Angular dependence of $I_c(H)$ in $Bi_2Sr_2Ca_2Cu_3O_x$ tapes

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(Received 27 June 1996)

Measurements of the critical current, I_c, as a function of the angle between the applied magnetic field and the face of a $Bi_2Sr_2Ca_2Cu_3O_x$ tape have been performed. Defining θ as the angle between the basal plane and the magnetic field but perpendicular to the current, the data do not scale well with $H\sin(\theta)$. For a given value of magnetic field, as θ increases I_c decreases much faster than would be expected from a simple $\sin(\theta)$ law. This paper shows that other scaling functions, based on the anisotropy of the critical field, fit the data much better over the entire angular range. [S0163-1829(96)09441-6]

INTRODUCTION

There have been many studies of the critical current of $Bi_2Sr_2Ca_2Cu_3O_x$ tapes as a function of magnetic field and the angle that the field makes with the sample.[1–4] In the referenced papers, the authors find that the data scales reasonably well with $H\sin(\theta)$ over much of the range of θ studied. They have interpreted the fact that the data deviates from this scaling at low angle as being due to misalignment of the grains in the tapes. In a paper by Hao and Clem[5] it is suggested that the data from the various high temperature superconductors should be able to be explained by the same theory. This would lead to the scaling of $I_c(H,\theta)$ with the same functional form for all the materials. They point out that a $1/\sin(\theta)$ scaling function will not explain what has been observed in $YBa_2Cu_3O_{7-\delta}$ and $La_{1.8}Sr_{0.2}CuO_4$. (Here the convention that the scaling function, f, appears as H/f for scaling of the magnetic field is being used.) These authors show that the differences in the Gibbs free energy between the superconducting and normal states is a function only of $H/H_{c2}(\theta)$ for $H \gg H_{c1}$, leading to the use of other scaling functions. This procedure was used in a paper discussing the scaling of the angular dependence of the critical current in an epitaxial film of $Bi_2Sr_2CaCu_2O_8$.[6] In Ref. 6, it is shown that several functions derived from expressions for the upper critical field, H_{c2}, in Josephson coupled layers or thin films fit the data. The best fit of the data is to a scaling function derived from an expression for $H_{c2}(T,\theta)$ originally developed by Tinkham[7] for thin films. We have scaled our angular dependent data, as well as that of others, to these lower dimensional equations. Surprisingly, these more complicated scaling functions are a very good description of the data for rolled tapes.

EXPERIMENT

As part of a program to investigate $Bi_2Sr_2Ca_2Cu_3O_x$ tapes the critical current as a function of applied magnetic field at 77 K was measured. The tapes were made using the powder-in-tube method. All of the studies involved short pieces of the tapes; a typical sample being 2 cm long, 5 mm wide, and 0.3 mm thick. The c axes of the grains in the tape were aligned predominately with the normal of the tape. Measurements as a function of angle were performed at an applied magnetic field of 0.2 and 0.4 T, while the sample was immersed in liquid nitrogen. The dewar was inserted into the room temperature bore of a split coil superconducting magnet. Measurements of the critical current were taken with the applied magnetic field oriented from $-10°$ to $+125°$ with respect to the plane of the tape. In this paper $\theta = 0°$ is taken as being when the magnetic field is in the plane of the tape, but perpendicular to the current. At all times the field was perpendicular to the current in the tape. The orientation of the field, current, and sample are shown in the inset to Fig. 1. The data were collected by a computer which also controlled the current source. The current was gradually increased as the voltage along the sample was measured. A measurement criterion of 5 μV/cm was used to define the critical current. Choosing another criterion did not effect the data analysis significantly.

DATA AND DISCUSSION

The normalized critical current as a function of angle of the applied magnetic field is shown in Fig. 1. It can be seen

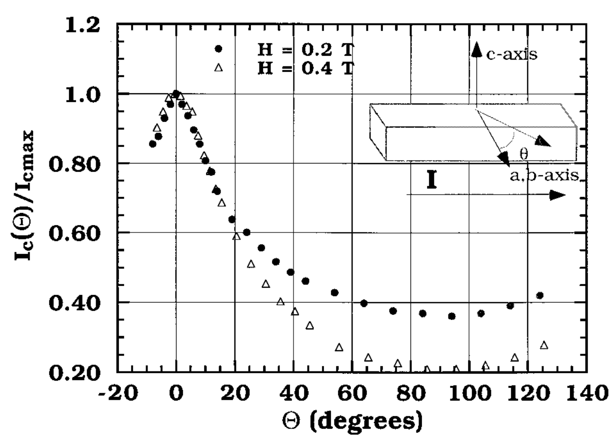

FIG. 1. The normalized critical current as a function of angle for a $Bi_2Sr_2Ca_2Cu_3O_x$ tape for two applied magnetic fields, 0.2 T and 0.4 T at 77 K. The critical current is normalized to the maximum value for a given field. The insert shows that θ is the angle between the magnetic field direction and the plane of the tape (the ab plane of the $Bi_2Sr_2Ca_2Cu_3O_x$). In all cases the magnetic field is perpendicular to the current in the tape.

that the critical current falls off rapidly as the magnetic field moves out of the plane of the tape. The figure shows that a change in the field orientation of only 10° from the parallel direction causes nearly a 20% reduction in the measured critical current.

If I_c were to depend simply on the component of the field parallel to the c axis of the grains, one would expect the data to collapse onto a single curve, at a given temperature, when plotted against $H\sin(\theta)$. The data are plotted in this fashion in Fig. 2(a). Figures 2(b) and 2(c) show similar data from other groups.[1,3] It is obvious that the data deviate from a $1/\sin(\theta)$ scaling behavior at low angles. This discrepancy has been interpreted in the past as being due to a misalignment of the grains in the rolled tapes.[1,3,4,8] This is a plausible explanation since one would not expect the grains of $Bi_2Sr_2Ca_2Cu_3O_x$ to be perfectly aligned in a rolled tape. In fact fitting $I_c(\theta)$ at a constant applied H to $\sin(\theta)$ with a Gaussian distribution of grain orientation gives reasonable agreement with data.[8]

However, perhaps a different scaling function should be examined. In their paper on scaling of the critical current in films of $Bi_2Sr_2CaCu_2O_8$, Fastampa *et al.*[6] show that it is possible to use an expression derived from the angular dependence of the upper critical field to scale their data. In their paper they show that $I_c(H,\theta)=I_c[H/f(\theta)]$ where $f(\theta)$ is the function needed to collapse the curves onto the curve for $I_c(H,90°)$. From the work of Hao and Clem[5] it is known that the Gibbs free-energy difference between the normal and superconducting states is a function of $H/H_{c2}(\theta)$ and not H alone. Fastampa *et al.*[6] thus used the anisotropic behavior of the critical field as a scaling function. They investigated two different models. The first expression was derived by Tinkham[7] for a thin superconductor of finite thickness:

$$\frac{|H_{c2}(\theta)\sin(\theta)|}{H_{c2\perp}}+\left[\frac{H_{c2}(\theta)\cos(\theta)}{H_{c2\parallel}}\right]^2=1. \tag{1}$$

The second was for the case where there is an anisotropic effective mass, which implies an anisotropic critical magnetic field:[9]

$$\left[\frac{H_{c2}(\theta)\sin(\theta)}{H_{c2\perp}}\right]^2+\left[\frac{H_{c2}(\theta)\cos(\theta)}{H_{c2\parallel}}\right]^2=1. \tag{2}$$

In these expressions $H_{c2\parallel}$ and $H_{c2\perp}$ are the upper critical field when the field is in the plane and perpendicular to the plane of the superconductor, respectively. Lawrence and Doniach[10] used an anisotropic effective mass approach to derive expressions for $H_{c2\parallel}$ and $H_{c2\perp}$ in terms of the coherence length for Josephson-coupled layers. Equation (2) is also basically the same as that derived by Katz[11,12] in considering layered superconductors in a Green's function method. Following the paper of Fastampa *et al.*[6] the scaling functions are obtained from these expressions by considering

$$H_{c2}=H_{c2\perp}f(\theta).$$

This immediately leads to the following scaling functions:

$$f_T(\theta)=\frac{1}{2\epsilon^{-2}\cos^2(\theta)}\left[\sqrt{\sin^2(\theta)+4\epsilon^{-2}\cos^2(\theta)}-|\sin(\theta)|\right], \tag{3}$$

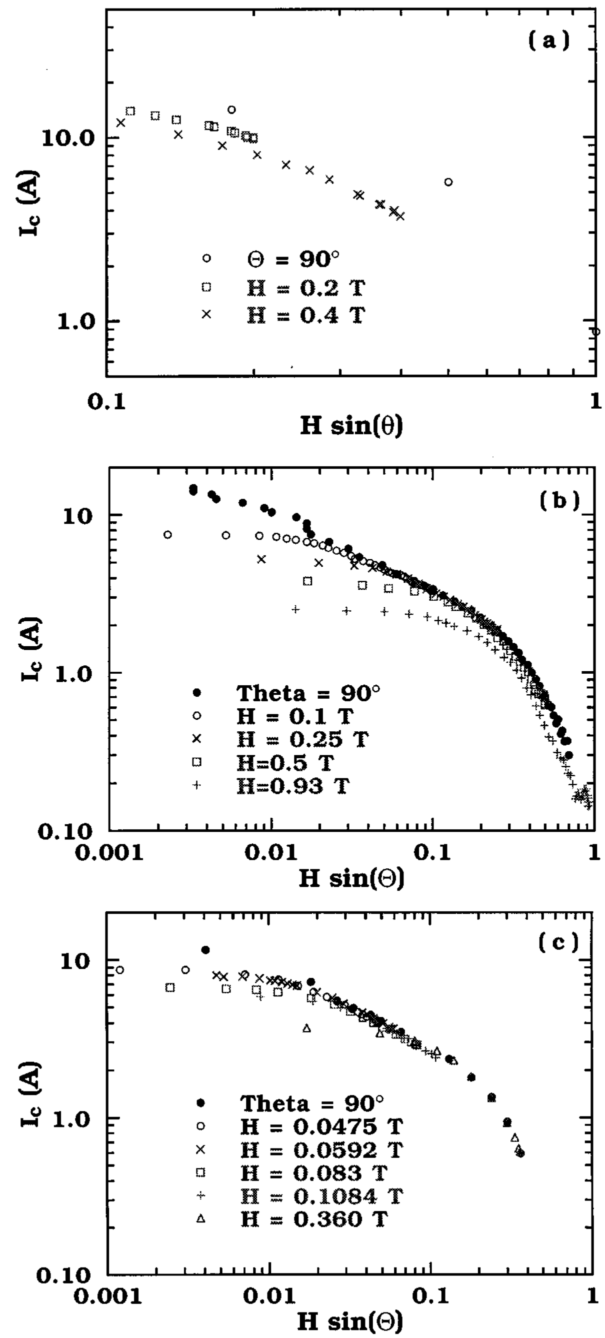

FIG. 2. The critical current of a $Bi_2Sr_2Ca_2Cu_3O_x$ tape as a function of the scaled field, $H_{scale}=H/f(\theta)$. For this graph the scaling function is $f(\theta)=1/\sin(\theta)$. (a) The data taken at NRL. The data labeled θ=90° is the $I_c(H)$ curve that the $I_c(H,\theta)$ data should collapse onto via scaling. (b) The data reported by Willis *et al.* (Ref. 1). (c) The data reported by Hu *et al.* (Ref. 3).

$$f_L(\theta)=\frac{1}{\sqrt{\sin^2(\theta)+\epsilon^{-2}\cos^2(\theta)}}. \tag{4}$$

Here ϵ is the anisotropy ratio of the critical fields,

$$\epsilon=\frac{H_{c2\parallel}}{H_{c2\perp}}.$$

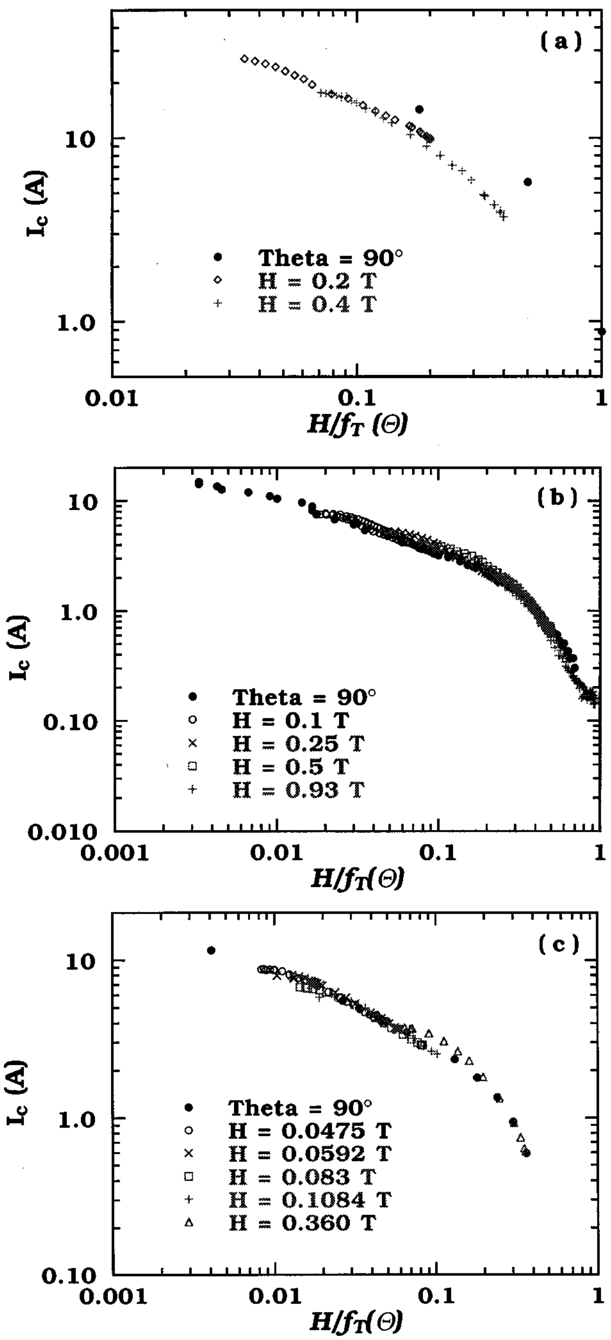

FIG. 3. The critical current of a $Bi_2Sr_2Ca_2Cu_3O_x$ tape as a function of the scaled field, $H_{\mathrm{scale}}=H/f(\theta)$. For this graph the scaling function is $f(\theta)=f_T(\theta)$ [Eq. (3)]. (a) The data taken at NRL. The data labeled θ=90° is the $I_c(H)$ curve that the $I_c(H,\theta)$ data should collapse onto via scaling. (b) The data reported by Willis *et al.* (Ref. 1). (c) The data reported by Hu *et al.* (Ref. 3).

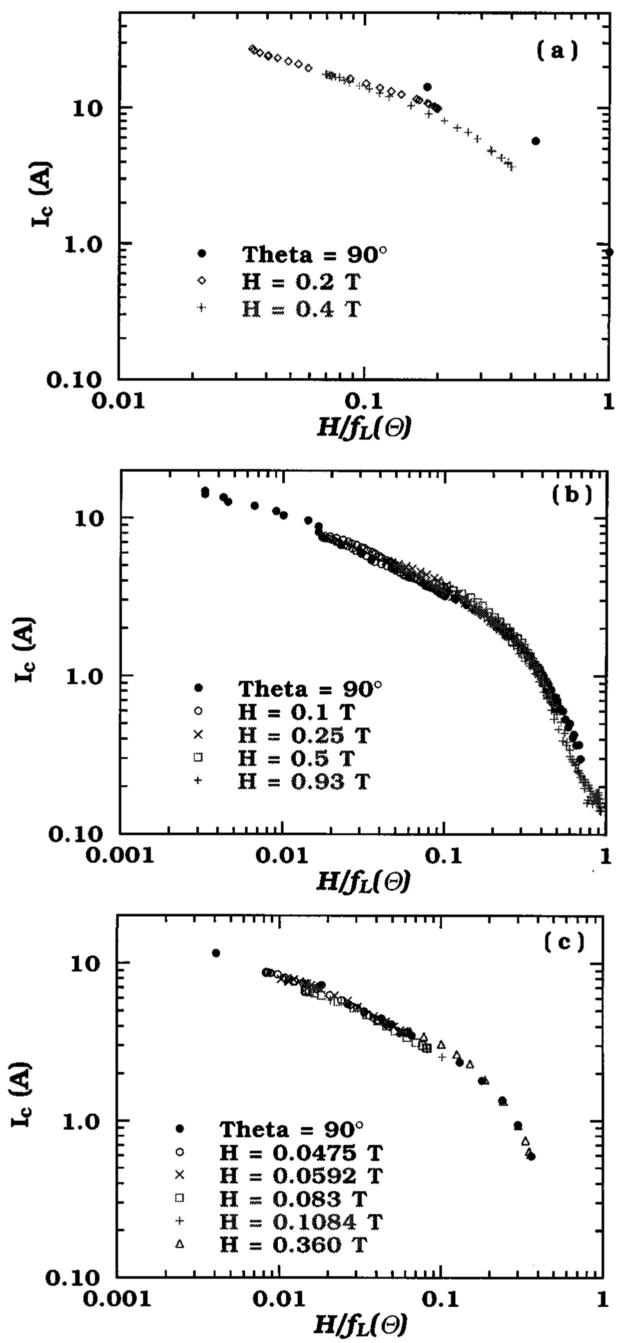

FIG. 4. The critical current of a $Bi_2Sr_2Ca_2Cu_3O_x$ tape as a function of the scaled field, $H_{\mathrm{scale}}=H/f(\theta)$. For this graph the scaling function is $f(\theta)=f_L(\theta)$ [Eq. (4)]. (a) The data taken at NRL. The data labeled θ=90° is the $I_c(H)$ curve that the $I_c(H,\theta)$ data should collapse onto via scaling. (b) The data reported by Willis *et al.* (Ref. 1). (c) The data reported by Hu *et al.* (Ref. 3).

In the anisotropic effective mass model, both $H_{c2\perp}=\varphi_0/2\pi\xi^2$ and $H_{c2\parallel}=\varphi_0/2\pi\xi\xi_c$ have the same temperature dependence, namely that of the coherence length. Thus ϵ does not change with temperature. Here ξ is the coherence length in the basal plane, and ξ_c is the coherence length in the c direction. In the model for thin superconductors of Tinkham,[7] the fluxon core is constrained to the thickness of the superconductor, d, when the field is in the parallel orientation. This means that there will be a different temperature dependence for $H_{c2\perp}=\varphi_0/2\pi\xi^2$ and $H_{c2\parallel}=\varphi_0/2\pi\xi d$ and ϵ will be temperature dependent in Tinkham's model.

The NRL data, as well as that from other groups,[1,3] are plotted in Figs. 3 and 4 as a function of $H/f(\theta)$. Figure 3 uses the scaling function obtained from Tinkham's expression for the angular dependence of the critical field in thin superconductors. In Fig. 4 the scaling function comes from the angular dependence of the critical field when there is an anisotropic effective mass or a layered superconductor. The critical field was not measured during this study. From earlier critical current data taken in the perpendicular and parallel directions an estimate could be made that $4<\epsilon<6$. A value closer to 6 seems to give the best results. For lack of any better information, a similar value was used for analyzing the data from other groups. Since all data was reported on rolled $Bi_2Sr_2Ca_2Cu_3O_x$ tapes, this is a reasonable assumption. As can be seen by comparing Figs. 2, 3, and 4 either the Tinkham or anisotropic effective mass model scales the data better than the simple $1/\sin(\theta)$. In order to distinguish between these two scaling functions, it would be necessary to have a more complete set of temperature dependent data.

It is not clear why these functions scale the data so much better than the $1/\sin(\theta)$. For either function one would expect that the grains would have to be very well aligned to obtain a good fit. In a rolled tape the misalignment between the grains can be as much as 10°. However, looking at the scaled results it is obvious that these functions derived from expressions for the critical field in thin or layered superconductors scale the data very well.

ACKNOWLEDGMENTS

I would like to thank the American Superconductor Corporation for providing the Ag-sheathed $Bi_2Sr_2Ca_2Cu_3O_x$ tape used in this study. I would also like to acknowledge financial support from the Office of Naval Research. Robert Soulen provided a critical reading of the manuscript.

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