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Josephson oscillations and noise temperatures in $YBa_2Cu_3O_{7-x}$ grain-boundary junctions

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The ac Josephson effect was studied in $YBa_2Cu_3O_{7-x}$ grain-boundary junctions (GBJ) in the temperature range from 4 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 may 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.

Recently, many different types of high T_c superconducting weak links have been studied and some of them have shown Josephson behavior.[1] One of the most promising types is the grain-boundary junction (GBJ) fabricated by the epitaxial growth of $YBa_2Cu_3O_{7-x}$ thin film on a bicrystal substrate.[2] 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.[2] Motivated by the promising applications of GBJ in dc SQUIDs, noise studies have mainly been confined to low frequencies and $1/f$ 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 was done with weak links fabricated from conventional low T_c superconductors.[3,4]

To estimate the power and the spectral width of the Josephson radiation in a high T_c GBJ, we consider the RSJ model to be applicable. The main parameters are the critical current I_c and the normal-state resistance R_n. The total power P of the Josephson radiation supplied to an external circuit with impedance $R_e \gg R_n$ at the fundamental frequency $f=(2e/h)V$ is equal to[5]

$$P=2V^2[(V^2+V_c^2)-V]^2/V_c^2R_e, \qquad (1)$$

where $V_c=I_cR_n$ is the characteristic voltage of the Josephson junction. The maximum power $P=V_c^2/R_e$ is reached at $V>V_c$. For an YBCO GBJ at 77 K, V_c is of the order 0.1 mV and with a typical $R_e \sim 100\ \Omega$, we get $P \sim 10^{-10}$ W.

Two main sources of voltage fluctuations may be considered in GBJs, broadband thermal noise and low-frequency $1/f$ noise. The latter may result both from fluctuations in the critical current and from fluctuations of the normal-state resistance.[6] For broadband thermal fluctuations, which are the dominant here, the linewidth is[5]

$$\delta f=4\pi(2e/h)^2kT(R_D^2/R_n)[1+(I_c^2/2I^2)], \qquad (2)$$

where R_D is the dynamic resistance. The linewidth in Eq. (2) is always larger than the minimum value $\delta f=4\pi(2e/h)^2kTR_n$ which is reached for $I \gg I_c$ and will be used for estimates. At liquid-nitrogen temperatures and for a GBJ with $R_n=1\ \Omega$, we get $\delta f \sim 3$ GHz.

In the present study of the Josephson linewidth, we use the same indirect technique based on the self-detected dc response of the Josephson junction to low-intensity microwave radiation, as was used in a study of low T_c microcontacts.[4] The technique is based on the analytical properties of the voltage dependence of the dc response $\Delta V(V)$, which is the voltage difference between the IV curves with and without applied microwave radiation. $\Delta V(V)$ shows an odd-symmetric resonance at the voltages $V \sim (h/2e)f$ and 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 $\delta f=(2e/h)\delta V$.

Thin-film $YBa_2Cu_3O_{7-x}$ bicrystals were 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 was then patterned by another laser into a number of bridges, each crossing a grain boundary and having widths ranging from 5 to 300 μm. The parameters are shown in Table I.

The sample holder had a loosely coupled 60–90 GHz waveguide connection to the sample and ~70 GHz radiation from a Gunn oscillator could be applied. A lock-in technique was used to measure the derivative of the dc IV characteristics and the dc response $\delta V(V)$. The response measurements were obtained by an on-off modulation of the microwave power; the modulation frequency was 531 Hz, determining the minimum frequency of noise observations. The sample holder was placed inside a vacuum can immersed in a glass helium Dewar surrounded by a double μ-metal shield. All measurements were made in an rf shielded room.

The main results are based on the assumption that the RSJ model[5] applies. Hence, we first discuss the validity of this assumption. For the GBJ used in this study, the dc IV characteristics agreed with the hyperbolic dependence predicted by the RSJ model for $R_n \sim 0.1$ to 1 Ω. For narrow and high-ohmic GBJs with $R_n > 1\ \Omega$, hysteresis was observed in the IV curve at low temperatures with no stable

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TABLE I. Parameters of grain-broundary junctions used for linewidth measurements.

Junc. No.	Substrate	Misorient. angle	Width (μm)	R_n (Ω)	I_c(4.5 K) (mA)	V_c(4.5 K) (mV)
GBJ11	$SrTiO_3$	25°	5	4.6	0.4	1.8
GBJ12	$SrTiO_3$	25°	16	0.57	2.0	1.1
GBJ13	$SrTiO_3$	25°	88	0.07	7.0	0.5
GBJ21	Y-ZrO_2	45°	34	0.67	0.11	0.07
GBJ22	Y-ZrO_2	45°	93	0.22	0.35	0.08

bias point at voltages from zero to several hundreds μV, while for low-ohmic GBJ, there was no hysteresis in the *IV* curves. These observations suggest the hysteresis may be due to the shunting of the Josephson oscillations by the intrinsic stray capacitance,[1] which we estimate to be around 1 pF for a 5-μm-wide GBJ on $SrTiO_3$. The *IV* characteristics of the wider GBJ with resistance $R_n < 0.1\ \Omega$ 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 $R_n = 0.07\ \Omega$. An excess current not consistent with the RSJ model is clearly seen on the *IV* curve at $I \gg I_c$. This excess current is due to flux motion along the GBJ.[1] The deviation from the RSJ model, however, does not prevent us from measuring the response curve as in the hysteretic case. The corresponding data are shown in Fig. 1 (curve 3). The response ΔV is proportional to the differential resistance R_D (curve 2) at low voltages; 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 V_+ and V_- corresponding to the minimum and the maximum response, was equal to $(0.8 \pm 0.1)\ \mu$V at 78 K corresponding to a Josephson linewidth $\delta f = (2e/h)\delta V = (380 \pm 50)$ MHz at liquid-nitrogen temperature. The amplitudes of the resonance response at $V \sim (h/2e)f$ of low-ohmic GBJ were always less than the response at low voltage (see curve 3 in Fig. 1); this means that the ac Josephson effect in low-ohmic GBJ is comparatively depressed.

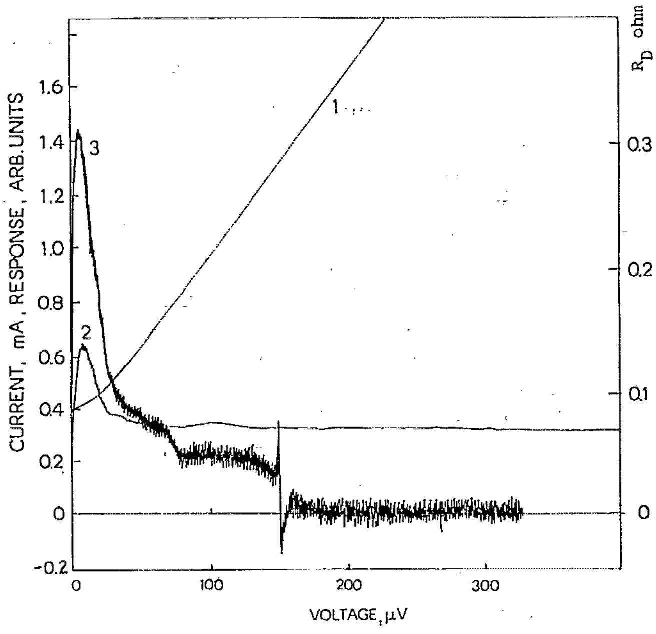

FIG. 1. (1) dc *IV*-characteristic, (2) voltage dependence of the differential resistance, $R_D(V)$, and (3) response $\Delta V(V)$ to 73 GHz radiation for $YBa_2Cu_3O_{7-x}$ grain-boundary junction GBJ13. The temperature is T=78 K.

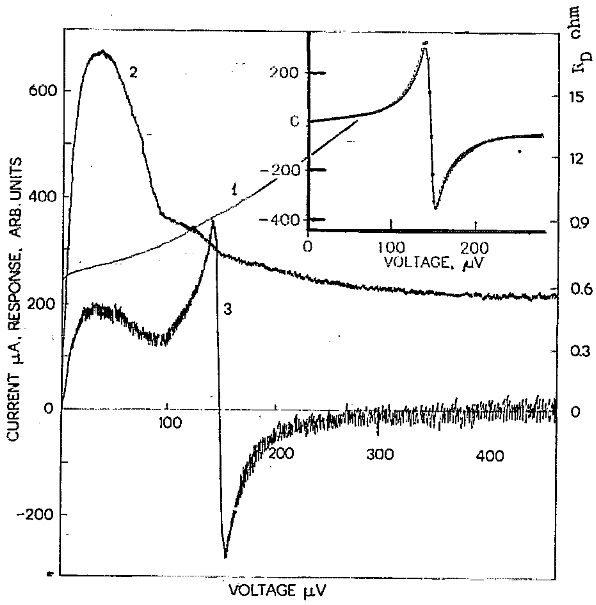

FIG. 2. (1) dc *IV* characteristic, (2) differential resistance, and (3) response to 72 GHz radiation for $YBa_2Cu_3O_{7-x}$ grain-boundary junction GBJ12 at T=78 K. The inset shows the normalized response $h(V) = (\Delta V/R_D)\ I \cdot V$, calculated and experimental.

Figure 2 shows the same data for GB12. Here, the *IV*-curve is close to being hyperbolic and the differential resistance $R_D(V)$ has a maximum at low voltages and decreases with increasing voltage approaching a constant value. The response ΔV is proportional to the differential resistance at low voltages, and at voltages around $(h/2e)f$, it shows an odd-symmetric resonance. The absence of resonances at voltages $n \cdot (h/2e)f$ shows that the response is measured at sufficiently low intensity and the absence of $(1/n)(h/2e)f$ resonances demonstrates a pure $\sin\varphi$ current-phase relationship.

In order to get quantitative results, we calculated the normalized response $h(V) = (\Delta V/R)IV$ in the RSJ model with thermal fluctuations[5,7] and compared it to the normalized response calculated from experimental data shown in Fig. 2. The comparison is shown in the inset. Two fitting parameters were used—the amplitude of the rf current induced in the GBJ by external radiation and the linewidth δf of the Josephson radiation. As it can be seen from Fig. 2, 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. Other results of the RSJ model can therefore be considered applicable to GBJ and we will use Eq. (3) to determine the effective temperature T_N from the experimental values of linewidth δf.

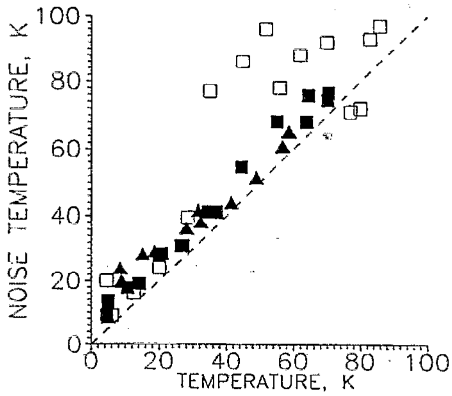

FIG. 3. Noise temperature vs physical temperature of the $YBa_2Cu_3O_{7-x}$ grain-boundary junctions derived from the experimental values of the millimeter-wave Josephson linewidth. Filled triangles—GBJ21; filled squares—GBJ22; open squares—GBJ12.

In Fig. 3 we present the noise temperatures T_N for three GBJs as a function of the physical temperature T in the range from 4.5 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 GBJs having small characteristic voltages $V_c(T) \ll (h/2e)f$ (filled squares and triangles). A larger difference between T_N and T was observed for GBJ12 with $V_c(T) > (h/2e)f$ (unfilled squares) at intermediate temperatures. For some junctions of the microbridge type, a fit was not possible, indicating nonthermal noise sources dominating.

The data presented in Fig. 3 shows that wideband thermal noise is the dominant cause of the observed Josephson linewidth. This is especially so for Josephson oscillations at voltages $(h/2e)f \gg V_c$. In this case, the bias current I is much larger than critical current I_c so that low-frequency fluctuations of the critical current will not contribute to voltage fluctuations.[6] The $1/f$ noise from resistance fluctuations can also give such a contribution,[6] 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 in the range of intermediate temperatures. We suspect $1/f$ noise due to critical current fluctuations to be responsible for this extra contribution to the linewidth because, in this case, current bias is closer to I_c.[6] 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. The GBJ had a highly inhomogeneous spatial distribution of the critical current density, as was seen from the $I_c(H)$ dependence, and hence, the GBJ may be considered more as a multijunction interferometer. Magnetic flux can come and go in 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 $\delta I_c/\delta B$ when $LI_c \sim \Phi_0$, and this may be the cause of the extra noise as observed at some temperatures.

In conclusion, we have shown that the effective noise temperature of high-quality $YBa_2Cu_3O_{7-x}$ grain-boundary junctions may be as low as their physical temperature in the range from 4.5 to 90 K. This allows us to use thermal fluctuations to get the limiting performance of high-frequency high T_c devices utilizing the ac Josephson effect. The lowest value of the linewidth of 72 GHz Josephson oscillations at 78 K was equal to 380 MHz, which shows the applicability of the GBJ particularly in the field of radiation spectroscopy,[7] even at liquid-nitrogen temperatures.

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