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LINEWIDTH OF JOSEPHSON OSCILLATIONS IN $YBa_2Cu_3O_{7-x}$ GRAIN-BOUNDARY JUNCTIONS

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Abstract - - We have studied the ac Josephson effect in $YBa_2Cu_3O_{7-x}$ grain-boundary junctions (GBJ) in the temperature range from 4 K to 90 K. The temperature dependence of the linewidth of millimeter-wave Josephson oscillations was measured and it is shown that the derived effective noise temperatures of GBJ might be as low as the physical temperature in the temperature range investigated. In the millimeter-wave range linewidths as low as 380 MHz were found at liquid nitrogen temperatures.

INTRODUCTION

During the last few years many different types of high-T_c superconducting weak links have been studied and some of them have shown Josephson behaviour (see Ref. 1 and references therein). One of the most promising types is the grain-boundary junction (GBJ) fabricated by epitaxial growth of a $YBa_2Cu_3O_{7-x}$ thin film on a bicrystal substrate[1]. Such a GBJ is stable against thermal cycling and its parameters can be rather reproducibly controlled by changing the misorientation angle of the bicrystal substrate[1]. The latter is of importance not only for optimizing the GBJ for particular applications, but it also enables a basic study of the physical properties of GBJ. So far this study, as motivated by the very promising applications of GBJ in dc SQUIDs, was mainly confined to dc Josephson effect and 1/f noise[1]. For high frequency applications detailed investigations of the ac Josephson effect and wideband fluctuations in GBJ are required. This can be carried out by studying the linewidth of the Josephson radiation as it was done with weak links made of low-T_c superconductors.

THEORY

In order to estimate the power and the spectral width of the Josephson radiation in a high-T_c GBJ we use the RSJ model which, as justified below by our measurements, will be considered applicable to this type of Josephson junctions. The main parameters are: the critical current, I_c, and the normal-state resistance, R_n.

Maximum rf-power is transferred from the Josephson junction to the external measuring circuit with complex impedance $Z_e(f)$ when the optimum coupling condition $\mathrm{Re}[Z_e] = R_n$ is fulfilled. In this case, due to the non-linearity of the GBJ both its dc and ac characteristics will be strongly influenced by the loading circuit[3]. The intrinsic Josephson behaviour of such junctions can therefore only be studied with external circuits having comparably large impedances ($|Z_e(f)| \gg R_n$) so that they do not shunt the junction in the frequency range of the Josephson radiation. Of course, this requirement results in decreasing the power emitted by the Josephson junction to the external analyzing circuit.

When the Josephson junction is biased at an operating current, $I > I_c$, the voltage, $V(t)$, across the junction oscillates and the spectrum of Josephson oscillations consists of δ-function lines at frequencies $f_k = k(2e/h)V$, where $V = R_n(I^2 - I_c^2)^{1/2}$ is the average voltage across the junction and $k = 1,2,\ldots$ The total power, P_1, of the Josephson radiation supplied by the junction to the external circuit with active impedance $R_e \gg R_n$ at the fundamental frequency $f_1 = (2e/h)V$ is equal to[3]

$$P_1 = \frac{2V^2[(V^2 + V_c^2)^{1/2} - V]^2}{V_c^2 R_e}, \quad (1)$$

where $V_c = I_c R_n$ is the characteristic voltage of the Josephson junction. The maximum power of Josephson radiation is reached at $V > V_c$ and is equal to

$$P = \frac{V_c^2}{R_e}. \quad (2)$$

The characteristic voltage V_c for YBCO GBJ at 77 K is of the order 0.1 mV and for conventional external circuits with $R_e \sim 100\Omega$ we get $P \approx 10^{-10}$ W.

When the voltage across the junction fluctuates, the total power P_1 will be distributed over a spectral range with some spectral density, $S_p(f)$, which may be characterized by its maximum value $S_p(f_1)$ and linewidth δf_1 so that $P_1 = S_p(f_1)\delta f$. The linewidth δf_1 can be estimated from the spectral density $S_V(f)$ of the voltage fluctuations as

$$\delta f_1 \sim (2e/h)[\int_{f_m}^{\delta f_1} S_V(f)df]^{1/2}, \quad (3)$$

where f_m is the minimum frequency at which noise is observed.

Two main sources of voltage fluctuations may be considered in GBJ, broadband thermal noise and low-frequency 1/f noise. The latter may originate from fluctuations both in the critical current and in the normal-state resistance[4]. Considering the spectral density of critical current fluctuations of the form $S_{I_c}(f) = C_{1/f} {I_c}^2/f$, where $C_{1/f}$ is a dimensionless constant used in standard 1/f noise theory (see Ref. 5 p. 483), we get the following estimate for our experimental conditions:

$$\delta f_1 \sim 4{C_{1/2}}^{1/2}(2e/h)R_D I_c, \quad (4)$$

where $R_D = dV/dI = {R_n}^2 I/V$ is the differential resistance of the junction in the bias point. In the case of broadband thermal fluctuations the linewidth will be equal to[3]

$$\delta f_1 = 4\pi\,(2e/h)^2\,kT\,\frac{{R_D}^2}{R_n}[1 + \frac{I_c^2}{2I^2}] \quad (5)$$

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It follows from the comparison of Eq. (4) and Eq. (5), that for given bias and the same frequency of radiation, the thermal noise may dominate the linewidth at higher temperatures and at high current bias $I \gg I_c$. For GBJ with different critical currents biased at the same frequency of radiation, the 1/f noise from the critical current may dominate in the linewidth for GBJ with larger I_c.

The linewidth Eq. (5) is always larger than the minimum value

$$\delta f_1 = 4\pi\,(2e/h)^2\,kT\,R_n, \tag{6}$$

which is reached at currents $I \gg I_c$ and will be used for estimates. At liquid nitrogen temperatures the Josephson linewidth is rather wide and for GBJ with $R_n = 1\Omega$ $\delta f \sim 3$ GHz. Due to this the maximum spectral density $S_p(f_1)$ of the Josephson radiation which can be delivered by a GBJ at liquid nitrogen temperatures to an external measuring circuit will be rather low $\sim 3 \cdot 10^{-20}$ W/Hz. Considering some losses in the waveguides and a signal/noise ratio of ~ 10, the sensitivity of the external circuit should be better than $\sim 10^{-21}$ W/Hz, which is difficult to achieve with a room temperature spectrum analyzer. Advanced microwave technique (low-noise cooled mixers or amplifiers) or alternatively some indirect methods are required.

Table 1: Parameters of grain-boundary junctions used in the linewidth measurements.

GBJ No	Substr.	Misorient angle	Width μm	R_n Ω	I_c(4.5K) mA	V_c(4.5K) mV
11	$SrTiO_3$	25°	5	4.6	0.4	1.8
12	$SrTiO_3$	25°	16	0.57	2.0	1.1
13	$SrTiO_3$	25°	88	0.07	7.0	0.5
21	Y-ZrO_2	45°	34	0.67	0.11	0.07
22	Y-ZrO_2	45°	93	0.22	0.35	0.08

EXPERIMENTAL TECHNIQUES

In this study of the Josephson linewidth we used the same indirect technique based on the measurements of the self-detector dc response of the Josephson junction to low-intensity monochromatic radiation, as was used in a similar study in low-T_c superconducting microcontacts. The technique is based on the analytical properties of the voltage dependence of the dc response $\Delta V(V)$, which shows an odd-symmetric resonance at the voltages $V \simeq (h/2e)f$. The difference δV between voltages V_+ and V_-, corresponding to the positions of the maximum and the minimum of the response ΔV in this region, gives us a linewidth δf according to the relation $\delta f = (2e/h)\delta V$. The form of the voltage dependence of the response $\Delta V(V)$ depends on the spectrum of the voltage fluctuations in the junction, and this fact can be used to determine the main source of fluctuations.

The grain-boundary junctions for this study were fabricated by conventional technique. Thin-film $YBa_2Cu_3O_{7-x}$ bicrystals have been prepared by depositing c-axis oriented epitaxial $YBa_2Cu_3O_{7-x}$ films on $SrTiO_3$ and Y-ZrO_2 bicrystals using laser ablation deposition. The thin-film bicrystal then was patterned in another laser ablation process into a number of bridges, each crossing a grain boundary and having different widths in the range from 5 μm to 300 μm. The parameters of the GBJ obtained by this procedure and used in the study of Josephson linewidth are shown in Table 1.

The substrate was fixed with vacuum grease across the end of a 26 – 40 GHz waveguide with the GBJ placed in centre. An interleaved 12 μm mylar foil was used to prevent galvanic contacts to the waveguide walls. The sample holder also had a loosely coupled 60 – 90 GHz waveguide connection to the sample. In the experiments millimeter-wave radiation around 35 and 70 GHz from Gunn oscillators or generated by harmonic doubling from a microwave synthesizer could be applied to the GBJ. In the same bands signals from the samples could be directed to a room-temperature mm-wave spectrum analyzer.

Full four-point electrical measurements could be made simultaneously for two GBJ. Lock-in technique was used to measure the derivative of the dc IV-characteristics and the dc response $\Delta V(V)$. In the response measurements the modulation frequency was 531 Hz, which actually determined the minimum frequency of noise observations.

The sample holder was placed inside a sealed vacuum can immersed in a glass helium dewar. The pressure inside the can could be regulated for thermal insulation. At 4.2 K helium gas at a pressure of 500 mb was used as exchange gas. The temperature of the copper sample holder was measured by two calibrated thermometers in connection with a temperature controller. A coil wound around the vacuum can could supply a magnetic field perpendicular to the substrate. The cryostat was electrically shielded and surrounded by a double μ-metal shield. All measurement were made in an rf shielded room.

RESULTS

The main theoretical results are based on the RSJ model[3] and in order to get quantitative data on the fluctuations in GBJ we first establish that the junctions investigated can be described by this model. For many of the GBJ used in this study the dc IV-characteristics differed from the hyperbolic dependence predicted by the RSJ model. For narrow and high-ohmic GBJ with $R_n > 1\ \Omega$ a pronounced hysteresis was observed in the IV-curve at low temperatures with no stable bias point at voltages from zero to several hundreds μV, while for low-ohmic GBJ there was no hysteresis in the IV-characteristics. Consequently, the hysteresis may be ascribed to shunting of the Josephson oscillations by the intrinsic stray capacitance[1], which might be rather large for GBJ on $SrTiO_3$ substrates and according to our estimate is around 1 pF for a 5 μm wide GBJ. This observation gives an upper limit for the resistance of the high-ohmic samples of around 1 Ω to be used in the estimation of the intrinsic linewidth of GBJ's on $SrTiO_3$ substrates.

In the other limit the IV-characteristics of wider GBJ with resistances $R_n < 0.1\Omega$ are also different from that of the RSJ model. In Fig. 1 the IV-curve and mm-wave response ΔV versus voltage V are shown for a GBJ with $R_n = 0.07\Omega$. The excess current is clearly seen on IV-curve at $I \gg I_c$, which is absent on the IV-curve in the RSJ model. The nature of this excess current may be considered as flux motion along the GBJ[1] with the length L larger than the Josephson penetration length λ_J. This deviation from the RSJ model does not prevent us from measuring the response curve as in the hysteretic case. The corresponding data are show in Fig. 1 (curve 3). The response ΔV is proportional to the differential resistance R_D (curve 2) at low voltages, and at voltages close to $(h/2e)f$ the response shows a resonance structure due to the interaction between the externally applied 72 GHz signal and the Josephson oscillations. The width δV of this resonance structure, calculated as a difference in the voltages

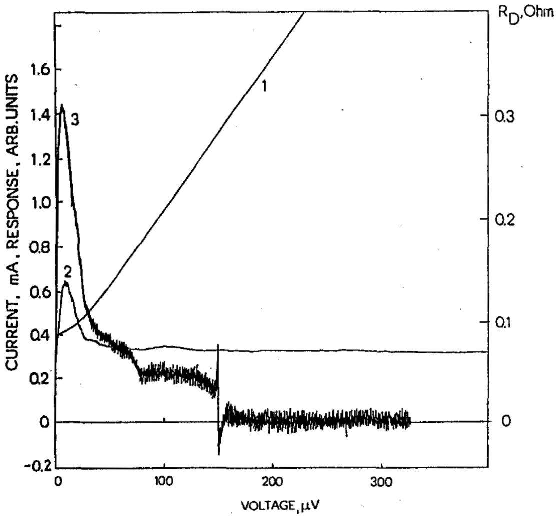

Figure 1: (1) dc IV-characteristic, (2) voltage dependence of the differential resistance, $R_D(V)$, and (3) response, $\Delta V(V)$, to 72 GHz radiation for $YBa_2Cu_3O_{7-x}$ grain-boundary junction GBJ13. The temperature is $T = 78$ K.

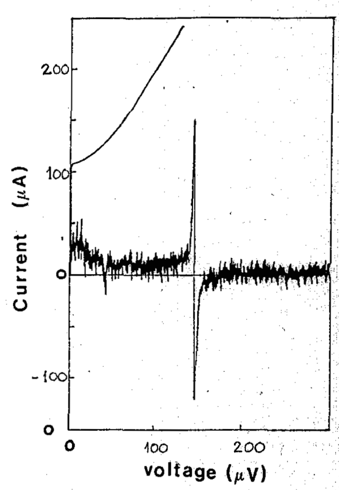

Figure 2: (1) dc IV-characteristic and (2) response, $\Delta V(V)$, to 72 GHz radiation for $YBa_2Cu_3O_{7-x}$ grain-boundary junction GBJ21 at $T = 4.5$ K.

V_+ and V_- corresponding to the minimum and the maximum response, was equal to (0.8 ± 0.1) μV at 78 K. That means a rather low value of the Josephson linewidth $\delta f = (2e/h)\delta V = (380 \pm 50)$ MHz at liquid nitrogen temperature. The magnitude of the resonance response at $V \sim (h/2e)f$ of low-ohmic GBJ were always smaller than observed at low voltages (see curve 3 in Fig. 1), indicating that the ac Josephson effect in low-ohmic GBJ is comparably depressed.

IV-curves being very similar to those predicted by the RSJ model were observed for GBJ with resistances in the range from 1 to 0.1 Ω. Data for a GBJ with $R_n = 0.67\Omega$ at 4.5 K are shown in Fig. 2. The GBJ was made on an Y-ZrO_2 bicrystal substrate and had a width $w = 34$ μm. The IV-characteristic (curve 1) is close to the hyperbolic curve predicted by the RSJ model. The response ΔV (curve 2) of this GBJ shows a very sharp odd-symmetric resonance at the voltage $V \sim (h/2e)f$. An important feature of this response $\Delta V(V)$ is the absence of harmonic and subharmonic resonances at voltages $n(h/2e)f$ and $(1/n)(h/2e)f$, $n = 2,3,\ldots$, respectively. The first observation means that the response is measured for sufficiently low intensities of the external radiation and the second guarantees a pure $\sin\varphi$ dependence of the supercurrent $I_s(\varphi)$ on the phase difference φ. This single resonance behaviour of the response was observed with a finite magnetic field applied to the GBJ in order to maximize the critical current. If the critical current were not maximized by the magnetic field resonances appeared at voltages close to $(1/2)(h/2e)f$ and $(1/3)(h/2e)f$, and the response $\Delta V(V)$ was asymmetric with respect to voltage reversal. The dependence of the critical current I_c on magnetic field B for this junction looks like an interference from several slits, rather than a single-slit Fraunhofer diffraction pattern. This indicates an inhomogeneous current distribution in the GBJ with several conducting channels which has been confirmed by direct laser probing technique[6].

GBJ made on $SrTiO_3$ bicrystal substrate also have nearly hyperbolic IV-curves for resistances in the range 0.1 – 1 Ω. In order to get a more quantitative description we have calculated the normalized response $h(V) = (\Delta V/R_D)IV$ in the RSJ model with thermal fluctuations[3] and compared it to the normalized response calculated from experimental data. The results are shown in Fig. 3, where the solid line is the theoretical curve $h(V)$ and the squares represent the experimental data. Two fitting parameters were used for the theoretical curve, one is the amplitude of the rf current induced in the GBJ by the external radiation and the other is the linewidth δf of the Josephson radiation, which actually is the separation in voltage positions of the minimum and the maximum of $h(V)$ multiplied by $(2e/h)$. As it can be seen from Fig. 3 the fit is good within an accuracy of a few percent. This confirms that the response of the GBJ can be described in terms of the RSJ model with thermal fluctuation. A result of this is that Eq. (5) can be used to determine the effective noise temperature T_N from the experimental values of linewidth δf.

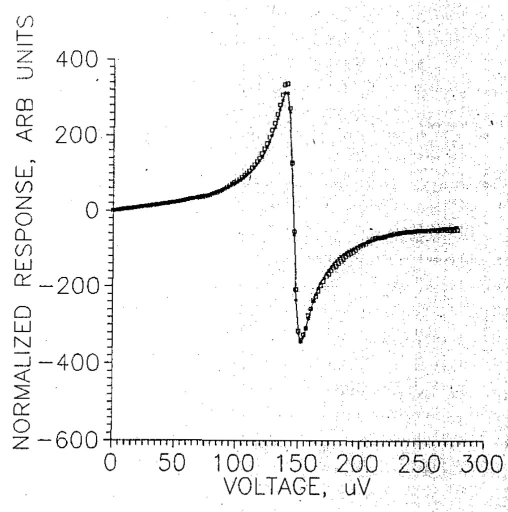

Figure 3: The normalized 72 GHz response $h(V) = (\Delta V/V)IV$ vs. voltage of a grain-boundary junction. Squares - experimental data for $YBa_2Cu_3O_{7-x}$ GBJ12 at $T = 78$ K, solid line - RSJ model with thermal fluctuations.

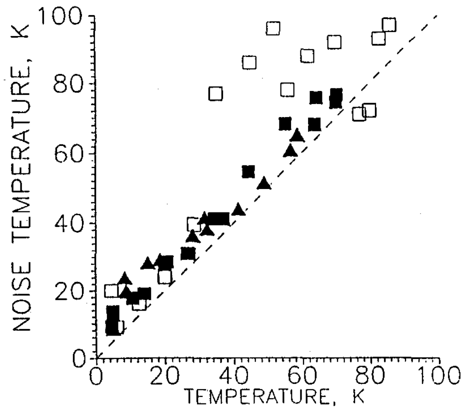

Figure 4: Noise temperature vs. physical temperature of various grain-boundary junctions, derived from the experimental values of the millimeter-wave Josephson linewidth. Filled triangles - GBJ21, filled squares - GBJ22, open squares - GBJ12.

Fig. 4 shows the noise temperatures T_N for three GBJ as function of the physical temperature T in the range from 4.5 K to 90 K. The general trend is that in this wide temperature range the noise temperature follows the physical temperature. The best agreement between T_N and T is obtained for GBJ having small characteristic voltages $V_c(T) \ll (h/2e)f$ (filled squares and triangles). A large difference between T_N and T was observed for GBJ with $V_c(T) > (h/2e)f$ (unfilled squares) at intermediate temperatures, while at low temperatures and temperatures close to the critical temperature T_c this difference is rather small.

DISCUSSION AND CONCLUSIONS

The data presented in Fig. 4 shows that wide band thermal noise gives the dominating contribution to the observed Josephson linewidth. In particular for Josephson oscillations at voltages $(h/2e)f \gg V_c$ this statement holds since the bias current I is much larger than critical current I_c meaning that low frequency fluctuations of the critical current will not contribute to the voltage fluctuations[4]. The 1/f noise from resistance fluctuations can also give such contribution[4], but as it is seen from the data this is not the case here.

The largest difference between T and T_N was observed for $(h/2e)f < V_c$ and at intermediate temperatures. We may suspect 1/f noise due to critical current fluctuations to be responsible for this excess contribution to the linewidth because in this case the current bias is closer to I_c[4]. The abrupt changes in the $T_N(T)$ dependence in the intermediate temperature range correspond to the spontaneous changes in $I_c(T)$ and this also indicates a contribution from the critical current fluctuations. As was inferred from the $I_c(H)$ dependence the GBJ had a highly inhomogeneous distribution of the critical current density; in reality the GBJ may be considered more as a multi-junction interferometer. Magnetic flux Φ may thread or leave the loops of this interferometer giving rise to changes in the critical current of the GBJ and to noise fluctuations. Like other interferometers the GBJ should have a maximum responsivity[3] $\delta I_c/\delta\Phi$ when $LI_c \sim \Phi_0$, the magnetic flux quantum, and this may be the cause of the extra noise observed at some temperatures.

In summary, the effective noise temperature of the best $YBa_2Cu_3O_{7-x}$ grain-boundary junctions may be as low as their physical temperature in the range from 4.5 K to 90 K. This allows us to use the RSJ model with thermal fluctuations to get a limiting performances of high-T_c devices utilizing the ac Josephson effect. The lowest value of the linewidth of 72 GHz Josephson oscillations observed at 77 K was equal to 380 MHz which demonstrates the applicability of GBJ particularly in the field of radiation spectroscopy[7] even at liquid nitrogen temperatures.

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