Proposed Tests to Evaluate The Frequency-Dependent Capacitor Ratio for Single Electron Tunneling Experiment

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Abstract. A precise measurement of the ratio of two cryogenic capacitors is needed for a capacitor charging experiment using Single Electron Tunneling (SET) phenomena. To support the capacitor charging metrology a frequency characterization of the capacitors is required. To cover the frequency range from 1 Hz to 1 kHz, resistive and inductive voltage divider bridges are proposed. Preliminary tests suggest that the uncertainty with which the capacitor ratio can be evaluated is less than one part per 10^6.

Introduction

In recent years there has been an increased interest in Single Electron Tunneling (SET) metrology [1,2]. One of the reasons is the possibility of a precise capacitance measurement. The capacitor charging experiment [3] depends on reliable realization of a SET pump and SET electrometer, as well as cryogenic capacitors. This experiment is an ongoing effort by both the National Institute of Standards and Technology (NIST) Boulder and Gaithersburg groups. The NIST Gaithersburg group is developing the SET electrometer and capacitors. To substitute for the SET pump the combination of a voltage source and a capacitor is used. A specific voltage pattern is used to simulate the direct and reverse pump operation.

The goal is to test the capacitance transfer standard and validate the use of the SET electrometer as a null detector. The ratio of the two capacitors was determined with 1σ uncertainty of 3 parts per 10^6 in 1995 [3]. It is desirable to evaluate the capacitors over a frequency range up to 1 kHz with less uncertainty in the next phase of the SET experiment. This paper addresses the preliminary testing of the ratio bridges to be used for evaluation of the capacitors' performance.

Voltage ratio bridges to support SET metrology

A generalized voltage ratio bridge to support the capacitor charging experiment is shown in Fig 1. To measure the capacitor ratio at frequencies that are on the order of 10 Hz to 1 Hz and less, a resistive voltage divider is used. The bridge drive voltage consists of a ramp and a constant DC regime, and the voltage pattern alternates the polarity periodically. This voltage pattern simulates the SET pump and ratio measurements are made during the hold (DC) mode. To cover the rest of the frequency range an inductive voltage divider with an AC isolated voltage source is used.

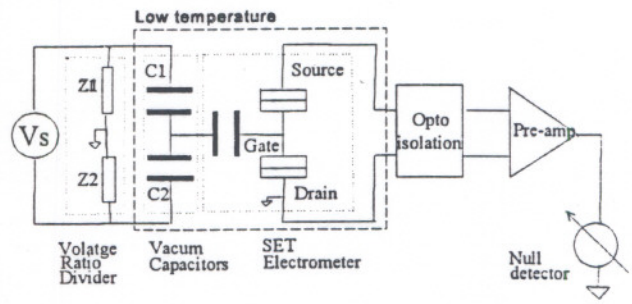

Figure 1. General voltage ratio bridge to support capacitor charging experiment. Source and drain are made from ultra small tunnel junctions.

If the resulting capacitor ratios obtained by these two methods (inductive and resistive voltage dividers) are within specified uncertainties, it is reasonable to assume that the proposed measurement procedure characterizes the frequency dependence of the capacitor ratio satisfactorily. If the results show significant discrepancy, a special inductive voltage divider for very low frequencies has to be developed and the whole frequency range must be measured with an inductive voltage divider bridge.

In order to achieve an uncertainty of the capacitor ratio measurements better than 1 parts per 10^6 it is necessary to calibrate the voltage divider used in the bridge and to evaluate the uncertainty of the bridge itself to better than 0.15 parts per 10^6. This task is simplified since there is only one pair of capacitors to be evaluated. From the previous experiment the ratio was 1.02223 which translates to a voltage divider ratio of 0.50549. It is possible to calibrate the voltage ratio of 0.5 very precisely by interchanging leads to the voltage dividers [4]. Since the required capacitor ratio is considerably different from 0.5, extra calibration steps have to be performed.

Measurements using resistive divider

The first step in calibrating the resistive divider is to test the ratio 0.5. The divider was calibrated in a simple bridge that compared two similar commercially available dividers. The combination of measurements interchanging eight leads resulted in a 0.5 ratio error of 0.2 parts per 10^6 with an uncertainty of 0.05 parts per 10^6.

The second step utilized a high performance commercially available voltmeter with manufacturer's declared sub parts per 10^6 accuracy. It is used to measure the voltage difference between the outputs of the reference divider set to the ratio 0.5 and the divider under test set to the ratio of interest (in this case 0.51). The bridge drive voltage tested was 10 V, so the offset produced about 100 mV. The measurement resolution due to the voltmeter stability was on the order of 50 nV. Since we are comparing the voltages at balance (both dividers set to a ratio 0.5) and offset mode (test divider set to a ratio 0.51 and reference divider set to ratio 0.5) this is a voltage difference measurement, and the instrument stability is crucial. The other source of error is leakage current due to the voltmeter input impedance (more than 10 GΩ) and the resistance of the divider (100 kΩ input resistance). The divider current is about 100 μA, and the voltmeter current is about 10 pA in the worst case when 100 mV is measured. This produces an error on the order of 0.1 parts per 10^6.

In summary, this preliminary test suggests that the required resistive divider ratio can be calibrated with an uncertainty of 0.1 parts per 10^6. Due to the limitation of the voltmeter ranges only ratios from 0.5 to 0.51 can be calibrated using this method.

Measurements using inductive divider

The inductive voltage divider calibration procedure also starts with calibration of the ratio 0.5. The commercially available divider tested had 0.5 ratio errors on the order of 0.1 parts per 10^6 in the frequency range from 100 Hz to 1 kHz. These errors were measured with an uncertainty of 0.05 parts per 10^6 using lead interchanging measurements in a simple bridge that compared two similar dividers. To measure the required ratio in the range from 0.5 to 0.51 the calibration procedure that is based on error decomposition method is proposed [5]. This method compares two inductive voltage dividers with different transformer design structures and uses a mathematical model to extract the errors for each instrument. Due to noise concerns in the SET experiment, a manually-operated decade inductive voltage divider will be used to test the capacitors. That divider will then be compared with an available 30 bit binary inductive voltage divider over the range of interest (0.5 to 0.51). This translates in binary transition to the 4th bit, and based on previous tests at 400 Hz with similar instrumentation, the binary divider in-phase errors were on the order of 0.01 parts per 10^6, and the decade divider errors were on the order of 0.05 parts per 10^6. The 1σ uncertainty of the error decomposition method in the ratio range of interest is 0.01 parts per 10^6.

In summary, based on the preliminary tests presented, it is reasonable to assume that the inductive voltage divider can be calibrated throughout frequency and ratio ranges of interest at the order of 0.1 parts per 10^6.

References

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