# Flux-creep effects in the microwave absorption of $YBa_2Cu_3O_x$ single crystals

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Time-dependent anomalies in the microwave absorption have been studied. These anomalies are associated with transitions between different states of the vortex lattice in the case of a pinned magnetic flux. The shift of the extrema observed in the derivative of the absorbed power with respect to the field is described in terms of a flux creep.

The behavior of the vortex lattices, which largely determines the critical properties of superconducting materials, has attracted considerable interest. The high-$T_c$ superconductors, with the pronounced anisotropy and short coherence length characteristic of metal oxides, are particularly complex. It is accordingly necessary to keep trying new methods to learn about various aspects of this situation. It is for this reason that we undertook the study of the microwave absorption of superconducting $YBa_2Cu_3O_x$ single crystals which we report below. Our goal was to see how the kinetics of the magnetic flux is manifested in the observed absorption, in order to see whether this powerful research tool could be used to determine several critical properties.

The measurements were carried out on a Bruker BER-418s ESR spectrometer at a frequency of 9.4 GHz over the temperature range from 1.6 to 40 K. The residual field of the magnet was canceled by Helmholtz coils. The test samples were $YBa_2Cu_3O_x$ single crystals with typical dimensions of $1\times1\times0.1$ mm, with various

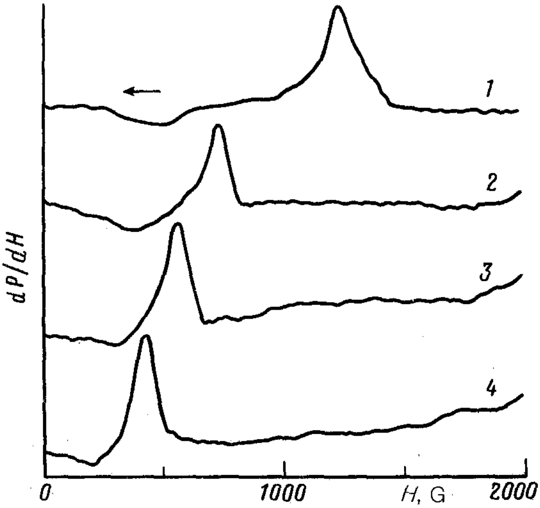

FIG. 1. Amplitude of the derivative of the absorbed power versus the field at various times. 1—$t = 2$ *min*; 2—4 *min*; 3—8 min; 4—16 min. Crystal K1; $\mathbf{H}\|(\mathbf{ab})$; $T = 14.5$ K.

superconducting transition temperatures and various degrees of twinning. The size of the twins was evaluated with a polarizing microscope.

The measurements were carried out by the following procedure. The crystal, in the cavity of the spectrometer, was oriented in a static magnetic field of fixed magnitude $\mathbf{H}_f$ in such a way that the field was directed perpendicular to the plane of the sample ($\mathbf{H}_f\|\mathbf{c}$). The sample was cooled to the specified temperature below 40 K. A nonequilibrium state was first produced, to allow a study of the flux relaxation. For this purpose, the cooled crystal was rotated in such a way that the field $\mathbf{H}$ became parallel to the basal plane [$\mathbf{H}\|(\mathbf{ab})$]. As the field $\mathbf{H}_f$ was then lowered to zero, the change in the amplitude of the derivative of the microwave power absorption $dP/dH$, was recorded. In magnetic fields between 2000 and 100 G, a narrow peak was observed. This peak corresponds to a sharp change in the absorption level (Fig. 1). A comparison of this peak with the ESR signal from a reference sample (LiF:Li) led to the conclusion that the microwave absorption decreases sharply in this narrow region as the field is lowered. When the field was subsequently scanned over the range 0–2000 G, this signal was reliably observed as $H$ was either increased or decreased (with some hysteresis). Its position, $H_R$, however, changed as time elapses (Figs. 1 and 2). (The results in these figures were obtained on crystal K1, with $T_c = 92$ K and an average domain size of 0.7 $\mu$m.) In general, the signal shifted down the field scale. An increase in the measurement temperature resulted in an increase in the initial amplitude of the signal, but this amplitude decayed rapidly over time. The range of variation of the resonant fields and the rate at which the signal moved also varied with the temperature (Fig. 2).

We also studied how the changes in the signal and in its dependence on the freezing field $H_f$ varied with the orientation of the crystal with respect to the scanning field, the microwave power level, and the modulation amplitude.

Looking at the entire set of experimental results, we should stress that as the external field is varied, the power absorption changes abruptly (it decreases when the field is reduced, and it increases when the field is increased). It is reasonable to suggest that the primary mechanism for the microwave absorption in YBaCuO crystals of fairly good quality is the mechanism proposed by Gittleman and Rosenblum[1] for type-II superconductors. In this case the dissipation results from a viscous retardation of vortices driven into oscillation by the alternating field. At sufficiently high frequencies, the dissipation is insensitive to whether there is a pinned vortex. The absorbed energy per unit surface area in this case is

$$P = J_0^2 \phi_0 H_0 / 2c^2 \eta, \tag{1}$$

where $J_0$ is the amplitude of the microwave current, and $\phi_0$ is the flux quantum. Our experiments revealed specifically a linear dependence of the dissipation on the incident microwave power. It can be seen from this expression that the quantity associated most strongly with the jumps in the absorption is the viscosity $\eta$, which is a measure of the motion of vortex threads. The idea here is that since the layered high-$T_c$ superconducting compounds are anisotropic, the viscosity will clearly depend on the direction in which the vortex threads move in the course of their oscillations. Using the simple approximate equations of the Bardeen–Stephen theory,[2]

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

along with some characteristic values for $YBa_2Cu_3O_x$, $H_{c2}^{(ab)}/H_{c2}^{(c)} = (m^{(c)}/m^{(ab)})^{1/2} \simeq 6\text{–}8$ and $\rho_n^{(c)}/\rho_n^{(ab)} \simeq 10^2\text{–}10^3$, we easily see that the absorption by

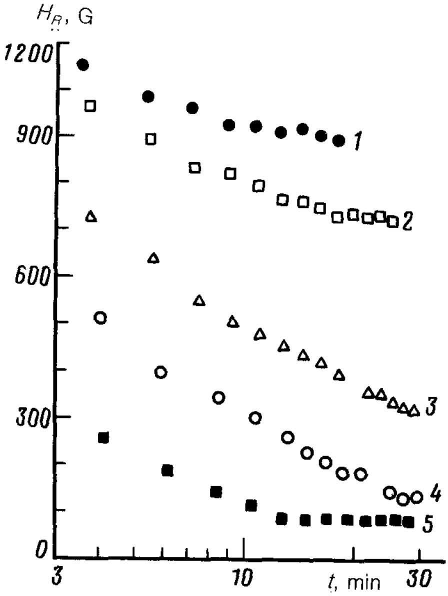

FIG. 2. Shift of the signal as time elapses at various temperatures. 1—10.7 K; 2—12 K; 3—14.5 K; 4—19 K; 5—24.5 K. Crystal K1; H||(ab).

fluxoids running parallel to the layers and oscillating in the direction across the basal plane is stronger by at least an order of magnitude than that by fluxoids running normal to the layers ($\rho_n$ is the resistance in the normal state, $m$ is the effective mass, $H_{c2}$ is the upper critical field, and the superscripts specify the crystallographic axes). It is thus reasonable to suggest that the sharp change in the absorption detected by us is due specifically to the appearance or disappearance of a large number of fragments of vortex threads which are moving across the layers.

Changes of this sort may result from transitions between two different states of the vortex lattice in the oblique magnetic field [the pinned field $\mathbf{H}_{\text{rem}}$ ($\|\mathbf{c}$) plus the external field $\mathbf{H}(\|\mathbf{c})$]. One of these states, which is realized in weak fields, corresponds to a step-shaped vortex lattice.[3] The second state (corresponding to large $H$) is a system of vortex threads which are pinned between layers. Consequently, the effective number of threads moving across the layers is considerably larger in this case. The fact that we observe a clear signal upon the transition between these different phases is evidence that they are homogeneous at the macroscopic level. The line of the transition between these phases is determined by the balance between the magnetic forces which tend to rotate the flux line toward the direction of the oblique magnetic field and the pinning forces which tend to put the fluxoids between layers. The inclination angle $[\arctan(H_{\text{rem}}/H)]$ depends on the amount of flux pinned during cooling; because of the relaxation of this flux, this angle also depends on the time. The critical value of the inclination angle[4,5]—at which the observed transition occurs—is thus reached at different values of $H_R$ at different times. The field $H_R(t)$ falls to its critical value $H_{c1}$ in the corresponding direction.

Over a significant temperature interval, the observed shift of the signal as time elapses (Fig. 2) is logarithmic over large regions. This behavior correlates with a Kim–Anderson law for vortex creep:[6]

$$H_R(t) = H_{R0}[1 - (kT/U)\ln(t/t_0)].$$

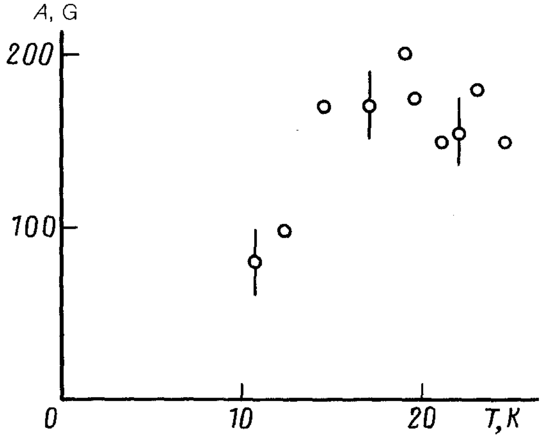

FIG. 3. Temperature dependence of the coefficient $A$ for crystal K1 at $H_f = 5000$ G [$A = dH_R/d(\ln t)$].

Here $H_{R0} = H_R(t_0)$, and $t_0$ is the time at which the signal is first observed. We can thus estimate the pinning energy: $U = 0.01$ eV. This figure is evidence that the pinning of vortices is slight. From the expression $U = H^2_{\mathrm{cm}} \xi^2_{\mathrm{ab}} d/8$ we can estimate the size of the pinning centers: $d = 50$ Å. For this particular crystal, the rate of decrease of the resonant field, $A$, is equal to $H_{R0}kT/U$ and goes through a maximum at $T = 20$ K (Fig. 3). Maxima of this sort[7] occur because at this temperature the flux of the external field which enters the sample from the plane surfaces reaches the core of the sample first.

We should point out that the field $H_{R0}$ and its rate of change are different for crystals with a higher density of domain walls, but the estimates of the energy of the pinning by individual defects turn out to be close to the value found above. For crystal K2, with $T_c = 70$ K and an average domain size less than 0.1 $\mu$m, for example, we find $U = 0.007$ eV.

The apparent reason for the disappearance of the effect at temperatures above 35 K is that the interaction of vortex lines becomes important because of an increase in thermal fluctuations, and a transition to a collective pinning occurs.[8] This transition is accompanied by an exponential decay of the critical current density and by a fast relaxation of the flux.

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