Current-voltage characteristics and vortex dynamics in highly underdoped La$_{2-x}$Sr$_x$CuO$_4$

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Abstract The temperature dependence of the nonlinear current-voltage ($I$-$V$) characteristics in highly underdoped La$_{2-x}$Sr$_x$CuO$_4$ ($x=0.07$ and $0.08$) thick films has been studied in both zero and perpendicular magnetic fields $H$. Power-law behavior of $V(I)$ is found for both $H = 0$ and $H 
eq 0$. The critical current $I_c$ was extracted, and its temperature and magnetic field dependences were studied in detail. The Berezinskii-Kosterlitz-Thouless physics dominates the nonlinear $I$-$V$ near the superconducting transition at $H = 0$, and it continues to contribute up to a characteristic temperature $T_s(H)$. Nonlinear $I$-$V$ persists up to an even higher temperature $T_B(H)$ due to the depinning of vortices.

Keywords nonlinear current-voltage · Berezinskii-Kosterlitz-Thouless · vortexes · cuprates

1 Introduction

In underdoped cuprates, which are layered materials with weak interlayer coupling, studies of paraconductivity have shown a strong 2D character of the superconducting fluctuations [12]. However, the existence of a Berezinskii-Kosterlitz-Thouless (BKT) transition in bulk cuprates has been controversial [3,4,5]. For example, the penetration depth measurements in bulk YBa$_2$Cu$_3$O$_{7-δ}$ found no signatures of the BKT physics [6] or crystals [7], while dc transport measurements suggested BKT-like behavior in bulk samples of several cuprates (see, e.g., Refs. [8,9,10,11]). A recent study of the paraconductivity and the $I$-$V$ characteristics in highly underdoped La$_{2-x}$Sr$_x$CuO$_4$ ($x = 0.07$ and $0.08$) thick films (150 Å CuO$_2$ layers) in zero magnetic field [5] showed that the effective dimensionality of the samples is 2D, and that the thermally-driven transition to the superconducting state is of the BKT type with a large vortex-core energy $μ ≈ 1.4μ_{XY}$ ($μ_{XY} = π/2J_d/2$ is the conventional value that it assumes in the XY model; $J_d$ is the superfluid stiffness). At the BKT transition, $J_s$ jumps from $0$ above $T_{BKT}$ to $2T_{BKT}/π$ at $T_{BKT}$, leading to a change from linear to super-linear behavior in the $I$-$V$ characteristics: $V \propto I^{α(T)}$, where $α(T) (= πJ_s/T + 1)$ jumps from $1$ to $3$. $T_{BKT}$ was determined to be $4.0$ K and $9.7$ K for the $x = 0.07$ and $x = 0.08$ samples, respectively [5]. The presence of inhomogeneities leads to some smearing of the transition, giving rise to finite superfluid stiffness even for $T > T_{BKT}$ [5]. Here we present a detailed study of the evolution of the $I$–$V$ characteristics of the same La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) samples in a perpendicular magnetic field $H$. At small fields, $H$-induced free vortices coexist with BKT-like thermally generated vortex-antivortex pairs [12,13,14]. As $H$ increases, vortex-antivortex pairs break and $H$-induced free vortices proliferate, leading to novel phases of the vortex matter [15,16]. Indeed, in the same underdoped LSCO films, two quantum critical points have been found to associate with boundaries of different vortex phases [17]. In general, both the BKT physics and the physics of vortex matter have been subjects of intensive studies, but they have been mostly treated as two separate topics [14,15,16]. Some efforts have been put forward to treat the BKT physics in a magnetic field and vortex matter physics on the same footing [18,19], though much remains to be understood. The goal of our study is to bridge the BKT physics and the physics of vortex matter.
2 Experiment

The samples were ≈100 nm thick LSCO films with $x = 0.07$ and $x = 0.08$, grown by molecular beam epitaxy. The samples have been described in detail elsewhere [5][20]. The mean-field transition temperature $T_c$ was determined to be 6.5 K and 11.3 K for the $x = 0.07$ and $x = 0.08$ samples, respectively [5]. Standard four-probe I-V measurements were performed up to 9 T ($H \parallel c$-axis). A low-pass pi-filter was used to eliminate current noise that leads to Ohmic tails at low excitations [21]. Great care was taken to exclude Joule heating effects, including (1) a comparison of the I-V measurements using dc current and pulsed current (50 μs pulse width) and (2) a comparison of the $R$ vs. $I$ curve with the $R$ vs. $T$ curve for different $H$.

From the I-V characteristics, the critical current $I_c$ is determined as the intersection of a power-law fit at 100 nV, just above the noise background. At large $H$ where BKT physics is absent, this $I_c$ indicates the onset of depinning in the vortex matter description, similar to previous studies in conventional superconductors [22] and in cuprates [23]. For the zero-field BKT transition, however, the regime for non-linear voltage response is bounded by lower and upper critical currents. Below the lower critical current, the system exhibits Ohmic behavior due to finite-size effects [24]. On the other hand, above the upper critical current, Ohmic behavior occurs from Cooper pair depairing and a return to the normal state [25]. Although our definition of $I_c$ is, strictly speaking, neither of these, $I_c$ as defined here will still be a measure of excitation needed to observe nonlinear I-V in the sample. Most importantly, since similar definitions of $I_c$ have already been used in other studies of I-V characteristics in both $H = 0$ [26] and $H \neq 0$ cases [22][23], using this criterion for $I_c$ becomes a bridge that helps address the crossover regime at small fields where both BKT physics and vortex matter dynamics are relevant.

3 Results and Discussion

From the I-V measurements at $H = 0$ for the $x = 0.07$ and $x = 0.08$ samples, $I_c(T)$ were extracted, as shown in Fig. 1. Near $T_{BBKT}$, $I_c$ decreases exponentially as $T$ increases and disappears when the superfluid stiffness $J_s$ becomes zero and the exponent $\alpha$ becomes 0 (e.g. near 6 K for the $x = 0.07$ sample [5]). The data are best fitted with $I_c = I_0 e^{-T/T_0}$, where $T_0 = 0.27 \pm 0.01$ K and $0.40 \pm 0.01$ K for the $x = 0.07$ and $x = 0.08$, respectively. The strong, exponential dependence of $I_c(T)$ at $H = 0$ is an interesting result and has not been reported to the best of our knowledge.

![Fig. 1 $I_c$ vs. $T$ is plotted on a semi-log scale for the $x = 0.07$ and $x = 0.08$ samples at $H = 0$. $T_{BBKT}$ is marked with arrows. Dashed lines show exponential $I_c = I_0 e^{-T/T_0}$ for both samples, where $T_0 = 0.27 \pm 0.01$ K and $0.40 \pm 0.01$ K for $x = 0.07$ and $x = 0.08$, respectively. Inset: $V(I)$ for the $x = 0.07$ sample in $H = 0.2$ T, plotted on a log-log scale for $T = 4.5$ K, 4.0 K, 3.4 K, 3.2 K, 3.0 K, 2.5 K and 2.0 K (from top to bottom). Solid lines are fits.](image)

The nonlinear $V(I)$ characteristics in $H \neq 0$ have been studied in detail for the $x = 0.07$ sample. Figure 1 inset shows the typical traces of $V(I)$ at 0.2 T for various $T$ from 2.0 K to 4.5 K. Power-law fits $V \propto I^\alpha(T)$ were obtained in the lowest current regime at each $T$, and a change from nonlinear $V(I)$ at low $T$ to linear $V(I)$ at high $T$ was observed. This power-law behavior of $V(I)$ at $H \neq 0$ bears a close resemblance to that at $H = 0$, though the underlying physics is more complicated. First, it could have contributions from the BKT physics[12][13][14][15]. In addition, the presence of a finite $H$ facilitates the formation of the vortices along the field direction and suppresses the vortices in the opposite direction. As $H$ is increased, the density of vortices increases and the BKT physics becomes less relevant [10]. Vortices are pinned as soon as they are formed and a critical force (current) is needed to depin them. Therefore, the vortex matter dynamics also contributes to the power-law behavior of $V(I)$. The role of excitation current changes from breaking apart vortex-antivortex pairs in the BKT scenario to inducing flux creeps (for small $I$) and depinning the vortices (for large $I$) in the vortex matter scenario. We note that we did not observe any exponential $V(I)$, such as that suggested by Kim-Anderson flux creep model [27].

As $H$ increases, $I_c$ at a given $T$ is suppressed, but $I_c(T)$ remains near-exponential (Fig. 2). The fact that $I_c(T)$ does not change abruptly seems to suggest a crossover regime in the $H - T$ phase diagram where the
BKT physics is still important, consistent with magnetometry measurements in Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$ single crystals [13]. Above $\sim 0.4$ T, the curvature of the $I_c(T)$ on the semi-log scale changes its sign, and $I_c(T)$ no longer resembles its zero-field counterpart, suggesting that the effect of BKT physics becomes negligible. Different regimes can be distinguished more clearly from the $I_c(H)$ dependence, as discussed below. Here we note that the observed near-exponential decrease of $I_c(T)$ is consistent with early studies on vortex matter in other cuprates at much higher doping [22,30]. It was attributed to the melting of the vortex lattice [23] or a vortex glass phase with $I_c \propto I_0 \exp[(-(T/T_0)^n)]$, where $n$ depends on the ratio of the electronic mean free path to the superconducting coherence length [28]. Here we suggest that the BKT physics may also need to be taken into account.

Figure 2 shows that $I_c(H)$ at low $T$ exhibits a kink-like feature that separates the low-$H$ regime, where $I_c$ varies relatively slowly with $H$, from the high-$H$ regime, where $I_c$ drops sharply with $H$. This kink-like feature, as well as the nonlinearity of $V(I)$, are suppressed with increasing $T$, and disappear above 4.5 K. Two different regimes of $I_c(H)$ were also observed in some previous studies of conventional superconductors [22,30,31]. In those studies, $I_c$ is independent of $H$ in the low-$H$ regime, and it evolves into a power-law behavior, $I_c \propto H^m$ with $m \sim -1$, in the high-$H$ regime. These observations were interpreted as signatures of individual vortex pinning in the low-$H$ regime and collective pinning in the high-$H$ regime. In Fig. 3 a $I_c \propto H^{-1}$ line, expected from the Larkin-Ovchinnikov (LO) theory of collective pinning [29], is drawn for comparison. In our samples, $I_c$ does tend to saturate at the lowest $H$, consistent with individual vortex pinning, but it decreases much faster in the high-$H$ regime compared to the prediction of the LO theory ($e.g.$, $m \sim -6$ at 2.0 K). The rather sharp drop of $I_c$ at high $H$ indicates that the weak collective pinning picture of the LO theory is not sufficient in our highly underdoped LSCO films.

The onset of the high-$H$ regime is identified as shown in Fig. 2. It is striking that the corresponding crossover fields $H_c(T)$, i.e. crossover temperatures $T_c(H)$, follow closely $T_{R=0}(H)$ (Fig. 1), the temperatures at which the resistance drops to zero. The $T_{R=0}(H)$ line was interpreted as the transition between a pinned vortex solid (Bragg glass) and an unpinned one [17]. Nevertheless, $V(I)$ remains nonlinear up to $T_b(H)$ (the discrete drop and the apparent step in $T_b(H)$ in Fig. 2) are due to the limited resolution of our data; we expect $T_b(H)$ to change smoothly as suggested by the dashed guide line). $T_c(H)$ in Fig. 2 is the temperature below which there are no data available. Therefore, we identify three regimes in the phase diagram. Up to $T_b(H)$, $V(I)$ is nonlinear due to both the BKT physics and the depinning of vortices. Between $T_c(H)$ and $T_b(H)$, the nonlinear $V(I)$ is due to the depinning of vortices and the BKT physics is not relevant. Above $T_b(H)$, $V(I)$ is linear and vortices are no longer pinned.

Finally, since the presence of inhomogeneities leads to finite $J_c$ up to $\sim 6$ K ($> T_{P,BKT} = 4$ K) in $H = 0$ [5], we note that it is reasonable to expect that their effect may be important up to $T_b(H)$, giving rise to nonlinear $V(I)$ over extended $T$ and $H$ ranges. Interestingly, signatures of the BKT physics in a magnetic field have also been observed in strongly disordered conven-
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