Application of single electron tunneling: Precision capacitance ratio measurements

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(Received 16 December 1994; accepted for publication 13 March 1995)

A metrological application is reported of the single electron tunneling (SET) phenomena: a precise measurement of the ratio of two cryogenic capacitors. The measurement used a superconducting SET electrometer as the null detector for a capacitance bridge. A 3-ppm level of imprecision has been achieved in the measurement of the capacitance ratio from 100 to 1000 Hz. Further improvements can be made in the attempt to obtain an imprecision of 10^{-8} at lower frequencies, sufficient for the metrological measurement of capacitance or the fine-structure constant using a SET pump.

The study of electron tunneling in small devices at low temperatures has led to the discovery of the Coulomb blockade, which causes reduced conduction below a critical bias voltage. This discovery has inspired extensive research into the basic phenomenon of single electron tunneling (SET) and several suggestions for important potential applications.[1] These include digital logic, digital single-electron memory, and metrology, in particular for better definitions of capacitance or current. Here we report the use of a superconducting SET electrometer to perform capacitance ratio measurements on a new design of cryogenic vacuum capacitors.

One proposal for SET applications, that of metrological measurements, was recently suggested for a capacitor charging experiment.[2] This application is driven by the development of single electron pumps, which can provide a current (in the pA range) with metrological accuracy.[3] These pumps directly convert a frequency f, to a current, fe, where e is the electronic charge. The small current possible with present-day pumps is a significant limitation to their direct use as current standards, which has led to the idea of charging a capacitor with a given number of electrons and measuring the voltage that develops.[2]

There are several critical elements which are needed before this metrological experiment can be demonstrated at the competitive 10^{-8} level. These include the development of a pump with sufficiently low error rate,[3] the development of cryogenic capacitors with sufficiently low dissipation, and the use of SET electrometers as null detectors. Here we report on results for the second and third elements, and show the application of a superconducting SET electrometer to achieve ppm-level measurements of capacitance ratios using cryogenic capacitors.

The SET electrometers[4] were made using the standard lithography and processing for $Al/Al_2O_3/Al$ tunnel junctions. Fabrication consisted of an initial photolithographic step followed by deposition of Au contact pads, and then an electron-beam lithography (EBL) step to produce an EBL stencil. Al was then deposited at two different angles, with an oxidation between the two, to produce two tunnel junctions in series with a metal island in between. The island is capacitively coupled to the common point a (Fig. 1) between the two cryogenic capacitors.[4] The SET electrometer measurement circuit is shown in Fig. 1. The tunnel junctions had a total normal-state tunnel resistance of about 280 kΩ with a total island capacitance of about 1.0 fF, and a gate capacitance $C_c = 0.04$ fF.

The cryogenic vacuum-gap capacitors were custom-fabricated, three-terminal devices (two plates plus a grounded guard),[5] made from machined Cu kinematically supported by small (1.5 mm) spherical sapphire standoffs, chosen for their low electrical and high thermal conductivity. The capacitors had about 0.5 pF of capacitance each, arising from a plate-to-plate gap of about 0.76 mm and an area of about 0.79 cm^2. Monitoring the charge stability on the capacitors with the SET electrometer after the application of dc step voltages up to 10 V, established a lower limit of 10^{18} Ω for their leakage resistance.

The electrical measurements were done with a source-

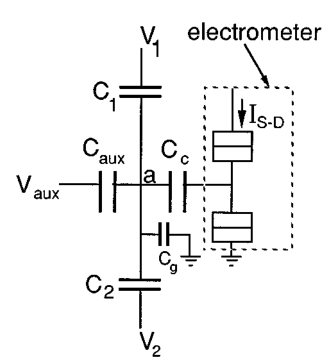

FIG. 1. Electrical circuit for the capacitance balance measurement, using the SET electrometer as the null detector. The balance (virtual null) point is at position a.

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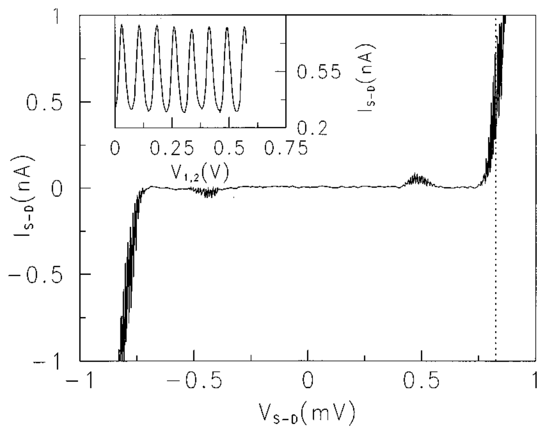

FIG. 2. Source-drain current as a function of the source-drain voltage V_{S-D}, while rapidly modulating the gate voltage $\Delta V_{1,2}$. This curve shows the gross features of superconducting SET electrometers: onset of conduction at the gaps and Josephson quasiparticle (JQP) peaks. The oscillations in the figure are the reproducible modulation of I_{S-D} due to the gate modulation. The dotted line indicates the position of large modulation used in the inset and in the measurements shown in Fig. 3. Inset: SET oscillations, as measured at V_{S-D}=0.83 mV. This cusplike periodic modulation is due to the addition of one electron to the central island.

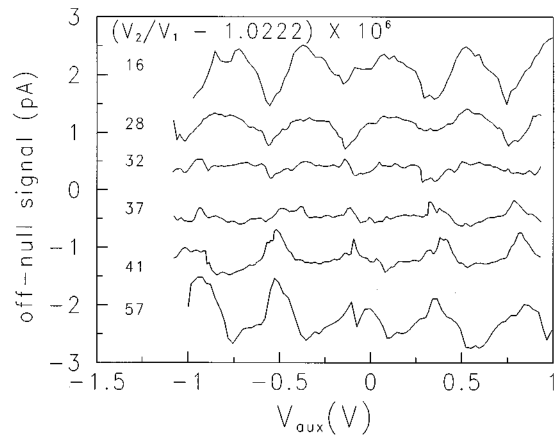

FIG. 3. Demonstration of the measurement of capacitance ratio using the SET electrometer as a null detector. The numbers are the ratios of ac voltages V_2/V_1 applied to the outer capacitor plates. The curves are vertically offset for clarity and represent the off-null signal at point *a*, as a function of voltage applied to an auxiliary gate. The top and bottom curves show results far away from the balance, with the inner four spaced by ~5 ppm change each. The true balance point is between the two middle curves, and C_1/C_2 can thus be identified as 1.022 235(3).

drain bias voltage (across both tunnel junctions) of amplitude less than 1 mV, which was produced by an optically isolated battery-driven circuit. The resultant current passed through a current amplifier and was recorded on an *x-y* recorder, or demodulated with a lock-in amplifier locked to a sinusoidal voltage applied through the SET auxiliary gate (or equivalently through the cryogenic capacitors). dc or ac (up to 1 kHz) voltages of up to 10 V amplitude were applied to the capacitors (V_1 and V_2), which were connected to the SET electrometer coupling capacitor (see Fig. 1). Since SET electrometers are quite sensitive to rf noise, in-line filtering was done both at room-temperature and at the mK operating temperatures. The latter pi-section (CLC) filtering was provided by commercial in-line filters which were heat sunk in the metallic wall of the sample enclosure. These filters were on the source and drain lines; the lines to the capacitors (V_1 and V_2) only had 100 Ω in-line resistors at the low-temperature end. All measurements reported herein were at cryostat temperatures of about 10 mK. The electrometer was operated in the superconducting state where the current sensitivity to gate voltage is highest.[6]

Figure 2 shows the $I_{S-D}(V_{S-D})$ results for the SET electrometer. This figure shows the standard features in the $I_{S-D}(V_{S-D})$ curve for a superconducting SET electrometer.[7] The gross features are: (1) the onset of quasiparticle conduction above the gap ($V_{S-D} \gtrsim 0.75$ mV), and (2) Josephson quasiparticle peaks (JQP) at about ±0.5 mV. The supercurrent branch at 0 V is too small in amplitude (~2 pA) to be seen on this scale. We also show that the current through the SET device can be modulated by the voltage on the capacitors in two regions: just beyond the gap edges and in the JQP peaks.

This modulation is shown directly in the inset to Fig. 2. Here, V_{S-D} was fixed at 0.83 mV (the position of the dotted line in the main figure), and $V_{1,2}$ ($V_1 = V_2$) was swept over the range shown. Each oscillation corresponds to one additional electron on the central island.[1,4].

These oscillations form the basis for using the SET device as a null detector, as outlined in Fig. 1. In particular, an imbalance in the bridge produces a voltage at the balance point *a*, resulting in an electrometer current modulation. One way to do this is by applying sinusoidal voltages (at audio frequencies from 100 Hz to 1 kHz) V_1 and V_2 which are out of phase by π. Any imbalance in the products C_1V_1, and C_2V_2 at point *a* thus results in an ac modulation of the charge on the island, and thus of the electrometer current, at the same frequency. To ensure such a signal arises from the imbalance and to achieve a higher sensitivity, we slowly swept the voltage (V_{aux}) at an auxiliary gate to the electrometer island.[8] In this case, an imbalance manifested itself as a modulation of the amplitude of the ac electrometer current with respect to the voltage on the auxiliary gate. In fact, with the imbalance amplitude small compared to the oscillation period $\Delta V_{1,2}$, this procedure swept out the derivative of $I(V_{1,2})$ shown in Fig. 2 inset. At balance $C_1/C_2 = V_2/V_1$ and no oscillations with the gate voltage were observed.

The results of this measurement technique are illustrated in Fig. 3 where the horizontal axis is the voltage applied to the auxiliary gate. The six curves (shown vertically offset for clarity) correspond to six ratios of V_1/V_2 applied to C_1 and C_2. The middle four curves successively differ by 4–5 ppm each. We see that these curves (much smaller in magnitude than those in Fig. 2 inset) have a periodic, cusplike structure. Starting from the top (~20 ppm away from balance) and moving down the figure, the amplitude of the imbalance signal decreases, goes through a minimum, and then increases again. The polarity of the signal reverses at the minimum, as expected for this derivative measurement. We note that the period ΔV_{aux} is larger than for $\Delta V_{1,2}$, because the capacitance for this auxiliary gate is smaller (and thus the period e/C_{aux} is larger). We also note that a change in the ratio

V_1/V_2 of 10 ppm, for an applied amplitude of 5 V, corresponds to a change in the island charge of about $10^{-3}e$. With the amplitude of the SET oscillations $I(V_{1,2})$ in Fig. 2 inset of about 1 nA, this yields an ac signal of about 1 pA for a 10 ppm imbalance as shown in Fig. 3.

We identified the balance as occurring between the two middle curves at a ratio of $C_1/C_2=1.022\,235(3)$, and that the resolution is less than the change of 5 ppm between the two successive traces. *We estimate that our uncertainty in the ratio of the capacitors is thus about 3 ppm.* Achieving *accurate* measurements of the capacitance value will involve the replacement of C_2 by the SET pump.[2] The present result is two orders of magnitude better than our previous results[8] which were compromised by the poor performance of the silica dielectric capacitors C_1 and C_2.

The ac balance experiment results shown in Fig. 3 are for voltages V_1 and V_2 of amplitude ~5 V peak-to-peak, at 290 Hz. Measurements at a variety of frequencies from 100 Hz to 1 kHz showed no appreciable dependence of the balance point on frequency. In addition, measurements for a range of amplitudes over a factor of 100 (0.05–5.0 V *p-p*) also showed no dependence, except for the linear increase in resolution with higher drive voltages. Successive measurements over a two-week period showed no systematic change in the capacitor ratio, within the uncertainty; continuous short-term measurements (of duration ~1 h) also showed no drift.

The ultimate SET pump capacitor charging experiment which we are aiming towards requires much lower frequencies, probably on the order of 1 Hz.[2] We have done measurements which approximate these experimental conditions as follows: We applied a positive and negative V_1 and V_2, and used the voltage across the auxiliary gate to achieve a rough balance. We then used a mechanical switch to change the polarity of V_1 and V_2 (but *not* the absolute magnitudes or ratios) and looked for changes in the off-null signal synchronous with the switching. We fixed the balance point at the minimum of the synchronous off-null signal. This procedure yielded a ratio for the two capacitors C_1/C_2 of 1.0221 with an uncertainty of about 10^{-4}, consistent with the ac results. The larger uncertainty was mostly due to the large amount of random (excess-low-frequency) noise in the electrometers. Most troublesome is the ''telegraph'' or ''two-level-fluctuator'' noise commonly seen in such devices.[9,10] This points out a required element for the future metrological experiments: SET electrometers with low noise at low frequencies, e.g., $10^{-4}e/\sqrt{\mathrm{Hz}}$ at 0.1 Hz.

In the ongoing effort to achieve 10^{-8} imprecision in this experiment, several points need to be addressed. First of all, the planar coupling capacitor should be increased to about 1 fF to achieve a higher off-null signal for the same voltage imbalance. This will be done in the next round of experiments and should allow us to achieve about 10^{-7} imprecision for the ac measurements. Better measurement techniques, especially reducing environmental noise, to further reduce system noise should allow even better resolution. For the important dc measurements (i.e., at or near 1 Hz), it is clear that we must use better SET electrometers with lower low-frequency ''telegraph-type'' noise to achieve the desired imprecision and, ultimately in combination with the SET pump, the desired accuracy.

In summary, we have shown an important application for SET devices by determining with high precision the ratio of two cryogenic capacitors. We have achieved a resolution at audio frequencies of ~3 ppm in the ratio of two capacitors, each about 0.5 pF and with very good short- and long-term stability and very high leakage resistance. We are continuing to work to improve the overall performance, and particularly the lower frequency performance, in anticipation of the metrological capacitor-charging experiment.

The pioneering development work of Ruby N. Ghosh is gratefully acknowledged as are the helpful suggestions of John M. Martinis. We also acknowledge the extensive technical assistance of William E. Fogel, useful discussions with John Q. Shields, and the assembly and initial testing of the capacitors by Katy E. Lease.

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