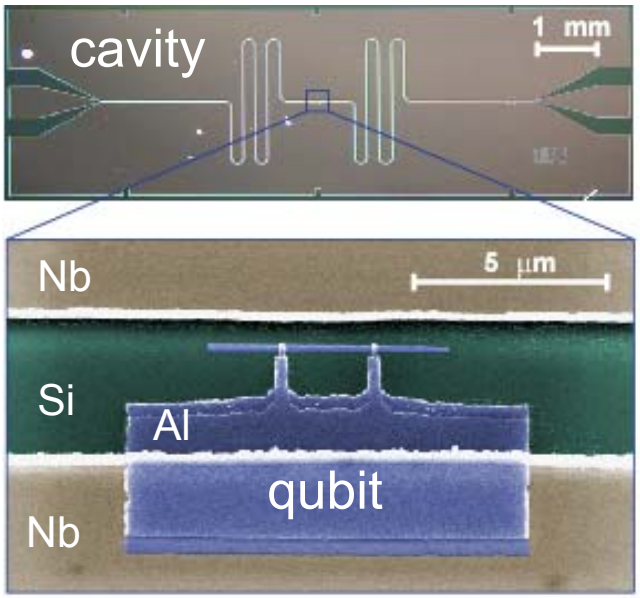
Circuit Quantum Electrodynamics: Coupling a Superconducting Qubit to a Single Photon

R.J. Schoelkopf and S.M. Girvin; *Yale University, ITR/DMR-0325580*



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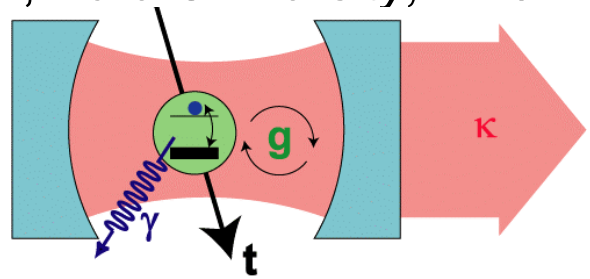
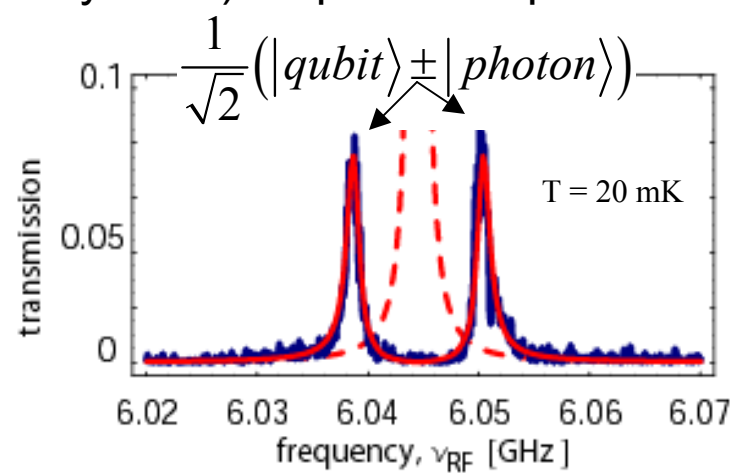


Cavity QED: an atom trapped between mirrors

We have built an integrated circuit in which a superconducting "qubit," or artificial atom, is coupled to a single μ-wave photon trapped in a superconducting transmission line "cavity." It has direct analogies with the field of cavity quantum electrodynamics (cavity QED) in quantum optics.

A qubit or an atom in its excited state relaxes by emitting a photon, but if the photon is trapped by a cavity, it can be re-absorbed and emitted many times. The system is then a strange "molecule" that is half atom and half photon. This is observed by the vacuum Rabi splitting of the cavity transmission into two peaks, indicating that the qubit and photon have been strongly and coherently coupled together.



vacuum Rabi splitting of cavity

This paper reports the first experiment to coherently couple a single microwave photon to a single superconducting qubit (quantum bit or artificial ‘atom’). The artificial ‘atom’ actually consists of roughly 1 billion aluminum atoms acting in concert like a single atom. The microwaves have a wavelength of about 1 cm and yet act like particles (photons). A single photon is trapped in a special cavity and absorbed and re-emitted by the ‘atom’ some 12 million times per second, causing the formation of novel quantum state which is partly photon and partly atom. This represents a new paradigm in which quantum optics experiments can be performed in a micro-chip electrical circuit using microwaves instead of visible photons from lasers. This new regime of matter light interaction in a circuit, which we refer to as *circuit quantum electrodynamics*, will open new possibilities to perform quantum optics experiments in solids. The Yale team intends to continue developing and refining their approach and to apply it to multiple qubits in a cavity. The techniques being developed could allow in the future for the production and detection of individual microwave photons with high efficiency and might someday form the basis for a new architecture for quantum computation.

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Education:

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Undergraduates:

This project has formed parts of three senior theses at Yale by
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Will Braff '05
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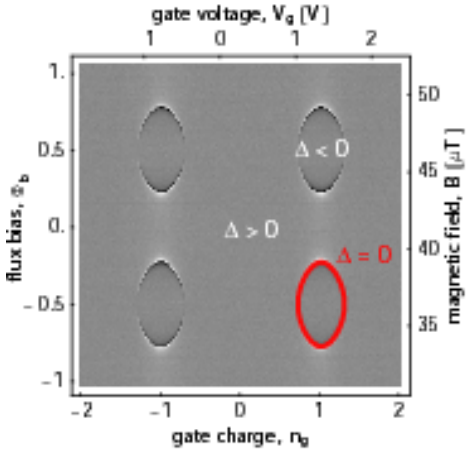
Publications:

A. Wallraff et al., to appear in Nature, Sept. 2004. (cond-mat/0407325)

D. Schuster et al., submitted to PRL, 2004. (cond-mat/0408367)

A. Blais et al. , Phys. Rev. A **90**, 062320 (2004). (theory)



Circuit QED measurement of qubit. The phase shift (grey-scale) of microwaves transmitted through the cavity varies with the gate voltage and flux bias on the qubit. The red oval (Δ=0) indicates when resonance between the qubit and cavity occurs.

Impact: This experiment and the new paradigm of "circuit quantum electrodynamics" creates many new possibilities for doing quantum optics with circuits, and will have applications in quantum computing and cryptography, as well as for single photon generation and detection. The strong coupling to single photons was only achieved with real atoms within the last decade or so, and future improvements may access new regimes of matter-light interactions.