Proc. 18th Int. Conf. on Low Temperature Physics, Kyoto, 1987
Japanese Journal of Applied Physics, Vol. 26 (1987) Supplement 26-3

Effect of Dissipation on Macroscopic Quantum Tunneling

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We report measurements of the escape rate from the zero-voltage state of a current-biased Josephson junction shunted by a normal-metal resistor. The critical current, capacitance, and resistance of the junction were measured in the classical regime. The escape rate was measured in both the high-temperature regime, where thermal activation dominates, and in the low-temperature regime, where macroscopic quantum tunneling dominates. The measured escape rates are in good agreement with the predicted escape rates with respect to both the effect of dissipation and the existence of quantum corrections to thermal activation.

1. INTRODUCTION

Measurements [1] of the escape rate of current-biased Josephson junctions from the zero-voltage state have shown good agreement with predictions for the rate of macroscopic quantum tunneling (MQT) [2] when the dissipation is small. However, measurements on Josephson junctions and flux-biased rf SQUIDs in which dissipation was considered important [3,4] showed qualitative agreement with theory [5-8], but with significant quantitative disagreement. As a result, no conclusive evidence exists to support the predictions of the effect of dissipation on MQT.

In this paper, we report measurements on a current-biased Josephson junction shunted by a thin-film resistor, with all the relevant parameters of the system measured using classical phenomena. The measured escape rate of the junction shows good agreement with theory for all temperatures at which measurements were made, with no adjustable parameters.

In the resistively shunted junction model, the current-biased Josephson junction is represented as a particle moving in a tilted cosine potential. The zero-voltage state corresponds to the particle confined in one well of the potential; the voltage state appears when the junction escapes from the well and runs down the tilted potential. For bias currents slightly less than the critical current I_0 the barrier separating the two states has height $\Delta U = (2\sqrt{2}I_0\Phi_0/3\pi)(1 - I/I_0)^{3/2}$, the frequency of small oscillations in the bottom of the well is $\omega_p = (2\pi I_0/C\Phi_0)^{1/2}\{1 - (I/I_0)^2\}^{1/4}$, and the damping is given by $Q = \omega_p RC$. The important parameters are the critical current I_0, the capacitance C and the shunt resistance R, each of which we determined using classical phenomena.

2. EXPERIMENT

The experimental configuration is described elsewhere [1]. The junction was patterned photolithographically on a bare Si wafer (Fig. 1). The shunt resistor was made of a 20 nm thick layer of CuAu alloy (25%wt.Cu) in a 5 µm wide L-shaped strip, connected to a 1 mm^2 cooling fin made of the same material. The shunt was covered with a 200 nm thick layer of insulating SiO, and contacts to the ends of the shunt were made by the 200 nm thick Nb base electrode and the 200 nm thick PbIn counterelectrode. The counterelectrode acted as a groundplane for the shunt, reducing its inductance to about 3 pH. The capacitance between the groundplane and the shunt was estimated to be less than 0.1 pF. The junction formed by the Nb and PbIn electrodes had a nominal area of 5 × 10 µm^2.

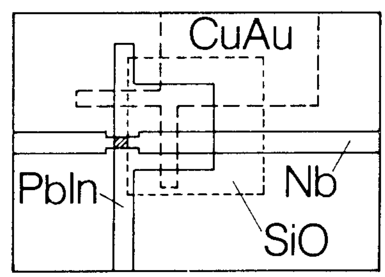

Fig. 1. Configuration of junction.

In a separate experiment, performed without disturbing the junction from its mount, the capacitance of the junction and its leads was measured using resonant activation [9] in the frequency range 7 to 12 GHz, while the shunt resistance was measured from the slope of the static current-voltage characteristic at currents well above the critical current. The capacitance was determined to be 4.28 ± 0.34 pF, and the shunt resistance was 9.3 ± 0.1 Ω.

The low temperature part of the experiment was performed in a dilution refrigerator with the junction, junction mount and microwave filters attached to the mixing chamber. Escape rates from the zero-voltage state were determined using standard techniques [1]. Typical escape distributions included at least 10^4 events over the temperature range from 18 mK to 830 mK. We took considerable care to ensure that after each escape event the shunt cooled to its original temperature before we measured the next lifetime.

We determined the critical current from the dependence of the escape rate on bias current. In the thermal activation regime at high temperatures, the escape rate is

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$$\Gamma = a_t(\omega_p/2\pi)\exp(-\Delta U/k_BT), \qquad (1)$$

where, in the strong damping limit which applies here, the prefactor $a_t = (1 + 1/4Q^2)^{1/2} - 1/2Q$ is near unity. If this prefactor were exactly unity, a plot of $\{\ln[\omega_p(I)/2\pi\Gamma(I)]\}^{2/3}$ vs. I would be a straight line intersecting the current axis at I_0. The true critical current is calculated from this intercept by including the small correction due to the actual value of a_t. We measured the critical current from 4 distributions taken at temperatures between 330 mK and 830 mK, where quantum corrections to the thermal activation prefactor are smaller than the uncertainties in the extrapolation. The average value of the critical current was found to be 24.873 ± 0.004 μA. Corrections for the cubic approximation to the barrier height are negligible.

3. RESULTS AND DISCUSSION

We present the escape rate in terms of the escape temperature, defined by the expression

$$\Gamma = (\omega_p/2\pi)\exp(-\Delta U/k_BT_{esc}). \qquad (2)$$

In the thermal activation regime the escape temperature is almost equal to the temperature T, with a small correction due to the thermal prefactor. In the quantum regime, T_{esc} approaches a limiting value determined by the tunneling rate. In Fig. 2, we plot T_{esc} vs. T, where T_{esc} was calculated at the value of bias current at which the number of escape events was a maximum.

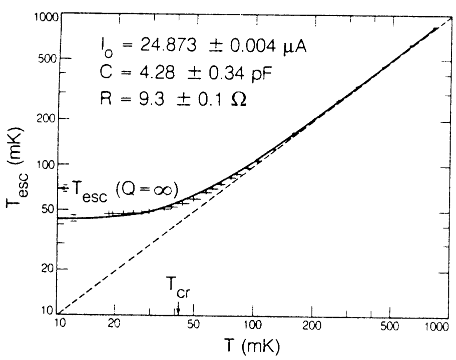

Fig. 2. T_{esc} vs. T for junction with listed values of I_0, C and R. The data have error bars of ± 1 standard deviation. The standard deviation in the predicted curve at low temperatures is also shown, while the crossover temperature for this junction and T_{esc} for a junction with no dissipation are indicated with arrows. The dashed line is the classical prediction T_{esc} = 0.98 T which is valid for high T.

The solid line through the points represents the theoretical predictions; the crossover from activation over the top of the barrier to tunneling through the barrier occurs at the temperature T_{cr} given by [7]

$$T_{cr} = (\hbar\omega_p/2\pi k_B)[(1 + 1/4Q^2)^{1/2} - 1/2Q]. \qquad (3)$$

For the parameters in this experiment T_{cr} = 42 mK. For $T > T_{cr}$ the curve in Fig. 2 includes quantum corrections to thermal activation [7], while for $T < T_{cr}$ the temperature dependence of the quantum tunneling rate is included [8].

The agreement between the experimental values and the theoretical predictions is very good, within one standard deviation over the entire temperature range. At the lowest temperature of the experiment, where Q = 1.77 ± 0.07, the measured value of T_{esc} is 47 ± 2 mK, compared with the predicted value of 45 ± 2 mK. Under the same conditions but with no dissipation the predicted value of T_{esc} is 69 ± 3 mK. Between T_{cr} and approximately $3T_{cr}$ the measured values of T_{esc} lie significantly above the classical prediction T_{esc} = 0.98 T, in good agreement with the predictions of Grabert and Weiss [7]. We emphasize that there are no fitted parameters in the comparison of theory and experiment.

To demonstrate that the flattening of T_{esc} at low temperatures was not due to external noise sources, a magnetic field was applied to reduce the critical current of the junction, thereby reducing the plasma frequency ω_p and lowering T_{cr} to 14 mK. We found that T_{esc} followed the classical theory down to about 30 mK, flattening slightly as T approached T_{cr}. This measurement demonstrates that spurious noise sources made negligible contributions to the data in Fig. 2.

In summary, we have shown: (i) that measurements of the macroscopic quantum tunneling rate in the presence of moderate damping (Q ~ 1) are in excellent agreement with theory, and (ii) that the escape rate above the crossover temperature is in excellent agreement with the predicted quantum corrections.

We thank F. Wellstood, K. Daly, R. E. Packard, S. Lacy, N. E. Phillips and the staff of the Microfabrication Laboratory at U.C. Berkeley for valuable conversations and/or experimental assistance. A.C. acknowledges a Berkeley Fellowship from U.C. Berkeley. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03- 76SF00098.

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