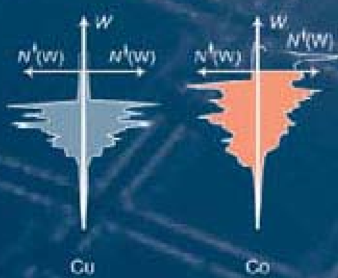
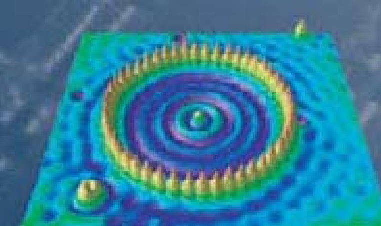
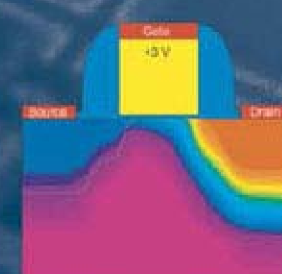
Rainer Waser (Ed.)

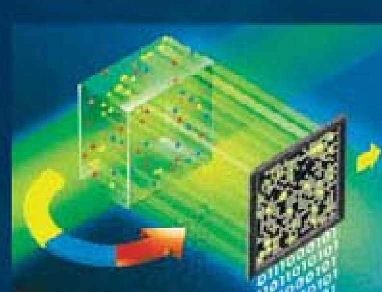
Nanoelectronics and Information Technology

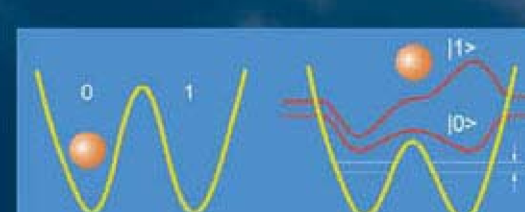
Advanced Electronic Materials and Novel Devices

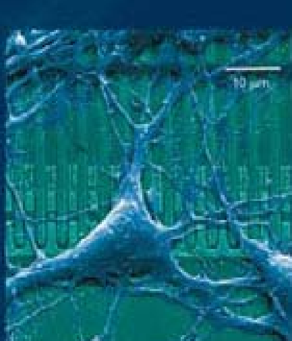












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Rainer Waser is Professor at the faculty for Electrical Engineering and Information Technology of the RWTH Aachen University and director at the Institute of Solid State Research (IFF) at the HGF Research Center Jülich, Germany. In 1984, he received his PhD in physical chemistry at the University of Darmstadt, and worked at the Philips Research Laboratory, Aachen, until he was appointed professor in 1992. His research group is focused on fundamental aspects of electronic materials and on such integrated devices as non-volatile memories, specifically ferroelectric memories, logic devices, sensors and actuators. Throughout, he has been collaborating with major semiconductor industries in Europe, the US , and the Far East. He has organized international conferences, published about 200 technical papers and holds ten patents. Since 2002, he has been the coordinator of the research program Nanoelectronic Systems within the German National Research Centers (Helmholtz-Gemeinschaft).

The Book:

Providing an introduction to electronic materials and deviceconcepts for the major areas of current and future information technology, the value of this book lies in its focus on the underlying principles. Illustrated by contemporary examples, these basic principles will hold, despite the rapid developments in this field, especially emphasizing nanoelectronics. There is hardly any field where the links between basic science and application are tighter than in nanoelectronics & information technology. As an example, the design of resonant tunneling transistors, single electron-devices or molecular electronic structures is simply inconceivable without delving deep into quantum mechanics. This textbook is primarily aimed at students of physics, electrical engineering and information technology, as well as material science in their 3rd year and higher. It is equally of interest to professionals wanting a broader overview of this hot topic.

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Quantum Computing using Superconducting Circuits

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1 The principle of quantum computing

The Quantum Computing (QC) has become a very hot topic in the past few years. It excited many scientists from various areas, i.e. theoretical and experimental physics, computer science and mathematics. What is QC? Although the concept of information underlying all modern computer technology is essentially classical, physicists know that nature obeys the laws of quantum mechanics. The idea of QC has been developed theoretically over several decades to elucidate fundamental questions concerning the capabilities and limitations of machines in which information is treated quantum mechanically. In contrast to classical computing that we all know, QC deals with quantum information processing. In quantum computers the ones and zeros of classical digital computers are replaced by the quantum state of a two-level system. Shortly speaking, QC is based on the controlled time evolution of quantum mechanical systems.

Classical computers operate with *bits*; quantum computers operate with quantum bits that have been named *qubits*. Unlike their classical counterparts, which have states of only 0 or 1, qubits can be in a complex linear superposition of both states until they are finally read out. For example, the states of a spin 1/2 particle can be used for quantum computation. For a qubit, the two values of the classical bit (0 and 1) are replaced by the ground state ($|0\rangle$) and the first excited ($|1\rangle$) state of a quantum two-level system.

Figure 1 illustrates the difference between a classical bit and a quantum bit. A classical two-state system can be prepared and stored in either of the states 0 or 1. This system is characterized by two stable states, e.g. as a particle placed in a double-well potential. In quantum mechanics, a particle is described by a quantum-mechanical wavefunction and it can tunnel under the barrier, which separates two wells. As a consequence, a particle can be in two or more states at the same time — a so called superposition of states. A quantum system characterized by the double-well potential has the two lowest energy states $|0\rangle$ and $|1\rangle$. The wave function for the ground state $|0\rangle$ is symmetric, for the excited state $|1\rangle$ it is antisymmetric. Quantum theory predicts that a system prepared in a superposition state should follow coherent oscillations between the two wells. Once a measurement is performed, the probability of finding the particle in the specific well (left or right) oscillates periodically with time. The frequency ω of these coherent oscillations is proportional to the quantum tunneling rate between the wells. This leads to splitting of the lowest energy level by a so-called coherence gap $\Delta = \hbar\omega$. Many elementary books on quantum mechanics treat the physics of two-level systems that is essential for the understanding of QC.

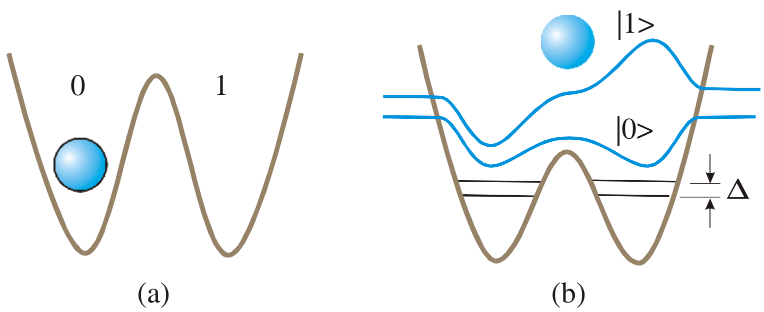

Figure 1. (a) A Classical computer manipulates with bits, which may take the values 0 or 1. (b) A Quantum computer manipulates with quantum-mechanical two-level systems called qubits. The two quantum states are noted as $|0\rangle$ and $|1\rangle$.

While one classical bit of information is stored as either 0 or 1, a qubit can be in a weighted superposition of both states. For example, $a|0\rangle + b|1\rangle$, where a and b are complex numbers that vary with time t, and $|a|^2 + |b|^2 = 1$. Thus, not only 0 and 1, but all the states $|\psi(t)\rangle = a(t)|0\rangle + b(t)|1\rangle$ can be used to encode information in a qubit. This fact provides massive parallelism of QC due to *superposition of states*. When measured with a readout operator, the qubit appears to collapse to state $|0\rangle$ with probability $|a|^2$, and to state $|1\rangle$ with probability $|b|^2$. The state of two qubits can be written as a four-dimensional vector $|\psi\rangle = a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$, where $|a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$. The probability of measuring the amplitude of each state is given by the magnitude of its squared coefficient. In general, the state of n qubits is specified by $(2^{n+1} - 1)$ real numbers — an exponentially large amount of information, relative to the number of physical particles required. Most of these states are *entangled* — to create them requires some kind of interaction between the qubits, and the qubits cannot be treated entirely independently from one another. An entangled state cannot be written simply as a product of the states of individual qubits.

2 Computing with qubits

The great interest in QC is related to the fact that some problems, which are practically intractable with classical algorithms, can be solved much faster with QC. Factorization of large numbers, a quantum algorithm for which was proposed by P. Shor [1], is probably the best-known example in this respect. Shor showed that quantum computers could factor large numbers into prime factors in polynomial number of steps, compared to exponential number of steps on classical computers. What it practically means can be illustrated by an example: Using a modern workstation cluster, a factorization of a number N with L=400 digits will require 10^{10} years, which is larger than the age of the Universe. But a single hypothetic quantum computer should be able to do this job for less than 3 years! Shor's factoring algorithm works by using a quantum computer to quickly determine the period of the function $F(x) = a^x \bmod N$ (that means the remainder of a^x divided by N), where a is a randomly chosen small number with no factors in common with N. From this period, the techniques developed in the number theory can be used to factor N with high probability. The two main components of the algorithm, modular exponentiation (computation of $a^x \bmod N$) and the inverse quantum Fourier transform take only ~L^3 operations.

Prime factorization is an essential part of modern public key cryptographic protocols, paramount to privacy and security in the electronic world. As quantum computers can, at least in theory, factor numbers in exponentially fewer steps than classical computers, they can be used to crack any modern cryptographic protocol. Another problem that can be treated very efficiently by QC is sorting [2]. Quantum computer should be able to search databases in $\sim\sqrt{N}$ queries rather than $\sim N$ on an ordinary machine.

Let us briefly discuss the basic computational operations with a spin system of qubits as an example [3]. Manipulations of spin systems have been widely studied and nowadays nuclear magnetic resonance (NMR) physicists can prepare the spin system in any state and let it evolve to any other state. Controlled evolution between the two states $|0\rangle$ and $|1\rangle$ is obtained by applying resonant microwaves to the system but state control can also be achieved with a fast dc pulse of high amplitude. By choosing the appropriate pulse widths, the NOT operation (spin flip) can be established as

$$|0\rangle \to |1\rangle; \quad |1\rangle \to |0\rangle, \tag{1}$$

or the Hadamard transformation (preparation of a superposition)

$$|0\rangle \to (|0\rangle + |1\rangle)/\sqrt{2}; \quad |1\rangle \to (|0\rangle - |1\rangle)/\sqrt{2}. \tag{2}$$

These unitary *single bit* operations alone do not make a quantum computer yet. Together with single-bit operations, it is of fundamental importance to perform *two-bit* quantum operations; i.e., to control the unitary evolution of entangled states. Thus, a universal quantum computer needs both one and two-qubit gates. An example for a universal two-qubit gate is the controlled-NOT operation:

$$|00\rangle \to |00\rangle; \quad |01\rangle \to |01\rangle; \quad |10\rangle \to |11\rangle; \quad |11\rangle \to |10\rangle. \tag{3}$$

It has been shown that the single-bit operations and the controlled-NOT operation are sufficient to implement arbitrary algorithms on a quantum computer. *Quantum computers can be viewed as programmable quantum interferometers*. Initially prepared in a superposition of all the possible input states using the Hadamard gate (2), the computation evolves in parallel along all its possible paths, which interfere constructively towards the desired output state. This intrinsic parallelism in the evolution of quantum systems allows for an exponentially more efficient way of performing computations.

Without going into any detail due to space limitation of this review, it is worth noting that the above mentioned Shor's algorithm uses two registers of $n = 2\lceil \log_2 N \rceil$ and $m = \lceil \log_2 N \rceil$ qubits. The algorithm is realized by five major computation steps, namely: (1) Initialization of both registers by preparing their initial state; (2) Applying a Hadamard transformation to the first n qubits; (3) Multiplying the second register by $a^x \bmod N$ for some random $a < N$ which has no common factors with N; (4) Performing the inverse quantum Fourier transformation (based on two-qubit controlled-phase rotation operator) on the first register; (5) Measuring the qubits in the first register. For detailed reviews devoted to algorithms of QC, we refer to Refs. [4—6].

3 Qubits: how to realize them?

It is common to adopt the spin 1/2 particle language for describing quantum algorithms (see Figure 2). Manipulations of spin systems have been widely studied and already used for practical applications. Nowadays, by applying electromagnetic fields and pulses to spins in molecules, nuclear magnetic resonance (NMR) physicists can prepare these spin systems in any state and let them evolve to any other state. The controlled evolution between the two states $|0\rangle$ and $|1\rangle$ is obtained by applying resonant microwaves to the system.

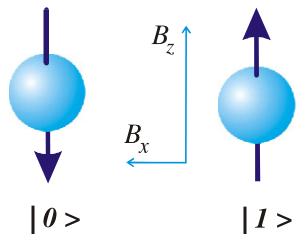

Figure 2. An example of a two-level system is a particle with the spin 1/2. The two basis quantum states $|0\rangle$ and $|1\rangle$ correspond to the spin orientations down and up with respect to the quantization axis B_z of the external magnetic field.

Quantum theory predicts that if such a system is strongly coupled to the environment, it remains localized in one state and so behaves classically. Thus it is very important to have the quantum system decoupled from the rest of the world. Weak coupling to the environment damps the coherent oscillations between the states discussed in Section 1. The damping rate vanishes as the coupling to the environment goes to zero. The inverse of the damping rate is often called *decoherence time* τ_{dec}. This time is essentially the quantum memory of the system — after long enough time $t > \tau_{dec}$ the system "forgets" its initial quantum state and is not any more coherent with it. In the ideal case, for using a quantum system as qubit we would want to have $\tau_{dec} \to \infty$.

There are at least five important criteria that must be satisfied by possible hardware for a quantum computer [7]. To do QC, one needs:

1. Identifiable qubits and the ability to scale them up in number. This means that being able to build up only few qubits is not sufficient for making any useful quantum computation. For practical QC one would require making very many (ideally, any desired number) of qubits in some controlled and reliable way.
2. Ability to prepare the initial state of whole system. All the qubits have to be first prepared in a certain state (like, e.g. $|0\rangle$ or $|1\rangle$) and only after that quantum computation can be started.
3. Low decoherence — the key issue, which rules out many of possible candidate system for the quantum hardware. For quantum-coherent oscillations to occur, it is required that $\tau_{dec}\Delta / h >> 1$. An approximate benchmark for low enough decoherence is a fidelity loss of less than 10^{-4} per elementary quantum gate operation.
4. Quantum gates. The universal set of gates is needed in order to control the system Hamiltonian. After preparing a certain state, we have to be able to switch on and off the interaction between them in order to make qubits act together and do useful computation.
5. Perform a measurement. The final requirement for QC is the ability of performing quantum measurements on the qubits to obtain the result of the computation. Such readout transfers the information to the external world, i.e. to classical computers, in order to make the information useful.

Any candidates for quantum computing hardware should be assessed against this "DiVincenzo checklist" [7].

A number of two-level systems have been examined over the last few years as candidates for qubits and quantum computing. These include ions in an electromagnetic trap [8], atoms in beams interacting with cavities [9], electronic [10] and spin [11] states in quantum dots, nuclear spins in molecules [12],[13] or in solids [14], charge states of nanometer-scale superconductors [15],[16], flux states of superconducting circuits [17],[18],[19], quantum Hall systems [20], electrons on superfluid helium [21], and nanometer-scale magnetic particles [22]. Though all these systems fulfill some points of the checklist, some open questions remain. There is currently no clear quantum computing favorite, analogous to the transistor for silicon-based classical computing. In addition to further work on existing systems, new candidates for quantum computing hardware should be explored.

Maintaining the coherence of a quantum device throughout the calculation is the major challenge for practical quantum computation. The device should be maximally decoupled from the environment in order to avoid decoherence and thus the loss of the quantum information.

4 Why superconductors?

The advantage of microscopic quantum systems (atoms, spins, photons, etc.) is that they can be easily isolated from the environment, which reduces decoherence. The disadvantage is that the integration of many qubits into a more complex circuit in order to build a practical computer is a formidable task. From that point of view, macroscopic quantum systems offer much more flexibility to design a quantum computer using standard integrated circuit technology. Already proposed macroscopic qubits are based on nano-structured electronic circuits, which may consist of either quantum dots or superconducting Josephson junctions.

The large number of degrees of freedom associated with a solid-state device makes it more difficult to maintain the coherence. As of today, this problem has been met by either resorting to well isolated spins (on quantum dots [11] or through deliberate doping of semiconductors [14]) or by making use of the quasi-particle spectrum in superconductors that is characterized by an energy gap.

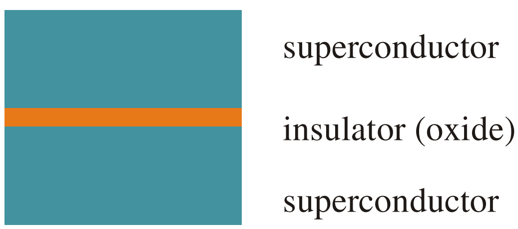

Figure 3. A Josephson tunnel junction is a structure formed by two superconductors separated by a very thin (2-3 nm) layer of a dielectric. Typically, Nb or Al is used as the superconducting material and Al_2O_3 as the dielectric.

All proposed superconducting quantum circuits are based on superconducting structures containing Josephson junctions. A Josephson junction is a structure consisting of two superconducting electrodes separated by a thin dielectric tunnel barrier (see Figure 3).

There are two possibilities for constructing a superconducting qubit. They differ by the principle of coding the quantum information. The first approach is based on very small Josephson junctions, which are operated maintaining coherence between individual states of electron Cooper pairs. This type of qubit is called a *charge qubit*. The charge states of a small superconducting island (a so-called electron box) are used as the basis states of this qubit. The second, alternative approach relies on the macroscopic quantum coherence between magnetic flux states in relatively large Josephson junction circuits. The latter qubit is known as magnetic *flux (phase) qubit*. In fact, the flux qubit is based on a special realization of a superconducting quantum interference device (SQUID). An up-to-date review devoted to the implementation of quantum computation by means of superconducting nanocircuits has been recently published by Makhlin, Schön and Shnirman [23].

5 Charge qubits

These devices combine the coherence of Cooper pair tunneling with the control mechanisms developed for single-charge systems and Coulomb-blockade phenomena. The qubit is realized as a small (few 100 nm in dimensions) superconducting island attached to a larger superconducting electrode. The charge on the island, separated from a superconducting reservoir by a low-capacitance Josephson junction, is used in the qubit as the quantum degree of freedom. The basis states $|0\rangle$ and $|1\rangle$ differ by the number of superconducting Cooper pair charges on the island. The charge on the island can be controlled externally be a gate voltage. In the description of the charge qubits, I follow the guideline of review [23].

Quantum-coherent tunneling of Cooper pairs is, to some extent, similar to single-electron tunneling between very small conducting islands. These islands must be small enough so that the charging energy of a Cooper pair moving between the superconducting islands dominates over all other characteristic energies in the system.

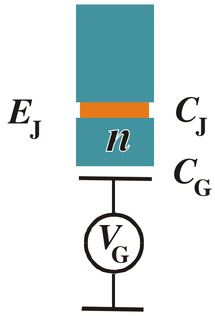

Figure 4. A Josephson charge qubit, in its simplest design, is formed by a superconducting electron box [23]. The box is separated from the superconducting reservoir by a Josephson tunnel junction.

The simplest Josephson junction qubit is shown in Figure 4. It consists of a small superconducting island (“box") with n excess Cooper pair charges relative to some neutral reference state. The island is connected to a superconducting reservoir by a tunnel junction with capacitance C_J and Josephson coupling energy E_J. A control gate voltage V_G is applied to the system via a gate capacitor C_G. Suitable values of the junction capacitance, which can be fabricated routinely by present-day technologies, are in the range of femtofarad.

At low temperatures (in the mK range), the only charge carriers that tunnel through the junction are superconducting Cooper pairs. The system is described by the Hamiltonian:

$$H = 4E_C(n - n_G)^2 + E_J \cos\varphi\,. \qquad (4)$$

Here φ is the phase of the superconducting order parameter of the island. The variable φ is quantum mechanical conjugate of the number of excess Cooper pair charges n on the island:

$$n = -i\hbar\,\partial/\partial(\hbar\varphi)\,. \qquad (5)$$

Equation (5) is linked to the fundamental quantum-mechanical uncertainty relation for a Josephson junction between the superconducting grain and reservoir, which writes as $\Delta n \cdot \Delta\varphi \geq 1$. Thus, the superconducting phase difference φ between the island and reservoir cannot be determined simultaneously with the number of electron pairs n on the island. It is analogous to a condition that holds, e.g., for an optical pulse in a fiber — the number of photons in the pulse cannot be fixed simultaneously with the phase of the pulse.

In the charge qubit, the charge on the island acts as a control parameter. The gate charge is normalized by the charge of a Cooper pair, $n_G = C_G V_G/(2e)$, it accounts for the effect of the gate voltage V_G . For the charge qubit, the charging energy $E_C = e^2/(2(C_J+C_G))$ is much larger than the Josephson coupling energy E_J. A convenient basis is formed by the charge states, parameterized by the number of Cooper pairs n on the island. In this basis the Hamiltonian (4) can be written

$$H = \sum_n \left\{ 4E_C(n-n_G)^2 |n\rangle\langle n| + \frac{1}{2}E_J\left(|n\rangle\langle n+1| + |n+1\rangle\langle n|\right)\right\}. \qquad (6)$$

For most values of $n_{G,}$ the energy levels are dominated by the charging part of the Hamiltonian. However, when n_G is approximately half-integer and the charging energies of two adjacent states $n=0$ and $n=1$ are close to each other, the Josephson tunneling mixes them strongly, see Figure 5.

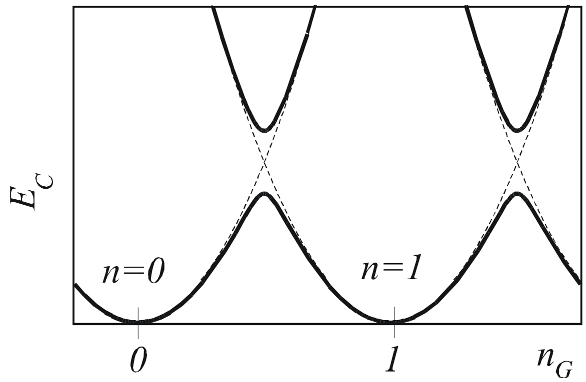

Figure 5. The plot shows the charging energy of the superconducting island as a function of the normalized gate charge n_G for different numbers of extra Cooper pairs n on the island (dashed lines). Near degeneracy points, the weaker Josephson coupling mixes the charge states and modifies the energy of the eigenstates (solid lines) and the system reduces to a two-state quantum system [24].

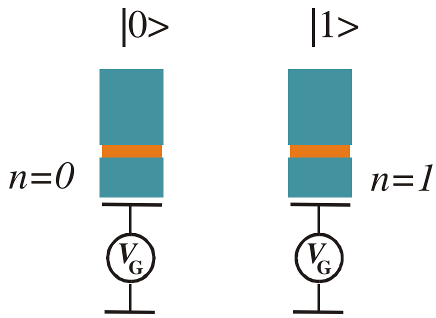

Figure 6. The basis states $|0\rangle$ and $|1\rangle$ of the superconducting charge qubit. They differ by the number of excess Cooper pairs n on the small superconducting island.

The two states of the charge qubit differ by one Cooper pair charge on the superconducting island. In the voltage range near a degeneracy point only the two states with n=0 and n=1, play a role, while all other charge states having much higher energy can be ignored. In this case, the superconducting charge box behaves as a two-level (two-state) quantum system. In spin-1/2 notation its Hamiltonian can be written as

$$H = -\frac{1}{2}B_z\hat{\sigma}_z - \frac{1}{2}B_x\hat{\sigma}_x \,. \tag{7}$$

The charge states n=0 and n=1 correspond to the spin basis states $|\downarrow\rangle$ and $|\uparrow\rangle$ as illustrated in Figure 2. The charging energy splitting, which is controlled by the gate voltage V_G , corresponds in spin notation to the z-component of the magnetic field

$$B_z \equiv 4E_C(1-2n_G)\,. \tag{8}$$

In its turn, the Josephson energy plays the role of the x-component of the magnetic field

$$B_x \equiv E_J\,. \tag{9}$$

The manipulations of charge qubits can be accomplished by switching the gate voltages [15] that play the role of B_z and modify the induced charge $2en_G$. The Josephson coupling energy E_J that corresponds to B_x can be controlled by replacing the single junction by two junctions enclosed in a superconducting loop (SQUID) [24], as shown in Figure 7. In this modified circuit, a current supplied through a superconducting control line that is inductively coupled to the SQUID induces a magnetic flux Φ_x , which changes the critical current and thus the Josephson coupling energy E_J of the device.

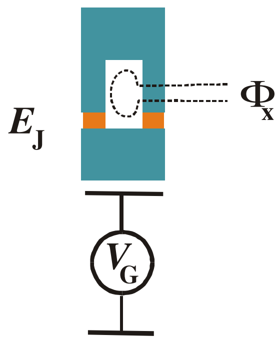

Figure 7. A charge qubit with tunable effective Josephson coupling. A flux-threaded SQUID replaces the single Josephson junction. A current carrying loop coupled to the SQUID controls the magnetic flux.

In addition to the manipulation of the qubit, its final quantum state has to be read out. For a Josephson charge qubit, this can be accomplished by coupling it to a single-electron transistor (SET). As long as the transport voltage is turned off, the transistor has only a weak influence on the qubit. When the voltage is switched on, the dissipative current through the SET destroys the phase coherence of the qubit within a short time.

Experimentally, the coherent tunneling of Cooper pairs and the related properties of quantum mechanical superpositions of charge states has been demonstrated in spectacular experiments of Nakamura et al. [16]. These authors observed in the time domain the quantum coherent oscillations of a Josephson charge qubit prepared in a superposition of eigenstates. The layout of their qubit circuit is shown in Figure 8. It includes a small superconducting grain (a Cooper pair "box") attached to a superconducting reservoir by two Josephson junctions as shown above schematically in Figure 7.

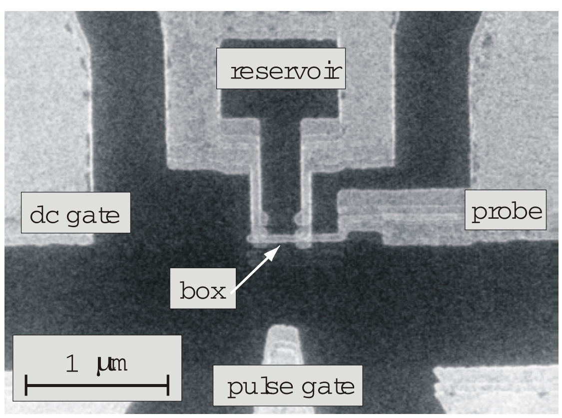

Figure 8. Micrograph of a Cooper-pair box with a magnetic flux-controlled Josephson junction and a probe junction (Nakamura et al. [16]).

Using a dc gate, the Josephson charge qubit ("box") is prepared in the ground state far from the degeneracy point. In this regime, the ground state is close to the charge state, say, $|0\rangle$. Then the gate voltage is changed for a short time (less than one nanosecond) to a different value using the pulse gate. If it is switched to the degeneracy point, the initial state, a pure charge state, is an equal-amplitude superposition of the ground state $|0\rangle$ and the excited state $|1\rangle$, as it is illustrated in Figure 5. These two eigenstates have different energies; hence, in time they acquire different phase factors.

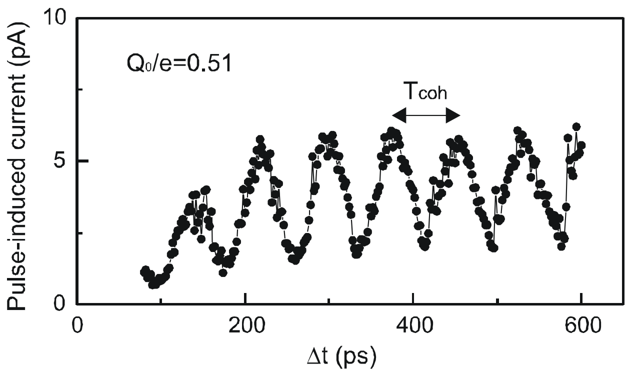

Figure 9. The coherent (Rabi) oscillations in the Josephson charge qubit observed in the experiments of Nakamura et al. [16].

The final state of the qubit in the experiment by Nakamura et al. [16] was measured by detecting a tunneling current through an additional probe-junction. Ideally, zero tunneling current implies that the system ended up in the $|0\rangle$ state, whereas maximum current is expected when the final state corresponds to the excited one. In the experiment, the tunneling current shows an oscillating behavior as a function of pulse length, as shown in Figure 9. These data demonstrate the coherent time evolution of a quantum state in the charge qubit.

6 Flux qubits

Since superconductivity is a macroscopically coherent phenomenon, macroscopic quantum states in superconductors offer a challenging option for quantum computing. There have already been experiments that demonstrated macroscopic quantum tunneling (MQT) of the superconducting phase in current-biased Josephson junctions and superconducting quantum interference devices (SQUIDs). Moreover, it has been found that the tunneling rate agrees well with the value predicted by the Caldeira-Leggett theory with a phenomenological treatment of the dissipation. Since MQT involves only a single potential well from which the tunneling of the system takes place, there is no issue of coherence between different quantum states attached to it.

A quantum superposition of magnetic flux states in a SQUID is called macroscopic quantum coherence (MQC). It is called macroscopic because the currents are built of billions of electrons coherently circulating within the superconducting ring. Figure 10 illustrates its main idea. If the applied magnetic flux bias to a SQUID is equal to $\Phi_0/2$ (where $\Phi_0 = \pi\hbar/e = 2.07\times10^{-15}$ Wb is a magnetic flux quantum, $\hbar$ is Plank's constant, e is the electron charge), its potential energy has two symmetric minima. The flux in the SQUID loop can tunnel between the two minima. This implies that the degenerate ground state energy of the SQUID is split by the energy difference ΔE related to the tunneling matrix element, and the two states are mixed energy states. Therefore, if the coherence of this mixture can be maintained long enough, the magnetic flux will oscillate back and forth between the two states at the frequency $\Delta E/(2\pi\hbar)$. Since the observation of MQT in Josephson structures in the 80's, there is a great interest towards detecting MQC in SQUIDs. However, experiments were not successful and many of them were interrupted after the advent of high-temperature superconductivity in 1986.

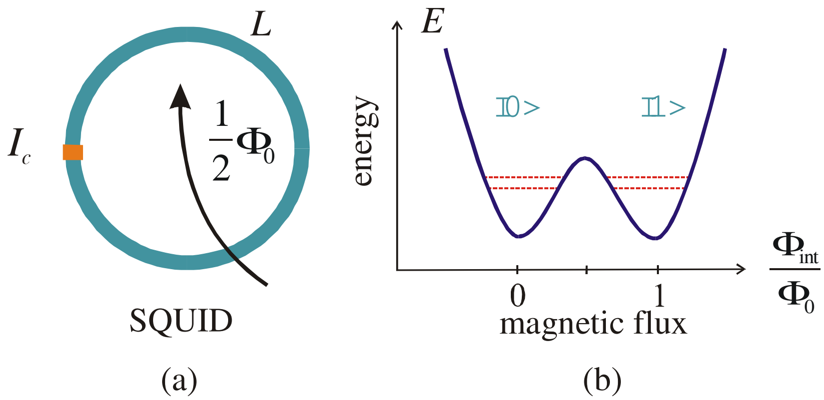

Figure 10. (a) Sketch of MQC experiment with a SQUID, which is a superconducting ring containing a Josephson junction. (b) SQUID energy as a function of the internal flux Φ_{int}. The external flux is equal to $\Phi_0/2$. Horizontal levels indicate mixed energy states.

A qubit can also be realized with superconducting nano-circuits in the limit $E_J >> E_C$, which is opposite to charge qubits. The magnetic flux qubits are larger than the charge qubits, which makes them easier to fabricate and test. The flux qubit dynamics is governed by the superconducting phase difference across the junction rather than by the charge. The flux qubit consists of a SQUID as a macroscopic quantum coherent system.

The Hamiltonian of a single-junction SQUID (which is also called rf-SQUID) reads

$$H = -E_J \cos\left(\frac{2\pi\Phi}{\Phi_0}\right) + \frac{(\Phi - \Phi_x)^2}{2L} + \frac{Q^2}{2C}. \tag{10}$$

Here, L is the self-inductance of the superconducting loop, and Φ is the magnetic flux in the loop. The externally applied flux is denoted by Φ_x. In the limit in which the self-inductance is large, the two first terms in the Hamiltonian form a double-well potential near $\Phi = \Phi_0/2$. The charge Q is a canonically conjugated variable to the phase difference across the junction $\varphi=2\pi\Phi/\Phi_0$, see Eq. (5). The Hamiltonian (10) can be reduced to that of a two-state system. By controlling the applied magnetic field, all elementary operations can be performed.

Flux qubits seem more robust then charge qubits, they can be relatively easy coupled inductively. In the proposal of Mooij et al. [18], a qubit is formed by 3 junctions as shown in Figure 11. Flux qubits can be coupled by means of flux transformers, which provide inductive coupling between them.

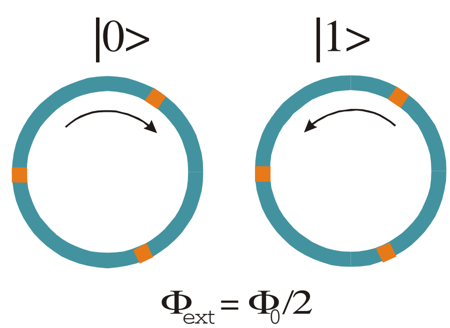

Figure 11. The basis states $|0\rangle$ and $|1\rangle$ of the superconducting flux (persistent current) 3-junction qubit [18]. They differ by the direction of the persistent current in the superconducting loop containing the junctions.

The quantum mechanical properties of SQUIDs were thoroughly investigated in the recent past, but only last year the quantum superposition of different magnetic flux states was evidenced experimentally [19] by the SUNY group at Stony Brook. One state corresponds to a persistent current in the loop flowing clockwise whereas the other corresponds the current flowing anticlockwise. The major experimental result of the SUNY group is presented and briefly explained in Figure 12.

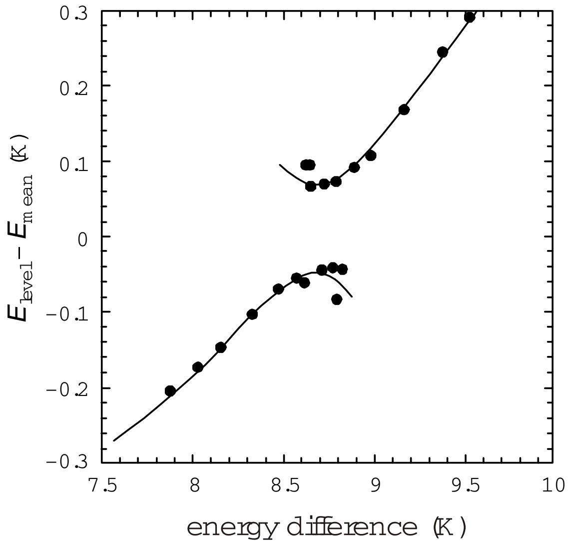

Figure 12. Experimental results of Friedman et al. [19]. The plot shows energy of two spectroscopically measured levels, relative to their mean energy, as a function of the energy difference between the bottoms of the wells. At the midpoint of the figure, the measured tunnel splitting Δ between the two states in this "anticrossing" is about 0.1 K. The calculated energy levels are indicated by the lines.

Nearly simultaneously with the SUNY team, the Delft group observed the quantum superposition of macroscopic persistent current states in their 3-junction SQUID [25]. Both experiments used a spectroscopic technique to detect the energy level splitting (more precisely, the level anti-crossing) due to the tunnel coupling between the two macroscopically distinct circulating current states of the circuit.

Coherent quantum oscillations in the time domain have not yet been detected in SQUID systems. To probe the time evolution, pulsed microwaves instead of continuous ones have to be applied. Observation of such oscillations would imply the demonstration of MQC, awaited since the 80's. The determination of decoherence time is the major remaining task to evaluate the feasibility of this type of flux qubits for practical quantum computing.

7 Other qubits

Recently our group suggested using the *macroscopic quantum states of Josephson vortices* as a flux qubit for quantum computation [26]. Our original idea was to use the two distinct states of a fluxon trapped in a magnetic field-controlled double-well potential inside a narrow long junction to design a qubit. Theory predicts that a fluxon in a double-well potential behaves as a quantum-coherent two-state system.

The physical principles of the fluxon qubit and the persistent current qubit are similar. It is possible by variation of the external field and the junction shape to form an arbitrarily shaped potential for a magnetic fluxon in the long Josephson junction. The amplitude of this potential can be easily varied by tuning the magnetic field. The superposition of two macroscopically distinct quantum states of the fluxon as quantum particle can be expected at the low temperatures.

In the quantum regime, the coupling between the two states depends exponentially on the size of the energy barrier separating them. The energy barrier can be tuned in a wide range by changing the magnetic field applied to the junction. At low fields, the vortex tunnels through the barrier, and thus coupling between the two states appears. At high fields, however, tunneling is essentially suppressed and the vortex remains localized in one of the states. Thus, by applying a sufficiently large field the system can be switched into the classical regime in which the quantum states of the vortex correspond to their classical counterparts.

Recently we experimentally demonstrated a protocol for the preparation and read-out of the vortex qubit states in the classical regime [27]. We were able to manipulate the vortex states by varying the magnetic field amplitude and its direction, and by applying a bias current to the junction.

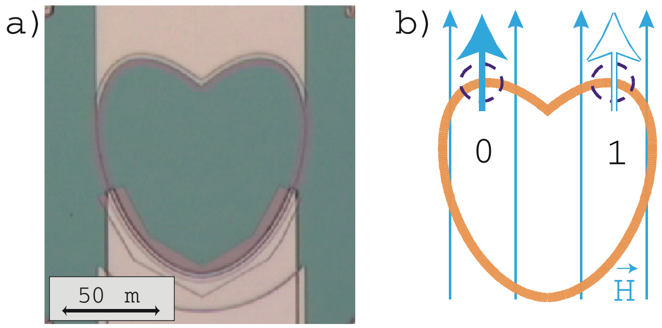

Figure 13. a) Photograph of a 300 nm wide heart-shaped long Josephson junction. b) The two degenerate vortex states in a heart-shaped junction are formed by applying an in-plane magnetic field. Arrows indicate the vortex locations that correspond to the states $|0\rangle$ and $|1\rangle$.

Other proposals using multi-junction loops for designing better flux qubits are under development. In particular, the use of π-junctions, which have an unconventional current-phase relation, is considered for the design of qubits [28]. The hope here is that the combination of conventional and π-junctions in a single circuit may allow designing so-called "quiet" qubits, which do not require any external magnetic field for their operation. Thus, "quiet" qubits may be easier to decouple from the environment. However, a reliable technology for π-junctions still does not exist. The long-discussed approach to realize a π-junction by making use of a copper-oxide d-wave superconductor is still very hard to realize in practice. The most promising approach in this respect seems using so-called SFS (superconductor – ferromagnet - superconductor) junctions that are made with magnetic impurities in the Josephson channel [29].

8 Decoherence mechanisms

For performing quantum computing, it is very important that qubits are protected from the environment, i.e., from any source that could cause decoherence. This is a very difficult task because at the same time one also has to control the evolution of the qubits, which inevitably means that the qubit has to be coupled to control systems in the environment. Single atoms, spins and photons can be decoupled from the outside world. However, large-scale integration that is needed to make a quantum computer useful seems to be impossible for these microscopic systems. Qubits made using solid-state devices (quantum dots or superconducting circuits), may offer the great advantage of scalability.

In their experiment with the superconducting charge qubit, Nakamura et al. [16] estimate the decoherence time to be about 2 ns. It may be speculated that the probe junction directly coupled to their circuit and the $1/f$ noise (presumably due the motion of background charges) are the main source of decoherence. In their absence (which so far has been difficult to accomplish), the main dephasing mechanism is thought to be spontaneous photon emission to the electromagnetic environment. Decoherence times of the order of 1 μs should then be possible for charge qubits.

The decoherence time for flux qubit has not been measured yet. In general, here estimates are more optimistic than for charge qubits. The decoherence times as large as milliseconds have been guessed. The 3-junction geometry has the advantage that it can be made much smaller than rf-SQUID with appropriate self-inductance L, so that it will be less sensitive to noise introduced by inductive coupling to the environment. Nevertheless, in all designs the measuring equipment coupled to qubits is expected to act destructively on quantum coherence.

9 Perspective

Superconducting tunnel junction circuits can be manipulated in a quantum coherent fashion in a suitable parameter range. Currently, they seem to be very promising to be used for quantum state engineering and as hardware for future quantum computers. We discussed their modes of operation in two basic regimes, dominated by the charge and the magnetic flux. There are several important constraints to overcome (mainly dephasing effects due to various decoherence sources) before a first useful QC circuit will be made. Nonetheless, there are several important advantages of nano-electronic devices as compared to other physical realizations of qubits; this leaves us hope for the future.

If a quantum computer will ever be made, it would require both an input and an output interface to interact with the external world. It is worth mentioning that such interface hardware does already exist for flux qubits. It can be designed using the rapid single-flux quantum (RSFQ) logic implemented in classical superconducting electronics. Indeed, the classic-computer RSFQ interface can be used for the preparation of initial states and for the read out circuitry of the magnetic-flux carrying states. RSFQ is a well-developed technique that will be the natural choice for communicating between classic and quantum parts of superconducting quantum computer. Thus, all control and data exchange with classically operated electronics can be provided by high-speed on-chip RSFQ circuitry (see Bocko et al. [17]), and the external communication between RSFQ and room temperature semiconductor electronics can be realized by using optical fiber channels combined with MSM (metal-semiconductor-metal) switches and laser-emitting diodes.

Experimental observation of the macroscopic quantum coherent oscillations in a flux qubit, which is awaited in the near future, should open the way for practical QC based on the existing superconducting electronics technology.

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