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Dependence of dissipation on magnetic field orientation in high T_c superconductor ceramics

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Abstract

With the vibrating-reed technique, the internal friction Q^{-1} and resonant frequency f associated with the pinned flux of $(Bi_{0.9}Pb_{0.1})_2Sr_2Ca_2Cu_3O_{10+y}$ and $YBa_2Cu_3O_{7-x}$ ceramics were measured as a function of the angle θ between the transverse magnetic field orientation and the vibrating direction (perpendicular to the face of the sample) at fixed temperature and magnetic field. A relation between Q^{-1} (or f) and θ, i.e. Q^{-1} (or f) $\alpha (H_a \cos\theta)^{1.5}$ was found, and this indicates that only the magnetic field component parallel to the vibrating direction $H_a\cos\theta$ gives rise to the enhancement of internal friction and resonant frequency in ceramic samples. The anisotropic deformation of the flux-line lattice is used to explain the observed results.

1. Introduction

Two melting temperatures and two field-dependent activation energies for a magnetic field perpendicular to and parallel to the (a,b) plane of a single crystal have previously been found [1, 2]. Recently, there have been many reports on the double peaks in the dissipation associated with the flux-line lattice (FLL) as a function of temperature for both polycrystals and single crystals with a magnetic field misaligned with one of the symmetry axes of the specimen [3–7]. These conspicuous phenomena were interpreted as evidence of a two-step melting transition, with the low-temperature peak originating from the softening of interplanar coupling and the high-temperature peak from the melting or depinning of the two-dimension pancake vortices [3, 4], or explained by thermally activated diffusion across the thickness and width (or length) of the slab [6, 8].

In order to clarify the way in which the magnetic field orientation alone affects the FLL's properties, it is necessary to exclude complicating factors such as the temperature and anisotropy of the crystal structure. So, in this paper, we studied the response of high-temperature superconductor ceramics to an applied magnetic field with varying orientation by means of the vibrating-reed technique.

2. Experimental technique

The vibrating-reed technique was used in this experiment, with one end of the sample clamped and electrostatically driven and detected. Two as-sintered samples $(Bi_{0.9}Pb_{0.1})_2Sr_2Ca_2Cu_3O_{10+y}$ (T_c = 103 K) and $YBa_2Cu_3O_{7-x}$ (T_c = 90 K), prepared by solid-state reaction, were measured.

Instead of the longitudinal magnetic field used in most vibrating reed experiments, a transverse magnetic field normal to the length direction of the sample was applied in our measurement (Fig. 1). By rotating the sample with respect to the z axis (length direction of the sample) for a fixed magnetic field, the relative angle θ between the orientation of the magnetic field and the vibrating direction of the sample (x axis) could be changed continuously as required. The applied magnetic field varied from 0 to 500 mT.

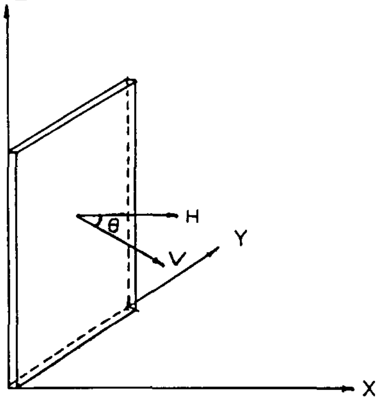

Fig. 1. Schematic diagram of the vibrating mode of the reed. The applied magnetic field H_a is perpendicular to the length direction of the sample.

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3. Results

Figure 2 shows the change of internal friction Q^{-1} and resonant frequency f associated with pinned flux as a function of magnetic field (H_a) at $\theta=0°$; *i.e.* the magnetic field is applied parallel to the vibrating direction for BSCCO (Fig. 2 (a)) and YBCO (Fig. 2(b)) respectively. Both Q^{-1} and f increase with the magnetic field and are approximately proportional to $H_a^{1.5}$ (Fig. 2 inset); *i.e.* Q^{-1} (or f) $\propto H_a^{1.5}$, in contrast to several other vibrating experiments [9, 10], indicating the response of a superconducting reed vibrating in this mode to a transverse magnetic field. The $H_a^{1.5}$ dependence of Q^{-1} (or f) may be due to the granular behaviour of our ceramic sample.

Figure 3(a) shows the field orientation dependence of Q^{-1} and f of BSCCO for $H_a=247$ mT at 61 K. Because of the symmetry of the sample, measurements were made only in the range 0–90°. The similar results for YBCO are shown in Fig. 3(b).

At $\theta=90°$, Q^{-1} and f are minimum and almost equal to the value without an applied magnetic field; this indicates that there is no dissipation when the flux

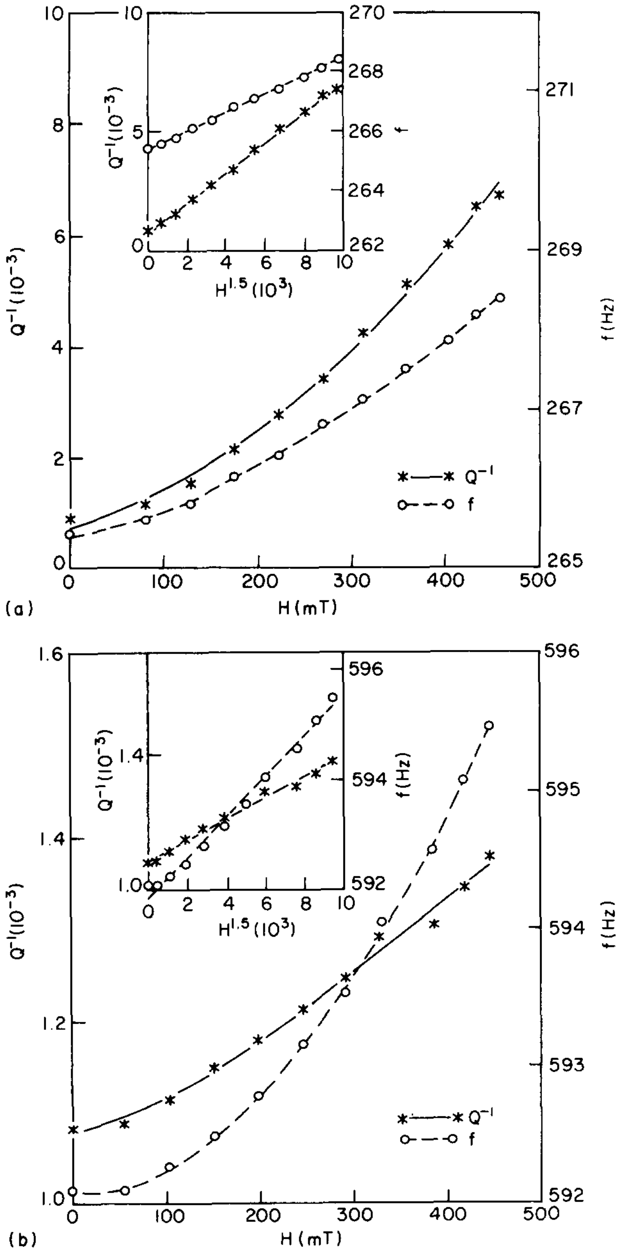

Fig. 2. Internal friction Q^{-1} and resonant frequency f as a function of magnetic field (H_a) at $\theta\approx0°$ for (a) BSCCO ($f=265$ Hz) and (b) YBCO ($f=591$ Hz) at 61 K. Inset: Q^{-1} and f vs. $H^{1.5}$.

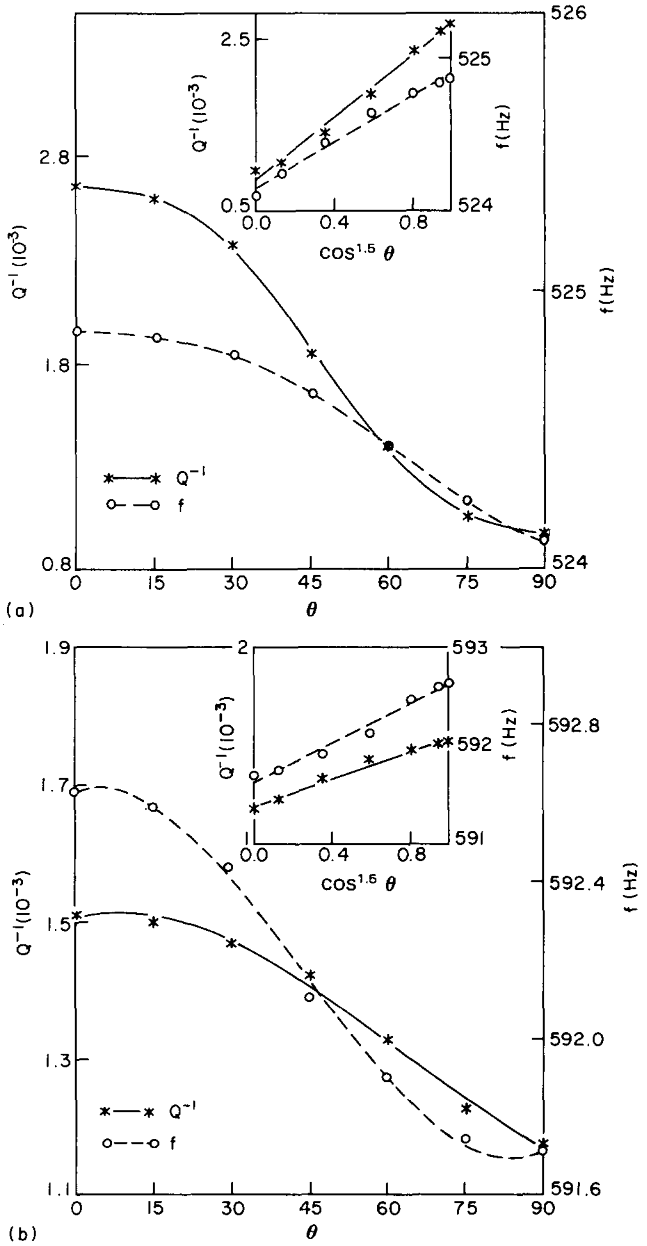

Fig. 3. Internal friction Q^{-1} and resonant frequency f vs. θ for (a) BSCCO ($f=524$ Hz) and (b) YBCO ($f=591$ Hz) at $H_a=247$ mT, $T=61$ K. Inset: Q^{-1} and f vs. $(H_a \cos\theta)^{1.5}$.

lines are arranged in this way, and agrees with the previous result [8, 11] that no dissipation should be observed at all if B is exactly parallel to the rotation axis of the sample. As the angle decreases, both Q^{-1} and f increase, and reach their maximum values at $\theta=0°$. It is interesting to note that the shape of the curves is characteristic of a $\cos\theta$ function; *i.e.* Q^{-1} (or f) $\alpha\,(H_a\cos\theta)^{1.5}$.

The measurements described above were made below the temperature where the dissipation peak appeared. A similar dependence of Q^{-1} and f on θ was also obtained above the temperature of the dissipation peak, but the changes were smaller owing to the higher temperature (results not shown).

4. Discussion

In a single crystal, the temperature at which the dissipation peaks appeared was found to be decided solely by the magnetic component perpendicular to the CuO_2 [2–4]. Also, it is suggested that in a single crystal of BSCCO only the magnetic field normal to the CuO_2 plane leads to dissipation [12]. In this work, with the ceramic sample used, the anisotropy of the crystal structure need not be taken into account. So the angular dependence of Q^{-1} and f cannot be interpreted in terms of the melting transition of interplanar or two-dimension pancake vortices [3, 4]. Meanwhile, the theory of thermally activated flux diffusion with different diffusivity across the thickness and width (or length) only accounted for the double-peak temperatures and the maximum dissipation [8]. The angular-dependent dissipation at temperatures other than the peak temperature is still unexplained. Therefore there may be some other reason for the angular effect on dissipation in our experiments. As shown in Fig. 3 (inset), the response of Q^{-1} and f to the angle is proportional to $(H_a\cos\theta)^{1.5}$ for both the BSCCO and YBCO samples, and although the change is greater in BSCCO than in YBCO, a similar tendency of Q^{-1} (or f) with θ is found regardless of their different critical temperatures and coherent lengths.

With the mounted condition of the vibrating reed unchanged, when the orientation of the magnetic field is varied, the deformation of the FLL will be different. If the FLL is rigidly pinned, the flux lines move with the sample, and the FLL's deformation is in phase with the force acting on it; hence there is no dissipation because in-phase deformation does not contribute to the dissipation, according to the internal theory of Nowick [13]. In fact the interaction between the flux lines and the pinning centres is not rigid, and so the deformation of the FLL include both in-phase and out-of-phase deformation. It is the out-of-phase deformation that leads to the dissipation. We discuss three kinds of cases for magnetic field along the x, y and z axes, respectively:

$$H\|Z,\ V\|X,\ \epsilon=\frac{\partial u_x}{\partial z}=\epsilon_5=\epsilon_5{}'+\mathrm{i}\epsilon_5{}''\sim\varphi \tag{1}$$

$$H\|X,\ V\|X,\ \epsilon=\frac{\partial u_x}{\partial z}=\epsilon_5=\epsilon_5{}'+\epsilon_5{}''\sim\varphi \tag{2}$$

$$H\|Y,\ V\|X,\ \epsilon=\frac{\partial u_x}{\partial x}=\epsilon_1=\epsilon_1{}'+\mathrm{i}\epsilon_1{}''\sim\varphi^2 \tag{3}$$

where V is the vibrating direction of the sample, u_x is the displacement of the flux lines along the x axis, φ is the angle of tilt of the sample, X, Y, Z are the coordinates of the sample and x, y, z are those of the FLL, with the z axis always along the magnetic field.

In case (1) and case (2), the deformation of the FLL is the same shear, ϵ_5, but the response of Q^{-} and f to the magnetic field in case (1) is greater than that in case (2); the reason for this is not evident as yet. In case (3), the flux lines are arranged along the y axis and the deformation of the FLL is tension, ϵ_1. Because of the very small angle of tilt, φ ($\approx 10^{-4}$), the tension ϵ_1 is estimated to be $\epsilon_1\approx\varphi^2$ and 10^4 smaller than the shear $\epsilon_5\approx\varphi$. Therefore a small deformation of the FLL in case (3) will not result in the observed response of Q^{-1} and f to the magnetic field if the equipment precision is not high enough. Brandt's view [8] that no dissipation should be observed at all if B is exactly parallel to the rotation axis is accurate when the very small dissipation originating from ϵ_1 is neglected.

So the magnetic field with any orientation in the x–y plane can be decomposed into two components, one parallel to V ($H_a\cos\theta$) and the other perpendicular to V ($H_a\sin\theta$). With the effect of the perpendicular field component on the dissipation neglected, only the contribution of the parallel component to the dissipation should be taken into account. According to the change of Q^{-1} (or f) as a function of magnetic field H_a (Fig. 2): at $\theta=0°$, Q^{-1} (or f) $\alpha H_a{}^{1.5}$, if the angle between H_a and V is θ, then the change of Q^{-1} (or f) as a function of magnetic field will be Q^{-1} (or f) α $(H_a\cos\theta)^{1.5}$. This is in agreement with the experimental results (Fig. 3 inset). This leads to the conclusion that in general equipment precision, the internal friction and resonant frequency of ceramic samples are only related to the magnetic field parallel to the vibrating direction.

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