Research Summary
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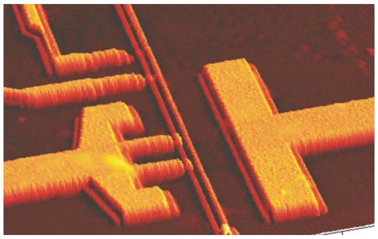
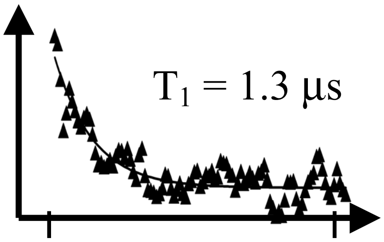
4/21/03

1) Quantum coherence and quantum fluctuations in single electron devices:

We have an experimental program aimed at understanding quantum coherence and the effects of quantum fluctuations in superconducting circuits, especially the single Cooper-pair box and single electron box. Measurements of the discrete charge states in these devices are performed using microwave techniques at millikelvin temperatures, usually based on the Radio-Frequency Single-Electron Transistor (RF-SET, see item #2 below). With these fast and sensitive measurements, we can probe the quantum properties of these circuits, which are macroscopic, engineered quantum systems. We are particularly interested in their applications for quantum computing. In our first experiments, we observed macroscopic quantum coherence in the single Cooper-pair box (CPB), a superconducting charge qubit, and confirmed its behavior as a coherent two-level system. We performed the first measurement of the excited state lifetime (T1 in NMR language) of the CPB, which was over 1 microsecond, and close to the limit set by spontaneous emission (Lehnert et al., 2003). By performing measurements of the Coulomb staircase with very high sensitivity and precision (1/1000 of an electron), we have also observed, for the first time, the effects of quantum charge fluctuations in a metallic (normal) single electron box (Lehnert et al, submitted to PRL). The quantum fluctuations of charge due to tunneling lead to "fine structure" effects, which have analogies with both the Lamb shift and the Kondo effect and can be rigorously compared with the well-developed theoretical literature. A current research direction, in collaboration with Steve Girvin (Yale Physics) and coworkers, is aimed at implementing ideas from cavity quantum electrodynamics for entanglement of superconducting qubits and to perform quantum nondemolition (QND) measurements of qubits, using a new microwave technique with high-Q superconducting transmission line resonators.





Left: an atomic force microscope image of a Cooper-pair box qubit, integrated with RF-SET electrometer readout, used for investigations of coherent quantum behavior of a microelectronic circuit, and (right) a measurement of the relaxation time, T_1.

Publications:

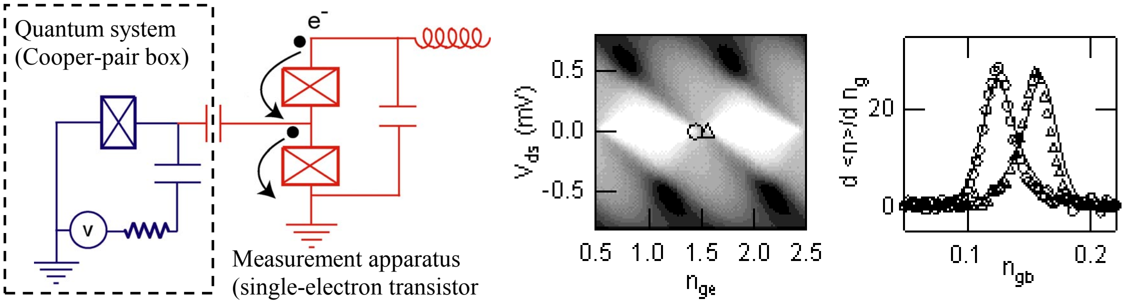
"Measurement of the Excited-state Lifetime of a Microelectronic Circuit," K. W. Lehnert, K. Bladh, L.F. Spietz, D. Gunnarsson, D.I. Schuster, P. Delsing, and R.J. Schoelkopf, Phys. Rev. Lett. **90**, 027002 (2003).

"Quantum Fluctuations of Charge and the Polarizability of the Single-Electron Box," K. W. Lehnert, B.A. Turek, K. Bladh, D. Gunnarsson, P. Delsing, and R.J. Schoelkopf, submitted to Phys. Rev. Lett. (2003).

"Prospects for Cavity QED with Superconducting Circuits: An Architecture for Solid-State Quantum Computing," S.M. Girvin, R. Huang, A. Blais, A. Wallraff, and R.J. Schoelkopf, in preparation (2003).

2) Quantum measurement with the single-electron transistor:

The single-electron transistor (SET) is an interesting quantum device in its own right, since it can serve as a quantum-limited amplifier. With the advent of the RF-SET (Schoelkopf et al., 1998), we can approach the expected limits on the SET's sensitivity for a *classical* measurement, $\varepsilon = S_q / 2C \sim \hbar$; the current state of the art (Aassime et al., 2001) is now $< 5\hbar$. However, when measuring a *quantum* signal, such as a qubit, the backaction of the measurement becomes important, and the appropriate figure of merit is instead the noise temperature or noise energy. The noise energy of the SET is also expected to approach the fundamental limit set by the uncertainty principle, though there have been no experiments addressing this question to date. In a review article on quantum measurement with SETs (Devoret and Schoelkopf, 2000), we presented a simple picture for the backaction of the SET, and showed the analogy between the Heisenberg microscope and continuous measurements of a qubit with the SET. Because of the controllability of the CPB qubits and the SET measurement, the capability to perform time-gated or continuous measurements, and the good theoretical models for the noise of the SET in both normal and superconducting state, this system forms an interesting testbed for the theory of quantum measurement. We have observed several manifestations of the backaction of the SET, and have recently succeeded in quantifying the backaction of the SET in the normal state, and making a rigorous comparison with a model for the combined SET/box system (Turek et al., 2003). The good agreement, without adjustable parameters, indicates that the dominant mechanism is the interaction via the capacitive coupling to the box, as considered in the theory. Current experiments are extending this work to the superconducting case, where the coherence of the CPB qubit acts as a "spectrum analyzer" (Schoelkopf et al., 2003), capable of distinguishing between emission and absorption (i.e. positive and negative frequency noise), as well as detecting the dephasing due to measurement and the approach to the quantum limit.



Left: Circuit diagram of Cooper-pair box qubit and SET measurement electrometer. Center: Differential resistance of SET as a function of drain and gate voltage, showing two example operating points. Right: Derivatives of the charge measured on the box, dn/dn_g, showing variations due to SET operating point and good agreement with backaction model (lines). From Turek et al., 2003

Publications:

"The Radio-Frequency Single-Electron Transistor (RF-SET): A Fast and Ultra-Sensitive Electrometer," R.J. Schoelkopf et al., Science **280**, 1238 (1998).

"Radio-Frequency Single-Electron Transistor: Towards the Shot-Noise Limit," A. Aassime, D. Gunnarsson, K. Bladh, P. Delsing, and R.J. Schoelkopf, Appl. Phys. Lett. **79**, 4031 (2001).

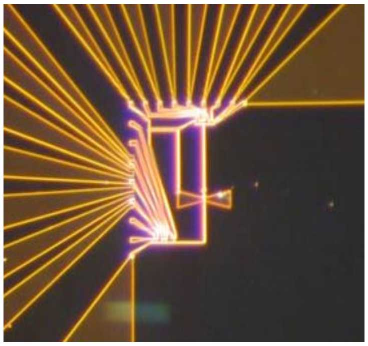
"Amplifying Quantum Signals with the Single-electron Transistor," M.H. Devoret and R.J. Schoelkopf, Nature **406,** 1039 (2000).

"Measuring the Backaction of a Single-Electron Transistor on the Single-Electron Box" B.A. Turek, K. W. Lehnert, K. Bladh, D. Gunnarsson, P. Delsing, and R.J. Schoelkopf, in preparation (2003).

"Qubits as Spectrometers of Quantum Noise" R.J. Schoelkopf et al., cond-mat/0210247 and "Quantum Noise in Mesoscopic Systems," Y.V. Nazarov (ed.), Kluwer Academic Publishers, ISBN#1-4020-1239-X, 2003.

3) Single millimeter-wave photon detectors and RF-SET readouts for astrophysics:

We are developing ultrasensitive detectors for millimeter and submillimeter wavelength photons that are of interest for applications in space astrophysics. In particular, we use a device we proposed (Schoelkopf et al., 1999), called the Single Quasiparticle Photon Counter (SQPC), which can have several orders of magnitude higher sensitivity than current state-of-the-art cryogenic detectors. The SQPC should even be able to detect single millielectronvolt photons, which has not previously been possible. The SQPC is based on so-called "STJ" detectors where a photon's energy is used to break Cooper pairs in a superconductor, creating quasiparticles. We extend this concept to photons energies that are able to break only a single pair, and rely on an integrated RF-SET electrometer to measure the resulting (2e) charge signal when the quasiparticles tunnel across a high-resistance superconducting tunnel junction. In collaboration with Chalmers University in Sweden and NASA's Goddard Space Flight Center, we have fabricated and characterized these integrated superconducting devices. One area of work has focused on adapting RF-SET electrometers to serve as robust, sensitive amplifiers for these detectors. We have obtained record levels of voltage noise for an SET device, and demonstrated the use of feedback to realize a transimpedance amplifier with very high speed even for high impedance levels (Segall et al., 2001). A scheme for frequency multiplexing of multiple SETs on a single microwave readout line was invented and demonstrated (Stevenson et al., 2001). Measurements of the dark current, and hence the ultimate sensitivity limits for the SQPCs have also been performed (Stevenson et al., 2000), showing good agreement with the expected dependence on temperature. More recently, we have observed extremely low dark currents of less than 1 femtoamp using the SET transimpedance amplifier, corresponding to false count rates of 6 kHz or less, and indicating that single photon counting should be possible. Present experiments are integrating these photodetectors with a cryogenic blackbody to measure the quantum efficiency and sensitivity of the full detector/SET readout system. Another area of current work is the use of time-resolved noise thermometry to realize high-speed and high-dynamic range bolometers based on hot-electron effects in micron-sized wires. The same devices are used to realize a calibrated, high-speed photon source which will allow calibrations of the SQPC detectors and on-chip generation and detection of millimeter-wave signals at the single-photon level.



Optical micrograph of an integrated superconducting photodetector chip, with niobium bowtie antenna, aluminum SQPC detector junctions, and integrated RF-SET readouts.

Publications:

"A Concept for a Submillimeter-Wave Single-Photon Counter," R.J. Schoelkopf, S.H. Moseley, C.M. Stahle, P. Wahlgren, and P. Delsing, IEEE Trans. on Applied Superconductivity, **9**, 2935 (1999).

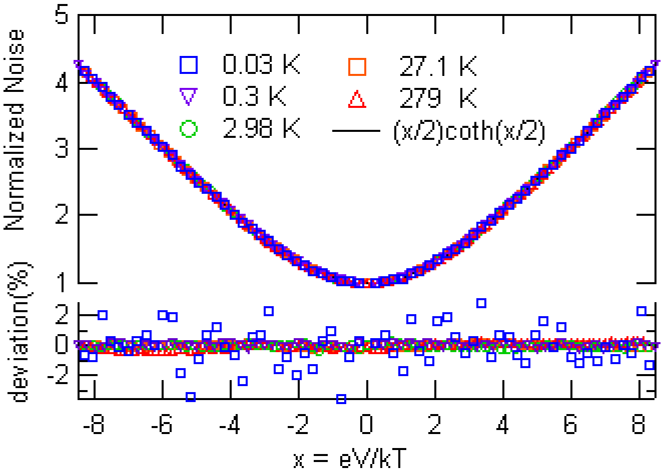
"RF Single Electron Transistor Readout Amplifiers for Superconducting Astronomical Detectors of X-ray to Sub-mm Wavelengths," T.R. Stevenson, A. Aassime, P. Delsing, R.J. Schoelkopf, K. Segall, and C.M.Stahle, IEEE Trans. on Appl. Superconductivity **11**, 692 (2000).

"Multiplexing of Radio-Frequency Single Electron Transistors," T. R. Stevenson, F.A. Pellerano, C.M. Stahle, K. Aidala, and R.J. Schoelkopf, Appl. Phys. Lett **80**, 3012 (2001).

"A High-Performance Cryogenic Amplifier Based on an RF-SET," K. Segall, K.W. Lehnert, T.R. Stevenson, R.J. Schoelkopf, P. Wahlgren, A. Aassime, and P. Delsing, Appl. Phys. Lett. **81**, 4859 (2001).

4) Temperature and current metrology with solid-state devices:

Another of our interests is the application of quantum devices and microwave measurement techniques to metrology. We have developed a new type of electronic thermometer, called the ideal electron gas thermometer (EGT), which utilizes the crossover between thermal (Johnson) noise and shot noise in a tunnel junction. By measuring the current noise as a function of applied voltage, and using techniques of microwave comparison radiometry, we are able to relate the thermodynamic temperature to an easily measured dc voltage, using only the electron's charge (e) and Boltzmann's constant (k_b). This characteristic makes it a candidate as a new "quantum" standard of temperature, similar to the Josephson voltage or quantum hall resistance standards, which relate various SI units using quantum physics. We originally used a crude form of the EGT as our standard test of the performance for new cryostats in our lab. Recently, we have demonstrated that the simple universal behavior of the noise in tunnel junctions is accurately obeyed over four orders of magnitude in temperature. We have used this device for thermometry from room temperature to 20 mK, with an accuracies as high as 0.1%, and precisions of up to 200 parts per million (Spietz et al., 2003). A next experiment, in collaboration with the Temperature Metrology Group at NIST Gaithersburg, is to perform a determination of the thermodynamic temperature of the hydrogen triple point (13.8303 K), where the demonstrated precision of our EGT is already better than the uncertainty in this metrology standard. Future experiments are aimed at refining the precision and accuracy at the highest temperatures and a comparison with the water triple point, by which the Kelvin is defined. Because of the simple and fundamental thermodynamics of the EGT, this might eventually allow a new determination of Boltzmann's constant. Another project with applications to metrology is the use of the RF-SET to perform rapid single-electron counting. This goal is to convert a measurable current to a frequency by observing the rate of passage of electrons in a circuit, using the relationship f = I/e. Because of the small size of the electron charge (f = 6.24 MHz/picoamp), this requires high speeds and sensitivities only possible with the RF-SET. Current experiments are using an RF-SET with a resistive gate to directly couple charge to the sensing island of the electrometer.



Measurements of normalized noise (current spectral density relative to Johnson noise) of a tunnel junction versus normalized voltage, $x = eV/k_BT$, showing the agreement with the simple universal form over four decades in temperature. (from Spietz et al., 2003)

Publications:

"The Ideal Electron Gas Thermometer" L.F. Spietz, K.W. Lehnert, I. Siddiqi, and R.J. Schoelkopf, submitted to Science (2003).