Deviations from plastic barriers in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ thin films

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Resistive transitions of an epitaxial Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ thin film were measured in various magnetic fields ($\mathbf{H} \parallel \mathbf{c}$), ranging from 0 to 22.0 T. Rounded curvatures of low resistivity tails are observed in Arrhenius plot and considered to relate to deviations from plastic barriers. In order to characterize these deviations, an empirical barrier form is developed, which is found to be in good agreement with experimental data and coincide with the plastic barrier form in a limited magnetic field range. Using the plastic barrier predictions and the empirical barrier form, we successfully explain the observed deviations.

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One of the most intriguing features of high $T_c$ superconductors (HTSCs) is the remarkable broadening of resistive transitions in applied magnetic fields. The broadening is related to thermal barriers (thermal activation energies) for vortex motion. In general, the vortex motion can be divided into three characteristic regimes. In the high temperature regime where the barrier $U_0 \leq T$, resistivity is given by flux flow resistivity $\rho \propto B/H_c^2$. In the intermediate temperature regime, flux motion occurs through thermally assisted flux flow (TAFF), where flux lines are weakly pinned in the vortex liquid with $U_0 \gg T$, and resistivity $\rho \propto \exp(-U_0/T)$, where $U_0$ is independent of the current density $j$ for $j \to 0$. In the low temperature regime, the form $\rho \propto \exp(-U_0/T)$ remains valid for the resistivity analysis with $U_0(j)$ growing unlimitedly for $j \to 0$, thus leading to $\rho \to 0$.

Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi-2212) is a strongly anisotropic superconductor with a layered crystalline structure. The corresponding vortex matter is highly two-dimensional (2D) in high magnetic fields, and three-dimensional (3D) in low magnetic fields. The study of the activation energy of Bi-2212 is very interesting, as its TAFF regime is very broad and gives the necessary knowledge for understanding the vortex characteristics in HTSCs. Generally, resistivity in the TAFF regime is of resistive transitions in applied magnetic fields. The broadening is related to thermal barriers (thermal activation energies) for vortex motion. In general, the vortex motion can be divided into three characteristic regimes. In the high temperature regime where the barrier $U_0 \leq T$, resistivity is given by flux flow resistivity $\rho \propto B/H_c^2$. In the intermediate temperature regime, flux motion occurs through thermally assisted flux flow (TAFF), where flux lines are weakly pinned in the vortex liquid with $U_0 \gg T$, and resistivity $\rho \propto \exp(-U_0/T)$, where $U_0$ is independent of the current density $j$ for $j \to 0$. In the low temperature regime, the form $\rho \propto \exp(-U_0/T)$ remains valid for the resistivity analysis with $U_0(j)$ growing unlimitedly for $j \to 0$, thus leading to $\rho \to 0$.

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In this paper, we report measurements of resistive transitions of a Bi-2212 thin film in magnetic fields parallel...
Epitaxial Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ thin films with a thickness of 210 ± $\mu$m in the most range for the measurement [8].

The studied thin films are highly c-axis oriented and epitaxial. We find that this empirical form coincides with the plastic barrier form in a limited magnetic field range. By using this new expression, we successfully explain the observed deviations.

FIG. 1: The Arrhenius plot of the Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ thin film. From left to right: $\mu_0 H = 0.0$, 0.0037, 0.0052, 0.0070, 0.0089 0.013, 0.021, 0.030, 0.050, 0.078, 0.113, 0.157, 0.302, 0.604, 1.0, 2.0, 3.0, 5.0, 8.0, 12.0, 15.0, 18.0, 22.0 T. The dashed lines are linear regressions of the data in the range $10^{-4} \rho_n \leq \rho \leq 10^{-2} \rho_n$. The inset is the $\rho(T, H = 0)$ curve.

FIG. 2: Magnetic field dependence of $U_0$ in both of the double log scale and the double linear scale (inset). The solid lines are plot regressions of $U_0$ for two different field regimes.

These values shall be close to the precise characteristic field values of the sample in reality and give very close information about the vortex matter.

Figure 2 shows $U_0(H)$ data. The linear regressions of $U_0(H)$ in the plot suggest a power law dependence $U_0 \propto H^{-\alpha}$ with $\alpha \approx 0.258$ for $\mu_0 H \leq 0.113$ T, and $\alpha \approx 0.490$ for $\mu_0 H \geq 0.157$ T. The second $\alpha$ value consists with the plastic barrier form and the results determined in Refs. [8, 9]. However, rounded curvatures in the low resistivity portions are observed in the Arrhenius plot for $\mu_0 H < 0.021$ T and $\mu_0 H > 1.0$ T, which are apparently not described by the plastic barrier form. Figure 2 shows the $\ln \rho_0(U_0)$ relation in both linear-linear and log-log scales. Note that $\ln \rho_0(U_0)$ is approximately linear for $1190 < U_0 < 5620$ K corresponding to the field regime of $0.021 \leq \mu_0 H \leq 1.0$ T, where the regressions in the Arrhenius plots as shown in Fig. 1 are also linear, so that the determinations of $\ln \rho_0(U_0)$ are quite accurate through the regime, and can be assuredly used to deduce some important information as discussed below.

Considering the fact that many authors suggested $U_0 \propto (1 - t)^\beta$ with $\beta = 1$ in Refs. [4, 6, 9, 11, 14, 15], $\beta = 1.5$ in Refs. [4, 8, 10, 11, 14, 15], $\beta = 2$ in Refs. [4, 11, 14, 15], and the $\beta$ value selected from 1.5 to 2.4 in Ref. [16], we start by assuming that $\rho = \rho_0 f \exp[-U(T, H)/T]$, where $\rho_0 f$ is constant, $U(T, H) = g(H)(T)$, $g$ is the magnetic field dependence, $f = (1 - t)^\beta$, and $\beta$ accounts for the non-linearity in the Arrhenius plot. Using the progression $(1 - t)^\beta = 1 - \beta t + \beta(\beta - 1)t^2/2! - \beta(\beta - 1)(\beta - 2)t^3/3! + \ldots$, we obtain $\ln \rho \approx (\ln \rho_0 + g\beta/T_c) - (g/T)[1 + \beta(\beta - 1)t^2/2! - \beta(\beta - 1)(\beta - 2)t^3/3! + \ldots]$, where the term $(\ln \rho_0 + g\beta/T_c) \approx \ln \rho_0$ is temperature independent. With $\beta = 1$, we have $\ln \rho_0 \approx \ln \rho_0 + U_0/T_c$ as observed in the linear part of Fig. 1 for $1190 < U_0 < 5620$ K (denoted by arrows), where $U_0 = g$. Here, the linear ln $\rho_0(U_0)$ portion corresponds to the field range of 0.021 ≤ $\mu_0 H$ ≤ 1.0 T. By linearly extrapolating ln $\rho_0(U_0)$ to $U_0 = 0$, we find that $\rho_0 f \approx 69.7 \mu\Omega cm$, and $T_c \approx 83.1$ K is the approximation of the inverse value of the slope in the double linear scale. Assuming $\beta = \text{const}$, a linear $\ln \rho_0(U_0)$ relation will be found. Obviously, $\beta = \text{const}$ (including $\beta = 1$).
FIG. 3: $\ln \rho(U_0)$ data in both of the linear-linear scale and the log-log scale (inset). The dashed lines represent the plot linear regressions for $1190 < U_0 < 5620$ K (as denoted by the arrows).

FIG. 4: (a) The different symbols give $-\partial \ln \rho / \partial T^{-1}$ data in several magnetic fields as denoted by corresponding symbols. The dotted line is the flux flow boundary determined in (b). (b) The solid lines present $U(T, H) \approx T \ln(\rho_0 / \rho(T, H))$ data for all the tested magnetic fields. The dotted line is $U = T$ corresponding to the flux flow boundary. (c) The solid lines are $\rho(T, H)$ data for all the fields. The dashed lines in (a), (b), and (c) are regressions using the empirical barrier form with the same $g(H)$ and $\beta(H)$ (see text).

can not account for the nonlinear portions of $\ln \rho_0(U_0)$ curves in the regimes of $U_0 < 1190$ K and $U_0 > 5620$ K. It is interesting to note that if $\beta$ is magnetic field dependent, $f$ becomes magnetic field dependent, and thus a non-linear character is introduced into the $\ln \rho_0(U_0)$ dependence.

Previously, a magnetic field dependent $f$ was proposed by Palstra et al. [6] and Kim et al. [16] by introducing a magnetic field dependent $T_s(H)$ instead of $T_c$ for the barrier scaling. Assuming $T_s = T_c / \beta$, we find $\ln \rho_0 \approx \ln \rho_0^f + g / T_s$ for the similar explanation of the nonlinear $\ln \rho_0(U_0)$. In Bi-2212 thin films, Kucera et al. [7] and Wagner et al. [8] suggested that the barriers should scale according to $U \propto H^{-1/2}(1 - t)$ with a constant $T_c$ in $t$. However, $U(T, H)$ data for the low resistivity portion as mentioned by the authors in Fig. 4 of Ref. [7] do more favor $T_s(H)$ than $T_c$. Fig. 4(a) shows $-\partial \ln \rho(T, H) / \partial T^{-1}$ data with different symbols for different magnetic fields. In the field range $0.021 < \mu_0 H < 1.0$ T (not all shown in the figure for clarity), the data are roughly temperature independent in the TAFF regime, indicating that $U \propto (1 - t)$. Note that $f = 1 - t$ will lead to $-\partial \ln \rho / \partial T^{-1} = U - T \partial U / \partial T = g$, where the $g$ is temperature independent. For $\mu_0 H > 1$ T in the TAFF regime, $-\partial \ln \rho / \partial T^{-1}$ of our Bi-2212 thin film in Fig. 4(a) and Bi-2212 crystals in Ref. [8] are temperature dependent. It seems that similar temperature dependences can also be deduced from high field data in Refs. [7, 8]. These temperature dependences do not support the $f = 1 - t$ argument even by substituting $T_s(H)$ for $T_c$.

For high fields, each $-\partial \ln \rho / \partial T^{-1}$ monotonously decreases with temperature from low temperature to a local minimum. One may take the data around these minima for $U$ simulation in which a constant $\beta$ for which the resistivity data in the range of $10^{-4} \rho_n \leq \rho \leq 10^{-2} \rho_n$ are
used, where $g$ and $\beta$ are free fitting parameters. We also present dashed lines using the same $g(H)$ and $\beta(H)$ for $-\partial \ln \rho(T, H)/\partial T^{-1}$ and $\rho(T, H)$ in Fig. 1(a) and (c), respectively. These regressions are in good agreement with $U(T, H)$, $-\partial \ln \rho(T, H)/\partial T^{-1}$, and $\rho(T, H)$ in the TAF regime.

Figure 5 shows $g(H)$ and $\beta(H)$ data, respectively. From the figure, we can roughly divide the $g$ data into four magnetic field regimes according to the field values that were used in the measurements. We find that both $g(H)$ and $\beta(H)$ have an apparent increase for $\mu_0 H \leq 0.013$ T where $\alpha \approx 0.751$, and $\beta$ increases with decreasing field, indicating a deviation from the plastic barrier model. As mentioned in many articles [1, 2, 3, 4, 5, 12], the binding and unbinding behaviors of 2D vortex-antivortex pairs dominate the low resistivity in the low magnetic field range. Obviously, the 2D behaviors do not relate to the plastic vortex motion. In the range of $0.021 \leq \mu_0 H \leq 1.0$ T, $\beta \approx 1$, $\alpha \approx 0.275$ for $0.021 \leq \mu_0 H \leq 0.113$ T, and $\alpha \approx 0.502$ for $0.157 \leq \mu_0 H \leq 1.0$ T. For $0.021 \leq \mu_0 H \leq 0.113$ T, the intervortex spacing is relatively large and the vortex matter is in a 3D state where the vortex system is very close to or can be in the plastic barrier regime [7, 8]. For $0.157 \leq \mu_0 H \leq 1.0$ T, both $\alpha$ and $\beta$ have the values predicted by the plastic form, indicating that the vortex system is in the plastic barrier regime. Note that the vortex system changes from 3D to 2D at a crossover field $\mu_0 H_c \approx 4\phi_0/\gamma^2d^2$, where $\gamma$ is the anisotropic factor with $50 \leq \gamma \leq 200$ in Bi-2212 [1, 2, 3], $d$ is the interplanar spacing, and $\phi_0$ is the flux quantum. If $0.157 \leq \mu_0 H < \mu_0 H_c$, the vortex system is 3D for the plastic barriers. If $\mu_0 H < \mu_0 H < 1$ T, the system is in a 2D state where it maintains some 3D characteristics allowing plastic barrier behaviors. These 3D characteristics are gradually destroyed by further increasing the magnetic field ($\mu_0 H > 1.0$ T), where $\alpha \approx 0.355$ and $\beta$ increases with $\mu_0 H$ as shown in Fig. 6. For $\mu_0 H > 1.0$ T, the vortex matter gradually crosses over into a highly 2D state where 2D vortices (pancake vortices) are largely overlapped and 2D collective interaction dominates the vortex behaviors; besides, the plastic vortex behavior has to fade away due to a strong interlayer decoupling [1, 2, 3, 4, 5, 12]. In particular, Kucera et al. [7] and Wagner et al. [8] also mentioned deviations of the plastic barriers at high magnetic fields which were suggested to relate to a 3D to 2D transition.

Note that both $U(T, H)$ and $-\partial \ln \rho(T, H)/\partial T^{-1}$ increase with decreasing temperature and deviate from the regressions in low temperature. This implies that the vortex coupling and pinning are enhanced. The deviations corresponding to the curvature differences and the curve separations between experimental data and fittings are a consequence of changes of competitive relations between pinning and depinning, and between coupling (reconnecting) and decoupling (cutting). These changes may gradually drive $U(T, H)$ into the $j$ dependent regime with decreasing temperature for $j \to 0$.

It is easily found that the barrier estimations with the empirical and the plastic barrier forms ($g$ in Fig. 5 and $U_0$ in Fig. 2) have the same order that is just consistent with the plastic barrier prediction for any vortex deformation [3]. In this case, the empirical form coincides with the plastic barrier prediction. The similar barrier relation and values, obtained by AC susceptibility measurements of a similar Bi-2212 thin film for $\mu_0 H \leq 1.0$ T, give a support to the $g(H)$ determination [22].

Note that the increasing $\beta (\beta > 1)$ is a common behavior with increasing 2D feature for $\mu_0 H \leq 0.013$ T and $\mu_0 H > 1.0$ T. This implies that the increasing $\beta$ features, as shown in Fig. 5, give the signs of a crossover from 3D to 2D, which differs on both field sides by its strength. For $H \to 0$, the low resistivity portion is dominated by the 2D behaviors of binding and unbinding of vortex-antivortex pairs. In high field, influences of interlayer decoupling and 2D collective behaviors must be taken into account for increasing $H$.

In summary, based on experimental results, we have developed an empirical barrier form $U \propto H^{-\alpha(H)}(1 - t)^{\beta(H)}$ in Bi-2212 thin films. This expression coincide with the plastic barrier prediction over the magnetic field range $0.021 \leq \mu_0 H \leq 1.0$ T, and can be applied to account for the deviations from plastic barriers in Bi-2212 thin films. Moreover, this model may possibly be used for the analysis of TAF behaviors in other HTSCs.

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