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A CAPACITANCE STANDARD BASED ON COUNTING ELECTRONS: PROGRESS REPORT

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Abstract

We have combined an electron pump and a vacuum-gap capacitor to create a prototype capacitance standard based on electron counting. We are testing various components individually to determine whether a standard with an overall uncertainty of 1 part in 10^8 is feasible.

Introduction

We are working to realize a capacitance standard directly from the definition of capacitance: A charge of 1 coulomb on a capacitance of 1 farad produces a potential difference of 1 volt. The critical technologies for this standard are single electron tunneling (SET) devices and a vacuum-gap capacitor. An electron pump will be used to place a known number of electrons onto the vacuum-gap capacitor and a measurement of the resulting voltage will yield the value of capacitance[1]. The vacuum-gap capacitor will then serve as a primary standard to which other capacitors can be compared.

Our recent work has focused on the characteristics of individual pumps and capacitors. We have made a 7-junction pump that counts electrons with an uncertainty of about 1 part in 10^8[2, 3]. A vacuum-gap capacitor with a parallel leakage resistance of greater than $10^{19}\ \Omega$ has also been demonstrated[4]. Our present work involves combining the pump and the capacitor with other components to make a complete standard.

Prototype Standard

Figure 1 shows the various components of the prototype capacitance standard. The cryogenic needle switches *S1* and *S2* allow four different circuit configurations. As described previously[5], by closing both *S1* and *S2* we can characterize the pump and the SET electrometer, and by opening both *S1* and *S2* we can verify the accuracy of the pump by detecting single electrons at the electrometer input. With *S1* closed and *S2* open, we can pump electrons onto the vacuum-gap capacitor *C*. As we do this, the electrometer will control a feedback circuit *F* which delivers a voltage *V* to the outer terminal of *C* so that the voltage across the pump remains at zero, as required for accurate pumping. We will then stop the pump after *N* cycles, measure the voltage *V*, and the value of *C* will be simply Ne/V. We expect to have $C \sim 1$ pF, $N \sim 10^8$, and $V \sim 10$ V. With *S1* open and *S2* closed, we can compare *C* with another capacitor at room temperature using an ac bridge (see Figure 2b of ref. [6]).

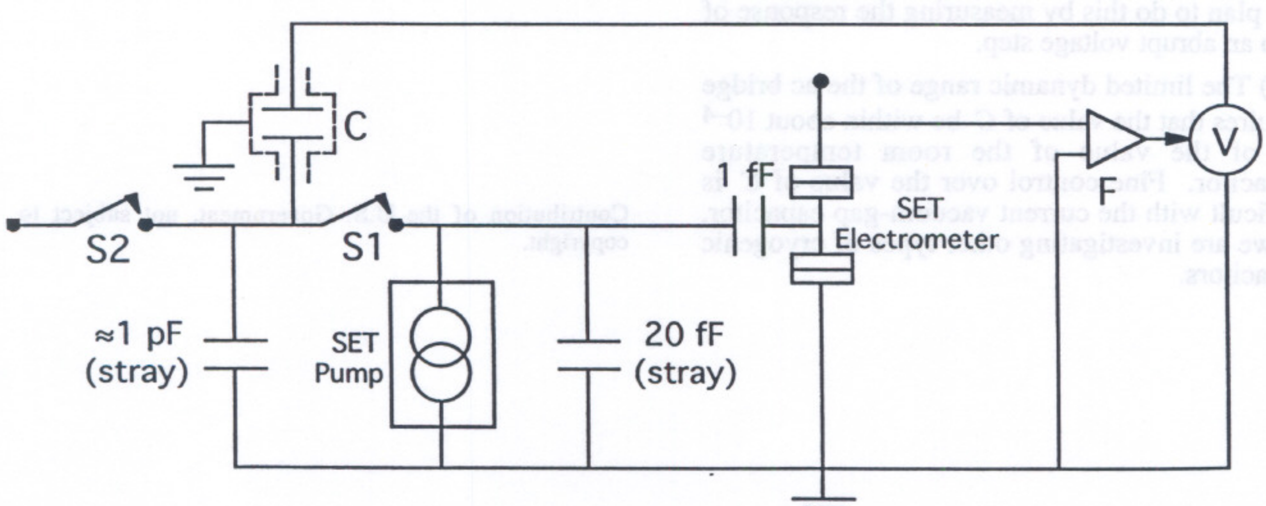

Fig. 1 Schematic circuit of capacitance standard. All components except *F* and *V* are at 40 mK.

We are currently focusing on four major challenges facing this approach to a capacitance standard.

(1) The electrometer cannot maintain exactly zero voltage at the node between the pump and the vacuum-gap capacitor because it has finite noise. This translates into an uncertainty in the actual voltage across C. Recent calculations show that an uncertainty of 1 part in 10^8 will require better noise performance than has been routinely achieved to date[6]. We are exploring a variety of ideas for reducing electrometer noise, which appears to come from charged defects that are near the device and move even at very low temperature.

(2) Once C has been charged by the pump, the charge must not leak off the node between the pump and C during the time needed to measure V. Our tests show that the pump is the dominant path for leakage, with one electron escaping about every 10 minutes. This should allow sufficient time for a measurement of V (~ 10 V) with an uncertainty of 1 part in 10^8.

(3) The frequency dependence of C must be very small. Pumping 10^8 electrons onto C will take about 20 s and the measurement of V may take another 10 s. Thus the value of C is determined at an effective frequency of about 0.03 Hz. The ac bridge used to compare C with another capacitor at room temperature will operate at about 1 kHz. Thus we must determine whether C is constant within 1 part in 10^8 over more than 4 orders of magnitude in frequency. We plan to do this by measuring the response of C to an abrupt voltage step.

(4) The limited dynamic range of the ac bridge requires that the value of C be within about 10^{-4} pF of the value of the room temperature capacitor. Fine control over the value of C is difficult with the current vacuum-gap capacitor, so we are investigating other types of cryogenic capacitors.

References

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