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Dynamic scaling of ac susceptibility in melt-textured YBCO superconductors

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Abstract

Based on vortex glass phase transition analysis, using homogeneous function analysis, it is very convenient to obtain the dynamic scaling law of ac susceptibility in high temperature superconductors. The experimental results of melt-textured YBCO system and other high temperature superconductors are consistent with the scaling function. The critical exponent γ is estimated from the scaling result. The asymptotic properties at low frequencies are discussed.

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1. Introduction

The phase transition of vortex matter from solid to liquid has been extensively studied recent years [1–6]. The separation of the mixed vortex state into two different phases is favored by the large anisotropies, high temperatures, and extreme type-II character. The vortex solid state is characterized by a nonzero critical current density, while the vortex liquid is dissipative at all currents. The solid-to-liquid phase transition is most likely a first order melting transition in very clean systems, but turns into a second order vortex glass transition for highly disordered systems involving point defects or Bose glass transition in systems with corrected defects like ion-induced columnar defects or twin boundaries. With the assumption of the coherence length $\xi_g(T) \sim |T - T_g|^{-\upsilon}$ with υ the static critical exponent and the characteristic time scale $\tau_g \propto \xi_g^z$, the dc current–voltage $(I–V)$ characteristics for a vortex glass with quenched disorder are scaled with:

$$\frac{E}{J|T - T_g|^{\nu(z+d-2)}} \propto F_{\pm}\left[\frac{J}{T|T - T_g|^{2\nu}}\right], \qquad (1)$$

where d is the dimensionality, E is the electrical field, J is the current density, and z is the dynamic critical exponent [7–10]. Rydh et al. [3,4] modifies the original vortex glass theory by introducing a modified coherence length: $\xi_g(T) \sim |k_B T/U_{eff} - 1|^{-\upsilon}$, with U_{eff} effective pinning energy. In our previous work [5,6], a further discussion has been presented associated with the competition of thermal activation and pinning energy. The dynamic characteristic has also been investigated widely. The scaling behavior of the complex electrical conductivity $\sigma(\omega)$ determined from the linear ac susceptibility has been discussed by Kötzler et al. [11,12]. The frequency dependence peak temperature T_p of imaginary part shows a scaling relation in several families of cuprate superconductors [13–15]. In this Letter, we present a dynamic scaling behavior of ac susceptibility in YBCO melt-textured superconductors deduced from homogenous function analysis.

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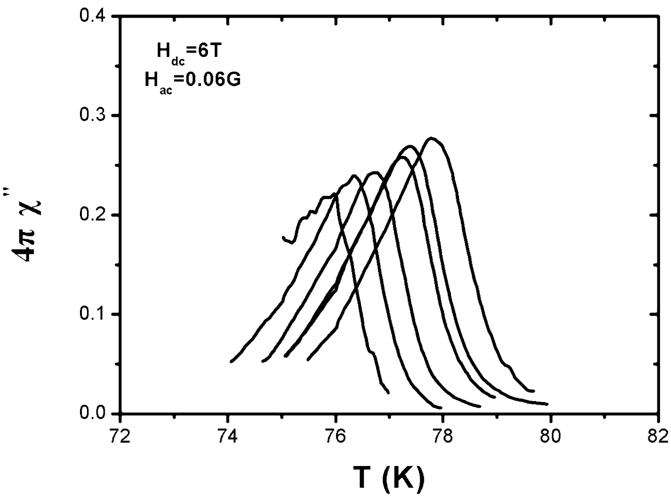

Fig. 1. Ac susceptibility for YBCO melt-textured samples at different frequencies: 9.21, 32.1, 91.1, 377, 577, 1771 Hz (from left to right).

2. Experimental details

The samples examined were high quality melt textured YBCO $\sim 2 \times 2\ \mathrm{mm}^2$ and ~ 1 mm along the c axis [16,17]. The $\chi(T, H)$ was measured by a ultra-sensitive ac susceptometer. The susceptometer consisted of a pair of carefully balanced secondary coils of 5000 turns each and a 700 turns primary coil. An adjustable sinusoidal ac current source was constructed to excite the primary coil at frequencies between 3 and 10 000 Hz without distortion. A single crystal sapphire strip was used to connect the sample inside one of the secondary coils with carbon glass thermometer outside the coil to reduce thermal lag. A dc magnetic field of a few Tesla was superimposed on the ac field during all measurements. Both the dc and ac fields were parallel to the c axis of the sample. The $\chi(T, H)$ data were recorded by a computer for later analysis.

3. Result and discussion

The measurements are done for several dc fields. The temperature dependence of $4\pi\chi''$ is shown in Fig. 1 with various frequencies. The results are similar and only the data with $H_{dc} = 6$ T are discussed in detail here. The peaks at T_p, when H_{ac} fully penetrates into the sample, shift to higher values with increasing frequencies. The scaling form of frequency dependence peak temperature has been discussed extensively. Following the interpretation proposed by Geshkenbein et al. [18], the ac susceptibility can be expressed as

$$4\pi\chi' = \frac{\sinh u + \sin u}{u(\cosh u + \cos u)} - 1, \tag{2a}$$

$$4\pi\chi'' = \frac{\sinh u - \sin u}{u(\cosh u + \cos u)}, \tag{2b}$$

where

$$u = \frac{d}{\lambda_s} = \left[\frac{\omega}{\rho}\frac{2\pi d^2}{c^2}\right]^{1/2}, \tag{3}$$

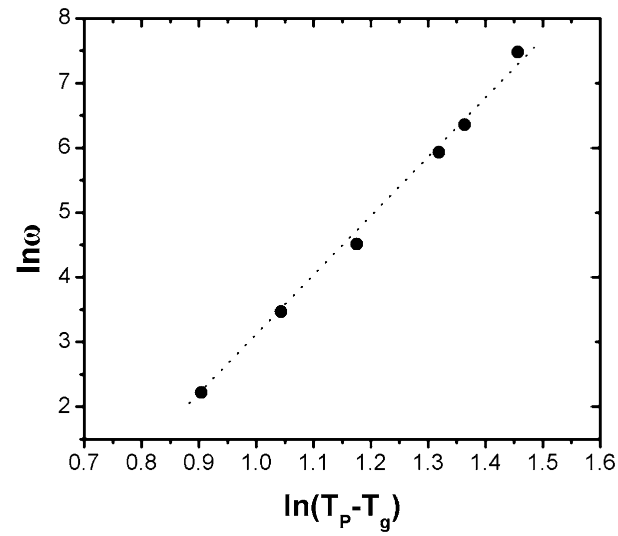

Fig. 2. Plot of $\ln\omega$ vs. $\ln(T_p - T_g)$ to determine vortex glass temperature $T_g \approx 73.8$ K and exponent $v(z-1) \approx 9.3$.

with d the sample size and λ_s the skin penetration depth. The imaginary part of χ attains a maximum at $u_{max} = 2.25$ corresponding to the relation

$$\omega \cong 0.8\frac{c^2}{d^2}\rho(H, T). \tag{4}$$

Based on vortex glass phase transition analysis, for $T > T_g$, the right term on Eq. (1) goes to a constant as $J/J_0 \to 0$ where J_0 is a characteristic current density, then one has a linear resistivity, which vanishes with the form

$$\rho = \rho_n(T - T_g)^{v(z+2-d)}. \tag{5}$$

Then combining Eq. (4) with Eq. (5), for a $d = 3$ system, the peak temperature has the scaling form

$$(T_p - T_g)^{v(z-1)} = \omega/\omega_0, \tag{6}$$

where T_g is the vortex glass transition temperature and ω_0 is a characteristic frequency. Thus a plot of $\ln\omega$ vs. $\ln(T_p - T_g)$ should be a straight line with a scope of $v(z-1)$, which was shown in Fig. 2. From this plot, one obtains the vortex glass temperature $T_g \approx 73.8$ K, and $v(z-1) \approx 9.3$. Further vortex glass analysis gives the value of exponents $v \sim 2.1$ and $z \sim 5.4$, respectively [19].

A dynamic scaling law expresses the fact that, if we increase the frequency at which we study a system by some scaling factor λ, we obtain the same effect as if we had reduced the relaxation time by a factor $1/\lambda$. Now, reducing the correlation length by a factor of $1/\lambda^{1/z}$ has just this effect, dividing the relaxation time by a factor λ [20]. Therefore, in order to accelerate relaxation of the system by the scaling factor, it suffices to move away from the critical point by a factor $1/\lambda^{1/z}$. With respect to the vortex glass transition, it expresses the fact that the free energy and its derivatives are homogeneous functions of $\tau = (T - T_g)/T_g$ and ω. For example, this homogeneity condition requires the susceptibility to take the form

$$\chi(\tau, \omega) = \lambda\chi\left(\lambda^x\tau, \lambda^y\omega\right). \tag{7}$$