

Flux qubits: controllable coupling, single-shot readout and hot electrons

John Clarke,¹ T. Hime,¹ S. Linzen,¹ B.L.T. Plourde,¹ P.A. Reichardt,¹ T.L. Robertson,¹ K.B. Whaley,² F.K. Wilhelm,³ C.-E. Wu,¹ and J. Zhang²

Departments of ¹Physics and ²Chemistry, University of California, Berkeley, CA 94720, USA
³Ludwig-Maximilians-Universität, 80333 München, Germany

The flux state of a three-junction qubit is measured with a dc Superconducting QUantum Interference Device. The qubit and SQUID are fabricated from evaporated aluminum films that are patterned using electron-beam lithography. The qubit encloses an area of $11280 \mu\text{m}^2$, so that on-chip flux lines can be used to generate the necessary half-flux quantum of bias (Fig. 1); nonetheless, the geometrical inductance of the qubit is small compared with the kinetic inductance of the three junctions. The flux state of the qubit is determined by applying current pulses to the SQUID and adjusting the amplitude of the pulse to obtain a 50% switching probability. We discuss two aspects of the experiment: single-shot readout of the qubit with a SQUID in which each junction is shunted with a frequency-dependent impedance, and the role of hot electrons in the SQUID in reducing the relaxation time of the qubit. We begin, however, with a proposed scheme for varying the coupling between two flux qubits by adjusting the bias current of the readout SQUID in the zero-voltage state.

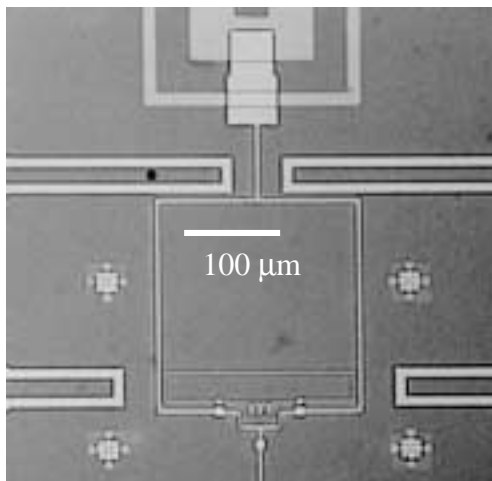


Fig. 1: SQUID and three-junction flux qubit. SQUID bias current and voltage leads at top and bottom of SQUID loop. Flux bias lines located at top and sides of SQUID loop. The Josephson tunnel junctions, located at the bottom of the SQUID and qubit loops, are typically $200 \times 200 \text{ nm}^2$ and are formed with double-angle evaporation.

In order to entangle two flux qubits, it is highly desirable to be able to control their mutual inductance M . In particular, manipulations to achieve entanglement are much more straightforward if M can be reduced precisely to zero at specified times. This is not a trivial problem because of the inherent coupling of the two qubits even in the absence of external circuits. A scheme that enables one to vary the coupling and to reduce it to zero is shown in Fig. 2(a), in which two qubits are surrounded by a SQUID. The technique relies on the fact that the inverse dynamic inductance of a SQUID in the zero-voltage state can be either positive or negative. When a flux is applied to the SQUID, the flux generated by the induced supercurrent opposes applied flux in the first case, but supports it in the second. Thus, if there is a change in the current in (say) qubit 1, there will be a change in the flux in qubit 2 due to the mutual inductance between the qubits, and a second contribution that is mediated by the SQUID. This SQUID-mediated contribution can be made positive or negative simply by changing the magnitude of the bias current in the SQUID at an appropriate, fixed value of flux [Fig. 2(b)]; the SQUID remains in the zero-voltage state. Since the change in bias current required to control the inductive coupling of the two qubits is small, less than the critical current of the SQUID, it can be pulsed rapidly with existing technology. A set of

device parameters is proposed that is realistically achievable. This method enables one both to vary the mutual inductance between two qubits and to read their flux states with a single SQUID, simply by applying current pulses of appropriate magnitude. A scheme for a Controlled Not (CNOT) gate is suggested that involves only current pulses and precisely chosen microwave pulses (Fig. 3).

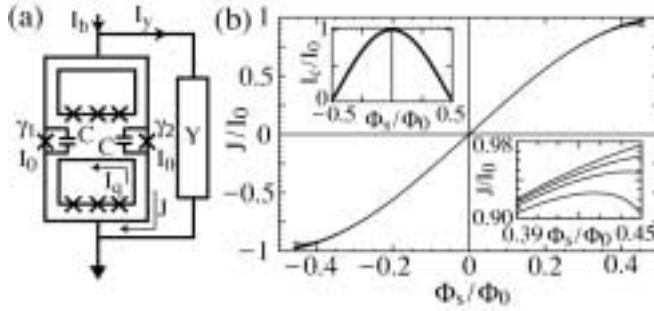


Fig. 2: (a) SQUID-based coupling scheme. The SQUID has inductance L and critical current I_c . The admittance Y represents the SQUID bias circuitry. (b) Response of SQUID circulating current J to applied flux Φ_s for $\beta_L = 2 L I_0 / \Phi_0 = 0.04$ and I_b / I_c ($0.45 \Phi_0$) = 0, 0.4, 0.6, 0.85 (top to bottom). Lower right inset shows $J(\Phi_s)$ for same values of I_b near $\Phi_s = 0.45 \Phi_0$. Upper left inset shows I_c versus Φ_s .

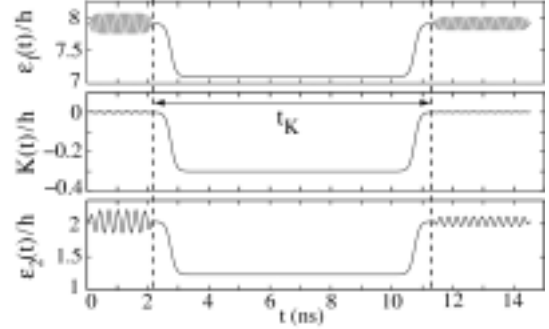


Fig. 3: Pulse sequence for implementing CNOT gate. Energy scales in GHz. The bias current is pulsed to turn on the interaction in the central region. Total single-qubit energy bias $\epsilon_i(t) = \epsilon_i^0 + \epsilon_i^m(t) + \delta\epsilon_i(t)$, where ϵ_i^0 are the static qubit bias energies and $\epsilon_{1,2}^m(t)$ are microwave pulses which produce single-qubit rotations in the decoupled configuration; crosstalk shift of $\epsilon_i(t)$ due to bias current pulse, $\delta\epsilon_i(t)$, along with modulation of coupling energy $K(t)$ due to microwaves are shown.

The use of a dc SQUID with unshunted tunnel junctions has the advantage of creating low dissipation in the flux qubit but the disadvantage of a broad switching distribution due to the onset of macroscopic quantum tunneling (MQT) at low temperatures. Adding resistors across the junctions narrows the distribution but substantially increases dissipation in the qubit. We demonstrate that a resistor R in series with a capacitor C connected across each junction enables one to achieve single-shot readout while maintaining low dissipation in the qubit. The RC-time constant is chosen so that the reactance of the capacitor is small at the plasma frequency of the junctions, ~ 100 GHz, providing substantial damping that suppresses MQT. On the other hand, at the qubit frequency, ~ 1 GHz, the reactance of the capacitor is much greater than R , and the dissipation coupled to the qubit is low. Detailed calculations of the width of the switching distribution and of the qubit relaxation and dephasing rates due to the RC shunts are presented.

When the SQUID switches to the gap voltage $2\Delta/e$ (Δ is the energy gap of the Al films) following a measurement of its critical current, there is substantial dissipation. In spectroscopic measurements on a flux qubit, we have measured the relaxation of the microwave-induced peaks as a function of the delay time t between successive current pulses in the readout SQUID. We find that the relaxation rate increases dramatically as t is reduced. We explain this behavior in terms of a model in which hot electrons, generated when the SQUID switches to $2\Delta/e$, increase the subgap conductance of the tunnel junctions. This conductance increases the dissipation experienced by the flux qubit for a remarkably long time, ~ 1 ms, after the SQUID has been restored to its zero-voltage state.

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