

MEASUREMENT OF VERY HIGH LEAKAGE RESISTANCES IN 1 pF CRYOGENIC CAPACITORS USING A SET DETECTOR

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1 pF cryogenic capacitors form an important element of a future measurement system for the small currents generated by single electron pumps [1]. This application sets a stringent requirement on the minimum leakage resistance of the cryogenic capacitor, at $6 \times 10^{19} \Omega$. In this work, a Single Electron Transistor (SET) was used as a sensitive charge detector to evaluate the leakage resistance of two types of cryogenic capacitor. These resistances were found to be $3 \times 10^{16} \Omega$ for fused-quartz dielectric and $> 10^{18} \Omega$ for ^3He - ^4He mixture dielectric capacitors.

Background

Single electron pumps based on small capacitive tunnel junctions offer the possibility of a current standard based on the passage of an exactly known number of electrons through a solid-state device in unit time. Such a standard would be a 'quantum' standard for the Ampere in the same way that the Josephson effect and quantum Hall effects are quantum standards for the Volt and the Ohm respectively. The current from a single electron pump is given by $I = ef$, where f is the frequency at which the pump is operated.

Pump frequencies cannot at present exceed ≈ 10 MHz without loss of accuracy, so the maximum current generated by a pump will be in the region of 1-2 pA [2,3]. For the electron pump to be useful as a metrological device, this current must be measurable to 1 part in 10^8 . The limit of a cryogenic current comparator in resolving 1 pA is approximately 1 in 10^5 , well below the level required. It is therefore envisaged that the current measurement will consist of charging a capacitor with a precisely known number of electrons and measuring the voltage developed across the capacitor plates using a Josephson array voltmeter. If the value of the capacitor was related to the quantum Hall resistance through the conventional impedance measurement chain, the experiment would represent 'closure of the metrological triangle', providing a measure of the ratio $R_K/(h/e^2)$ [1].

To calculate the required minimum capacitor leakage resistance, we envisage that the single electron pump will be run at 6.25 MHz for 1s, generating a current of 1 pA and charging a 1 pF capacitor up to 1V. The capacitor must not lose any electrons during the time taken to measure the voltage, which will be about 5 s. To meet this requirement the leakage resistance across the capacitor plates must be greater than $6 \times 10^{19} \Omega$.

Apparatus design

The capacitors were designed to fit into the 25 mm diameter sample holder of an Oxford Instruments top-loading (sample into liquid) dilution refrigerator. Two types of capacitor were under consideration; a fused silica dielectric type with evaporated metal electrodes (fig. 1), and a helium-mixture dielectric type (fig. 2). The dielectric in the latter capacitor was the ^3He - ^4He mixture of the dilution refrigerator, and the plates were separated from the outer shield by 1.5 mm diameter sapphire balls.

Sapphire was chosen in this case for its very low electrical conductivity. The capacitors were designed to have values of 1 pF, and after manufacturing were found to deviate from this nominal value by up to 20%.

An Al-Al₂O₃ SET was also mounted in the sample holder, and the gate electrode of the SET was connected to one of the capacitor plates. The other plate was connected via a co-axial cable to a computer-controlled 16 bit DAC. A similar DAC controlled the SET bias voltage, and the SET current was measured with a low-noise current amplifier.

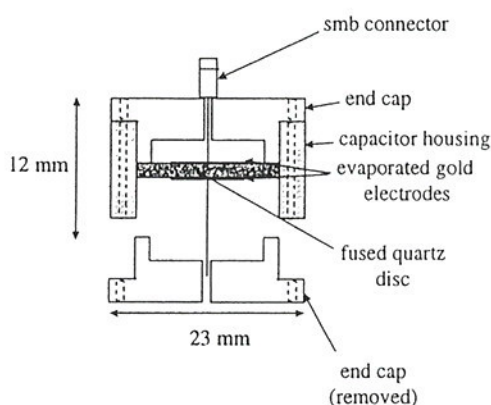


Figure 1 Cross-section through SiO capacitor

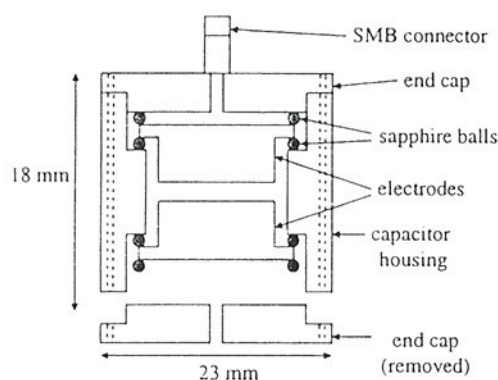


Figure 2 Cross-section through ³He-⁴He mixture capacitor

Experimental Method

A circuit diagram of the cold part of the apparatus is shown in fig. 3. The SET bias voltage was set at its optimal value, which for a typical SET device was close to 1 mV. At the optimal value of bias voltage, the largest modulation of output current is seen as a function of gate voltage [4]. This is the basis of using the SET as a sensitive voltage detector. The value of the gate capacitance C_G was measured by removing the capacitor C (so that $V_G = V$ in fig. 3), and observing the oscillations in output current as a function of V_G . The period of the oscillations in V_G is equal to e/C_G . C_G was typically between 30 and 80 aF, depending on the SET device used. With the cryogenic capacitor connected in series with the gate capacitor, the cryogenic capacitor and its stray capacitance to ground act as a voltage divider, and the value of the stray capacitance can be deduced from the apparent periodicity of the SET oscillations in the source voltage.

To measure the leakage resistance, the voltage source was programmed to apply a step voltage to the cryogenic capacitor, and then return the voltage to its original value after a few minutes. During this time, any leakage through the capacitor would change the voltage on the SET gate capacitor, and result in a modulation of the current through the SET. For some experiments, the SET current was measured by superimposing a small ac modulation onto the source voltage, and

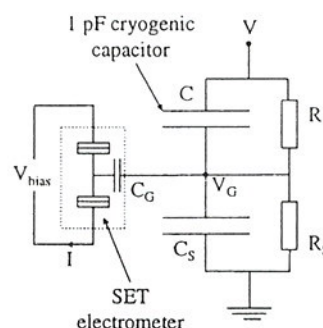


Figure 3 Arrangement of cryogenic capacitor and SET detector. C_S is stray capacitance of C to ground, and R and R_S represent the leakage resistances of C and C_S respectively.

detecting the SET output using a lock-in amplifier, although this method did not yield a higher signal to noise ratio than a simple dc source-drain measurement.

If initially $V=V_G=0$, the general behavior of V_G after applying a voltage step of magnitude V is given by

$$V_G(t) = \frac{VR_S}{R+R_S} \left[1 + \frac{CR - C_S R_S}{R_S(C+C_S)} \exp\left(-t \left(\frac{R+R_S}{RR_S(C+C_S)} \right) \right) \right] \quad (1).$$

It can be seen that on application of the voltage step, V_G immediately jumps to $VC/(C+C_S)$, and decays exponentially to $VR_S/(R+R_S)$ with time constant $RR_S(C+C_S)/(R+R_S)$. An interesting feature of eq. (1) is that the magnitude of the exponential time dependence depends on the difference between the time constant of the actual capacitor, and that of the stray capacitor. If $CR = C_S R_S$, then there will be no time dependence to V_G , no matter how low the value of R . Conversely, information about R can only be obtained from a measurement of $V_G(t)$ if an assumption is made about the value of R/R_S .

Results of leakage experiment

Figures 4 and 5 show the current through the SET electrometer as a function of time for leakage measurements on the quartz and mixture dielectric capacitors respectively. In the case of the quartz capacitor, the measurement was made using ac modulation of V , so the y-axis shows the lock-in amplifier voltage output. Clearly in the case of the mixture capacitor no change is seen in V_G over the duration of the measurement, and V_G returns to its original value when the source voltage is returned to zero. The current noise in the measurement is about 5 pA, and the gradient of the linear fit is $(0.90 \pm 4.2) \text{ fAs}^{-1}$. Using eq. (1) in the linear approximation of $t \ll RC$, and making the assumption that $R=R_S$, we can set a lower limit to R of $10^{18} \Omega$.

We conducted experiments with longer hold times in an attempt to increase

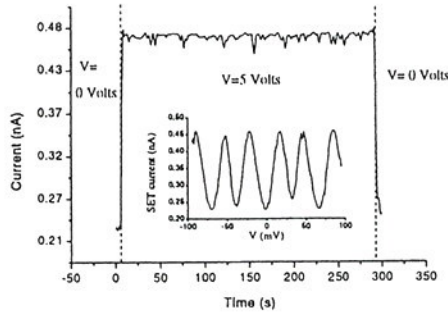


Figure 4 Result of leakage measurement on mixture capacitor. Dotted lines separate regions with different source voltage V . Inset: oscillations in SET current as a function of V (see fig. 3).

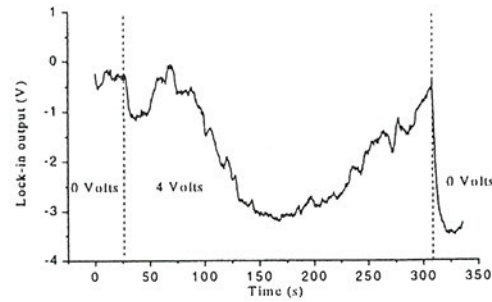


Figure 5 Result of leakage measurement on quartz capacitor, using ac modulation of V and detecting SET output current using a PSD.

this lower limit, but the data suffered from random jumps in the SET current, on average once every 1000s. We also saw some linear drift in the SET current, with magnitudes of up to 10^{-5} nAs^{-1} , similar to drift seen by Zimmerman [5]. The cause of this drift is not known. Zimmerman attributed it to drift in V (applied by a battery), but since our voltage source was a DAC with an internal reference we think this is

unlikely. The drift would be compatible with a leakage resistance of $\approx 10^{17}\Omega$, but does not appear in all the data sets.

Fig. 5 shows the result of a measurement on the quartz dielectric capacitor. There is clearly leakage through the capacitor, as the SET current passes through almost a complete oscillation, corresponding to a change in V_G of 4.8 mV. Using eq. 1, with the assumption that $R=R_S$, enables the calculation of R , which is found to be $3 \times 10^{16}\Omega$. This is consistent with the observation that the leakage resistance is greater than $10^{15}\Omega$, which is the highest resistance that can be measured using our Hewlett-Packard 4329A electrometer. The quartz-dielectric capacitor is clearly not suitable for a capacitor charging experiment.

Future work

Table 1 summarises the properties of the two types of cryogenic capacitor measured so far, including results reported in this paper. The mixture-dielectric capacitor is clearly more suitable for use in a single-electron pump charging experiment. Although it has not been shown that the mixture capacitor has leakage resistance greater than $6 \times 10^{19}\Omega$, confidence has been gained that its leakage resistance is of a high enough order of magnitude to be used in a single electron charging experiment. Future experiments at NPL will concentrate on testing electron pumps, and ultimately using them to charge a capacitor. Further work will be done on the capacitors to bring their values to within 0.1% of 1 pF, to enable more accurate bridges to be used to compare them with a room temperature standard.

Table 1 Summary of capacitor properties

	mixture capacitor	quartz capacitor
Max. long-term drift at 30 mK (ppm s ⁻¹)	0	2.8×10^{-10}
Temp. co-efficient at 50 mK (ppm mK ⁻¹)	-1.2	-14
Stray capacitance (pF)	6.4	2.4
Leakage resistance (Ω)	$> 10^{18}$	3×10^{16}

The Authors acknowledge the support of the European Commission Standards, Measurement and Testing 4'th Framework Program, and the National Measurement System Policy Unit of the Department of Trade and Industry.

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