PHYSICAL REVIEW B VOLUME 43, NUMBER 13 1 MAY 1991

Microwave transmission and harmonic generation in granular high-T_c superconducting films: Evidence for viscous flux motion and weak links

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(Received 27 August 1990; revised manuscript received 15 January 1991)

We have studied the microwave transmission τ through thin superconducting films of Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O in the presence of a dc magnetic field H_0 and an alternating magnetic field, $H_1 \cos 2\pi f_0 t$. The alternating field generates many harmonics due to the nonlinear response of the complex resistivity. The microwave transmission with $\mathbf{H}_0$ in the plane of the film depends on the orientation φ of $\mathbf{H}_0$ with respect to the microwave electric field. We found experimentally that the field-dependent part of the transmission behaves like $\delta\tau_f \propto |H_0 \sin\varphi|$. This indicates a macroscopic Lorentz force and strongly suggests that the complex resistivity in the magnetic field is dominated by a viscous-flux-motion dissipation mechanism. We demonstrate a simple model for the harmonic generation based on viscous fluxon motion. A comparison of the experiment with the model allows an estimate of the viscosity coefficient η for the fluxons in the direction of the c axis to be $\eta=(2-4)\times 10^{-9}$ cgs units for Y-Ba-Cu-O film at $T=70$ K. Theoretical models suggest that the magnitude of η is appropriate to weakly pinned Abrikosov fluxons. The dc transport properties of superconducting films containing internal Josephson junctions are strongly affected by microwave irradiation and serve, therefore, as a diagnostic tool to detect the presence of "weak links." Higher-order harmonics can be generated in all types of studied films independent of the presence or absence of weak links. However, in the presence of weak links, the onset temperature for the harmonic generation T_c' is lower than the onset temperature for the change in the microwave transmission, T_c. A simple model based on the granularity of the film can explain these observations.

I. INTRODUCTION

The resistvity of type-II superconductors in the presence of a magnetic field is generally attributed to several different dissipation mechanisms, including[1,2] "flux creep" when the fluxons hop between pinning sites, and "flux flow" when the fluxon viscosity dominates. Early dc-resistivity studies of high-temperature superconductors have shown that the resistivity is thermally activated.[3] This was initially interpreted in terms of flux-creep and flow models.[3,4] However, more recent studies[5–7] have shown that the dc resistivity is independent of a macroscopic Lorentz force, which is the driving force for the fluxon motion. This suggests that the dissipation mechanism in the dc-resistivity study is not associated with simple fluxon motion.[5] A mechanism caused by Josephson coupling between grains was suggested.[8] In view of the very unusual dissipation mechanism for dc and at low frequencies, it is of much interest to explore the dissipation mechanism at high frequencies and especially in the microwave range, where flux creep does not occur.[4,9] A model by Gittleman and Rosenblum[10] has predicted that in type-II superconductors the fluxon motion is dominated by pinning forces at low frequencies, but by viscous forces at high frequencies. The crossover frequency was estimated to be several megahertz for conventional superconductors[10] and $\sim$40 GHz for high-temperature superconductors.[11] However, today no clear picture of the dissipation mechanism in the microwave resistivity is available for high-T_c superconductors. A knowledge of the complex resistivity in the microwave range is important, because it also provides a basis for the development of many practical devices, such as transmission lines, filters, microwave cavities, etc.

An elegant method to measure the complex resistivity in the microwave range is by a microwave transmission experiment through thin superconducting films.[12] Recently, we have shown[13,14] that microwave transmission through high-T_c superconducting films is field dependent. Furthermore, we have demonstrated[13,14] that the microwave transmission can be modulated by an alternating magnetic field, $H_1\cos 2\pi f_0 t$, with the generation of many even harmonics in the low-frequency spectrum of the transmitted microwave. Additional odd harmonics are observed in the presence of a dc field H_0. A flux-flow mechanism was suggested to explain the field-dependent microwave transmission and the harmonic generation, although the importance of "weak links" and internal Josephson junctions in the harmonic generation could not be ruled out.[14] Both fluxon resistivity and the internal Josephson junctions are very sensitive to magnetic field. However, the former mechanism can be critically checked by the existence of a Lorentz-type force between the microwave current and the fluxons. In our early ex-

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periments the magnetic field was mostly perpendicular to the film, and the validity of the Lorentz term could not be checked experimentally.

The aim of this paper is to provide evidence that the magnetic-field-dependent part of the complex resistivity in the microwave range, as measured by microwave transmission and harmonic generation, is dominated by a viscous-flux-motion dissipation mechanism. Another purpose of this paper is to clarify the importance of weak links or internal Josephson junctions in the harmonic generation. The strategy of the paper is as follows: In Sec. II we present a simple model for the microwave transmission, the complex resistivity, and the harmonic generation. Section III describes the experimental setup that we have used to carry out three different experiments; namely (a) microwave transmission through thin films in the presence of a dc magnetic field in the plane of the film, (b) harmonic generation, and (c) dc transport properties in the presence of microwave irradiation. Section IV provides experimental results and comparison with the model. Conclusions are given in Sec. V.

II. MODEL

A. rf fluxon resistivity

We adapt the model of Gittleman and Rosenblum[10] to calculate the fluxon rf resistivity of a thin superconducting film in the presence of a magnetic field. This model was recently used to describe the rf properties of high-T_c superconductors.[14–16] According to this model, the classical equation of motion for an isolated flux line is given by[10]

$$\mu\ddot{x}+\eta\dot{x}+kx=\frac{1}{c}(\mathbf{J}\times\boldsymbol{\phi}_0)\ , \qquad (1)$$

where x is the fluxon displacement, μ is the fluxon inertia per unit length, η is the viscosity coefficient, k is the pinning force coefficient, $\mathbf{J}$ is the microwave current density, $\boldsymbol{\phi}_0$ is the vector whose magnitude is equal to the flux quantum, and parentheses on the right-hand side indicate a cross-product Lorentz force. The moving fluxons produce an electric field that opposes the current: $E=-\dot{x}\phi_0 n_f(H)/c$ where $\dot{x}$ can be obtained from the above differential equation (1) as follows:

$$\dot{x}=(J\phi_0/c)(\sin\varphi)(-i\omega\mu+\eta+ik/\omega)^{-1}\ .$$

Here φ is the angle between the fluxon direction (i.e., the magnetic field direction) and the microwave current. One observes an expression for the fluxon resistivity at a frequency ω, neglecting the inertia term,[17] as follows:[10,14]

$$\rho_f=\frac{E}{J}=\frac{i\omega t_0}{1+i\omega t_0}\frac{\phi_0^2 n_f(H)}{c^2\eta}|\sin\varphi|=\rho_{f1}+i\rho_{f2}\ , \qquad (2)$$

where $n_f(H)$ is the fluxon density, t_0 is given by the ratio $t_0=\eta/k$, and ρ_{f1} and ρ_{f2} are the real and imaginary parts of the fluxon complex resistivity. According to Ref. 18, $n_f(H)=f|H|/\phi_0$, where f is the fraction of free or weakly pinned fluxons. It is clearly seen from Eq. (2) that pinning forces dominate for $\omega t_0 \ll 1$, while for $\omega t_0 \gg 1$ viscous forces prevail. For conventional superconductors the crossover frequency[10] is $\approx 10^7$ Hz. Recent estimates[11,16] for the high-T_c superconductors suggest that for single crystals the crossover frequency is $\approx 10^{11}$ Hz. However, for weakly pinned fluxons in polycrystalline superconducting ceramic this frequency was estimated[16] to be $\approx 10^7-10^8$ Hz. The observation of second-harmonic generation[19] at 3 GHz provides evidence that the crossover frequency in polycrystalline material is lower than 3 GHz. We shall assume, therefore, that the crossover frequency for weakly pinned fluxons is lower than 10 GHz, i.e., $\omega t_0 \gg 1$. Under this assumption $\rho_{f1} \gg \rho_{f2}$, and one obtains for the flux resistivity

$$\rho_{f1}=\frac{\phi_0|H\sin\varphi|f}{c^2\eta}\ . \qquad (3)$$

B. Microwave transmission

The microwave transmission τ and the phase shift θ through a thin film of thickness d mounted across a waveguide with impedance Z_0, is given[20] by

$$\tau=\left[\left[1+\frac{\sigma_1 dZ_0}{2}\right]^2+\left[\frac{\sigma_2 dZ_0}{2}\right]^2\right]^{-1}, \qquad (4)$$

where $\sigma=\sigma_1-i\sigma_2$ is the complex conductivity of the film. Equation (4) assumes an extremely thin substrate, e.g., $ql \ll 1$, where q is the wave vector in the substrate and l is the substrate thickness. For the phase shift θ we obtain

$$\theta=-\text{acrtan}\left[\frac{\sigma_2 dZ_0}{2+\sigma_1 dZ_0}\right]. \qquad (5)$$

For a BCS superconductor[21] and for $T_c > T > 0.8T_c$, the value of σ_1 is of the same order of magnitude as the normal-state conductivity σ_n. Therefore, for sufficiently highly conducting films the inequality $\sigma_1 dZ_0 \gg 1$ holds at least for $T > 0.8T_c$. Then the microwave transmission, according to Eq. (4), is directly related to the complex resistivity ρ [$\rho=(\sigma-i\sigma_2)^{-1}$] as follows:

$$\tau=\frac{4|\rho|^2}{d^2Z_0^2}\ . \qquad (6)$$

In the presence of fluxons and for temperatures lower than T_c (but not low enough to violate the relation $\sigma_1 dZ_0 \gg 1$) Eq. (6) should be written as[18]

$$\tau=\frac{4|\rho+\rho_f|^2}{d^2Z_0^2}\ , \qquad (7)$$

where ρ is the bulk complex resistivity ($\rho=\rho_1+i\rho_2$) and ρ_f is the fluxon complex resistivity. The field-dependent part of the transmission, $\delta\tau_f$, can be estimated by subtracting (6) from (7). At low magnetic fields, such that $\rho_f \ll \rho$, one observes

$$\delta\tau_f=\tau(H)-\tau(H=0)\approx\frac{8}{d^2Z_0^2}(\rho_1\rho_{f1}+\rho_2\rho_{f2})\ . \qquad (8)$$

We demonstrated above that for weakly pinned fluxons at microwave frequencies, pinning can be neglected, e.g., $\rho_{f1} \gg \rho_{f2}$. Then, for $T > 0.8T_c$ one obtains

$$\delta\tau_f = \frac{8\rho_1\rho_{f1}}{d^2 Z_0^2} = \frac{8\rho_1\phi_0 f}{d^2 Z_0^2 c^2 \eta} |H \sin\varphi| \ . \tag{9}$$

C. Harmonic generation

As demonstrated above, the transmission τ is field dependent through the dependence of the fluxon resistivity ρ_{f1}. Therefore, a magnetic field of the form $\mathbf{H} = \mathbf{H}_0 + \mathbf{H}_1 \cos(2\pi f_0 t)$ can modulate the microwave transmission and generate harmonics. For the special case that both dc and ac fields are perpendicular to the plane of the film, one may observe for the fluxon resistivity

$$\rho_f = \alpha |\mathbf{H}_0 + \mathbf{H}_1 \cos 2\pi f_0 t| \ , \tag{10}$$

where $\alpha = \phi_0 f / c^2 \eta$. We have already emphasized[14] that expression (10) yields even harmonics in microwave transmission for $H_0 = 0$, even and odd harmonics for $|H_0| < H_1$, and only the fundamental frequency for $H_0 > H_1$.

The fluxon resistivity [Eq. (10)] can be expressed as a Fourier sum as follows:

$$\rho_f = \sum_n h_n \cos 2\pi n f_0 t \ , \tag{11}$$

where the coefficients h_n determine the amplitudes of the nth harmonics. The coefficients h_n are obtained by a Fourier transform of (10). For $H_1 > H_0$ we obtain

$$h_1 = \alpha H_1 \left[\frac{2\gamma - \sin 2\gamma - \pi}{\pi} \right] , \tag{12}$$

$$h_{n\neq 1} \frac{4\alpha H_1}{\pi(n^2-1)} \left[\cos n\gamma \sin\gamma - \frac{\sin n\gamma \cos\gamma}{n} \right] , \tag{13}$$

where

$$\gamma = \cos^{-1}(-H_0/H_1) \ . \tag{14}$$

For the case $|H_0| > H_1$ we find

$$h_1 = \alpha H_1 \ , \tag{15}$$

$$h_{n\neq 1} = 0 \ . \tag{16}$$

For large n and for $|H_0| < H_1$, h_n is an oscillatory function of H_0 with a quasiperiod of oscillation $\delta H_0 = 2\pi H_1 / n$. This behavior was demonstrated in our previous paper.[14] The intensities of the nth harmonics decrease approximately as $1/(n^2-1)$ [Eq. (13)].

III. SAMPLES AND EXPERIMENTAL PROCEDURES

As the presence of weak links is associated, presumably, with the granularity of the high-T_c superconductors, we have used several thin films with different degrees of granularity. We have studied Y-Ba-Cu-O films prepared either by spray pyrolysis method[22] or by Metalloorganic chemical vapor deposition[23] (MOCVD) and Bi-Sr-Ca-Cu-O films prepared by the spray pyrolysis[24] on a MgO substrate with a thickness of 1 mm. Both methods of preparation are known to yield granular films. The films, obtained by spray pyrolysis, are 1–3 μm thick and exhibit large grains and a certain amount of pinholes. The MOCVD films are 0.3–0.5 μm thick with a low quantity of pinholes. The surface of these films is rough and the grain size is $\approx 1-3$ μm. At least six films of Y-Ba-Cu-O and three films of Bi-Sr-Ca-Cu-O have been studied with consistent results. Here we emphasize our measurements on Y-Ba-Cu-O films obtained by MOCVD method, which contain a significant concentration of weak links (as we shall demonstrate), and a film of Bi-Sr-Ca-Cu-O obtained by spray pyrolysis, which presumably does not contain weak links. X-ray measurements indicate the Y-Ba-Cu-O films are preferentially oriented with the c axis perpendicular to the film. The Bi-Sr-Ca-Cu-O films, doped with Pb, are unoriented and contain a mixture of 2:2:1:2 and 2:2:2:3 phases.[24] The dimensions of the films are 1×1 cm^2; the sheet resistance at 300 K is in the range 20–100 Ω. The experimental setup was described previously.[13] Here we just provide a short outline for the different experiments.

For the studies of the microwave transmission the film-substrate combination was glued, using silver paint, to the circular iris with the film facing the iris and placed across the waveguide as shown in Fig. 1(b) (lower panel). This type of arrangement prevents any microwave leaks except through the film and the iris hole. A dc magnetic field up to 500 G can be rotated in the plane of the film. The microwave transmitted power is picked up electrically by a detector. The microwave source is a klystron

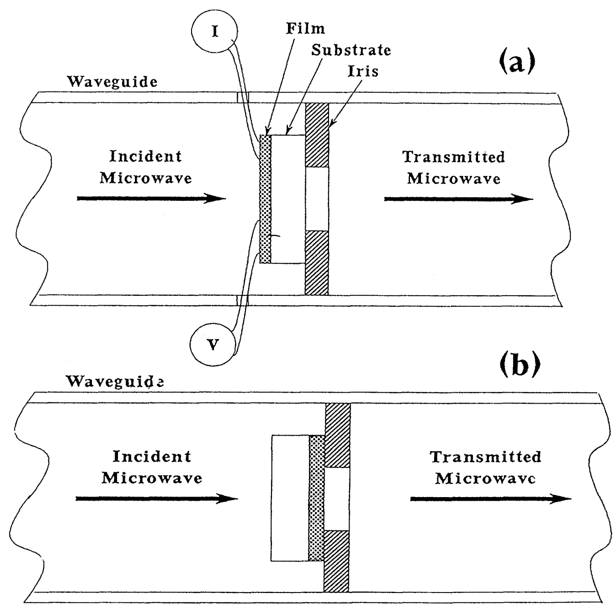

FIG. 1. Experimental setup. (a) A schematic description of the setup for the dc transport measurements in the presence of microwave irradiation. (b) A schematic description of the setup for the microwave transmission and harmonic generation experiments. The direction of microwave incidence in both cases may be reversed.

operating at 9.2 GHz. The maximum incident power is ~ 100 mW. The films used have a much lower sheet resistance than the impedance of the waveguide ($Z_0 \sim 600\ \Omega$). Therefore, the condition $\sigma_1 d Z_0 \gg 1$ is valid here.

Harmonic generation by field modulation was measured using a spectrum analyzer or a lock-in amplifier after the crystal detector (see Fig. 1 of Ref. 13). The ac magnetic field, $H_1\cos 2\pi f_0 t$ ($H_1 < 90$ G, 10 Hz $< f_0 < 5$ kHz) perpendicular to the film is produced by a coil whose axis is along the waveguide. A colinear dc magnetic field H_0 was produced by independent coils.

I versus V characteristics and dc resistivity versus temperature were obtained in the presence (or absence) of microwave irradiation. We have used a four-probe technique in the Van der Pauw geometry and indium contacts. The film-substrate combination was glued to the circular iris across the waveguide with the substrate facing the iris as shown in Fig. 1(a) (upper panel).

IV. RESULTS AND COMPARISON TO THE MODEL

A. Microwave transmission and harmonic generation

The inset in Fig. 2 shows the variation of the microwave transmission versus the in-plane dc magnetic field $\mathbf{H}_0$ at a particular temperature for Y-Ba-Cu-O film and for $\mathbf{H}_0$ perpendicular to the microwave current ($\varphi = 90°$). As clearly seen, the transmission is field dependent and shows hysteretic behavior as a function of field. The transmission strongly depends on the orientation of the in-plane field with respect to the microwave current. In Fig. 2 we have plotted $d\tau/dH$ (as determined from the linear part of τ versus H; see inset, Fig. 2) versus the magnetic field orientation φ with respect to the microwave current in the film $\mathbf{I}_{mw}$. As is clearly seen, $d\tau/dH$ is roughly proportional to $|\sin\varphi|$, where φ is the angle between $\mathbf{H}_0$ and $\mathbf{I}_{mw}$. Results on Bi-Sr-Ca-Cu-O (not shown here) exhibit similar behavior to that shown in Fig. 2.

The harmonic generation is a very sensitive method to study the effects of small magnetic fields on the microwave transmission. In the presence of an ac field, $H_1\cos 2\pi f_0 t$, the transmitted microwave is modulated in the superconducting state and its low-frequency spectrum contains many even harmonics. Figure 3 exhibits the various harmonics (nf_0, $n = 2,4,6,\ldots$) in the presence of an alternating field. Note that the intensity of the harmonics decreases with n according to $1/(n^2-1)$ (see dashed line in Fig. 3). In the presence of an additional dc field H_0, colinear with H_1, additional odd harmonics appear. After a removal of H_0 these odd harmonics remain, although their intensities somewhat decrease (see inset in Fig. 3). This effect occurs at sufficiently low temperatures and clearly demonstrates irreversibilities.

Figures 4 and 5 show the temperature dependences of the microwave transmission, dc resistivity, and second-harmonic amplitude for Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O thin films, respectively. As is clearly seen, the onset for the change in the microwave transmission occurs at the same temperature T_c at which superconductivity starts (as measured by dc resistivity versus temperature). Note, however, that for Y-Ba-Cu-O (Fig. 4) the onset temperature for the second-harmonic generation T_c' is lower than the onset temperature for the change in the dc resistivity T_c, while for Bi-Sr-Ca-Cu-O (Fig. 5) the onset temperature for both the harmonic generation and the change in the resistivity is the same, namely, $T_c' = T_c$. The phase shift θ in Y-Ba-Cu-O also drops in the superconducting state, but the onset of this drop occurs at T_c', and not at T_c.

The angular dependence of the magnetic-field-dependent microwave transmission, as well as the linear dependence of the transmission on $|H|$ (Fig. 2), confirm the theoretical model [Eq. (9)]. This result indicates a Lorentz force and strongly supports the idea that the field dependence of the microwave transmission is due mostly to viscous flux motion. The finite value of $d\tau/dH$ observed for $\varphi = 0$ (Fig. 2) is probably due to the fact that

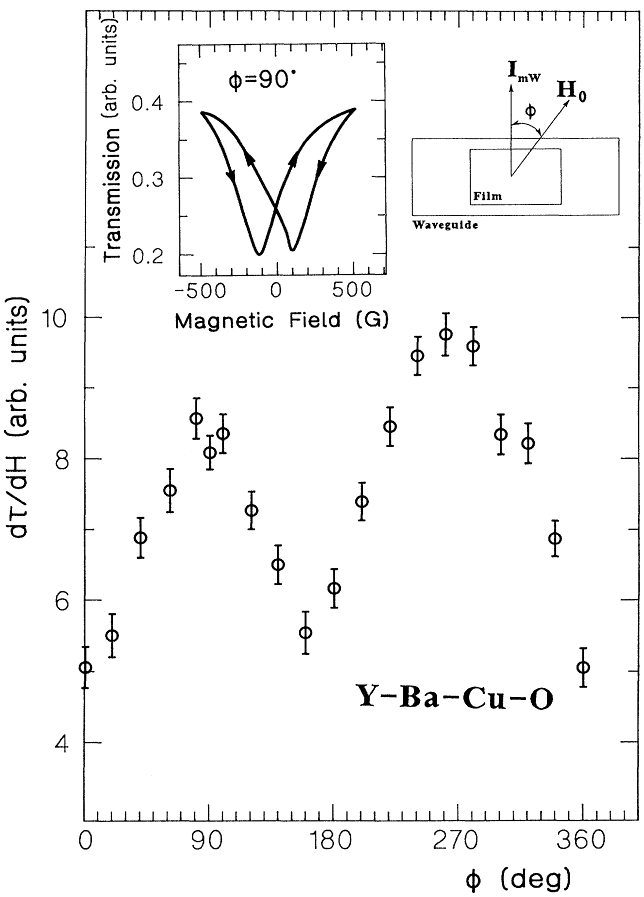

FIG. 2. The angular dependence of $d\tau/dH$ at temperature $T = 63$ K for Y-Ba-Cu-O (sample 1). The angle ϕ between the microwave current, $\mathbf{I}_{mw}$ and magnetic field in the plane of film $\mathbf{H}_0$ is defined at the right-hand side of the upper panel. $d\tau/dH$ was determined from the field dependence of the transmission. The inset shows the microwave transmission τ versus dc magnetic field (in the plane of the film) at $T = 63$ K and $\phi = 90°$. These measurements were carried out by sweeping the field at a rate of 5 G/sec.

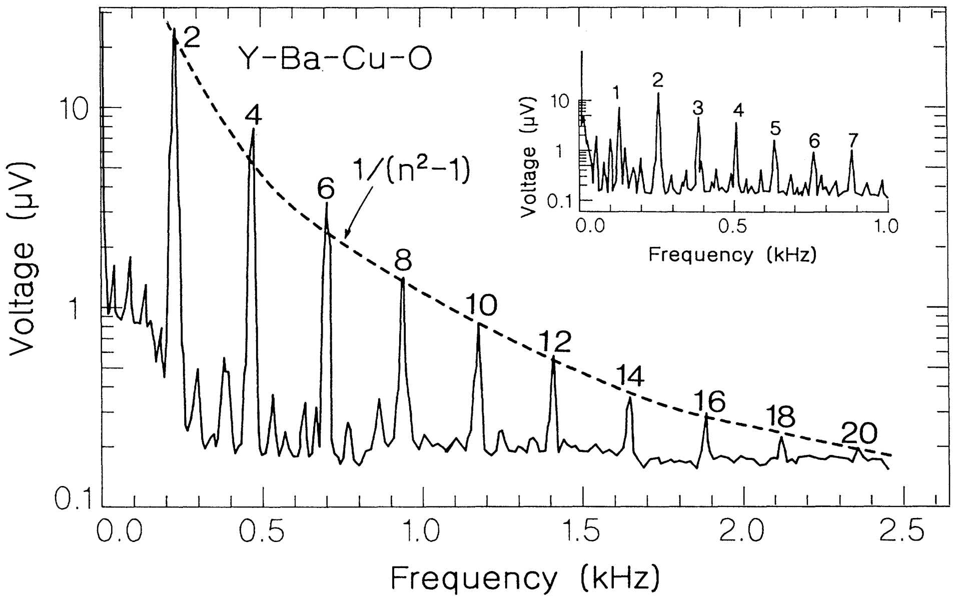

FIG. 3. Low-frequency spectrum of the transmitted microwave power through Y-Ba-Cu-O (sample 3) in the presence of an ac magnetic field, $H_1\cos(2\pi f_0 t)$. $f=128$ Hz, $H_1=70$ G, $T=71$ K. The ac magnetic field is perpendicular to the film ($\mathbf{H}\|\mathbf{c}$). The inset shows the same spectrum but after applying and removing of a dc magnetic field, $H_0=100$ G, perpendicular to the film. Note the appearance of odd harmonics in the inset.

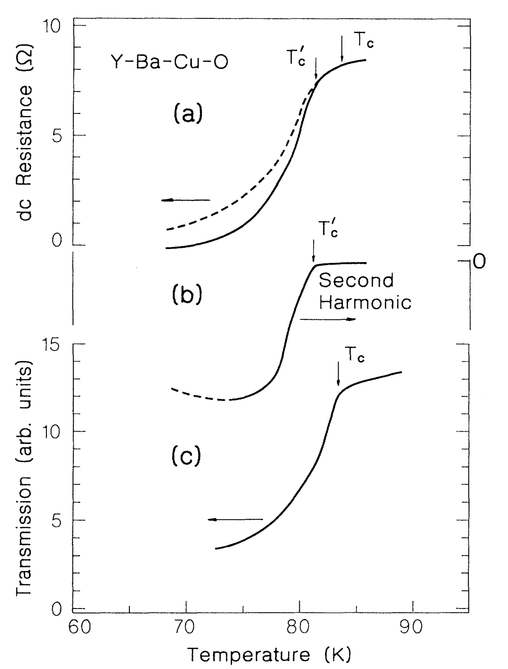

FIG. 4. Temperature dependence of (a) resistance, (b) second harmonic, and (c) microwave transmission for Y-Ba-Cu-O (sample 2). The resistance was measured at 1.3 kHz, using current 23 μA. The dotted line shows the resistance in the presence of microwave power (incident power 100 mW). The second harmonic in microwave transmission is obtained in an ac magnetic field perpendicular to the film ($\mathbf{H}\|\mathbf{c}$), $f=130$ Hz, $H_1=8$ G.

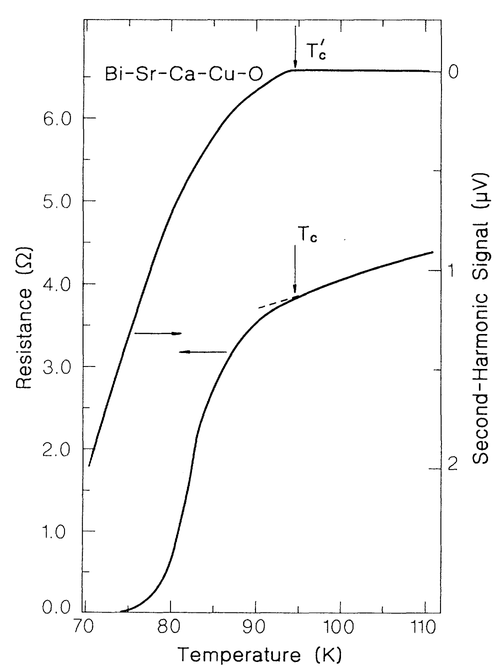

FIG. 5. Temperature dependence of (a) dc resistance in the presence and absence of microwave irradiation, (b) second harmonic for Bi-Sr-Ca-Cu-O (sample 2) film. $H_1=38$ G, $f=130$ Hz. The resistance is measured with the current of 0.5 mA. Second harmonic in microwave transmission is obtained in an ac magnetic field perpendicular to the film.

$\mathbf{I}_{mw}$ is not unidirectional across the sample, but may exhibit some curvature due to boundary effects (probably due to the metallic glue at the sample edges). The dependence of the microwave resistivity on the direction of $\mathbf{H}_0$ is in apparent contradiction with dc measurements,[6] which demonstrate that dc resistivity does not depend on the direction of the in-plane magnetic field. This conflict can be reconciled if we take into account the different mechanisms of fluxon resistivity at dc and at high-frequency measurements. Fluxon resistivity at low frequencies is due to fluxon jumps above a certain pinning potential, i.e., flux creep. However, fluxon resistivity at high frequencies is determined by viscous losses of fluxons oscillating with small amplitudes and is independent of the pinning potential.

The harmonic generation in an ac magnetic field is fairly well described by our model. Particularly, the amplitude of the harmonics (Fig. 3) is in fair agreement with Eq. (10). The dependence of the harmonics on the magnitude of H_0 and H_1 was discussed elsewhere,[14] and we shall not discuss it further here.

The agreement between the experimental results and the model of viscous flux motion allows an estimate of the viscosity coefficient η for temperatures not very close to T_c. For fluxons in the direction of the c axis, we can roughly estimate ρ_f and η from the field-dependent part of the microwave transmission, $d\tau_f$, using Eqs. (6) and (9). We obtain

$$\eta=\frac{8\phi_0\rho_1 H_1 f}{c^2 d^2 Z_0^2 \delta\tau_f} . \tag{17}$$

$\delta\tau_f$ can be determined from the measured intensity of the harmonics using Eqs. (9), (11), and (13). For Y-Ba-Cu-O at $T=85$ K the normal-state microwave transmission was measured to be $\tau_n=6\times10^{-3}$. For the same film in the superconducting state at $T=70$ K, in the presence and in the absence of a small magnetic field $H_1=23$ G, we have measured $\tau_s=4\times10^{-4}$, $\theta_n-\theta_s=15°$, and $\delta\tau_f=2.5\times10^{-6}$. The resistivities ρ_n and ρ_1 [from Eqs. (4) and (5)] are estimated to be $\rho_n=2.3\times10^{-3}$ Ω cm and $\rho_1=6.3\times10^{-4}$ Ω cm (for $d=10^{-4}$ cm). Assuming $\rho_{f1}\gg\rho_{f2}$, $f=1$, we finally obtain $\eta=2.6\times10^{-9}$ cgs units for fluxons in the c direction in Y-Ba-Cu-O at $T=70$ K. The value of η is even lower if we assume $f=0.1$.[18]

B. Transport properties

Figure 6 (lower panel) describes our experimental results for *I-V* curves for Y-Ba-Cu-O thin film in the absence and in the presence of microwave irradiation. We note that the microwave irradiation dramatically suppresses the critical current in the case of Y-Ba-Cu-O. Figure 7 demonstrates the dependence of the critical current on the microwave amplitude for Y-Ba-Cu-O. The microwave markedly affects *I-V* curves also for $I>I_c$ (Fig. 6), leading to an apparent increase of resistance. Figure 4 shows the temperature dependence of resistance in the presence and in the absence of microwave irradiation for the Y-Ba-Cu-O film. Note that the microwave-induced resistance appears first at T_c', which is slightly lower than T_c (the onset temperature for the superconductivity), but is the same as the onset temperature for the second-harmonic generation.

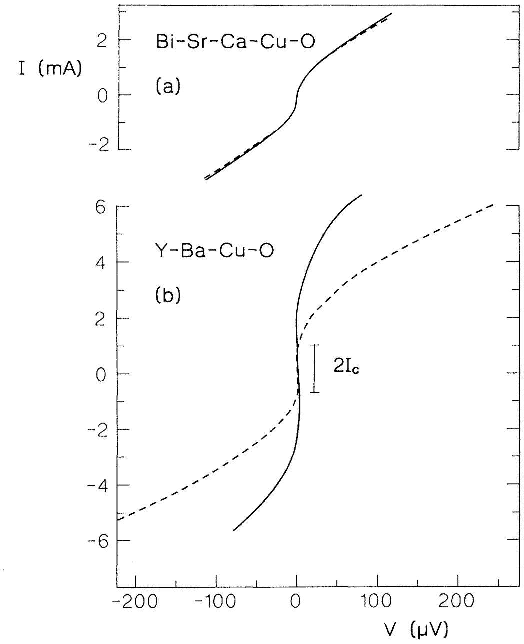

FIG. 6. Effect of microwave irradiation on *I-V* curves: (a) Bi-Sr-Ca-Cu-O (sample 2) at $T=67$ K, T_c (onset)$=93$ K. (b) Y-Ba-Cu-O (sample 1) at $T=65$ K, T_c (onset)$=82$ K. Solid lines: *I-V* curves in the absence of the microwave. Dotted lines: *I-V* curves in the presence of the microwave. Microwave intensity is 100 mW; frequency is 9.2 GHz.

In contrast to the case of Y-Ba-Cu-O, where microwave irradiation strongly affects the *I-V* curves, no such effect was observed for our Bi-Sr-Ca-Cu-O film (Fig. 6, upper panel).

Similar effects (microwave-induced resistance) were observed earlier for granular high-T_c superconductors.[25,26]

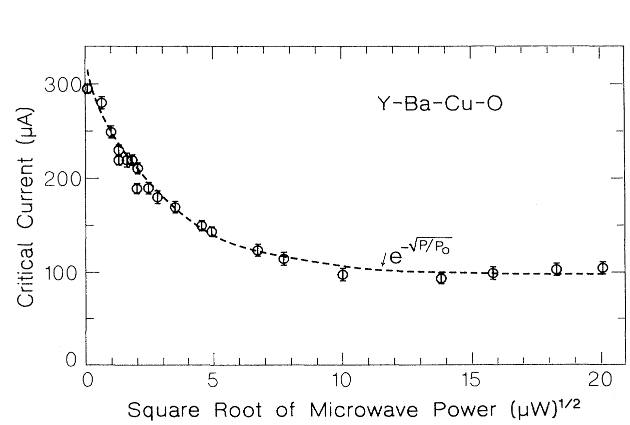

FIG. 7. Critical current vs square root of the microwave power for Y-Ba-Cu-O (sample 1) at $T=65$ K. The microwave power is measured after the film.

It was demonstrated[25] that these effects are associated with the presence of internal Josephson junctions and are not related to the heating of weak links due to the microwave absorption.[27] We take the data in Fig. 6 as evidence for the presence of the weak links in our Y-Ba-Cu-O films and their absence in our Bi-Sr-Ca-Cu-O films.

Recently Sobolewski[28] has measured the critical current suppression upon microwave irradiation and was able to explain this suppression in granular high-T_c films assuming a simple model. This model considers the film as a two-dimensional array of Josephson junctions. It is well known that microwave irradiation on a single Josephson junction leads to an oscillatory dependence of the critical current on the microwave voltage.[29] Sobolewski[28] has demonstrated that microwave irradiation on an array of junctions leads to averaging and "smearing" of the oscillatory behavior expected for a single junction. Furthermore, Sobolewski[28] has demonstrated that under certain conditions the averaging procedure can give for the critical current I_c versus the microwave power P the following expression:

$$I_c = I_{0c}\exp(-\sqrt{P/P_0}) \ . \tag{18}$$

This dependence of I_c on P is different from the exponential behavior: $I_c = I_{0c}\exp(-P/P_0)$, suggested by Tinkham, Octavio, and Skocpol[27] for the case of the heating of the weak links caused by microwave absorption. Our experimental results in Fig. 7 (except for the very small microwave levels) could be fitted with the empirical expression

$$I_c = I_1 + I_0\exp(-\sqrt{P/P_0}) \ , \tag{19}$$

and thus agree with the model of Sobolewski.[28] Also, we believe that the absence of Shapiro steps in the I-V characteristics (Fig. 6) is caused by the averaging phenomena similar to that suggested by Sobolewski.[28] The presence of the I_1 [Eq. (19)] may be attributed to conducting paths without weak links.

V. DISCUSSION

A. Fluxon viscosity

It is of interest to compare our experimental value for the viscosity coefficient with other theoretical estimates, particularly for Abrikosov fluxons and Josephson fluxons. The semiempirical relation of Bardeen and Stephen[1] predicts, for the Abrikosov lattice of fluxons,

$$\eta = \phi_0 H_{c2}/c^2\rho_n \ , \tag{20}$$

where H_{c2} is the upper critical field and ρ_n is the normal-state resistivity. Using[30] $(dH_{c2}/dT)_{T=T_c} = (0.5-1.9)$ T/K for Y-Ba-Cu-O in the direction of the c axis and the measured value of $\rho_n = 2.3\times10^{-3}$ Ω cm, we estimate $\eta \approx (4-16)\times10^{-9}$ cgs units for $T=70$ K ($T_c - T = 10$ K). Thus the value of η obtained from our experiments for fluxons parallel to the c axis is small by 1 order of magnitude compared to estimates based on the Bardeen-Stephen theory for Abrikosov vortices. The difference may be related to the layered structure of oxide superconductors. Indeed, recent calculations of Clem and Coffey[31] for fluxon viscosity in layered superconductors with Josephson-coupled layers indicate that at least for fluxons within superconducting layers the viscosity may be 1 order of magnitude different from that given by the Bardeen-Stephen theory.

For fluxon viscosity in a Josephson junction, Portis and Blazey[32] have calculated

$$\eta = \phi_0 Hs/(R_n c^2) \ , \tag{21}$$

where R_n is the normal-phase tunneling resistance across the junction, and s is the distance of the magnetic field penetration in the vicinity of the junction. An estimate, using Eq. (21), yields for η a value which is 5 orders of magnitude lower than the fluxon viscosity in the bulk [Eq. (20)], e.g., $\eta \approx 10^{-13}$ cgs units. This value is 4 orders of magnitude smaller than our experimental estimate.

Finally, Sonin and Tagantsev[33] have treated a granular superconductor as a Josephson medium and found for η the following expression:

$$\eta = \phi_0^2/c^2\rho_n d^2 \ , \tag{22}$$

where d is the grain size. Using measured values of ρ_n, Eq. (10) gives $\eta = 1.5\times10^{-12}$ cgs units. This value is 3 orders of magnitude lower than our experimental value.

We conclude, therefore, that the magnetic-field-dependent microwave transmission and harmonic generation in our films are mainly associated with weakly pinned Abrikosov vortices and not with the Josephson vortices.

B. Evidence for granular effects

An interesting feature of our experimental results is the different onset temperatures for the harmonic generation (T_c') and the change in the microwave transmittance (T_c) for Y-Ba-Cu-O (Fig. 4) for which evidence of weak links exists, but the same onset temperature ($T_c' = T_c$) for Bi-Sr-Ca-Cu-O, for which there is no evidence of weak links (Fig. 5). Different onset temperatures for the dc resistance and for magnetic-field-sensitive microwave properties in granular superconductors have been observed earlier,[34,35] but the origin of this fact was not well understood.

In granular superconductors with weakly coupled grains there are two different superconducting transition temperatures associated with the grains themselves, T_c, and with intergrain regions, T_c' ($T_c' < T_c$).[36] Let us consider such a granular film in a perpendicular field (Fig. 8). In the normal state [Fig. 8(a)] the magnetic field uniformly penetrates the film. For $T_c' < T < T_c$ the grains are superconducting, but the intergrain regions are not. The magnetic field penetrates into the intergrain region, but is almost completely expelled from the grains [Fig. 8(b)] (assuming that the demagnetization factor of a single grain is $\ll 1$). Certainly, there are no fluxons, and no harmonic generation is expected in this temperature range. However, for $T < T_c'$, the grains are coupled and the field penetrates into superconducting regions (due to the

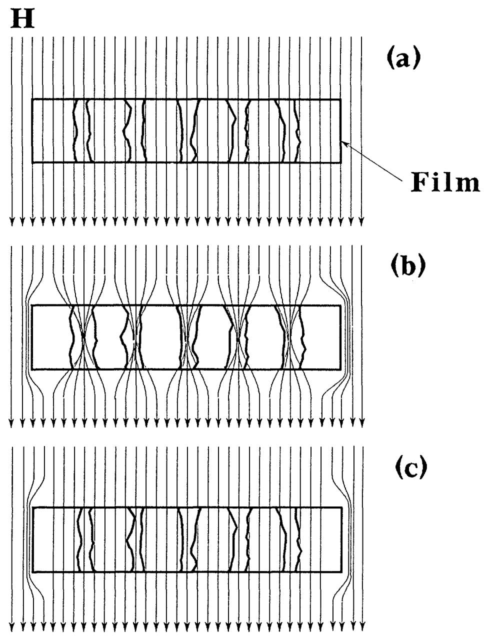

FIG. 8. A model description of the magnetic field penetration into the thin granular superconducting film at different temperatures. The plane of the film is perpendicular to the paper. (a) $T > T_c$, normal state, (b) $T_c' < T < T_c$, superconducting state, decoupled grains, and (c) $T < T_c'$, superconducting state, coupled grains.

demagnetization factor of a thin film in a perpendicular field). Fluxons in the intra- and intergrain regions are formed, and harmonic generation occurs due to dissipation associated with viscous fluxon motion. The fact that microwave irradiation affects the transport properties only below T_c' (Fig. 4) provides further evidence that the intergrain regions behave like Josephson junctions only below T_c'. Certainly, for such a granular film one expects both the microwave transmission and the dc resistivity to drop already at T_c, as observed experimentally in Y-Ba-Cu-O. For Bi-Sr-Ca-Cu-O, for which no strong evidence of weak links exist (the I-V curve is not affected by microwave irradiation) (Figs. 5 and 6), the perpendicular magnetic field penetrates into superconducting regions and forms fluxons already below T_c. The onset temperature for the harmonic generation in this case is almost identical to the onset temperature for the change in the transmission. It is probably due to the fact that the intergrain coupling in Bi-Sr-Ca-Cu-O is strong,[28] and grain boundaries are not weak links.

VI. SUMMARY

(a) Microwave transmission in the presence of in-plane dc field $\mathbf{H}_0$ is very sensitive to the orientation of the magnetic field with respect to the microwave current $\mathbf{I}_{\mathrm{mw}}$, indicating a Lorentz force at microwave frequencies. This fact, together with the almost linear dependence of the microwave transmission on the magnitude of the field (and not on its sign), provides strong evidence that the magnetic-field-dependent complex resistivity is dominated by fluxon motion. (b) Harmonic generation in microwave transmission in the presence of alternating and dc magnetic fields can be explained by the fluxon motion mechanism. The model can explain most of the experimental features even in the irreversible regime. (c) The viscosity coefficient in Y-Ba-Cu-O for weakly pinned Abrikosov fluxons in the direction of the c axis at 70 K is $(2-4)\times 10^{-9}$ cgs units. (d) The microwave irradiation effect on the transport properties provides excellent diagnostic tools to detect the presence of weak links. (e) The presence of weak links is not essential for harmonic generation. (f) The different onset temperatures for the harmonic generation, T_c', and the microwave transmission, T_c, in granular Y-Ba-Cu-O films are explained by the fact that for $T_c' < T < T_c$ magnetic field penetrates into the intergrain regions without forming fluxons.

ACKNOWLEDGMENTS

We are grateful to Professor P. Monod, Professor M. Weger, Professor Y. Yeshurun, and Dr. L. Burlachkov for useful discussions.

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