Anisotropy of critical current density in *c*-axis-oriented MgB_2 thin films

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The critical current density (J_c) has been measured in *c*-axis oriented MgB_2 thin films as a function of applied magnetic field (H) and angle (θ) between H and the ab plane. The measurements have been carried out at various temperatures between 32 and 38 K. The field and angular dependence of J_c indicates pinning by point pinning centers and is in a good agreement with the predictions of anisotropic Ginzburg-Landau model. Anisotropy parameter (γ) of 2.55 was determined from scaling behavior of J_c.

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INTRODUCTION

Following the recent discovery of superconductivity in MgB_2 with a critical temperature T_c of 39 K, a large number of studies have been carried out to establish fundamental properties of this material so as to understand the mechanism of superconductivity.[1–5] MgB_2 is found to have a hexagonal crystal structure and band-structure calculations indicate that quasi-2D (two-dimensional) boron planes are responsible for superconductivity.[1] The material shows anisotropic superconducting properties and various measurements indicate an upper critical field $H_{c2\|ab}(0)$ between 12 and 40 T and an anisotropy ratio γ of 1.2–13.[2–4] Fluctuation conductivity measurements made in thin films of MgB_2 show two-dimensional nucleation of superconductivity.[1] Thin films of MgB_2 show very high values of critical current density J_c and films with *c*-axis oriented normal to the substrate show magnetization J_c of 1.6×10^7 A/cm^2 in zero field and 1×10^5 A/cm^2 in a field of 5 T (at a temperature of 15 K).[5] While this shows the potential of MgB_2 for practical applications, measurement of critical current anisotropy to understand flux-pinning mechanism has not been reported. Such a study is of considerable importance for various applications of the material and we report here results of such a study.

The study of current voltage (I-V) characteristics and critical current I_c of superconductors as a function of various parameters, such as magnetic field H, temperature and angle between field and crystal axis or current direction, has been carried out in many conventional and high-temperature superconductors. In many investigations made for conventional isotropic superconductors, field and temperature dependence of critical current density has been analyzed in terms of critical state model.[6,7] In terms of this model, the critical current is determined by competition between Lorentz force due to applied current and pinning forces on the vortices. For magnetic field H applied normal to the current direction, critical current density J_c is related to pinning force per unit volume F_p as $F_p=J_cH$. The dependence of J_c on magnetic field and temperature is seen to have similar behavior over a wide range of microstructure, field, and temperatures and the scaling behavior of J_c and F_p is generally given by[7,8]

$$F_p=J_cH=A(H_{c2})^n(H/H_{c2})^m(1-H/H_{c2})^l. \qquad (1)$$

High-temperature superconductors are highly anisotropic and show a rich variety of interesting behavior. The critical current has a strong dependence on the orientation of magnetic field with respect to crystal axis. Highly anisotropic superconductor, $Bi_2Sr_2CaCu_2O_x$ (BSCCO) displays a 2D superconducting behavior where superconducting CuO_2 planes are separated by non-superconducting or weakly superconducting intermediate layers. The material shows very high J_c for $H\|ab$ plane compared to that for $H\|c$ axis. Measurements as a function of angle show that J_c is determined by the component of magnetic field along the c axis. This arises because the vortices parallel to the ab plane are strongly pinned by weakly superconducting layers between CuO_2 planes. This is called intrinsic pinning and has been used to explain angular dependence of J_c.[9] Another high-temperature superconductor, $YBa_2Cu_3O_x$ (YBCO), has lower anisotropy, and many of its physical properties can be understood in terms of anisotropic Ginzburg-Landau (GL) model. Blatter *et al.*[10] have shown that the anisotropic properties of superconductors (with anisotropy parameter γ) scale with reduced magnetic field $\epsilon_\theta H$, where

$$\epsilon_\theta=\sqrt{\sin^2\theta+\epsilon^2\cos^2\theta} \qquad (2)$$

θ is angle between H and the ab plane and $\epsilon=1/\gamma=H_{c2\|c}/H_{c2\|ab}$.

Gupta *et al.*[11] have shown that I-V characteristics in YBCO thin films scale with $\epsilon_\theta H$ except at small angles ($\theta<10°$) where the effect of intrinsic pinning has been observed. Similarly, Braithwaite *et al.*[12] have found that critical current scales with $\epsilon_\theta H$ indicating agreement with anisotropic GL model. Above scaling theory of Blatter *et al.*[10] does not give a functional dependence of J_c with H and θ. Watanabe *et al.*[8] have obtained such a functional dependence using the conventional scaling law of Eq. (1), assuming that the anisotropy in J_c depends on the anisotropy of upper critical magnetic field $H_{c2}(\theta)$.[8,13] This scaling behavior of J_c is given by

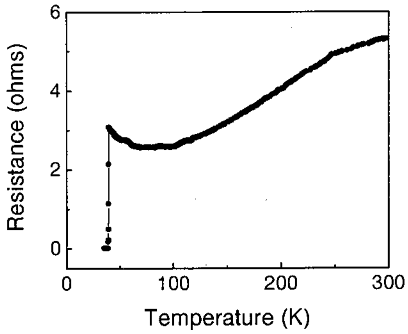

FIG. 1. Resistance vs temperature plot of the thin bridge used for measurement of critical current anisotropy.

$$\frac{J_c(\theta)}{J_c(90°)}=\left[\frac{H_{c2}(\theta)}{H_{c2}(90°)}\right]^p\left[\frac{1-H/H_{c2}(\theta)}{1-H/H_{c2}(90°)}\right]^q \tag{3}$$

Typical value of parameters for YBCO is $p=1.5$ and $q=2.0$,[8] and anisotropy of H_{c2} is given by[13]

$$H_{c2}(\theta)=\frac{H_{c2}(90°)}{\sqrt{(\sin^2\theta+\epsilon^2\cos^2\theta)}}=\frac{\epsilon H_{c2}(0°)}{\epsilon_\theta}. \tag{4}$$

Studies on YBCO indicate good agreement with Eq. 3,[8,13,14] except that a sharp peak is seen at $\theta=0°$,[14] which originates from intrinsic pinning and a second peak at $\theta=90°$ that has been attributed to pinning by twin boundaries.

In the present study, measurements of critical current density were carried out on a c-axis oriented MgB_2 thin film as a function of angle θ between H and the ab plane. Magnetic field was maintained normal to the current (I parallel to the ab plane). The results have been analyzed using anisotropic GL model and a value of anisotropy parameter γ has been determined. The critical current density for fields applied parallel to the ab plane showed small deviation from GL model. This has been attributed to the effect of pinning at substrate-film interface.

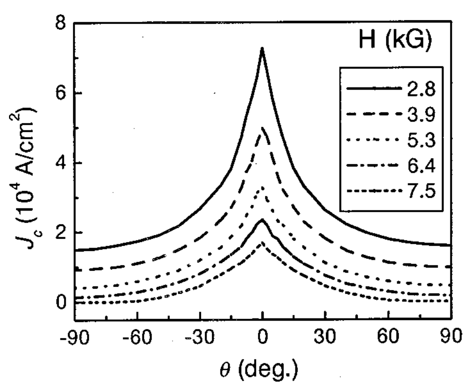

FIG. 2. Angular dependence of critical current density recorded at different values of magnetic fields at a constant temperature of 35.70 K.

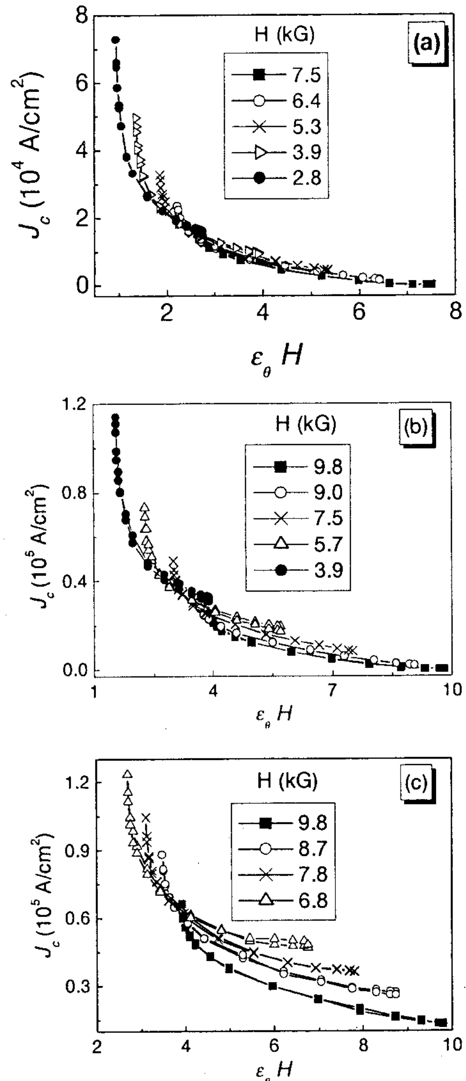

FIG. 3. Scaling behavior of critical current density with reduced field observed at different temperatures (a) 35.70 K, (b) 34.45 K and (c) 32.80 K.

EXPERIMENT

Epitaxial MgB_2 thin films were prepared on single-crystal Al_2O_3 substrates using a two-step process as described earlier.[15] Briefly precursor films of amorphous boron were deposited by pulsed laser ablation technique at energy density of 20 to 30 J/cm^2. These films were sintered at 900 °C for 10–30 min under Mg vapors in sealed Ta tubes. After sintering, the films were quenched to room temperature. X-ray diffraction analysis showed that the films were epitaxial with c axis normal to the substrate. For measurement of critical current density, the films were patterned (to form a bridge) using photolithographic process. For the measurements reported here a 400-nm-thick film with a bridge of 1 mm length and 79 μm width was used. For I_c measurement, gold contacts (with contact resistance of <0.5 Ω) were deposited using vacuum evaporation technique and silver wires were attached using silver paint.

TABLE I. Value of parameters ϵ and γ determined by scaling of critical current with $\epsilon_\theta H$.

Temperature (K)	ϵ	γ
37.81	0.35	2.88
36.38	0.42	2.36
35.70	0.35	2.88
35.53	0.40	2.50
34.45	0.40	2.50
33.86	0.46	2.17

The measurements were carried out using dc current and four-probe resistivity technique. The sample was cooled using a closed cycle cryostat and the sample temperature was controlled to within ± 0.02 K of set value using a Lakeshore temperature controller. Magnetic field was applied in horizontal direction using an electromagnet. The sample was mounted with current in the vertical direction. The sample holder could be rotated around vertical axis so as to vary the angle θ between magnetic field and ab plane of the film while maintaining the angle between B and I at 90°. The angle θ could be measured with an accuracy of better than 1°. Critical current measurements were made with voltage criteria of 2.0 μV across the bridge.

RESULTS AND DISCUSSION

A resistance vs temperature plot of the film used for measurements is shown in Fig. 1. The film shows a sharp transition to superconductivity with zero resistance transition temperature of 39.0 K. Critical current I_c was measured as a function of angle at different temperatures between 32 K and 38 K. Typical plots of J_c vs θ at different values of magnetic field are shown in Fig. 2. The notable features of the angular dependence of J_c are (i) significantly higher critical current densities for $H \| ab$ plane compared to $H \| c$ axis indicating the effect of anisotropy, (ii) smooth dependence of critical current density with angle indicating pinning due to point defects, and absence of pinning by planar defects as observed due to twin planes in YBCO (Ref. 12), and (iii) a cusp in critical current density at $\theta = 0°$ similar to that seen for YBCO/BSCCO thin films where it was attributed to intrinsic pinning.[16,17]

We analyze the H and θ dependence of J_c in terms of anisotropic GL model, as described in the Introduction. The dependence of critical current density data on reduced field ($\epsilon_\theta H = H\sqrt{\sin^2\theta + \epsilon^2\cos^2\theta}$) is shown in Fig. 3 for three different temperatures. In order to obtain optimum scaling behavior, ϵ was used as an adjustable parameter. The data obtained at higher temperatures of 35.70 K and 34.45 K shows good scaling behavior (except at small angles) while that at lower temperature of 32.80 K does not scale with $\epsilon_\theta H$. Data obtained at other temperatures also showed good scaling for temperatures above 33.5 K but showed disagreement with anisotropic scaling behavior for lower temperatures. The deviation from anisotropic scaling at lower angles (as also indicated by cusp in J_c vs θ characteristics of Fig. 2) is attributed to pinning at film-substrate interface and will be discussed later. Deviations from anisotropic scaling behavior at lower temperatures could arise due to (i) GL model being valid for temperatures close to T_c only and (ii) deviation of MgB_2 superconducting behavior from GL model due to reported existence of two energy gaps[2] in this material with larger gap having 2D nature and smaller one having 3D behavior.[18] The smaller energy gap would be more effective at lower temperatures, leading to increased disagreement. The values of ϵ and anisotropy parameter γ obtained from scaling behavior at different temperatures ($T > 33.5$ K) are given is Table I. The average value of $\gamma (= 2.55)$ obtained from this data is found to be in good agreement with other studies.[2]

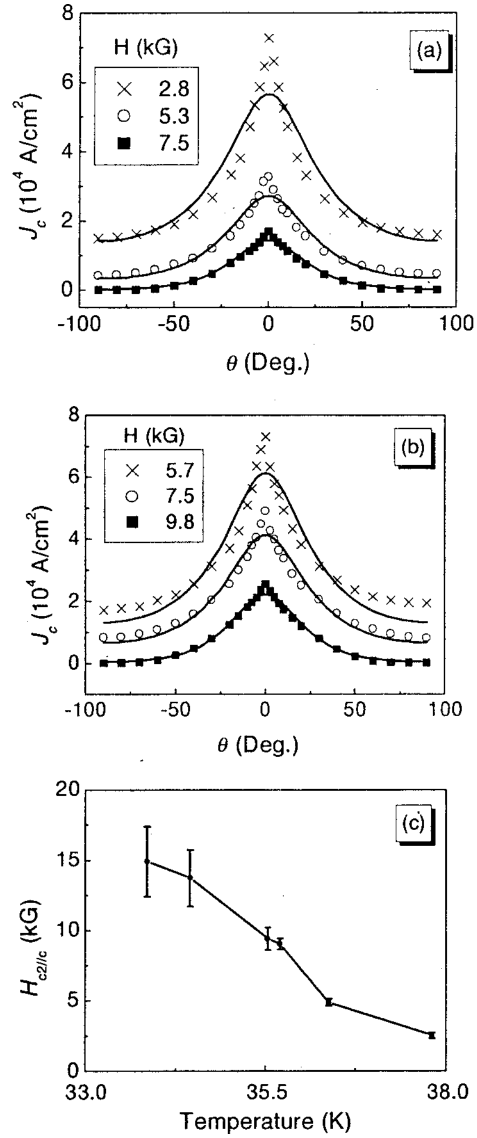

FIG. 4. Fitting of normalized J_c vs θ data to Eq. (3) using $H_{c2}(90°)$ as fitting parameter at different magnetic fields and temperatures of (a) 35.70 K and (b) 34.45 K. Fig. 4(c) gives optimum value of parameter $H_{c2}(90°)$ as function of temperature.

We have also investigated the angular dependence of critical current by fitting the measured data with the scaling law

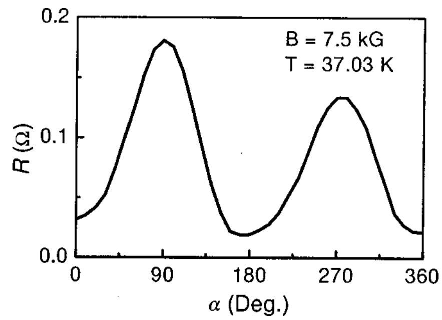

FIG. 5. Dependence of film resistance R on angle α between H and I with both applied parallel to the ab plane.

of Eq. (3). The typical results are shown in Fig. 4. Fitting was carried out using fixed values of parameters p,q ($p=1$ and $q=2$) and ϵ ($\epsilon=0.4$, average value obtained from Table I). The parameter $H_{c2}(90°)$ was varied to fit the data obtained at different fields and temperatures. Temperature dependence of the optimum value of $H_{c2}(90°)$ is shown in Fig. 4(c). The error bars in this figure indicate the variation in $H_{c2}(90°)$ obtained at different magnetic fields. The value of $H_{c2}(90°)$ obtained at different temperatures are in agreement with earlier studies[2] on MgB_2. The results shown in Figs. 4(a,b) indicate good agreement except that the critical currents at angles $\theta<5°$ are larger than that predicted by scaling law based on GL theory. These deviations at small angles indicate the presence of line or planar defects parallel to the ab plane. Similar to the data reported here, cusp in J_c at small angles has been observed for YBCO and BSCCO samples and has been attributed to intrinsic pinning. The intrinsic pinning effect is not expected in MgB_2, because the coherence length ($\xi_c \sim 3$ nm) is much larger than the distance (~ 0.35 nm) between superconducting boron planes.[19] The deviations of J_c from GL model at low angles could be attributed to pinning caused by defects at MgB_2/substrate interface. To confirm this conjecture we have measured resistance as a function of the angle α between the magnetic field and current directions when both H and I are applied parallel to the ab plane. To obtain this data the sample was mounted in horizontal plane and rotated along the vertical axis. The results are shown in Fig. 5. The angular dependence of resistance in this case arises from the variation of Lorentz force with α.[20] It is seen that the resistance in $0°-180°$ range is quite different from that in $180°-360°$ range and the maxima in resistance at 90° differs from that at $270°$. Similar asymmetry in resistance in two ranges has been seen for YBCO films and attributed to the different pinning strengths of the two film surfaces, i.e., film-substrate interface and film-air interface.[20] In one case the vortices move out from the film-substrate interface and in other case they move out from the film-air interface causing a difference in resistance. Similar to the asymmetry in resistance, the values of critical current at $\theta=90°$ and 270° were found to be 1.30 and 1.45 mA, respectively, i.e., the difference in pinning at two interfaces leads to about 10% difference in critical current density. This shows that the interface pinning can change J_c about 10% or more for vortices parallel to the ab plane. This is of similar magnitude as the observed deviations from GL model (Fig. 4) and therefore the interface pinning effect explains the observed data.

CONCLUSIONS

We have shown that critical current density in MgB_2 thin films is strongly dependent on the angle between magnetic field and the ab plane. The pinning in MgB_2 is seen to arise from point pinning centers. The magnetic field and angle dependence of J_c is in agreement with anisotropic Ginzburg-Landau model. Effect of pinning at film-substrate interface is observed for magnetic field applied nearly parallel to the ab plane.

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