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13. ABSTRACT (Maximum 200 words)

An implementation of a quantum computer using superconducting electronics has been proposed and studied. A single Josephson junction superconducting quantum interference device (SQUID) may serve as a suitable two-state quantum system to be used as the qubits of a possible quantum computer. The quantum states of the superconducting qubits may be manipulated by single flux quantum pulses created and controlled by other "on-chip" superconducting circuitry. Gates to allow logical interactions of qubits have also been conceptualized. The parameters of the qubit SQUIDs and other associated circuitry were found to be within current technological constraints and a first experiment to demonstrate quantum coherence in a superconducting qubit was designed.

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QUANTUM COMPUTING WITH SUPERCONDUCTING ELECTRONICS

FINAL PROGRESS REPORT

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UNIVERSITY OF ROCHESTER

A. Statement of the problem studied

In a one year exploratory research program we have developed a paradigm for a possible superconducting quantum computer. The elements of a quantum computer are first; a suitable superconducting two-state quantum system that serves as the qubit, second, a technique that will allow the manipulation of the quantum state of the qubits (tipping pulses) and finally, circuits to bring the qubits into interaction with each other (logic gates). Using computer simulations and analytical modeling we have concluded that there are practical schemes, within current technological constraints, to realize each of these elements using superconductors and we have formulated concrete plans for the first experimental steps to assess the viability of this approach.

B. Summary of the most important results

In our proposed scheme a rf SQUID will serve as the superconducting qubit. A rf SQUID is a single Josephson junction in parallel with an inductor, and for a specific range of SQUID parameters (critical current of the Josephson junction and the SQUID inductance) there will be only two allowed flux states. If an external magnetic flux bias equal to one-half flux quantum is applied to the SQUID loop then the system can be described by a symmetric double-well potential. The two quantum states that will serve as the qubit basis states correspond to the system being localized in either one or the other potential well minima. In the "0" state there is a circulating current in the SQUID that opposes the applied magnetic field and in the "1" state there is a circulating current that reinforces the applied external field. These two "flux" states are the symmetric and antisymmetric superpositions of the lowest two energy eigenstates of the potential and thus are non-stationary so the system will periodically tunnel back and forth between the two potential minima; a display of macroscopic quantum coherence (MQC). However, macroscopic quantum coherence has not yet been experimentally observed in such systems.

It is proposed to use the nonstationary flux quantum states as the qubit basis states. The SQUID parameters may be chosen so that the tunneling oscillation period is very long, on the order of microseconds or longer, compared to the dynamical time scale of the junction, which is on the order of picoseconds. Thus, if we prepare the SQUID in one of its states it will be essentially stationary over experimental (eventually computational) time-scales. This brings us to the next feature of the proposed scheme - the technique for preparing and manipulating the quantum state of the rf SQUID qubit. Suppressing the critical current of the Josephson junction in the SQUID lowers the barrier between the two potential wells and speeds up the tunneling oscillation rate. By lowering the barrier for a controlled interval of time the SQUID may be manipulated into any desired superposition of the two qubit basis states.

Schroedinger equation simulations of a rf SQUID show that the SQUID qubit may indeed be manipulated into any desired superposition of qubit basis states on a time-scale of approximately 100 psec. It would be exceedingly difficult to provide external control to the SQUID with such precise time resolution, indeed the required wide-bandwidth control lines that would couple the SQUID qubit to the outside world would introduce excessive noise and destroy the SQUID's quantum coherence.

To solve this problem we plan to employ on-chip control of the SQUID qubits using Josephson junction digital circuits. Existing Rapid Single Flux Quantum (RSFQ) technology is based on the manipulation of single flux quanta and with such circuits it is possible to generate and manipulate ~ 3 picosecond duration single flux quantum (SFQ) pulses - ideal for manipulating a SQUID qubit. An on-chip RSFQ shift register [1] may be used to provide an adjustable number of SFQ pulses that in turn may be used to suppress the critical current of the qubit junction by propagating the pulses over a superconducting microstrip line inductively coupled to the qubit junction. In our simulations we have demonstrated that a modest number of SFQ pulses, 10-20, each one providing a critical current suppression by about 5%, may act as a $\pi/2$ pulse for our SQUID qubit, the exact number of required SFQ pulses is determined by the SQUID parameters and the magnetic coupling strength. As a practical matter the single junction of the rf SQUID will actually be replaced by two junctions in parallel so that a sufficient amount of flux may be coupled into the structure to provide the required critical current suppression. [2] The dynamics of the two junction system is essentially identical to the single junction rf SQUID in the limit in which a SQUID qubit would operate.

We have designed the experiment to demonstrate quantum coherence in a rf SQUID and we are currently in the process of simulating and laying out the necessary RSFQ circuits for the MQC demonstration experiment. We also have developed preliminary designs, based on the corresponding classical simulations, for fundamental qubit gates - NOT, COPY, AND, and the controlled NOT, the latter being of particular interest since it may form the basis of an experiment to demonstrate conditional logic using superconducting qubits. However this is the subject of future experiments - there are other fundamental issues that first must be experimentally explored.

One of the chief accomplishments during the project was to determine the SQUID parameters, i.e., the Josephson junction critical current density, junction capacitance, sub-gap resistance, the SQUID inductance and the temperature needed for a demonstration of MQC. In the following we discuss the determination of the SQUID parameters.

We will use Nb circuitry throughout. The junctions will be $Nb/Al_2O_3/Nb$ trilayer junctions (specific capacitance ~50 fF/μm^2). The inductor will be Nb microstrip (specific inductance ~0.5 pH/square) for excellent isolation from stray fields. The sub-gap leakage current of the qubit junctions must be as small as possible. That said, the Schrödinger equation of motion of the rf SQUID at one-half flux bias contains three experimental parameters, the SQUID inductance L, the critical current of the SQUID Josephson junction I_c, and the junction capacitance C. The last two of these can be reexpressed as the junction's critical current density j_c and its area d^2. We must choose optimum target values for these parameters.

Given L and I_c the SQUID potential versus internal flux is determined. Then given C the energy levels and hence the ground state splitting ΔE and hence the qubit oscillation frequency $\Delta E/h$ can be calculated using Schrödinger's equation. We have performed such calculations for ~ 100 parameter sets spanning the interesting region of the parameter space. We are interested in $\Delta E/k$ between 3 mK which gives an oscillation period of 16 ns, and 100 mK which gives an oscillation period of 0.5 ns. Specifying ΔE however is not sufficient; there is still a two dimensional surface within this three dimensional parameter space which gives any desired ΔE.

Many practical factors must be considered to further specify the target parameter values. For instance, if I_c is large then j_c may be too large to attain high-quality junctions, whereas if I_c is too small then L may need be so large that light-travel time across the qubit is a complicating factor. Or, if C is small then d will be too small to reliably fabricate the junction, whereas if C is too large the ground state energy approaches or exceeds the potential maximum and the flux can never be properly localized. All such trade-offs must be balanced together, and as in any realistic experiment the trade-offs are not easily analytically quantifiable.

To deal with this, we performed an extensive analysis which focused on six criteria affecting the choice of the three experimental parameters. A careful weighing of these considerations gave well-defined target parameters. These are: $d = 1.0\ \mu m$, $I_c = 4\ \mu A$, and $L = 100$ pH. This implies $j_c = 400$ A/cm^2 and $C \approx 50$ fF. Experience will certainly change these target parameters, but not drastically.

As mentioned above an adjustable I_c is accomplished by replacing the qubit junction by two such junctions in parallel in a very small inductance loop. If the inductance of the qubit "junction" dc SQUID is much less than the inductance of the principal rf SQUID, then it behaves exactly as an extended single junction; the small SQUID loop however allows the moderate magnetic field supplied an external adjustment current to adjust the effective junction I_c. For our experiment, each of the two junctions should have $d = 0.71\ \mu m$ so the total junction area is still $1.0\ \mu m^2$, but j_c remains 400 A/cm^2.

The looming issue that will determine whether or not quantum computing may eventually be realized in macroscopic superconducting circuits is whether or not quantum coherence actually exists over useful time intervals in such systems or is there some fundamental property of such macroscopic systems that will destroy quantum coherence? The planned experiments will be a critical first step in this determination. What we learn from these experiments will likely alter the following analysis, never-the-less we conclude this report our best estimate of the ultimate performance of superconducting quantum computers given the present state of knowledge.

Ultimate performance of a SQUID quantum computer

A critical figure of merit to compare the suitability of technologies for quantum computation is the quantum dephasing time, t_ϕ, divided by the switching time, t_S. This gives the maximum number of coherent computational steps that could possibly be performed using that qubit, without error correction. Several years ago DiVincenzo [3,4] collected or evaluated such data for a variety of suggested qubits. The ratios ranged from 10^3 to, in one case, 10^{13}. DiVincenzo used $h/\Delta E$ as an estimate of the time required to switch one quantum gate, surely a very optimistic estimate. We now estimate this ratio for the magnetic-flux qubit.

We do not use $h/\Delta E$ for the switching time because we propose flux basis states rather than energy basis states, and in fact ΔE will be changed during qubit operations. Lacking a rigorous derivation, we use semi-classical arguments to estimate of the switching time of a single qubit. The switching of the rf SQUID implies that the direction of the circulating current is reversed. The SQUID inductor then develops a transient voltage, $V = L\,dI/dt$. This voltage should not exceed the energy gap voltage, 3 mV for the Nb Josephson junctions we plan to use, or else there is loss; this loss corresponds to the qubit coupling to dissipative modes which lie at energies above the energy gap. Since $L\ \delta I$ is about one-half flux quantum, $\Phi_0/2$, for SQUID qubits, this gives a minimum t_S of 0.3 ps. Today's laboratory RSFQ SQUID circuits have switching times of about 3 ps, so this estimate appears reasonable.

The predicted phase coherence time t_ϕ in the intermediate temperature region is given by [5]:

$$t_\phi = \frac{2\hbar^2}{(\delta_0\Phi_0)^2}\frac{R}{kT} = 0.06\ \mathrm{s}\ \frac{R}{10^{10}\ \Omega}\ \frac{1\ \mathrm{mK}}{T} \quad . \qquad (1)$$

δ_0 is the fractional flux separation of the potential energy minima, about 1/4 for reasonable parameters. R is the resistance of the Josephson junction in the simplest model, but in general it represents all of the dissipation coupled to the SQUID.

To make an optimistic "ultimate" estimate for t_ϕ, we extrapolate a few years into the future and choose a temperature T approaching 1 milliKelvin. We assume that the SQUID is perfectly shielded and decoupled from external dissipation. Then R arises only from the leakage current of the Josephson junction. We could with reason choose an extremely large value for R by using the BCS theory prediction that the leakage current goes exponentially to zero as T goes to zero. But we wish to use a much more conservative estimate of future junction quality and choose a resistance ratio of 10^{10} (ratios greater than 10^8 have been experimentally achieved [6]) multiplied by our intended normal resistance R_N of 500 Ω. Then the quantum dephasing time is thirty seconds. Thus the ratio of t_ϕ to t_s is 10^{14}. This is larger than the numbers for any other technology in DiVincenzo's [3] table. This large ratio demonstrates the promise of magnetic-flux-based quantum coherent computation.

Publications during the Project Period

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Participating Scientific Personnel

Mark F. Bocko - Principal Investigator

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