relatively ambiguous, but here it is simply used to describe a system containing a large number of particles.

The Josephson junction is a solid-state device of macroscopic dimensions that has a structure in which two superconductors are weakly coupled, allowing Cooper pair transport (see Fig. 1). The superconducting electron state is described by the macroscopic wavefunction (order parameter) \( \Psi(x) = \Psi_0(x) e^{i \varphi(x)} \), and the supercurrent flowing through the Josephson junction is represented by \( I = I_0 \sin \theta \), where \( \theta = \varphi(x_1) - \varphi(x_2) \) is the phase difference between the two ends across the Josephson junction, \( \varphi \) is the phase of the macroscopic wavefunction, and \( I_0 \) is the maximum Josephson current (a constant). The voltage difference \( V \) at the junction is the product of the temporal variation in the phase difference and the fundamental physical constant, and is expressed as \( V = (h/2e)(d\varphi/dt) \). This is called the Josephson relationship.

Current and voltage are the physical quantities that directly reflect the phase difference in the macroscopic wavefunction. The Josephson effect is therefore also called the macroscopic quantum effect. Despite being a macroscopic system, the Josephson junction is one of the purest and most elegant objects in the world of physics, because the state in the junction can be described accurately by such a simple formula.
Is it thus possible to realize a coherent quantum superposition state such as \( \Psi = \Psi_1 + \Psi_2 \) in the state represented by this macroscopic wavefunction, as in the case of the true Schrödinger’s wavefunction? Is it also possible for this state to maintain coherence for a finite period? Coherence in superconductors needs to be maintained for a relatively long period because, unlike metals and semiconductors, superconductors possess a superconducting ground state without dissipation, and the excitation of quasiparticles, which is the source of the dissipation, is suppressed by the superconducting gap.

The superconducting quantum interference device (SQUID), an ultra-sensitive fluxmeter, consists of the Josephson device and a superconducting loop [Fig. 2(b)]. The supercurrent flowing through the fluxmeter is expressed by \( I = I_L + I_R = I_{0L} \sin \theta_L + I_{0R} \sin \theta_R \). When the magnetic flux quantization relationship \( \theta_L - \theta_R = \frac{2\pi \Phi}{\Phi_0} \) is used, the maximum supercurrent flowing through the SQUID is given by

\[
I_{\text{max}} = 2I_0 \left| \cos \frac{\pi \Phi}{\Phi_0} \right|
\]

where \( I_0 = I_{0L} = I_{0R} \), \( \Phi \) is the magnetic flux in the superconducting loop, \( \Phi_0 = \hbar/2e \) is the flux quantum, and the shielding flux \( \Phi_S \) is negligible (\( \Phi_S \ll \Phi_0 \)). This is the interference effect caused by the fact that the macroscopic phase difference is coherently maintained in the loop. Nevertheless, the supercurrents \( I_L \) and \( I_R \) flowing through the two branches of the superconducting loop are still classical quantities, and their relationship is given by \( I = I_L + I_R \) and not by the quantum superposition \( |I\rangle = |I_L\rangle + |I_R\rangle \), as can clearly be seen by considering the difference between the SQUID and the interference of light (Fig. 2(a)). In the double-slit interference of light, a single photon is a quantum wave passing through either both the left or right slit, creating the quantum superposition state defined by \( |\text{Right}\rangle + |\text{Left}\rangle \). By contrast, the supercurrent flowing through the SQUID is classical current that can flow through either branch of the loop, creating a classical current superposition. This introduces the following question: how can we prepare the state for quantum behavior in the superconducting system?

3. Macroscopic quantum tunneling and macroscopic quantum levels in superconducting systems

In the quantum treatment of the Josephson junction, the phase difference across the junction (\( \theta \)), and its conjugate quantity, the difference in the numbers of Cooper pairs across the capacitor (\( N \)), need to be treated as operators. In this case, the Hamiltonian of the Josephson junction is given by

\[
H = E_c N^2 E_3 (1 - \cos \theta)
\]

\[
E_c = \frac{2e^2}{C}
\]

\[
E_3 = I_0 \Phi_0,
\]

where \( E_c \) is the charging energy of the junction equivalent to a single Cooper pair accumulated in the capacitance \( C \) of the junction, and \( E_3 \) is the Josephson energy and the indicator of the strength of the Josephson junction. The Cooper pair’s uncertainty relationship \( \Delta\theta \Delta N \geq 1/2 \) holds because \( \theta \)
and $N$ are in a conjugate relationship. In the Josephson circuit, the microscopic freedom of the individual electrons is lost, absorbed by the macroscopic degrees of freedom $\theta$ and $N$, resulting in a very simple physical system. If $E_3 \gg E_c$, the quantum fluctuation is small for $\theta$ and large for $N$. The opposite holds if $E_3 \ll E_c$.

If $E_3 \gg E_c$, the dynamics of the junction can be approximated as the movement of a classical particle with mass $(\Phi_0/2\pi)^2 C$ moving in the ‘washboard potential’, which has the phase space as its parameter under current bias $I_0$, as expressed by

$$U(\theta) = E_1 \left(1 - \cos \theta - \frac{I_0}{I_0} \theta \right).$$

If $I_b < I_0$, the classical particle remains in the potential well, and has a certain stationary phase value.

From the Josephson relationship and the law of induction voltage $V = -LdI/dt$, it follows that the Josephson junction has the intrinsic nonlinear inductance $L_J = \Phi_0/\Phi_0 \cos \theta$. LC plasma resonance occurs between this Josephson inductance and the capacity $C$ of the junction, where the plasma frequency is given by $\omega_p = (L_J C)^{0.5} = (2E_cE_3)^{0.5}/h$.

In the classical picture, the phase oscillates at this frequency, and the resulting time-averaged voltage is zero. In the quantum picture, by contrast, by confining the oscillating phase within the potential well $U(\theta)$, a quantized energy level emerges. The difference in energy between levels is equivalent to the plasma frequency $\omega_p$ (Fig. 3). The quantized energy level emerges from the quantum treatment of the quantities $\theta$ and $N$, and is called the secondary macroscopic quantum effect.

Although it describes the state of the Josephson junction involving a macroscopic number of electrons, the macroscopic phase $\theta$ exhibits quantum behavior. This behavior was experimentally confirmed for the first time by the observation of macroscopic quantum tunneling. A range of experiments have provided evidence that a virtual particle that moves along the potential $U(\theta)$ in the macroscopic quantum state with phase freedom is not a classical particle but instead a quantum particle that can tunnel through the potential. Moreover, the existence of a discrete level such as that shown in Fig. 3 was confirmed by the photon-assisted macroscopic quantum tunneling experiment. Although only a single Bardeen Cooper Schrieffer (BCS) superconducting ground state is formed in a superconductor, by employing the Josephson junction it is possible to create multiple anharmonic macroscopic energy levels in such systems due to the nonlinearity of the Josephson Effect.

### 4. Macroscopic quantum coherence in superconducting systems—eigenstates

Quantum information processing takes crucial advantage of the fact that qubits can have discrete energy levels, as found in atoms. Besides the current-biased Josephson junction mentioned above, there are two other important circuits that can achieve these energy bands. One is the flux qubit circuit (Fig. 4), which uses the quantized flux state $|m\rangle$ with a small fluctuation of the phase $\theta$ where $E_3 \gg E_c$, and the other is the charge qubit circuit (Fig. 5), which uses the quantized charge-number state $|n\rangle$ with a small fluctuation of the charge number $N$ where $E_3 \ll E_c$.

The flux qubit consists of a Josephson junction and a superconducting loop (Fig. 4(a)), and its Hamiltonian can be described as follows when the neighboring field states $|m\rangle$ and $|m + 1\rangle$ are designated as the qubit bases:

$$H = -\frac{1}{2} (\varepsilon_\Phi \sigma_z + \Delta \sigma_x)$$

$$\varepsilon_\Phi = \frac{(mF_0 - \Phi_{ex})^2 - [(m + 1)F_0 - \Phi_{ex}]^2}{2L}$$

$$\Delta = \frac{F_{ex}^2}{2L} \left(\frac{\Phi_{ex}}{F_0} - 1\right).$$

![Diagram of macroscopic quantum tunneling](image-url)
Here, $\sigma_x$ and $\sigma_z$ are Pauli operators. The magnetic flux in the superconducting loop is quantized to form the quantum state $|m\rangle$, in which $m$ fluxes are retained. If the shielding flux $\Phi_S$ is sufficiently small as $\Phi_S = I_0L \ll \Phi_0$, then increasing the externally applied magnetic field $\Phi_{ex} = I_{ex}M$ (where $I_{ex}$ is current flowing through the magnetic field application coil, and $M$ is the mutual inductance between the external coil and superconducting loop) will cause the flux quantum to enter and exit the loop near
\( \Phi_{ex} = (m + 0.5)\Phi_0 \) and change the flux state \( m \). Also in this equation, \( \varepsilon_e \) is the difference in the magnetic field energy \( \Phi^2/2L (\Phi = m\Phi_0 - \Phi_{ex}) \) [the difference between the dotted lines in Fig. 4(b)], \( L \) is the effective loop inductance and \( \Delta \) is the energy of the macroscopic quantum tunneling of the magnetic flux mentioned above.

Neighboring flux states are coupled via coherent quantum tunneling of magnetic flux, and the coupling strength is expressed as \( \Delta \). To change the flux content in the superconducting loop, it is normally necessary to destroy the superconducting state. However, if this type of coherent coupling exists, then the flux content can also be changed without dissipation (distraction of superconductivity).

Figure 4(b) shows an energy schematic diagram for a flux qubit. The horizontal axis indicates the onset of the magnetic \( \Phi \) tunneling near \( \Phi_{ex} \), the horizontal axis indicates the difference of superconductivity). \( \Phi_{ex} \) content can also be changed without dissipation necessary to destroy the superconducting state. How-ever, if this type of coherent coupling exists, then the flux content can also be changed without dissipation (distraction of superconductivity).

Figure 4(b) shows an energy schematic diagram for a flux qubit. The horizontal axis indicates the external flux \( \Phi_{ex} \). In overlapping magnetic field energy curves \((m\Phi_0 - \Phi_{ex})^2/2L\) (the dotted lines in Fig. 4(b) corresponding to the flux state \(|m\rangle\), the onset of the energy gap \( \Delta \) occurs as the degeneracy between the neighboring flux states is lifted by coherent flux tunneling near \( \Phi_{ex} = \Phi_0(m + 0.5) \). Figure 4(c) shows a schematic diagram of the energy of qubits with respect to \( \theta \), as in Fig. 3. This diagram also shows the potential \( U(\theta) \) at \( \Phi_{ex} = \Phi_0(m + 0.5) \). In this case, \( U(\theta) \) has the additional term of the magnetic field energy of the loop from equation \( [2] \).

Under these conditions, two symmetrical potential wells of \( U(\theta) \) are formed, and two symmetrical quantized ground states emerge in these wells. At \( \Phi_{ex} = 0.5\Phi_0 \), these two energy levels are coupled via coherent macroscopic quantum tunneling associated with tunneling of flux quanta in the loop. As a result, the degeneracy in the energy is lifted and an energy gap corresponding to the coupling energy \( \Delta \) emerges, as shown in Fig. 4(b) and 4(c).

The charge qubit is composed of a Josephson junction and a superconducting box (single Cooper pair box), and the Hamiltonian is described as follows, when the neighboring charge-number states \(|n\rangle \) and \(|n + 1\rangle \) are designated as the qubit bases:

\[
H = -\frac{1}{2}(\varepsilon_e \sigma_z + E_1 \sigma_x)
\]

\[
\varepsilon_e = \frac{(2ne - Q_{ex})^2}{2C} - \frac{[(n + 1)e - Q_{ex}]^2}{2C}
\]

\[
\varepsilon_e = \frac{4e^2}{C}(\frac{Q_{ex}}{e} - 1).
\]

The number of Cooper pairs in the box is quantized, and the quantum state \(|n\rangle \) is formed in which \( n \) excess Cooper pairs are retained (Fig. 5(a)). If the externally applied charge \( Q_{ex} = C_g V_g \) (where \( C_g \) is the gate capacitance, and \( V_g \) is the gate voltage) is increased, then only a single Cooper pair will enter and exit the box near \( Q_{ex} = 2\varepsilon(n + 0.5) \), and the charge-number state \( n \) will change. In this equation, \( \varepsilon_e \) denotes the difference in charge energy \( Q^2/2C \) (where \( Q = 2ne - Q_{ex} \)) between two neighboring charge-number states (the difference between the two dotted lines in Fig. 5(b)), \( C \) is the effective capacitance of the box, and \( E_1 = E_J \) is the Josephson energy.

The neighboring charge-number states are coherently coupled without dissipation via coherent Cooper pair tunneling, and the coupling strength is given by \( E_J \).

Figure 5(b) shows the energy schematic diagram for a charge qubit. The horizontal axis indicates the external charge \( Q_{ex} \). The overlapping charge energy curves \((2ne - Q_{ex})^2/2C\) (dotted lines in Fig. 5(b)) correspond to the charge-number state \(|n\rangle \), and the onset of the energy gap \( E_1 \) occurs as the degeneracy between the neighboring states is lifted by coherent Cooper pair tunneling near \( Q_{ex} = 2\varepsilon(n + 0.5) \). Figure 5(c) shows a schematic diagram of the energy of the qubits with respect to \( \theta \) as in Fig. 3. This diagram also shows \( U(\theta) \) without the junction bias current. Given that \( E_J \ll E_C \), there is a large fluctuation in the phase, so the localized phase state bounded in the potential well of \( U(\theta) \) cannot be formed, and extended energy bands will form in the phase space. In this case, the forbidden band (energy gap) corresponding to \( E_J \) is formed as shown in the diagram.

Near the degeneracy point for the magnetic field energy or the charge energy \( \Phi_{ex} = \Phi_0(m + 0.5) \) in Fig. 4(b) or \( Q_{ex} = 2\varepsilon(n + 0.5) \) in Fig. 5(b)], the neighboring flux states or charge-number states are superposed by the coherent interaction, and a new eigenstate is formed. At the degeneracy point, the following two states are realized, and energy bands are formed at two levels as a result:

Superposition state of flux state

\[
\frac{1}{\sqrt{2}}(|m\rangle \pm |m + 1\rangle)
\]

Superposition state of charge state

\[
\frac{1}{\sqrt{2}}(|n\rangle \pm |n + 1\rangle)
\]
Therefore, the observation of such energy bands implies the existence of macroscopic quantum coherence.

In an experiment attempting the direct spectroscopic observation of energy bands in a single Cooper pair box, we demonstrated the existence of the energy gap for the first time.9) A gate-controlled change in the average charge number, reflecting the onset of the energy gap, was observed using a single Cooper pair box.10) These experiments correspond to the observation of the ground state and the excited state of the energy eigenstate generated by the macroscopic quantum superposition of charge-number states (Fig. 5(b)). Subsequently, teams of scientists succeeded in the spectroscopic observation of the energy eigenstate generated by the macroscopic quantum superposition of flux states.11),12)

5. Superconducting qubit device—
   phase control

More generally, the superposition of two quantum states $|0\rangle$ and $|1\rangle$ can be expressed as an arbitrary superposition state:

$$\Psi = \cos \alpha |0\rangle + e^{i\beta} \sin \alpha |1\rangle$$

$$0 \leq \alpha < \frac{\pi}{2}, \quad 0 \leq \beta < 2\pi$$

where $2 \alpha$ is the angle that defines the amplitude of the state and $\beta$ is the angle that defines the phase of the state. These two angles define the surface of the Bloch sphere (Fig. 6). The qubit, which is the fundamental unit for quantum information processing, is the superposition of such $|0\rangle$ and $|1\rangle$ states.

To be able to execute the quantum algorithm, the qubit state needs to be arbitrarily controlled on the Bloch sphere. The qubit can be modeled as a virtual spin inherent in the Bloch sphere. The north and south poles of the Bloch sphere correspond to the $|0\rangle$ and $|1\rangle$ states, respectively. In this model, the energies associated with the Pauli operators $\sigma_x$ and $\sigma_z$ in Equations [3] and [4] are the external magnetic fields in the $x$- and $z$-axis directions, respectively. The qubit state can be described as the spin parallel to the vector sum of the two magnetic fields. The strength of the vector sum magnetic field that moves the virtual spin (rt.$\sqrt{\Delta^2 + \varepsilon_F^2}$ in the flux qubit and $\sqrt{E_J^2 + \varepsilon_e^2}$ in the charge qubit) is equivalent to the qubit energy $E$, which is the energy difference between qubit states $|0\rangle$ and $|1\rangle$.

In preparing the eigenstate by the static superposition described in the previous chapter, changing the external flux and the external charge will change the angle ($x$) and amplitude of the superposition, but will not change the phase angle ($\beta$). The ground states in Figs. 4(b) and 5(b) are shown as the green line on the Bloch sphere in Fig. 6. Controlling the quantum state by means of this quasi-static magnetic field does not change the phase of the qubit and is generally not useful for quantum information processing, in which quantum interference is frequently used. To control the phase, a transition from the ground state to the excited state is needed. We now describe one specific example of qubit control that enables phase control.

Yasunobu Nakamura, Yuri Pashkin and I have
succeeded in freely controlling the quantum state of the charge qubit on the Bloch sphere in the experiment using the superconducting Cooper pair box, a significant bit of headway in the study of solid-state qubits. In this early experiment, we succeeded in inducing quantum oscillations by rapid non-adiabatic changes in the gate voltage of the charge qubit. In the context of virtual spin space (Fig. 6), when the effective magnetic field changes rapidly with a time constant faster than the coherent time ($\hbar/E_J$), the spin will lose parallelism to the magnetic field because the spin cannot follow the fast movement of the magnetic field.

Then the non-adiabatically changing external charge reaches the degeneracy point, the virtual spin will start precessing, with period $\hbar/\Delta E$, around the effective magnetic field that is not parallel to the virtual spin. This is the quantum oscillation observed in the experiment. Using this method, we realized a qubit state with an arbitrary phase by the control of bias charge, and succeeded in one-qubit control. Figure 7 shows this first superconducting qubit, the observed quantum oscillation and the simulation. We used a thin aluminum film as the superconductor, which allowed the easy creation of a tunnel barrier in the Josephson junction.

Unlike the device shown in Fig. 5, the superconducting box in this case is connected to the external electrode via two Josephson junctions. This SQUID-like design has the advantage of allowing control of the effective Josephson energy using an external magnetic field. The readout of the quantum state was performed by observation of the transport current flowing through the readout junction, which is dependent on the excess charge of the island. In Fig. 7, which shows the quantum oscillation, the $z$-axis corresponds to the probability of the observed $|1\rangle$ state, the $x$-axis to the static external charge applied to the device, and the $y$-axis to time.

In the above experiment, with control of the quantum state in the time domain, we achieved a quantum superposition of a solid state two-level system for the first time. The phase angle $\beta$ of the resulting coherent state rotated at the frequency $\Delta E/\hbar$. The generation and control of the coherent state (amplitude and phase) in such a macroscopic system has been our long-standing research goal. The clear demonstration of quantum coherent control has motivated many researchers to jump into this new field of research, leading to many great advances.

A qubit control method called ‘Rabi oscillations’, first developed in atomic systems, as opposed to non-adiabatic bias manipulation, was also achieved using superconducting qubits. Microwave irradiation at a wavelength corresponding to the qubit energy $\Delta E$ causes the qubit state to undergo a transition between the $|0\rangle$ and $|1\rangle$ states, and the transition probability oscillates temporally with frequency as expressed by $\omega_{\text{Rabi}} = J(V_{ac})\Delta E 2\pi/\hbar$, where $J(V_{ac})$ is a Bessel function dependent on the microwave intensity.

In this case, the virtual spin in the Bloch sphere undergoes a complex movement in which the tip of the spin traces out a helical trajectory curve. In the rotating coordinate system that rotates around the $z$-axis at microwave frequency, the complex spin rotation can be understood as a precession around an axis that resulted from the rotation of the $x$-axis along the equator by the phase angle of the microwave $\beta$. With this technique, a qubit state with an arbitrary phase can be achieved by temporal control of microwave irradiation, thus achieving the control of one qubit.

The control of qubits based on Rabi oscillations was later used in experiments on many different types of superconducting qubits. Successful experi-
ments on quantronium-type charge qubits (a qubit having the same structure as the charge qubit in Fig. 7, but with lower charge energy),\textsuperscript{14} flux qubits\textsuperscript{15,16} and phase qubits (explained in the following paragraphs)\textsuperscript{17,18} have been reported. Microwave irradiation was used in all of these experiments. This method is advantageous over non-adiabatic control in terms of the accuracy of state control and its ability to protect qubits from decoherence by utilizing the optimal bias point, which will be described in the following section.

Figure 8 shows a photograph of a typical flux qubit. A device made of thin aluminum film. The readout SQUID latches on to the voltage state when the $|1\rangle$ state is detected.

6. Decoherence

There is no such thing as a “closed system” in the universe, and no physical system is completely isolated from its environment. Qubits are no exception. No matter how perfect, qubits eventually lose coherence through interactions with the external degree of freedom. Decoherence occurs mainly by processes associated with two types of time constant: the energy relaxation time $T_1$ for relaxation from the higher state of energy $|1\rangle$ to the lower state $|0\rangle$, and the dephasing time $T_2$ during which the phase becomes indeterminate. The relationship between the two time constants is given by $1/T_2 = 1/2T_1 + 1/T_0$, where $T_0$ is the ‘pure phase perturbation time’.

Because quantum computation can only be performed while the coherence of the computer is maintained, the decoherence time must be sufficiently long. This condition, which is not found in classical computers, is the most challenging obstacle to constructing a quantum computer. Experimentally, the decoherence time of superconducting qubits has been increasing at a remarkable pace since the first experiment in 1999.

The evolution of the decoherence time is shown in Fig. 9. With advances in technology, researchers have succeeded in extending the decoherence time by five orders of magnitude over just 10 years. The yellow circle in the diagram denotes the $T_2$ value achieved in the Ramsey interference experiment, and the red circle is that obtained by the echo technique. The Ramsey fringe experiment is an experiment in which the pseudo-spin is rotated along the equator of the Bloch sphere. In the quantum oscillations in Fig. 7, the state is rotated along the great circle that passes through the north and south poles of the Bloch sphere. The echo technique is designed to effectively suppress fluctuations of phase caused by low-frequency noise by the additional 180° rotation around the $z$-axis between the Ramsey rotation.\textsuperscript{19}

The improvement of the phase relaxation time by the echo technique suggests the existence of low-frequency noise. The dominant low-frequency fluctuations responsible for this phase relaxation have
been attributed to charge fluctuations\(^ {19} \) in charge qubits and flux fluctuations\(^ {20} \) in flux qubits. The cause of energy relaxation for charge qubits is also limited by the fluctuation of the charge degree of freedom.\(^ {21} \)

The microscopic mechanism and distribution of such fluctuations of charge and flux have yet to be clarified. Using the echo technique, the phase relaxation time can be readily improved to \( T_2 \cong 2T \)\(^ {20} \) in many types of qubits. In such case, the decoherence is limited by the energy relaxation process. Some suggestions have been made as to the cause and microscopic mechanism of this energy relaxation, but the truth remains elusive.\(^ {22}, {23} \)

Although charge qubits and flux qubits have nearly the same decoherence time, when biased at an optimized condition (see below), in general, the very-low-frequency charge noise is more detrimental in the actual experimental environment.

Including those in the studies depicted in Fig. 9, almost all qubits demonstrated to date have been made using vapor-deposited thin aluminum films with a natural aluminum-oxide film tunnel barrier. Future advances in materials research may be able to reduce the occurrence of the fluctuation sources compared with the present systems, resulting in dramatic enhancements of qubit performance.

The experiments within the white dotted circle in Fig. 9 are qubit manipulation experiments based on microwave pulsing at the operating point where the energy band is flat (see inset in Fig. 9). At the operating point, the fluctuation of the qubit energy is sufficiently suppressed despite the presence of the low-frequency fluctuation, and the decoherence time is effectively improved. Therefore, this operating point is called the optimal operating point.\(^ {14} \)

The decoherence time rapidly deteriorates with even a small displacement in bias from the optimal point.\(^ {24} \) The decoherence time rapidly deteriorates with even a small displacement in bias from the optimal point.\(^ {24} \) The decoherence time rapidly deteriorates with even a small displacement in bias from the optimal point.\(^ {24} \) The decoherence time rapidly deteriorates with even a small displacement in bias from the optimal point.\(^ {24} \) This suggests that the allowable range of operation (operation margin) is relatively narrow for this type of Josephson qubit.

The qubit is basically a reversible computing device. According to Landauer’s principle, non-reversible logic operations involving the erasure of information are thermodynamically non-reversible, thereby requiring an increase in the relevant thermodynamic entropy and involving a minimum energy dissipation of \( k_B T \ln 2 \). However, the possibility of energy consumption below this limit in a reversible logic operation is subject to debate.\(^ {24} \) In classical devices, energy consumption below the thermal limitation is being established.\(^ {25} \) By contrast, the basic premise of a qubit device is its reversibility without energy dissipation, but in reality, the qubit device has a finite energy relaxation time, and non-zero energy dissipation.
The longest energy relaxation time experimen-
tally obtained to date for solid-state qubits is approximately 10 ms, which was obtained for a superconducting flux qubit. The energy dissipation per gate operation estimated from the relaxation time is less than $10^{-6}$ of the thermal energy $k_B T \ln 2$ at temperatures in the tens of millikelvin (assuming 1 GHz gate operation). It is experimentally established that the superconducting qubit is sufficiently below the index of low energy dissipation, which is the most striking characteristic of reversible computing.

7. Readout method

The review above so far focuses on the experimental results for qubits. This section covers how the quantum state is read out from these systems. The readout technique used to determine whether the quantum state is $|0\rangle$ or $|1\rangle$ at a desired time is very important in qubit experiments. In the readout process, the virtual spin vector in the Bloch sphere that represents the coherent superposition state (Fig. 6) is projected into the pure $|0\rangle$ state or $|1\rangle$ state of the $z$-axis, and the phase information is lost. From Equation [5], the probability of being projected into $|0\rangle$ is $|\cos \chi|^2$, and the probability of being projected into $|1\rangle$ is $|\sin \chi|^2$. This probability can be obtained by repeating the experiment and readout many times and taking their average. However, it is desirable to perform a single-event readout in which the 0 or 1 determination is made by a single measurement without repetition. Moreover, it is most desirable to achieve a non-destructive quantum readout, in which the projected 0 or 1 state persists after a single-event readout.

Various readout experiments have been performed on various types of qubits, and can be broadly summarized as follows. In the case of two energy levels, e.g., the flux qubits and charge qubits shown in Figs. 4(b) and 5(b), the readout is performed by determining whether the state occupies the bottom band (ground state) or the top band (first excited state) (Fig. 10(a)). At the operating point $(\Phi_{ex}, Q_{ex})$, the slopes of the energy bands $\partial E / \partial \Phi$ and $\partial E / \partial Q$ correspond to the junction voltage and the orbiting current, respectively (Fig. 10(b)). Since the slopes of the two bands have different signs, the qubit state can be determined by measurement of either the current or the voltage. Observations via the readout junction of quasi particle transport derived from the island’s potential as well as experiments based on the single electron transistor (SET) have been used for reading the voltage in charge qubits. To read the current, the SQUID fluxmeter is generally used in both flux qubit and charge qubit systems.

Two conditions are generally required for single-event readout. One is sufficiently high readout efficiency (as close to 100% as possible) and the other is a much shorter readout time than the energy relaxation time $T_1$ of the qubit. Experiments based on SET and SQUID demonstrate high readout efficiency because of their high sensitivity characteristics. The introduction of the latching effect derived from the hysteresis characteristic facilitates faster readout. Specifically, the SQUID and the SET coupled with a single-electron trap with hysteresis in current-voltage characteristics are applied to achieve single-event readout.

Fig. 10. (a) Typical energy band. The blue dot is the optimal operating point for charge qubit and flux qubit. (b) The first derivative of the charge and flux corresponding to voltage and current, respectively. (c) The second derivative is proportional to the capacitance and inverse of inductance, respectively.
In these readout methods, when measuring the voltage and current, the signal will become zero at the optimal operating point where decoherence is strongly suppressed, because $\frac{\partial E}{\partial \Phi} = 0$ and $\frac{\partial E}{\partial Q} = 0$. Therefore, it is necessary to move the operating point adiabatically from the optimal operating point during the readout after the completion of qubit manipulation. This type of readout is generally destructive.

The ‘dispersive readout’ technique, which allows non-destructive readout at the optimal operating point, has attracted significant attention in recent years. The second derivative of the charge or flux of energy is proportional to the capacitance or the inverse of inductance, respectively (Fig. 10(c)), and the value reaches a maximum at the optimal operating point. When the qubit is connected to the outside $LC$ circuit, the resonance frequency will change according to the qubit state. In the decentralized readout method, this change is used for the readout. A change in the resonance frequency is normally observed as a change in the phase of the AC signal of the $LC$ circuit. The readout of the charge qubit with high visibility has been achieved based on this linear $LC$ circuit.\(^{27}\)

In another recently developed readout method, the dynamic bifurcation phenomenon resulting from the non-linearity of the Josephson junction is used as a dissipationless amplification switch, which is then incorporated into the $LC$ tank circuit.\(^{28}\) In this phenomenon, the resonance frequency of the Josephson junction is displaced to the low-frequency side with increasing driving ac voltage, generating hysteresis as a result. With this method, a stronger readout signal can be obtained than that obtained with the method based on the linear $LC$ circuit. One drawback is the relatively strong driving signal required to generate the bifurcation phenomenon, which results in unwanted energy relaxation of the qubit. Non-destructive quantum readout has also been achieved using the dispersive readout method based on the bifurcation switch for a flux qubit.\(^{29}\)

Destructive readout has been performed for the readout of phase qubits. Phase qubits have the energy level structure shown in Fig. 3, but the probability of macroscopic quantum tunneling (or barrier crossing by thermal energy) increases exponentially with the energy level. If this tunneling phenomenon occurs, the junction will switch to the voltage state. The observation of the transition from the $|1\rangle$ state to the voltage state is then used to read the phase qubit. Generally, microwave irradiation excites the $|1\rangle$ state to the $|2\rangle$ state with higher energy, causing a transition to the voltage state during readout.

Single-event readout has been achieved by incorporating a phase qubit into the superconducting loop, and by changing the phase state by modifying the $U(\theta)$ potential through application of a flux pulse during readout.\(^{30}\) In this case, the $|1\rangle$ state would induce a change in the phase state and cause a quantum flux to be trapped in the superconducting loop during readout; this is finally read out by the SQUID. This readout mechanism is the flux version of the experiment in ref. 25 that used a charge trap.

8. Quantum information processing and quantum algorithm

Quantum information processing is expected to be able to simultaneously handle vast orders of magnitude more information than is possible with conventional computers. When the $K$ qubit system is in the coherent state, all $2^K$ combinations of bit spaces can be superposed. Since the typical energy (energy difference between two levels) of the superconducting qubit is in the gigahertz region, the number of operations processed in one second will be roughly $2^K$ GHz. This means that performance approximately on the order of $10^{24}$ floating point operations per second (flops) is possible for a 50-qubit system (considering slower 2-qubit gate operation, this rough number should be one order of magnitude or so smaller). On the basis of these figures, the potential power of quantum computing is far greater than that of conventional computers. It is known that useful calculations can be performed using superposition states, and a number of quantum algorithms are known.\(^{31}\)

Quantum information processing is, in a sense, a quantum interference experiment involving multiple qubits. As in the interference experiment, the outputs (readout results) are black (0) and white (1) interference fringes. The periodicity and location of the interference fringe are the solution to the quantum algorithms, in general. Although it is true that observation of the quantum state involves a probabilistic element, the state of each qubit immediately before readout is manipulated so as to become as close to $|0\rangle$ or $|1\rangle$ as possible in order to minimize the probabilistic element.

We now compare the basic concepts of quantum
information processing with those of classical information processing. The notable characteristic of classical information processing is binary digital operation. Quantum information processing is also a binary operation in the sense that two quantum states $|0\rangle$ and $|1\rangle$ are used. However, the formation of superposition states and the manipulation of phase and quantum interference are predominantly analog elements, and the acceptable margin of operation of a qubit is much narrower than that of a classical bit. Another significant feature of classical information processing is that any complex calculation can be broken down into many simple basic gate operations, such as AND, OR, and NAND, which are collectively called the universal set of gates.

Likewise, any complex quantum information processing operation can also be broken down into many simple gate operations. In this case, only two types of gate operation are required, the one-qubit control and the two-qubit logic gate control; these are the universal gates of quantum information processing. Figure 11 shows a conceptual diagram of quantum information processing. A quantum computing system consists of qubits connected by coupling switches. Two types of basic gate operations are imposed on the qubits and coupling switches by externally controlled manipulations, applied in a fixed time sequence. The one-bit gate operation (S in the diagram) can be performed if neighboring coupling switches are turned off, and the two-bit logic gate operation (T in the diagram) may be made if the coupling switch is turned on. It is necessary to maintain coherence during the calculation.

Performing quantum algorithm by applying prefixed external control signal to qubits in a time sequence is conceptually more like playing a piano than like the operation of a classical computer. However, there is a large difference between a classical wave and the quantum wave. Moreover, it is necessary to complete the performance (algorithm) by successively applying key (qubit) operations before the oscillations (coherence) of the strings (qubits) are attenuated. The need for a two-bit logic gate is also a fundamental difference.

Quantum computing is most significantly different from classical computing in the need to maintain coherence during quantum computing. This is the
greatest challenge to realizing quantum computers. The number of operations necessary for a calculation depends on the quantum algorithm and the size of the problem (qubit number, $K$). The Shor algorithm for quantum prime factorization requires about $K^3$ steps, and Grover’s quantum search algorithm has about $K^{1/2}$ steps. If the number of steps is compared with the classical algorithm, then an exponential acceleration is expected for the former, and a squared acceleration is expected for the latter. In terms of the circuit size (bit number, $K$), it is possible for the quantum algorithm to reduce the circuit size logarithmically compared to the classical algorithm. Another major feature to be expected of quantum computing is its low power consumption. No energy dissipation is allowed at the gates during the operations.

A quantum error correction algorithm has also been proposed\(^{34}\) for the correction of errors due to decoherence. If this algorithm is made available, the problem of decoherence, the biggest challenge to quantum computing, will be resolved. However, a large computational overhead resource is required for the execution of this algorithm, and an unusually high level of precision in manipulation (e.g., $10^{-2}$ to $10^{-5}$) will be required. At the one-qubit level, about 10,000 calculation steps are feasible with the qubit with the longest decoherence time operated at 1 GHz in Fig. 9 (as of 2009). Further improvement in the decoherence time is therefore necessary for quantum computing to be made practical.

9. Quantum operation gate and coupling switch

In addition to one-bit quantum state manipulation as explained above, a two-qubit quantum logic gate is necessary for quantum information processing, as shown in Fig. 11. The two-qubit system is a fascinating physical system in which quantum entanglement appears. Quantum entanglement occurs naturally in the course of quantum logic operations.

Since the superconducting qubit is a solid-state device, there is a high degree of design freedom in designing a two-bit quantum gate. In this respect, this qubit is far superior to microscopic qubits. The first coupled solid-state qubit was realized by a system in which two superconducting charge qubits were coupled by capacitance.\(^{33}\) In this experiment, two qubits were driven into quantum oscillations (in the time domain) and the beating between these oscillations was observed. The creation of quantum entanglement in a macroscopic system was thus demonstrated for the first time.

In subsequent research, the state of each qubit was read out independently in a coupled two qubit system, and quantum entanglement was clearly shown by the quantum state tomography technique.\(^{34}\) By this observation, the quantum state is projected into the $|0\rangle$ and $|1\rangle$ states, losing a large amount of information. Quantum state tomography is a procedure that reproduces the original quantum state before the projection readout, not unlike the procedure of restoring an original 3-D image from the projected 2-D X-ray images by computer aided tomography (CAT).

The first two-bit quantum logic operation gate was realized using coupled charge qubits.\(^{35}\) In this circuit, two qubits were coupled by a fixed capacitor. A controlled NOT (CNOT) operation was achieved using this circuit. CNOT is a typical two-qubit operation that consists of the control bit and the target bit. When CNOT is executed, the target bit will flip if the control bit is $|0\rangle$, but the target bit will remain unchanged if the control bit is $|1\rangle$. If the control bit is a superposition of $|0\rangle$ and $|1\rangle$, the CNOT operation will generate an entangled state. CNOT movement based on the fixedly-coupled flux bit has also been reported.\(^{36}\)

To achieve both accurate quantum state control for each bit as well as execution of two-bit operations in the same system, as shown in Fig. 11, a coupling switch capable of controlling the on and off state of coupling between bits is necessary. In qubits based on microscopic atoms and molecules, there is no physical way of making such a switch. If the coupling between bits is constantly fixed, it is possible to apply a complex bit operation sequence to effectively decouple the qubits in order to perform one-bit operations. Since the superconducting qubit is a solid-state device, it is possible to realize this type of coupling switch physically (not as a bit operation sequence), thus greatly simplifying the quantum information processing. The possibility of the realization of coupling switches has been shown for various types of devices by spectroscopic analysis\(^{37}\)\(^{38}\) and analysis of the state stability region\(^{39,40}\)

This dynamic quantum gate operation experiment was successfully performed using a two-qubit system with a coupling switch. In this system, two flux qubits were used, with their bias kept at their
respective optimal operating points, and a third flux qubit was used as a coupling switch (Fig. 12). The photograph in Fig. 12 shows the two qubits on each side, and the qubit in the middle function as a coupling-switch. Assuming that the qubit energy of the coupled qubit $\Delta_3$ is sufficiently large compared to the energies of the two qubits $\Delta_1$ and $\Delta_2$, the coupling-switch qubit will not be excited. Under this condition, the coupling-switch qubit remains consistently in the ground state, and merely acts as a non-linear inductor (Fig. 10(c)).

Under the bias conditions at the optimal operating point, inductive coupling only appears in the off-diagonal matrix elements. In the first approximation, this coupling is zero. Since the coupling is negligible, one-qubit control may be readily operated. Coupling of two bits and logic operations can be achieved by microwave irradiation applied to the coupling-switch qubit with energy of $\Delta_1 + \Delta_2$ or $\Delta_1 - \Delta_2$. During this operation, the state transition of $|00\rangle \leftrightarrow |11\rangle$ or $|01\rangle \leftrightarrow |10\rangle$ was observed. This is the logic operation called ‘ISWAP’ (swap with phase shift). Based on this two-qubit system, a quantum state manipulation consisting of three operation steps, including two one-qubit operations and one two-qubit operations, was performed. The expected results were achieved, and the coupling switch was shown to function effectively.\textsuperscript{41}

In addition, an experiment on variable coupling was reported, based on a superconducting electromagnetic resonator. This electromagnetic resonator is a transmission line circuit consisting of a niobium-thin-film coplanar waveguide. Named after the cavity electrodynamics (QED) that describe the interaction between atoms and an optical cavity, this circuit consisting of superconducting qubits as artificial atoms is sometimes called a circuit QED. An experiment coupling two phase qubits via the resonator,\textsuperscript{42} and another experiment coupling two transmon qubits (charge qubits with extremely small charge energy) via the resonator\textsuperscript{43} were reported.

These are new types of quantum systems in which the electron state in the superconducting qubit is coupled with the photon state in the superconducting resonator. The former achieves the coupling of qubits through the exchange of real photons. In the latter case, the qubits are coupled via the exchange of virtual photons. The coupling is turned on and off by non-adiabatic displacement of energy, as shown in ref. 2.

The coupling scheme based on an electromagnetic resonator and the scheme based on coupling qubit have many different characteristics. First, there is a size difference. Since the electromagnetic resonator requires the length to be equivalent to the wavelength of gigahertz frequencies, the system is larger than the coupling qubit by about three orders of magnitude. In return, however, the system allows coupling with a remote qubit. Basically, the coupling-switch qubit is designed to couple with neighboring qubits. By contrast, the electromagnetic resonator is basically a coupling bus, and there is no such limitation.

The experiment based on the qubit-based coupler is characterized by operation at the optimal point for the maximum protection against decoherence. Ref. 41, however, describes an experiment based on phase qubits, which by their nature lack an optimal operating point, and ref. 42 describes an experiment based on “transmon” qubits whose operation is independent of the optimal point. Basically, transmon qubits are a device based on charge qubits, but under the condition that $E_C \ll E_1$ instead of the usual $E_C \gg E_1$. In these qubits, the slope of the band [see Fig. 5(b)] is very flat, and the optimal operating point is effectively expanded,\textsuperscript{44} resulting

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Fig. 12. Photographs of two-qubit circuits capable of switching the coupling on and off. Coupling of flux qubits is achieved using a third qubit as the variable coupler (see ref. 40).
in considerable improvement in decoherence time outside of the optimal point. Such devices are rather large, requiring a large meandering capacitance outside the qubit to reduce the charging energy $E_C$. Based on such coupled 2-transmon system, a two-qubit superconducting processing that executing the Grover search and Deutsch–Jozsa quantum algorithms was demonstrated recently.\[45\]

10. Future prospects

This article has touched on the concept of macroscopic quantum coherence and quantum computing, and reviewed the current state of Josephson-junction qubit research. Will the superconducting quantum computer become a reality? Josephson qubit research so far has been making far greater progress than was initially predicted, but there are many difficult challenges to be met before a quantum computer is finally created, and its future is not easily prophesied.

The greatest difficulty is the insufficient decoherence time. Although so many important steps have been achieved since the early work in the field and we have much better understanding of the subject, our current knowledge is still inadequate and further advances are needed. As a solid-state device, the integration of the superconducting qubit is expected to make great progress. A basic device called the ‘universal gate’ is starting to appear, but a more detailed design must be developed that will allow the integration level to be scaled up.

Research on superconducting qubits has much room for growth because the degree of design freedom is high, the structure is relatively simple, and the previously accumulated technology on superconductor integrated circuits is readily available. For the entire superconducting device technology community, the newly acquired ability to manipulate the coherent state opens promising new frontiers of research that offer opportunities to maximize the potential of superconducting devices. Moreover, this area of science and technology is a very strong candidate for the basic building block of future quantum computers.

We will need to choose schemes that use realistic experimental parameters in order to begin fully operational quantum error correction experiments. Quantum computing based on gate operations was discussed above; however, there are many other interesting developments in related research fields, such as adiabatic quantum computing, quantum emulation and quantum simulation.

Superconducting qubits stand out as the basic devices for high-speed gates for quantum computing. However, superconducting qubits are also attractive as an ultra-low energy device. In the near future, it is expected that researchers in the field of classical superconducting devices will be inspired by the present qubit research to develop a reversible computing device with energy consumption below the thermodynamic limit.\[46\] The coherence of the election state of the superconducting qubit can coherently couple with the photon state of an electromagnetic cavity\[47\] or with the mechanical degree of freedom of a mechanical resonator. This diversity suggests that the new science and engineering in the field will go beyond information processing with potential for new physics and applications.

This research into superconducting macroscopic quantum states has obviated much of the prior generation’s ‘common sense.’ Through macroscopic quantum tunneling, macroscopic quantum coherence, macroscopic quantum entanglement and other related experiments, these striking results have audaciously shown us the fundamental “spookiness” of quantum theory on an enlarged, macroscopic human scale. Most recently, violation of Bell’s inequality was successfully demonstrated with macroscopic Josephson qubits.\[48\] With such result, our classical realistic worldview will be utterly broken down.\[49\]

Our worldview is not entirely imprinted in our genes, but is mostly acquired by education. This is the lesson we have learned from the history of change of our worldview and common sense. Almost three quarters of a century after the birth of quantum theory, the theory is finally about to enter the common sense shared by the ordinary people. The research on superconducting qubits is actively involved in the making of this new common knowledge, expanding our horizon from the microscopic world to the macroscopic world.

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Profile

Jaw-Shen Tsai was born in 1952. He graduated from department of physics of University of California at Berkeley in 1975 and received his Ph.D. in Physics from State University of New York at Stony Brook in 1983. His research life has been devoted to the study of macroscopic quantum effect in superconductors, especially which associated with Josephson junctions. He has contributed to the area of condensed matter physics in both fundamental physics and their technological potential. The most celebrated work of his is the demonstration of quantum coherent oscillations in a solid state system. He is a Fellow at NEC Nano Electronics Research Laboratories, where he leads the Josephson junction based qubit project. He is also the Laboratory Head of Macroscopic Quantum Coherence Research laboratory, Advanced Science Institute, RIKEN. He joined NEC R&D unit in 1983, and since 1996 he has been working on the experiments connected quantum coherence in the Josephson systems. In this direction, his group has been pioneering the science and technology of superconducting quantum computing. His group has demonstrated the first solid-state based qubit in 1999, and subsequently demonstrated the first solid state CNOT gate in 2003, a switchable coupling between qubits required for a quantum universal gate in 2007. He received Nishina Memorial Prize in 2004 and Simon Memorial Prize in 2008. He is a fellow of American Physical Society and is an Honorary Professor of National Chiao Tung University, Taiwan.