Millimeter-wave response and linewidth of Josephson oscillations in $YBa_2Cu_3O_7$ step-edge junctions

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We have studied the response of $YBa_2Cu_3O_7$ step-edge junctions to low-intensity millimeter-wave radiation in the temperature range from 4 to 80 K. The linewidth of the Josephson oscillations derived from the resonant part of the response at voltages $V \simeq (h/2e)f$ is shown to be determined by thermal fluctuations at liquid nitrogen temperatures. At lower temperatures the observed linewidth increases indicating that low-frequency fluctuations become dominant in the junction as the temperature is reduced. Due to an inhomogeneous spatial distribution of the current the step-edge junction might be considered as a multijunction multiloop interferometer and the excess noise can be discussed in terms of spontaneous transitions between the different states of these interferometers.

One of the promising types of high-T_c superconducting weak links is the step-edge junction (SEJ).[1,2] These junctions are fabricated by epitaxial growth of a high-T_c thin film on a steep step etched in the substrate prior to the film deposition. As follows from high resolution electron microscopy (HREM) studies,[3] the SEJ is actually a series connection of at least two grain-boundaries formed at the upper and the lower edges of the step. Josephson behavior of a single SEJ and quantum interference in superconducting quantum interference devices SEJs have been demonstrated.[1,2] To assess the applicability of SEJs for high-frequency detection and emission we have measured the small-signal response of SEJs to millimeter-wave radiation. Using the analytical properties of this response, we have determined the linewidth of the Josephson oscillations. The results were compared to a direct low-frequency measurement of the voltage fluctuations across the SEJ.

The SEJs were fabricated by pulsed laser deposition of a $YBa_2Cu_3O_7$ thin film on a $LaAlO_3$ substrate. The step was etched by ion milling.[2] Bridges of different widths, from 2 to 32 μm, were defined by photolithography in the region of the step. The normal-state resistance, R_n, of the different SEJs was found to be 0.1–10 Ω, and the critical temperature, T_c, determined from the temperature dependence of the critical current I_c, was $\geqslant$80 K. The spatial distribution of the current across the SEJ was inhomogeneous, as inferred from the dependence of the critical current on the applied magnetic field.[2]

The Josephson linewidth was determined by an indirect method used in a similar study of low-T_c point contacts.[4] This technique is based on the analytical properties of the voltage dependent response, $\Delta V(V)$, which is the voltage difference between the dc IV curves obtained with and without applied microwave radiation. The response $\Delta V(V)$ of a Josephson junction in the RSJ model shows an odd-symmetric resonance at the voltages $V \simeq (h/2e)f$, and the difference, δV, between the voltages, corresponding to the positions of maximum and minimum of the response ΔV in this region, gives a linewidth, δf, according to the relation $\delta f = (2e/h)\delta V$.

A 70 GHz Gunn oscillator was used to irradiate the SEJ sample, which was mounted onto the open end of a rectangular waveguide with a thin mylar foil interleaved for dc insulation. The rf coupling was sufficiently loose to prevent interference from external resonances and thus guaranteed an unperturbed Josephson behavior of the SEJ. The applied power could be varied by two precision attenuators, and was kept so low that the Josephson junctions were operated in the small signal limit. Standard lock-in technique with modulation of the radiation intensity at a frequency of 531 Hz was used to measure the response. All electrical connections were carefully filtered and the sample holder was inserted into a magnetically shielded cryostat. The experiments were carried out in a rf shielded room.

In Fig. 1 the IV-characteristic (curve 1) and the millimeter-wave response $\Delta V(V)$ (curve 2) to radiation with the frequency $f = 70.2$ GHz are shown for a SEJ with a width $W = 32$ μm at 77.3 K. Two odd-symmetric resonances at voltages $V \simeq \pm (h/2e)f = \pm 145$ μV are observed in $\Delta V(V)$, thus demonstrating the nonlinear interaction between the weak millimeter-wave radiation and the Josephson oscillations. Application of the millimeter-wave power also gives a noncoherent contribution to the $\Delta V(V)$ dependence, which offsets the response also at the voltage $V = (h/2e)f$. At liquid-nitrogen temperatures this non-Josephson contribution dominates in the response of SEJs with larger resistances R_n and smaller widths W, thus preventing us from measuring the dependence of the resonant response on junction size.

The width δV of the resonant response in Fig. 1 is equal to $(2.5 \pm 0.4)\mu$V corresponding to a Josephson line-

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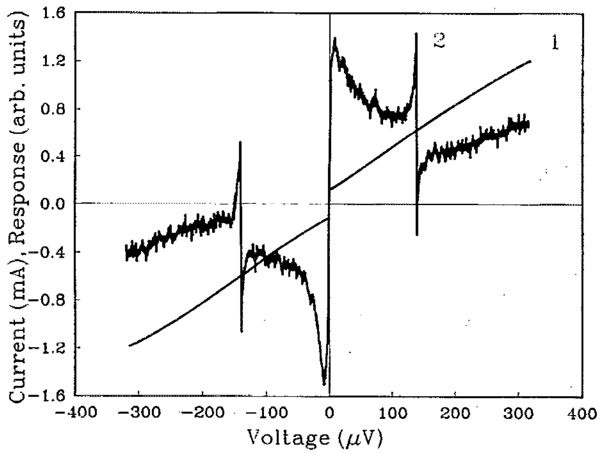

FIG. 1. The IV characteristic (1) and the response $\Delta V(V)$ (2) to 70.2 GHz radiation for a $YBa_2Cu_3O_7$ SEJ32 at 77.3 K.

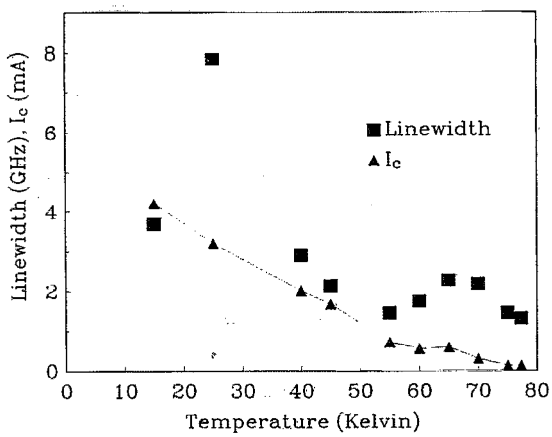

FIG. 3. The linewidth of 70.2 GHz Josephson radiation (squares) and critical current (triangles) of $YBa_2Cu_3O_7$ SEJ32 as function of temperature. The solid line is a guide to the eye.

width $\delta f=(2e/h)\delta V=(1.2\pm0.2)$GHz. This value of the linewidth is close to the value $\delta f=0.9$ GHz estimated for this SEJ using the RSJ model with thermal fluctuations at 77.3 K. A recent study of the Josephson linewidth in bicrystal grain-boundary junctions showed that thermal fluctuations might be the dominant contribution to the linewidth between liquid-nitrogen and liquid-helium temperatures.[5] In the step-edge junctions studied here the temperature behavior of the linewidth is quite different.

When the temperature is lowered from 77.3 K, the response $\Delta V(V)$ starts to be strongly dependent upon magnetic fields of the order of 10^{-5} T. An example of this behavior at 70.3 K is shown in Fig. 2. Different values of the magnetic field were necessary to maximize the resonance response for positive bias [Fig. 2(a)] and for negative bias [Fig. 2(b)]. Not only the IV characteristic (curve 1) but also the response (curve 2) becomes strongly asymmetric. In fact no coherent response is observed for negative bias, when the response is maximized at the positive bias point [Fig. 2(a)]. The linewidth was also dependent on the magnetic field of the order of 10^{-5} T and e.g., at 70.3 K the magnetic field necessary to minimize the critical current could result in a decrease of the linewidth by the factor of 2. At some temperatures lower than 60 K, switching and chaotic behavior in both the IV curve and the response $\Delta V(V)$ were observed. These fluctuations were so pronounced at some bias points that they prevented us from measuring the response at some temperatures lower than 60 K. At bias currents close to I_c, the IV characteristic also shows a hysteresis which was dependent on the maximum bias current used in the previous measurement.

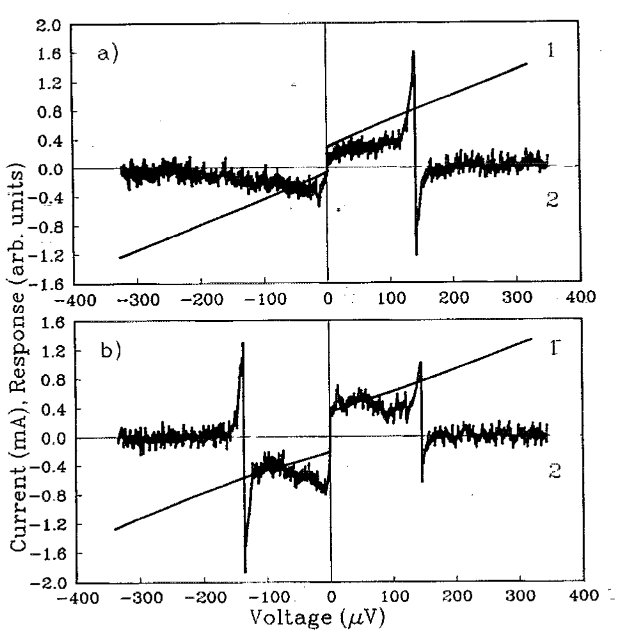

FIG. 2. The IV curve (1) and 70.2 GHz response $\Delta V(V)$ (2) for SEJ32 at 70.3 K for the two magnetic fields which maximizes the resonant response at positive (a) and negative (b) bias.

The temperature dependence of the linewidth of 70.2 GHz Josephson radiation in a step-edge junction with the width 32 μm is shown in Fig. 3(a) (filled squares). The triangles show the critical current vs temperature. All data were measured with the magnetic field, which maximized the critical current of the SEJ. Obviously, the linewidth does not decrease with temperature, as expected in the case of dominating thermal fluctuations. A $1/f$-noise-type fluctuations in the critical current[6] might be responsible for the excess contribution to the linewidth at lower temperatures. In this case the linewidth should be proportional to the critical current. As can be seen in Fig. 3, the general trend is an increase in the linewidth with decreasing temperature combined with some oscillatory behavior. Similar data were obtained for a SEJ with $W=16$ μm at temperatures in the range 20–70 K.

This general trend in the temperature dependence of the linewidth is similar to that in the low-frequency voltage noise measured directly across the SEJ. The temperature dependence of the noise voltage for the same SEJ biased at $V=(h/2e)f=145$ μV is presented in Fig. 4. The noise voltage is obtained by integrating the measured spectral density of the voltage fluctuations (see insert in Fig. 4) from 0.25 Hz to 3 kHz. At some temperatures and in some

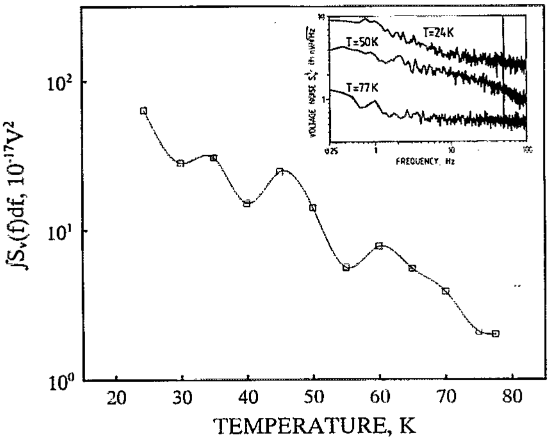

FIG. 4. The integral voltage noise in a bandwidth from 0.25 Hz to 3 kHz vs temperature for SEJ32 at bias voltage 145 μV. The insert shows the spectral density of the voltage fluctuations at $V=145$ μV for different temperatures.

bias points, telegraph noise was observed in the junction voltage, and this behavior is responsible for the nonmonotonic increase of the noise voltage (Fig. 4) and the spectral density $S_V(f)$ with decreasing temperature. It follows from Figs. 3 and 4 that both the low-frequency noise voltage and the linewidth increase with decreasing temperature. In the temperature range 25–60 K, the noise voltage is proportional to the critical current $I_c(T)$. The linewidth δf is determined by the spectral density $S_V(f)$ integrated over a wide frequency range up to the frequencies of about δf, and hence the behavior of the linewidth may be more complicated than found from the spectral density $S_V(f)$ integrated at low frequencies. From the data shown in Figs. 3 and 4 we may draw the conclusion that fluctuations in SEJs at low temperatures are of nonthermal nature. It should be noted that excess low-frequency noise or nonthermal contributions to the linewidth have been observed practically for all types of high-T_c Josephson junction.[5–7]

We may suspect the spatially inhomogeneous current distribution in the SEJ to be responsible for the behavior observed in the averaged dc IV characteristics and in the fluctuations of the junction. In spite of the fact that the SEJ contains at least two grain boundaries, the measurements show no evidence of Josephson oscillations from two (or more) series connected junctions. It is most probable that the behavior of the SEJ is mainly determined by one, the weakest, grain boundary. Due to its inhomogeneous current distribution, this grain boundary may be considered as an interferometer consisting of parallel connected, randomly distributed Josephson junctions. This multijunction multiloop interferometer is characterized by different values of the critical currents $I_{c,i}$ in the ith junction and different values of the kth loop inductance L_k. At low temperature the characteristic energies $E_{\Phi,k}=\Phi_0^2/8L_k$ and $E_{J,i}=(\hbar/2e)I_{c,i}$ of this interferometer may be larger than kT, thus increasing the complexity of the system studied and introducing new available states with closely spaced energies. In such a system even a small amount of thermal noise may induce hopping between the different states. Transitions between the states of this interferometer can also be introduced by the external current and the magnetic field and this may give rise to the effects observed.

In conclusion, we have studied the millimeter-wave response and Josephson oscillations in $YBa_2Cu_3O_7$ step-edge junctions. It is shown, that at liquid-nitrogen temperatures, the linewidth of Josephson oscillations is determined by thermal noise. At lower temperatures, the low-frequency noise contribution to the Josephson linewidth might be significant for this type of high-T_c weak links. The excess noise might be caused by spontaneous transitions between the different states of the SEJ which might be considered as a multi-loop multi-junction interferometer.

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