Flux-creep dissipation in Y-Ba-Cu-O superconductors at microwave frequencies

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Microwave measurements of the absorbed power in granular Y-Ba-Cu-O samples for temperatures in the range 1–50 K are reported. The hysteretic behaviors observed are attributed to the fluxon motion in the flux-creep regime. A calculation of the surface resistance, based on the hypothesis of validity of the Bean model and which qualitatively explains the experimental results, is given. The potential of the surface-resistance measurement technique at microwave frequencies to detect various types of losses (flux creep, flux flow, and Josephson-junction dephasing) is discussed.

I. INTRODUCTION

The resistive losses in the presence of an external magnetic field for traditional type-II superconductors in the mixed state have been attributed to two different processes, both connected to the existence of flux lines (vortices). In one case, the energy dissipation in the limit of unpinned fluxon motion is due to the viscous drag force on the fluxons which opposes the Lorentz-like force and is directed along the transport current (flux-flow regime). In the other case, the pinning centers are active, the fluxons become trapped and the motion is possible only when the thermal fluctuations are effective (flux-creep regime).

In the flux-creep regime, the Anderson-Kim model[1] considers a single flux line trapped at a pinning side and introduces the escape rate ν due to the thermal activation $\nu=\omega_0\exp(-U/k_BT)$, where ω_0 is the attempt frequency and U is the pinning energy barrier. It is then possible to obtain an equivalent resistivity $\rho_C=\rho_0\exp(-U/k_BT)$ for the resistive losses. This model has been successfully applied to the high-T_c superconductors (HTSC's) with some limitations and modifications to interpret both the magnetization measurements and, near the transition temperature T_{c0}, the dc resistive measurements.[2] The behavior of the pinning energy U as a function of temperature T and magnetic field H has been extensively studied.[2,3] To maintain the validity of the model of the thermally activated flux motion, an anomalous dependence of the pinning energy as a function of T must be assumed.[4] With the hypothesis of a distribution of pinning energies, Hagen and Griessen[5] are able to interpret the experimental results of the time-dependent decreasing of the remanent magnetization.

In the flux-flow regime, following the Bardeen-Stephen model, the direct-current resistivity is given by $\rho=\rho_nB/B_{c2}$, where ρ_n is the normal-state resistivity, B the magnetic field, and B_{c2} the upper critical field. This model is hard to be directly tested in HTSC's, due to the extremely high value of B_{c2} for T not close to T_{c0}. However many works[6,7] show that, near T_{c0}, a transition from a dissipative state to a superconductive one can be interpreted as a transition from a flow to a pinning phase. Furthermore, close to T_{c0}, the H-T vortex phase diagram becomes very complicated,[8] and the existence of a new phase with two types of vortices is possible: the intrinsic vortices, induced by thermal fluctuations, and the extrinsic vortices, produced by the external magnetic field when $H>H_{c1}$.

Another method for the determination of the flow resistivity (frequently used in traditional type-II superconductors) consists in the measurement at microwave frequencies of the sample surface resistance as a function of the magnetic field. This method has been carried out by us[9] in HTSC granular superconductors Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O at two different frequencies. The measurements have shown that the dissipation due to the vortex motion is analogous to that of conventional superconducting alloys. The fit of the experimental results obtained by means of a very low pinning energy (70 K) is in agreement with the Griessen assumption, if his hypothesis is supplemented considering that only the pinning energy values which permit a thermally activated escape within a time window depending on the experimental technique are of importance. However, also at microwave frequencies close to T_{c0}, the experimental results are difficult to interpret and various explanations can be suggested.[8]

In addition to the fluxon losses, another dissipation mechanism for HTSC's, in twinned and/or granular samples, is connected to the presence of a large number of Josephson junctions (JJ's). In a previous paper,[10] we have quantitatively verified that at a fixed temperature the exponential-like behavior of the microwave absorbed power as a function of H at low field intensity ($H<500$ G) is due to the gradual decoupling of the junctions with increasing magnetic field. A simple model of independent junctions is able to explain the measurements at high temperatures, while below a certain temperature the thermal and magnetic histories play a preeminent role and the independent junction model fails.[11] We came to the conclusion that these effects, detected in Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O samples at low magnetic field, cannot be easily interpreted in the frame of the flux-creep model, but find a possible explanation in the theoretical works on the superconducting-glass systems based on arrays of Josephson junctions.[12]

The previous discussions have shown that in HTSC's the presence of different dissipation mechanisms (flux flow, flux creep, and dephasing of JJ's) in connection with a very complex $H-T$ phase diagram makes the physical situation very complicated and hard to grasp.

In this paper, we will show that the microwave magnetoabsorption is able to detect the effects connected to the flux creep, the effects due to the flux flow, and those connected to the JJ's, depending on the ranges of variation of magnetic field and temperature selected. As flow and JJ effects have been already presented elsewhere,[9–11,13] here we will mostly focus our attention on the hysteretic effects connected to the flux-creep in the low-temperature range.

II. EXPERIMENTAL RESULTS

Measurements of the microwave absorbed power $P(H)$ as a function of the external magnetic field H in samples of Y-Ba-Cu-O have been taken at the frequencies 23 and 48 GHz. The samples were the bottom of a cylindrical resonant cavity tuned in the TE_{011} mode. The surface resistance of the sample, as well known, is proportional to the absorbed power via geometrical factor. The temperature was stabilized within 0.01 K. The experimental apparatus has been described in a simplified design elsewhere.[9] The samples are pellets having a measured density of 4.6 g/cm^3. The grains are randomly oriented with typical sizes measured on a fresh fracture surface of the order of 30–40 μm.

The microwave power $P(H)$ absorbed by the sample exhibits different physical behaviors in different ranges of temperature and magnetic field. These thermal and magnetic behaviors are qualitatively independent of both the amplitude of the microwave power in the range 1–10 mW and the frequency for our two-microwave setup (23 and 48 GHz). At low magnetic fields an exponential-like behavior up to a temperature $T_{cj}<T_{c0}$ related to the dephasing of the JJ's is present. We have shown[11] that a model of absorption based on a set of independent JJ's, statistically distributed with respect to their geometrical parameters, is able to fit the exponential-like curve $P(H)$ as a function of both the magnetic field and the temperature, for $T/T_{c0}>0.4$. At lower temperatures, the exponential behavior depends on the magnetic and thermal history of the sample: for $T<0.2T_{c0}$ the saturation amplitude ΔP_0 (Ref. 11) of the exponential-like curve $P(H)$, present at low magnetic field, is zero in every successive H run, after the sample is subjected to a magnetic field H_m at least as high as $\simeq 3$ kG. This means that, at low temperature, a strong magnetic field drives the system of JJ's into a frozen state from which it is possible to remove it only if the temperature is again increased well above $T=0.2T_{c0}$.

In Fig. 1 the typical behavior of $P(H)$ vs H is shown after zero field cooling (ZFC), increasing and successively decreasing the magnetic field for $T<0.2T_{c0}$ (the figure refers to a Y-Ba-Cu-O sample at $T=1.5$ K and $\nu=48$ GHz). The exponential-like behavior appears only in the first run (curve 1). The successive runs in H exhibit the hysteretic behavior of Fig. 2(a), the loops being reproducible for varying H provided that the maximum magnetic field H_m is the same in each run. The magnetic loops, for different H_m, are reported in Fig. 2(b). For increasing temperature, the hysteresis loop becomes more and more narrow [Fig. 3(a)] and disappears at $T\cong 0.4T_{c0}$. For $T>0.4T_{c0}$, $P(H)$ linearly increases with H and this behavior becomes reversible [Fig. 3(b)]. In the same figure, the exponential behavior due to the JJ absorption at low magnetic field is also present. In this range of temperature, the linear part of the curves $P(H)$ is well interpreted in the flux-flow model, as we have shown.[9]

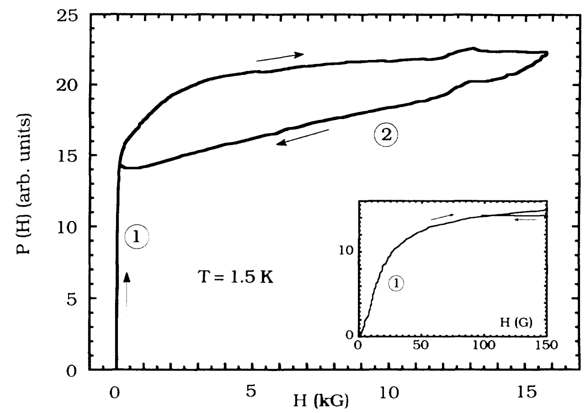

FIG. 1. Microwave absorbed power in the first run after the zero field cooling (curve 1). Curve 2 is obtained when the magnetic field is lowered to zero. In the inset the absorption at low fields is shown (Y-Ba-Cu-O at $\nu=48$ GHz).

The hysteretic behavior (not the freezing effect for JJ's, which is history dependent) can be interpreted in the flux-creep frame using the critical-state model introduced by Bean,[14] as we will show in the next section.

In summary, the main experimental results are: (i) for $T<0.2T_{c0}$ the microwave absorption due to JJ's is present only in the first run after ZFC (curve 1 of Fig. 1); (ii) a microwave remanent absorption is present in the successive runs of H, but the absorption is lower when H is decreasing (Fig. 2); (iii) the area enclosed by the hysteretic loops depends on both the maximum magnetic field H_m reached [Fig. 2(b)] and the temperature (Fig. 3);

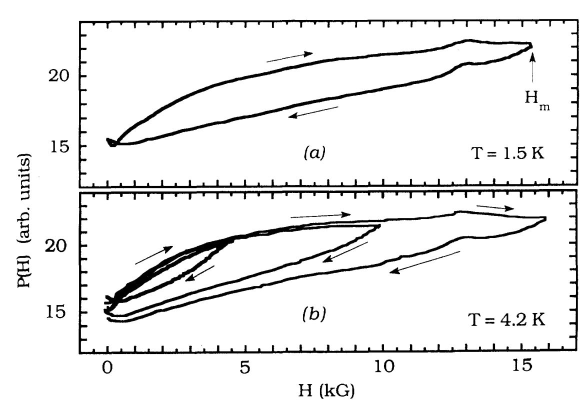

FIG. 2. The same as in Fig. 1 in subsequent runs. The loops are reproduceable provided that the maximum magnetic field H_m is the same in each run. In (b) the loops for different H_m are shown.

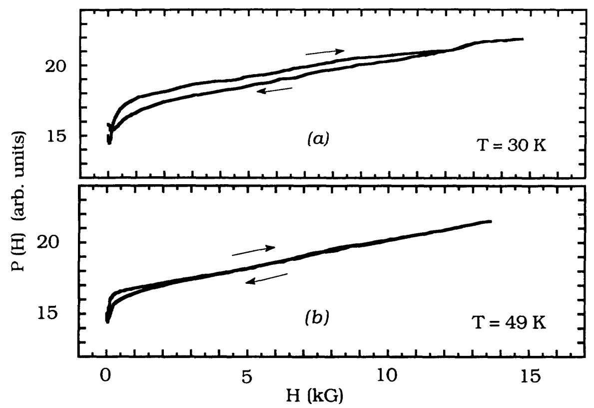

FIG. 3. The same as in Fig. 2(a), at $T=30$ and 49 K. In (b) the linear reversible behavior is connected to the flux-flow regime.

(iv) for $T>0.4T_{c0}$ the hysteretic loop disappears and the curve $P(H)$ becomes a linear function at high fields up to 2 T, provided that the temperature is not close to T_{c0} [Fig. 3(b)].

III. DISCUSSION OF EXPERIMENTAL RESULTS

The explanation of the above experimental results is found considering three different dissipation mechanisms (flux flow, flux creep, and dephasing of the array of JJ's) each of which is preminent in a particular range of temperature and magnetic field. Here we are considering the flux-creep regime and its evolution in the flux flow, using the Bean model for the penetration of the external magnetic field. The problem in the case of microwave absorption is much more complex with respect to the magnetization measurements, because in the Maxwell equation the conductivity σ depends on the magnetic field and, as a consequence, is spatially dependent. We will find that the microwave absorption strongly depends on the ratio between the static magnetic-field penetration length $b(H)$ and the microwave skin depth $\delta(H)$.

Let us consider a plane-harmonic time-dependent $\exp(-i\omega t)$ electromagnetic wave propagating along the x axis which is perpendicular to the superconductor surface. The surface impedance Z is given by the expression

$$Z=\left[\frac{4\pi i\omega}{c^2}\right]\left[\frac{E}{(\partial E/\partial x)}\right]_{x=0}, \tag{1}$$

where ω is the frequency, $x=0$ is the plane separating the vacuum ($x<0$) from the superconductor ($x>0$), and the microwave electric field $\mathbf{E}$ is directed along the y axis. We use the method of symmetrization of field and specular limit conditions. In this case, the Maxwell equations give for the electric field E the equation[15]

$$\frac{d^2E(x)}{dx^2}-2\left[\frac{dE}{dx}\right]_{x=0}\delta(x)=-\frac{4\pi i\omega}{c^2}\sigma(x)E(x)\ , \tag{2}$$

where $\sigma(x)$ is the conductivity. Taking the Fourier transform of Eq. (2), we get

$$-4\pi k^2E(k)-2\left[\frac{dE}{dx}\right]_{x=0} =-\frac{4\pi i\omega}{c^2}\int_{-\infty}^{+\infty}dk'E(k')\sigma(k-k')\ , \tag{3}$$

where $\sigma(k)$ is the Fourier transform of $\sigma(x)$. The conductivity $\sigma(x)$ is calculated at low temperature, considering two contributions to the conductivity:

(i) the London term

$$\sigma_L=i\frac{c^2}{4\pi\omega\lambda_L^2} \tag{4}$$

with λ_L the London penetration depth;

(ii) the fluxon motion,

$$\rho^{-1}=\rho_F^{-1}+\rho_c^{-1}\ , \tag{5}$$

where

$$\rho_F=\rho_n B/B_{c2} \tag{6}$$

is the Bardeen-Stephen flux-flow resistivity[16] and

$$\rho_c=\frac{\rho_0}{1+i\omega/\omega_0 e^{-U(B)/k_BT}} \tag{7}$$

is the flux-creep contribution for which the Debye phenomenological expression for the frequency dependence of conductivity has been used.[6,17] In Eq. (7) $\omega_0\exp[-U(B)/k_BT]$ is the resonance frequency dependent on the magnetic field through the pinning energy $U(B)$ and B is the static magnetic field *inside* the sample.

Finally, the behavior of the static magnetic field inside the superconductors is obtained in the Bean model by means of the relation for the critical state

$$\frac{dB}{dx}=\pm\frac{4\pi}{c}J_c(B)=CB^{-n}\ , \tag{8}$$

where $C=nJ_c(T)H_{c1}$, $J_c(T)$ is the zero-field critical current, and the $\pm$ sign, respectively, occurs for increasing and decreasing magnetic field. The local flux density $B(x)$ for $n=\frac{3}{2}$, is shown in Fig. 4. When the function $B(x)$ is used in Eqs. (6)–(8) the x dependence of the conductivity $\sigma(x)$ is obtained.

It is practically impossible to integrate Eq. (2) or find

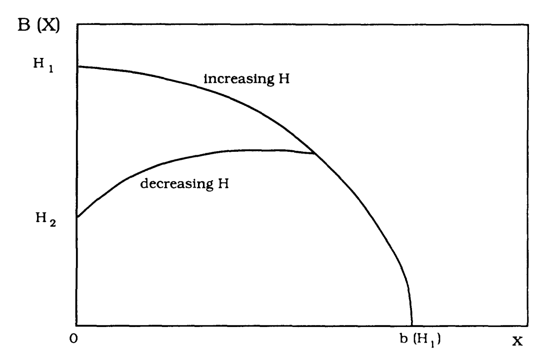

FIG. 4. Spatial variation of the field $B(x)$ inside the sample following the Bean model with $n=\frac{3}{2}$ for the exponent in Eq. (8).

the Fourier transform in Eq. (3) for this very complicated $\sigma(x)$ function. In Fig. 5, we present the $\sigma(x)$ behavior for some values of the parameters at different values of the external magnetic field H_m (the field at $x=0$). The behaviors of $\sigma(x)$ shown in Fig. 5 suggest for the conductivity the approximate expression

$$\sigma(x)=\sigma_0-\sigma_1(H)\Lambda(x/b(H)) ,$$

where σ_0 is the conductivity at $H=0$, $\sigma_1(H)$ the conductivity variation at $x=0$, $\Lambda(x/b(H))$ the lambda function, and $b(H)$ the x value at which the field $B(x)$ is zero, $B(b(H))=0$. This approximation allows us to obtain an analytical solution for the surface impedance. We have for the surface impedance $Z(H)$ in the first run of the magnetic field, after the integration of Eq. (3), the following equation:

$$Z(H)=Z_0+R_0\frac{\sigma_1}{\sqrt{\sigma_e}(\sqrt{\sigma_e}+\sqrt{\sigma_0})}\left[\left[\frac{2}{i\sigma_e}\right]^{1/2}-\frac{1}{[b(H)/\delta(H)](\sqrt{\sigma_e}+\sqrt{\sigma_0})}[1-e^{-\gamma}(\cos\gamma+i\sin\gamma)]\right]$$

where $Z_0=(1-i)(2\pi\omega/\sigma_0 c^2)^{1/2}$ is the surface impedance at $H=0$, $\gamma=b(H)[1/\delta(H)+1/\delta(0)]$, $\delta(H)=(c^2/2\pi\omega\sigma_e)^{1/2}$ is the skin depth of the electromagnetic field at H value, and $\sigma_e=\sigma_0-\sigma_1(H)$.

The $Z(H)$ function for the successive runs in magnetic field is obtained in a straightforward but cumbersome way adding additional $\Lambda(x)$ functions appropriately chosen in order to reproduce the correct $\sigma(x)$ behavior.

An important point to stress is that the field-dependent ratio $b(H)/\delta(H)$ between the penetration length of $B(x)$ and the microwave skin depth, is the main parameter.

In Fig. 6 the results of our calculation for $\mathrm{Re}[Z(H)]/\mathrm{Re}(Z_0)$ at $T=4$ K, for three different values of the maximum magnetic field H_m, are shown. The complicated expression $\mathrm{Re}[Z(H)]/\mathrm{Re}(Z_0)$ is not reported here for simplicity. The magnetic dependence of the activation energy $U(B)$ is that found by Inui, Littlewood, and Coppersmith[17] (the continuous line corresponds to increasing magnetic field while the dashed lines corresponds to decreasing field). For increasing temperature the hysteresis disappears if in Eq. (9) the experimental temperature dependence of $J_c(T)$ is taken into account.[18] The disappearance of the hysteresis occurs at $T\cong 0.4T_{c0}$ because the critical current at this temperature is an order lower than $J_c(0)$; in the same way the coefficient C in Eq. (8) is reduced.

The former model explains the main qualitative aspects of the experimental results shown in Figs. 2 and 3, as can be seen from the theoretical curves of Fig. 6. However, as we have pointed out, a peculiar feature of the microwave hysteretic absorption is shown by these HTSC samples, that is the absorbed power is *lower* when H is lowered. This feature, which is also present in the measurements of other authors,[19] has not been in our opinion suitably underlined. Note that a trapped flux should give a larger absorption rather than a lower one. We think that this phenomenon is understandable, if the magnetic-field dependence of the resonance frequency is taken into account. In fact, if $\omega\cong\omega_0\exp[-U(B)/k_BT]$ at $H=0$, the presence of the external magnetic field takes off resonance the fluxon system and the absorption is lower when the field is trapped.

Finally, it is to be noted that the onset of reversible behavior at $T\cong 0.4T_{c0}$ is lower than that found by means of measurements of magnetization and rf susceptibility reported in the literature. A possible explanation may lie in the fact that at microwave frequencies the fluxons are weakly pinned. This is confirmed by the low values of the activation energy deduced from the thermally activated flux motion measurements.[9,20] As a consequence, to a smaller pinning energy corresponds a lower temperature of the onset of reversible behavior. Another explanation can be found in the fact that, due to the randomly oriented grains, the fluxon motion along a and/or b directions, having lower pinning energies, dominates.

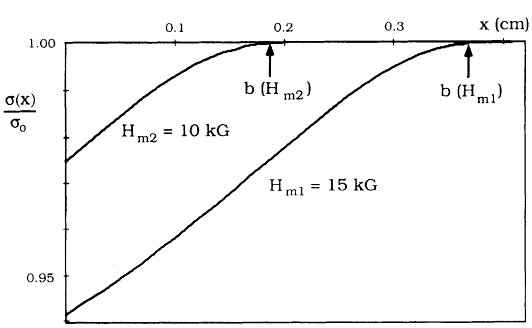

FIG. 5. Spatial variation of the conductivity $\sigma(x)/\sigma_0$ for two values of the external magnetic field at $T=4$ K. The parameters used are $\omega_0=5\times 10^{10}$ Hz, $U(0)/k_B=20$ K, $\lambda_L=0.13$ μm, $\rho_n=\rho_0=1$ m Ω cm, $J_c(0)=10^6$ A/cm^2.

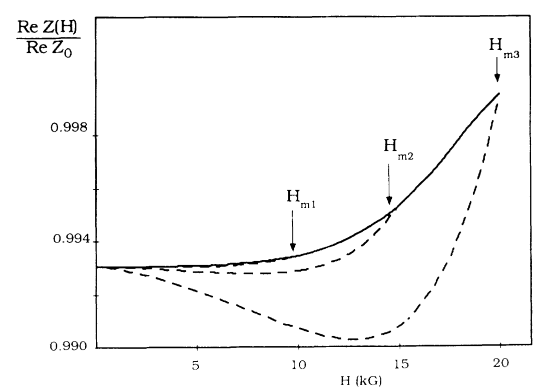

FIG. 6. Surface resistance $\mathrm{Re}Z(H)/\mathrm{Re}Z_0$ at $T=4$ K calculated for different values of H_m. The fit parameters are the same as in Fig. 5.

IV. CONCLUSIONS

This work follows a set of papers[9–11,13] concerning measurements of microwave absorption in external magnetic fields in HTSC ceramic superconductors Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O. A brief discussion of microscopic absorption processes and their experimental evidence is presented. The possible absorption models are related to the presence of Josephson junctions and fluxons. In particular, we show the possibility to separate, selecting the range of variation of the temperature and of the external magnetic field, the effects related to the dephasing of JJ's, to the fluxon motion, and to the creep of the pinned fluxons. Moreover, we have shown that, at low temperatures (1–40 K) and at high magnetic fields ($H > 10^3$ G), a number of effects (the existence of an hysteresis loop with absorption lower in the decreasing field run, the reduction and the disappearance of the loop with the increasing of temperature) can be explained within the framework of a model of electromagnetic field propagation that uses the critical-state Bean model and, as a consequence, relates the absorption to the flux creep. The Maxwell equations for the surface-impedance calculation are solved in a simplified case, and it is shown that the relevant parameters are the magnetic-field-dependent resonance frequency ω_0 of the pinned fluxons and the ratio between the static magnetic-field penetration $b(H)$ and the microwave skin depth $\delta(H)$.

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