Effect of two bands on the scaling of critical current density in MgB_2 thin films

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The dependence of critical current density (J_c) on applied magnetic field (B) and angle (θ) between B and the c axis has been investigated to determine the anisotropy of MgB_2 thin films at different temperatures. The results have been compared with upper critical field (H_{c2}) anisotropy (γ_H) determined by measuring H_{c2} for fields applied parallel to the ab plane and the c axis. Contrary to the case of $Bi_2Sr_2CaCu_2O_8$ and $YBa_2Cu_3O_x$, where $J_c(\theta,H)$ scales with $H/H_{c2}(\theta)$, $J_c(\theta,H)$ for MgB_2 did not follow this scaling. Surprisingly, the temperature dependence of anisotropy determined from $J_c(\theta,H)$ is similar to the predictions for penetration depth anisotropy of MgB_2. These results have been understood as a combined effect of a two-band theory and the collective pinning model, in which J_c strongly depends on the elastic properties of a vortex lattice.

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One of the most peculiar properties of the recently discovered superconductor MgB_2 is the two-band nature of its superconductivity.[1] First-principle calculations of MgB_2 showed the existence of two-distinct groups of energy gaps that originate from two dimensional (2D) σ bands and three-dimensional (3D) π bands. The superconducting gap varies from 5.5 to 8 meV on σ bands and 1.5 to 3.5 meV for π bands.[2,3] The nature of two-band superconductivity has been confirmed by studies of specific heat,[4,5] tunneling,[6] and photoemission spectroscopy,[7–9] etc. One of the surprising predictions of the two-band superconductivity of MgB_2 is the difference between absolute value and temperature (T) dependence of anisotropy of upper critical field ($\gamma_H = H_{c2\|ab}/H_{c2\|c}$) and that of penetration depth ($\gamma_\lambda = \lambda_c/\lambda_{ab}$).[1,10,11] This is in contrast to one-band anisotropic superconductors, where these two values are nearly the same and independent of T. Kogan[10] has shown that, in the case of MgB_2, γ_λ should increase with temperature from a value of nearly 1.1 at low temperatures to about ~ 2.6 at transition temperature (T_c). Compared to this, the value of γ_H has been predicted to reduce with temperature[1,11] from a value of nearly 6 at low temperatures to ~ 2.6 at T_c. Quite a number of studies have claimed the observation of γ_H as predicted by theory,[1] but very few measurements have been reported on γ_λ and even these have been limited to low temperatures[12] despite the importance of its determination over a wide temperature range.

Critical current density (J_c) is one of the most important superconducting quantities for industrial applications. The J_c is determined by physical parameters of superconductors and vortex pinning. In anisotropic superconductors such as $YBa_2Cu_3O_x$(YBCO) and $Bi_2Sr_2CaCu_2O_8$(Bi-2212), the J_c is found to strongly depend on angle θ between magnetic field (H) and the crystal c axis, and $J_c(\theta)$ is seen to scale with $H/H_{c2}(\theta)$. In thin films[13] and tapes[14] of Bi-2212, J_c was found to scale with $H/H_{c2}(\theta)$ with $H_{c2}(\theta)$ described by a 2D model for superconducting thin films. This is in accordance with 2D behavior of the Bi-2212 superconductor.[15] In studies[16–18] reported on 3D superconductor YBCO, J_c was found to scale with $\varepsilon_\theta H$, where $\varepsilon_\theta = \sqrt{\cos^2(\theta) + (1/\gamma^2)\sin^2(\theta)}$ and γ is the anisotropy parameter. This is because, for anisotropic superconductors, H_{c2} scales with $(\varepsilon_\theta)^{-1}$. A theoretical basis for the scaling of $J_c(\theta)$ with $\varepsilon_\theta H$ for anisotropic superconductors has been provided by Blatter *et al.*[19] They have formulated a general scaling approach based on the one-band anisotropic Ginzburg-Landau (GL) model and found that various physical properties at a given temperature scale with $\varepsilon_\theta H$.

A few studies on the anisotropy of J_c have been reported for MgB_2. In a study on aligned crystallites, de Lima and Cardoso[20] found that J_c anisotropy (defined as J_c^{ab}/J_c^c) is temperature independent with a value of 1.5 ± 0.1. In an earlier study on MgB_2 thin films[21] carried out in temperature range of 33.5–38 K, J_c was found to scale with $\varepsilon_\theta H$ with an anisotropy parameter of $\gamma_H = 2.55$. The scaling behavior was, however, seen to deviate from the anisotropic GL model at $T < 33$ K.

A perfectly periodic vortex lattice is not pinned by random pinning centers. This is because for any position of the rigid vortex lattice, pinning centers will exert force in different directions and the net pinning force will be zero.[15,22,23] For pinning, vortex lines need to adjust their position with respect to pinning centers. Therefore, the elasticity of flux line lattice (FLL) plays an important role in determining the pinning energy and J_c. Effective pinning energy in such a case has been described by the collective pinning model. Typically, J_c is found to depend on λ, applied field, and H_{c2}. For one-band superconductors, anisotropies of penetration

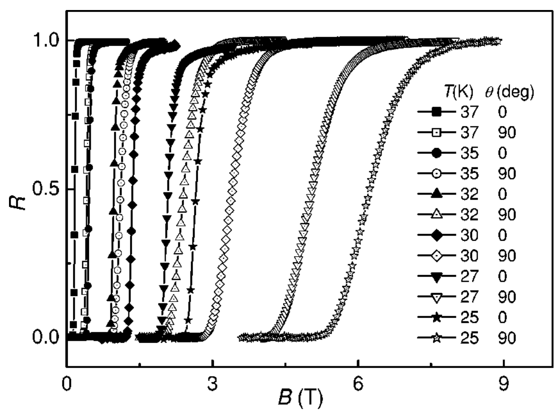

FIG. 1. Normalized resistance as a function of magnetic field at different temperatures for $B//ab$ plane (θ=90°) and $B//c$ axis (θ =0°).

depth and H_{c2} are nearly the same. Therefore, scaling of J_c does not distinguish between the effects of H_{c2} and λ. However, this is no longer true for MgB_2, and a study of J_c anisotropy can help us to experimentally determine the importance of various parameters in pinning. In the present study, we extend the measurement of $J_c(\theta)$ in MgB_2 thin films to include temperatures much lower than those previously reported. The results can be understood in terms of the collective pinning model and two-band nature of superconductivity in MgB_2. The pinning energy at low fields is seen to be strongly influenced by elastic properties of the vortex lattice. Further, the measurement of J_c anisotropy provides a new method for determining γ_λ.

MgB_2 thin films were prepared by *ex situ* laser ablation technique on sapphire substrates as described earlier.[24] X-ray diffraction spectra showed that the films are oriented with the c axis normal to the substrate. Anisotropy of H_{c2} and scaling of J_c were studied in a large number of samples and similar results were obtained. We report here results of both measurements performed on a single sample to enable a better comparison between γ_λ and γ_H. The film used in the present study had a thickness of 500 nm and was patterned to have two bridges. The first bridge of 1000 μm linewidth was used

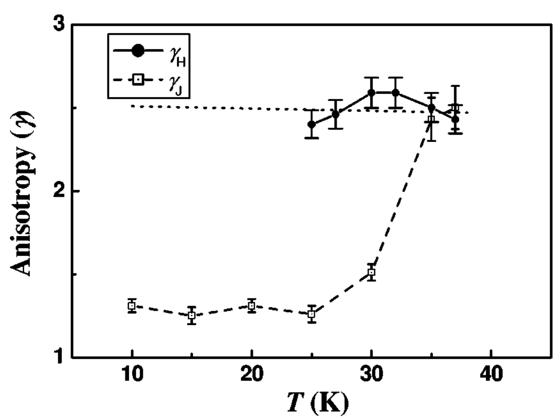

FIG. 2. Temperature dependence of γ_H (determined from data of Fig. 1) and γ_J (determined from scaling of J_c at low magnetic fields). The dotted line shows a linear fit to γ_H data.

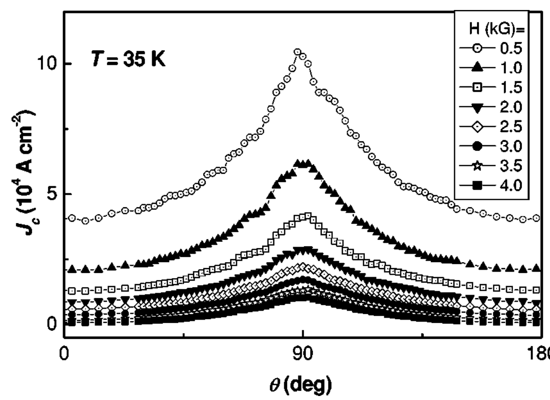

FIG. 3. Angular dependence of J_c measured at a temperature of 35 K for different magnetic fields between 0.5 to 4.0 kG.

for measuring H_{c2} anisotropy as the low current density in a wide bridge helps to reduce the vortex motion. The second bridge of 10 μm width and 180 μm length was used to measure J_c. The resistivity and J_c were measured using a PPMS system (Quantum Design, Inc.) with a rotation option. To determine γ_H, resistance of the film was measured as a function of H for θ=0° and 90°. For measuring J_c, a current ramp of a few ms duration was applied to the sample and the voltage across the sample was acquired. Then, the J_c was determined with a criterion of 2–20 μV. The results reported here were found to be independent of the criteria used. The contact resistance on each of the contacts in the film was ~1 ohm. The calculations using thermal conductivity of sapphire showed that at a dc current of 20 mA (the maximum used in this study) heating effects are limited to less than 0.02 K. Insignificant heating during measurements was also confirmed by using dc and 200 μs pulse currents where the same value of J_c was obtained. We have used current ramps in this study to facilitate the acquisition of large data by PC. During the measurements, the film was rotated along the microbridge direction in the ab plane. In this manner, the angle θ was varied while maintaining an angle of 90° between the B and the I. The angle θ was measured with an accuracy of 0.1°.

Resistance as a function of H measured at different temperatures and θ=90°and 0° is shown in Fig. 1. Upper critical field $H_{c2}(\theta,T)$ was determined as the field at which resistance drops to 90% of the normal state value. Anisotropy (γ_H) at different temperatures was calculated as a ratio of $H_{c2}(90°)$ to $H_{c2}(0°)$, where $H_{c2}(\theta)$ is the value of H_{c2} at the angle θ measured in degrees. The results are shown in Fig. 2. Anisotropy is found to be nearly independent of T, in agreement with our earlier results in the temperature range of 1 K to T_c.[25] The use of different criteria (90%–99% or onset of transition) for determining H_{c2} yields values of γ_H within a range of ~5%[26] and does not affect the findings. A temperature-independent value of γ_H is in agreement with theoretical models applicable in dirty limit[11] and indicates that the diffusivity in two bands is nearly same. The same value of diffusivity in two bands was also independently confirmed by the agreement of the angular dependence of H_{c2} with the GL model as theoretically expected.[11] This has been seen in many samples prepared in a similar manner and has been reported previously.[26]

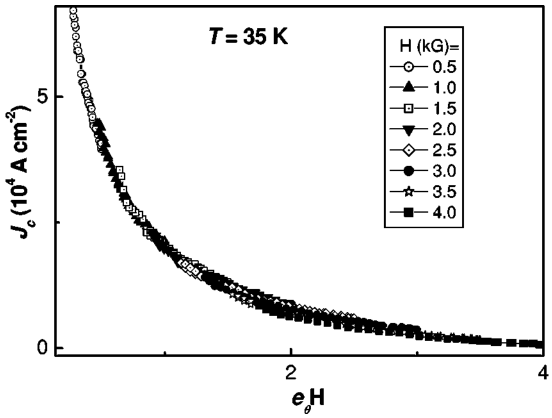

FIG. 4. Scaling of J_c data obtained at a temperature of 35 K excluding data within 10° of the *ab* plane.

The measured $J_c(\theta)$ plots at $T=35$ K and different magnetic fields are shown in Fig. 3. To study the scaling behavior, we show $J_c(\theta)$ as a function of reduced magnetic field $\varepsilon_\theta H$ in Fig. 4. Here, γ was used as a parameter and its optimum value (called γ_J) was found to be 2.43. In Fig. 4 we have excluded the data for magnetic field within 10° of the *ab* plane because it is a region of the enhanced pinning of vortices at the interface between MgB_2 thin films and sapphire substrates, as reported in earlier studies.[21,26] The value of γ_J determined at 35 K was found to be in good agreement with that determined for H_{c2} anisotropy.

While the J_c was found to scale well with reduced field for $T \geqslant 35$ K, deviations were observed for $T \leqslant 30$ K. The typical low temperature scaling behavior is shown in Fig. 5 for $T=10$ K. While low magnetic field data scale well with $\varepsilon_\theta H$ (with $\gamma_J=1.28$), data at higher fields show deviations. Similar results were obtained at other temperatures and the temperature dependence of γ_J is shown in Fig. 2 along with that of γ_H. It is seen that while $\gamma_J=\gamma_H$ at high temperatures, they differ significantly at lower temperatures. It is quite interesting if we compare the temperature dependence of γ_J with the temperature dependence of γ_λ, predicted for MgB_2. Surprisingly, $\gamma_J(T)$ is found to be very similar to the predicted temperature dependence of γ_λ.[1] This is in strong contrast to earlier studies[13–18] of high T_c superconductors, where the scaling of J_c is believed to yield γ_H.

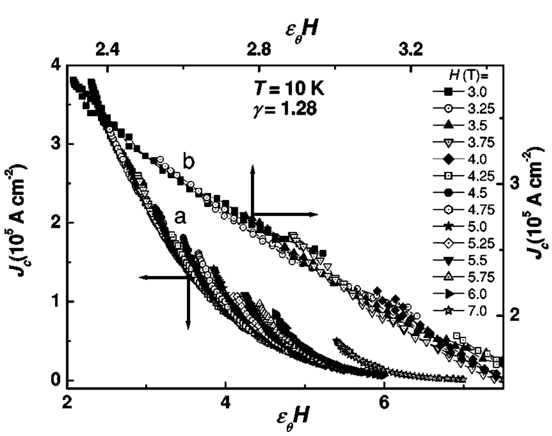

FIG. 5. Scaling of J_c data obtained at a temperature of 10 K. Plot (a) shows the data in full magnetic field range and (b) shows the same data at low magnetic fields.

In what follows, we will give an explanation for (a) why the scaling of anisotropy in J_c at low fields is related to γ_λ, (b) the deviation in scaling at higher fields, and (c) why such deviations have not been seen in one-band anisotropic superconductors, such as YBCO and Bi-2212. We have used the collective pinning theory to qualitatively understand the results. This is because a quantitative agreement with the collective pinning model is generally not observed, due to uncertainties in parameters used in this theory.[27]

In the collective pinning theory,[22,23] the effective pinning force is determined by the sum of the individual pinning forces acting on a correlation volume V_c of flux line lattice. Correlation volume is determined by considering the change of free energy when boundaries of V_c are displaced by distance of the order of lattice parameter a. This change in free energy, and therefore J_c, depends on three parameters: (a) shear (c_{66}) and tilt (c_{44}) moduli of the vortex lattice, (b) vortex lattice parameter, and (c) pinning force f. The typical expression for J_c of superconductors may be written as[23] $J_c = J_c(f, a, c_{44}, c_{66}, B)$. The angular dependence of J_c has not been investigated but would be expected to depend on the angular dependence of various parameters (in the direction of motion and normal to it). For this purpose, we consider the crystal frame (X,Y,Z) with a current along the Y axis and the crystal c axis coinciding with the Z axis.[28,29] The angular dependence of parameters has been investigated in the "vortex frame" (x,y,z) obtained from the crystal frame by a rotation θ about the Y axis (coinciding with the y axis) such that the magnetic field is along the z axis.[28,29] In the vortex frame (for a current along the y axis) vortices will move along the x axis. The vortex lattice in uniaxial superconductors has been determined by Campbell *et al.*[29] who found a triangular lattice with unit cell parameters given by $\mathbf{b_1} = L_\Delta \sqrt{\varepsilon_{\theta\lambda}}\hat{x}$ and $\mathbf{b_2} = L_\Delta(\sqrt{\varepsilon_{\theta\lambda}}\hat{x} + \sqrt{3/\varepsilon_{\theta\lambda}}\hat{y})/2$, where L_Δ is the side of an equilateral triangle with an area of $\phi_0/2B$ and $\varepsilon_{\theta\lambda} = \sqrt{\cos^2(\theta) + (1/\gamma_\lambda^2)\sin^2(\theta)}$. It is seen that intervortex distances along the x axis (b_1) and the y axis ($\mathbf{b_2}\cdot\hat{y}$) scales with $\varepsilon_{\theta\lambda}$. A shear modulus ($c_{66}$) has also been determined for uniaxial superconductors. Its values for vortex motion along the y axis (c_e) and the x axis (c_h) are given by $c_e = m_1 m_3 \varepsilon_{\theta\lambda}{}^3 c_{\text{is}}$ and $c_h = m_1 m_3 c_{\text{is}}/\varepsilon_{\theta\lambda}$, where $c_{\text{is}} = \phi_0 H/64\pi^2\lambda^2$ is the modulus for the isotropic case with λ equal to the average value of uniaxial material, and m_3 and m_1 are effective masses along the c axis and the ab plane, respectively. It is seen that c_{66} is a function of $\varepsilon_{\theta\lambda}$ in both directions. The tilt modulus for $H \ll H_{c2}$ is independent of angle θ and may be written as $c_{44} \sim H^2$ (see Sudbo and Brandt[30]). We consider strong pinning by small normal defects with size (d) smaller than the coherence length. The pinning energy (U_p) in this case will be given by the loss of condensation energy in the pinning volume,[31] i.e., $U_p \sim H_c^2 d^3$. This is independent of field and angle. This is also supported by earlier studies,[23] where the pinning force is reported to be proportional to $\Delta^2 \sim (1/H/H_{c2})$. This is independent of the angle at low fields. From above, we see that all the parameters determining V_c and the pinning force at low fields depend on $\varepsilon_{\theta\lambda}$ and H. As the results determined from the collective pinning model usually do not yield good quantitative agreement with experiments due to many unknown parameters,[27,32] we use the scaling result of Blatter *et al.*[19] for the study of J_c anisotropy. Blatter *et al.* predicted that the physical parameters of anisotropic superconductors should scale with $\varepsilon_\theta H$, and based on the above discussion, we expect J_c at low magnetic fields to scale with $\varepsilon_{\theta\lambda}H$. This explains our observation that γ_J is related to γ_λ.

From the explanation mentioned above, the deviations in J_c scaling (at low temperatures) at higher magnetic fields are easily understandable as the parameter $c_{66}\sim(1/H/H_{c2})^2$ for H near H_{c2}.[33] Since C_{66} is a function of H_{c2}, we expect that J_c will depend both on γ_λ and γ_H at higher fields. Consequently, deviations in the scaling behavior in Fig. 5, at higher fields, may be explained as the transition of scaling from that determined by γ_λ to that determined by both γ_λ and γ_H. Since γ_H has been predicted to be same as γ_λ at high temperatures (and measured γ_J, identified by us as γ_λ is nearly equal to γ_H at $T\geqslant 35$), J_c is expected to scale with $\varepsilon_{\theta\lambda}H$ over the whole magnetic field range in this case, as has been observed (Fig. 4). Finally, in the case of other anisotropic superconductors, $\gamma_\lambda=\gamma_H$ and we expect good scaling behavior with a single value of γ as observed in various studies.

Finally, we will briefly discuss the possible sources of pinning in the MgB_2 thin films. Earlier studies[21,26,34] on the angular dependence of vortex glass transition, critical current, and resistivity show that pinning in MgB_2 is dominated by point pinning centers. The random point disorder could arise due to the reported formation of MgO nanoparticles in the film during annealing[35,36] and interaction of the film with Al_2O_3 substrate, leading to the formation of $MgAl_2O_4$ and MgB_4 as revealed by TEM studies on epitaxial thin films.[36] The presence of additional pinning at the film-substrate interface leads to a gradient of pinning centers with a higher density of defects at the interface and has been confirmed by an asymmetry of vortex motion on the reversal of current direction, as has been reported previously.[21]

In conclusion, we find that the magnitude and temperature dependence of anisotropy determined by scaling of J_c at low magnetic fields is in agreement with predictions for γ_λ in terms of two-band superconductivity in MgB_2. The results show that elastic deformations of the vortex lattice play an important role in the determination of effective pinning energy, and thereby J_c of anisotropic superconductors, and that γ_λ can be determined by scaling of angular dependence of J_c. Since $\gamma_\lambda<\gamma_H$ (for MgB_2), the anisotropy of J_c is much less than what would have been expected in terms of upper critical field anisotropy. The lower anisotropy in J_c is important for applications. Finally, in other anisotropic superconductors where J_c is believed to scale with $\varepsilon_{\theta H}H$, it may actually be a function of $\varepsilon_{\theta\lambda}H$, but indistinguishable in view of $\gamma_\lambda=\gamma_H$. This may need further investigation.

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