



AC response of YBa₂Cu₃O₇ thin film superconductor

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ABSTRACT

Low-field ac measurements of magnetic susceptibility of YBa₂Cu₃O₇ high-temperature superconducting thin film were carried out over a wide range of temperatures and ac magnetic field amplitudes. A strong field dependence of the real χ' and imaginary χ'' components was observed. The field dependence of the imaginary component is used to extract the temperature dependence of the critical current density in the sample using the critical state model. The exponent β of the power law relation $J_c \sim (1 - T/T_c)^\beta$ was determined from ac-susceptibility data and different values were found. Experimental results are compared with predictions of some existing theoretical models describing the ac response of superconducting thin film in perpendicular ac field.

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1. Introduction

Vortex dynamics in high- T_c superconductors (HTS) continues to attract the attention of many researchers [1,2]. This interest arises because vortex dynamics plays a fundamental role in determining transport and magnetic behaviour of HTS materials.

Measurements of complex ac-susceptibility $\chi = \chi' + i\chi''$ have been widely used to investigate the ac response of high-temperature superconductors. The ac response of high- T_c superconductors is characterized by the real part (χ') which represents the dispersive magnetic response of the sample. The imaginary component χ'' is related to the dissipation in the sample. This is illustrated by the fact that the mean energy dissipation (Q) per unit time per unit volume in the material is related to the χ'' component by the relation [3]

$$Q = \frac{1}{2} \mu_0 \omega H_{ac}^2 \chi'' \quad (1)$$

The critical state model can account for many features of the ac response of type-II superconductors. The response of a thin film superconductor in an ac magnetic field perpendicular to the surface is a difficult problem due to the extreme geometry with large demagnetization effect. An important step towards obtaining ana-

lytical expressions for χ' and χ'' for thin films in perpendicular external magnetic field was provided by Mikheenko and Kuzovlev [4] who considered the ac response on the framework of the Bean's critical state model [5,6] (i.e. J_c is independent of the local field). Based on the work of Mikheenko and Kuzovlev and Zhu et al. [7], Clem and Sanchez [8] have obtained the following expressions for the ac-susceptibility components χ' and χ'' for a thin circular disk of radius R and thickness d in a perpendicular ac magnetic field:

$$\chi' = \frac{2\chi_0}{\pi} \int_0^\pi (1 - \cos \theta) S[(x/2)(1 - \cos \theta)] \cos \theta d\theta, \quad (2)$$

$$\chi'' = \frac{2\chi_0}{\pi} \int_0^\pi \{-S(x) + (1 - \cos \theta) S[(x/2)(1 - \cos \theta)]\} \sin \theta d\theta, \quad (3)$$

where $x = H_{ac}/H_d$, $H_d = J_c d/2$, and $\chi_0 = 8R/3\pi d$, and

$$S(x) = \frac{1}{2x} \left[\cos^{-1} \left(\frac{1}{\cosh(x)} \right) + \frac{\sinh(x)}{\cosh^2(x)} \right]. \quad (4)$$

In the limit of very small ac field amplitudes ($x \ll 1$), the components of the ac-susceptibility become,

$$\chi' \approx -\chi_0 \left(1 - \frac{15}{32} x^2 \right), \quad x \ll 1, \quad (5)$$

$$\chi'' \approx \chi_0 \left(\frac{x^2}{\pi} \right), \quad x \ll 1. \quad (6)$$

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Clem and Sanchez [8] also found from numerical calculations that the peak in χ'' occurs at $x = 1.942$, where $\chi'' = \chi''_{\max} = 0.241\chi_0$ and $\chi' = -0.382\chi_0$. Thus the temperature dependence of the critical current density can be calculated using:

$$J_c(T) = \frac{H_m}{0.971d}, \quad (7)$$

where H_m is the amplitude of the applied ac magnetic field corresponding to the peak in $\chi''(T)$.

In addition, the measured χ' and χ'' data have been analysed using the following theoretical expressions [9,10]:

$$\chi' = -\frac{1}{x} \tanh(x), \quad (8)$$

$$\chi'' = -\frac{1}{x} \tanh(x) + \frac{2}{x} \tanh\left(\frac{x}{2}\right). \quad (9)$$

Based on the Bean model and assuming that the critical current density is field independent, Brandt [11] found the following expression of the $\chi''(\chi')$ relationship:

$$\chi'' \approx 0.8|\chi'|^{2/3}(1 - |\chi'|)^{1.19} \quad (10)$$

for all values of $0 \leq \chi' \leq -1$. It has been shown that in the low-temperature limit, the relationship between χ' and χ'' for thin film geometry is given by [9,11]

$$\chi'' = \alpha(1 + \chi') \quad (11)$$

with $\alpha = 0.68$ when the ac magnetic field is perpendicular to the surface of the film.

In the present work, the ac response of YBa₂Cu₃O₇ thin film is studied using nonlinear ac-susceptibility measurement. The temperature dependence of χ' and χ'' was analysed using the above theoretical models. The applicability of the critical state model to describe the present data was discussed.

2. Experimental

Nonlinear ac-susceptibility of YBa₂Cu₃O₇ thin film was measured as a function of temperature at different ac magnetic fields. The ac-susceptibility was measured using a standard mutual inductance technique. The primary coil served as an exciting coil which was used to produce a sinusoidal magnetic field of amplitude 1 μ T–1.2 mT and frequency 10–10,000 Hz. A pair of compensated secondary coils, 10 mm apart, was mounted coaxially inside the primary coil and sample was placed in the middle of one of the secondary coils. The in-phase and quadrature signals, which are proportional to the real (χ') and imaginary (χ'') components of the complex susceptibility, respectively, were measured simultaneously by a dual-phase lock-in amplifier.

The YBa₂Cu₃O₇ thin film used in this study was fabricated using laser ablation onto a SrTiO₃ substrate. The film has a circular shape with diameter of 1 cm and thickness of 200 nm. As shown below, $T_c = 90.8$ K was determined. The applied ac field is perpendicular to the surface of the film. Both components of the susceptibility are normalized assuming perfect diamagnetism at low temperatures and low ac fields.

3. Results and discussion

The temperature dependence of χ' and χ'' for a YBa₂Cu₃O₇ thin film at various ac-magnetic fields (0.8, 8, 48, 80, 160, 318, 480, 640, 800, 960 A/m) and at $f = 1000$ Hz is shown in Fig. 1. The first drop of the χ' at the smallest ac field is used to determine the transition temperature (T_c). From the figure, we find $T_c = 90.8$ K. As evident from Fig. 1, a significant shift in both χ' and χ'' scans to lower temperatures accompanied by a noticeable broadening are observed as the applied ac field is increased.

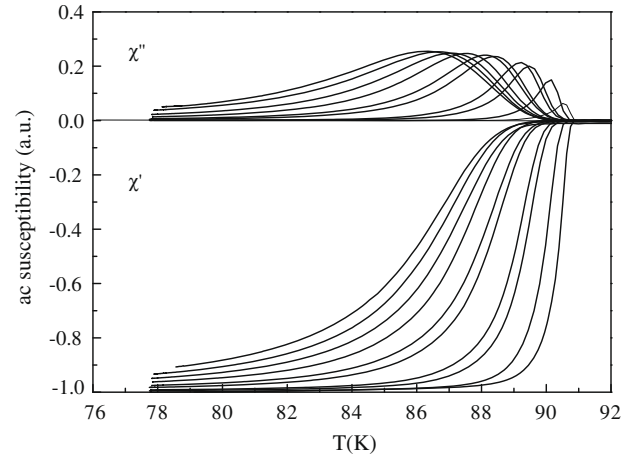


Fig. 1. Temperature dependence of the ac-susceptibility at $f = 1000$ Hz for YBCO(123) thin film at various ac magnetic fields (right to left): 0.8, 8, 48, 80, 160, 318, 480, 640, 800, 960 A/m. The magnetic field is perpendicular to the surface of the film.

The field dependence of the χ'' peak temperature, T_p at $f = 1000$ Hz is shown in Fig. 2. A shift to lower temperatures (of about 4 K) in T_p as the field amplitude is increased from ~ 1 to ~ 1000 A/m is observed. It is worth noting that compared with granular YBa₂Cu₃O₇ samples; this amount of shift is very small. This observation can be used as an indication of the vortex pinning strength. It is also evident from this graph that there is a crossover in behaviour of T_p vs. H_{ac} at about 100 A/m. The $T_p(H_{ac})$ curve is a characteristic relationship indicating the strength and nature of flux line pinning of high- T_c superconductors. As reported by many authors [12, and references therein], this $T_p(H_{ac})$ line can be represented mathematically by a power law relationship of the following form:

$$1 - t = aH^q, \quad (12)$$

where the reduced temperature $t = T_p/T_c$, a and q are constants. The straight line in Fig. 2 is the least squares fit to the above power law relation for $H_{ac} > 100$ A/m, yielding $q \sim 0.3$. At low ac fields, the experimental data cannot be described by Eq. (12).

It is worth noting that according to Bean's critical state model, the height of the χ'' peak is independent of the amplitude of H_{ac} .

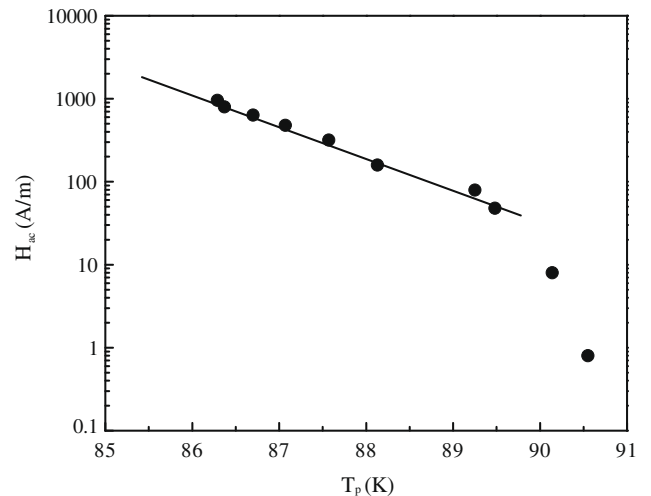


Fig. 2. Variation of the peak temperature, T_p , with the applied ac field. The straight line represents the curve fit using Eq. (11).

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