Towards a quantum capacitance standard

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1. Abstract

Dc characteristics of a 3-junction resistive electron pump (R-pump) have been measured. Large modulation of the current as a function of gate voltage has been seen, and evidence of the suppression of co-tunneling by the resistors observed. The temperature dependence of a tunable 1 pF co-axial cryogenic capacitor is also reported. The capacitor can be tuned such that its value at 4 K is within 100 parts per million (ppm) of 1 pF. The R-pump and cryogenic capacitor are important elements in a future quantum standard of capacitance.

2. Introduction

Since 1990, the Ohm and the Volt have been represented at NPL, and many other National Measurement Institutes (NMI's), by the quantum Hall effect (QHE) and the Josephson effect respectively. The Farad and Henry are also derived from the QHE via a chain of dc and ac bridges. Use of these quantum standards has lowered measurement uncertainties and facilitated accurate international comparisons. Over the last 15 years, advances in sub-micron fabrication techniques have made feasible a new type of quantum electrical standard known as the electron pump. This is one of a general class of nanostructures, made from small resistive tunnel junctions, exploiting single electron tunneling (SET) effects (see [1] for a review). These effects occur if one or more metallic islands with capacitance C_Σ are isolated from an external circuit by tunnel junctions of resistance R_j, and the conditions $C_\Sigma << e^2/2k_BT$, $R_j >> R_K$ are met, where T is temperature, e is the electron charge and $R_K = h/e^2 \approx 26\ \mathrm{k}\Omega$ the resistance quantum. Manipulation of the charges on the islands by means of capacitive gates can then completely suppress tunneling through the junctions. The simplest electron pump has 2 islands and 3 junctions (see Fig. 1), and coherently cycling the two island charges at a frequency f can produce sequential tunneling of single electrons through the device, with the quantised current given by I=ef [2].

The maximum pumping frequency is limited by the time constant of the tunnel junctions (i.e. f $\approx 0.001\ R_jC_\Sigma$) to around 10 MHz, corresponding to a current of 1.6 pA. A metrological use of this small current would be to charge a small capacitor with a known number of electrons. Combined with a measurement of the voltage across the capacitor in terms of a Josephson voltage standard, this procedure yields a quantum capacitance standard based on a defined value of e. In this work, we report characterization measurements on two of the most important components of the capacitance standard: the electron pump and cryogenic capacitor.

3. The R-Pump

Since the early work of Pothier et al, where controlled pumping of electrons was demonstrated for the first time using a 3-junction pump [3], metrological single-electron work has focused on the error mechanisms limiting the accuracy of the electron pump [4-6]. An important error mechanism is co-tunneling, a quantum process whereby an electron tunnels through all junctions simultaneously. Co-tunneling errors can be reduced below 10^{-8} by increasing the number of junctions in the pump, and this approach has been used successfully by Keller et al in the construction of a prototype capacitance standard at the National Institute of Standards and Technology (NIST)[7-9]. Their 7-junction pump is complex to operate, requiring careful tuning of the 6 gate voltages. Another approach to reducing co-tunneling using just 3-junctions has been pioneered at PTB [10-12]. In this approach, miniature

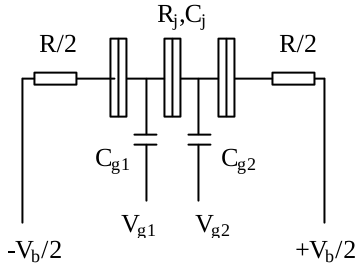

Fig. 1 Schematic diagram of R-pump

resistors, $R_j>R>R_K$ are fabricated onto the sample wafer, in series with the pump and the external measuring circuit. Theory predicts that the resistors suppress co-tunneling as effectively as *n* additional junctions, where $n = R/R_K$ [13]. Thus, a resistive pump, or 'R-pump', with metrological accuracy could be constructed with 3-4 junctions and resistors R = 50-100 kΩ, provided other sources of error, such as photon-assisted tunneling, could be effectively suppressed [6].

The schematic layout of the R-pump is shown in fig. 1. The R-pump was fabricated by a shadow evaporation technique [14]. The tunnel junctions were formed from layers of Al and AlO on an oxidized Si substrate, with junction dimensions typically 20 nm by 40 nm. The on-chip resistors were Cr, with dimensions 80 nm by 7 µm by 7 nm, calculated to yield R=50 kΩ. Measurements were made in a top-loading dilution refrigerator at a bath temperature of 20 mK. A magnetic field of 1 T was applied to suppress superconductivity in the pump. A transimpedance amplifier was used to provide a symmetric bias voltage across the pump and to measure the current in the pump [15]. To filter unwanted microwave noise, 1m coiled lengths of Thermocoax® cable were used as the measurement leads in the coldest part of the refrigerator [16].

4. dc R-pump measurements

The current through the pump was measured as a function of V_b, V_{g1}, and V_{g2}. At large bias voltage, the I-V_b curve of the pump asymptotically approaches ohmic behavior, $V_b/I = \Sigma(R+R_j) = 496$ kΩ. The positive and negative branches are offset by $V_{off} = 4.2$ mV, so we evaluate $C_j \approx 80$ aF. For $V_b <\approx 1.5$ mV, Coulomb blockade of tunneling is seen. Fig. 2 shows a 3-d plot of I as a function of V_b and V_{g1}. To compensate for the cross-capacitance between the gates, in this measurement $V_{g2} = -aV_{g1}$, where the attenuation factor a=0.28 was determined empirically to yield perfect periodicity of I(V_{g1}). C_{g1} can be calculated from this periodicity: $C_{g1}=e/\Delta V_{g1}$, and similarly for C_{g2}. Calculated values were C_{g1}=12.8 aF, C_{g2}=13.3 aF.

Fig. 3 shows the current as an intensity map in the (V_{g1},V_{g2}) plane, at 0.4 mV (Fig. 3a) and 1.3 mV (Fig 3b) bias voltages. This view of the parameter space shows the 'triple points', pairs of values of V_{g1} and V_{g1} at which the Coulomb blockade is suppressed. The electron pumping regime consists of cycling around a triple point by applying sinusoidal voltages to gates 1 and 2 with the appropriate phase shift, amplitude and dc offset [2]. One complete cycle has the effect of transferring a single electron through the pump. It was found that the positions of the triple points changed by several mV over 24 hours. This is due to drift of charged defects present presumably in the substrate oxide, with resulting polarization of the islands [17]. A single mobile charge gives rise to two-level fluctuator behavior, which was seen in some of our data, while several defects will produce 1/f noise giving rise to the drifts seen in all our data [18]. The state of the pump cannot be predicted accurately over time scales of hours due to this drift, so the phase space of the pump will need re-measuring regularly. In contrast to [19], the amplitude of the background charge fluctuations did not decrease over 5 days with the pump kept cold.

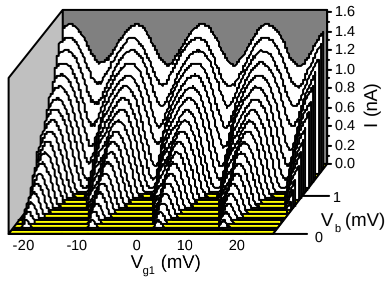

Fig. 2 Current through R-pump as function of V_b and V_{g1}

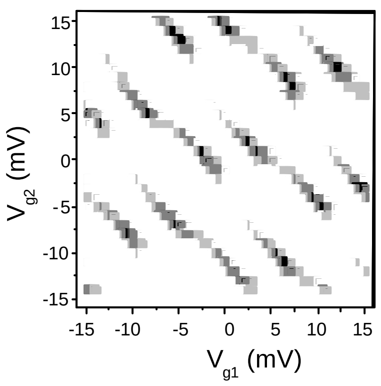

Fig. 3a Intensity map of current through R-pump as fn. of dc gate voltages. white = 0 nA, black = 0.4 nA. V_b = 0.4 mV.

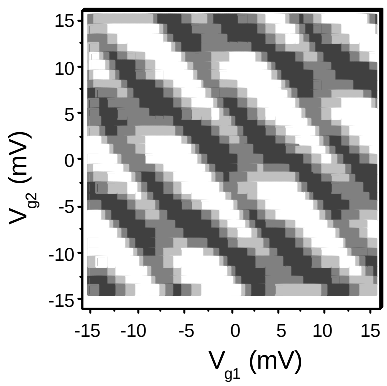

Fig.3b As fig. 3a, but white = 0 nA, black = 1 nA, V_b = 1.3 mV.

The theory of co-tunelling in an R-pump predicts that in the middle of the Coulomb blockade regime, $I \propto V_b^{2(n+N)-1}$, where $n=R/R_K$ and N is the number of junctions [10,11,13]. An estimate of the resistances R can therefore be made from the $I(V_b)$ characteristic at small I. We find an exponent of 11, yielding $R \approx 80\ k\Omega$. In common with [11], we observe the power-law behavior of I(Vb) extending out to much higher values of V_b than expected according to a strict interpretation of theory.

5. Capacitor characterisation

A tunable co-axial capacitor, similar to that described in [20], was constructed, with the dimensions calculated to yield a nominal value of 1 pF. The tuning is by means of two screws, which provide coarse and fine tuning. The fine tuning adjusts the capacitance by ≈ 100 aF/turn. The tuning can only by performed at room temperature. However, for use in the quantum capacitance standard, the capacitor must be mounted as closely as possible to the electron pump to minimize the stray capacitance of the lead connecting them. The capacitor will therefore be operated in a vacuum-loading dilution refrigerator at 20 mK. It is intended that the capacitor should be within 100 parts per million (ppm) of its nominal value at its operating temperature, to enable the use of the most accurate types of co-axial ac bridge to transfer its value to a room temperature standard.

For testing, the capacitor was mounted in a vacuum cryostat which could be lowered into a liquid helium dewar. Small amounts of helium exchange gas could be admitted to the cryostat, so the capacitor could be slowly cycled from room temperature to 4 K and back. Semi-rigid Be-Cu co-axial cables were used to connect the capacitor to the top plate of the cryostat. The outer conductors of the cables were electrically isolated from the cryostat and dewar, so the capacitor was properly defined as a 2 terminal-pair impedance [21]. The capacitor was thermally cycled between room temperature and 4 K several times, while measuring its value using an Andeen-Hagerling AH-2500 capacitance bridge. Based on the temperature dependence observed during these thermal cycles, the capacitor was tuned at room temperature for a target value of 1.000 pF at 4 K, and then cooled to 4 K in 20 mbar He exchange gas. The cooling time was 2 hours. The C-T curve from this cooling cycle is shown in fig. 4. The final value of the capacitor was 0.99991 pF, or 91 ppm below nominal. Once the temperature of the capacitor had stabilized at 4 K, the capacitance did not deviate by more than one ppm over several hours.

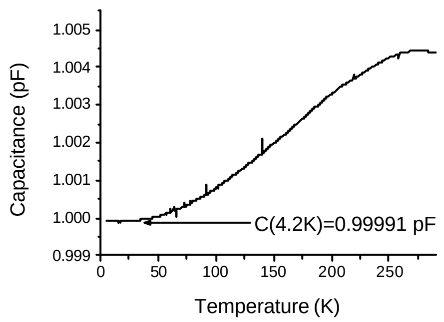

Fig. 4 Temperature dependence of capacitor during cooling, after tuning at room temperature.

6. Conclusions and Further work

Charging a cryogenic capacitor with the current from an electron pump is one element in a future quantum capacitance standard. We have performed preliminary characterization measurements on a new type of electron pump, the R-pump, incorporating on-chip resistors to suppress co-tunneling. We have also constructed a 1 pF co-axial capacitor, and demonstrated that it can be tuned to within 100 ppm of its nominal value at 4 K. The next stage of the R-pump measurements is to apply ac voltages to the gates, and measure the current as a function of frequency. A 10000:1 turn cryogenic current comparator is available at NPL for measuring the small current produced by the R-pump. Verification of the relation I=ef to the 10^{-4} level will be possible using this technique. Next, the capacitor and R-pump will be mounted together in a vacuum-loading dilution refrigerator for testing of the prototype capacitance standard.

7 Acknowlegments

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8. References

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