I–V characteristics of the vortex state in MgB_2 thin films

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The current-voltage (I-V) characteristics of various MgB_2 films have been studied at different magnetic fields parallel to the c-axis. At fields $\mu_0 H$ between 0 and 5 T, the linear resistivity $\rho_{\rm lin} \equiv E/j|_{j\to 0}$ in the vortex liquid state, with E the electric field and j the current density, is proportional to $(T - T_{\rm g})^{\nu(z+2-D)}$ as expected for a vortex glass transition, where $T_{\rm g}$ is the vortex liquid-glass transition temperature. Consistently, the I-V curves measured at different temperatures show a scaling behavior in the framework of quasi-2D vortex glass theory. However, at $\mu_0 H \geq 5$ T, a finite dissipation has been observed at the lowest temperature, $T = 1.7$ K here, and the I-V isotherms cannot be scaled by any existing scaling laws with any dimensionality, which may be caused by the mixture of vortices and qusiparticles contributed mainly from the π band. Interestingly, the I-V curves at zero field can still be scaled by the quasi-2D vortex glass formulism, indicating the equivalent effect of the self-field given by the current in this superconductor.

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I. INTRODUCTION

Since the discovery of the two-gap superconductor MgB_2 in 2001, the mechanism of its superconductivity and vortex dynamics have attracted considerable interests. The two 3D π bands and two quasi-2D σ bands in this simple binary compound seem to play important role in the superconductivity[1], as well as the normal state properties[2,3]. 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.[4,5] The coherent length of the π bands is much larger than that of the σ bands[1]. Many experiments have demonstrated that the π-band superconductivity is induced from the σ-band and there are rich physics associated with both the inter-band and intra-band scattering. Owing to the complication of superconductivity in this system, its vortex dynamics may exhibit some interesting or novel behaviors. Among various experimental methods, measuring the 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 MgB_2 have been studied on both the polycrystalline samples[6] and the thinfilms[7]. In both cases, the I-V characteristics were demonstrated to be in good agreement with the 3D vortex glass (VG) theory and no any novel behaviors has been observed. This is partially due to the low magnetic field used in the measurements. Since the properties of MgB_2 are very sensitive to the impurities or defects introduced in the process of sample preparation, the vortex dynamics must be influenced correspondingly. Therefore, it is necessary to investigate the vortex dynamics in clean MgB_2 epitaxial thin films with high quality and to reveal the intrinsic properties of the vortex matter in this interesting multi-band system.

In this paper, we present the detailed I-V characteristics of high-quality MgB_2 thin films measured at various temperatures and magnetic fields. The vortex dynamics in this system are then investigated in detail. It is found that all the I-V curves below 5 Tesla can be well scaled according to the quasi-2D vortex glass theory instead of the 3D model. This is consistent with the multi-band superconductivity in this system contributed by two bands with different pairing strength and dimensionality. Moreover, the data above 5 Tesla can not be described by any known scaling theory with any dimensionality. Combined with the recent reports on the investigation of spectroscopy, these analysis suggests the existence of a novel vortex state characterized by the mixture of vortices and qusiparticles contributed mainly by the π band above a certain magnetic field.

II. EXPERIMENT

The high-quality MgB_2 thin films studied in this work were prepared by HPCVD technique[18] on (0001) $4H$-SiC substrates. All the films have c-axis orientation with the thickness of about 100 nm. Ion etching was used to pattern a four-lead bridge with the effective size of 380 μm × 20 μm. The resistance measurements were made in a Oxford cryogenic system Maglab-Exa-12 with magnetic field up to 12 T and the field was applied along the c-axis of the film for all the measurements. The tem-

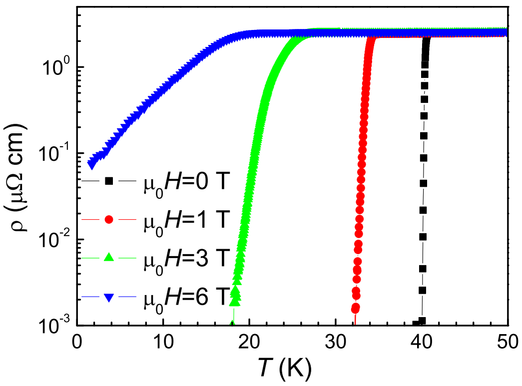

FIG. 1: Temperature dependence of resistive transitions for $\mu_0 H = 0$, 1, 3, 6 T with the current density $j = 500$ A/cm^2.

perature stabilization is better than 0.1% and the resolution of the voltmeter is about 10 nV.

In Fig. 1, we present the resistive transitions ($R-T$ relations) of a MgB_2 thin film measured at various magnetic fields in semi-logarithmic scale. The current density in the measurement is about 500 A/cm^2 which is much smaller than the critical current density above 10^6 A/cm^2 in low temperature region[19]. It can be determined from Fig. 1 that the sample has a superconducting transition temperature of $T_c = 40.05$ K with a transition width of about 0.5 K. Its normal state resistivity is about 2.45 $\mu\Omega$·cm and the residual resistance ratio $RRR \equiv \rho(300\text{ K})/\rho(42\text{ K})$ is about 6.4. All these parameters indicate the high quality of the MgB_2 film studied in this work. The I-V curves were measured at various temperatures for each field, and then we got the electric field and the current density according to the dimension of the sample. The current density was scanned from 5 A/cm^2 to 10^5 A/cm^2.

III. THEORETICAL MODELS

In the mixed state of high T_c superconductors with random point pinning centers, a second-order phase transition is predicted between VG state and vortex-liquid state.[9] The I-V curves at different temperatures near the VG transition temperature T_g can be scaled onto two different branches[10] by the scaling law

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

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-2D[11], and "±" represent two sets of the branches above and below T_g. Above T_g, the linear resistivity is given by

$$\rho_{\rm lin} \propto (T-T_g)^{\nu(z+2-D)}. \tag{2}$$

At T_g, the electric field versus the current density (E-j) curve satisfies the relationship

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

In 2D superconductors at $\mu_0 H = 0$ T, a Berezinskii-Kosterlitz-Thouless (BKT) transition was found at a specific temperature $T_{\rm BKT}$.[8] At $T_{\rm BKT}$, $E \propto j^3$, 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 $T_g = 0$ K was found in TlBaCaCuO film,[17] 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 by[13]

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

where T_0 is a characteristic temperature, $\nu_{2D} \approx 2$, and $p \geq 1$. The linear resistance is given by

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

This 2D scaling law can be achieved in the very thin films[14] or in highly anisotropic system when the magnetic field is high.[15,16]

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Quasi-2D VG scaling in 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. 2 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 a constant in small current limit. The current density of 500 A/cm^2 used in ρ-T measurement shown in Fig. 1 lies in this linear resistivity regime from about 10^{-3} $\mu\Omega$·cm to 1 $\mu\Omega$·cm. Consequently, these data sets provide the basic information for doing the VG scaling if they are describable by the VG theory.

The inset in Fig. 3 shows the data of the $\rho_{\rm lin}$ versus $(T-T_g)$ and the fit to Eq. 2. The data are the same as

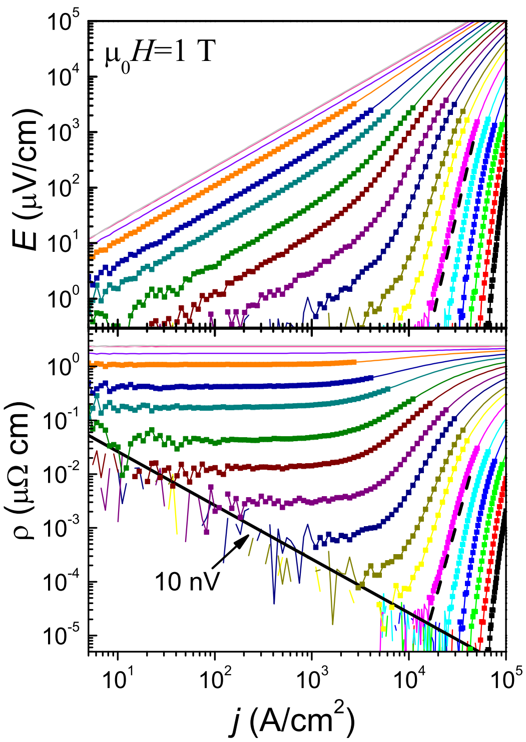

FIG. 2: (color online) (a) E-j characteristics measured at fixed temperatures ranging from 30 K to 36 K for $\mu_0 H = 1$ T. The increments are 0.30 K in the range from 30.00 K to 31.20 K and 0.25 K in the range from 31.50 K to 34.00 K, respectively. The top three curves correspond to 34.5 K, 35 K, 36 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 can be well scaled according to the quasi-2D VG theory. The thin solid lines are also the measured data which locate 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.

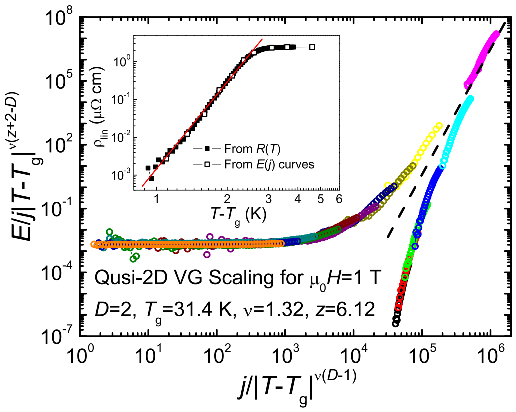

FIG. 3: (color online) Quasi-2D VG scaling of the E-j curves measured at 1 T. The inset shows a double-logarithmic plot of the temperature dependence of the linear resistivity. The dashed line is the guide for eyes.

that shown in Fig. 1 for $\mu_0 H = 1$ T and the attempt T_g value is 31.4K. 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 associated 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 BSCCO.[11,12]. This is further supported by the VG scaling on the data of 1 T. As shown in the main frame of Fig. 3, the measured E-j curves can be scaled very well onto two universal branches corresponding to the data above and below T_g (31.4K) with $\nu = 1.32$, and $z = 6.12$. At very large current density or a temperature near the onset superconducting transition, the free flux flow regime is dominated and hence the data can not be scaled. The symbols in the figure denote the range of the data which can be well described by the scaling law.

The situation of $\mu_0 H = 3$ T is similar to that of $\mu_0 H = 1$ T. As shown in Fig. 4(a), the determined parameters are $T_g = 15.4$ K, $\nu = 1.17$, and $z = 6.58$. It is interesting to note that the previous work on MgB_2 film[7] supported 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 low fields less than 1 T. Moreover, the $I-V$ curves were demonstrated to be well scaled in another form with the argument of $j/(T\,|T-T_g|^{2\nu})$. The same conclusions were also drawn on the polycrystalline MgB_2 samples[6]. In order to clarify this issue, we have also tried to analyze our data with the form suggested in Ref. 7. As shown in Fig. 4(b), such 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 dimensional parameter D is still required to be 2 instead of 3 as proposed in the Refs. 6,7. 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 2D σ bands. Therefore, the structure of the vortex matter must be affected by both of them. Although the superconductivity of π bands may be induced by σ bands and much weaker, they provide a large coherence length with 3D characteristics in the low field region. Therefore, the vortices in this system may be quasi-2D like while at the same time with a large core size 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 more disorders are introduced into the system, especially into the boron sites, the interband scattering will get stronger and the anisotropy will become lower, which may lead to a 3D vortex scaling. In this case, a more rigid

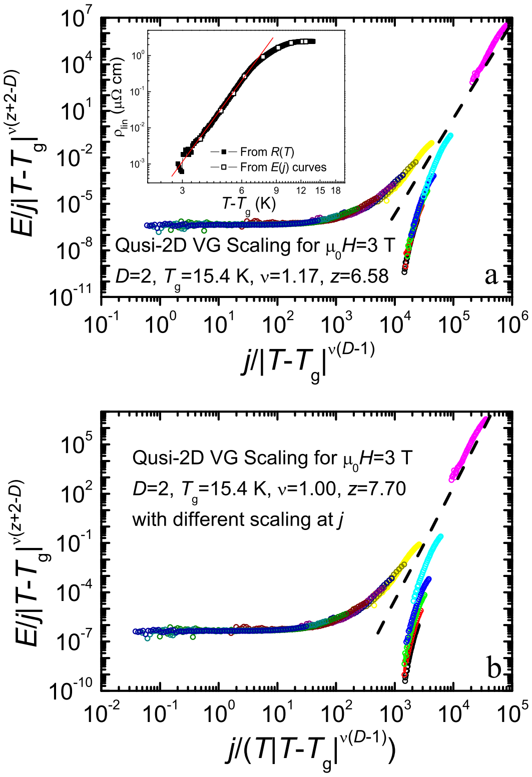

FIG. 4: (color online)(a) Scaling curves of the E-j data measured in 3 T based on the quasi-2D VG scaling theory. The inset shows a log-log plot of the temperature dependence of the linear resistivity. (b) VG Scaling with another form of scaling variable $j/(T\,|T-T_{\rm g}|^{\nu(D-1)})$.

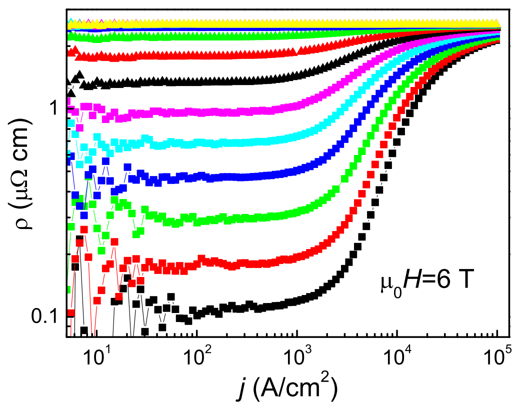

FIG. 5: (color online) ρ-j data at various temperatures ranging at 1.7 K and from 4 K to 26 K with an interval of 2 K for $\mu_0 H = 6$ T. Temperature of the isotherms increases from bottom to top.

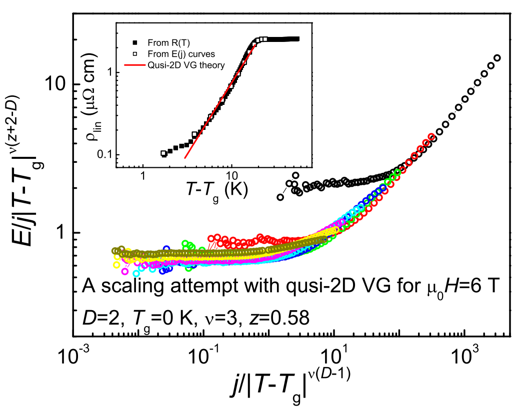

FIG. 6: (color online) The scaling of the E-j isotherms with quasi-2D VG model for $\mu_0 H = 6$ T. The inset shows the deviation of the $\rho_{\rm lin}$ vs $T - T_{\rm g}$ ($T_{\rm g} = 0$) relation from the linearity in the double logarithmic scale.

vortex line can be observed especially at low fields[20]. The good quasi-2D scaling at 1 T 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 it is safe to 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 band. Regarding the concerns[21] of using the VG scaling to determine the glass transition temperature $T_{\rm g}$, we must say that in obtaining the nice scaling as shown for $\mu_0 H = 1$ T and 3 T, we need to choose $T_{\rm g}$ properly, namely the temperature with a straight $\log E - \log j$ curve in the low dissipation part. In other words, the tolerance for changing the $T_{\rm g}$ is quite limited (say ± 0.3 K) from the values we determined above. If an inappropriate $T_{\rm g}$ is chosen, the yielded scaling quality immediately becomes worse. Meanwhile the values of ν and z deviate quickly from the ones reported above and are certainly far from the theoretical expectations. This validates our analysis here.

B. Anomalous vortex properties in high field region

As shown in Fig. 1, when the magnetic field reaches 6 T, no zero-resistance state can be observed down to the lowest temperature here, i.e., 1.7 K. Consequently, there is no VG transition existing above 1.7 K in this field as shown in Fig. 5. 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.[22] As shown in Fig. 6, the $\rho_{\rm lin}$ versus $T - T_{\rm g}$ seriously deviates from linearity by choosing any $T_{\rm g}$ values, indicating the inapplicability of Eq. 2 in the present case. Correspondingly, the

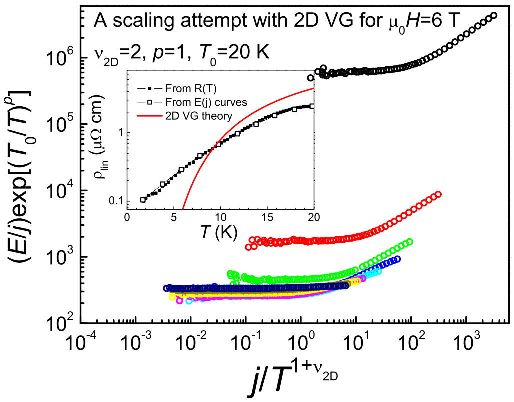

FIG. 7: (color online) Attempted scaling of the data with 2D VG model (Eq. 4) for $\mu_0 H = 6$ T. The inset shows the nonlinearity of the relationship between $\rho_{\rm lin}$ and temperature, the solid line shows the theoretical curve of true 2D VG theory (Eq. 5).

quasi-2D scaling law fails here. A natural explanation is that, with increasing field, the 3D supercurrent from π bands is seriously suppressed[5,23] and a transition from quasi-2D vortex structure to the σ band superfluid dominated (2D-like) one occurs. As presented in Fig. 7, we apply the 2D VG scaling on these data. Surprisingly, this attempt also fails, 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.[15,16]

The most reasonable explanation for this anomaly is that the supercurrent contributed from the π bands is much easier to be suppressed by magnetic field than that of the σ bands since the gap in the π band is several times smaller than that of the σ band. In a high magnetic field around 6 T, a novel state with the coexistence of the quasiparticles from the π band and the vortices constructed mainly by the residual superfluid from the σ band exists. It is these π band quasiparticles that diminish the long range phase coherence of superconducting phase leading to a finite dissipation. Once the long range superconducting phase coherence is destroyed by the proliferation of large amount of these π band quasiparticles, the 3D or quasi-2D VG scaling are certainly inapplicable. Such a mixed state is obviously difficult to be simply described by any known scaling theory. Recently, the STM work shows that the quasiparticles of the π bands disperse over all of the superconductor both within and outside the vortex cores[24], strongly supporting our argument. This is the very basis for the non-vanished vortex dissipation at a high field in the zero temperature limit found recently on MgB_2 thin films.[22]

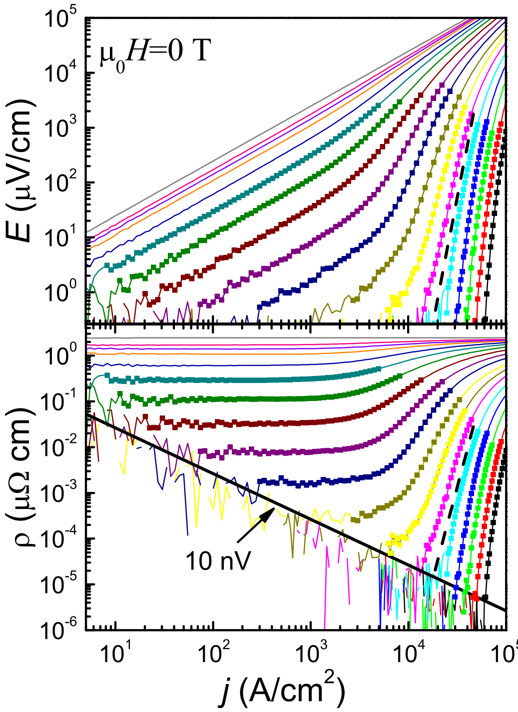

FIG. 8: (color online) (a) E-j data at various temperatures from 39.7 K to 41 K for $\mu_0 H = 0$ T, the symbols denote the region where the data are scaled (from 39.70 K to 40.30 K with an interval of 0.05 K). Temperature of the isotherms increases from bottom to top. The dashed line shows the position of $T_{\rm g}$, and the symbols denote the segments which can be well scaled according to the quasi-2D VG theory. The thin solid lines are also the measured data which locate 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.

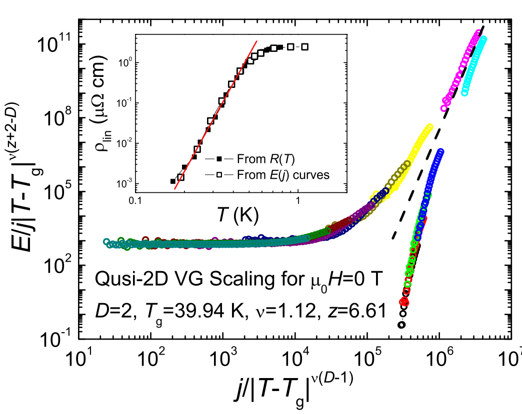

FIG. 9: (color online) Quasi-2D VG Scaling of the data measured at 0 T. The inset shows the good linearity of the temperature dependence of the linear resistivity.

C. Self-field effect for μ_0H = 0 T

For a 2D layered superconductor in zero-field, the above mentioned BKT transition may exist and be reflected in the I-V characteristics[17]. In the present MgB_2 samples, we cannot see any evidence of this transition, consistent with the quasi-2D (instead of 2D) configuration of the vortex matter in this system in low field region. Moreover, both the E-j curves and the ρ-j curves are similar to the situation of $\mu_0 H = 1$ T (as presented in Fig. 8). 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 the self-generated vortices, it might be interesting to look at whether the quasi-2D VG model applies here.

Just like the data treatment in Sec. (A), we plot $\rho_{\rm lin}$ versus $(T - T_{\rm g})$ in double logarithmic scale and then determine the exponent in Eq. 2 (as shown by the inset of Fig. 9). A quasi-2D scaling was obtained and the parameters are $T_{\rm g} = 39.94$ K, $\nu = 1.12$, and $z = 6.61$, as presented in Fig. 9. Using the parameters determined here one finds a self-consistency with the value of $\nu(z+2-D)$ as determined in fitting the linear resistivity (Eq. 2). It has been proved that the current and the magnetic field have analogous effects in suppressing the superconductivity and generating the quarsiparticles in conventional superconductors.[25] Similarly, the current induced self-field may lead to similar effect in the vortex state as in applying a magnetic field. Nonetheless, the good agreement of this simple scaling law with the zero-field data is interesting and worth to be studied in detail. Moreover, the values of ν and z for zero field are very close to that of $\mu_0 H = 1$, 3 T, indicating the similar physics of vortex dynamics at low fields.

V. SUMMARY

We have measured I-V curves on high-quality MgB_2 films at various magnetic fields and temperatures. At low fields below about $\mu_0 H = 5$ T, the curves can be well scaled according to the quasi-2D VG theory instead of the 3D model, in good agreement with the multi-band superconductivity of MgB_2 contributed from the strong 2D σ bands and weak 3D π bands. At the fields above $\mu_0 H = 5$ T, all the curves cannot be scaled by any VG scaling laws accompanied by the disappearance of zero-resistance state. Combining the result from tunneling experiments, a novel vortex state is then suggested, namely, the vortices by the superfluid from the σ bands move in the background of plenty of quasiparticles from π bands.

VI. ACKNOWLEDGMENTS

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