

Two-Qubit Dynamics with Josephson Qubits

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Background

Background

Cooper Pair Box

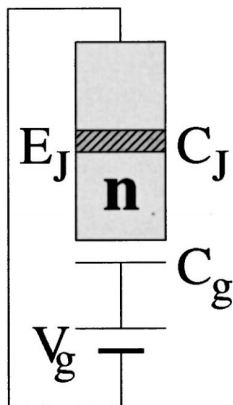


Figure : <http://journals.aps.org/rmp/pdf/10.1103/RevModPhys.73.357>

Background

SQUIDs

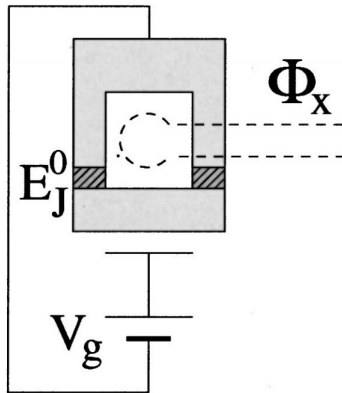


Figure : <http://journals.aps.org/rmp/pdf/10.1103/RevModPhys.73.357>

Background

Single-Qubit Charging Diagram

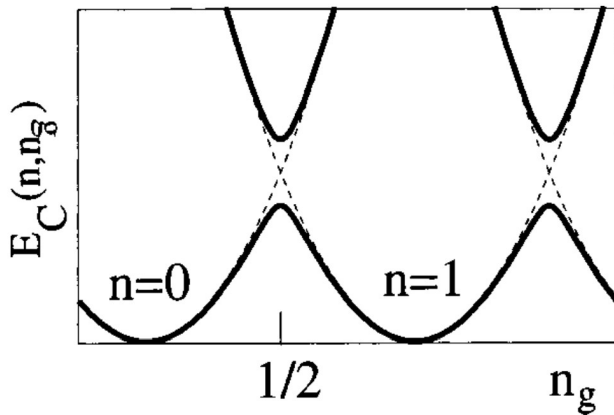


Figure : A simple caption

Background

Previous Experiments

Ref

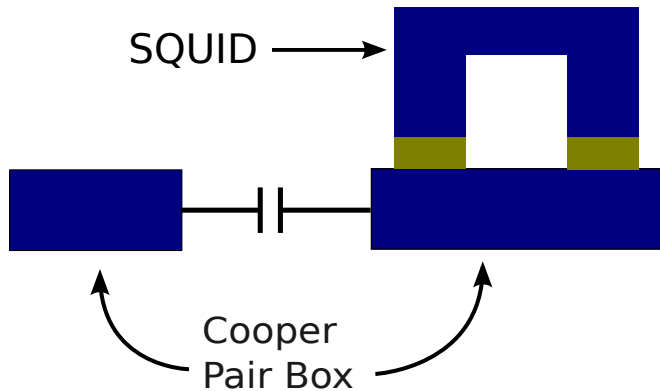
<http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.78.4817>

<http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.79.2328>

Coupling of Two Qubits

Coupling of Two Qubits

Basic Idea



Coupling of Two Qubits

The Circuit

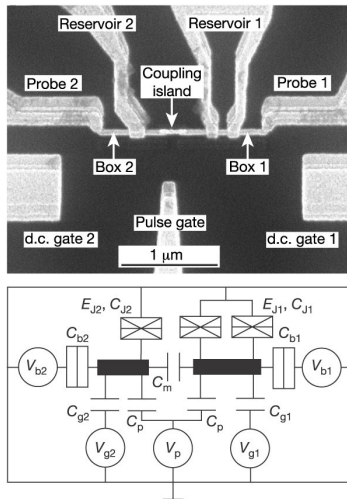


Figure : <http://www.nature.com/nature/journal/v421/n6925/full/nature01365.html>

Coupling of Two Qubits

Charging Diagram of Two-Qubit Case

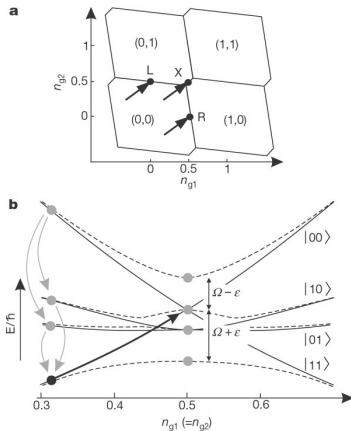


Figure : <http://www.nature.com/nature/journal/v421/n6925/full/nature01365.html>

Coupling of Two Qubits

Points L and R

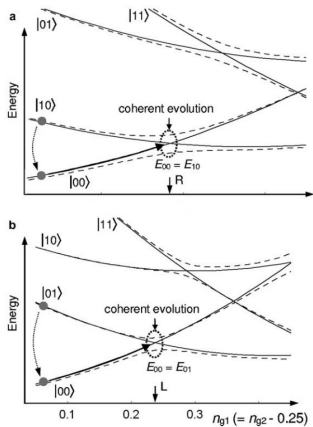


Figure : <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.193.5098&rep=rep1&type=pdf>

Coupling of Two Qubits

Charging Diagram Level Curves

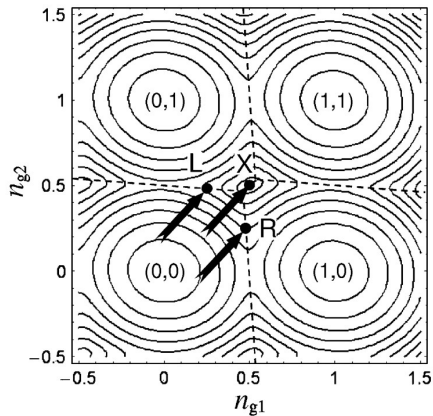


Figure : <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.193.5098&rep=rep1&type=pdf>

Coupling of Two Qubits

Charging-Energy Diagram

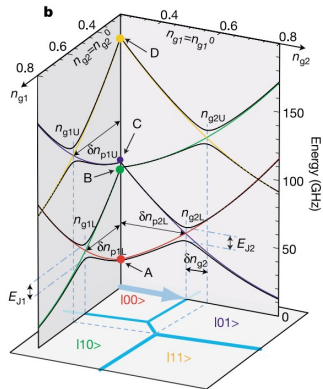


Figure : <http://qudev.ethz.ch/content/courses/QSIT09/pdfs/Yamamoto2003.pdf>

Coupling of Two Qubits

Theory

Hamiltonian

$$H = \begin{bmatrix} E_{00} & -\frac{1}{2}E_{J1} & -\frac{1}{2}E_{J2} & 0 \\ -\frac{1}{2}E_{J1} & E_{10} & 0 & -\frac{1}{2}E_{J2} \\ -\frac{1}{2}E_{J2} & 0 & E_{01} & -\frac{1}{2}E_{J1} \\ 0 & -\frac{1}{2}E_{J2} & -\frac{1}{2}E_{J1} & E_{11} \end{bmatrix}$$

Where...

- ▶ $E_{n1n2} = E_{c1}(n_{g1} - n_1)^2 + E_{c2}(n_{g2} - n_2)^2 + E_m(n_{g1} - n_1)(n_{g2} - n_2)$
- ▶ E_{Ji} is the Josephson energy of the i^{th} box
- ▶ $E_{c1,c2} = 4e^2 C_{\Sigma 2, \Sigma 1} / 2(C_{\Sigma 1} C_{\Sigma 2} - C_m^2)$ are the effective Cooper pair charging energies
- ▶ $C_{\Sigma i}$ is the sum of all capacitances connected to the i^{th} island
- ▶ $n_{g1,g2} = (C_{g1,g2} V_{g1,g2} + C_p V_p) / 2e$ is the charge, indexed by the gate and pulse voltages, on the qubits
- ▶ $E_m = 4e^2 C_m / (C_{\Sigma 1} C_{\Sigma 2} - C_m^2)$ is the coupling energy of the qubits

Coupling of Two Qubits

Theory

Probabilities

Initially, $|\psi\rangle = |00\rangle$

Using this Hamiltonian and an ideal rectangular pulse of length Δt ,

$$p_{1,2}(1) = \frac{1}{4} \left(2 - (1 - \chi_{1,2}) \cos[(\Omega + \epsilon)\Delta t] - (1 + \chi_{1,2}) \cos[(\Omega - \epsilon)\Delta t] \right)$$

Where...

- ▶ $\chi_{1,2} = \frac{E_{J2,J1}^2 - E_{J1,J2}^2 + E_m^2/4}{4\hbar^2\Omega\epsilon}$
- ▶ $\Omega = \sqrt{(E_{J1} + E_{J2})^2 + (E_m/2)^2}/2\hbar$
- ▶ $\epsilon = \sqrt{(E_{J1} - E_{J2})^2 + (E_m/2)^2}/2\hbar$

Coupling of Two Qubits

State Readout

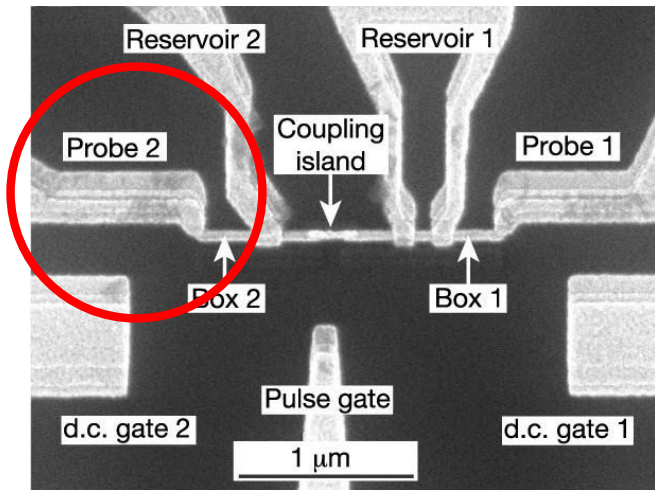


Figure : <http://www.nature.com/nature/journal/v421/n6925/full/nature01365.html>

Coupling of Two Qubits

Parameter Measurements / Frequency Responses

- ▶ Tune system by bringing to point L or R, exciting oscillations in one qubit
- ▶ Get cosines with exponential decay
- ▶ Fourier transform gives frequencies, which define E_{J1} or E_{J2}
- ▶ Drive system to point X and perform same Fourier measurement
- ▶ This time, get 2 frequencies, $\Omega \pm \epsilon$

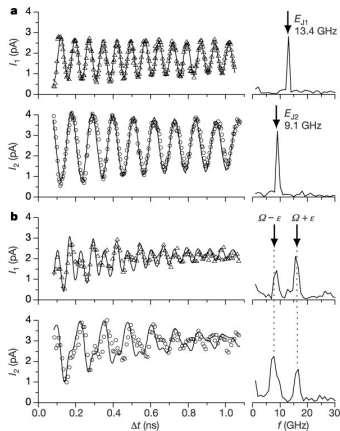


Figure : <http://www.nature.com/nature/journal/v421/n6925/full/nature01365.html>

Coupling of Two Qubits

E_{J1} dependence of spectrum components

Note: Frequency repulsion at $E_{J1} \approx E_{J2}$

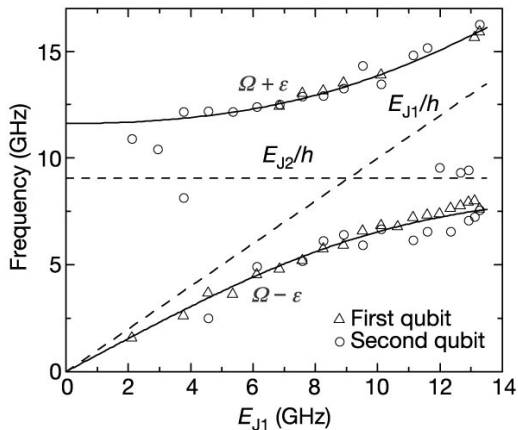


Figure : <http://www.nature.com/nature/journal/v421/n6925/full/nature01365.html>

Coupling of Two Qubits

Coherence

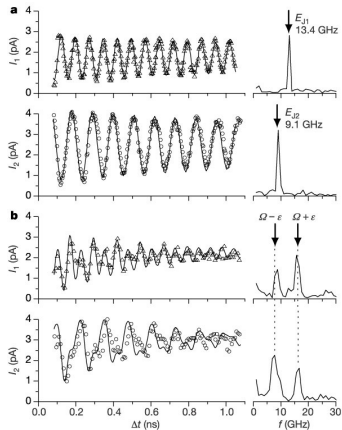


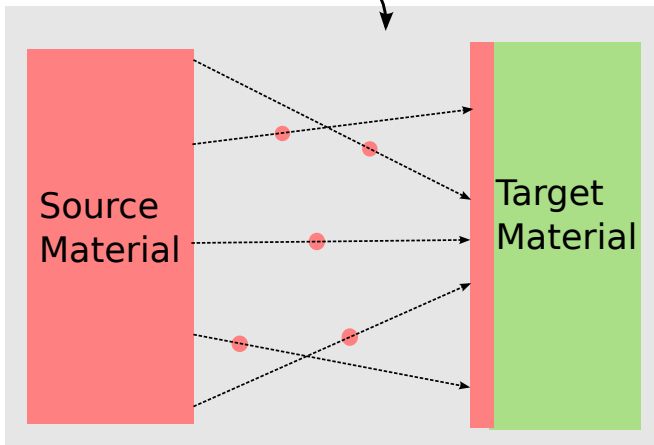
Figure : <http://www.nature.com/nature/journal/v421/n6925/full/nature01365.html>

Fabrication Techniques

Fabrication Techniques

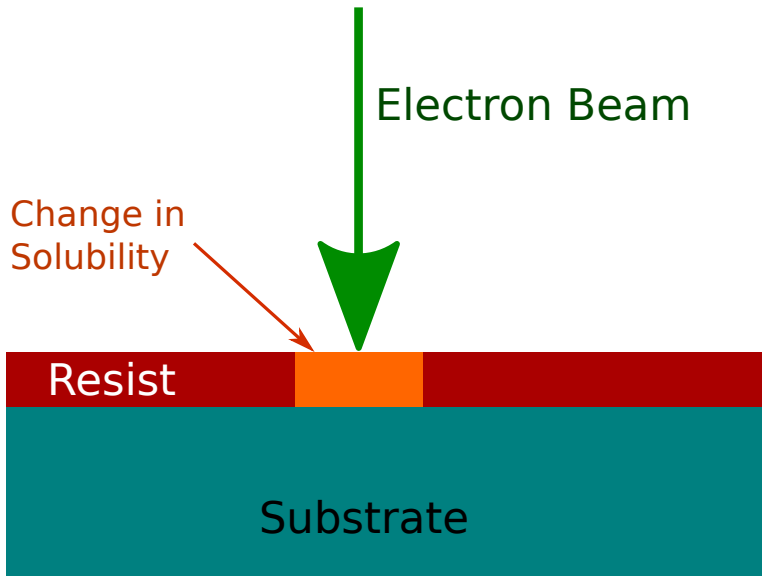
Evaporation (Deposition)

Vacuum and Heat



Fabrication Techniques

Electron Beam Lithography (EBL)



Fabrication Techniques

Etching

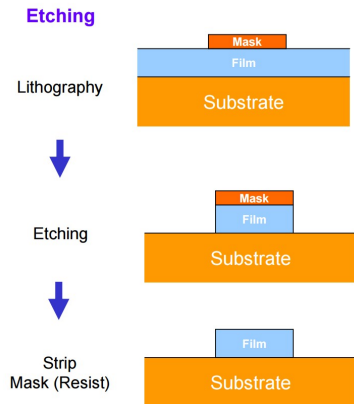


Figure : <http://www.mrsec.harvard.edu/education/ap298r2004/Erli%20chen%20Fabrication%20III%20-%20Etching.pdf>

Fabrication Techniques

Lift-off

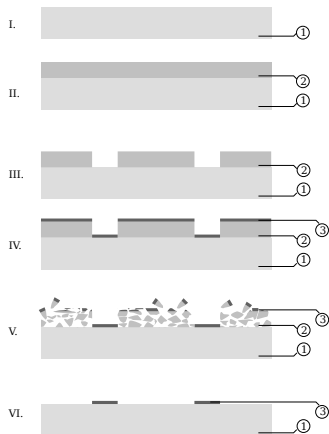


Figure : http://en.wikipedia.org/wiki/Lift-off_%28microtechnology%29

Fabrication Techniques

SEM image of a SQUID qubit

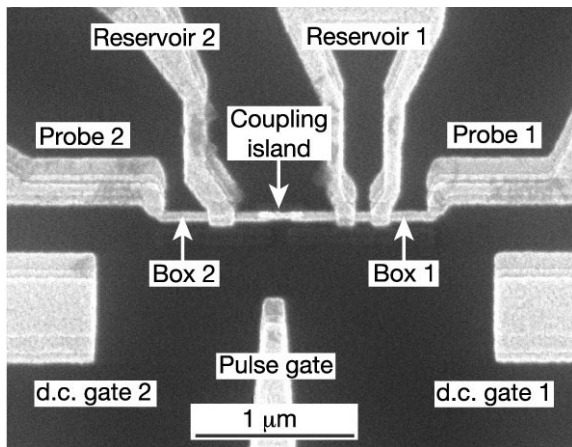


Figure : <http://www.nature.com/nature/journal/v421/n6925/full/nature01365.html>

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Reference Papers

<http://www.nature.com/nature/journal/v421/n6925/full/nature01365.html>

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(Figures cited individually)