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Cryogenic precision capacitance bridge using a single electron tunneling electrometer*

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The electronic charge can be determined by placing a known number of electrons on a calibrated capacitor and measuring the resulting voltage. 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 to measure two capacitors in a dilution refrigerator. This includes discussion of issues such as the leakage rate of a capacitor at cryogenic temperatures and the optimum coupling of the electrometer to the bridge circuit.

Recent developments in the field of single electron tunneling (SET) have made possible a new and very precise technique to measure the charge of an electron. These devices are based on metal/insulator/metal tunnel junctions whose current-voltage (I-V) characteristics are determined by individual electron tunneling events. We have proposed[1] an experiment to determine the electron charge (e) by using an SET pump to place n electrons on a standard capacitor of capacitance C_S and then measuring the resulting voltage V_S. In terms of this voltage and capacitance, e is determined from the relationship $ne = V_S C_S$. The circuit in Ref. 1 is a variant of a bridge balance with a SET pump device on one arm and the standard capacitor on the other arm. Electrons are pumped onto an isolated island while an electrometer is used to maintain a constant potential at the island. A SET electrometer with sufficient charge sensitivity (10^{-4} e/√Hz at 10Hz) to determine e has been described[2]. In order to explore questions of fundamental importance for the experiment to measure e, we report here on a cryogenic capacitance bridge using a SET electrometer to determine the capacitance ratio of two fused silica capacitors in a dilution refrigerator.

Fig. 1 shows our capacitance bridge circuit for measuring the two standard capacitors C_S. The electrometer in the left portion of the figure, including the coupling capacitor C_c, is fabricated on a single chip. The boxed symbols represent tunnel junctions. Electron beam lithography and a shadow evaporation technique[3] are used to fabricate Al/AlO/Al tunnel junctions on an oxidized Si substrate. We can make $(30\mathrm{nm})^2$ junctions which are reproducible across several $1\mathrm{cm}^2$ dies. The electrometer chip has four electrodes, two for voltage leads and one each for the gate capacitor C_o, and the coupling capacitor C_c. The chip is placed inside one chamber of a three

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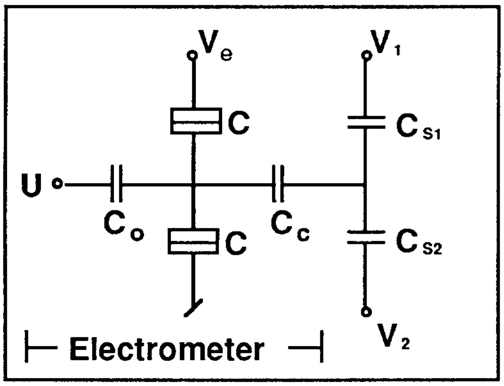

FIG. 1 Capacitance bridge circuit for determining the ratio of the standard capacitors C_{S1} and C_{S2} .

chamber copper box with each standard capacitor in a separate chamber. The capacitors are metallized fused silica disks with a grounded guard ring and have a nominal capacitance of 1pF. Our goal is to separate the two standard capacitors from each other and the electrometer chip to minimize cross capacitance effects. Coaxial leads are used for the two voltage leads V_1 and V_2. The assembled copper box is then thermally anchored to the platform of the dilution refrigerator.

In order to make precision bridge measurements, a ground shield must be provided to prevent the potentials V_1 and V_2 from affecting the detector or electrometer except through their respective capacitances. The bridge is balanced by adjusting the potentials $V_1/V_2 = C_{S2}/C_{S1}$. Stray capacitance to ground will degrade the electrometer sensitivity so it must be kept small. The sensitivity of the electrometer to the bridge balance point is given approximately by $C_c / (C_{S1} + C_{S2} + C_g)$, where C_g represents all stray capacitance to ground. We expect to keep C_g near 1pF. Choosing C_s to be small both increases V_s and maximizes the electrometer sensitivity. A 1pF capacitor constitutes a practical compromise. Our tunnel junction capacitances are typically a few tenths of a femto farad. A large value for C_c would increase the electrometer sensitivity, however C_c also contributes directly to the electrometer island capacitance. We plan to keep C_c just under 1fF.

Measurements on the capacitance bridge are in progress to address the following issues. First, what is the leakage rate of a capacitor at cryogenic temperatures and what are the physical mechanisms involved? Second, can the charge noise of a SET electrometer be reduced using semiconductor processing techniques such as rapid thermal annealing? Third, how effective is our technique to minimize stray capacitance and what are the optimum circuit parameters for coupling the electrometer to the capacitance bridge while maintaining the electrometer sensitivity? The answers to these questions are of importance in both the field of single electron tunneling and for the experiment to measure e.

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