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IN A JOSEPHSON TUNNEL JUNCTION*

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Effect of the Subgap Conductance on the Metastable States in a Josephson Tunnel Junction

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An investigation of the decay rate of metastable states in Josephson tunnel junctions in presence of thermal noise is presented. We have observed that, in the extremely underdamped regime, there is an exponential temperature dependence of the best fit value for the shunt conductance. Such a dependence shows a close relation with the temperature dependence of the subgap conductance, suggesting that the effective conductance for the escape from the metastable states obeys to a quasi-particle thermal activation mechanism. The introduction of this effective conductance into the lifetime expression for the zero-voltage states leads to significant changes in the width of the switching current distributions. A comparison of the experimental data with the proposed model is reported.

1. THEORETICAL MODEL

The problem of the noise-induced transitions from the zero voltage state of a Josephson junction has received recently a great attention in literature, both for its interest in setting the limit performances of practical devices (e.g. logic devices, nuclear particles detectors, etc.) and for the basic physics involved (e.g. M.Q.T.).

In the present work we investigate the effect of the tunneling conductance on the thermal intrinsic noise in extremely underdamped Josephson junctions.

As first pointed out by Kramers [1], in the extremely underdamped case the lifetime τ of the zero-voltage ($V=0$) state depends on an "effective junctions resistance" R :

$$\tau = RCT/E_b \exp(E_b/KT) \quad (1)$$

In the expression (1) C is the junction capacitance, T is the temperature; E_b is the energy barrier height defined by:

$$E_b = \hbar I_c / 2e [2x \cos^{-1}(x) + (1-x^2)^{1/2}] \quad (2)$$

where I_c and I are the critical current and the bias current respectively and $x=I/I_c$. Several authors [2] attempted to find an expression for τ which can provide a bridge between the expression (1) and the lifetime obtained by the transition-state theory valid in the Kramers "moderate" damping regime:

$$\tau = 2\pi/\omega_J \exp(E_b/KT) \quad (3)$$

where ω_J is the bias dependent plasma frequency.

All these theories based on the R.S.J. model, assume a constant resistance value, whereas unshunted tunnel junctions exhibit highly non-linear I-V curves. This circumstance leads to the problem of finding the "effective" resistance to be used in the model for the decay of the $V=0$ state. An answer to this problem would be of great utility in interpreting experiments on M.Q.T. [3, 4].

Recent experimental results [5] on very underdamped junctions show that the R value obtained

by best fitting the probability switching distributions has an exponential temperature dependence, typical of a quasi-particles excitation over an energy gap Δ :

$$R(T) = \exp(\Delta/KT) \quad (4)$$

We have performed a series of detailed measurements of the lifetime of the $V=0$ state at various temperatures on an hysteretic tunnel junction and compared the effective resistance value with the subgap resistance at different low-voltages, verifying the reported exponential temperature dependence. An interesting consequence of the introduction of an effective resistance into the lifetime expression (1) is a modification of the temperature dependence of the width of the switching current distributions from the $T^{2/3}$ law reported in literature [4, 6].

2. EXPERIMENTAL RESULTS

We have measured the switching current distribution of Nb-Nb₂O₅-Pb tunnel junctions at several temperatures.

The junctions exhibited a low subgap leakage current and a good diffraction pattern. In order to investigate the extremely underdamped regime, the measurements were made on a sample with a low critical current density ($J_c \approx 3 \text{ A/cm}^2$ at $T=4.2\text{K}$) and an area of $100 \times 50 \mu\text{m}^2$. The junction capacitance has a value of $C \approx 500 \approx 100 \text{ pF}$ estimated from the Fiske steps voltage. The normal resistance was $R_N \approx 8\Omega$.

The experimental apparatus used is similar to the one described in ref. 5. We just remark here that special care was taken in shielding the junction from the external noise and in controlling the temperature stability. Distributions of nearly 20000 switching events were recorded in about 6 min, with a current resolution of $20 \approx 40 \text{ nA}$ /channel. As a result characteristic asymmetric distributions were obtained with almost exponential tails on the low current side and a more abrupt cutoff on the high current side.

An analysis based on χ^2 -tests similar to that used in ref. 3, shows that no external noise affects our data.

In fig. 1, the widths $\sigma = (\langle I^2 \rangle - \langle I \rangle^2)^{1/2}$ of the distributions vs $T^{2/3}$ are reported. The solid line is the curve obtained by the usual transition state theory [1,2]. As it can be seen, below a certain temperature the experimental data deviates from the $T^{2/3}$ behavior. The dashed curve is obtained from the expression for σ of ref. 7, valid for the extreme underdamped regime, assuming a temperature dependence of the resistance R as in expression (4).

Fig. 1. Temperature dependence of the switching distribution widths obtained from Kramers "moderate damping regime" (solid line), from ref. [7] for the very low damping regime (dashed line) taking into account the R vs T dependence, and from experimental data (dots).

In fig. 2 the effective resistance R obtained from a best fit of the experimental switching distributions, using the extremely underdamped lifetime expression [7], is reported vs T^{-1} . A comparison with the full line, obtained from eq. (4) with $\Delta = 1.54$ meV, shows that the "effective" resistance has the typical temperature dependence of the thermally activated quasi-particles. Such behavior is also confirmed by a comparison with the temperature dependence of the junction dynamical resistance, shown in the figure as open dots, although the "effective" resistance does not match any value of the low voltage dynamical resistance down to 5 μ V. The deviation from the full line of the fitted R values at high T , reported as asterisk, is due to a change in the damping regime toward the region of validity of eq. (3). Moreover it has to be noticed that a saturation occurs in the dynamical resistance values at low T , due to non-thermally activated tunnelling mechanisms.

Fig. 2. Experimental and fitted values for R vs T^{-1} . Full dots represent the "effective" resistances obtained from a fitting of the switching distributions; open dots represent the dynamical resistances from the I-V curve at 300 μ V (upper) and 30 μ V (lower).

In conclusion, the observed exponential dependence of the effective resistance is responsible of a change in the damping regime and, as a consequence, of an apparent saturation in the switching distribution widths. However, such a saturation occurs at rather high temperatures and has not to be confused with M.Q.T. effects.

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