Superconducting Persistent Current Qubits In Aluminum

Personnel

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Quantum computers are devices that store information on quantum variables such as spin, photons, and atoms, and process that information by making those variables interact in a way that preserves quantum coherence. Typically, these variables consist of two-state quantum systems called quantum bits or ‘qubits’. To perform a quantum computation, one must be able to prepare qubits in a desired initial state, coherently manipulate superpositions of a qubit’s two states, couple qubits together, measure their state, and keep them relatively free from interactions that induce noise and decoherence.

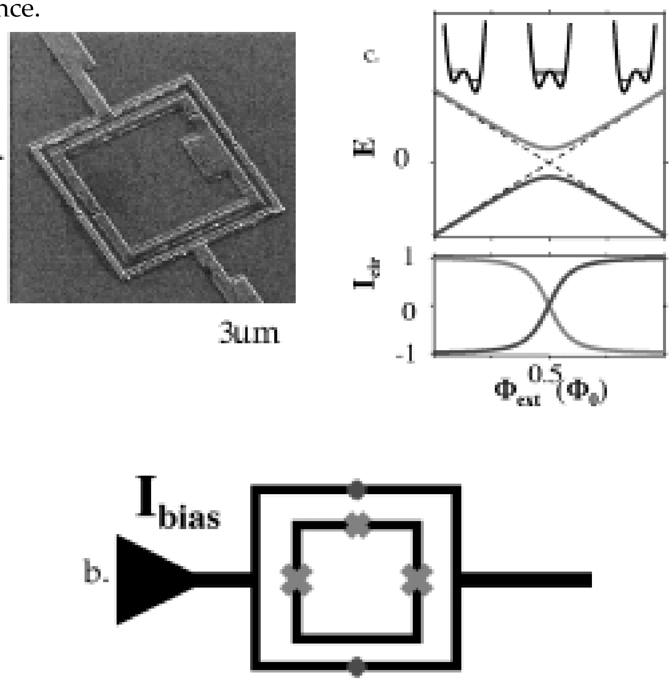

Fig. 1: (a) SEM image of the persistent current qubit (inner loop) surrounded by the measuring dc SQUID. (b) a schematic of the qubit and measuring SQUID, the x’s mark the Josephson junctions. (c) The energy levels for the ground state (dark line) and the first excited state of the qubit versus applied 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.

We have designed a superconducting qubit that has circulating currents of opposite sign as its two states. The circuit consists of three nano-scale aluminum Josephson junctions connected in a superconducting loop and controlled by magnetic fields.

Figure 1a shows a SEM image of the persistent current qubit (inner loop) and the measuring dc SQUID (outer) loop. The Josephson junctions appear as small “breaks” in the image. A schematic of the qubit and the measuring circuit is shown in Figure 1b, where the Josephson junctions are denoted by x's. The qubit loop is 5 ¥ 5 mm2 with aluminum-oxide tunnel junctions, microfabricated at the TU Delft, by a shadow evaporation technique. (This is in contrast to the samples fabricated at MIT's Lincoln Laboratory that are made in niobium by photolithographic techniques on a trilayer of niobium-aluminum oxide-niobium wafer.) The capacitance of the junction is estimated to be about 3 fF and the ratio of the Josephson energy to the charging energy is about 40. The inductances of the inner qubit loop and the outer measuring loop are about 11 and 16 pH respectively, with a 7 pH mutual inductive coupling.

The energy levels of the ground state (dark line) and the first excited state (light line) are shown in Figure 1c near the applied magnetic field of 0.5 F0 in the qubit loop. Classically the Josephson energy of the two states would be degenerate at this bias magnetic field and increase and decrease linearly from this bias field, as shown by the dotted line. Since the slope of the E versus magnetic field is the circulating current, we see that these two classical states have opposite circulating currents. However, quantum mechanically, the charging energy couples these two states and results in a energy level repulsion at Φ_{ext} = 0.5 F0, 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 $\Phi_{ext} = 0.5\ \Phi_0$ to above, we see that the circulating current goes from negative, to zero at Φ_{ext} = 0.5 F0, to positive as shown in the lower graph of Figure 1c. This flux can be measured by the sensitive flux meter provided by the dc SQUID.

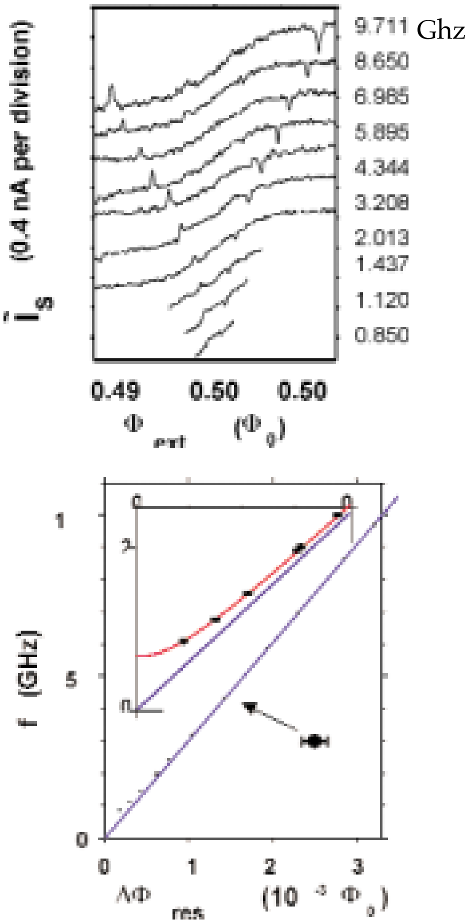

Fig 2. (a) The circulating current as inferred from the dc SQUID measurements for various applied microwave frequencies. The curves are offset for clarity. (b) Half the distance in Φ*ext measured between the resonant peaks and the dips at different frequencies f. The inset shows the low frequency data points. The grey line is a linear fit through the high frequency points and zero. The black line is a fit of the quantum theory.*

Figure 2a shows the circulating current as inferred from the dc SQUID measurements for various applied microwave frequencies. The curves are offset for clarity, and each curve shows the expected change from negative circulating current at low applied flux, to zero at half a flux quantum, and then to positive current at higher flux. This clearly shows that the qubit has the change in flux profile expected of the ground state. When microwaves are applied at the energy difference matching the difference between the ground state and the first excited state, then a transition is induced from the ground state to the first excited state. These are shown by the resonant-like structures in each curve. A plot of the distance in Φ_{ext} at the resonance from $\Phi_{ext} = 0.5\ \Phi_0$ is shown in the figure on the left. Quantum mechanically the energy is expected to follow the form where I_p is the circulating current and V is the

$$\Delta E = \sqrt{\left[2I_p\left(\Phi_{ext} - 0.5\Phi_0\right)\right]^2 + \left(2V\right)^2}$$

tunneling matrix element between the two circulating current states at $\Phi_{ext} = 0.5\ \Phi_0$. The inset shows a fit to the curve which gives an energy gap of about 600 MHz and a circulating current of about 500 nA as expected. These results are among the first experimental verification of the superposition of macroscopic circulating current states.