Microwave heating of a high-T_c $YBa_2Cu_3O_{6.9}$ superconductor through a Josephson-junction system

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An overheating of a Josephson-junction system (JJS) in ceramic $YBa_2Cu_3O_{6.9}$ samples was induced by microwave irradiation in a microwave cavity. The amplitude of the Josephson microwave absorption (JMA) was used as a monitor of the local JJS temperature. The difference between the JJS temperature and a sample temperature depends linearly on the power of the microwave field. A thermal hysteresis of T_c for heating and cooling is proportional to the microwave power applied in the JMA experiment.

INTRODUCTION

After the discovery of high-temperature superconductivity (HTS) by Bednorz and Müller,[1] and the identification of superconductivity at 90 K by Chu *et al.*[2] in $YBa_2Cu_3O_{7-d}$, many authors have used standard EPR techniques for investigations of the microwave absorption in HTS ceramics.

In granular superconducting materials both dielectric losses and magnetic excitation losses can appear at microwave frequencies. The surface microwave impedance rapidly decreases on cooling through a superconducting transition and achieves the lowest value at liquid-helium temperature.[3–7] The decrease of the impedance is monotonic in $YBa_2Cu_3O_{6.9}$ ceramics. The real part of the dielectric permittivity ϵ' is proportional to the density of normal current carriers. Losses, described by the imaginary part of the permittivity ϵ'', are proportional to the London penetration depth.[5] Contacts between grains in a ceramic material form a Josephson-junction system. In a microwave field of frequency ω, a junction is polarized with the voltage $\tilde{V}=\omega h/2e$. When the voltage $\tilde{V}$ is higher than the critical value $\tilde{V}_t=R_J I_c$, a transition to a nonequilibrium state of the junction occurs and the emission of radiation at the Josephson frequency $\omega_J=\tilde{V}/\phi_0$ is observed. This mechanism causes losses at frequency $\omega\approx\omega_J$. It is a resonancelike phenomenon and gives a main contribution to the so-called Josephson microwave absorption (JMA).[8–10] The second mechanism of microwave energy dissipation is related to excitations of Cooper pairs to the state of quasiparticles.[11] This mechanism operates when $\omega\approx 2\Delta/\hbar$ and gives a strong peak of JMA close to the superconducting transition at $T<T_c$. Two mechanisms, losses caused by nucleations of domain walls between Meissner and mixed Abrikosov (vortex) states, and fluxon pinning are responsible for a dissipation of microwave energy in strong magnetic fields.[12]

Stankowski *et al.*[9] and others[8,10] have noticed a Josephson nature of the low-field absorption observed by the EPR technique and suggested that it is an effect of the resonant interaction between the microwave field and Josephson-junction system (JJS) in granular $YBa_2Cu_3O_{7-d}$ samples. This JMA is due to fluctuations of the wave-function phase of tunneling carriers in a zero-magnetic-field area (low-field peak) whereas a penetration of fluxons causes absorption at a higher magnetic field in a classical EPR experiment. The dissipation of energy is connected with oscillations of fluxons in the Josephson junction perpendicular to the external magnetic field B_0 modulated with an amplitude B_m.[13] This phenomenon is analogous with the excitation of spin waves in magnetic materials.

The JMA signal is observed as an inverted absorption line as compared with "normal" EPR signals and follows the well-known dependence of the critical current I_c on an external field:

$$P_{\mathrm{JMA}}=P_0\left[1-\left[\frac{\sin(\pi\phi/\phi_0)}{\pi\phi/\phi_0}\right]^2\right], \tag{1}$$

where $P_0=RI_c^2(0)$ is a maximal power absorbed by JJS. The Josephson-junction system is in resonance with a microwave field when the modulation field B_m is sufficiently high, i.e., B_m is higher than the elementary periodicity in JJS: $B_m>\phi_0/S_{\mathrm{eff}}$, where S_{eff} is an effective area of the Josephson-junction loop in the granular superconductor. When that condition is fulfilled the JMA line is smooth, whereas for lower modulation amplitudes the JMA line becomes "noisy." The JMA line is recorded as (dP/dB) on an EPR spectrometer. The line appears at T_c and increases on cooling. A value of (dP/dB) is a measure of the difference between the temperature T^* of JJS and the critical temperature T_c. The disappearance of the microwave absorption shows that JJS has the temperature $T^*\geq T_c$ even when the whole sample has a temperature lower then T_c. The system of junctions is heated by the microwave field up to T^* while the sample temperature T can be lower. It depends on the level of incident microwave power: for the low power ($P<1$ mW), $T=T^*$, whereas for the high power ($P>10$ mW), $T^*>T$. The result of experimental studies and a theoretical description of the interaction between JJS and a bulk superconducting sample are presented in this paper.

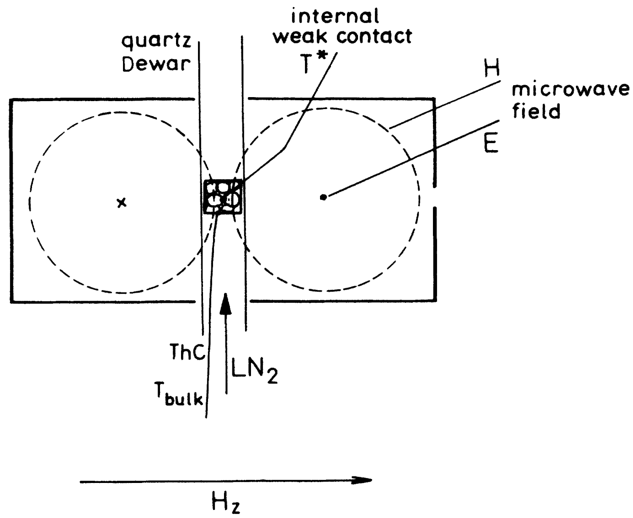

FIG. 1. The geometry of experiment. The superconducting sample of dimensions $2\times2\times2$ mm^3 placed in the center of the microwave TE_{102} cavity in the maximum magnetic component of the microwave field B_1. The static magnetic field B_z is perpendicular to B_1. Two separated temperatures are indicated: T^*, the temperature of the Josephson-junction system, and T_{bulk}, measured by thermocouple.

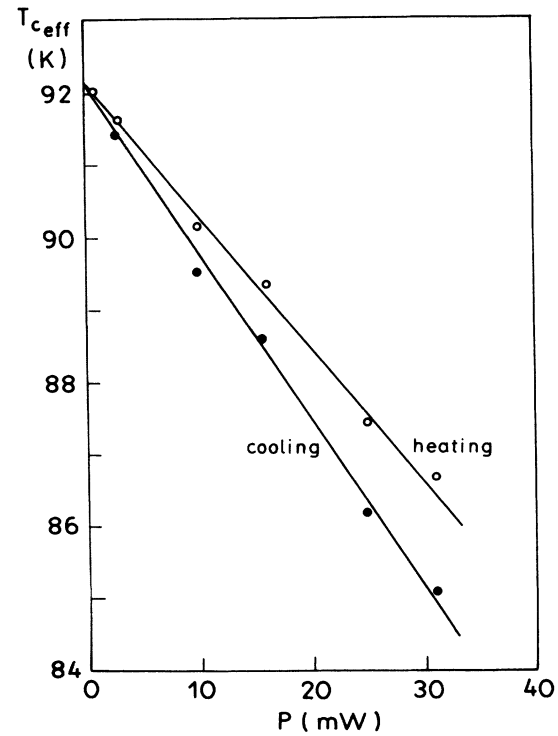

FIG. 3. The dependence of the temperature $T_{c\,\mathrm{eff}}$ for the JJS vs the microwave power P for heating and cooling runs.

EXPERIMENT

A high-quality, monophase $YBa_2Cu_3O_{6.9}$ ceramic sample was used. The sample was characterized by the absence of a Cu^{2+} ion EPR spectrum. The temperature of the superconducting transition was found to be $T_c=92.2$ K. The derivative of absorption (dP/dB), i.e., the JMA signal, was recorded on a Radiopan SE/X-2543 Electron Paramagnetic Resonance spectrometer operating at 9.4 GHz with a TE_{102} cavity (Fig. 1), and a 100-kHz magnetic-field modulation B_m. The sample was cooled by liquid-nitrogen vapors flowing through a quartz Dewar tube. The temperature of the sample was stabilized in selected points where the JMA signals were recorded. The signals were also recorded during a continuous quasistatic change of temperature with the rate 0.3 K/min. The temperature was measured by a copper-constantan thermocouple attached to the sample. Microwave absorption was studied in the applied magnetic field $B_0=20$ G modulated with an amplitude $B_m\approx4$ G. The microwave power was controlled with a microwave attenuator of the EPR microwave unit.

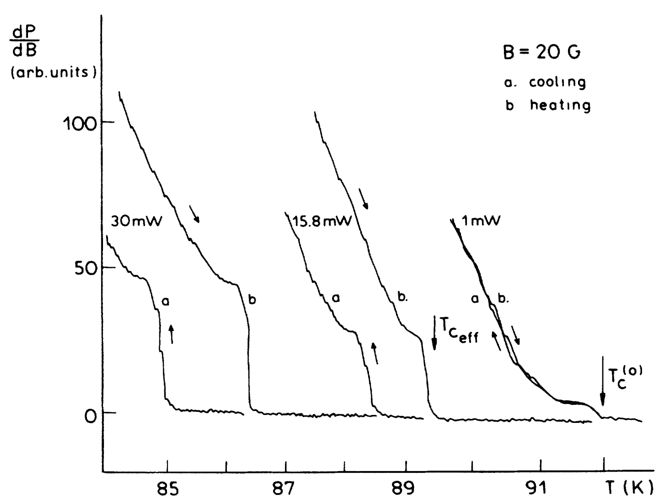

FIG. 2. The first derivative of the microwave absorption of $YBa_2Cu_3O_{6.9}$ ceramic vs temperature for the microwave power $P=1$, 15.8, and 30 mW for (a) cooling and (b) heating the sample.

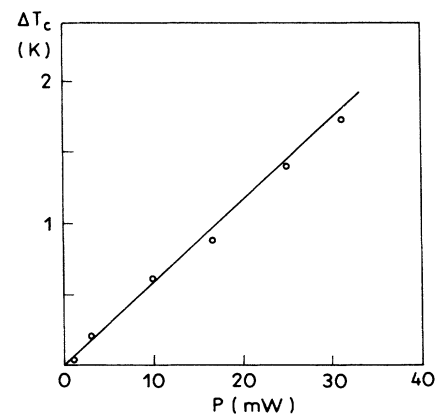

FIG. 4. The value of thermal hysteresis of $\Delta T_c = T^{(h)}_{c\,\mathrm{eff}} - T^{(c)}_{c\,\mathrm{eff}}$.

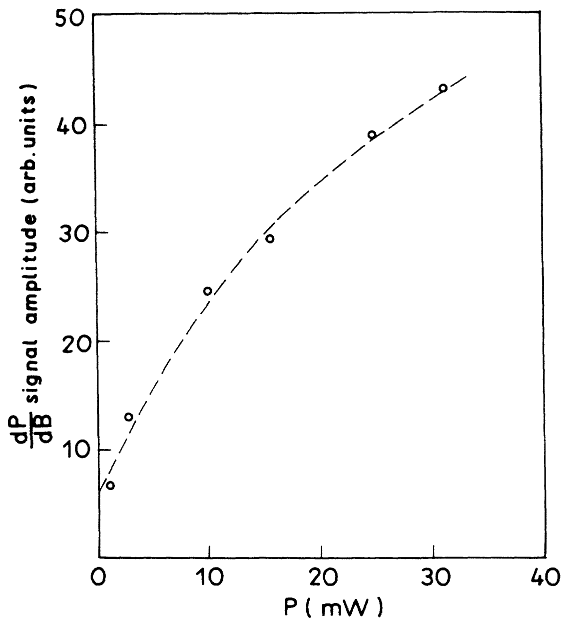

FIG. 5. The power dependence of (dP/dB) measured at the plateau region.

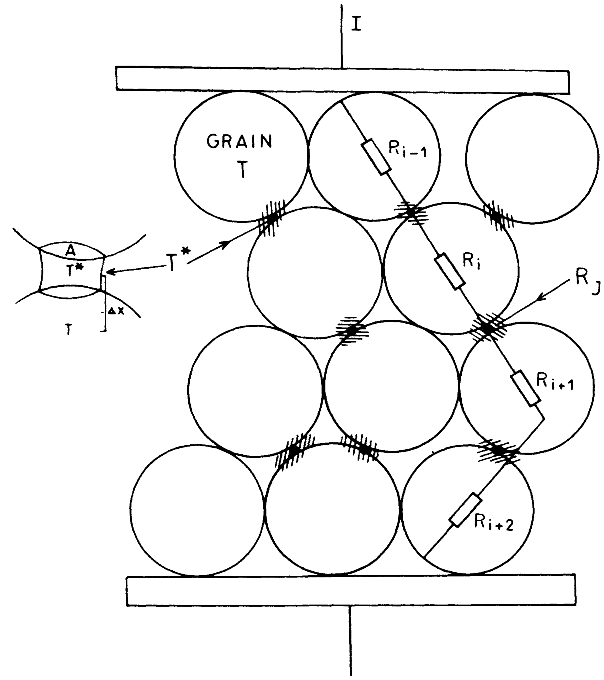

FIG. 6. The view of the granular high-T_c superconductor. R_i, resistance of bulk material; r_J, resistance of Josephson junctions.

For a low level of the incident microwave power ($P=1$ mW), a cooling run and a heating run gave the same results, with the JMA signal appearing at $T_c=92$ K and having a steplike plateau at about 0.25 K below T_c (Fig. 2). With an increase of the microwave power, three effects are observed: (i) the JMA signal appears at $T_{c\,\mathrm{eff}}<T_c$ values, (ii) a thermal hysteresis of (dP/dB) appears, and (iii) the plateau shifts to higher (dP/dB) values. The effective temperature $T_{c\,\mathrm{eff}}$ linearly decreases with the increasing of P (Fig. 3). A disappearance of the JMA signal at $T_{c\,\mathrm{eff}}$ indicates that the temperature of junctions is equal to $T_c=92$ K, whereas the rest of the sample has the temperature $T_{c\,\mathrm{eff}}<T_c$. A value of the hysteresis measured as $[T_{c\,\mathrm{eff}}(\text{heating})-T_{c\,\mathrm{eff}}(\text{cooling})]$ increases linearly with the incident microwave power as is shown in Fig. 4.

Figure 5 shows the observed increase in an amplitude of the (dP/dB) plateau of the characteristic in Fig. 2 which indicates that absorbed power P increases with the incident P_{mic}. The increase of the absorbed power is connected with a decrease in the Josephson critical current I_c between junctions due to microwave irradiation.[14]

THEORETICAL DESCRIPTION

A ceramic superconducting sample is a system of grains connected by Josephson junctions (Fig. 6). Above T_c each grain has resistivity R_i and each junction has resistivity R_J. Thus, in the normal state the total resistivity of a sample is

$$R=\sum_i R_i+\sum_J R_J \ . \tag{2}$$

In the superconducting state the total resistivity becomes zero $R=0$. This means that the bulk resistivity $\sum_i R_i=0$ as well as $\sum_J R_J=0$ since a nondissipative current of tunneling Cooper pairs flows through the junctions. When the Josephson-junction current comes to slightly exceed the critical I_c value, fluctuations of voltage occur:

$$\tilde{V}=R_J(I^2-I_c^2)^{1/2} \ ; \tag{3}$$

it leads to a high-frequency energy dissipation depending on the current I and the external magnetic field value as is shown in Eq. (1). Junctions resonantly absorb microwave power and then emit microwave power spontaneously inducting fluxons.[13,15] A heating of the junction system is very intensive in a microwave field since superconductors are known to be very bad heat conductors. For classical metallic superconductors the ratio of k_n/k_s is equal to about 10^2, where k_n and k_s are heat-conductivity coefficients for normal and superconducting states, respectively. The heat transport between JJS and a bulk sample is described by the equation

$$\dot{Q}=k'T \ , \tag{4}$$

where $\dot{Q}$ is a velocity of heat transport and $k'=kA/\Delta x$ is a heat-transport parameter. Here A is the area of junction, and Δx is the distance of the order of the junction thickness. The ΔT is the difference in temperature between two points in the distance Δx. A thermodynamic picture of interaction between the JJS, the microwave field, and the superconducting grains is shown in Fig. 7. Microwaves heat the Josephson junctions to the temperature T^* and among the junctions system, sample, and the microwave field, an equilibrium is achieved. It depends

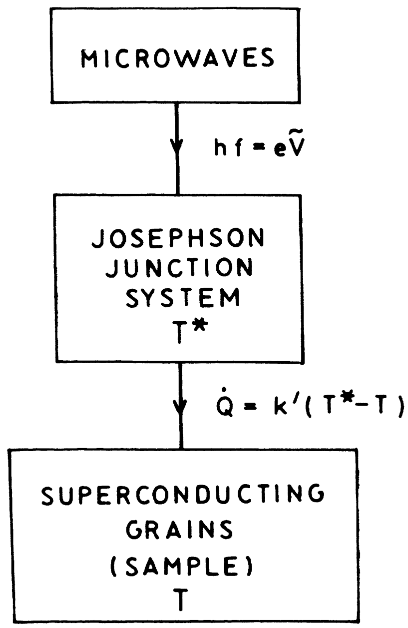

FIG. 7. Microwaves, the Josephson-junction system, and the bulk sample as three thermodynamic reservoirs interacting by the Josephson microwave absorption and the heat transport.

on the incident microwave power P:

$$\dot{Q}=aP \ , \tag{5}$$

where a is a fraction of the incident microwave power that is absorbed in JJS. In the equilibrium, the absorbed power emitted from JJS to the sample [Eq. (4)], and a difference between the JJS temperature T^* and sample temperature T is equal to

$$\Delta T = T^* - T = \frac{aP}{\kappa'} \ . \tag{6}$$

In our experiment (Fig. 2) we observe an appearance of the microwave absorption signal at $T^*=T_c$, which is different from the thermocouple measured temperature of a sample $T=T_{c\,\mathrm{eff}}$. Thus, from Eq. (6), one can calculate the temperature on which the JMA signal appears:

$$T_{c\,\mathrm{eff}} = T_c - \left| \frac{aP}{\kappa'} \right| \ . \tag{7}$$

Above $T_{c\,\mathrm{eff}}$ the JJS is in the normal state while the bulk sample is in the superconducting state.

From the data presented in Fig. 3 we can find the $|a/\kappa'|$ value as being 0.18 K/mW and 0.23 K/mW for the heating and cooling runs, respectively. The difference in slope between the lines in Fig. 2 reflects the thermal hysteresis, which is due to an influence of microwave power on the critical current I_c. It is well known[14,15] that the I_c value decreases proportionally to microwave power, thus the hysteresis effect can be written as

$$\delta(\Delta T) = bI_c \frac{dI_c}{dP} \delta P \ , \tag{8}$$

where $b=2R_J/\kappa'$. The slope of Eq. (8), $\delta(\Delta T)/\delta P$, has a constant value (Fig. 4) and it leads to $I_c \sim -\sqrt{P}$, which is in agreement with the experimental data for the first Shapiro step ($n=0$) in the current-voltage characteristic of a point junction.[16]

The granular superconductor consists of two systems: JJS and the grains. The JJS can be kept above its transition temperature by the microwave overheating on cooling the sample, in spite of the whole sample temperature being below the $T_{c\,\mathrm{bulk}}$. On warming through the superconducting state, the JJS follows after the bulk-grain system (which is mostly superconducting in this case), only slightly heated by the junctions. The nonlinear dependence of (dP/dB) on the microwave power P shown in Fig. 5 is waiting for an explanation.

CONCLUSION

The Josephson-junction system can be characterized by a local temperature T^*. The resonant microwave field, JJS, and the superconducting sample can be described as a thermodynamic system. The heating effect described in this paper is quite similar to a heating of JJS by the external dc flowing through a granular $YBa_2Cu_3O_{6.9}$ superconductor.[17,18] The observed thermal hysteresis shows that a microwave irradiation changes a character of the superconducting transition of the JJS from a continuous transition to a discontinuous one.

ACKNOWLEDGMENTS

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