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QUANTUM FLUCTUATIONS AND COULOMB BLOCKADE IN SMALL TUNNEL JUNCTIONS

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We describe an experiment in which we attached high- and low-resistance thin film leads to normal metal tunnel junctions with capacitances of order 10^{-15} F. At 20 mK we observed a pronounced Coulomb blockade in the former case, and a very smeared blockade in the latter case. We outline a model which indicates that the low temperature behavior of the junctions is dominated by quantum fluctuations in the external circuit. The predictions of the model are in fairly good agreement with the observed current-voltage characteristics.

1. INTRODUCTION

A number of recent reports (1) indicate that the low-temperature current-voltage (I-V) characteristics of single small-capacitance tunnel junctions do not match the predictions of theoretical models (2). In particular, the resistance at zero bias is much smaller than expected, and the Coulomb blockade is only visible at very large bias currents. In contrast, the I-V characteristics of two or more junctions in series have much higher zero-bias resistance, and the Coulomb blockade is more sharply defined. Explanations for these observations have been proposed (3), but only recently one (4) that allows comparison with experiments.

In this paper we present data on junctions where the external circuit is shown to have a strong effect on the I-V characteristic, and propose an alternative theoretical model to explain the behavior of single junctions. We show that the model predicts the experimental trends quite well.

2. EXPERIMENT

Our devices consist of single Al-Al oxide-Al tunnel junctions, with linewidths of about 0.2 μm and junction areas of about 0.04 μm^2. Four resistive leads were connected to the junction as shown inset in Fig. 1. Each resistive lead was 2 μm wide and 12 mm long, and was made with one of two alloys; one set were of CuAu alloy (25wt.% Cu) with a sheet resistance of 4 Ω per square, and the other set were of NiCr alloy (80wt.% Ni) with a sheet resistance of 60 Ω per square. The Al was driven normal with an external magnetic field.

In Fig. 1 we show the I-V characteristics at 20 mK

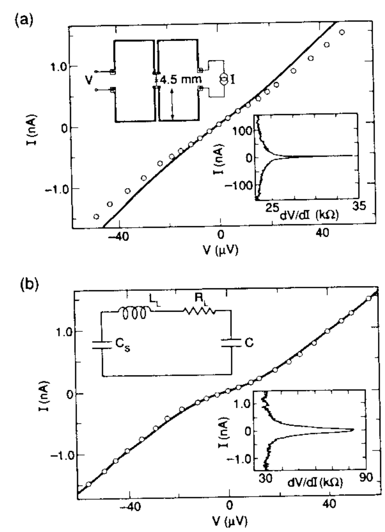

Figure1
I-V characteristics at 20 mK for junctions with (a) R=23 kΩ, C=4 fF and (b) R=28 kΩ, C=5 fF. Dots are theory. Inset in each figure is dV/dI vs. I. Also inset in (a) is the junction configuration and (b) the model circuit.

for two junctions, one with CuAu alloy resistors and the other with NiCr resistors. It is clear that the higher resistance leads give rise to a much sharper Coulomb blockade. This is made even more obvious in the insets of dV/dI vs. I. Similar results were obtained for all the devices we measured. In all cases, the zero-bias resistance increases with decreasing temperature, until the resistance

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saturates.

We have attempted to explain these results in terms of noise or heating effects in the junctions. Addition or removal of noise filters has no effect on the characteristics, and measurements of heating in the superconducting state , as well as calculations of the hot-electron effect (5) indicate that heating is not a problem.

3. THEORETICAL MODEL

We propose a model circuit for the tunnel junctions and their leads, and consider the effect of the energy fluctuations intrinsic to this circuit. Our circuit model, shown inset in Fig. 1, consists of the junction capacitance C in series with a resistor R_L and inductor L_L used to model the resistive leads, and a capacitor C_s representing the ~1pF stray capacitance from the coaxial lead connections.

The quantum Langevin equation of motion for the charge Q on the junction capacitance C is used to solve for the mean square fluctuation $\langle Q^2\rangle$ in terms of $\omega^2_{LC} = 1/L_LC$ and $\omega_{RC} = 1/R_LC$. We obtain

$$\langle Q^2\rangle = \int_0^\infty \frac{C^2\, S_V(\omega)\, d\omega}{(1-\omega^2/\omega^2_{LC})^2+(\omega/\omega_{RC})^2}\ , \qquad (1)$$

where $S_V(\omega) = (\hbar\omega R_L/\pi)\coth(\hbar\omega/2k_BT)$ is the spectral density of the noise from the resistor R_L.

In the limit of large T this integral gives the classical equipartition result $\langle Q^2\rangle/2C = k_BT/2$. In the limit T=0, the results are most easily expressed in terms of $\alpha = \omega_{LC}/\omega_{RC}$. For $\alpha = 0$, we obtain $\langle Q^2\rangle/2C = \hbar\omega_{LC}/4$, as expected for a harmonic oscillator. For the limit of interest here, $\alpha > 2$, we find

$$\frac{\langle Q^2\rangle}{2C} = \frac{\hbar\omega_{LC}}{2\pi}\frac{1}{\sqrt{\alpha^2-4}}\ln\left(\frac{\alpha^2-2+\alpha\sqrt{\alpha^2-4}}{\alpha^2-2-\alpha\sqrt{\alpha^2-4}}\right). \qquad (2)$$

For $\alpha \gg 2$ this approaches $\langle Q^2\rangle/2C = (\hbar\omega_{RC}/\pi)\ln\alpha$.

The mean square amplitude $\langle Q^2\rangle$ of the fluctuations represents the width of the probability distribution of the charge P(Q). We include this distribution in the theory by convolving the expression for the tunneling rate of electrons, $\Gamma(Q)$, with the probability distribution P(Q):

$$\langle\Gamma(Q)\rangle = \int_{-\infty}^{\infty} \Gamma(Q+q)\, P(q)\, dq\ . \qquad (3)$$

We numerically simulate the charging sequence of a junction for a fixed bias current I. The charge Q on the junction increases in a time step dt by I dt, and the discharge probability is $\langle\Gamma(Q)\rangle dt$. The voltage V=Q/C is averaged for a given I, and by varying I we generate an I-V characteristic.

In order to make comparisons with our experiment, we must choose parameter values for the model circuit. The model is an approximation to the actual circuit. In particular, we have neglected the capacitance C_p associated with the coupling of the leads to the nearest ground plane, which is 10 mm away from the device, and which we estimate to be 1-5 fF/mm of lead. Field analyses indicate that the coupling between leads on opposite sides of the junction is an order of magnitude less than this. The capacitance to ground shorts the leads at $\omega \approx 1/R_LC_p$, and above this frequency the impedance scales as $(R_L/\omega C_p)^{1/2}$. As the model does not reproduce this high-frequency behavior, we have chosen values of R_L and L_L corresponding to the first 4.5 mm of each lead. Separate experiments show that shorting out the rest of the leads does not affect the I-V characteristic, so the maximum length of lead involved in the loading of the junction is 4.5 mm. The values we have used in the model are R_L = 8 kΩ and 130 kΩ for the low- and high-resistance leads, respectively, and L_L = 5 nH.

The comparison of the model with the experiment is shown in Fig. 1. We see that the comparison with the low-resistance lead I-V is fairly good at low bias currents and less good at higher currents, whereas the model reproduces the I-V for the high-resistance leads rather well. Comparisons of the model with the characteristics of other junctions follow the same trends.

4. CONCLUSION

We have presented data from small-capacitance junctions with low- and high-resistance leads attached to them, and have shown that in the former case the Coulomb blockade is heavily smeared, while for the latter case the Coulomb blockade is much sharper. We have presented a model involving quantum fluctuations in the external circuit, and have shown that the trends seen in the experiment are reasonably well reproduced by the model.

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