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Quantum Oscillations in Two Coupled Charge Qubits

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1. Introduction

Realization of quantum computing algorithms [1] requires integration of a large number of quantum bits (qubits). Despite apparent progress in the implementation of individual solid-state qubits [2], there have been no experimental reports of multiple qubit gates - a basic requirement for building a real quantum computer. Among a variety of solid-state qubits proposed, superconducting Josephson qubits have already been implemented demonstrating a potential of Josephson-junction quantum information processing.

A charge qubit [3] is a small superconducting island connected to a reservoir through a Josephson junction. When the island's charging energy exceeds the Josephson coupling energy, its charge states become quantized. At certain conditions, the system can be considered as a two-level system. We use two neighboring charge states differing by one Cooper pair in the island that correspond to logical |0> and |1>. By using short pulses, two charge states can be mixed, and coherent oscillations can be traced by changing the pulse length and using a probe junction.

Here we take one step further on the way to implementation of quantum logic gates by integrating two charge qubits and demonstrating their interaction [4].

2. Two-qubit circuit

Our circuit is shown schematically in Fig. 1. It was fabricated by three-angle evaporation of Al on a SiN_x insulating layer through a Ge suspended mask formed by electron-beam lithography and dry etching. The circuit consists of two charge qubits. The right qubit has a SQUID geometry to allow the control of the Josephson coupling to its reservoir. Both qubits have a common pulse gate but separate dc gates, probes and reservoirs. The pulse gate has nominally equal coupling to each box. Two qubits are coupled electrostatically by an on-chip capacitor. The capacitor is made by an extra island overlapping each Cooper pair box thus forming two tunnel junctions connected in series. Although the coupling island has a finite tunneling resistance ~ 10 MΩ to the boxes, we consider the coupling as purely capacitive because all the tunneling processes are completely blocked. To reduce cross-talk between the qubits and suppress unwanted

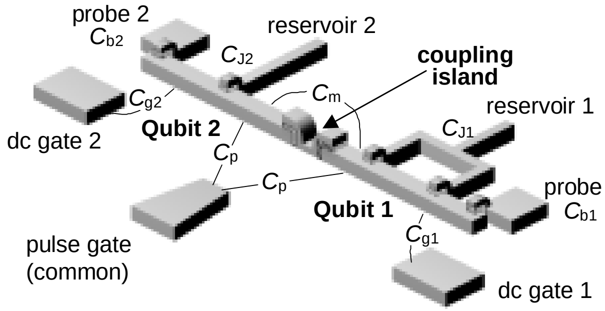

Fig. 1 Schematic layout of two coupled charge qubits.

resonances in the sample package, we used a ground plane beneath the SiN_x layer.

The estimated capacitance of the island to the ground is ~ 1 aF. Our circuit is made such that using dc current-voltage-gate voltage measurements we can estimate all the capacitances shown in Fig. 1 and thus obtain corresponding charging energies: E_{c1} = 484 μeV (117 GHz in frequency units), E_{c2} = 628 μeV (152 GHz) and the electrostatic coupling energy E_m = 65 μeV (15.7 GHz). Josephson coupling energies, E_{J1} = 55 μeV (13.4 GHz) and E_{J2} = 38 μeV (9.1 GHz), were determined from the single qubit measurements described later in the text.

3. Model

We describe our system using two-qubit charge basis $|00\rangle$, $|10\rangle$, $|01\rangle$ and $|11\rangle$, where left and right indices refer to the number of Cooper pairs in the first and second qubits, respectively. Such a four level approximation is justified by the fact that the circuit was fabricated to have the following relation between the characteristic energies: $E_{J1,2} \sim E_m < E_{c1,2}$. Time evolution of the wavefunction of the system is calculated analytically by solving Schrödinger equation with the $|00\rangle$ initial condition. The analysis of the system shows that it has two kinds of resonance: single-qubit resonance corresponding to the degeneracy between either $|00\rangle$ and $|10\rangle$ states or $|00\rangle$ and $|01\rangle$ states, and co-resonance where the state $|00\rangle$ is degenerate with the state $|11\rangle$ and the state $|10\rangle$ is degenerate with the state $|01\rangle$. In the first case, only one qubit (first or second) is excited by the non-adiabatic pulse of length Δt giving rise to the pulse-induced current:

$$I_{1,2} \propto \cos\left[(E_{J1,2}/\hbar)\Delta t\right]. \tag{1}$$

The oscillating frequency depends only on $E_{J1,2}$ and this allows precise determination of Josephson energies.

In the second case, both qubits are excited simultaneously, and the oscillation pattern becomes more complex and reflects interaction between the qubits. The pulse-induced current for the second qubit can be expressed as:

$$I_2 \propto A_1 \cos\left[(\Omega+\varepsilon)\Delta t\right] + A_2 \cos\left[(\Omega-\varepsilon)\Delta t\right], \tag{2}$$

where the amplitudes $A_{1,2}$ and the frequencies Ω and ε depend only on $E_{J1,2}$ and E_m. The expression for I_1 contains same frequency components with different amplitudes.

4. Results and discussion

The experiment is done in the following way. We apply arrays of pulses to the pulse gate and measure induced probe currents I_1 and I_2 that are result of the system relaxation to the ground state. Time dependence of the currents is obtained by changing the pulse length Δt. Fig. 2 shows time dependence of I_2 for two different cases. The top panel corresponds to the single-qubit resonance and the observed dependence can be fitted using (1) with an introduced exponential decay with 2.5 ns time constant. Fourier spectrum of the oscillation contains one pronounced frequency component in accordance with (1). We associate this peak with E_{J2}. The bottom panel shows I_2 oscillation at the co-resonance. The oscillation spectrum has two frequency components in agreement with (2). Two arrows in Fig. 2b indicate the position of $\Omega-\varepsilon$ and $\Omega+\varepsilon$ calculated from E_{J1} and E_{J2} obtained from the single-qubit oscillation and E_m estimated from the dc transport measurements. To fit I_2 oscillation in co-resonance, we took into account finite pulse rise/fall time and realistic initial condition deviating from pure $|00\rangle$ state. In this case, the introduced decay time appeared to be 0.6 ns, a factor of 4 shorter. The fact that the decay time of the coupled oscillations becomes shorter compared to the case of independent single-qubit oscillations is not surprising because an extra decoherence channel is added to each qubit after coupling it to its neighbor.

Next, we checked the dependence of the oscillation frequencies at co-resonance $\Omega-\varepsilon$ and $\Omega+\varepsilon$ on E_{J1} controlled by a weak magnetic field (up to 20 G). The overall dependence of the frequency peaks agrees well with the prediction of our model. In particular, instead of crossing when $E_{J1} = E_{J2}$, the two curves are separated by the gap equal to $E_m/2$.

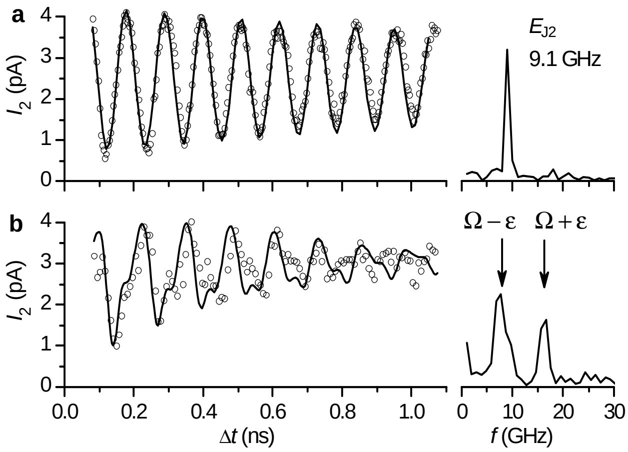

Fig. 2 Oscillations of the pulse induced probe current in the second qubit. Open circles: experimental data, solid lines: fitted curves. (a) Probe current oscillations at the second-qubit resonance point. (b) Probe current oscillations at the co-resonance point. Right panels show oscillations spectra obtained by the Fourier transform.

Our result demonstrates feasibility of electrostatic coupling of qubits, however, such a coupling is not controllable. Nevertheless, a straightforward continuation of our experiment would be a demonstration of conditional operation of two qubits when the result of manipulation of one qubit depends on the state of the second qubit. For this, two pulse gates are required so that each qubit can be individually addressed.

5. Conclusions

We have succeeded in constructing an “integrated” circuit comprising two coupled charge quantum bits. We have measured pulse-induced oscillations of probe currents in time domain and obtained a clear evidence for the interaction between the two coupled qubits. The observed dependence of the frequency components in the oscillation spectra indicates the existence of entangled states, however, direct measurement of the amount of entanglement was not possible.

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References

[1] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information,* (Cambridge: Cambridge Univ. Press, 2000).

[2] R. G. Clark, (ed) *Experimental implementation of quantum computation*, (Princeton: Rinton Press, 2001).

[3] Y. Nakamura, Yu. A. Pashkin, and J. S. Tsai, *Nature* 398, 786 (1999).

[4] Yu. A. Pashkin , T. Yamamoto, O. Astafiev, Y. Nakamura, D. V Averin and J. S. Tsai, *Nature* 421, 823 (2003).