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Experimental study of noise and Josephson oscillation linewidths in bicrystal YBCO junctions

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Abstract
The intensities of the noise in a bicrystal high-T_C (HTS) Josephson junction have been precision-measured at 1–2 GHz frequency band at bias voltages up to 50 mV at $T = 4.2$ K. At large bias voltages, $V > 30$ mV, the dependence of current noise density was found exactly coinciding with the Schottky shot noise asymptote $2eI$. At relatively low voltages, $V < 4$ mV, a noticeable noise rise has been registered. The broadening of Josephson oscillation linewidths Δf_J over the values Δf_{RSJ} predicted by the RSJ model has been experimentally studied at different frequencies in the mm and submm wave range up to voltages $V = 2$ mV in connection with low-voltage noise rise. Both the features observed, the linewidth broadening and the excess noise over the noise level of thermal fluctuations, are discussed in terms of multiple Andreev reflection, giving rise to a nonequilibrium shot noise—the case which may take place in the d-wave superconducting junctions. Experimental results on noise performance are also compared with the qualitatively similar dependences of the current noise, known for the s-superconducting ballistic point-like or diffusive-type SNS junctions, where the excess low-voltage noise is manifested due to multiple Andreev reflections. Increasing the operating temperature, the thermal (equilibrium) fluctuations were found to predominate, resulting in a decrease of ratio $\Delta f_J/\Delta f_{RSJ}$. The characteristics of the ac Josephson effect in HTS junctions measured at submm wave frequencies at temperatures close to the transition temperature T_C are also discussed.

1. Introduction

Experimental studies of the ac Josephson effect in high-T_C (HTS) YBaCuO Josephson junctions (JJ) give evidence of self-oscillation linewidth broadening [1–3] and excess noise, evident also from the noise performance of the HTS mixers [4]. Assuming a component with a d-wave order parameter symmetry for HTS electrodes [5], several kinds (low-energy $\varepsilon_B \ll \Delta$ and non-zero $\varepsilon_B < \Delta$ midgap) of bound states may occur [6], leading to a behaviour rather more complicated than that known for diffusive SNS or ballistic point contacts made from isotropic s-superconductors, where the Josephson effect is manifested over quasiparticle bound states. The Andreev reflections in such junctions give rise to a shot noise [7]—a

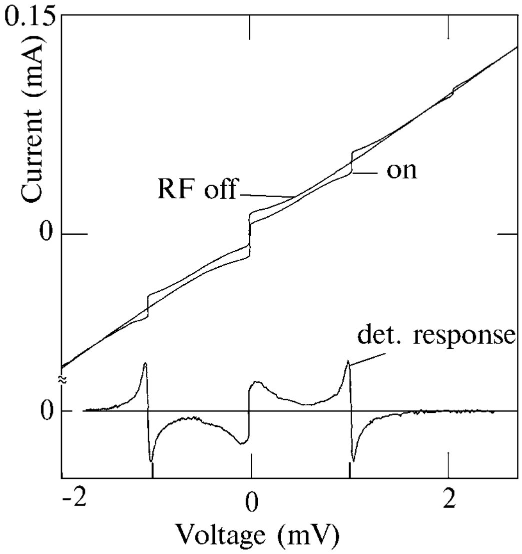


Figure 1. The IVCs of a YBCO bicrystal Josephson junction with (RF on) and without (off) applied signal at frequency $f = 500\,\mathrm{GHz}$ and the detector response function with intensity given in arbitrary units, $T = 18$ K.

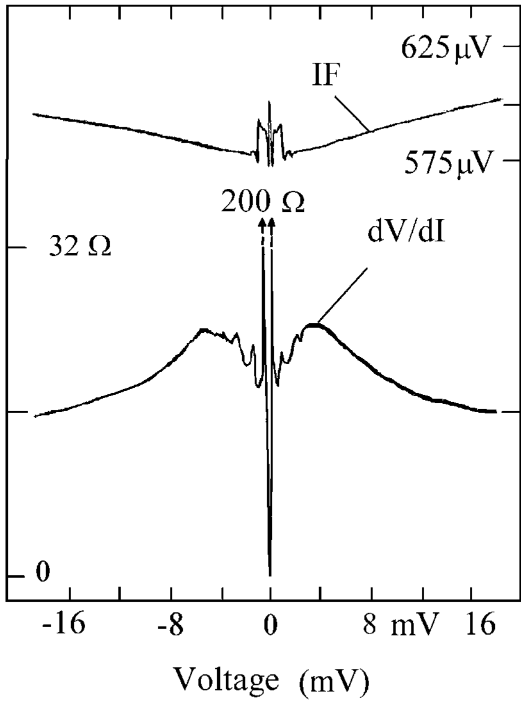


Figure 2. Voltage dependence of noise power $S_P(V)$ at $F = 1$–2 GHz and the differential resistance $R_D(V)$ of a YBCO bicrystal Josephson junction, $T = 4.2$ K.

process likely to also take place in HTS JJs. However, the problem of excess noise in HTS JJs has not been studied yet. Since the first theoretical results for d-wave junctions have recently has appeared in [8], our experimental studies are aimed both at the low frequency ($f \ll \Delta/h$) noise performance (not $1/f$ noise) at low temperature $T = 4.2$ K, and at the problem of Josephson oscillation linewidths Δf_J broadening in HTS JJs.

2. Experimental details

Experimental samples [9] were bicrystal $d \cong 200$ nm thick YBaCuO thin film JJs with patterned log-periodic antenna in the electrodes, fabricated on symmetric sapphire substrates with 24° misorientation angle. The JJs had $w = 4$–5 μm widths and a resistively-shunted junction (RSJ) like I–V characteristic (IVC) with the normal state resistance $R_N = 20$–30 Ω and a product of the $I_C R_N = 1-2\,\mathrm{mV}$ at $T = 4.2\,\mathrm{K}$. An experimental study of the Josephson oscillation linewidths was carried out by examining the selective detector response functions at the mm and submm wave frequencies $f = 50-900\,\mathrm{GHz}$, using backward wave oscillators as tunable monochromatic signal sources. For mm waves a rectangular waveguide sample holder was used, while for submm waves the measurements were carried out either in a close circle cryocooler with operating temperatures $T = 18$–21 K, or in a quasioptic cryostat with precision temperature control. Detector response functions were obtained by means of a modulator–demodulator technique with the help of a low-noise selective lock-in amplifier. The power of noise emitted by the same samples was examined. Noise power $P_N(V) = S_P(V)\Delta F$ was studied by a low-noise ($T_N = 8$ K at ambient temperature $T = 4.2$ K) cooled HEMT balanced amplifier at relatively low (comparing with Δ/h) frequencies at $F = 1$–2 GHz, where $S_P(V)$ is the spectral density of the noise power, measured within the frequency band $\Delta F = 1.5$ GHz. The noise $S_P(V)$ dependences were registered simultaneously with the IVCs, from the output of the quadratic detector, connected after the second stage 'room-temperature' amplifier. All measurements of the noise functions were carried out in a microwave screened room at $T = 4.2$ K.

3. Results and discussion

Figure 1 demonstrates typical IVCs and a detector response function, measured at $T = 18$ K and applied frequency $f = 500$ GHz. Under strong signal power clear Shapiro steps are seen at the bias voltages, corresponding to the voltage/frequency Josephson relation. Under a weak signal (with a current amplitude $I_S \ll I_C$) symmetric odd-resonant shape selective detector response functions were registered for both positive and negative biasing. A broadband detector response around $V = 0$ is also seen. Although the oscillating functions of the critical current $I_C(I_S)$ and the first Shapiro step $I_1(I_S)$ were in good agreement with the RSJ model [10], the Josephson oscillation linewidth was 3.5 times larger than that predicted by the RSJ model. Note again that the RSJ model takes into account thermal fluctuations only. This means that a source in addition to thermal noise fluctuations does exist. Figure 2 demonstrates the dependence of the noise power, emitted by the same JJ, and its differential resistance R_D as functions of the bias voltage at $T = 4.2$ K—the temperature where the low-voltage noise rise was rather pronounced. However, similar dependences measured in the wide frequency range 50–900 GHz demonstrate the increase in the broadening of the Josephson oscillation linewidths with decreasing operating frequency. Figure 3(*a*) demonstrates the spectral density of the current noise $S_I(V)$ calculated

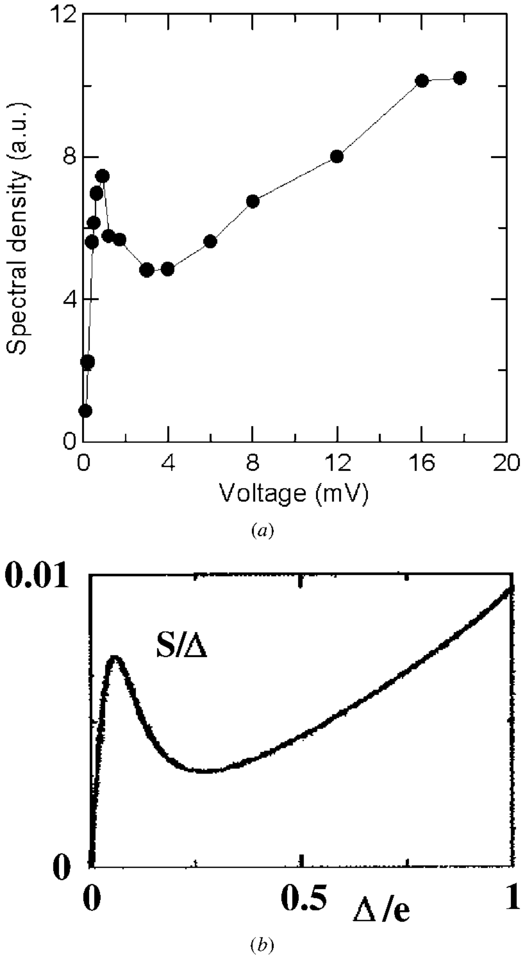


Figure 3. Spectral density of current noise $S_I(V)$ of a HTS JJ at $T = 4.2$ K. Input data are as in figure 2(*b*). The theory [8] for spectral density S/Δ at low frequency $f \ll \Delta/h$ (not $1/f$) noise for a symmetric d/d junction with $D = 0.01$ transparency at $T = 0$.

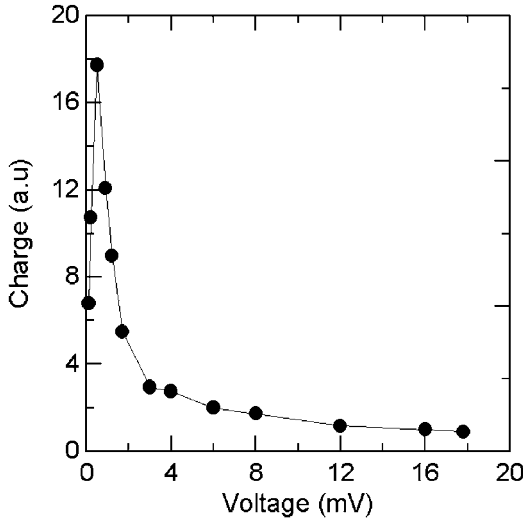


Figure 4. Effective transferred charge $q(V) = S_I(V)/2I$, calculated from the spectral density of current noise $S_I(V) = S_P(V)/R_D(V)$.

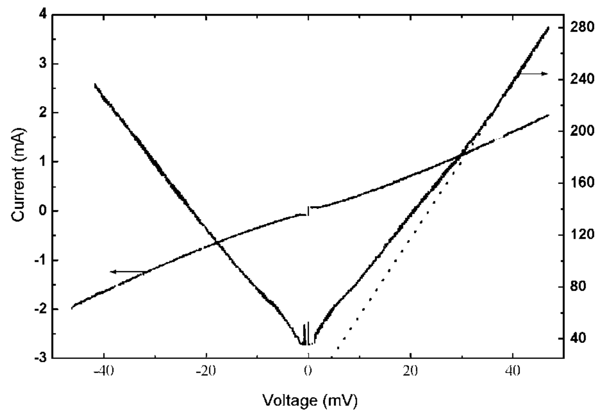
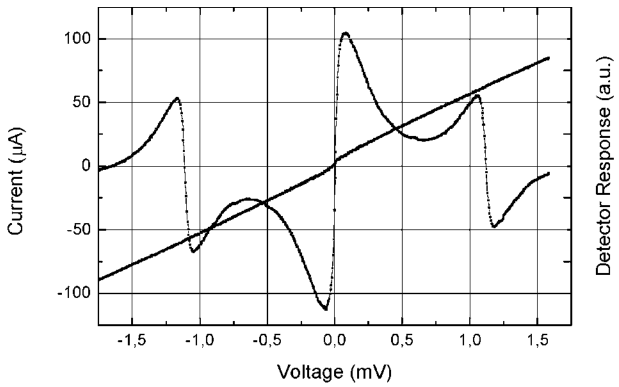


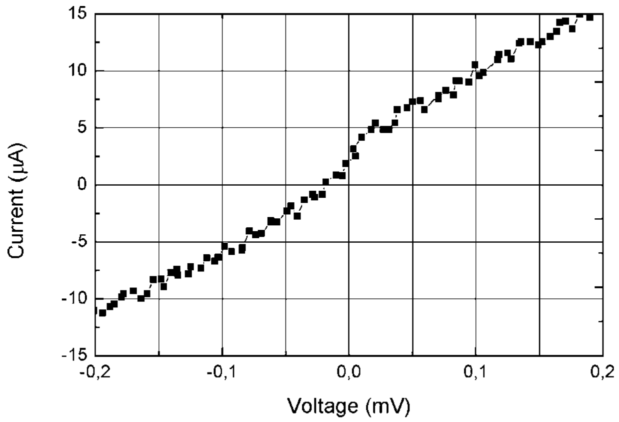
Figure 5. *I–V* characteristics of a bicrystal Josephson junction with $I_C = 90$ μA, $R_N = 23$ Ω at $T = 4.2$ K. Noise power, given in units of noise temperature, was measured with a cooled HEMT amplifier at frequency band $F = 1$–2 GHz. The dashed line represents the Schottky noise slope: $T_{SH}(V) = (e/2k)I(V)R_D$.

from the data for $S_P(V)$ and $R_D(V)$, shown in figure 2. A noise rise linear with the applied voltage is seen for the $S_P(V)$ and $S_I(V)$ functions. The theory [8] for the spectral density S/Δ at $T = 0$ at low frequency $f \ll \Delta/h$ (not $1/f$) noise for a symmetric d/d junction with low transparency $D = 0.01$, inherent to tunnel-type junctions, is given in figure 3(*b*). At low voltages $V < 2$ mV a relatively large differential resistance R_D (also varying with changing V) resulted in an impedance mismatch. That is why the noise dependence for relatively low voltages $V < 20$ mV demonstrates noise performance qualitatively. However, the shapes of the experimental curve and the theoretical one in figure 3 are similar. Figure 4 demonstrates a transferred charge dependence $q(V) = S_I(V)/2I$. A behaviour similar to this: the low voltage $V \ll \Delta/e$ $S_I(V)$ noise rise is known for diffusive SNS [11] and the ballistic point-like contacts [12] with transparent boundaries $D \approx 1$, where multiple Andreev reflections take place. In the contacts with a barrier transparency $D \approx 1$ the spectral density of the current noise $S_I(V)$ saturates at high voltages $V \approx \Delta/e$, reaching a plateau. It is seen that the experimental low voltage peak on the $q(V)$ is pronounced and exceeds the level of $q(V = 16\,\text{mV})$ by factor of 15. Note that our junctions have no normal metal interlayer and Andreev reflections and midgap energy states [6] are caused by the existence of d-wave symmetry for superconducting electrodes of HTS JJs, at least in bulk.

Figure 5 shows the IVC and the RF noise temperature $T_{SH}(V) = S_P(V)/k$, (k denotes the Boltzmann constant) measured at YBCO JJ with high accuracy. At $V > 30$ mV (near to an estimated value of Δ/e) the amplitudes of $S_P(V)$ coincide with the shot noise dependence $S_P(V) = (e/2k)I(V)R_D\Delta F$, as taken for an SIS tunnel junction [13]. This allows us to calculate the noise power with accuracy ($\delta T = \pm 5$ K) in units of the noise temperature. The two peaks seen around $V = 0$ are caused by Josephson oscillations at a frequency of HEMT amplifier operation. Surprisingly, a linear rise in noise power of the discussed JJs fits very well with the Schottky shot noise function at the 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 T_{EX}, based on noise power calibration using Schottky fit, gives a value of the excess noise $T_{EX} = T(\Delta f_J - \Delta f_{RSJ})/\Delta f_{RSJ}$ close to that defined from the linewidth of Josephson oscillation,



(*a*)



(*b*)

Figure 6. (*a*) IVC and detector response at $f = 500\,\text{GHz}$, $T(V = 0) = 60.5\,\text{K}$, $T(V = -1\,\text{mV}) = 60.5\,\text{K}$, $T(V = +1\,\text{mV}) = 60.6\,\text{K}$. (*b*) A part of the IVC around $V = 0$.

measured at 900 GHz frequency at $T = 12.5$ K. Note that at 900 GHz, the measured Josephson oscillation linewidth Δf_J was only 2.4 times larger than that predicted by the RSJ model.

On increasing the temperature, a thermally activated phase slippage took place, washing out the curvature of IVC. Figure 6 demonstrates the IVC and detector response at $f = 500$ GHz for $T = 60.5$ K; an enlargement of part of IVC around $V = 0$ is given in figure 6(*b*). At the same time the detector response function remains a clear one. Varying the power of the applied signal, we observed a deviation from the quadratic detection regime for $I_S > I_C$. Note that for the temperature range $T = 65$–80 K we did not obtain the correct data for I_C amplitudes, but only estimations using theory [14]. At the same time the change in oscillation linewidth was much weaker. We have observed a linewidth reduction at $T = 60.5$ K in the case when $I_S > 5I_C$. Fixing the applied power at the highest level, the self-oscillation suffers synchronization under external force, leading to approximately 1.5 times reduction in Δf_J value. Figure 7 demonstrates temperature dependence of experimental linewidths at 500 GHz, measured under strong applied power and the corresponding theoretical dependence, calculated in accordance with the RSJ model. It is seen that function $\Delta f_J(T)$ deviates from RSJ predictions, although the ratio of I_S/I_C increases, assuming I_S as a fixed value and decreasing (approximately linear with temperature) I_C amplitudes. On the other hand, the losses in superconducting antenna may rise considerably when

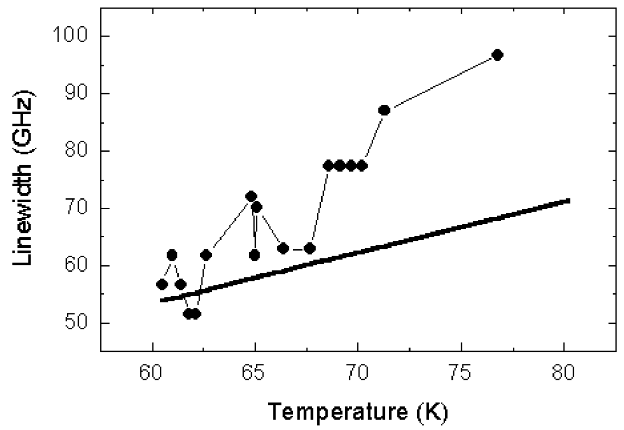


Figure 7. The temperature dependence of Josephson oscillation linewidths extracted from left-hand (●) selective detector response at $f = 500$ GHz; straight line: prediction of RSJ model.

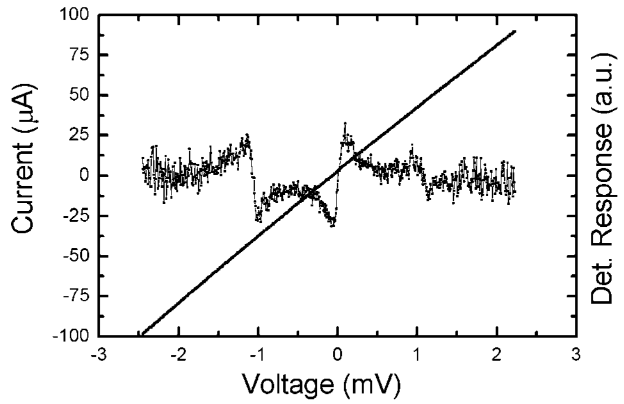


Figure 8. *I–V* characteristics and detector response at $f = 500$ GHz from a bicrystal Josephson junction, plotted in the regime of slow temperature rise. $T(V = -1\,\text{mV}) = 76.8\,\text{K}$, $T(V = 0) = 77.7\,\text{K}$, $T(V = +1\,\text{mV}) = 78.9\,\text{K}$. Plotting time = 30 min.

the temperature approaches T_C, significantly suppressing the applied signal power. However, uncertainty in linewidths does not exceed a factor of 1.5 and, thus, the main low-voltage noise power at large temperatures $T > 0.8T_C$ is believed to be due to thermal fluctuations. It should also be noted that at high temperatures we observed a rise in R_N values from $R_N(T < 60\,\text{K}) = 22\,\Omega$ to $R_N(80\,\text{K}) = 35\,\Omega$—a behaviour which could also be caused by d-wave symmetry of junction electrodes. Figure 8 presents the IVC and the detector response at $f = 500\,\text{GHz}$ from a bicrystal Josephson junction, plotted in a regime of slow temperature rise, demonstrating the evolution of the detector response function with increasing temperature. The highest temperature where we have registered a detector response at frequency $f = 500\,\text{GHz}$ for the discussed sample (not the best one with $I_C R_N = 1.2\,\text{mV}$ at $T = 4.2\,\text{K}$) was $T = 80\,\text{K}$. Note that the bias voltage for this case was roughly 40 times larger than the estimated value of $I_C R_N$ at $T = 80\,\text{K}$—a feature absolutely impossible for low-T_C Josephson junctions.

4. Conclusion

Experimental HTS 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 at low temperature $T = 4.2$ K exhibit low-voltage noise rise as contacts with a direct conductivity $D \approx 1$. Both the experimentally observed features fit (at least qualitatively) the theoretical dependence for low frequency shot noise in d-wave junctions with midgap bound states [8] for the case $D = 0.01$, $T = 0$. Surprisingly, the linear rise of the noise power of the discussed JJs fits very well to the Schottky shot noise function at $V > 0.5\Delta/e$ voltages—a behaviour known for tunnel SIS junctions at $V > 2\Delta/e$. Moreover, the estimation of excess noise temperature, based on noise power calibration using a Schottky fit, gives a value of the excess noise T_{EX} close to that defined from the linewidth of the Josephson oscillation, measured at 900 GHz frequency. Enhancing the ambient temperature close to T_C, the influence of midgap states on the noise performance becomes rather less pronounced than the predominating thermal fluctuations. At the same time, a clear ac Josephson effect experimentally is evident up to the critical temperature at submm wave frequency, corresponding to a voltage which was at least 40 times larger than the voltage of the $I_C R_N$ product.

Acknowledgments

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