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Low voltage excess noise and shot noise in YBCO bicrystal junctions

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Abstract

The spectral density of background noise emitted by symmetric bicrystal YBaCuO Josephson junctions on sapphire substrates have been measured by a low noise cooled HEMT amplifier for bias voltages up to $V \approx 50$ mV. At relatively low voltages $V < 4$ mV a noticeable noise rise has been registered. At large bias voltages $V > 30$ mV a clear dependence of noise power, exactly coinciding to the asymptote of the Schottky shot noise function, has been observed for the first time. Experimental results are discussed in terms of multiple Andreev reflections which may take place in d-wave superconducting junctions with low transparency $D \ll 1$. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Experimental studies of ac Josephson effect in high-T_C (HTS) YBaCuO Josephson junctions (JJs) give evidence of self-oscillation line width broadening [1] and excess noise, revealed also from mixer noise performance [2]. Assuming a component with d-wave order parameter symmetry for the HTS electrodes [3] quasiparticle midgap bound states (BS) may be present [4,5] at the junction interface. Existence of BS is known long ago for diffusive SNS or ballistic point contacts made from isotropic s-superconductors, resulting in multiple Andreev reflections—the process, giving rise to low voltage excess noise [6–8]. The contribution of the BS into the current transport of d-wave superconducting JJs has been studied extensively (see, e.g. Refs. [5,9]). However, up to now excess noise in HTS JJs has not been studied well enough. To our knowledge the first theoretical results on noise in d-wave junctions recently appeared in Ref. [9]. Here we report on experimental data on low frequency (not $1/f$) noise in YBaCuO bicrystal JJs.

2. Experimental

Experimental samples [10] were bicrystal $d \cong 200$ nm thick YBaCuO thin film JJs fabricated on

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symmetric sapphire substrates which had widths of $w = 4$–5 μm and RSJ-like I–V characteristics with normal state resistance $R_N = 20$–30 Ω and a product of $I_C R_N = 1$–2 mV at $T = 4.2$ K. As a test for junction quality the Josephson oscillation line widths Δf were measured (and roughly compared to prediction of RSJ model as $\Delta f_{RSJ} \approx R_N T/25$ GHz) by examining the shape of selective detector response functions at submm wave frequencies $f = 450$–900 GHz, using backward wave oscillators as the tunable monochromatic signal sources. The detector response functions were obtained by help of low noise selective lock-in technique. Fig. 1 shows a typical I–V characteristics and frequency selective detector response function, measured at frequency $f = 900$ GHz. Symmetric odd-resonant shape of detector response at $V \cong 1.8$ mV ensured Josephson effect for examined junction. Noise power of the same samples was measured by low noise cooled HEMT balanced amplifier with the noise temperature $T_A = 8 \pm 2$ K at $T = 4.2$ K, operating at much low (comparing to a gap Δ/h) frequencies $f = 1$–2 GHz. Note that achieved impedance match between the experimental sample and the HEMT amplifier allowed us to obtain exact data on noise power $P_N = kT_J \Delta F$ (k: Boltzmann's constant, T_J: equivalent to power noise temperature of JJ, ΔF: operating frequency band of HEMT amplifier) for wide range of bias voltages, where the differential resistance $R_D(V)$ did not change noticeably. The $P_N(V)$ dependence was registered simultaneously with recording the I–V characteristics. The output from quadratic detector, connected after the second stage of the "room-temperature" amplifier was plotted as a function of bias voltage. Measurements of noise were carried out in microwave screened room at $T = 4.2$ K.

3. Results and discussion

Fig. 2 demonstrates the wide voltage range of I–V characteristics for the same JJ (see also Fig. 1) with the corresponding $P_N(V)$ dependence, given in units of noise temperature T_J. At voltages $V > 30$ mV (close to Δ/e) the magnitude of $P_N \propto kT_J$ shows a Schottky shot noise dependence $T_{SH}(V) = (e/2k)I(V)R_D$ as for SIS tunnel junctions [11]. This allows us to calculate the noise power or T_J with high accuracy ($\delta T = \pm 5$ K) for P_N values at $V > 30$ mV. Two peaks on Fig. 2 which are seen around the $V = 0$ are caused by Josephson self-oscillations at frequency band of HEMT amplifier. Fig. 3 demonstrates the normalized voltage dependence of $T_J(V)/(T_A + T_{SH})$. The triangle on this figure indicates the ratio $\Delta f/\Delta f_{RSJ} \cong 2.5$, as extracted from the selective detector responses function shown in Fig. 1. An estimation of excess low voltage noise (over the thermal noise) $T_{EX} = T(\Delta f - \Delta f_{RSJ})/\Delta f_{RSJ}$ for $T = 12.5$ K and the Δf, measured

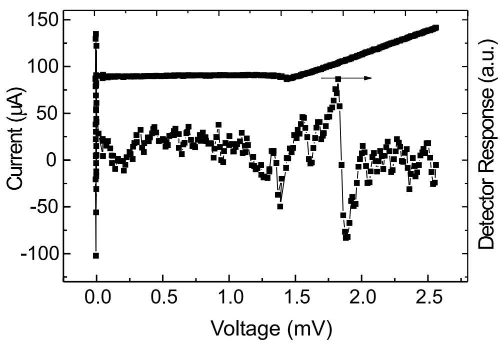

Fig. 1. I–V characteristics and detector response $\eta(V)$ for a bicrystal $d = 0.1$ μm thick and $w = 4$ μm wide thin film YBaCuO JJ on sapphire substrate. Frequency of applied weak signal is $f = 900$ GHz, $T = 12.5$ K.

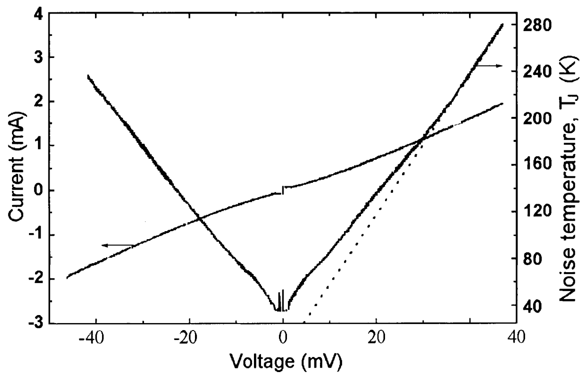

Fig. 2. I–V characteristics of bicrystal JJ with $I_C = 90$ μA, $R_N = 23$ Ω at $T = 4.2$ K. Noise power given as an effective noise temperature was measured by a cooled HEMT amplifier in frequency band 1–2 GHz. Dashed line represents the Schottky noise slope: $T_{SH}(V) = (e/2k)I(V)R_D$.

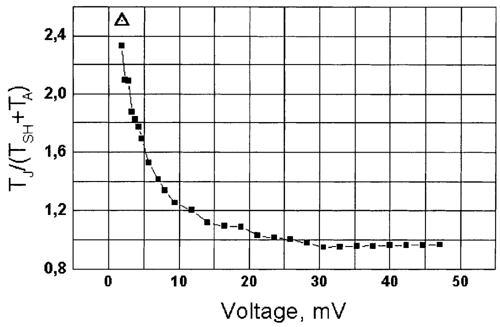

Fig. 3. Voltage dependence of the normalized noise temperature T_J of YBaCuO JJ on a bicrystal sapphire substrate. T_A: noise temperature of HEMT amplifier, $T_{SH}(V) = (e/2k)I(V)R_D$. Triangle shows the ratio $\Delta f/\Delta f_{RSJ}$ of the Josephson oscillation line widths, Δf: experimental (extracted from selective detector response at 900 GHz), Δf_{RSJ}: prediction of RSJ model.

at $V = 1.8$ mV, gives $T_{EX} \approx 19$ K, whereas the dependence of $T_J(V)/(T_A + T_{SH})$ yields $T_{EX} = T_J - (T_{SH} + T_A + T) \approx 22$ K. At low voltages a relatively large differential resistance $R_D > 100\ \Omega$ (again, changing as function of V) resulted in a impedance mismatch leading to a significant increase in uncertainty, δT. That is why the noise dependence of the noise temperature, $T_J(V)$, was separately investigated for relatively low voltages $V < 20$ mV. Fig. 4 shows the voltage dependence of noise temperature $T_J(V)$ and the differential resistance $R_D(V)$ which were measured for a similar JJ with smaller $R_N \approx 18\ \Omega$ at relatively low voltages. Calculations, based on the results shown in Fig. 4 are presented in Fig. 5a which demonstrates the transferred charge dependence $q(V) = S_I(V)/2I$, calculated from spectral density of current noise $S_I(V) \propto T_J(V)/R_D(V)$ shown in Fig. 5b.

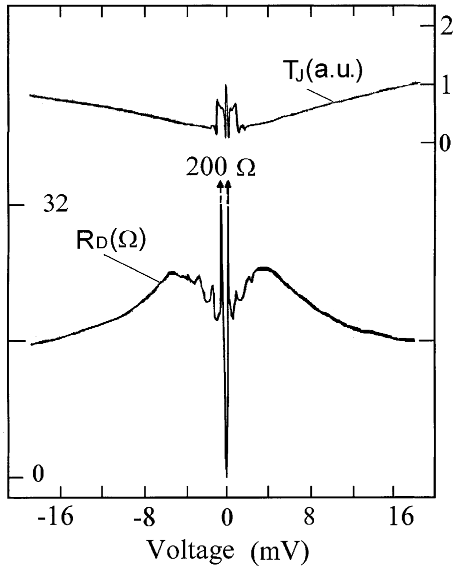

Fig. 4. Voltage dependence of the noise temperature T_J of JJ, measured in bandwidth of 1–2 GHz, and the differential resistance R_D of a YBaCuO bicrystal JJ with $R_N = 18\ \Omega$, $T = 4.2$ K.

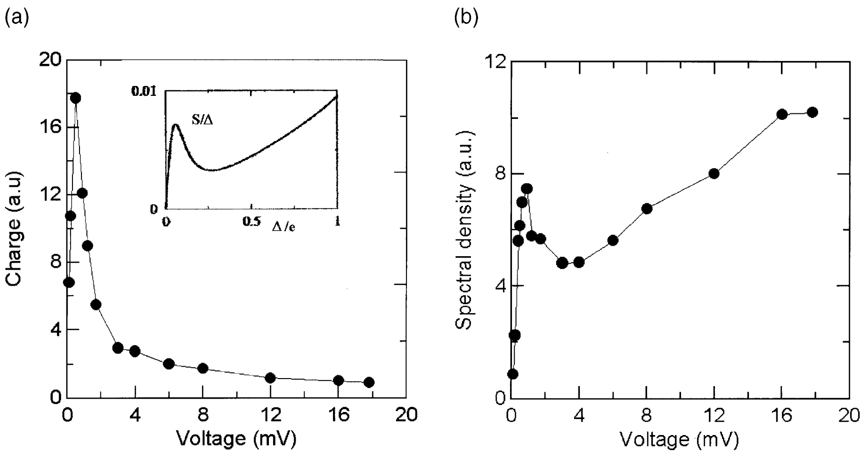

Fig. 5. (a) Effective transferred charge $q(V) = S_I(V)/2I$, calculated from the spectral density of noise current $S_I(V) \propto T_J(V)/R_D(V)$. Inset: theory for spectral density S/Δ [9] of low frequency $f \ll \Delta/h$ (not $1/f$) noise at $T = 0$ for symmetric d/d junction with transparency $D = 0.01$; (b) experimental $S_I(V)$ function.

For bicrystal JJ the rise in the $q(V)$ function is very pronounced: the level of $q(V)/q(0) > 16$ indicates that Andreev reflection process is involved. This may give rise to noise emission, as it was reported for diffusive SNS junctions [12]. In contacts with $D \approx 1$ the density of current noise $S_I(V)$ saturates at high voltages $V \approx \Delta/e$, reaching a plateau. Our estimations for $D \sim (SR_N)^{-1/2}$, $S = wd$ gave $D < 0.01$ far from the $D = 1$ value of ballistic constrictions or diffusion SNS junctions [7,8,12]. Only recently linear rise of the shot noise and the low voltage excess noise peak was theoretically predicted [9] (see inset to Fig. 5a) for d-wave junctions with transparency $D = 0.01$. Comparing the shape of experimental noise functions with the predicted one allows to suggest a d-wave origin of observed noise rise in symmetric bicrystal JJs, where BS and multiple Andreev reflection take place.

4. Conclusion

HTS YBaCuO symmetric bicrystal JJs demonstrate linear noise rise at $V \approx \Delta/e$ inherent to tunnel-like junctions with low transparency $D \ll 1$ and at the same time exhibit low voltage noise rise as contacts with direct conductivity, $D \approx 1$. Experimentally observed peak of transferred charge points at the process of multiple Andreev reflection, resulting in low voltage noise rise. The both experimentally observed features fit (at least qualitatively) to the theoretical dependence for low frequency shot noise in d-wave junctions with midgap BS [9] for the case $D = 0.01$, $T = 0$. Surprisingly the linear rise of noise power of the discussed JJs fits very well to Schottky shot noise function at voltages $V > 0.5\Delta/e$—a behaviour known for tunnel SIS junctions at $V > 2\Delta/e$. Moreover, the estimation of excess noise temperature basing on noise power calibration using Schottky fit gives a value of the excess noise T_{EX} close to that one, defined from the line width of Josephson oscillation, measured at 900 GHz frequency.

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