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COULOMB AND INTERFERENCE EFFECTS IN SMALL ELECTRONIC STRUCTURES

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CRYOGENIC PRECISION CAPACITANCE BRIDGE USING A SINGLE ELECTRON TUNNELING ELECTROMETER

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The value of the electronic charge can be determined by placing a known number of electrons on a calibrated capacitor and measuring the resulting voltage, which can lead to a measure of the fine structure constant, α. Single electron tunneling (SET) electrometers with sufficient sensitivity for this application have been fabricated. We report on the design and preliminary results of a capacitance bridge experiment using an SET electrometer as a detector to measure two capacitors in a dilution refrigerator. AC measurements of the capacitance ratio have a precision of one part in 10^4 and DC measurements provide information on the leakage rate of the standard capacitors.

I. INTRODUCTION

The single-electron-tunneling (SET) transistor can be used as a highly sensitive electrometer,[1] and noise figures of $10^{-4}e/\sqrt{\mathrm{Hz}}$ at 10 Hz have been reported.[2] We have proposed an experiment[3] to measure the fine structure constant α by counting electrons on a standard capacitor. This experiment[3] uses the sensitivity of the SET electrometer to small changes in charge on a coupling capacitor in order to monitor the voltage on an isolated island while electrons are being pumped onto the island. For the technique to be successful, the amount of charge pumped onto the island must be a well-defined quantity throughout the measurement time. Therefore, the leakage rate of charge from the island must be small in order to achieve metrological accuracy. In this paper, we report on a cryogenic capacitance bridge balance experiment which is a prerequisite to a precision measurement of α. We determined the AC and DC capacitance ratio of two standard capacitors in a dilution refrigerator, as well as the leakage rate of the capacitors.

II. THE SET ELECTROMETER

The SET electrometer, shown schematically in the left portion of Fig. 1a, consists of two nanoscale normal metal/insulator/metal tunnel junctions in series, represented by the double-box symbols. If the junctions are designed so that their tunneling resistances are large compared to the resistance quantum h/e^2, and if the capacitance C_Σ seen by the island between the junctions is small compared to $e^2/2k_BT$, the tunneling probability is greatly reduced for $|V_E| < e/2C_\Sigma$, the Coulomb blockade region. Under these conditions, the tunneling current I through the junctions can be sensitively controlled by varying the gate voltage U across the capacitor C_0. At constant bias V_E, the SET current undergoes oscillations as U is varied, with period $\Delta U = e/C_0$. To use the transistor as an electrometer, the voltages V_E and U are fixed at levels chosen to maximize sensitivity of the device, so that I is linearly proportional to small changes in charge induced on the interjunction region. The electrometer is then highly sensitive to charge induced on the coupling capacitor C_c, and it provides a high impedance technique to measure the potential controlling the charge on C_c.

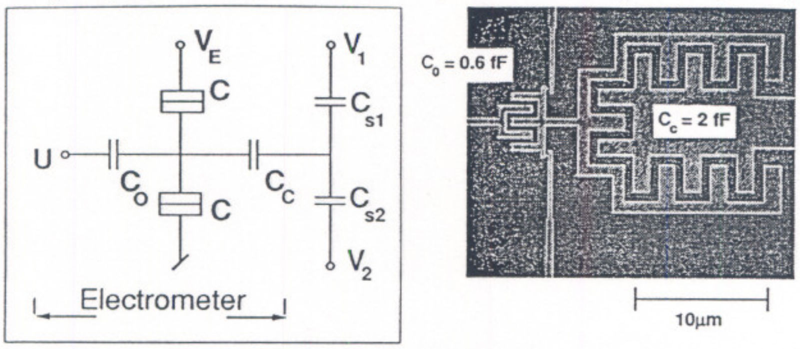

FIG. 1. a) Schematic of capacitance bridge circuit for determining the ratio of the standard capacitors C_{s1} and C_{s2}. b) Scanning electron micrograph of the SET electrometer.

The electrometer can be used as a null voltage detector in order to balance the two arms of a bridge circuit. The proposed experiment[3)] to determine α uses an SET pump to place n electrons on a standard capacitor C_s and then measures the resulting voltage V_s. In terms of this voltage and capacitance, e is determined from the relationship $ne = C_sV_s$. If V_s is related to the Josephson voltage standard, then α can be determined by comparing C_s to the calculable capacitor. The circuit in reference 3 is a variant of a bridge balance with the SET pump on one arm and the standard capacitor on the other arm. An SET electrometer is used to maintain a constant potential at the isolated island while electrons are pumped onto the island.

III. AC CRYOGENIC CAPACITANCE BRIDGE

In order to explore issues relevant to the experiment to measure α, we have experimented on a cryogenic capacitance bridge using an SET electrometer to determine the capacitance ratio of two fused silica capacitors at 10 mK. The electrometer in the left portion of Fig. 1a, including the coupling capacitor C_c, was fabricated on a single chip. Electron beam lithography and a shadow evaporation technique[4)] were used to fabricate Al/AlO/Al tunnel junctions on an oxidized Si substrate. We can make (30 nm)^2 junctions which are reproducible across several 1 cm^2 dies. The electrometer chip has four electrodes, two for voltage leads and one each for the gate capacitor C_0, and the coupling capacitor C_c. The chip was placed inside one chamber of a three chamber copper box with each standard capacitor in a separate chamber. The standard capacitors are metallized fused silica disks with a grounded guard ring and have a nominal capacitance of 1 pF. By separating the two standard capacitors from one another and the electrometer chip, we insured that C_{s1} and C_{s2} each have a well defined capacitance. Coaxial leads were used for the two voltage leads V_1 and V_2. The assembled copper box was then thermally anchored to the platform of the dilution refrigerator.

In order to make precision measurements, a ground shield must be provided to prevent the potentials V_1 and V_2 from affecting the electrometer except through their respective capacitances. Stray capacitance to ground will degrade the electrometer sensitivity, and therefore it must be kept small. The sensitivity of the electrometer to the bridge balance point is proportional to $C_c/(C_{s1}+C_{s2}+C_g)$, where C_g represents all stray capacitance to ground. We have measured C_g to be 5 pF, which is reasonably close to our target of a few pF. Choosing $C_s = C_{s1}+C_{s2}$ to be small both increases V_s and maximizes the electrometer sensitivity. A practical choice for C_s is 1 pF, because it is of similar magnitude to C_g as well as a convenient value to compare with existing capacitance standards. Our tunnel junction capacitances are typically a few tenths of a femtofarad. A large value for C_c would increase the electrometer sensitivity, however C_c also contributes directly to the electrometer island capacitance, thus reducing the Coulomb charging energy. We measured C_c to be 2 fF in our experiment.

For the AC bridge balance experiment, an inductive divider together with a 1:1 doubly-shielded transformer and an AC signal generator (V_{cap}) was used to supply the potentials V_1 and V_2.[5)] At balance, $C_{s2}/C_{s1} = V_1/V_2 = Z_1/Z_2$ where Z_1 is the setting of the inductive divider and $Z_2 = 1 - Z_2$. In order to improve our signal to noise ratio, a lock-in amplifier was used to detect the AC electrometer current that was in phase with V_{cap}. We also slowly ramped the gate voltage U to ensure that the electrometer was functioning properly. Fig. 2 shows the capacitance bridge data at 10 Hz and a platform temperature of 10 mK. We deduce from these data that the ratio of the two capacitors is $C_{s2}/C_{s1} = 1.0377 \pm 0.0001$ (one σ), where the precision of our measurements is one part in 10^4. Bridge balance measurements were also made at 270 Hz. Our precision was limited by the magnitude of the out-of-phase or quadrature signal. We therefore performed a double bridge experiment to determine both the in-phase and quadrature signals by introducing an orthogonal component to V_{cap} to cancel the quadrature signal. The large dissipation in the standard capacitors affected the SET oscillations and prevented an increase in the sensitivity of the bridge.

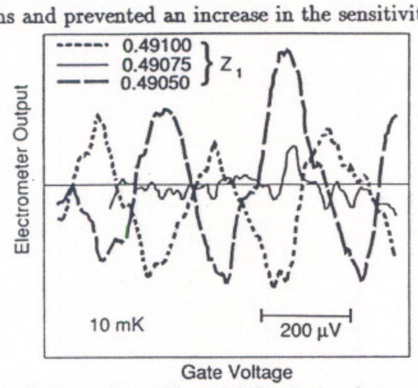

FIG. 2. AC bridge balance data. The solid line is the electrometer output at balance, $Z_1 = 0.49075$. The dashed and dotted lines are the off-balance traces which show SET oscillations due to charge accumulation on the island between the two standard capacitors.

IV. DISSIPATION

One of the advantages of our cryogenic capacitance bridge is the ability to make both AC and DC measurements. The DC capacitance ratio of the standard capacitors was measured using a resistive divider together with a battery (V_{cap}).[5] With the platform temperature at 10 mK, we found $C_{s2}/C_{s1} = 1.036 \pm 0.25\%$. Our precision was limited by a slow decay of the applied bias V_{cap} at balance. A second DC experiment was performed to measure the leakage rate of the standard capacitors at cryogenic temperatures. The two voltage leads V_1 and V_2 shown in Fig. 1a were connected together and a step voltage V_{step} was applied to the standard capacitors in parallel. In this configuration, the electrometer is sensitive to the charge induced on C_c by the potential $V_c = V_{step}[1 + C_g/(C_{s1} + C_{s2})]^{-1}$. If there were no leakage current at all, the electrometer output as a function of time would show rapid initial SET oscillations in response to the polarization charge induced by the step, but would detect no subsequent charge motion. In fact, after the initial response, we observed continued SET oscillations with increasing period as time progressed. This indicates that the electrometer was responding to charge on C_c controlled by a potential that was decaying with time.

The inset to Fig. 3 shows the SET oscillations against time observed after a 1.35 V step voltage was applied to the standard capacitors in parallel ($C_{s1}+C_{s2}=C_s$). Since each oscillation corresponds to one electron charge induced on the coupling capacitor C_c, the trace represents a voltage decay across C_s. Plotted in Fig. 3 is $N(t)$, the number of zero crossings as a function of time between t and T, where T is the final observation time. The times t were chosen so that $t \geq t_o$, where t_o is a time after the initial polarization response. $N(t)$ equals twice the number of charges induced at times between t and T. If charge leaked from C_s and induced charge on C_c at random times in the interval (t_o, T), then the curve would correspond to a simple exponential form with a single leakage rate. Fig. 3 shows that the data do not fit this form. However, $N(t)$ fits remarkably well to a sum of two exponentials, which indicates that the rates of two mutually dependent processes were governing the SET current. One model that is consistent with the two-exponential form is a two-level system subject to a decay process. Random telegraph switching between two charge states is frequently observed in SET devices[2] and the rate for this process could be folded into the measured leakage rate.

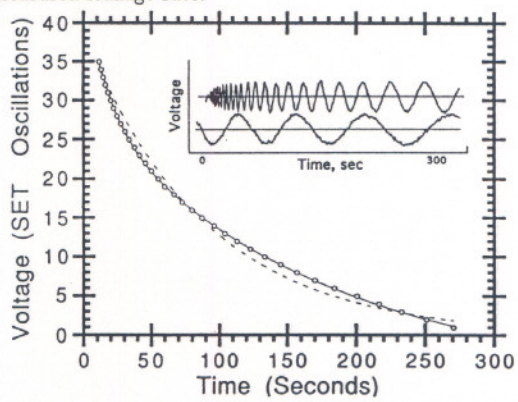

FIG. 3. SET oscillations vs time after application of 1.35V step voltage. The open circles are the experimental data points. The fit to a single exponential is shown by the dashed curve and the sum of two exponentials is shown by the solid curve.

From the data in Fig. 3, the apparent leakage rate measured by the SET electrometer is on the order of one charge per second, which is equivalent to a leakage resistance of $10^{12}\Omega$ for the parallel combination of C_{s1} and C_{s2}. Using a standard laboratory electrometer and a 45 V battery outside the cryostat, we obtain a lower bound of 10^{14} Ω for the leakage resistance across C_{s1} and C_{s2} in series at cryogenic temperature. Environmental noise caused by excessive dissipation could influence the SET electrometer signal and may be the reason we were limited in our ability to increase the voltage (V_{cap}) applied to the bridge. We are currently investigating the mechanisms responsible for the measured DC leakage and AC quadrature signal. If the dissipative signal is due to the leakage across the standard capacitors, alternative fabrication techniques, such as an air capacitor, can greatly improve the situation. To obtain a precision measurement of α as described in reference 3, we will need many orders of magnitude improvement on our standard capacitors.

In conclusion, we have used an SET electrometer in a capacitance bridge experiment to measure the AC ratio of two standard capacitors to one part in 10^4 in a dilution refrigerator. The stray capacitance to ground which limits the sensitivity of the electrometer was found to be 5 pF in our first design. DC capacitance and leakage rate measurements demonstrate that the SET electrometer is a very sensitive detector of any time-varying potentials that induce changes in the charge state of the bridge balance point. This experiment is a first step towards a precision measurement of α, but it is clear that greatly improved capacitors will be required for success in this experiment.

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1) P. Lafarge, H. Pothier, E.R. Williams, D. Esteve, C. Urbina, and M.H. Devoret, Z. Phys. B **85**, 327 (1991); T.A. Fulton, P.L. Gammel, and L.N. Dunkelberger, Phys. Rev. Lett. **67**, 3148 (1991).

2) G. Zimmerli, T.M. Eiles, R.L. Kautz, and J.M. Martinis, Appl. Phys. Lett. **61**, 237 (1992).

3) E.R. Williams, R.N. Ghosh, and J.M. Martinis, J. Res. Nat. Inst. Stand. Technol. **97**, 299 (1992).

4) T.A. Fulton and G.J. Dolan, Phys. Rev. Lett. **59**, 109 (1987).

5) B.P. Kibbel and G.H. Rayner, *Coaxial AC Bridges* (Adam Hilger, Bristol, 1984).