Magnetic Response of a Single-Crystal Thin Film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$

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SYNOPSIS

To test the utility of the modified Kim-Anderson model for study of the magnetic response of ceramic superconductors, we measured ac complex susceptibilities $\chi_n = \chi_n' - i\chi_n''$ ($n=1,2,3,5,7$) of a single-crystal thin film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$, and attempted to simulate the results in the framework of this model. Analyses of χ_n have shown that generation of the higher-harmonics can be reproduced pretty well, where the material parameters k and B_0 , the surface barrier ΔH and the lower critical field H_{c1} involved were used as the fitting parameters. From the even- n harmonic susceptibility χ_2 which reflects the asymmetric nature of the magnetization curve, we found that the critical-current density J_c of the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$ film depends sensitively on the local flux density B_i . This result is a provoking contrast to the B_i dependence of J_c for an $\text{YBa}_2\text{Cu}_3\text{O}_y$ film.

KEY WORDS

modified Kim-Anderson model, surface barriers, single-crystal thin film, harmonic susceptibility.

1 Introduction

The Kim-Anderson model introduced by Kim, Hempstead and Strnad¹⁾ and Anderson²⁾ has been widely used for study of the magnetic property of type-II superconductors. The essential aspect of this model is that, when a magnetic field is applied to a sample, a macroscopic supercurrent circulates in the sample with a critical-current density $J_c(B_i)$, where B_i is the local flux density inside the specimen. They assumed that the critical-current density has the form

$$J_c = k / (B_0 + |B_i|), \quad (1)$$

where k and B_0 are material parameters. As pointed out by Chen and Goldfarb³⁾, the relation given by Eq.(1) is a generalized form of the critical-state model, because it leads either to the liner model⁴⁾ or to the Bean model⁵⁾ or to the power-law model⁶⁾, depending on the relative magnitude of k , B_0 and B_i .

To test the utility of the Kim-Anderson model^{1,2)} through ac complex susceptibilities as a probe, we have carried out a series of investigations, where we used several kinds of ceramic superconductors, $\text{YBa}_2\text{Cu}_3\text{O}_y$ (YBCO) single-crystal thin films⁷⁾, an Fe-doped YBCO sintered sample⁸⁾, a melt-processed YBCO⁹⁾, $\text{HoBa}_2\text{Cu}_4\text{O}_y$ ¹⁰⁾ and $\text{Bi}_{1.6}\text{Pb}_{0.4}\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_y$ ¹¹⁾.

In these studies, the observed complex susceptibilities as a function of temperature were analyzed using the magnetization equations¹²⁾ based on the Kim-Anderson model. The reproducibility of the data has been found to be pretty good, except in one case of single-crystal thin films. In these previous treatments, we have neither taken into consideration surface barriers ΔH nor lower critical fields H_{c1} , both of these were assigned to be zero.

According to Dunn and Hlawiczka¹³⁾, the magnetization curves are somewhat complicated due to the nonzero values of ΔH and H_{c1} , but the effective field in the sample may be described by the following expression¹³⁾,

$$H_{\text{eff}} = H - \frac{H}{|H|} H_{c1} - \frac{dH/dt}{|dH/dt|} \Delta H, \quad (2)$$

where H is the applied field, ΔH and H_{c1} are assumed to be constants.

For analyses of χ_n for the thin film which cannot be reproduced by the Kim-Anderson model, we modified the Bean model using H_{eff} instead of H and fully derived the magnetization equations for type-II superconductors¹⁴⁾. Applying these equations, we could qualitatively well reproduce χ_n for YBCO

single-crystal thin films¹⁵⁾.

Recently, we extended the modified Bean model to a more generalized case, i. e., we modified the Kim-Anderson model by using H_{eff} and fully derived the magnetization equations for an infinitely long cylinder. The theoretical derivation will appear elsewhere.

The time-dependent magnetization $M(\omega t)$ of a specimen for a magnetic field $H(\omega t) = H_{dc} + H_{ac} \cos(\omega t)$ can generally be expressed in the form of a Fourier expression:

$$M(\omega t) = \chi_0 H_{dc} + H_{ac} \sum_{n=1}^{\infty} \text{Re}[\chi_n \exp(in\omega t)] \quad (3)$$

where $\text{Re}[\]$ denotes the real part of a complex variable and $\omega = 2\pi f$, where f is the fundamental frequency. The first term $\chi_0 H_{dc}$ is an offset by a dc magnet field H_{dc} , and the second is the ac component which varies in time with the ac magnetic field $H_{ac} \cos(\omega t)$. Here we define $\chi_n \equiv \chi'_n - i\chi''_n$ ($n=1,2,\dots$) as the Fourier coefficients of the magnetization, where χ_1 is the fundamental susceptibility and the others are the higher-harmonic susceptibilities.

In this paper, we present the observed χ_n of a single-crystal thin film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$ ($1\text{cm} \times 1\text{cm} \times 400\text{\AA}$). Analyses of the data were carried out using the modified Kim-Anderson model. Some discussion of the magnetic response of the film is also given.

2 Experimental

2.1 Sample preparation

A single-crystal thin film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$ was prepared by the RF magnetron sputtering method. The film epitaxially grew with the $[001]$ axis normal to the (100) surface of the MgO single crystal. The phase identification was made by X-ray diffraction patterns using Cu-K α radiations. The data have only $(00l)$ ($l=1,2,\dots$) reflections of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$ structure, suggesting that this sample is a single crystal.

2.2 Measurement of χ_n

The measuring system of χ_1 consisted of the Hartshorn bridge and the temperature control system. To avoid the bridge imbalance during one run of the experiment, the sample coil was directly immersed

in a liquid He bath. A null adjustment of the bridge was made at 100K and the sample temperature was decreased down to 4.2 K at a rate of about 0.3K/min. Phase setting of the lock-in amplifier was carefully made so as to give variation only to the in-phase signals, against the change in the bridge inductance. The ac magnetic field $H_{ac} \cos(\omega t)$ was applied to the sample using a function generator, where the applied ac field is parallel to the c axis.

For measurements of higher-harmonic susceptibilities χ_n ($n=2,3,5,7$), the device was modified, where two function generators were used. The ac magnetic field was applied using one generator F1 and the other generator F2 was used to supply the n th-harmonic sinusoidal wave synchronized with F1. In this experiment, magnetic shielding was not used, and so the applied ac field was superimposed on the Earth's field. Using a gaussmeter, the Earth's field was determined to be $\mu_0 H_{dc} = 0.03$ mT, where $\mu_0 = 4\pi \times 10^{-7}$ H/m. Details of the measuring system were previously reported¹⁶⁾.

3 Results and discussion

In Fig.1, we show the real and imaginary components of χ_1 versus temperature. The applied field amplitude $\mu_0 H_{ac} = 0.01$ mT and $f = 132$ Hz. The onset temperature $T_c(\text{onset})$ is 78.0 K.

In Fig.2, we show the $\chi_n - t_r$ ($n=2,3,5,7$) curves under $\mu_0 H_{ac} = 0.1$ mT and $f = 132$ Hz, where $t_r (=T/T_c)$ is the reduced temperature. The specific features are

Fig.1 Real and imaginary components of the fundamental susceptibility χ_1 vs temperature T for a single-crystal thin film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$, where $\mu_0 H_{ac} = 0.01$ mT and $f = 132$ Hz.

followings:

(1) The values of χ_2 are very large in comparison with those of YBCO single-crystal thin films¹⁵.

(2) In the χ_5-t_r and χ_7-t_r curves, we find small oscillations in the lower temperature region ($t_r \sim 0.85$).

When the sample magnetization $M(\omega)$ is expressed by Eq.(3), the real and imaginary components of χ_n can be calculated by

$$\chi'_n = \frac{1}{\pi H_{ac}} \int_0^{2\pi} M(\omega) \cos(\omega t) d(\omega t), \quad (4)$$

$$\chi''_n = \frac{1}{\pi H_{ac}} \int_0^{2\pi} M(\omega) \sin(\omega t) d(\omega t), \quad (5)$$

Using the magnetization equations derived from the modified Kim-Anderson model, we evaluated M . To

carry out the evaluation, one period of the alternating magnetic field ($0 \leq \omega t \leq 2\pi$) was divided into 360 regular intervals, and $M(\omega t)$ was numerically obtained at each point. Using the calculated results of $M(\omega t)$ in Eqs.(4) and (5), we evaluated χ'_n and χ''_n .

The temperature dependence of χ_n comes from the parameters which involve T . In the present case, the temperature dependence of χ_n is introduced through k , B_0 , ΔH and H_{c1} . Here we take $H_{c1}=0$. The physical reason for this assumption is discussed later. The temperature dependence of k and B_0 were determined experimentally as $k(t_r)=k(0)(1-t_r)^3$ and $B_0(t_r)=B_0(0)(1-t_r)^{3/2}$. Although the temperature dependence of ΔH still remains to be resolved, we tentatively assumed $\Delta H(t_r)=\Delta H(0)(1-t_r)^{3/2}$ to reproduce the

Fig.2 Observed χ_2 , χ_3 , χ_5 , χ_7 vs t_r ($\equiv T/T_c$) for a single-crystal thin film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$, where $\mu_0 H_{ac}=0.1$ mT and $f=132$ Hz. (a) is the real component and (b) is the imaginary component. Data are normalized to χ_1 .

Fig.3 χ_2 , χ_3 , χ_5 , χ_7 vs t_r calculated by the Kim-Anderson model ($\Delta H=0$ and $H_{c1}=0$), where $k(0)=250$ N/m³, $B_0(0)=1$ mT, $\mu_0 H_{ac}=0.1$ mT and $\mu_0 H_{dc}=0.03$ mT. (a) is the real component and (b) is the imaginary component.

profile of the observed χ_n-t_r curves. Here $k(0)$, $B_0(0)$ and $\Delta H(0)$ are fitting parameters.

In Fig.3, we show calculated χ_n ($n=2,3,5,7$) by the original Kim-Anderson model. As seen in the figures, we can reproduce the magnetic behavior in the temperature region near T_c ($\sim 0.85 < t_r < 1$), but small oscillations which appear in the temperature region $t_r < \sim 0.85$ of the χ_5-t_r and χ_7-t_r curves cannot be reproduced.

When we substitute $M(\omega t)$ derived from the modified Kim-Anderson model ($\Delta H \neq 0$) into Eqs.(4) and (5), the small oscillations appeared in the observed χ_5-t_r and χ_7-t_r curves can be reproduced (see Fig.4). This fact strongly suggests that the surface barrier ΔH plays an essential role for the

Fig.4 $\chi_2, \chi_3, \chi_5, \chi_7$ vs t_r calculated by the modified Kim-Anderson model ($H_{c1}=0$), where $k(0)=250 \text{ N/m}^3$, $B_0(0)=1 \text{ mT}$, $\mu_0\Delta H(0)=0.5 \text{ mT}$, $\mu_0H_{dc}=0.1 \text{ mT}$ and $\mu_0H_{ac}=0.03 \text{ mT}$. (a) is the real component and (b) is the imaginary component.

magnetic response of the thin-film superconductor.

In the calculations of χ_n demonstrated in Fig.4, we assumed $H_{c1}=0$. This assumption seems to be reasonable because the demagnetization effect for a thin film should be extremely large. Supposing a flat spheroid with a thin pancake shape whose length of the short axis reaches a limit value of zero, the demagnetization coefficient N can be approximated by $N = 1 - \frac{1}{2}\pi(d/R)$, where $2d$ is the film thickness and R is the radius¹⁷⁾. Eventually, for a thin film, N is very close to 1. This causes the increase of the internal field and thus the practical value of the lower critical field becomes zero.

As mentioned before, the even- n harmonics appear only when the magnetization curve has an asymmetric feature. The nonzero values of χ_2 shown in Fig.2 should therefore be originated from the asymmetric $M(H)$ curves. In Fig.5, we show the $M(H)$ curve used for theoretical simulation of χ_2 given in Fig.4, where $k(0)=250 \text{ N/m}^3$, $B_0(0)=1 \text{ mT}$, $\mu_0\Delta H(0)=0.5 \text{ mT}$ and $H_{c1}=0$. As demonstrated in Fig.5, the $M(H)$ curve has a strong asymmetric feature which is caused by the existence of H_{dc} and the B_i -dependent J_c , and this certainly gives rise to relatively large values of χ_2 .

It should be noted that when J_c is a constant, the $M(H)$ loop tends to hold a symmetric nature even when $H_{dc} \neq 0$. Since the dependence of J_c on B_i for YBCO thin films is quite small, χ_2 for them is expected to be small. In fact, the previous observations of χ_2 for YBCO thin films was relatively small and consequently the modified Bean model could reproduce qualitatively well the experimental χ_2 ¹⁵⁾.

Fig.5 $M(H)$ loop at $t_r=0.90$ calculated by using the modified Kim-Anderson model.

4 Summary

We measured the superconducting transition of a single-crystal thin film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$ in terms of higher-harmonic ac susceptibilities χ_n ($n=2,3,5,7$). Analyses of the results were made in the modified Kim-Anderson model which takes into consideration surface barriers ΔH and lower critical fields H_{c1} . Comparison of the observed χ_n with the calculated results has revealed that the modified Kim-Anderson model can reproduce pretty well the magnetic behavior of the present film. This means that the nonzero value of ΔH together with the B_c dependence of J_c plays an essential role for the magnetic response of the thin film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$.

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