Vortex characteristics in a superconducting $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ thin film

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Current versus voltage (I-V) measurements of an epitaxial superconducting $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ thin film have been made in magnetic fields parallel to its c axis. The curvature variations of the I-V isotherms have been analyzed using both two-dimensional (2D) and quasi-2D scaling laws. The temperature dependence of the vortex glass transition line is presented and confirmed the quasi-2D characteristics of the vortex matter in the Bi-2201 material. A phenomenological driving force relation has been derived.

$Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (Bi-2201) is an interesting high-T_c superconductor (HTSC) as its structure is the simplest in the series of the BiSrCaCuO (BSCCO) materials (one CuO_2 plane per half-unit-cell) and manifests highly anisotropic properties (quasi-2D). Although this compound is probably not of immediate practical use, its low T_c and low upper critical magnetic field values are very convenient for studying its superconductivity and understanding the properties of the CuO_2 based superconductors. As each CuO_2 layer of the Bi-2201 is separated from adjacent CuO_2 layers by SrO and BiO insulating layers, the superconductor can only manifest bulk superconductivity through proximity effects and Josephson couplings[1–3] which are affected by the values of field and current. The first studies of field induced vortex decoupling between two-dimensional (2D) superconducting layers were carried on low temperature superconducting thin films,[4] showing also the influence of the current.[4,5] Although the superconductors coupling was essentially of magnetic origin through an insulating buffer layer, its physical interpretation is of great interest to interpret the couplings of the CuO_2 layers at the nanoscopic level in the high-T_c material. In a given magnetic field, the interlayer vortex couplings can be thermally destroyed above a certain temperature. At low temperature, pancake vortices can be coupled from layer to layer resulting in flux lines through the superconducting layers forming a solid vortex lattice. At higher temperature, the solid vortex lattice can melt into a vortex liquid or even a vortex gas, as suggested by several authors.[1–3,6–19] In this article, we study the I-V isotherms of a Bi-2201 thin film and find that the determination of the $T_g(H)$ from I-V curves may be hindered by a large current, thus leading to a lowered T_g value. The driving force provided by the Lorentz force caused by an applied current, a magnetic field and temperature is discussed.

The epitaxial Bi-2201 thin film is nearly optimally doped ($x\rightarrow 0.4$).[12] The x-ray diffraction pattern shows that the film is c-axis oriented without a secondary phase. The thickness of the film is about 500 nm. This film is patterned into a bridge with a patterning rectangular size 100 μm wide and 1000 μm long with voltage pick up electrodes separated by about 210 μm around the center of the bridge. The electrodes, larger than 1 mm^2 each, are made by sputtering silver. Pt wires are bonded by silver epoxy on the electrodes, and the Bi-2201 thin film is baked in a furnace at 350°C in an oxygen atmosphere for 24 h. A Keithley 182 nanovoltmeter and a Keithley 220 current source are used. Pulsed current is applied for I-V measurements and the sample temperature has been checked not to be influenced by current induced thermal effects. Magnetic fields are applied parallel to the c axis. The temperature stability is better than 0.1 K during the I-V isotherm measurements.

The I-V isotherms, in a magnetic field of 1.0 T, between 5 to 28 K with temperature intervals of 1 K, are given in Fig. 1(a). The isotherms show positive curvatures for the higher temperatures, while they show negative curvatures for the lower temperatures. Figure 1(b) shows the I-V isotherms in a magnetic field of 0.1 T from 5 K to 28 K with the same 1 K

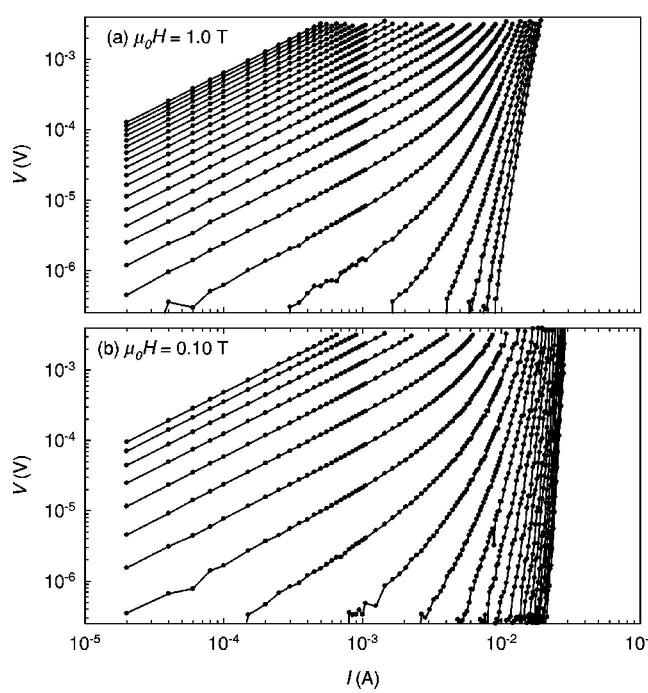

FIG. 1. (a) I-V isotherms in a magnetic field of 1.0 T, temperature range 5 to 28 K, with temperature intervals of 1 K. (b) I-V isotherms in a magnetic field of 0.10 T , temperature range 5 to 28 K with temperature intervals of 1 K.

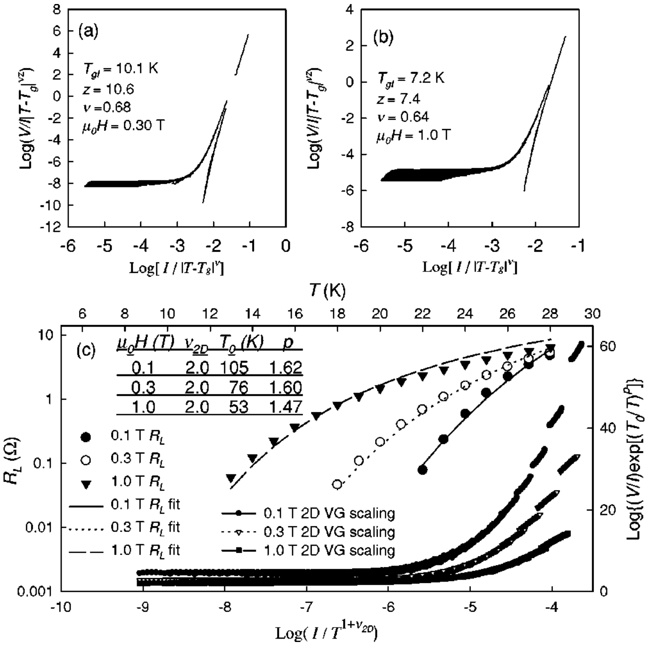

FIG. 2. (a) and (b) Quasi-2D VG scaling curves for 0.30 T and 1.0 T magnetic fields, respectively. (c) 2D VG scaling curves for isotherms in 0.10, 0.30, and 1.0 T magnetic fields with the corresponding R_L data and data fits. All the fitting parameters are listed in the corresponding figures.

temperature intervals. No negative curvature isotherm can be found for this magnetic field. One of the interesting questions is as follows: can a large current, in low fields and low temperature, cause the disappearance of the negative curvatures in the highly quasi-2D system?

Considering the data, the curvature of each isotherm can be approximated by the non-linear expression $\log V(I)=a_0+a_1\log I+a_2\log^2 I$, where a_0, a_1, and a_2 are regression parameters. This approach gives a corresponding transition temperature T_{gI} for $a_2=0$. According to the VG theory[13,14] at the VG transition temperature T_g, the I-V isotherm can be characterized by a power law:

$$V\propto I^{(z+1)/(D-1)}, \tag{1}$$

where z is a dynamic exponent and D is the dimensional number, $D=2$ for quasi-2D vortices. We extract z from the a_1 coefficient corresponding to the curve with $a_2=0$ and $T=T_{gI}$. For temperatures different from T_{gI}, the quasi-2D $(D=2)$ scaling law gives the relation

$$(V/I)/|T-T_{gI}|^{\nu z}=\mathcal{E}_{\pm}(I/|T-T_{gI}|^{\nu}), \tag{2}$$

where ν is a static exponent, and $\mathcal{E}_{+}(x)$ and $\mathcal{E}_{-}(x)$ are scaling functions for the data at temperatures above and below T_{gI}. These scaling relations lead to a collapse of the I-V isotherms onto two simple universal curves as shown in Figs. 2(a) and 2(b) for a 0.3 T and 1.0 T magnetic fields, where ν is determined by a best fit of Eq. (2). All our results are consistent with this two branch scaling of the data for magnetic fields above 0.2 T , but fail to do so for magnetic field below 0.2 T .

In the VG theory, the linear resistance should vanish as $R_L\propto(T-T_g)^{\nu(z+2-D)}$ when approaching T_g. Therefore we have the relation

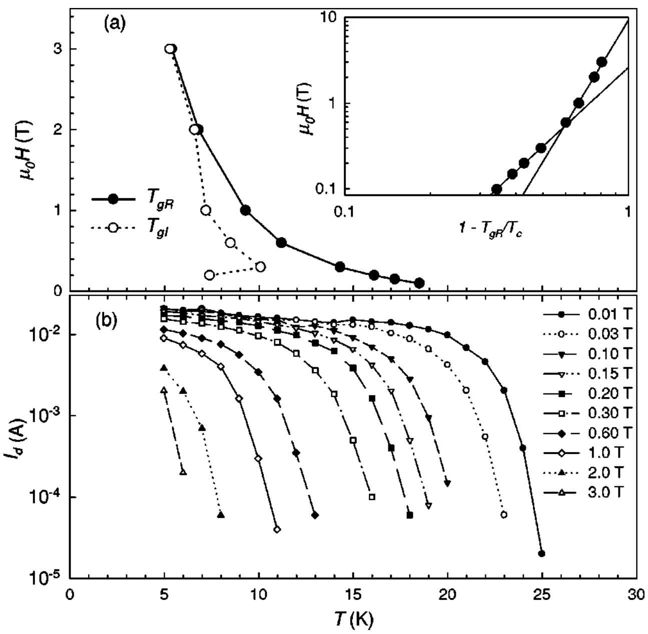

FIG. 3. (a) H-T phase diagram. T_{gR} is derived from Eq. (3). T_{gI} is derived from the analyses of the isotherm curvatures. Inset: H phase diagram as function of $(1-T/T_c)$. (b) Temperature dependent of the decoupling current for different magnetic fields.

$$\partial T/\partial \ln R_L\propto(T-T_g)/\nu(z+2-D), \tag{3}$$

characterized as a straight line with an intercept T_{gR} on the T axis ($\partial T/\partial \ln R_L=0$). We find that the T_{gR} values only coincide with T_{gI} for magnetic fields of 2.0 and 3.0 T as shown in Fig. 3(a), where T_{gI} are shown as open circles and T_{gR} as solid circles. Note that the deviation $\delta T_g=T_{gR}-T_{gI}$ increases with decreasing magnetic field. T_{gI} show a reentrant curve for magnetic fields lower than 0.3 T and, for magnetic field lower than 0.2 T , δT_g becomes rather large: $\delta T_g\approx T_{gR}$.

For a purely 2D system, the VG phase is not expected at finite temperature, but only at $T_g=0$ K, as given by the 2D VG scaling law.[18,19] According to this 2D scaling, the characteristic 2D current at which nonlinearity sets in should scale as

$$I_{nl}\propto T/\xi_{2\mathrm{D}}\propto T^{1+\nu_{2\mathrm{D}}}, \tag{4}$$

where $\xi_{2\mathrm{D}}$ is a 2D VG correlation length and ν_{2D} is the correlation-length exponent with a value around 2. Defining the I_{nl} by that value of I where $\partial\log V/\partial\log I=1.1$, we can derive the $\nu_{2\mathrm{D}}$ from Eq. (4) which gives $\nu_{2\mathrm{D}}\approx 2$ for fields above 0.3 T. When the magnetic field is reduced below 0.3 T, we observe a gradual increase of the $\nu_{2\mathrm{D}}$ value with decreasing magnetic field.

According to the 2D VG theory, the linear resistivity R_L is given by

$$R_L\propto \exp[-(T_0/T)^p], \tag{5}$$

where T_0 is a characteristic temperature, and $p>0$. Dekker *et al.*[18] suggested the 2D VG scaling form

$$(V/I)\exp[(T_0/T)^p]=\mathcal{G}(I/T^{1+\nu_{2\mathrm{D}}}), \tag{6}$$

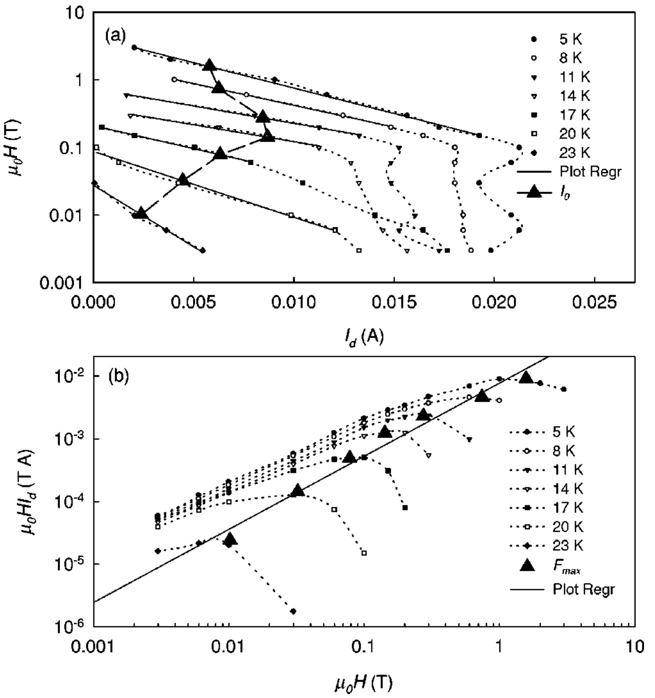

FIG. 4. (a) A $H(I_d)$ plot for different temperatures with 3 K temperature intervals. The dotted and dashed lines are guides to the eye, and the solid lines are linear fits. (b) Corresponding characteristic force as a function of magnetic field in (a). The dotted lines are guides to the eye and the solid line is the $F_{\max}$ fit whose slope is approximately 1.2.

where $\mathcal{G}$ is the 2D VG scaling function. This 2D scaling form allows I-V curves in a 2D system to collapse onto a universal curve. In Fig. 2(c), taking $\nu_{2D}=2$ for fields above 0.1 T (this value is almost correct for fields above 0.3 T), we show the 2D VG scaling curves corresponding to Eq. (6) together with the data and resistance (R_L) fits corresponding to Eq. (5). Note that the scaling curves are consistent with the 2D VG theoretical prediction. The 2D VG condition is of course very strict; the small deviations of the scaling curves which can be observed [see Fig. 2(c)] are probably due to a quasi-2D state very close to a purely 2D system with free 2D vortices.[9–12] These free 2D vortices can be produced by a large Lorentz force which can easily induce interlay vortex decoupling in the pancake vortex system. In this case, the critical current (which begins to induce a small detectable voltage) can be defined as the decoupling current.

Figure 3(b) shows the temperature dependence of the critical current $I_d(T)$ [for clarity, we omit several $I_d(T)$ curves at low fields] with a voltage criterion: $\sim 2\times 10^{-7}$ V. The transformation of the Fig. 3(b) data into the corresponding $H(I_d)$ isotherms with 3 K temperature intervals is given in Fig. 4(a) in a log-linear scale. For high values of the current, both $I_d(T)$ and $H(I_d)$ show irregular shapes in low fields. For small currents, the $H(I_d)$ isotherms can be approximated by the relation $H(I_d)\approx H_0 \exp(-I_d/I_0)$ shown as solid lines, where I_0 is a temperature dependent characteristic current, and H_0 corresponds to the zero current field value. Figure 4(b) shows the characteristic force (per unit length) $F=\mu_0 H I_d$ as function of magnetic field. In the low field regime, which corresponds to the high current part of the $H(I_d)$ curves, the force F shows an approximately linear relation with respect to H in log-log scale; the slopes are approximately equal to 1, suggesting that the forces are nearly current independent in the low field regime. Comparing the linear dependence in Fig. 4(a) and the data of Fig. 4(b), we have $F=\mu_0 H(I_d)I_d \approx \mu_0 H_0 I_d \exp(-I_d/I_0)$, so that the maximum forces, $F_{\max}\approx \mu_0 H_0 I_0 \exp(-1)$, can be obtained and are shown in Fig. 4(b) as solid upward triangles, with a solid line fit.

Note that the irregular $H(I_d)$ curves in the high current part of Fig. 4(a) are well separated from the $H(I_0)$ data points giving the maximum force, suggesting that the irregular $H(I_d)$ curves have no direct relation to the $F_{\max}$. The maximum value, I_0, corresponds to a crossover of the magnetic field around 0.2 T at a temperature around 14 K as shown in Fig. 4(a). This crossover field coincides with the reentrant field for T_{gI}, Fig. 3(a), suggesting different vortex coupling mechanisms above and below this magnetic field value. We notice that the irregular parts of $I_d(T)$ and $H(I_d)$ are limited to magnetic fields lower than 0.15 T which is very close to the I_0 crossover field, also suggesting two different behaviors. For high magnetic fields, highly 2D characteristics are expected, whereas at low magnetic fields, the vortex interactions are reduced. The vortices then go into a diluted vortex state and in a large current background do not hold steadily together, thus being induced in interlayer decouplings. This is similar to a DC transformer effect as observed in magnetically coupled low temperature superconducting thin films where the decoupling can be either due to the magnetic field[4] or to the current.[4,5]

Experimentally, the current must pass through current contacts which are fixed on the thin film surface, leading to an inhomogenous current distribution. This inhomogeneity can be reduced with large surface current contacts well separated by a long and narrow bridge. The crystal structure of Bi-2201 is built up by insulating double BiO layers having bulk superconductivity through the Josephson effect. Josephson effect breaks down once the current becomes larger than a critical value resulting in heating effects around the current contacts. Irregular $I_d(T)$ and $H(I_d)$ curves could thus be induced by large currents passing in the c-direction through the current contacts, leading to an avalanche of the interlayer vortex decoupling. The free 2D vortices produced by decoupling explain the 2D VG scaling curves as shown in Fig. 2(c). The T_{gI} values shall therefore be marred by artefacts for large applied currents. The coincidence of the T_{gI} and T_{gR} values at high magnetic fields is an indication that all the T_g values can be determined from T_{gR}.

The inset of Fig. 3(a) shows the VG phase transition curve H as a function of $(1-T_{gR}/T_c)$, where $T_c=28.2$ K is the mean field transition temperature at zero magnetic field.[12] Fitting the relation of $H\sim(1-T_{gR}/T_c)^n$, where n is a characteristic exponent, we find that the vortex matter can be divided into two regions, one related to low fields where the slope of the logarithmic fit gives $n=3.0\pm 0.1$, while the other is related to the high fields with $n=5.5\pm 0.3$ which coincides with the result of the irreversibility line of the Bi-2201 single crystal reported recently.[20] The crossover magnetic field is around 0.6 T. The first slope indicates that the vortex matter is in a quasi-2D state present with interlayer vortex interactions,[21–24] while the other suggests that the vortices are nearly uncoupled in the *c*-direction as described by a single vortex regime,[1,13]

In summary, the study suggests that the vortex matter of Bi-2201 thin film is a highly quasi-2D system which shows quasi-2D characteristics for magnetic field lower than 0.6 T, and can be in a completely uncoupled single vortex regime ($n=6$) above that field. We find that the determination of the $T_g(H)$ from a I-V curves may be hindered by a large current, thus leading to a lowered T_g value. From the experimental data, a phenomenological charateristic force relation has been derived: $F\approx\mu_0 H_0 I_d \exp(-I_d/I_0)$ with $I_d \approx I_0 \log(H_0/H)$.

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