I-V characteristic measurements to study the nature of the vortex state and dissipation in MgB_2 thin films

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(Received 26 April 2002; published 30 September 2002)

The temperature dependence of current-voltage (I-V) characteristics of MgB_2 thin films has been studied at different magnetic fields (H) and angles (θ) between H and the ab plane. The I-V characteristics obtained at different H and θ show critical scaling indicative of vortex glass transition. The critical exponents are found to be independent of H and θ indicating a universal behavior. The scaling functions are also seen to be field and angle independent when resistivity and current density are normalized with two parameters ρ_0 and J_0, which are functions of H and θ. Field and angle dependences of parameters ρ_0 and J_0, and vortex glass transition temperature T_g are seen to be in agreement with the anisotropic Ginzburg-Landau model.

DOI: 10.1103/PhysRevB.66.104525 PACS number(s): 74.60.Ge, 74.76.−w, 74.70.Ad

I. INTRODUCTION

Several studies have been reported in the literature concerning the mechanism of superconductivity in the recently discovered MgB_2 superconductor.[1] The studies show that it is an anisotropic type-II superconductor with a large coherence length, and has potential for various applications. Many of the applications of type-II superconductors depend on their ability to carry large currents in the presence of applied magnetic fields, which is determined by several factors, such as, the nature of the vortex state (VS), weak links at grain boundaries, anisotropy, and flux pinning properties. Various studies have shown that weak link effect in this material is negligible.[1] We have studied the effect of anisotropy on critical current density (J_c) and have seen that the angular dependence of J_c in MgB_2 thin films is well described by the anisotropic Ginzburg-Landau (GL) model with an anisotropy parameter (γ) of ~ 2.5.[2] However, further studies are necessary to understand the nature of VS and flux pinning properties in this material. Measurement of current-voltage (I-V) characteristics as a function of different parameters is an important technique for the study of pinning effects. We have therefore measured I-V characteristics in MgB_2 thin films as a function of magnetic field, temperature, and angle between magnetic field and the ab plane. The results have been analyzed using different models that have been reported for understanding the dissipation in superconductors and briefly described in the following.

Conventional theories of dissipation in superconductors have assumed that the vortices penetrating the superconductors form a lattice. The dissipation has been described in terms of flux creep and flux flow models. In flux creep model dissipation occurs by thermally activated hopping of flux bundles. The I-V (or J-E where J is the current density and E the electric field) characteristics in this case are described by[3,4]

$$E=(2f_0BL)\exp(-U/kT)\sinh(JBV_cL_p/kT), \qquad (1)$$

where f_0 is the attempt frequency for hopping, B is the average magnetic field penetrating the superconductor (nearly equal to applied field H for $H \gg$ lower critical magnetic field H_{c1}), L is the hopping distance, U is the activation energy, V_c is the volume of flux bundle, and L_p is the pinning potential range. For small current densities, i.e., $\Delta W = JBV_cL_p \ll kT$, $\sinh(\Delta W/kT)$ is nearly equal to $\Delta W/kT$ and linear I-V's are expected. For $\Delta W > kT$, we may approximate $\sinh(\Delta W/kT)$ by $(1/2)\exp(\Delta W/kT)$ and an exponential dependence of field with current is expected.

According to flux flow model,[5,6] at high current densities the Lorentz force on flux lines exceed the pinning forces and vortices move in a steady motion at a velocity limited by viscous drag. In this region the I-V characteristics are linear and can be expressed by

$$E=\rho_f(J-J_c), \qquad (2)$$

where J_c is a constant and ρ_f is the flux flow resistivity.

Random point disorder is found to play an important role in determination of physical properties of high-T_c superconductors. Disorder pins the vortex lines, destroying the translational long-range ordering of flux lattice.[7] In the presence of random point pinning centers, a second-order phase transition from vortex liquid to vortex glass state has been predicted. In the vortex glass (VG) phase, resistivity is expected to vanish at small currents in contrast to flux creep model where finite linear resistivity is expected at low current densities. Near the vortex glass transition temperature (T_g), resistivity (ρ) versus current density (ρ-J) characteristics are expected to scale with temperature (T) as[8,9]

$$\rho/|1-T/T_g|^{\nu(z-1)}=F_{\pm}(J|1-T/T_g|^{-2\nu}/T), \qquad (3)$$

where z and ν are dynamic and static VG exponents, respectively, and F_+ and F_- are scaling functions above and below the transition temperature. At the VG transition temperature a power law behavior of ρ-J characteristics has been predicted[8,9]

$$\rho(J)=aJ^{(z-1)/2}, \quad (4)$$

where a is a constant. Existence of VG phase has been confirmed in various high-temperature superconductors,[8,9] and particularly in $YBa_2Cu_3O_x$ (YBCO). In these studies [as predicted by Eq. (3)], ρ-J curves obtained at different temperatures are seen to collapse into two curves (for $T>T_g$ and $T<T_g$) when plotted as $\rho_{sc}=\rho|t|^{-\nu(z-1)}$ versus $J_{sc}=J(T_g/T)|t|^{-2\nu}$ where $t=(T\text{-}T_g)/T_g$.[10–13] Most of these studies have been carried out with magnetic field applied parallel to the c axis. Moloni *et al.*[10] have emphasized that in view of universality, scaling functions, and critical exponents should be independent of magnetic field and angle (θ) between the field and ab plane. Universality provides stronger test of critical scaling behavior. For the study of universality of VG transition at different magnetic fields they have introduced field dependent resistivity and current scales ρ_0 and J_0, respectively. Resistivity scale (ρ_0) has been defined using linear resistivity at low currents and temperatures above T_g:

$$\rho_0=\rho t^{-\nu(z-1)}|_{T>T_g,J\to 0}, \quad (5)$$

where $t=(T\text{-}T_g)/T_g$. Current scale J_0 is defined as the current density at which $\rho=\rho_0$ at $T=T_g$:

$$J_0=J(\rho_0/\rho)^{2/(z-1)}|_{T=T_g}. \quad (6)$$

Using ρ_0 and J_0; $\rho-J$ characteristics may be written as

$$\left[\frac{\rho}{\rho_0}\right]|t|^{-\nu(z-1)}=G_{\pm}\left[\frac{JT_g}{J_0T}|t|^{-2\nu}\right], \quad (7)$$

where ρ_0, J_0, and T_g are function of magnetic field. Scaling functions G_+ and G_- (corresponding to $T>T_g$ and $T<T_g$, respectively) and critical exponents (ν and z) are expected to show universal behavior. Using ρ_0 and J_0 determined at different magnetic fields, Moloni *et al.*[10] have shown that ρ-J characteristics obtained at different magnetic fields collapse into a single universal curve as given by Eq. (7). In other studies[11,12] angular dependence of VG transition has been investigated and it is shown that ρ-J characteristics obtained at different angles collapse when ρ and J are scaled by angle dependent fitting parameters (ρ_0 and J_0). However, the parameters ρ_0 and J_0 in these studies showed unsystematic dependence on angle θ. Gupta *et al.*[13] have studied combined field and angle dependence of VG transition in YBCO thin films. They have shown that field and angle dependence of parameters ρ_0, J_0, and T_g show a smooth dependence on reduced field $\epsilon_\theta H$ where $\epsilon_\theta=\sqrt{\sin^2\theta+\epsilon^2\cos^2\theta}$ and ϵ^2 $(=m_{ab}/m_c)$ is mass anisotropy ratio.[14] This is in accordance with anisotropic Ginzburg-Landau (GL) model.[15]

In the present study, we have measured I-V characteristics of MgB_2 thin films as a function of H, θ, and temperature. The results show critical scaling behavior predicted for vortex glass transition at all fields and angles. Within experimental errors, the values of critical exponents and scaling functions show universal behavior.

II. EXPERIMENTAL

MgB_2 thin films were prepared on (1102) oriented single crystal sapphire substrates as described earlier.[16,17] Briefly, amorphous boron thin films were deposited using pulsed laser ablation technique. These were annealed at high temperature under Mg vapors to yield highly c-axis oriented thin films. The films show very high critical current densities with typical J_c of 1.6×10^7 A/cm^2 at $T=15$ K under self-field.[18] For measurement of I-V characteristics, the films were patterned using photolithography to make a bridge of 79 μm width and 1.0 mm length. A film of 400 nm thickness was used for measurements reported here. The film showed a zero resistance transition temperature of 39.0 K.[16] I-V measurements were carried out using four probe resistivity technique. The film was cooled using APD Cryogenics make closed cycle cryostat and a Lakeshore temperature controller was used to maintain the film temperature to within ±0.02 K of the set value. For measurements, the sample was mounted with current parallel to the vertical axis and the magnetic field in horizontal direction was applied using an electromagnet. The sample could be rotated along vertical axis to vary the angle (θ) between the ab plane and the magnetic field while maintaining the current normal to H. Angle (θ) was measured with an accuracy of better than 1°.

III. RESULTS AND DISCUSSION

Typical field (E) versus current density (J) characteristics measured at fixed field and temperature are shown in Fig. 1 in linear [Fig. 1(a)] and semilogarithmic [Fig. 1(b)] plots. Absence of a linear region in both of these plots shows that dissipation in MgB_2 is not explained by flux creep and flux flow model in any significant region of I-V characteristics. The possibility of linear characteristics indicative of flux flow is, however, not ruled out at still higher current densities. Similar results were obtained at other magnetic fields and temperatures. However, linear I-V's at very low current densities were observed (at all fields and angles) for temperatures close to the transition temperature $T_c(H,\theta)$. Typical curves are shown in Figs. 1(c) and 1(d). It is seen that I-V's are nonlinear over most of current range but show linear behavior at very small current densities. While linear behavior at small current densities is in agreement with flux creep model, absence of any exponential dependence of field on J indicates that flux creep model does not explain the data. It may be noted that linear behavior at small current densities and temperatures above T_g had also been predicted by VG model. Analysis of measured data in terms of VG model, carried out below, shows that the linear behavior in each case is observed at $T>T_g$ (see values of T_g for different H and θ in Table I). No linear behavior at lower temperatures ($T<T_g$) was seen indicating disagreement with flux creep model but expected in terms of the VG model.

In order to study critical scaling behavior, resistivity versus current density characteristics (for fixed field and angle) were plotted as a function of temperature. Typical results are shown in Fig. 2. The ρ-J characteristics at higher temperatures show positive curvature with linear resistivity at low

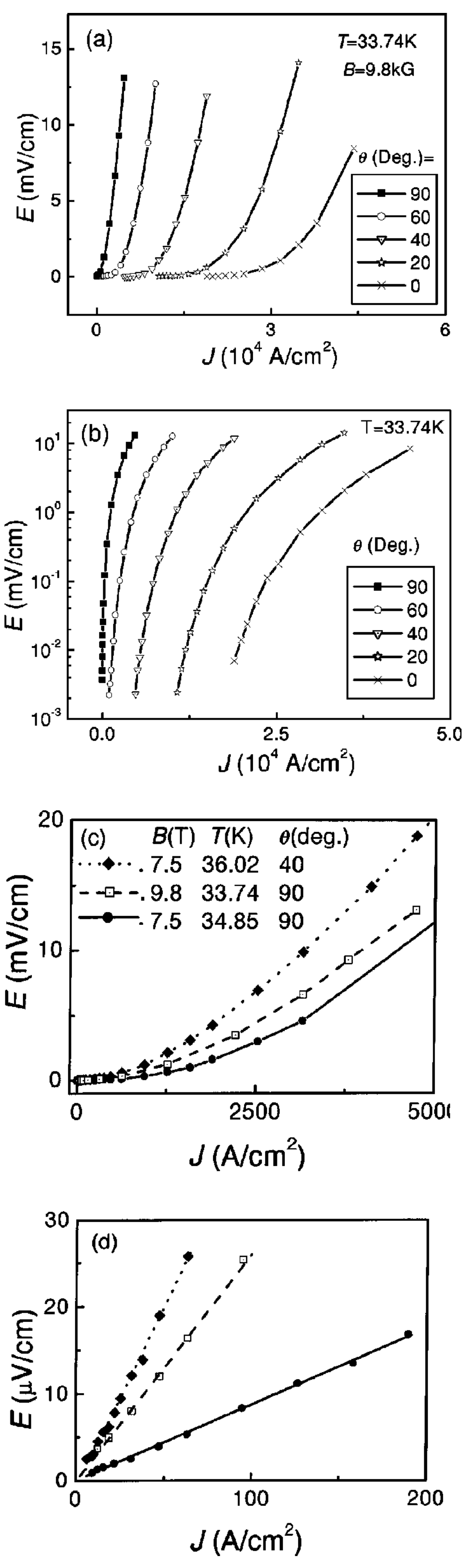

FIG. 1. Typical current-voltage characteristics of MgB_2 thin film (obtained at $B=9.8$ kG and $T=33.74$ K) plotted as electric field (E) versus current density (J) on linear (a) and semilogarithmic scale (b). Also shown are *I-V*'s measured at temperatures close to transition temperature for different fields and angles (c). (d) shows data of (c) at small current densities. Note that different units have been used along the y axis in (c) and (d).

TABLE I. Magnetic field and angle dependence of parameters T_g, ρ_0, and J_0.

H(kG)	θ	T_g	ρ_0(Ω cm)	J_0(10^7A/cm^2)
9.8	90	33.42	1.2	6.0
7.5	90	34.63	1.0	3.5
3.9	90	36.75	2.5	3.0
9.8	60	33.88	1.4	4.0
7.5	60	35.10	1.0	2.3
3.9	60	36.87	1.0	2.6
9.8	40	34.71	2.5	3.1
7.5	40	35.72	2.0	2.8
3.9	40	37.25	2.5	3.0
9.8	20	35.74	2.0	2.5
7.5	20	36.55	1.7	2.5
3.9	20	37.78	3.0	3.6
9.8	0	36.10	1.8	2.7
7.5	0	36.92	2.1	3.0
3.9	0	38.0	5.0	5.0

currents and those at lower temperatures show negative curvature with resistivity tending to zero at low currents. The characteristics are similar to those reported for vortex glass transition in earlier studies. At very high current densities (region marked X in Fig. 2) the curvature of ρ-J characteristics changes indicating a transition from activated flux motion to free-flux-flow with constant resistivity. The value of resistivity in this region is of same order as resistivity in normal state supporting the transition towards free-flux-flow behavior. As seen below the characteristics in this region show deviation from scaling behavior. Vortex glass transition temperature was determined from ρ-J characteristics of Fig. 2 as the temperature at which curvature changes from positive to negative. The exponent z was determined from the slope of curve at $T=T_g$ using Eq. (4). Value of ν was deter-

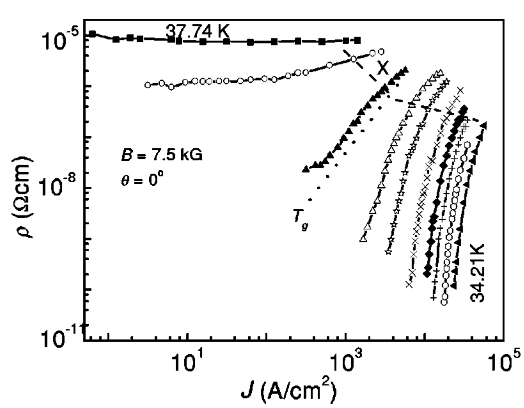

FIG. 2. Plots of resistivity as function of current density obtained at a fixed magnetic field of 7.5 kG applied at angle of $\theta=0°$. The plots shown were obtained at temperatures of 37.74, 37.39, 37.01, 36.38, 36.02, 35.68, 35.31, 34.85, 34.64, and 34.21 K, respectively. The dotted line indicates power law behavior at T_g (except in region X—marked by a dashed curve, which pertains to a transition from activated flux motion to free flux flow). Slope of the dotted line was used to determine exponent z.

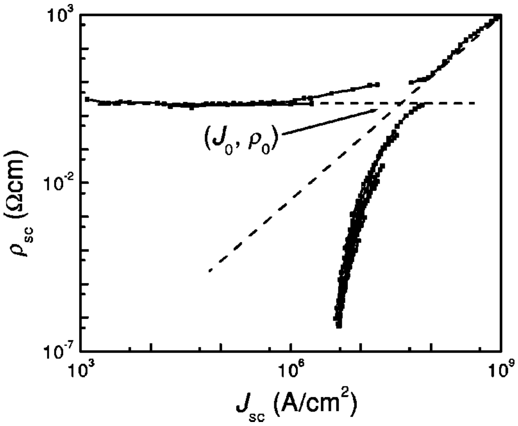

FIG. 3. Scaling collapse of the ρ-J data of Fig. 2 with $T_g = 36.92$ K, $z=4.3$ and $\nu=1.0$. The parameters ρ_0 and J_0 are obtained from this figure as shown. ρ_0 is the scaled resistivity at low currents and J_0 is the value of current density at which $\rho=\rho_0$ at $T=T_g$.

mined so as to obtain optimum collapse of ρ-J data plotted as ρ_{sc} versus J_{sc} as shown in Fig. 3. Values of T_g and z determined from data of Fig. 2 were also varied in a narrow range to optimize the collapse of data. Optimum values of ν and z were also determined using ρ-J characteristics obtained at different H and θ. These were found to be independent of H and θ and are $z=4.3\pm0.1$ and $\nu=1.0\pm0.1$. These values of ν and z are within the range predicted for vortex glass transition.[9] For comparison we note that for studies carried out on YBCO this films, value of z is found to be in the range 3.8–5.2 and that of ν in the range 1.6–1.9.[9–13] For further analysis we use average of ν and z values determined at different fields and angles, i.e., $\nu=1.0$ and z = 4.3. Collapsed curves of Fig. 3 (particularly for $T<T_g$) show some deviation (i.e., shift of individual curves towards right of collapsed common curve) corresponding to region X of Fig. 2. As the vortex glass scaling behavior has been worked out with activated motion of flux lines, it is not expected to be

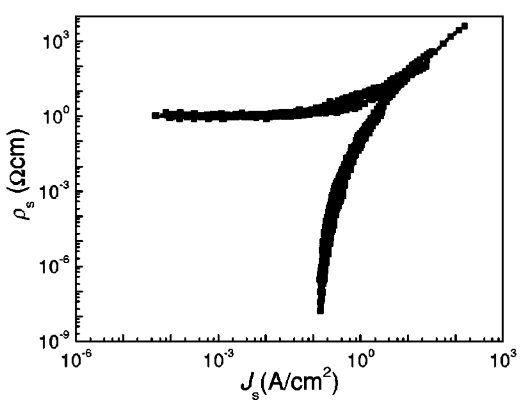

FIG. 4. Scaling collapse of ρ-J data obtained at three different fields and five different angles as given in Table I. The data are plotted as scaled resistivity (ρ_s) versus current density (J_s), defined using Eq. (7) as $\rho_s=(\rho/\rho_0)|t|^{-\nu(z-1)}$ and $J_s=(JT_g/J_0T)|t|^{-2\nu}$. The values of $\rho_0(B,\theta)$ and $J_0(B,\theta)$ have been determined (as shown in Fig. 3) from scaling of data obtained at different fields and angles.

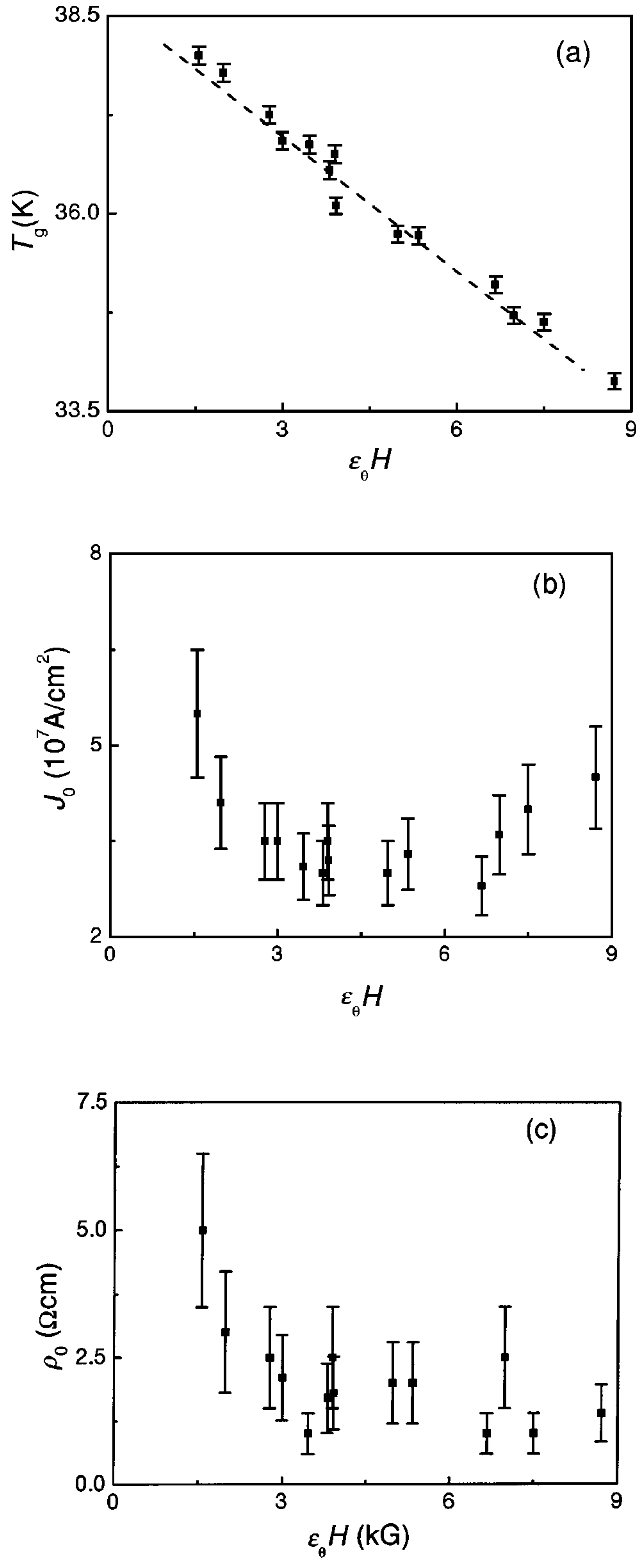

FIG. 5. Dependence of T_g (a), J_0 (b), and ρ_0 (c) on reduced magnetic field. Vortex glass transition temperature T_g is found to show approximately linear dependence on reduced magnetic field.

valid at current densities where transition to free flux flow takes place.[7,8] For further analysis of data obtained at different magnetic fields and angles we have not considered data in region X. For comparison of VG scaling functions at different fields and angles and study of universality, we determine resistivity and current density scales $\rho_0(H,\theta)$ and $J_0(H,\theta)$ as defined by Eqs. (5) and (6), respectively. The values of ρ_0 and J_0 were determined from collapsed curves obtained at different H and θ as shown in Fig. 3. The resistivity scale ρ_0 is defined as the resistivity at low currents and $T>T_g$. The current scale J_0 is the value of current density that gives $\rho=\rho_0$ at $T=T_g$. The values of ρ_0, J_0, and T_g obtained at different fields and temperatures are listed in Table I. Using these values of ρ_0 $(H,\ \theta)$, $J_0(H,\theta)$, and $T_g(H,\theta)$ we define scaled resistivity (ρ_s) and current density (J_s) using Eq. (7) as $\rho_s=(\rho/\rho_0)|t|^{-\nu(z-1)}$ and $J_s=(JT_g/J_0T)|t|^{-2\nu}$. As shown in Fig. 4, resistivity versus current density characteristics obtained at different fields and angles collapse into two curves when plotted as ρ_s versus J_s. This collapse supports universality of scaling functions $G_\pm$ of Eq. (7).

We have used anisotropic GL model to study the field and angle dependence of parameters ρ_0, J_0, and T_g. These parameters are plotted in Fig. 5 as a function of $\epsilon_\theta H$ using $\epsilon=0.4$ as determined in an earlier study on similar films.[2] The error bars in this figure indicate the range of parameters for which reasonable scaling was obtained. It is seen that the parameters show smooth variation with reduced field $\epsilon_\theta H$ as expected from anisotropic GL model.[15]

In some of the recent studies on *I-V*'s in peak effect region, a current induced transition from disordered vortex state (vortex glass) to ordered vortex state (vortex lattice) has been reported. Such a transition is typically indicated by a peak in differential resistivity versus current characteristics.[19,20] No such peak was observed for *I-V*'s reported here. However, the change of curvature in region marked X in Fig. 2 may indicate a possible tendency to ordering of vortex state at high currents. The absence of transition to ordered state in the present case is understandable because (a) such a transition occurs at currents much higher than critical current density[19] and the data in Fig. 2 is typically limited to 5 times J_c, (b) currents needed for the transition diverge at temperatures near T_g,[19,21] and (c) the transition is typically seen for weakly pinned superconductors and would be expected to occur at much higher currents for strongly pinned material. The *I-V*'s presented here show that a vortex glass state in MgB_2 is induced by strong point pinning centers and therefore critical currents may be improved by optimization of point defects. It may be noted that in contrast to high-T_c superconductors, MgB_2 single crystals do not show strong point pinning and vortex glass transition. This indicates that point defects and thereby the critical current density may be better controlled in this material. We may add that we have not observed a Bose glass transition behavior at any angle. A Bose glass transition arises from columnar defects[14] and presence of such defects would have been indicated by change in critical behavior as angle is changed.

IV. CONCLUSIONS

Current-voltage (*I-V*) characteristics of MgB_2 thin films have been studied at different temperatures, fields and angles between H and the ab plane. The *I-V*'s show absence of any significant region where flux flow or flux creep model could be valid. The *I-V*'s obtained at different fields and angles show critical scaling behavior predicted for a transition from vortex liquid state at higher temperatures to a strongly pinned vortex glass state at lower temperatures. The critical exponents are found to be independent of the field and angle indicating an universal behavior. The field and angle dependence of T_g, and scaling functions (ρ_0, J_0) is seen to be in agreement with anisotropic GL model. The results show that pointlike pinning centers play a decisive role in determining the vortex state of MgB_2 thin films.

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