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Flux-based superconducting qubits for quantum computation

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Abstract

Superconducting quantum circuits have been proposed as qubits for developing quantum computation. The goal is to use superconducting quantum circuits to model the measurement process, understand the sources of decoherence, and to develop scalable algorithms. A particularly promising feature of using superconducting technology is the potential of developing high-speed, on-chip control circuitry with single-flux quantum (SFQ) electronics. The picosecond time scales of SFQ electronics means that the superconducting qubits can be controlled rapidly on the time scale that the qubits remain phase-coherent. Recent progress and the major challenges are presented.

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1. Introduction—the qubit

Quantum computers are machines that store information on quantum variables and that process that information by making those variables interact in a way that preserves quantum coherence [1]. Qubits have been physically implemented in a variety of systems, including cavity quantum electrodynamics, ion traps, and nuclear spins. Although quantum coherence is high in these systems, it is difficult to scale them to the desired large number of interacting qubits. Solid-state circuits are capable of large-scale integration, but their coupling to the external states (the environmental degrees of freedom) leads in general to short decoherence times. Proposals have been made for solid-state qubits with spins of donor atoms in silicon, quantum dots, and with electrons trapped in standing acoustic wave devices; however, the technology to manufacture these solid-state systems still needs to be developed.

Superconducting qubits are capable of addressing the constraints of a long decoherence time and short operation times, scalability, and manufacturability: (1) they are calculated to have a long coherence time (∼1 ms); (2) they are compatible with Josephson junction control electronics that have been shown to have an extremely short

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operation time (~1 ps); (3) and finally, they are manufacturable using existing state-of-the-art semiconductor fabrication equipment. Integrability with fast on-chip electronics, scalability, and manufacturability—these are the central advantages that superconducting quantum devices bring to quantum computing.

Two classes of superconducting devices have been proposed as qubits: charge-state qubits and flux(phase)-based qubits [2].

As the Josephson tunnel junctions approach the nanometer scale, the capacitive charging energy will exceed the Josephson inductive energy, and the quantum states of these devices correspondingly approach charge states. Charge-state superconducting devices have been proposed as qubits [3–5], and coherent oscillations between charge states [6,7] have been observed in a single device [8]. However, charge-based qubits suffer from environmentally induced decoherence due to the long-range coupling from the test leads and also due to the shorter range coupling from the random fluctuating charges in the substrate. This coupling may prevent scaling of charge-state qubits beyond a few devices. Nevertheless, high-speed measurements with charging devices, such as the RF SET, make charge-state devices an important area for quantum coherence studies [9,10].

When the Josephson energy exceeds the charging energy of the junction, the quantum states approximate classical flux (or phase) states. Two types of flux-based superconducting qubits have been proposed. Both are superconducting loops whose qubit states are characterized by the magnetic flux generated by persistent currents (PCs) in opposite directions. The first type interrupts the superconducting loop with a single Josephson junction, and is known as an RF SQUID (RFS) qubit [11]. The second type uses three or more Josephson junctions in the loop, and is known as a PC qubit [12,13]. Recently, both types of qubits have been experimentally shown to display the avoided crossing of two quantum energy levels, proving for the first time that quantum superposition exists in these flux-based superconducting qubits [14,15]. A third type of phase-based superconducting qubit is based on single junctions that have been used for quantum coherence experiments in the past [16–19]. The π-junctions made from d-wave superconductors have also been proposed as qubits; they are intrinsically double well systems but the technology for making large numbers of these types of junctions still needs to be developed [20].

2. Operation of the qubit

In principle, any two distinct quantum states can serve as the logical $|0\rangle$ and $|1\rangle$ states. Examples include states which differ by one Cooper pair in the charge qubits and also states of different energies in a single junction potential well. In the flux-based qubits, the two states that are chosen usually differ in having opposite flux (and circulating currents).

The two states of the RFS and PC qubits can be shown schematically in the diagram of energy versus applied flux in Fig. 1. The logical $|0\rangle$ and $|1\rangle$ states can be taken as the ground state and first

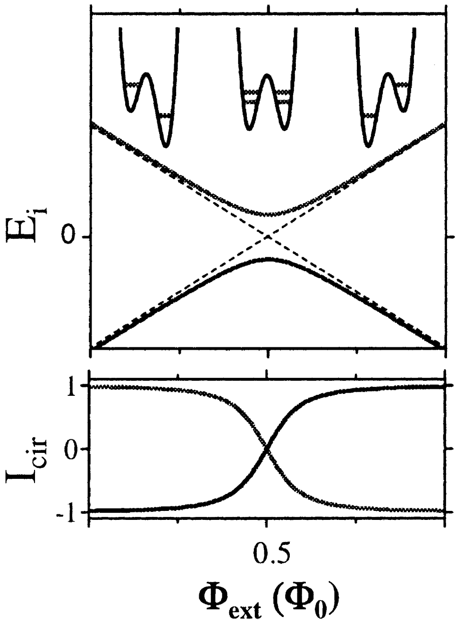

Fig. 1. The energy levels for the ground state (dark line) and the first excited state of the qubit versus applied flux. The double well potentials are shown schematically above. The lower graph shows the circulating current in the qubit for both states as a function of applied flux. The units of flux are given in terms of the flux quantum.

excited state. The energy levels of the ground state (dark line) and the first excited state (light line) are shown near the applied magnetic field of $0.5\Phi_0$ in the qubit loop. Classically the Josephson energy of the two states are degenerate at this bias field and increase and decrease linearly from this bias field, as shown by the dashed line. Since the slope of the E versus magnetic field is the circulating current, these two classical states have opposite circulating currents. However, quantum mechanically, the charging energy couples these two states and results in an energy level repulsion at $\Phi_{\text{ext}} = 0.5\Phi_0$, so that there the system is in a linear superposition of the currents flowing in opposite directions. As the applied field is changed from below $\Phi_{\text{ext}} = 0.5\Phi_0$ to above, the circulating current goes from negative, to zero at $\Phi_{\text{ext}} = 0.5\Phi_0$, to positive as shown in the lower graph of Fig. 1.

The qubit can be manipulated in two ways so that it is in some linear combination of its two quantum mechanical states. In both methods, the qubit is biased initially at some flux bias and the state relaxes to the ground state of the system. In the first method, radiation of frequency equal to the energy difference is pulsed to the qubit. Typically the energy difference is a few GHz. The system undergoes Rabi oscillations between the two states; by controlling the amplitude and duration of the pulse, the qubit can be put into a linear combination of states. In the second method, a similar oscillation can occur if the flux bias is quickly changed to a different flux bias.

The state of the qubit system is inferred by measuring the flux (equivalently, the circulating current) produced by the qubit state [11,12,21]. The measured flux is perpendicular to the plane of the qubit. Qubits must be coupled together to perform quantum computations. The flux-based qubits can be magnetically coupled together through mutual inductive coupling or through coupled with transformer loops [12] (More exotic capacitively couplings of qubits are also possible.).

3. Design constraints

For the flux-based qubits to operate with states of opposite circulating current, the major design constraints are twofold. First, the ground state and the first excited state of the qubit must have opposite circulating currents which produce measurable flux. This criterion is satisfied when the ratio of the Josephson energy ($E_J = \Phi_0 I_c/2\pi$) to the charging energy ($E_C = e^2/2C$) is in the range of $1000 > E_J/E_C > 10$. The two main fabrication variables that can be controlled are the critical current density J_c and the size of the Josephson junction.

Fig. 2 shows contours of constant E_J/E_C as a function of the junction size p and the critical current density. Hence, sub-micron junctions with critical current densities of a few hundred A/cm^2 are needed. Typical experimental parameters for the energy separation between the two-qubit states is about 10 GHz, and the circulating current is about 1 μA.

For the PC qubit the loop area is a few square microns. This results in a small, but measurable, flux of about 10^{-3} of a flux quantum, which is sensed by the measuring device and also can be used to couple to other qubits. With resonant microwave pulses, single qubit operations should take about 10 ns.

For the RFS qubit, the inductance of the loop must be chosen such that the circulating current

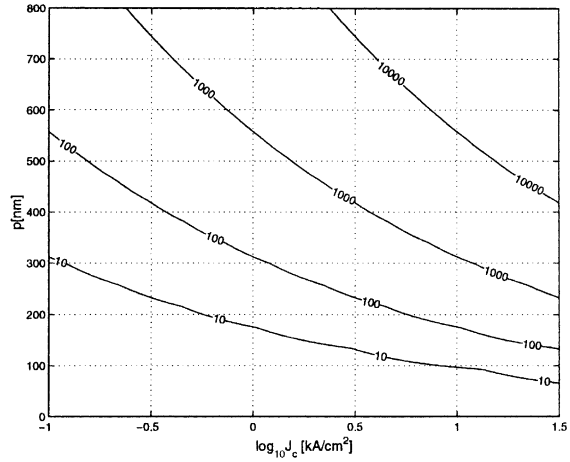

Fig. 2. Contours of constant E_J/E_C ratios plotted as a function of junction size in nanometers and the log of the critical current density in kA/cm^2. Values of the ratio between 10–1000 are suitable.

produces nearly a full flux quantum so that the potential has the needed double well shape. This flux is much larger than that of the PC qubit and hence provides more flexibility in measuring the RFS qubit. However, for a circulating current of the order of a μA, the inductance needed is a few nanohenries, which implies a loop diameter of the order of a few hundred to a thousand microns. Given the desire for manufacturability and scalability, the micron sized loops of the PC qubit offer a more compact choice for quantum computing applications which require a large number of qubits.

The second major constraint is that the flux-based qubits must operate coherently for a long enough time that error prevention techniques can be applied. Decoherence poses one of the most important theoretical problems that has to be solved to realize macroscopic quantum coherence in superconducting qubits. There are many sources of decoherence for superconducting qubits [22]. The potential sources of decoherence that are likely to have the strongest effect on the proposed experiments are decoherence induced by interaction with nuclear spins in the ambient material, decoherence induced by interactions with other qubits and decoherence induced by the measurement apparatus. We estimate that in the regime where quantum error correction must be used, the decoherence time is of the order of 1 ms, which give the needed quality factor for implementing error correction.

The interaction between the qubit and the nuclear spins is strong enough to induce significant decoherence due to the large number of nuclear spins [22]. Moreover, the dipole interaction between the nuclear spins induces fast nuclear spin flipping of the order of 10 μs. Consequently the qubit sees a fluctuating magnetic field. To achieve long time quantum computation, pulse techniques based on the average Hamiltonian approach of NMR need to be developed to decouple the qubit from the nuclear spins.

Interaction with other qubits supplies a potentially strong source of decoherence. Some of this effect can be avoided simply by placing qubits far apart. But in the long term, a more efficient method of decoupling qubits may be to use active decoupling or average Hamiltonian techniques developed for NMR to make the unwanted interaction between qubits average to zero over a desired time scale.

During measurement, information is transferred from a quantum system to a detector via their mutual coupling. The same coupling that extracts information from the quantum system transmits noise from the detector's environment to the system as well. For example, a DC SQUID placed near or around the qubit has been used to measure the flux of the qubit state. A calculation can be made of the noise transmitted to a superconducting PC qubit from the environment of this DC SQUID that measures the qubit. In fact a method has been found which maps the calculation onto an equivalent linear circuit which represents the linearized Hamiltonian of the interacting system [23–25]. The transmitted noise is the Johnson-Nyquist noise from the effective impedance of this linear circuit. The high frequency part of the transferred noise is reduced due to the filtering by the SQUID. This noise induces qubit relaxation and decoherence which are estimated with a master equation approach. Other systems that interact with the qubit, such as on-chip oscillators and control circuits, must be designed such that the effective noise that they present to the qubit is minimized.

4. Experimental prospects

At temperatures below 50 mK both the RFS qubit and the PC qubit have experimentally been put into a superposition of two flux states, one state corresponding to current of roughly 1 μA flowing clockwise in the loop and the other counterclockwise. What is mapped out in each case is the energy level difference between the two states as shown in Fig. 1. The observation of the energy level splitting at the degeneracy point of applied flux of half a flux quantum is evidence of the quantum superposition of the two circulating current states. The RFS qubit is a loop of Nb with an inductance of about 240 nH, and has a circulating current of a few microamps [14]. The two flux states used in the experiment are excited states of the system which are about 90 GHz below the initially populated state. The PC qubit is a loop of Al with an inductance of about 10 nH and a half a microamp of circulating current [15]. The two states in this case are the ground state and first excited state of the system, and at higher flux bias are separated by about 10 GHz.

The next crucial step in the experiments of superconducting qubits is the observation of coherent oscillations between these two quantum states driven by external radiation or by rapid changes of the flux bias. The first experiments will probably be driven by external control devices and will provide an indication of the decoherence time of a single qubit coupled to measuring devices and the external environment. Also, on-chip single-flux quantum (SFQ) control circuits [26] and oscillators [27] will be developed in parallel to manipulate the qubits. Effort will need to be made in studying the experimental sources of decoherence and limiting their influence on the operation of the qubits.

The coupling of two qubits will be necessary to observe a two-qubit gate operation. Different methods of implementing a two-qubit gate will also lead to better understanding of the sources of error and decoherence in coupled systems. As the number of qubits increases, algorithms which carry out more complex computing functions will need to be designed and the study of these systems will reveal the feasibility of increased scalability of the superconducting qubits.

5. Fabrication challenges

The choice of materials for the qubit still needs to be experimentally determined. Nb and Al are the materials of choice, since both have shown quantum superposition of macroscopic states [14,15]; Nb is used in most complex superconducting circuits, and Al has been used in modest scaled ultra-low temperature experiments on mesoscopic superconductors. Nevertheless, the quality of the junctions for quantum computation still must be investigated and improved. An important parameter is the sub-gap resistance R_{sg}. Recent experiments have shown that for typical samples, Al has a lower level of dissipation than Nb, but both may be sufficiently low for some quantum computing applications [28]. Improvements the quality of the Nb junctions remains an important challenge.

One of the most exciting and challenging prospects is to integrate superconducting control circuitry on the same chip as the qubits. Josephson microwave oscillators made from simple SQUID circuits, long Josephson junctions, or filtered SFQ circuits can be incorporated on the chip to manipulate the qubits. A particularly promising possibility is developing *on-chip*, superconducting SFQ logic circuits as the "classical" electronics to provide the functional interface between quantum coherent circuitry and the classical world. The picosecond time scales that SFQ circuits can achieve means that superconducting qubits can be controlled rapidly on a time scale over which the qubits remain phase coherent. Circuits that fully integrate SFQ circuits with quantum experiments have recently been proposed [29–31].

However, the integration of SFQ circuitry and superconducting flux-based qubits presents another challenge. As we mentioned earlier, the qubits need to operate with critical current densities of a few hundred A/cm^2; whereas, SFQ circuits have mostly been made in the 1000–10,000 A/cm^2 range. There are three possible fabrication strategies to overcome this problem. The first strategy is to develop an all-Nb, monolithic, single-chip approach. This will require that measurement and control circuits be developed for the lower critical current density, following design rules compatible with the small qubit junctions. The second strategy is to develop a flip-chip technology: The qubit can be fabricated by one process on one chip (and even at different fabrication laboratories either in Al or Nb) and the measurement and control circuitry can be fabricated by the same or different process on another chip. The two chips will then be bonded together so that they are inductively coupled. The third and final strategy is to develop a single-chip monolithic circuit incorporating two junction technologies, one for the SFQ circuitry, and the other for the qubit.

The flip-chip approach is much more versatile than the monolithic, and puts fewer constraints on

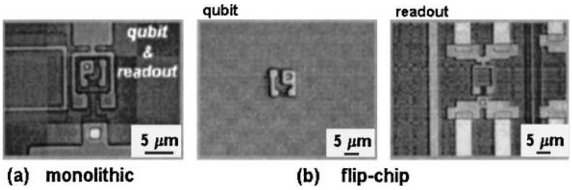

Fig. 3. A qubit and a measuring DC SQUID fabricated in Nb as a (a) monolithic process and (b) flip-chip process. Junctions have been fabricated down to 400-nm length-scale.

the fabrication technology. Fig. 3 shows samples fabricated at Lincoln Laboratory using each of the first two strategies listed.

Experiments on the flip-chip technology show that the two chips can be bonded together with better than 2 μm lateral spatial resolution, and with a distance between the chips of about 1 μm [32]. Experiments show that magnetic flux can be inductively coupled between the chips at the level needed for the operation of the qubit.

Finally, many fabrication and design issues will need to be investigated for packaging large number of qubits together for quantum computation and for integrating classical communication channels between nodes of small number of qubits for type-II quantum computation schemes [33].

6. Conclusions

Superconducting qubits are a good candidate for qubits for quantum computing because they should have sufficiently long decoherence times for computation; moreover, they are compatible with high-speed superconducting control electronics which can be integrated on the same or nearby chip, and the superconducting electronics and qubits are manufacturable with state-of-the-art semiconductor fabrication equipment which is necessary for large-scale configurations.

Flux-based superconducting qubits have been discussed in more detail here, but charge-based qubits are also of interest. Much work remains to realize the operation of superconducting flux-based qubits. Although experiments have shown energy level repulsion, experiments on Rabi oscillation, decoherence mechanisms, and coupled qubits will ultimately determine the feasibility of these qubits.

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