Systematic Evolution of the Magnetotransport Properties of Bi$_2$Sr$_{2-x}$La$_x$CuO$_6$ with Carrier Concentration

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We report that it is possible to obtain a series of high-quality crystals of Bi$_2$Sr$_{2-x}$La$_x$CuO$_6$, of which the transport properties have been believed to be “dirtier” than those of other cuprates. In our crystals, the normal-state transport properties display behaviors which are in good accord with other cuprates; for example, in the underdoped region the in-plane resistivity $\rho_{ab}$ shows the pseudogap feature and in the overdoped region the $T$ dependence of $\rho_{ab}$ changes to $T^n$ with $n > 1$. The characteristic temperatures of the pseudogap deduced from the resistivity and the Hall coefficient data are presented.

PACS numbers: 74.25.Fy, 74.62.Dh, 74.72.Hs

A useful way to elucidate the origin of the peculiar normal-state properties of high-$T_c$ cuprates is to study their systematic evolution upon changing the carrier concentration. Bi$_2$Sr$_2$CuO$_6$ (Bi-2201) system is an attractive candidate for such studies, because the carrier concentration can be widely changed by partially replacing Sr with La (to underdope) or Bi with Pb (to overdope). Moreover, this system allows us to study the normal-state in a wider temperature range, because the optimum $T_c$ (achieved in Bi$_2$Sr$_{2-x}$La$_x$CuO$_6$ with $x \approx 0.4$) is about 30 K, which is lower than the optimum $T_c$ of La$_{2-x}$Sr$_x$CuO$_4$. However, a number of problems have been known so far for Bi-2201 crystals: (i) the transport properties of Bi-2201 are quite non-reproducible even among crystals of nominally the same composition; (ii) the residual resistivity of $\rho_{ab}$ is usually large (the smallest value reported to date is 70 $\mu\Omega$cm), as opposed to other systems where the residual resistivity in high-quality crystals is negligibly small; and (iii) the temperature
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Fig. 1. $T$ dependence of (a) $\rho_{ab}$ and (b) $R_H$ of the BSLCO crystals with various $x$. Note that the extrapolated residual resistivity of $x=0.44$ sample is 25 $\mu\Omega\text{cm}$, which is the smallest value to date for Bi-2201 or BSLCO.

dependence of the Hall coefficient $R_H$ is weak and thus the cotangent of the Hall angle $\theta_H$ does not obey the $T^2$ law, while $\cot \theta_H \sim T^2$ has been almost universally observed in other cuprates.

Here we report the transport properties of a series of high-quality Bi-2201 crystals, in which the normal-state transport properties display behaviors that are in good accord with other cuprates. We show data on $\rho_{ab}(T)$ and $R_H(T)$ for a wide range of carrier concentrations, from which we extract the characteristic temperatures for the pseudogap.

The single crystals of Bi$_2$Sr$_{2-x}$La$_x$CuO$_6$ (BSLCO) are grown using a floating-zone technique in 1 atm of flowing oxygen. Note that pure Bi-2201 is an overdoped system, and increasing La doping brings the system from overdoped region to underdoped region. The actual La concentrations in the crystals are determined with the ICP analysis. Here we report crystals
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Fig. 2. Plots of cot $\theta_H$ vs $T^\alpha$ for (a) $x=0.74$, (b) $x=0.66$, and (c) $x=0.44$.

with $x=0.24$, 0.30, 0.44, 0.57, 0.66, and 0.74, for which the zero-resistance $T_c$ is 24, 30, 33.3, 29.2, 21.4 K, and 17.3 K, respectively. The optimum doping is achieved with $x \approx 0.4$, which is consistent with previous reports on BSLCO. 1, 2 The optimum zero-resistance $T_c$ of 33 K (which is in agreement with the Meissner-onset $T_c$) is, to our knowledge, the highest value ever reported for Bi-2201 or BSLCO system.

Figure 1(a) shows the $T$ dependence of $\rho_{ab}$ for the six $x$ values in zero field. Clearly, both the magnitude of $\rho_{ab}$ and its slope show a systematic decrease with increasing carrier concentration (decreasing $x$). One can see that it is only at the optimum doping that $\rho_{ab}$ shows a good $T$-linear behavior: In the underdoped region, $\rho_{ab}(T)$ shows a downward deviation from the $T$-linear behavior, which has been discussed to mark the pseudogap. 6 In the overdoped region, $\rho_{ab}(T)$ shows an upward curvature in the whole temperature range; the $T$ dependence of $\rho_{ab}$ in the overdoped region can be well described by $\rho_{ab} = \rho_0 + AT^n$ (with $n=1.14$ and 1.27 for $x=0.30$ and 0.24, respectively), which is a behavior known to be peculiar for the overdoped cuprates. 7, 8

Shown in Fig. 1(b) is the $T$ dependence of $R_H$ for the six samples. Here again, a clear evolution of $R_H$ with $x$ is observed; the change in the magnitude of $R_H$ at 300 K suggests that the carrier concentration is actually reduced roughly by a factor of 4 upon increasing $x$ from 0.24 to 0.74. Note that the $T$ dependence of $R_H$ is stronger than those previously reported. 3, 9 In our data, a pronounced peak in $R_H(T)$ is clearly observed for all carrier concentrations and the position of the peak shifts systematically to higher temperatures as the carrier concentration is reduced.
We observed that the cotangent of the Hall angle, cot $\theta_H$, obeys a power-law temperature dependence, $T^\alpha$, where $\alpha$ is nearly 2 in underdoped samples ($x=0.74$ and 0.66) but shows a systematic decrease with increasing carrier concentration. Figure 2 shows the plots of cot $\theta_H$ vs $T^\alpha$ for the two underdoped samples ($x=0.74$ and 0.66) and the optimally-doped sample ($x=0.44$). We note that the $T^2$ law of cot $\theta_H$ is confirmed for the first time for Bi-2201 in our crystals. A particularly intriguing fact here is that cot $\theta_H$ of the optimally-doped sample changes as $T^{1.7}$, not as $T^2$, while $\rho_{ab}$ shows a good $T$-linear behavior. This suggests that the Fermi-liquid-like behavior of the Hall scattering rate, $\tau_H^{-1} \sim T^2$, may not be a generic feature of the optimally-doped cuprates. The upward deviation from the $T^2$ behavior evident in Fig. 2(a) for the most underdoped sample ($x=0.74$) is likely to be related to the opening of the pseudogap.

Due to the limited space, we will concentrate below on the implication of our data to the pseudogap in Bi-2201. As we noted above, the downward deviation from the $T$-linear behavior in $\rho_{ab}(T)$ has been associated with the pseudogap and the onset of the deviation at $T^*$ gives a characteristic temperature for the pseudogap. Figure 3(a) shows the plot which emphasizes the deviation from the $T$-linear behavior to determine $T^*$. We should mention that this type of plot is subject to some arbitrariness and thus the errors in $T^*$ are inevitably large. (Interestingly, in Fig. 3(a), even the optimally-
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doped sample shows a $T^*$ which is well above $T_c$. It has recently been recognized that there are two different characteristic temperatures for the pseudogap, and $T^*$ corresponds to the higher characteristic temperature for the pseudogap. Also, it was proposed very recently that the peak in the $T$ dependence of $R_H$ may mark the lower characteristic temperature $T_0$ for the pseudogap, as does the NMR relaxation rate, ARPES, or the tunnelling spectroscopy. In our samples, the peak in $R_H(T)$ moves to higher temperatures as the carrier concentration is reduced, which is consistent with the behavior of the pseudogap. We note, however, that it is not clear whether the peak in $R_H(T)$ observed in the overdoped samples really corresponds to the pseudogap. For a more detailed discussion on the relation between the peak in $R_H(T)$ and the pseudogap, please refer to Ref. [12].

Figure 3(b) shows the phase diagram, $T$ vs $1−x$, for our BSLCO. Note that the horizontal axis is taken to be $1−x$ for convenience; this way, the left hand side of the plot corresponds to underdoping. One can see in Fig. 3(b) that a significant portion of the phase diagram has been covered and all the plotted temperatures, $T^*$, $T_0$, and $T_c$, show good systematics with the carrier concentration. It is intriguing that the magnitudes of the characteristic temperatures for the pseudogap is quite similar to other cuprates, while the $T_c$ of the present system is the lowest among the major cuprates.

In summary, we present the data of the in-plane resistivity, Hall coefficient, and the Hall angle of a series of high-quality La-doped Bi-2201 crystals in a wide range of carrier concentrations. The normal-state transport properties of our Bi-2201 crystals show systematics that can be considered to be “canonical” to cuprates. The characteristic temperatures for the pseudogap were deduced from the data to construct a phase diagram.

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