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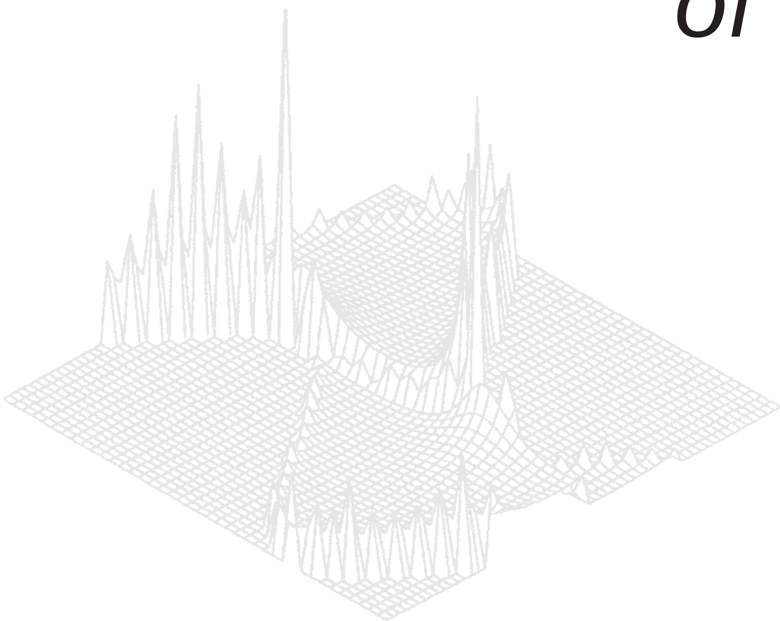

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Voltage Response of AC Susceptibility and Pinning Effects in $Hg_{0.69}Pb_{0.31}Ba_2Ca_2Cu_3O_{8+\delta}$

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Abstract

We have studied the voltage response of AC susceptibility, and from the imaginary part of the susceptibility experimental results a new method is presented in terms of the material equation to investigate the pinning properties and the dynamical response in our $Hg_{0.69}Pb_{0.31}Ba_2Ca_2Cu_3O_{8+\delta}$ sample. We also discuss the differences between the voltage criterion and our AC response measurement method in order to determine the value of the true critical current density. The result shows that the later method reflects the true critical state of high-temperature superconductivity better than the general voltage criterion.

1. Introduction

In recent years the AC response measurement technique has been widely applied to study vortex motion in high T_c superconductors (HTSC), and many papers have been reported. Firstly, Nikolo and Goldfarb (1989) and Muller *et al.* (1991) measured the pinning barrier $U_0(T, B)$ using the linear fit Arrehenius expression. To take into account the strongly nonlinear effect in flux vortex matter, Blattter *et al.* (1994) suggested a new expression for the imaginary part of the susceptibility for a slab sample. Based on this expression, Ding *et al.* (1995) and our group (Hung *et al.* 1997) have carried out numerous experiments to determine the corrections to the temperature dependence of the effective pinning potential of HTSC. However, it is well known that the true critical current J_c and the pinning barrier play important roles for investigating the flux dynamics and the vortex physics of the HTSC in a mixed state. In fact, how to measure the pinning barrier and the true critical current density J_c of the HTSC is the basic topic of the vortex dynamic response theory. Schnack *et al.* (1993) proposed the so-called generalised inversion scheme (GIS) to obtain the true critical current of the $YBa_2Cu_3O_{7-\delta}$ film by means of the magnetisation dynamical relaxation rate. Nevertheless, as far as we know, there is no direct report associated with the true critical current density and the pinning barrier by using the AC response technique. In this paper, we deduce an analytical expression of the flux conservation for a cylinder sample, which describes reasonably the flux behaviours of the grain superconductors. After that we study the electrical voltage response of the imaginary part of the AC susceptibility and, as a consequence, the analytical forms for the pinning barrier and the critical current density are obtained. Finally, we investigate the pinning properties and evaluate the true critical current density J_c of the $Hg_{0.69}Pb_{0.31}Ba_2Ca_2Cu_3O_{8+\delta}$ sample.

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Our work shows that the AC response technique may be another effective way to solve this problem.

2. Theoretical Analysis

For infinite length columnar samples of different cross-section shapes, when the external field is applied parallel to the edge of the sample, the flux conservation equation has been obtained by Beasley *et al.* (1969) based on the thermal excitation theory of flux (see Anderson 1962; Anderson and Kim 1964):

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \cdot \mathbf{D} \quad , \tag{1}$$

where **B** is the magnetic induction,

$$\mathbf{D} = -(\nabla B/|\nabla B|)\mathbf{B}\nu_0 l \exp[-U_{\mathrm{eff}}(T, B, J)/kT],$$

and where l is the mean hopping distance of the flux bundle, ν_0 is the attempt frequency, and U_{eff} is the effective pinning potential. On the boundary of the infinite length columnar sample, the magnetic induction is equal to $\mu_0 H$, where H is the magnetic intensity and μ_0 is the vacuum magnetic permeability. Integration of equation (1) with respect to the volume for unit height of the cylinder sample yields

$$\frac{1}{V}\int_V \frac{\partial B}{\partial t} dV = -\frac{1}{V}\int_V \nabla \cdot \mathbf{D}\, dV \quad . \tag{2}$$

According to the integration theorem, the integration over volume can change to integration over area. For the cylindrical symmetry sample, the integration result of the upper cross-section area is opposite to the lower, so we can easily obtain the following equation for a cylindrical sample:

$$\frac{\partial \langle B \rangle}{\partial t} = \frac{2\nu_0 l \mu_0 H}{r} \exp[-U_{\mathrm{eff}}(T, H, J_{\mathrm{s}})/kT] \quad , \tag{3}$$

where J_{s} is the driving current density, r is the radius of the sample, $\langle B \rangle$ is the mean result obtained by averaging the local field over the cross-sectional area and H is the external applied magnetic field. As mentioned by Anderson (1962), the vortex lines or bundle can move from one place to another due to thermal activated jumps even at the current density $J_{\mathrm{s}} < J_{\mathrm{c}}$. The consequence of this kind flux creep is to induce the electric field on the sample boundary, a relation given by

$$E = \nu_0 l \mu_0 H \exp[-U_{\mathrm{eff}}(T, H, J_{\mathrm{s}})/kT] \quad . \tag{4}$$

We proceed by combining equations (4) and (3), and then the relation between $\partial\langle B \rangle/\partial t$ and the electric field E is obtained as (the analogous result can also be found in the work of Wen *et al.* 1995)

$$\frac{\partial \langle B \rangle}{\partial t} = \mu_0 \left(1 + \frac{dM}{dH}\right)\dot{H} \quad . \tag{5}$$

As we know, $\partial\langle B\rangle/\partial t$ can be described as

$$\frac{\langle \partial B\rangle}{\partial t} = \mu_0\left(1+\frac{dM}{dH}\right)\dot{H} \quad . \tag{6}$$

In the presence of the AC field we have $H = H_0 + h_0\cos(2\pi\nu t)$, where H_0 is the applied magnetic background DC field, h_0 is the amplitude of the ac external field and ν is the driving frequency. If we take as $\dot{H}$ the mean result of $\partial\langle B\rangle/\partial t$ over a quarter of the period as an approximation, it should be equal to $4h_0\nu$. In the AC susceptibility measurement, we have $|dM/dH| << 1$ at the peak of the imaginary part corresponding to a fully field-penetrated state, where the hysteresis cycle can be derived by the AC field (Goldfarb *et al.* 1991), and so the voltage response of the AC susceptibility can be expressed by

$$E = 2\mu_0 h_0 \nu r \quad . \tag{7}$$

Brandt (1996, 1997) suggested the equation $E = E_c(J_s/J_c)^n$ to describe the relation between J_c and E, where E_c is a material constant and n is the exponent parameter. Substituting this equation into (7) gives

$$2\mu_0 \nu r h_0 = E_c\,(J_s/J_c)^n \quad . \tag{8}$$

If we substitute the logarithmic model proposed by Zeldov *et al.* (1989) into equation (4) and compare it with the material equation, n should be equal to U_0/kT, where $E_c = \nu_0 lB$. Here E_c is dependent on the applied field and the magnitude of $\nu_0 l$. At the peaks of the imaginary part of the AC susceptibility, J_s can be calculated by the Bean (1964) model from $J_s = h_0/r$. So equation (8) can be written in the form

$$U_0(T, H) = kT\left(\frac{\ln\nu}{\ln J_s}+1\right) \quad . \tag{9}$$

Equation (9) predicts that $U_0(T, H)$ is a linear function of $\ln\nu/\ln J_s$ at a given temperature. So we find that the pinning barrier can be easily determined provided the relation between $\ln\nu$ and $\ln J_s$ is obtained. Obviously the slope of the line of $\ln\nu$ versus $\ln J_s$ for a certain temperature is equal to U_0/kT. Fortunately, all the related data can be presented by the AC response measurement of the HTSC sample.

3. Experiment

Initially the sample was fabricated by the solid state reaction method. Raw powders of HgO, PbO, BaO, CaO and CuO were mixed with a predetermined molar ratio of Hg : Pb : Ba : Ca : Cu = 0.69 : 0.31 : 2 : 2 : 3. The mixture was then ground into a fine powder and pressed into pellets. By using the encapsulation and the short time annealing technique, the prepared sample was obtained. Eventually a post-annealing process with oxygen flux flowing at about 240–280°C for several hours was carried out for the prepared sample.

The diameter of the $Hg_{0.69}Pb_{0.31}Ba_2Ca_2Cu_3O_{8+\delta}$ sample was about 2 mm for the AC measurement. This sample almost consisted of Hg-1223 single phase. The average grain size of this sample was measured by SEM analysis and its value is about 4 μm. The critical temperature T_c of the Pb-doped and Hg-based superconductor is about 133 K.

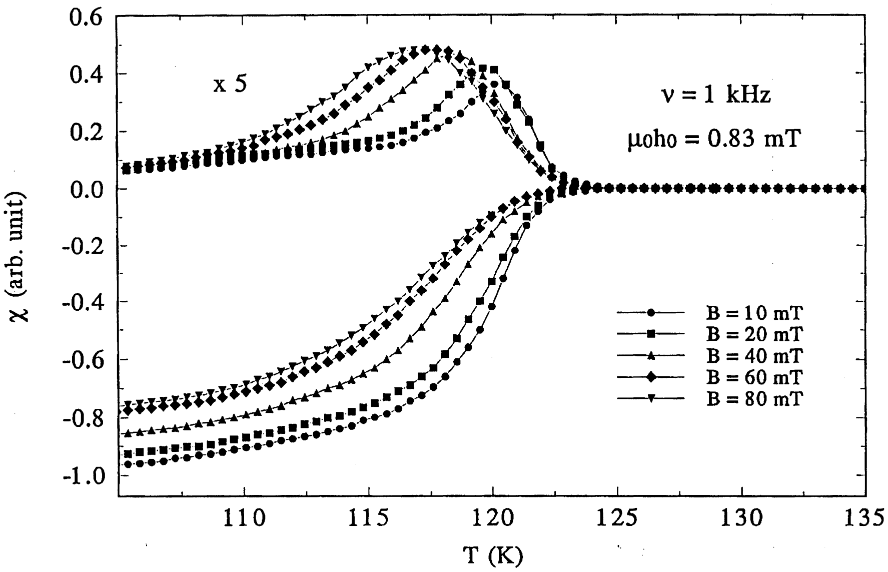

Fig. 1. Relation between the AC susceptibility and temperature for the granular superconductor of $Hg_{0.69}Pb_{0.31}Ba_2Ca_2Cu_3O_{8+\delta}$ under different DC magnetic fields.

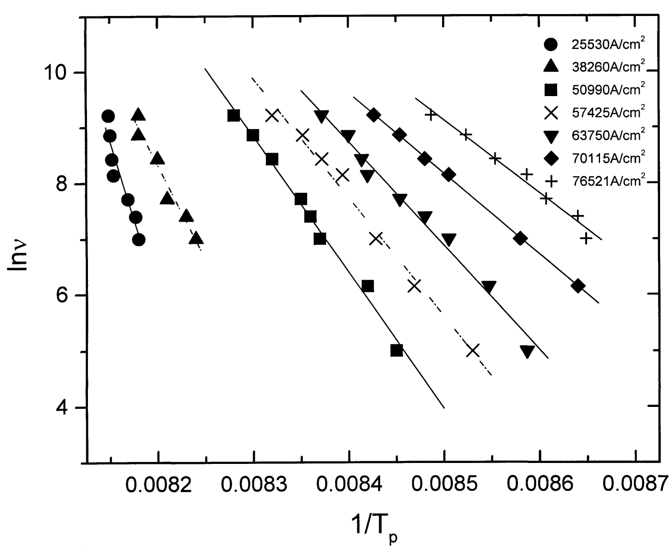

Fig. 2. Log plot of the driving frequency ν versus $1/T_p$ for values of $\mu_0 h_0$ equal to 0.64, 0.96, 1.28, 1.44, 1.60, 1.76 and 1.92 mT, under a DC field of 40 mT, where T_p is the peak temperature of the out-of-phase susceptibility χ'' and $T_c = 133$ K is the critical temperature of the $Hg_{0.69}Pb_{0.31}Ba_2Ca_2Cu_3O_{8+\delta}$ sample.

The AC magnetic susceptibility measurement was made using a specially designed cryostat. A double-coil probe combined with a high precision dual-phase lock-in amplifier of SR 530 Stanford Research System type were utilised to measure simultaneously the real and the imaginary parts of the susceptibility from the pick-up voltage signals. The driving frequencies used in this study were in the range 1–10 kHz. All of our measurements were performed during a heating process with a uniform heating rate of $dT/dt = 0.3$ K per minute. The accuracy of the temperature measurement was 0.1 K. The accuracy in measuring the peak in the imaginary part was within 0.16 K. The AC susceptibility data of our sample with various applied DC fields for the $Hg_{0.69}Pb_{0.31}Ba_2Ca_2Cu_3O_{8+\delta}$ superconductor are shown in Fig. 1. It can be seen that the corresponding T_p of the χ'' peak for various applied DC fields can be obtained. The amplitude of the AC field used in this figure is 0.83 mT at a driving frequency of 1 kHz.

For the sake of clarity, the components of the χ'' part are magnified by a factor of 5. The complex AC susceptibility measurements were also performed under a DC magnetic field of 40 mT and combined with an AC field of different amplitudes of $\mu_0 h_0 = 0.64$, 0.96, 1.28, 1.44, 1.60, 1.76 and 1.92 mT. In this AC susceptibility study, we only concentrate on the response due to the intragranular losses. This is because under our applied DC field of 40 mT the corresponding maximum peak observed in the imaginary part χ'' is due to the intragranular losses, whereas the component due to the intergranular (weak link) losses had shifted far away to the low temperature side, and so did not appear here.

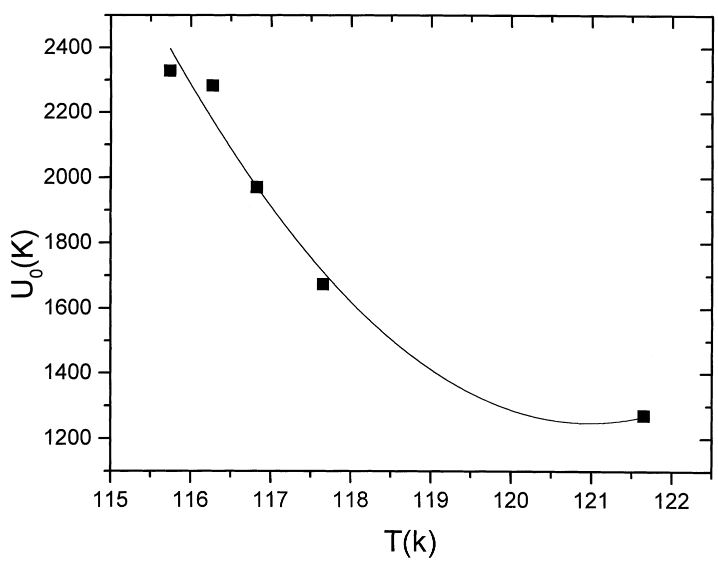

Fig. 3. Plot of the pinning barrier $U_0(T, H)$ versus temperature T for a fixed field of 40 mT.

4. Results and Discussion

From the set of experiment results on the AC susceptibility we obtain a plot of $\ln\nu$ versus $1/T_p$ as shown in Fig. 2. Here one finds that $\ln\nu$ varies with $1/T_p$ in certain amplitudes h_0, where T_p represents the temperature corresponding to the peaks of the imaginary part of the AC susceptibility. The experimental data lie on the straight lines for the various values of the current density J_s (see also Nikolo and Goldfarb 1989). From these lines we can pick out points for a given temperature, and hence the relation between $\ln\nu$ and $\ln J_s$ can be easily derived. Using equation (9), the value of the pinning barrier at a certain temperature was determined and the result is demonstrated in Fig. 3. One can see that the pinning barrier U_0 decreases dramatically with an increase of temperature, which indicates that it is more difficult for the flux to overcome the barrier in order to move at lower temperature. Equation (8) enables us to find a method to evaluate the value of the true critical current J_c if the exponent parameter n and the constant E_c are determined. Because $n = U_0/kT$, by using equation (9), we get the form

$$n = \frac{d\ln\nu}{d\ln J} + 1 \quad . \tag{10}$$

If we suppose the material equation is an accepted form, and the value of E_c has been determined, J_c can be derived by changing the form of equation (8) to

$$J_c = \exp[\ln(E_c J_s^{n-1}/2r^2\mu_0\nu)] \quad . \tag{11}$$

Equation (11) shows that the determination of J_c at a certain temperature for a given field somewhat depends somewhat on the choice of the corresponding electric field E_c. We have adopted a widely used criterion of $E_c = 1\ \mu\text{V cm}^{-1}$ suggested by Takacs (1997) to evaluate the true critical current density J_c . The result shows that the true critical current J_c is even lower than the current density J_s of our AC experimental data. This abnormal result implies that the voltage criterion does not describe the true critical state of the vortex flux for a high temperature superconductor due to flux creep. However, McHenry and Sutton (1994) determined the quantity $\nu_0 l$ with a DC magnetic relaxation method, and derived a result of the order of 10^4 cm s^{-1}. Using this result we calculated the true critical current density J_c with equation (11), as shown in Fig. 4. It is shown that the magnetic methods including the AC susceptibility measurement seem more reasonable than the general voltage criterion of the pure critical current density J_c because the general voltage criterion does not reflect the character of the true critical state. Note, however, that the true critical current density J_c is independent of the driving frequency. From equation (8), a power law of the form $J_s^{n-1} \propto \nu$ is clearly observed. This result shows the driving

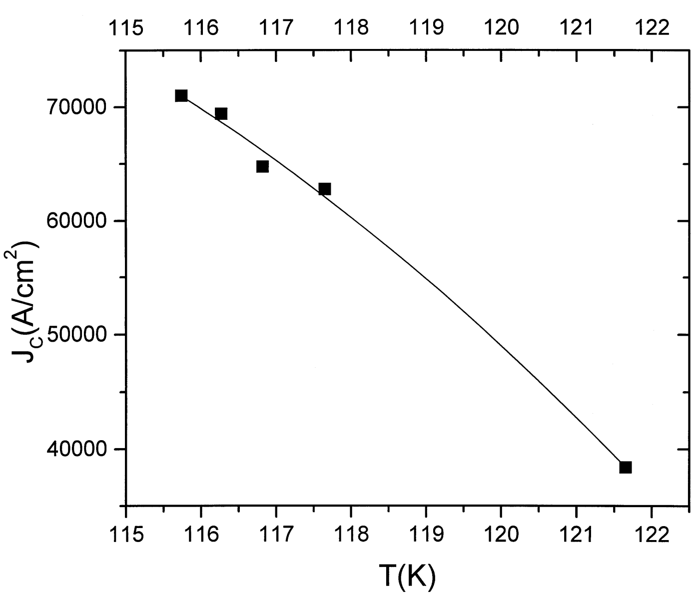

Fig. 4. Plot of the true critical current density $J_c(T, H)$ versus temperature T for a fixed field of 40 mT.

frequency ν dependence of the current density J_s. It implies that J_c is only a function of the magnetic field H and temperature. So here we can discuss the J_c–T character obtained by the above method. Fig. 4 shows the variation of J_c versus T as a result of our AC response technique. The figure shows that the true critical current density J_c decreases with an increase in temperature. The shape of this curve is identical to the result by Griessen *et al.* (1994), which indicates that the δL-type pinning centres are dominant in this regime. As we know, the logarithm pinning model describes the characteristics in the vicinity of the melt line, so the result discussed here may describe the pinning properties in this regime.

5. Conclusion

In summary, our work has put forward an analytical form of the pinning barrier from the material expression and the vortex flux conservation equation. A new and relatively easy method has been used to measure the pinning barrier and the true critical current density J_c by the AC response technique. Furthermore, the result shows that the magnetic measurement method is more appropriate than the voltage criterion to determine the true critical current density. In contrast to the results by Griessen *et al.* (1994), we can conclude that the dominant pinning in our sample is of δL type.

Acknowledgments

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