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LINEWIDTH OF JOSEPHSON OSCILLATIONS IN YBa2Cu3O7-δ GRAIN-BOUNDARY JUNCTIONS

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Abstract - We have studied the ac Josephson effect in YBa2Cu3O7-δ 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-Tc 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 YBa2Cu3O7-δ thin film on a bicrystal substrate. 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. 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 l/f noise. 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-Tc superconductors.

THEORY

In order to estimate the power and the spectral width of the Josephson radiation in a high-Tc 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, Ic, and the normal-state resistance, Rn.

Maximum rf-power is transferred from the Josephson junction to the external measuring circuit with complex impedance Zn(f) when the optimum coupling condition Re[Zn] = Rn 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. The intrinsic Josephson behaviour of such junctions can therefore only be studied with external circuits having comparably large impedances (|Zn(f)| ≫ Rn) 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 > Ic, the voltage, V(t), across the junction oscillates and the spectrum of Josephson oscillations consists of δ-function lines at frequencies fJ = k(2e/h)V, where V = Rn(I2 - Ic2)1/2 is the average voltage across the junction and k = 1, 2, ... The total power, P, of the Josephson radiation supplied by the junction to the external circuit with active impedance Rn ≫ Rn at the fundamental frequency f1 = (2e/h)V is equal to

$$P = \frac{2V^2(I^2 + V^2)^{1/2} - V^2}{V^2 R_n^2},$$  

(1)

where Vc = IcRn is the characteristic voltage of the Josephson junction. The maximum power of Josephson radiation is reached at V > Vc and is equal to

$$P = \frac{V^2}{R_n}.$$  

(2)

The characteristic voltage Vc for YBCO GBJ at 77 K is of the order 0.1 mV and for conventional external circuits with Rn ~ 100 kΩ we get P ~ 10^-10 W.

When the voltage across the junction fluctuates, the total power P will be distributed over a spectral range with some spectral density Sν(f), which may be characterized by its maximum value Sν(f1) and linewidth δf1 so that P = Sν(f1)df1. The linewidth δf1 can be estimated from the spectral density Sν(f) of the voltage fluctuations as

$$\delta f_1 \sim \frac{2e}{h} f_m \left[ \frac{dV}{df} \right]_{f_m}^{dV_d} S_V(f) df^{1/2},$$  

(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. Considering the spectral density of critical current fluctuations of the form Sν(f) = CνTf^2/I, where CνT 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:

$$\delta f_1 \sim 4C_{νT} f^2 \left[ \frac{dV}{df} \right]_{f_m} R_D I_D,$$  

(4)

where R_D = dV/dI = Rn^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

$$\delta f_1 = \frac{4\pi}{\gamma^2} \left( 2e/h \right)^2 kT \frac{R_n^2}{I_m} \left( 1 + \frac{I_m^2}{2\gamma^2} \right),$$  

(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
\[
\delta f_1 = 4\pi (2e/h)^2 kT R_n,
\]
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 \( R_n = 10 \\mu \Omega \sim 3 \text{ GHz} \). Due to this the maximum spectral density \( S_{\delta f}(f) \) of the Josephson radiation which can be delivered by a GBJ at liquid nitrogen temperatures to an external measuring circuit will be rather low \( \sim 3 \times 10^{-20} \text{ W/Hz} \). Considering some losses in the waveguides and a signal/noise ratio of \( \sim 10 \), the sensitivity of the external circuit should be better than \( \sim 10^{-20} \text{ W/Hz} \), 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.

<table>
<thead>
<tr>
<th>GBJ</th>
<th>Substr.</th>
<th>Misorient</th>
<th>Width</th>
<th>( R_n ) (4.5K)</th>
<th>( V_c ) (4.5K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>SrTiO(_3)</td>
<td>25°</td>
<td>5</td>
<td>4.5</td>
<td>0.4</td>
</tr>
<tr>
<td>12</td>
<td>SrTiO(_3)</td>
<td>25°</td>
<td>16</td>
<td>0.57</td>
<td>2.0</td>
</tr>
<tr>
<td>13</td>
<td>SrTiO(_3)</td>
<td>25°</td>
<td>88</td>
<td>0.07</td>
<td>7.0</td>
</tr>
<tr>
<td>21</td>
<td>Y-ZrO(_2)</td>
<td>45°</td>
<td>34</td>
<td>0.67</td>
<td>0.11</td>
</tr>
<tr>
<td>22</td>
<td>Y-ZrO(_2)</td>
<td>45°</td>
<td>93</td>
<td>0.22</td>
<td>0.35</td>
</tr>
</tbody>
</table>

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-\( T_\text{c} \) 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 \( V \approx (h/2e)f \). The difference \( \delta V \) between voltages \( V_0 \) and \( V_\text{m} \), corresponding to the positions of the maximum and the minimum of the response \( \Delta V \) in this region, gives us a linewidth \( \delta f \) according to the relation \( \delta f = (2e/h)\delta V/V \). 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 \( \text{YBa}_2\text{Cu}_3\text{O}_{7-x} \) bicrystals have been prepared by depositing c-axis oriented epitaxial \( \text{YBa}_2\text{Cu}_3\text{O}_{7-x} \) films on \( \text{SrTiO}_3 \) and \( \text{Y-ZrO}_2 \) 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 \( \mu \text{m} \) to 300 \( \mu \text{m} \). 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 \( \mu \text{m} \) 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 551 Hz, which actually determined the minimum frequency of noise observations.

The sample holder was placed inside a scaled vacuum can immersed in a bath of liquid helium. The pressure inside the can could be maintained by a cryostat. 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 metal shield. All measurements were made in an rf-shielded room.

RESULTS

The main theoretical results are based on the RSJ model 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 hundred \( \mu \text{V} \), 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, which might be rather large for GBJ on \( \text{SrTiO}_3 \) substrates and according to our estimate is around 1 \( \text{pF} \) for a 5 \( \mu \text{m} \) wide GBJ. This observation gives an upper limit for the resistance of the high-ohmic samples of around 1 \( \Omega \) to be used in the estimation of the intrinsic linewidth of GBJ's on \( \text{SrTiO}_3 \) 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 \( \Delta V \) 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 quantum motion along the GBJ with the length \( L \) larger than the Josephson penetration length \( \lambda_J \). This deviation from the RSJ model does not prevent us from measuring the response curve as in the hysteretic case. The corresponding data are shown in Fig. 1 (curve 2). The response \( \Delta V \) 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 \( \delta V \) 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$_2$Cu$_3$O$_{7-x}$ grain-boundary junction GBJ13. The temperature is $T = 78$ K.

$V_+$ and $V_-$ corresponding to the minimum and the maximum response, was equal to $(0.8 \pm 0.1) \mu V$ 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 $\Omega$. Data for a GBJ with $R_a = 0.67\Omega$ at 4.5 K are shown in Fig. 2. The GBJ was made on a Y-ZrO$_2$ bicrystal substrate and had a width $w = 34 \mu m$. The IV-characteristic (curve 1) is close to the hyperbolic curve predicted by the RSJ model. The response $\Delta V$ (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 $\sin \phi$ dependence of the supercurrent $I_s(\phi)$ on the phase difference $\phi$. 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.

GBJ made on SrTiO$_3$ bicrystal substrate also have nearly hyperbolic IV-curves for resistances in the range 0.1 – 1 $\Omega$. In order to get a more quantitative description we have calculated the normalized response $\alpha(V) = (\Delta V/V)IV$ vs. voltage of a grain-boundary junction. Squares - experimental data for YBa$_2$Cu$_3$O$_{7-x}$ GBJ12 at $T = 78$ K, solid line - RSJ model with thermal fluctuations.

Figure 2: (1) dc IV-characteristic and (2) response, $\Delta V(V)$, to 72 GHz radiation for YBa$_2$Cu$_3$O$_{7-x}$ grain-boundary junction GBJ21 at $T = 4.5$ K.

Figure 3: The normalized 72 GHz response $\alpha(V) = (\Delta V/V)IV$ vs. voltage of a grain-boundary junction. Squares - experimental data for YBa$_2$Cu$_3$O$_{7-x}$ GBJ12 at $T = 78$ K, solid line - RSJ model with thermal fluctuations.
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 $V_c(T) < (h/2e)f$ (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 $(h/2e)f > V_c$ 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. The 1/f noise from resistance fluctuations may also give such contribution, 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 critical bias is closer to $I_c$. The abrupt changes in the $T_N(T)$ dependence in the intermediate temperature range correspond to the spontaneous changes in $V_c(T)$ and this also indicates a contribution from the critical current fluctuations. As was inferred from the $I_c(R)$ 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 $\Phi$ 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 $\delta I_c/\delta \Phi$ when $L_c \sim \Phi_0$, 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$_2$Cu$_3$O$_{7-\delta}$ 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 even at liquid nitrogen temperatures.

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