Examination of the c-axis resistivity of Bi$_2$Sr$_{2-\delta}$La$_{\delta}$CuO$_{6+\delta}$ in magnetic fields up to 58 T

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We measure the magnetic-field dependence of the c-axis resistivity, $\rho_c(H)$, in a series of Bi$_2$Sr$_{2-\delta}$La$_{\delta}$CuO$_{6+\delta}$ (BSLCO) single crystals for a wide range of doping using pulsed magnetic fields up to 58 T. The behavior of $\rho_c(H)$ is examined in light of the recent determination of the upper critical field $H_{c2}$ for this material using Nernst effect measurements. We find that the peak in $\rho_c(H)$ shows up at a field $H_p$ that is much lower than $H_{c2}$ and there is no discernable feature in $\rho_c(H)$ at $H_{c2}$. Intriguingly, $H_p$ shows a doping dependence similar to that of $T_c$, and there is an approximate relation $k_B T_c \approx \frac{1}{4} B N H_p$. Moreover, we show that the data for the lowest-$T_c$ sample can be used to estimate the pseudogap closing field $H_{pg}$, but the method to estimate $H_{pg}$ proposed by Shibauchi et al. [Phys. Rev. Lett. 86, 5763 (2001)] must be modified to apply to the BSLCO system.

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I. INTRODUCTION

In high-$T_c$ cuprates, the c-axis transport occurs as a tunneling process, and therefore signifies the density of electrons available for the tunneling as well as the tunneling matrix elements. As a result, the c-axis resistivity $\rho_c$ is a useful probe of such features as the pseudogap or the superconducting correlations above $T_c$. On the other hand, there are a number of open questions regarding the interpretation of the magnetic-field $(H)$ dependence of $\rho_c$ below $T_c$, in which the suppression of superconductivity and the subsequent negative magnetoresistance $(MR)$ at higher $H$ defines a peak value of $\rho_c$ at $H_p$. One question is whether the magnetic-field region above $H_p$ can be viewed as the normal state and, if not, how one can determine the upper critical field $H_{c2}$. Another question is whether the $\rho_c(H)$ data can be used to derive a characteristic field for the closing of the pseudogap by the Zeeman splitting.

It was argued by Morozov et al., that $H_p$ separates the two regions in the superconducting state, one dominated by Cooper pair tunneling and the other dominated by quasiparticle tunneling. This proposal has been backed up by more recent argument and it seems indeed likely that $H_p$ signifies a crossover from a phase-coherent regime (where the c-axis transport is dominated by the Cooper pair tunneling) to a phase-incoherent regime. In this sense, if one assumes that the phase coherence is the defining factor for the superconducting state in cuprates, one can identify that $H_p$ is the characteristic field for superconductivity, although it clearly lies below the mean-field $H_{c2}$ which describes the onset of superconducting pair correlations. (Therefore, whether to call the region between $H_p$ and $H_{c2}$ the “normal state” is a matter of semantics; “fully resistive state” might better suit this regime that is so strikingly different from the normal state of BCS superconductors.)

Later, Shibauchi et al. argued that the negative MR data above $H_p$ can be used to estimate the field at which the pseudogap collapses due to the increasing Zeeman energy, calling this field the pseudogap closing field $H_{pg}$. Although their procedure relies on determining the putative intrinsic $\rho_c$ in the absence of the pseudogap and a necessary extrapolation to determine a value for $H_{pg}$, their central assertion is that the negative MR comes from a recovery of the electronic density of states near the Fermi energy $E_F$ that is suppressed in the pseudogap state. The work by Shibauchi et al. was done on Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi-2212) for which the intrinsically high $T_c$ makes the measurements and the analysis inherently difficult; it would be useful to examine $H_{pg}$ in another cuprate that has lower $T_c$ and is thus expected to have lower characteristic magnetic-field scales. From this point of view, the Bi$_2$Sr$_{2-\delta}$La$_{\delta}$CuO$_{6+\delta}$ (BSLCO) system is particularly suitable for examining the behavior of $\rho_c(H)$, because the $T_c$ of this system never exceeds 40 K and one can obtain high-quality single crystal samples for a wide range of hole doping.

Recently, it was shown that the Nernst effect in cuprates is a useful probe of the presence of vortices and, hence, superconducting correlations, from which Wang et al. deduced the pseudogap onset temperature above $T_c$ (Ref. 13) and $H_{c2}$ below $T_c$ (Ref. 14). In particular, recent Nernst effect measurements in magnetic fields up to 45 T make a very good case that the vortex Nernst signal disappears above a well-defined field $H_{c2}^N$ and it is reasonable to consider that $H_{c2}^N$ marks the field where the superconducting pair correlations disappear, i.e., the upper critical field. Therefore, it would be illuminating to compare the information obtained by $\rho_c$ measurements with that obtained by Nernst effect measurements. The BSLCO system is ideal for this purpose as well, because...
detailed Nernst effect measurements have already been performed on BSLCO.\cite{14,15}

In this work, we measure $\rho_c$ of a series of high-quality BSLCO single crystals in pulsed magnetic fields up to 58 T and examine the implication of the observed $\rho_c(H)$ behavior in the context of Nernst effect measurements that were performed on the samples from the same batch. It is found that the doping dependence of $H_p$ essentially tracks that of $T_c$, and, moreover, there is an approximate relation $1.3T_c$ (in Kelvin) $\simeq H_p$ (in Tesla), which suggests that the electronic Zeeman energy at $H_p$ ($\frac{g}{2}\mu_B H_p$) equals the thermal energy $k_B T_c$. Also, our $\rho_c(H)$ data are featureless at $H_{c2}$ ($H_{c2}$ as determined by the Nernst signal), which demonstrates that it is not possible to determine $H_{c2}$ from current state-of-the-art resistivity experiments using pulsed magnetic fields. Furthermore, our data support the definition of a pseudogap closing field $H_{pg}$ which can in principle be deduced from $\rho_c(H)$ behavior; however, we find that the procedure employed by Shibaiuchi et al.\cite{15} is not appropriate to correctly obtain $H_{pg}$.

II. EXPERIMENTS

The $\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$ (BSLCO) crystals used for this study are grown by the floating-zone method\cite{16} and they are the same as the ones used in our recent study of the $\rho_c(H)/\rho_{ab}(H)$ resistivity anisotropy in the fully resistive state.\cite{16} We note that the series of BSLCO samples used in the recent Nernst effect measurements by Wang et al.\cite{13,15,16,17} are obtained from the same batches. In the present study, to corroborate the data for the La-doped samples, we also measure one La-free sample with the composition of $\text{Bi}_{2.13}\text{Sr}_{1.89}\text{CuO}_{6+\delta}$ (denoted “La-free”), which shows zero resistivity at 9.1 K. For all the La-doped samples, we list in Table I the actual La content $x$, the corresponding doping concentration per Cu, $p$, and the zero-resistivity temperature $T_0$, as well as the peak temperature in the $\rho_c(T)$ curves, $T_p$. All the crystals are annealed according to the recipe described in our previous papers to optimize the sharpness of the superconducting transition.

The samples for the $\rho_c$ measurements are prepared by hand-painting ring-shaped current contacts and small circular voltage contacts in the center of the current-contact ring on the opposing $ab$ faces of the crystals.\cite{16} The $\rho_c(H)$ data are measured at fixed temperatures using a high-frequency ($\sim$100 kHz) four-probe technique\cite{18,19,20} during the 15 msec duration of the 58-T pulsed magnetic fields. As always, we pay particular attention to make sure that the data are not adversely affected by eddy-current heating.\cite{18,20} The temperature dependences of $\rho_c$ of the present samples in zero magnetic field are essentially the same as those we reported previously.\cite{15}

III. RESULTS AND DISCUSSIONS

Figure 1 shows the $\rho_c(H)$ curves at various temperatures for all six samples studied. From these data, we determine $H_p(T)$ for all the samples and plot them in Fig. 2(a). Similarly to Bi-2212,\cite{17} $H_p(T)$ of all the samples (except for $p = 0.10$) shows a pronounced upward cur-

| $x$  | 0.23  | 0.39  | 0.49  | 0.66  | 0.84  |
|-----|-------|-------|-------|-------|-------|
| $p$ | 0.18  | 0.16  | 0.14  | 0.12  | 0.10  |
| $T_0$ | 22    | 32    | 28    | 26    | 4     |
| $T_p$ | 25    | 34    | 30    | 28    | 8     |

TABLE I: Actual hole concentrations per Cu, $p$, the zero-resistivity temperature $T_0$, and the peak temperature $T_p$ (which marks the onset of the superconducting transition) for each La concentration $x$. The $p$ values are determined from the empirical relation between $x$ and $p$ obtained in Ref. \cite{13}.
Kelvin) is roughly equal to $H$. Using the right-hand-side axis. Intriguingly, $1.45$ T and with very little extrapolation gives $H$ and $0.18$, which corresponds to the La content of $0.6$, $0.4$, and $0.18$, respectively. In any case, these doping dependences are similar to that of $T_c$. To make a meaningful comparison, we consider the temperature $T_p$, where $\rho_c(T)$ shows a peak, to characterize the crossover between quasiparticle-dominated transport to the Cooper-pair dominated transport, similarly to $H_p$. In other words, $T_p$ is a measure of the onset $T_c$. The doping dependence of $T_p$ is also plotted in Fig. 2(b) using the right-hand-side axis. Intriguingly, $1.3T_p$ (in Kelvin) is roughly equal to $H_p$ (in Tesla), which suggests $k_B T_c \approx \frac{1}{2} g \mu_B H_p$. This means that both the thermal energy at $T_c$ ($k_B T_c$) and the electronic Zeeman energy at $H_p (\frac{1}{2} g \mu_B H_p)$ give the single energy scale required to destroy the phase coherence. A similar relation has also been reported for Bi-2212.

Now we compare our result with the Nernst effect measurements. Wang et al. have measured the Nernst effect in our BSLCO samples at $p = 0.12$, $0.16$, and $0.18$, which corresponds to the La content of $0.6$, $0.4$, and $0.2$, respectively. Their data for $p = 0.16$ extend to $45$ T and with very little extrapolation give $H_{c2}^N$ of $50$ T. This $H_{c2}^N$ is essentially temperature independent at low temperatures. For other dopings, Wang et al. obtained $H_{c2}^N$ values of $65$ and $41$ T for $p = 0.12$ and $0.18$, respectively. In Figs. 1(d) and 1(e), the position of $H_{c2}^N$ is marked by a vertical line. The $H_{c2}$ value determined for $p = 0.12$ is above the range of the present experiment and thus is not shown in Fig. 1(b).] There is no discernible feature in our $\rho_c(H)$ curves at $H_{c2}^N$, implying that the onset of superconducting pair correlations does not noticeably affect $\rho_c$, because $\rho_c$ is dominated by quasiparticle tunneling. Note that the same situation is known for the in-plane resistivity $\rho_{ab}$. Most likely, the extremely strong phase fluctuations in the cuprates play a key role, allowing the full recovery of the normal-state resistivity at a magnetic field smaller than $H_{c2}$. In any case, these data demonstrate that it is impractical or impossible to deduce $H_{c2}$ from resistivity measurements.

Next we examine whether the present data for $\rho_c(H)$ can be used to deduce the pseudogap closing field $H_{pg}$. According to the procedure proposed by Shibauchi et al., one first determines the putative $\rho_c$ in the absence of the pseudogap, $\rho_c^{\alpha}$ by linearly extrapolating the high-temperature part of $\rho_c(T)$ where it shows a metallic behavior (d$\rho_c$/dT > 0). As shown in Fig. 3(a), for our overdoped sample ($p = 0.18$), such an extrapolation gives $\rho_c^{\alpha}$ of about $3 \, \mu\Omega\, cm$ at low temperature. One then calculates $\Delta \rho_c(H) = \rho_c(H) - \rho_c^{\alpha}$ and fits the high-field part of $\Delta \rho_c(H)$ with an empirical formula  

FIG. 2: (a) Temperature dependences of the peak field $H_p$ for various dopings. The lower panel (b) shows the doping dependence of $H_{p0}$ (solid circles) as well as the measured $H_p$ values at $1.4$ K (solid triangle) and $4$ K (solid squares). The doping dependence of $T_p$ (open squares) is also plotted.

FIG. 3: (a) Temperature dependence of $\rho_c$ for $p = 0.18$; the dashed line is an extrapolation of the high-temperature $\rho_c(T)$ to zero temperature, giving the estimate of $\rho_c^{\alpha}$. (b) $\Delta \rho_c(H) = \rho_c(0) + b H^\alpha$ and its extrapolation, following the procedure of Shibauchi et al.
\[ \Delta \rho_c(H) = \Delta \rho_c(0) + bH^n; \] 
extrapolation of this fit to \( \Delta \rho_c = 0 \) gives the estimate of \( H_{pg} \) in the manner of Shibauchi et al. When applied to our \( p = 0.18 \) data, this analysis gives an estimate of \( H_{pg} \) of about 600 T [see Fig. 3(b)], which is almost certainly too high for an overdoped sample and suggests the inapplicability of the procedure proposed by Shibauchi et al. for determining \( H_{pg} \), at least for the BSLCO system. The reason for the inapplicability probably lies in the assumptions used to determine \( \rho_c^p \): as we have shown in our previous paper\(^3\) the “insulating” temperature dependence of \( \rho_c \) comes not only from the pseudogap but also from the charge confinement effect. Because of the existence of the latter, the assumption of a \( T \)-linear \( \rho_c^p \) down to the lowest temperature becomes dubious. Therefore, we claim that any determination of \( H_{pg} \) from resistivity data should not rely on any assumptions about \( \rho_c^p \) or \( \rho_c(H) \).

Incidentally, the \( \rho_c(H) \) data of our La-free sample (whose \( p \) value has been estimated\(^3\) to be 0.17) shows a behavior that is almost saturating at high field even at the lowest temperature. This is probably because this sample has the lowest \( T_c \) (\( T_b = 9.1 \text{ K} \) and \( T_p = 10.2 \text{ K} \)) and accordingly low magnetic field scales. As one can see in Figs. 4(a)-4(e), the high-field \( \rho_c \) is saturating to a value which increases with decreasing temperature, indicating that the true \( \rho_c^p \) presents an “insulating” behavior \( (d\rho_c/dT < 0) \) even when the pseudogap is closed by the magnetic field. Also, one can crudely estimate \( H_{pg} \) from this near-saturation as shown by the arrows in Figs. 4(a)-4(d). [The solid straight lines are the fits to the region where we consider the rapid decrease of \( \rho_c \) is finished; these lines at low temperatures are slightly sloped, which may mean that there is some intrinsic negative MR in the absence of the pseudogap or mean that the pseudogap is not yet fully closed.] Intriguingly, while there is no negative MR (and thus there appears to be no pseudogap) at 40 K, by 30 K the pseudogap opens and the \( H_{pg} \) suggested by the data is already higher than 30 T.

It is useful to note that if one were to apply the same method of extracting \( H_{pg} \) that we demonstrated for the La-free sample to the data for \( p = 0.18 \), the estimated \( H_{pg} \) would be larger than 60 T, because there is no saturation below 60 T [see Fig. 1(e)]. This might seem rather odd, since the doping level in the La-free sample is \( p = 0.17 \), which is slightly more underdoped than \( p = 0.18 \), and yet the estimated \( H_{pg} \) for the La-free sample would be smaller than that for \( p = 0.18 \); normally, one would expect \( H_{pg} \) to be larger in more underdoped samples. However, one must take into account the fact that the \( T_c \) of the La-free samples is significantly lower than that of the La-doped samples at the same doping level, which strongly suggests that there exists some additional pair-breaking mechanism in the La-free samples. Remember, as has been argued by Shibauchi et al.\(^3\) \( H_{pg} \) is likely to reflect the spin singlet formation; thus, if there is an additional pair-breaking mechanism in the La-free sample, it is rather natural for \( H_{pg} \) to become accordingly small. A recent work by Eisaki et al.\(^24\) reported a clear relationship between \( T_c \) and the cation disorder in the Sr site (A-site disorder) for the single-layer Bi-based cuprates, so that the strong A-site disorder caused by excess Bi in the La-free samples is likely to be responsible for the strong pair breaking.

**IV. CONCLUSIONS**

We measure and examine the behavior of \( \rho_c(H) \) for a series of BSLCO samples in magnetic fields up to 58 T. The salient points are: (i) The peak field in the
zero-temperature limit, \( H_{p0} \), shows a dome-shaped doping dependence and is related to \( T_c \) via the relation \( k_B T_c \propto g \mu_B H_{p0} \), which is understandable if both \( T_c \) and \( H_{p0} \) are determined by the onset of phase coherence. (ii) There is no feature in the \( \rho_c(H) \) data at the upper critical field determined by the Nernst effect, \( H^N_{c2} \). (iii) The pseudogap closing field \( H_{pg} \) can be determined by \( \rho_c(H) \) in overdoped samples with low \( T_c \), but one should not employ an extrapolation of high-temperature \( \rho_c(T) \) to low temperatures in its determination, because one cannot a priori know the temperature dependence of the \( c \)-axis resistivity in the absence of the pseudogap.

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