

I-V characteristics of the vortex state in MgB₂ thin films

Huan Yang,¹ Ying Jia,¹ Lei Shan,¹ Yingzi Zhang¹ and Hai-Hu Wen^{1*}

¹*National Laboratory for Superconductivity, Institute of Physics and National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences, P.O. Box 603, Beijing 100080, P. R. China*

Chenggang Zhuang,^{2,3} Zikui Liu,⁴ Qi Li,² Yi Cui² and Xiaoxing Xi^{2,4}

²*Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA*

³*Department of Physics, Peking University, Beijing 100871, PR China and*

⁴*Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA*

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The current-voltage (*I-V*) characteristics of various MgB₂ films have been studied at different magnetic fields parallel to *c*-axis. At fields $\mu_0 H$ between 0 and 5 T, vortex liquid-glass transitions were found in the *I-V* isotherms. Consistently, the *I-V* curves measured at different temperatures show a scaling behavior in the framework of quasi-two-dimension (quasi-2D) vortex glass theory. However, at $\mu_0 H \geq 5$ T, a finite dissipation was observed down to the lowest temperature here, $T = 1.7$ K, and the *I-V* isotherms did not scale in terms of any known scaling law, of any dimensionality. We suggest that this may be caused by a mixture of σ band vortices and π band quasiparticles. Interestingly, the *I-V* curves at zero magnetic field can still be scaled according to the quasi-2D vortex glass formalism, indicating an equivalent effect of self-field due to persistent current and applied magnetic field.

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I. INTRODUCTION

Since the discovery of the two-gap superconductor MgB₂ in 2001,¹ the mechanism of its superconductivity and vortex dynamics has attracted considerable interests. The two three-dimension (3D) π bands and two quasi-two-dimension (quasi-2D) σ bands in this simple binary compound seem to play an important role in the superconductivity,² as well as the normal state properties.^{3,4} The two sets of bands have different energy gaps, i.e., about 7 meV for the σ bands, and about 2 meV for the π bands.^{5,6} And the coherent length of the π bands is much larger than that of the σ bands². Many experiments have demonstrated that the π -band superconductivity is induced from the σ -band and there is a rich evidence for both the interband and intraband scattering. Owing to the complicated nature of superconductivity in this system, its vortex dynamics may exhibit some interesting or novel features. Among various experimental methods, measuring the current-voltage (*I-V*) characteristics at different temperatures and magnetic fields can provide important information for understanding the physics of the vortex state. Up to now, the transport properties of MgB₂ have been studied on both polycrystalline bulk samples⁷ and thin films⁸. In both cases, the *I-V* characteristics demonstrated good agreement with the 3D vortex glass (VG) theory. This was partially due to the limited magnetic fields in the experiment. In addition, it has been shown that the properties of MgB₂ are very sensitive to the impurities and defects introduced in the process of sample preparation, and the vortex dynamics must be influenced, too. Therefore, it is necessary to investigate the vortex dynamics in high

quality MgB₂ epitaxial thin films and to reveal the intrinsic properties of the vortex matter in this interesting multiband system. In this paper, we present the *I-V* characteristics of high-quality MgB₂ thin films measured at various temperatures and magnetic fields. The vortex dynamics in this system is then investigated in detail.

II. EXPERIMENT

The high-quality MgB₂ thin films studied in this work were prepared by the hybrid physical-chemical vapor deposition technique⁹ on (0001) 6H-SiC substrates. All the films had *c*-axis orientation with the thickness of about 100 nm. Fig. 1 (a) shows the θ -2 θ scan of the MgB₂ film, and the sharp (000 l) peaks indicate the pure phase of the *c*-axis orientation of MgB₂. In order to show the good crystallinity of the film, we present in Fig. 1(b) the same data in a semilogarithmic scale which enlarges the data in the region of small magnitude. It is clear that, besides the background noise, we can only observe the diffraction peaks from MgB₂ and the SiC substrate, i.e., there is no trace of the second phase in the film. The *c*-axis lattice constant calculated from the MgB₂ peak positions was about 3.517 Å (bulk value¹: 3.524 Å). The ϕ scan (azimuthal scan) shown elsewhere⁹ indicated well the six-fold hexagonal symmetry of the MgB₂ film matching the substrate. The full width at half maximum (FWHM) of the 0002 peak taken on the film in θ -2 θ scan [MgB₂ 0002 peak in Fig. 1(a)] and ω scan [rocking curve, shown in Fig. 1(c)] is 0.15° and 0.39°, respectively. The scanning electron microscopy (SEM) image in Fig. 1(d) gave a rather smooth top surface view without any observable

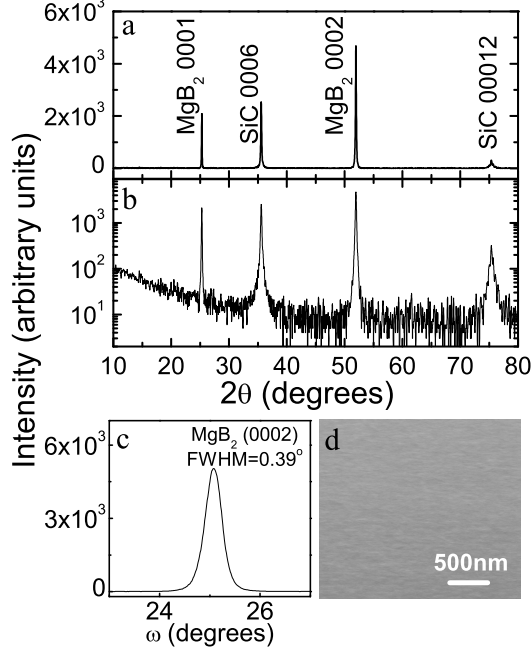


FIG. 1: (a) X-ray diffraction pattern of the MgB_2 film on a (0001) 6H-SiC substrate in the θ - 2θ scan, which shows only the 000 l peaks of MgB_2 in addition to substrate peaks, indicating a phase-pure c -axis-oriented MgB_2 film. (b) The semilogarithmic plot of the θ - 2θ scan. (c) The rocking curve of the 0002 MgB_2 peak, which shows the FWHM of about 0.39° . (d) The SEM image of the MgB_2 film, which shows the smooth surface without obvious granularity.

grain boundaries, which suggested that the film had a homogeneous quality. Ion etching was used to pattern a four-lead bridge with the effective size of $380 \times 20 \mu\text{m}^2$. The resistance measurements were made in an Oxford cryogenic system Maglab-Exa-12 with magnetic field up to 12 T. Magnetic field was applied along the c axis of the film for all the measurements. The temperature stabilization was better than 0.1% and the resolution of the voltmeter was about 10 nV. We have done all the measurements on several MgB_2 films, and the experimental data and scaling behaviors are similar; so, in this paper, we present the data from one film.

In Fig. 2, we present the resistive transitions (R - T relations) of a MgB_2 thin film measured at various magnetic fields in a semilogarithmic scale. The current density in the measurement was about 500 A/cm^2 , much smaller than the critical value for low temperatures, 10^6 A/cm^2 ¹⁰. It can be determined from Fig. 2 that the sample had a superconducting transition temperature of $T_c = 40.05 \text{ K}$, with a transition width of about 0.5 K. Its normal state resistivity was about $2.45 \mu\Omega \text{ cm}$ and the residual resistance ratio $[\equiv \rho(300 \text{ K})/\rho(42 \text{ K})]$ was about 6.4. The I - V curves were measured at various temperatures for each field, and then we got the electric

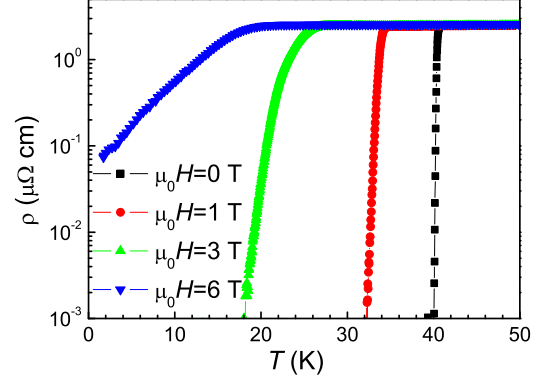


FIG. 2: Temperature dependence of resistive transitions for $\mu_0 H = 0, 1, 3$, and 6 T , with the current density $j = 500 \text{ A/cm}^2$.

field (E) and the current density (j) according to the sample dimension. The current density was swept from 5 to 10^5 A/cm^2 during the I - V measurements.

III. THEORETICAL MODELS

In the mixed state of high- T_c superconductors with randomly distributed pointlike pinning centers, a second-order phase transition is predicted between VG state and vortex-liquid state.¹¹ The I - V curves at different temperatures near the VG transition temperature T_g can be scaled onto two different branches¹² by the scaling law

$$\frac{E}{j(T - T_g)^{\nu(z+2-D)}} = f_{\pm} \left(\frac{j}{|T - T_g|^{\nu(D-1)}} \right). \quad (1)$$

The scaling parameter z has the value of 4–7, and $\nu \approx 1$ –2; D denotes the dimension of the system with the value 3 for 3D and 2 for quasi-2D¹³; f_+ and f_- represent the functions for two sets of the branches above and below T_g . Above T_g , the linear resistivity is given by

$$\rho_{\text{lin}} = dE/dj|_{j \rightarrow 0} \propto (T - T_g)^{\nu(z+2-D)}. \quad (2)$$

At T_g , the electric field versus the current density curve satisfies the relationship

$$E(j)|_{T=T_g} \approx j^{(z+1)/(D-1)}. \quad (3)$$

In 2D superconductors at $\mu_0 H = 0 \text{ T}$, a Berezinskii-Kosterlitz-Thouless (BKT) transition was found at a specific temperature T_{BKT} .¹⁴ At T_{BKT} , $E \propto j^3$, which is a sign of the BKT transition. A continuous change from the BKT transition at zero field to a quasi-2D VG transition, and then to a true 2D VG transition with $T_g = 0 \text{ K}$ was found in TlBaCaCuO film,¹⁵ which shows a field-induced crossover of criticalities.

A 2D VG transition may exist in a true 2D system with $T_g = 0$ K, i.e., there is no zero-resistance state at any finite temperatures. The E - j curves can be scaled by¹⁶

$$\frac{E}{j} \exp \left[\left(\frac{T_0}{T} \right)^p \right] = g \left(\frac{j}{T^{1+\nu_{2D}}} \right), \quad (4)$$

where T_0 is a characteristic temperature, $\nu_{2D} \approx 2$, and $p \geq 1$, while g is a scaling function for all temperatures at a given magnetic field. The linear resistance is given by

$$\rho_{\text{lin}} \propto \exp[-(T_0/T)^p]. \quad (5)$$

This 2D scaling law can be achieved in the very thin films¹⁷ or in highly anisotropic systems at high magnetic fields.^{18,19}

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Quasi-two-dimension vortex-glass scaling in the low-field region ($\mu_0 H < 5$ T)

The E - j characteristics have been measured at various magnetic fields up to 12 T. In Fig. 3 we show the typical example at $\mu_0 H = 1$ T for (a) E - j curves and (b) the corresponding ρ - j curves in double-logarithmic scales. It is obvious that when the temperature goes below some particular value (this is actually the vortex-glass transition temperature T_g according to following discussions), the resistivity falls rapidly with decreasing current density and finally reaches the zero-resistance state which is the characteristic of the so-called VG state. At the temperatures above T_g , the resistivity remains constant in small current limit. The current density of 500 A/cm^2 used in ρ - T measurement shown in Fig. 2 lies in this linear resistivity regime from about 10^{-3} to $1 \mu\Omega \text{ cm}$. Consequently, these data sets provide the basic information on scaling if the data are describable by the VG theory.

The inset in Fig. 4 shows the data of the ρ_{lin} versus $(T - T_g)$ and the fit to Eq. (2). The data are the same as those shown in Fig. 2 for $\mu_0 H = 1$ T, and the attempt T_g value is 31.4 K. In this double-logarithmic plot, the slope of the linear fitting gives just the exponent of $\nu(z+2-D)$, and the determined value is 8.08 ± 0.05 . In order to have reasonable values for ν and z , the dimension parameter D needs to be chosen as 2, i.e., the investigated system has the property of quasi-2D, which is similar to the situation found in BiSrCaCuO.^{13,20} This is further supported by the VG scaling of the data at 1 T. As shown in the main frame of Fig. 4, the scaling experimental E - j curves form two universal branches corresponding to the data above and below T_g (31.4 K) with $\nu = 1.32$ and $z = 6.12$. At very large current density or a temperature near the onset of superconducting transition, the free flux flow regime dominates and, hence, the data do not scale. The

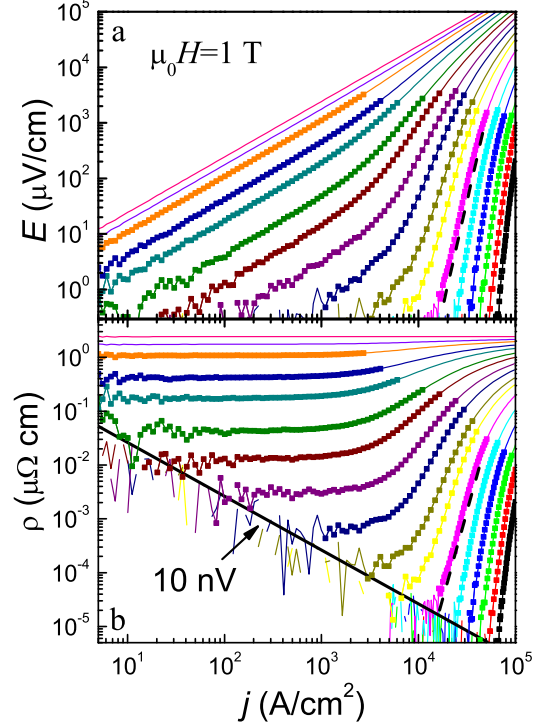


FIG. 3: (Color online) (a) E - j characteristics measured at fixed temperatures ranging from 30 to 36 K for $\mu_0 H = 1$ T. The increments are 0.30 K in the range from 30.00 to 31.20 K, and 0.25 K in the range from 31.50 to 34.00 K respectively, and finally 35 K on the top. The dashed line shows the position of T_g , and the symbols denote the segments that scale well according to the quasi-2D VG theory. The thin solid lines denote also the measured data, however, located outside the scalable range. (b) ρ - j curves corresponding to the E - j data in (a). The thick solid line in (b) denotes the voltage resolution of 10 nV.

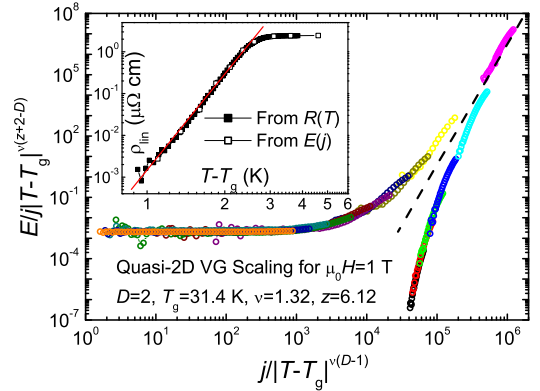


FIG. 4: (Color online) Quasi-2D VG scaling of the E - j curves measured at 1 T. The inset shows a double-logarithmic plot of the temperature dependence of the linear resistivity. The dashed line is a guide for the eyes.

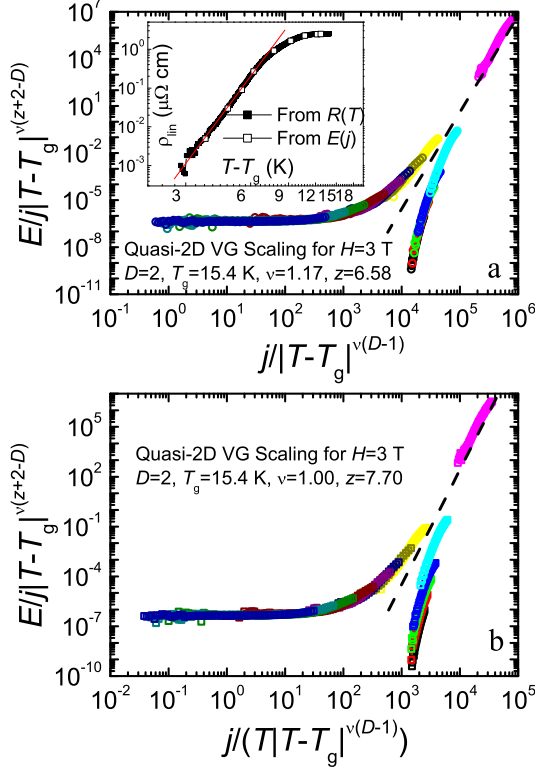


FIG. 5: (Color online)(a) Scaling curves of the E - j data measured in 3 T based on the quasi-2D VG scaling theory. The inset shows a log-log plot of the temperature dependence of the linear resistivity. (b) VG scaling with another form of scaling variable $j/(T|T - T_g|^{\nu(D-1)})$.

symbols in the figure denote the range of the data well described by the scaling law.

The situation at $\mu_0 H = 3$ T is similar to that at $\mu_0 H = 1$ T. As shown in Fig. 5(a), the determined parameters are $T_g = 15.4$ K, $\nu = 1.17$, and $z = 6.58$. Interestingly, the previous work on MgB_2 film⁸ indicated that the 3D VG scaling theory ($D = 3$) is a better choice in describing the I - V characteristics in this system, though this experiment was done at magnetic fields lower than 1 T. Moreover, the I - V curves were demonstrated to scale well by using the argument of $j/(T|T - T_g|^{2\nu})$. The same conclusions were also drawn on the polycrystalline MgB_2 samples⁷. In order to clarify this issue, we also analyzed our data using the form suggested in Ref. 8. As shown in Fig. 5(b), such a scaling with $j/(T|T - T_g|^{\nu(D-1)})$ as the scaling variable is worse than that with $j/|T - T_g|^{\nu(D-1)}$. Most importantly, the dimension parameter D is still required to be 2 instead of 3 as proposed in Refs. 7 and 8. This confusion can be easily understood in terms of the two-band superconductivity of MgB_2 . As we know, there are two types of bands contributing to the superconductivity of MgB_2 , namely, the 3D π bands and the

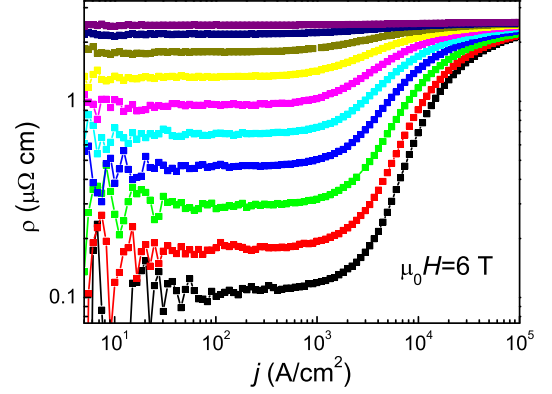


FIG. 6: (Color online) ρ - j data at temperatures 1.7 K and 4 K to 20 K with 2 K-step, for $\mu_0 H = 6$ T. Temperature of the isotherms increases from bottom to top.

2D σ bands. Therefore, the structure of the vortex matter must be affected by both of them. Although the superconductivity of π bands, induced possibly by that of σ bands, is much weaker, it provides a large coherence length with 3D characteristics in the low-field region. Therefore, the vortices in this system may be quasi-2D like and, at the same time, they can possess large cores characterized by the coherence length of the π band superfluid. In this sense, the quasi-2D scaling should be more appropriate than the 3D one. However, when a higher disorder is induced in the system, especially in the boron sites, the interband scattering gets stronger and the anisotropy decreases, which may lead to a 3D vortex scaling. In this case, a more rigid vortex line can be observed, especially at low fields.²¹ The good quasi-2D scaling at 1 and 3 T demonstrated here suggests that the phase transition from VG to the vortex liquid in MgB_2 resembles that in the high- T_c superconductors. Together with the data shown below, we can safely conclude that a vortex glass state with zero linear resistivity can be achieved in the low field region due to the presence of the finite superfluid density from the π bands. Regarding the VG scaling²² a principal requirement is a proper determination of T_g , namely the temperature with a straight log E -log j curve in the low dissipation part. The tolerance for T_g variation is very small (about ± 0.3 K). With an inappropriately chosen T_g , the scaling quality dramatically deteriorates and, simultaneously, the values of ν and z quickly deviate from those reported above and those proposed by theory. This validates our analysis here.

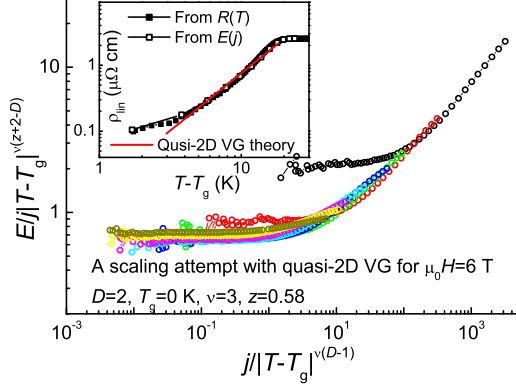


FIG. 7: (Color online) The scaling of the E - j isotherms with quasi-2D VG model for $\mu_0 H = 6$ T. The inset shows the deviation of the ρ_{lin} vs $T - T_g$ ($T_g = 0$) relation from the linearity in the double logarithmic scale.

B. Anomalous vortex properties in high field region

As shown in Fig. 2, when the magnetic field reaches 6 T, no zero-resistance state can be observed down to the lowest temperature, here 1.7 K. Consequently, no VG transition exists above 1.7 K at this field, as shown in Fig. 6. The shape of the curve at $T = 1.7$ K suggests that the resistivity goes to a finite value as the current density approaches zero.²³ As shown in Fig. 7, the ρ_{lin} versus $T - T_g$ seriously deviates from linearity for any possible T_g value, indicating the inapplicability of Eq. (2) in the present case. Correspondingly, the quasi-2D scaling law fails here. A natural explanation is that, with increasing field, the 3D supercurrent from π bands is seriously suppressed^{6,24} and the quasi-2D vortex structure transforms into a 2D-like one dominated by the σ band superfluid. In Fig. 8, we show our attempt to apply 2D VG scaling on the data. Surprisingly, this attempt also failed, even though this model has been successfully applied to the layered superconductors with large anisotropy (or 2D property) such as Tl- and Bi-based high- T_c thin films at high magnetic fields.^{18,19}

The most reasonable explanation for this anomaly is that the supercurrent contribution from the π bands is much easier to suppress by the magnetic field than that from the σ bands, since the gap in the π bands is several times smaller than that in the σ band. We suggest that at high magnetic fields (above 5 T), a different vortex matter state is formed, composed of quasi-particles from the π bands and vortices formed mainly by the residual superfluid from the σ band. The π -band quasiparticles diminish the long range phase coherence of the superconducting phase, which leads to a finite dissipation. Once the long range superconducting phase coherence is destroyed by the proliferation of a large amount of these

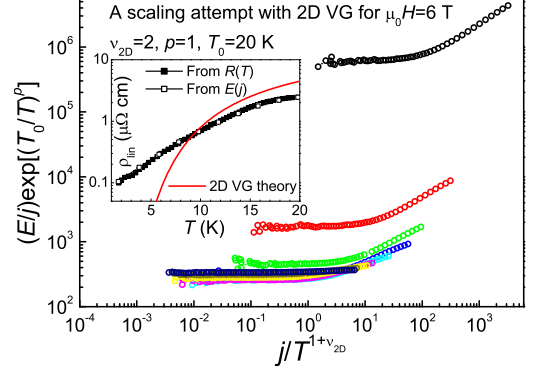


FIG. 8: (Color online) Attempted scaling of the data with 2D VG model [Eq. (4)] for $\mu_0 H = 6$ T. The inset shows the nonlinearity of the relationship between ρ_{lin} and temperature, the solid line shows the theoretical curve of true 2D VG theory [Eq. (5)].

π -band quasiparticles, neither 3D nor quasi-2D VG scaling is applicable. Such a mixed state is obviously difficult to be simply described by any known scaling theory. Recently, scanning tunneling microscopy studies showed that the quasiparticles of the π bands disperse over all of the superconductor, both within and outside the vortex cores²⁵, which strongly supports our arguments. This is the basis for the explanation of the nonvanishing vortex dissipation at high magnetic fields in a zero temperature limit found recently on MgB_2 thin films.²³

C. Self-field effect at $\mu_0 H = 0$ T

For a 2D layered superconductor in zero-field, the above mentioned BKT transition may exist and be reflected in the I - V characteristics¹⁵. In the present MgB_2 samples, we have not found any evidence of this transition in low magnetic fields which would be consistent with the quasi-2D (instead of 2D) configuration of the vortex matter. Moreover, both the E - j curves and the ρ - j curves (as presented in Fig. 9) are similar to the situation of $\mu_0 H = 1$ T. Considering the narrow transition width at zero-field, we did the measurement carefully with an increment of 0.05 K. Obviously, there is no $E(j)$ curve which satisfies the $E \propto j^3$ dependence, as expected by the BKT theory. Since the current can induce self-generated vortices, it might be interesting to look at whether the quasi-2D VG model applies here.

Similar in Sec. IV A, we present ρ_{lin} versus $(T - T_g)$ in a double logarithmic plot. From this graph, we determined the exponent in Eq. 2 (as shown by the inset of Fig. 10(a)). A good quasi-2D scaling was obtained with parameters $T_g = 39.94$ K, $\nu = 1.12$, and $z = 6.61$, as presented in Fig. 10(a). Using the parameters deter-

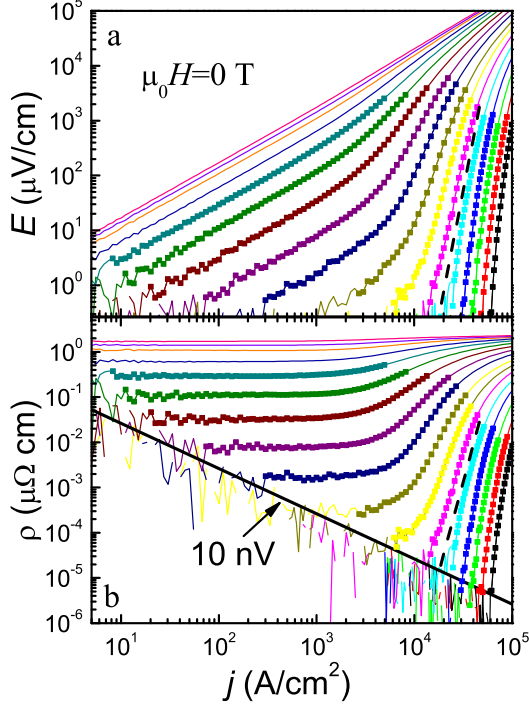


FIG. 9: (Color online) (a) E - j data at various temperatures from 39.7 K to 40.5 K with an interval of 0.05 K for $\mu_0 H = 0$ T, the symbols denote the region, where the data are scaled (from 39.70 K to 40.30 K). Temperature of the isotherms increases from bottom to top. The dashed line shows the position of T_g and the symbols denote the segments, which scale well according to the quasi-2D VG theory. The thin solid lines are also the measured data lying outside the scalable range. (b) ρ - j curves corresponding to the E - j data in (a). The thick solid line in (b) denotes the voltage resolution of 10 nV.

mined here, one finds a self-consistency with the value of $\nu(z + 2 - D)$, as determined in fitting the linear resistivity [Eq. (2)]. Both the temperature dependence of ρ_{lin} and the scaling curves at $\mu_0 H = 0$ T are similar to the situation at small field $\mu_0 H = 0.1$ T [shown in Fig. 10(b)] and $\mu_0 H = 0.5$ T (not shown in this paper), except for the slight differences of the scaling parameters. The scaling parameters including the ones at $\mu_0 H = 0.5$ T are listed in Table I. It was proven that current and magnetic field exhibit analogous effects in suppressing superconductivity and generating quasiparticles in conventional superconductors.²⁶ Similarly, the current-induced self-field may lead to a similar effect in the vortex state as an applied magnetic field. Nonetheless, the good agreement of this simple scaling law with the zero-field data is interesting and worth studying in detail. Moreover, the values of ν and z for zero field are very close to those for $\mu_0 H = 1$ and 3 T, indicating a similar vortex dynamics in the whole low-field region.

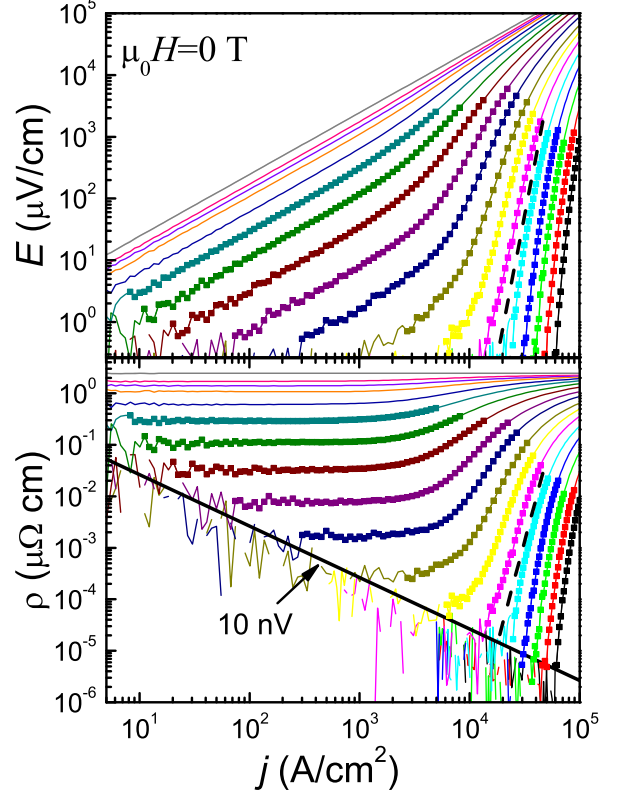


FIG. 10: (Color online) (a) Quasi-2D VG scaling of the data measured at 0 T. The inset indicates a good linearity of the temperature dependence of the linear resistivity. (b) Quasi-2D VG scaling of the data measured at 0.1 T. The inset indicates a good linearity of the temperature dependence of the linear resistivity.

TABLE I: Quasi-2D VG scaling parameters at different fields.

$\mu_0 H$ (T)	$T_g(K)$	ν	z
0.0	39.94	1.12	6.61
0.1	39.28	1.30	6.08
0.5	35.95	1.37	6.42
1.0	31.4	1.32	6.12
3.0	15.4	1.17	6.58

V. SUMMARY

We have measured I - V curves on high-quality MgB_2 films at various magnetic fields and temperatures. At magnetic fields below 5 T including the zero field, the curves scaled well according to the quasi-2D VG theory instead of the 3D model, in good agreement with the multiband superconductivity of MgB_2 contributed from the strong 2D σ bands and weak 3D π bands. At the fields above 5 T, the curves did not scale according to

any known VG scaling laws, accompanied by the disappearance of a zero-resistance state. Based on our result combined with recent tunneling experiments, a different vortex state was suggested, namely, a state where the vortices composed of the superfluid from the σ bands move through the space filled with numerous quasiparticles from π bands.

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- * Electronic address: hhwen@aphy.iphy.ac.cn
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