Measurement of the Frequency Dependence of a Single-Electron Tunneling Capacitance Standard

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Abstract

In the context of a proposed new capacitance standard based on counting electrons, we discuss a method to investigate its frequency dependence. We describe measurements of this frequency dependence using a technique that involves the same single-electron tunneling (SET) devices used in the capacitance standard.

Introduction

Using SET devices (a 7-junction electron pump and a 2-junction transistor/electrometer [1]) and a cryogenic vacuum-gap capacitor C_{cryo} [2], we have realized a new capacitance standard [3]. The operation of the standard has already shown very promising results [4]. However, the new capacitance standard operates at an effective frequency close to dc, whereas capacitance metrology usually relies on bridges operating at a fixed frequency around 1 kHz. Therefore, the frequency dependence of the cryogenic capacitor is critical to the practical application of this standard.

Experiment

The general concept consists of applying a voltage step V to a capacitor C and recording the time evolution of the charge $Q = CV$. With V held constant after applying the step, any change in Q over time implies a time dependence (or leakage) in C. Furthermore, a time dependence on a scale Δt implies a frequency dependence on a scale $\Delta f \sim 1/\Delta t$. If a particular model of the imperfections in C is assumed, any measured time dependence can be quantitatively converted to a frequency dependence $C(f)$. Our implementation of the general concept relies on an SET electrometer to monitor the charge and an electron pump in the hold mode (not pumping) that acts as a switch (see Fig. 1). From the current-voltage curve shown in Fig. 2a, it is clear that the pump behaves as an open switch if the voltage V_p across it does not exceed the Coulomb gap V_{gap}. If $V_p \gg V_{gap}$, the pump acts like a resistor of a few megohms.

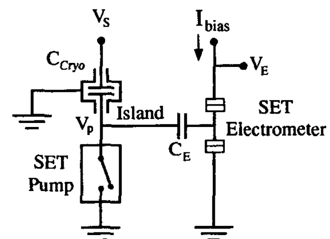

Figure 1: Experimental configuration of the frequency dependence measurement of C_{cryo}. The electron pump is presented as a switch. The island of the pump is capacitively coupled to an SET electrometer.

During the measurement, we can distinguish four different phases [5]:

(i) We start at point 1 (see Figs. 2a and b) with $V_p = 0$, and ramp up the voltage V_S on the external side of the capacitor. The ramp rate is chosen such that only a limited portion of V_S (typically < 50 mV) appears across the pump (during 1→2). This voltage still exceeds V_{gap}, and the pump acts as a resistor, allowing the island to discharge.

(ii) At the end of the ramp (2→3), we wait for a short time to finish discharging the island. On the current-voltage characteristic of the pump, discharging corresponds to going down the resistive branch to the edge of the gap.

(iii) At point 3, we apply a small reverse step (3→4, typically 1 mV) to reset V_p to the middle of the gap, thus putting the pump in its "open" state.

(iv) The island is now floating with $V_p \approx 0$, and the electrometer is monitoring any change in the island charge. If C_{cryo} depends on frequency (or leaks [6]), this charge will change with time, and by recording the electrometer signal between points 4 and 5, we access this information. The time it takes to go from point 1 to point 4 determines the upper limit of the frequency range we can reach, whereas the time between points 4 and 5 sets the lower limit.

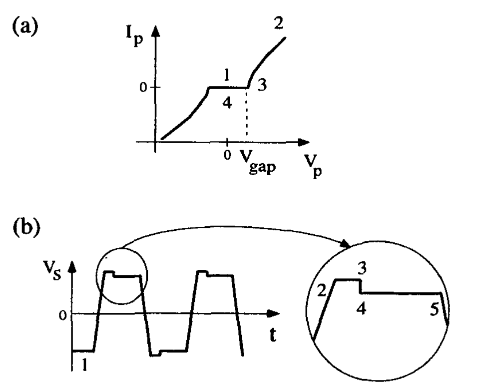

Figure 2: A typical current-voltage caracteristic of an SET electron pump is shown in (a). The applied voltage step V_S is sketched, not to scale, in (b). Points 1 through 5 refer to different phases in the measurement (see text).

Results and Conclusions

For each applied step, we extract a slope in the electrometer signal for the region located between points 4 and 5. This slope can be converted to a change in the island charge and interpreted as a change in C_{cryo}. Using this technique, we have placed an upper bound on the relative change in C_{cryo} (resulting from about 100 measurements averaged together) of $(0.6 \pm 2) \times 10^{-6}$ s^{-1}, measured between 0.1 s and 0.5 s after applying the voltage. From this null result we infer that the relative frequency dependence of C_{cryo} over the corresponding frequency range, 10 Hz to 2 Hz, is no larger than about 10^{-6}. This preliminary finding indicates that the cryogenic vacuum-gap capacitor is a promising candidate for the purpose of a new capacitance standard. We are currently pursuing improvements to our measurement technique and we expect that the $1/f$ noise of the electrometer will be the ultimate limit on the sensitivity of the frequency dependence measurement.

References

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[5] A. L. Eichenberger, M. W. Keller, J. M. Martinis, and N. M. Zimmerman, "Frequency Dependence of a Cryogenic Capacitor Measured Using Single Electron Tunneling Devices", Jour. of Low Temp. Physics, to be published.

[6] A direct measurement of the leakage of C_{cryo} has given a lower bound for its parallel resistance of $10^{21}\,\Omega$.