Collective nature of flux creep according to microwave absorption in $YBa_2Cu_3O_x$ single crystals

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A study of microwave absorption in a magnetic field has revealed the behavior of the creep activation barrier as a function of the amplitude of the microwave current. The behavior found is evidence that the lattice of vortex lines is in a vortex glass state at low temperatures.

The anisotropy of the crystal structure and the short coherence length of the high T_c superconductors are responsible for some distinctive properties of the vortex lattice in these materials.[1] Depending on the orientation of the magnetic flux penetrating the sample, the vortices are pinned either by the layers[2] characteristic of the structure of the superconducting metal oxides or by defects, both extended and local. It has been predicted[3] that in the case of randomly distributed small–scale defects the pinning and creep of vortices should be essentially collective processes. In the case of a collective behavior we would expect a glassy state of the vortices in the low–current limit, and we would expect a zero resistance at a nonzero temperature.[3–8] There are pieces of evidence which support this picture,[9,11] but the overall situation looks extremely contradictory. In the present letter we report an effort to extract information on the dynamics of vortices and on the nature of their pinning and creep from experiments on microwave absorption at low amplitudes of the microwave current. This idea is realized through an analysis of the behavior of a narrow signal which is associated with a restructuring of the vortex lattice and which we had observed previously.[12]

To detect the microwave absorption we used a standard ESR spectrometer with a frequency of 9.4 GHz. The remanent field of the magnet was canceled by Helmholtz coils. We studied $YBa_2Cu_3O_x$ single crystals with typical dimensions of $1\times1\times0.1$ mm and various superconducting transition temperatures. The test sample was cooled by a flow of cold gaseous helium. The temperature excursions in the course of the measurements were less than 0.3 K. In an experiment we monitored the changes in the absorbed power, recording the derivative of this power with respect to the field as the field was scanned. The exciting microwave power was varied over the range from 3 to 100 mW. The measurements were carried out under conditions such that the static field was oriented along the normal to the basal plane of the single crystal, while the alternating field ($\propto e^{i\omega t}$) was parallel to this plane.

Regardless of the sample cooling conditions, we observed a sharp signal at a temperature below 30 K as the field was slowly lowered (Fig. 1). This signal corresponds to an abrupt increase in the level of power absorption. (The direction of the change in the absorption was determined with the help of an ESR signal of a standard.) When the field was scanned in the opposite direction, i.e., from low to high values, we observed a decrease in the absorption, but not as sharp (there was some hysteresis). Figure 2 shows the applied field at which the sharp change in the absorption occurs, H_R. It is plotted here as a function of the upper limit of the field scan.

We believe that the abrupt change observed in the absorption occurs because a surface layer of thickness λ on the lateral faces of the sample becomes filled with vortex lines. The vortex lines interact with the microwave field at these lateral faces. The thickness λ is the field penetration depth. Upon a change in the external field, vortex lines can move toward the lateral surfaces of the crystal by surmounting a surface barrier or by virtue of a bending of these lines. If the lateral faces of the crystal are not treated in a special way, the vortices begin to enter the sample at fields on the order of the first critical field. As the flux is reduced, the vortices escape from the sample when the static magnetic field reaches zero at the surface. The value of the field at the surface is much lower than the applied field because of the oppositely directed

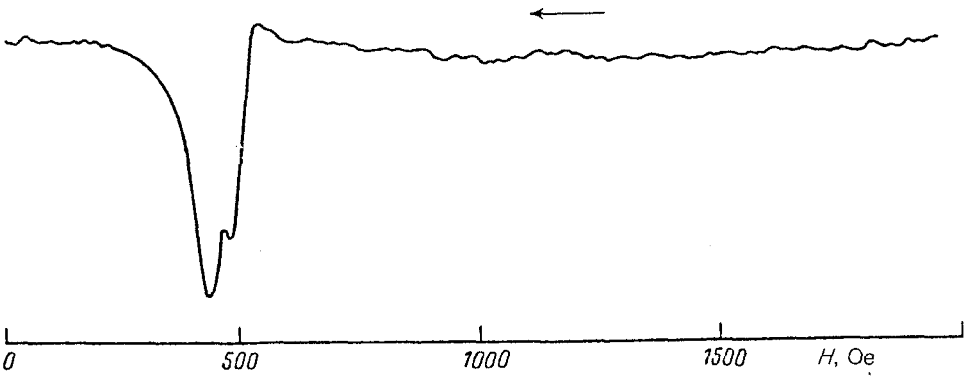

FIG. 1. Signal representing the derivative of the absorption, dP/dH, as the static magnetic field is lowered slowly from 2000 Oe to 0. The sample was a $YBa_2Cu_3O_x$ crystal (with $T_c = 93$ K). The temperature during the recording was 19 K; the field was in the orientation $H\|c$.

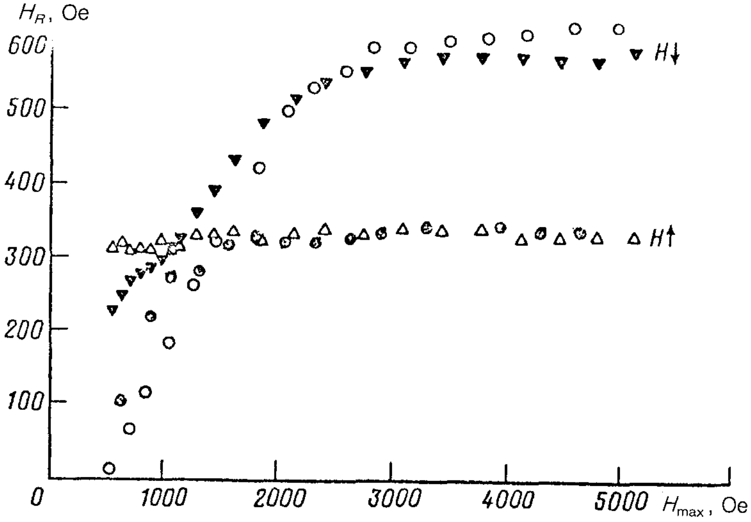

FIG. 2. Position of the signal, H_R, versus the upper limit of the field scan, H_{max}. ○, ●—Cooling in a zero field; △, ▼—cooling in a field $H = 5000$ Oe; ●, △—the field is increased from 0 to H_{max}; ○, ▽—the field is reduced from H_{max} to 0. The measurement temperature was 19 K.

field lines which close the flux pinned by the superconductor. The variations in the position of the signal as the upper limit of the field scan range is changed (Fig. 2) reflect changes in the amount of pinned flux. The change in the absorption should be (and is found to be) sharpest as the field is scanned downward, and the vortices approach the surface from the interior.

Since the signal remains constant in width, its amplitude is proportional to the magnitude of the abrupt change, i.e., to the increment in the absorbed power. A substantial increase in the amplitude is observed as the temperature is raised to 30 K (Fig. 3a). At $T > 30$ K the temperature dependence changes, suggesting a switch to a different pinning regime. As the strength of the alternating exciting field is raised, the amplitude of the observed signal also increases (Fig. 3b).

What is the relationship between the observed signal and the vortex dynamics in the rf field? The magnitude of the abrupt change in power is determined by the absorption of vortex lines or fragments thereof. They enter the surface layer which is effective in the absorption as the point H_R is crossed. The magnitude of this abrupt change in power depends on both the configuration of the lattice and the absorbed power per unit length of a vortex. To estimate it, we consider the motion of vortices in the rf Lorentz force. This motion occurs as jumps of individual vortex bundles which have depinned as a result of thermal activation. The rf power absorbed per unit length of a vortex is $\sim(\vec{f}\vec{v})$, where $\vec{f} = [\vec{j}(\vec{n}\phi_0)]$ is the Lorentz force, and $\vec{v} = \vec{u}\nu$ is the line velocity. Here $\vec{j}$ is the current density, $\vec{n}$ is a unit vector along the direction of the vortex line, ϕ_0 is the flux quantum, $\vec{u}$ is the average length of a jump, and ν is a

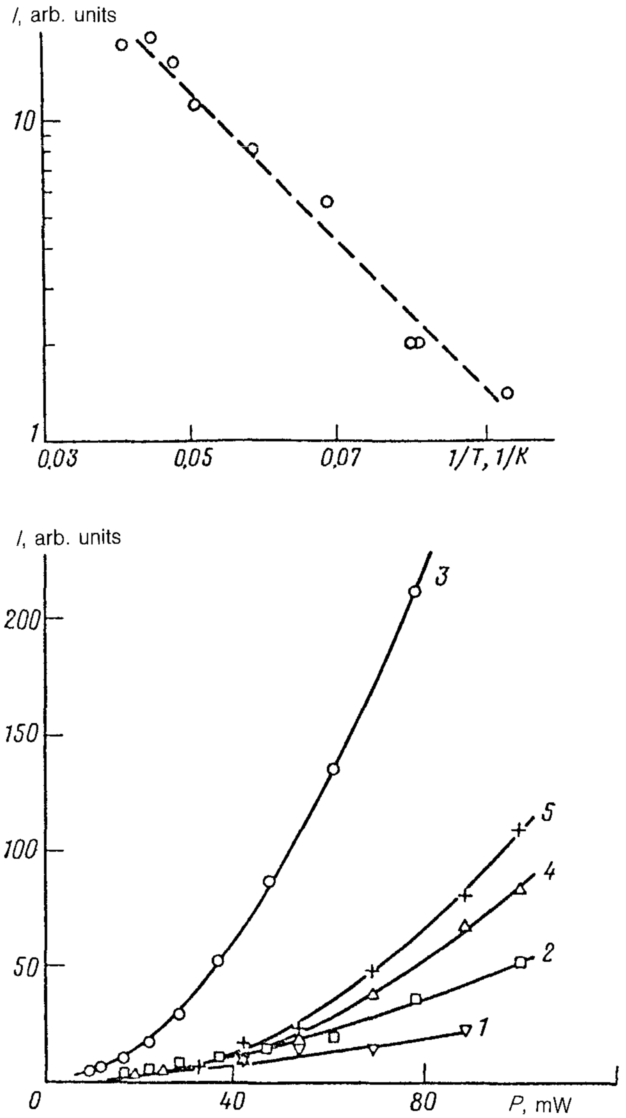

FIG. 3. a: Temperature dependence of the amplitude of the signal corresponding to the abrupt change in the absorption. b: Amplitude of the signal versus the power incident on the sample at various temperatures. 1—16 K; 2—18; 3—19; 4—21; 5—26 K. Curve 3 was found under cooling and detection conditions different from those for the other measurements. The conditions were identical for all the other curves. The solid curves were found through a fit by expression (4).

characteristic frequency of the jumps. This frequency is given by the thermal-activation expression $\nu = \nu_0 \exp(-E_p/kT)$, where ν_0 is the frequency of attempts. The height of the activation barrier, E_p, is determined by the change in the elastic energy of the vortex lattice[3] as the result of work performed by the Lorentz force in moving a vortex bundle a distance u ($E_L \sim jHV_c u$, where V_c is the volume of the bundle). If there are randomly distributed pinning centers, this distance is related to the length scale (R) over which the averaging occurs by $u \propto R^{\zeta}$. The critical exponent here, $0 \leqslant \zeta \leqslant 1$, describes the blurring of the boundaries in d-dimensional random media.[3-5,8] The increase in the average jump length with decreasing external current, which is described by $u \propto j^{-\zeta/(2-\zeta)}$, causes an increase in the dimensions of the deformable regions of the lattice. According to Ref. 3, this effect leads to the following dependence of the activation barrier on the current density:

$$E_p \sim E_L \sim C_{66}(u/R_\perp)^2 V_c \sim U_0(j_c/j)^{\alpha}, \quad \alpha = (d-2+2\zeta)/(2-\zeta)\,. \tag{1}$$

Here U_0 is an energy scale of the pinning; j_c is the critical current density; C_{66} is the shear modulus of the vortex lattice; and $R_\perp$ is the dimension of the vortex bundle in the direction perpendicular to the displacement. The value of ζ used to determine the height of the barrier depends on the geometry and the corresponding value of d. As a result, there are different creep regimes.

Working from these arguments, and noting that the current density decreases in accordance with $j = j_0 \exp(-x/\lambda)$ with distance from the surface, we find the power absorbed by the lateral faces of the sample by integrating over the volume of the sample ($L \times L \times l$):

$$W \sim \lambda_{eff} Ll(\nu_0/C_{66})(R_\perp)^2 H^2 (j_0)^2 \exp\{-E_p(j_0)/kT\}. \tag{2}$$

Here l and L are the dimensions of the sample ($l \ll L$). The absorption occurs effectively in a surface layer of thickness

$$\lambda_{eff} = \lambda(kT/\alpha U_0)(j_0/j_c)^{\alpha} \quad (<\lambda) \tag{3}$$

because of the growth of the activation barrier with distance from the surface. This growth hinders the vortex motion.

Figure 3a shows the measured temperature dependence of the signal intensity as a plot of $\ln I$ versus $1/T$. At $T < 30$ K, the plot is linear and does indeed correspond to a thermal activation in accordance with the Arrhenius law $I \sim \exp(-E_p/T)$. This result shows that we are dealing with pinning centers of a common type. Since the value found for E_p is small (~ 60 K), we can conclude that randomly distributed local structural defects are responsible here.

The temperature dependence $I(T)$ was found at a fixed value (about 100 mW) of the power applied to the cavity, P_1. The experimental results show that E_p depends on the microwave power incident on the sample, $P(\propto j^2)$.

We turn now to the behavior of the microwave absorption as a function of the current. It can be seen from Fig. 3b that the signal height is a nonlinear function of the power of the exciting field over the entire power range studied. This result is evidence of a nonlinear relationship between the microwave electric field and the current. Under conditions corresponding to a thermally activated motion of vortices, this result is evidence that the activation energy depends on the current density. To analyze the experimental data, we ignore the current dependence of $R_\perp$ in the preexponential factor, and we rewrite (2), using the relation $E_p(p) = U_0(P/P_c)^{-\alpha/2}$ (P_c is the power corresponding to the critical current density) and the parameters P_1 (discussed above) and $E_1 = E_p(P_1) = 60$ K:

$$W \sim \text{const} \left(\frac{P}{P_1}\right)^{1+\frac{\alpha}{2}} \exp\left[-\frac{E_1}{T}\left(\frac{P}{P_1}\right)^{-\alpha/2}\right]. \tag{4}$$

Comparing this result with the observed behavior of the signal height (the absorbed power) as a function of the exciting power (the square of the current), we find the value $\alpha = 0.7 \pm 0.2$ for temperatures near 20 K. Such values of α are characteristic of either flux bundles with a transverse dimension greater than the penetration depth λ ($\alpha = 7/9$; Ref. 3) or a jump length greater than the lattice constant of the vortex lattice ($\alpha = 1/2$; Ref. 8). As the temperature is lowered, we see a tendency for α to decrease to values on the order of 0.1. The apparent reason for this decrease is a switch to a different creep regime.

In general, the current dependence introduced by the factor R_1^2 may also be important in (4). At $d = 3$, this current dependence alters the preexponential factor by $(P/P_1)^{3(2+\alpha)/10}$. In this case, an analysis of the experimental data yields $\alpha = 0.9 \pm 0.2$ in the region 20–25 K; this value decreases to $\alpha = 0.2 \pm 0.1$ as the temperature is lowered.

In summary, we have observed a nonlinear dependence of the microwave absorption on the exciting power. This nonlinearity is evidence that the activation barrier increases in size with decreasing amplitude of the exciting current. The vortex lattice becomes frozen in a glassy state, and the resistance disappears in the zero–current limit $[\rho \propto (dV/dj)_{j\to 0} \to 0]$.

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