Examination of the c-axis resistivity of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ in magnetic fields up to 58 T

S. Ono and Yoichi Ando
Central Research Institute of Electric Power Industry, Komae, Tokyo 201-8511, Japan

F. F. Balakirev, J. B. Betts, and G. S. Boebinger*
NHMFL, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

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We measure the magnetic-field dependence of the c-axis resistivity, $\rho_c(H)$, in a series of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (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 $k_BT_c \simeq \frac{1}{2}g\mu_BH_p$. 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.[1] As a result, the c-axis resistivity ρ_c is a useful probe[2,3] of such features as the pseudogap[4] or the superconducting correlations[5] above T_c. On the other hand, there are a number of open questions regarding the interpretation of the magnetic-field (H) dependence of ρ_c below T_c, in which the suppression of superconductivity and the subsequent negative magnetoresistance (MR) at higher H defines a peak value of ρ_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}.[6,7] 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.[8–10]

It was argued by Morozov *et al.*[7] 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[10] 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[8] 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 ρ_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.*[8,9] was done on $Bi_2Sr_2CaCu_2O_{8+\delta}$ (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 thus is expected to have lower characteristic magnetic-field scales. From this point of view, the $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (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.[3,11]

Recently, it was shown that the Nernst effect in cuprates is a useful probe of the presence of vortices and, hence, superconducting correlations,[12] 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[14] 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 ρ_c measurements with that obtained by Nernst effect measurements. The BSLCO system is ideal for this purpose as well, because

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. 17.

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

detailed Nernst effect measurements have already been performed on BSLCO.[14,15]

In this work, we measure ρ_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 ($\frac{1}{2}g\mu_B H_p$) equals the thermal energy $k_B T_c$. Also, our $\rho_c(H)$ data are featureless at H_{c2}^N (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 Shibauchi *et al.*[8] is not appropriate to correctly obtain H_{pg}.

II. EXPERIMENTS

The $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (BSLCO) crystals used for this study are grown by the floating-zone method[3] 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.[16] We note that the series of BSLCO samples used in the recent Nernst effect measurements by Wang *et al.*[13,15?] 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 $Bi_{2.13}Sr_{1.89}CuO_{6+\delta}$ (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[17] 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 paper[3] to optimize the sharpness of the superconducting transition.

The samples for the ρ_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.[3] The $\rho_c(H)$ data are measured at fixed temperatures using a high-frequency (~100 kHz) four-probe technique[18–20] 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.[18,20] The temperature dependences of ρ_c of the present samples in zero magnetic field are essentially the same as those we reported previously.[3]

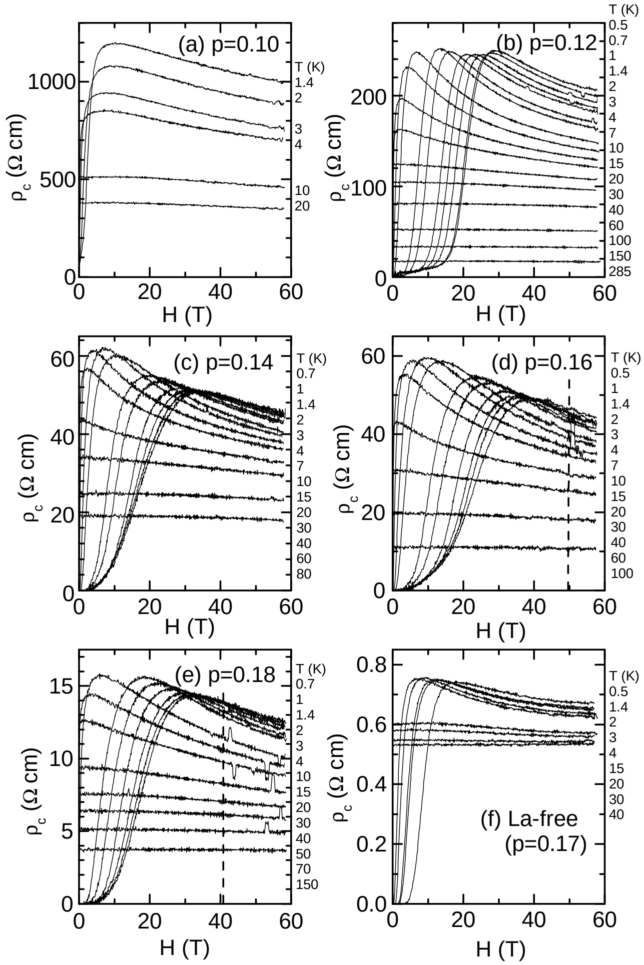

FIG. 1: Magnetic-field dependence of ρ_c at selected temperatures in BSLCO for a wide range of doping: (a) $p = 0.10$, (b) $p = 0.12$, (c) $p = 0.14$, (d) $p = 0.16$, (e) $p = 0.18$, and (f) La-free ($p = 0.17$). The position of H_{c2}^N is marked by a vertical dashed line. H_{c2}^N data is determined in Ref. 14.

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,[7] $H_p(T)$ of all the samples (except for $p = 0.10$) shows a pronounced upward cur-

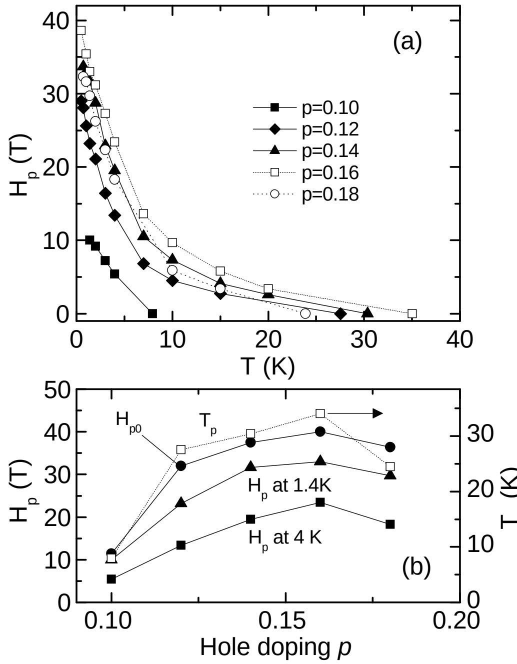

FIG. 2: (a) Temperature dependences of the peak field H_p for various dopings. The lower panel (b) shows the doping dependence of H_{p0} (solid circles) as well as the measured H_p values at 1.4 K (solid triangle) and 4 K (solid squares). The doping dependence of T_p (open squares) is also plotted.

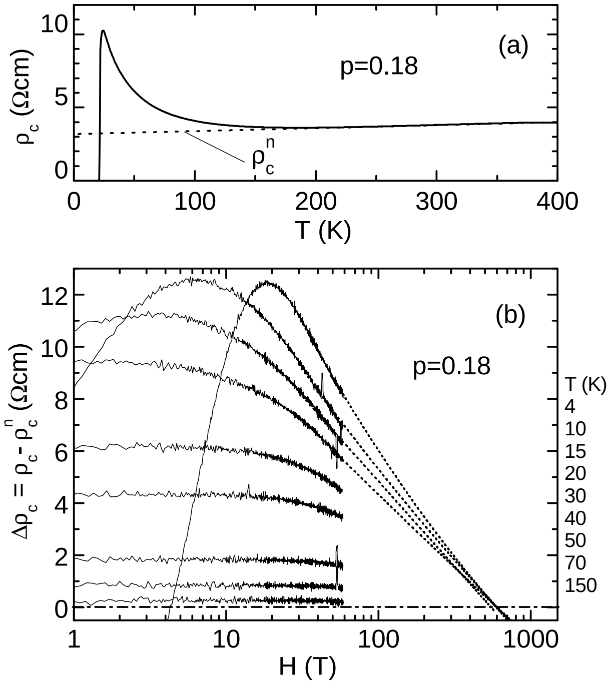

FIG. 3: (a) Temperature dependence of ρ_c for $p = 0.18$; the dashed line is an extrapolation of the high-temperature $\rho_c(T)$ to zero temperature, giving the estimate of ρ_c^n. (b) $\Delta\rho_c$(H) [$\equiv \rho_c(H) - \rho_c^n$] at selected temperatures for $p = 0.18$. Dotted lines in (b) are fits of the high-field data to $\Delta\rho_c(H) = \Delta\rho_c(0) + bH^\alpha$ and its extrapolation, following the procedure of Shibauchi et al.[8,9]

vature and steeply increases at low temperature. However, these temperature dependences are not really diverging, and one can obtain a reasonable fit to the data with an exponential function[10] $H_p = H_{p0}\exp(-T/T_0)$ for the low-temperature part; such fit gives an estimate of H_p in the zero-temperature limit, H_{p0}. Figure 2(b) shows the doping dependence of H_{p0}, together with the measured H_p values at 1.4 K and 4 K. It is clear that 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 $k_B T_c \simeq \frac{1}{2} g\mu_B H_p$. 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.[10]

Now we compare our result with the Nernst effect measurements.[14] Wang *et al.* have measured[14] 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.[21] 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[14] 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 ρ_c because ρ_c is dominated by quasiparticle tunneling. Note that the same situation is known for the in-plane resistivity ρ_{ab}.[22] 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.*,[8] one first determines the putative ρ_c in the *absence* of the pseudogap, ρ_c^n,[23] 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 ρ_c^n of about 3 mΩcm at low temperature. One then calculates $\Delta\rho_c(H) \equiv \rho_c(H) - \rho_c^n$ and fits the high-field part of $\Delta\rho_c(H)$ with an empirical formula[8,9]

$\Delta\rho_c(H) = \Delta\rho_c(0) + bH^\alpha$; 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 ρ_c^n: as we have shown in our previous paper,[3] the "insulating" temperature dependence of ρ_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 ρ_c^n 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 ρ_c^n 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_0 = 9.1 K and T_p = 10.2 K) and accordingly low magnetic field scales. As one can see in Figs. 4(a)-4(e), the high-field ρ_c is saturating to a value which increases with decreasing temperature, indicating that the true ρ_c^n 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 ρ_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.*,[8] 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.

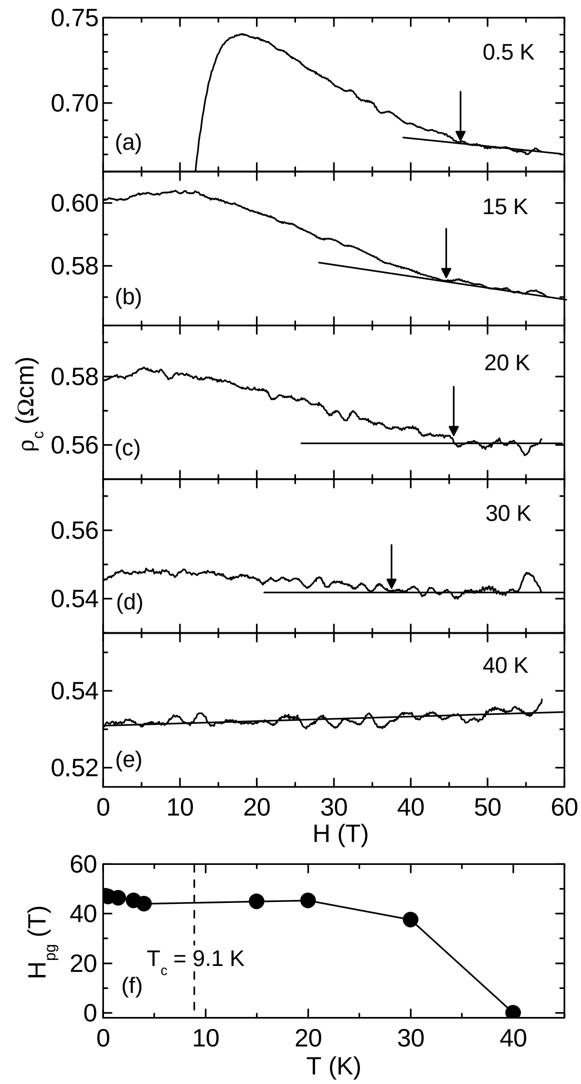

FIG. 4: (a)-(e) $\rho_c(H)$ of the La-free sample at selected temperatures; here the data are mildly filtered to remove the high-frequency noise apparent in the raw data shown in Fig. 1(f). The solid lines are linear fits of the high-field data. Arrows mark the field above which the $\rho_c(H)$ shows a near-saturation and thus would corresponds to H_{pg}. (f) Temperature dependence of H_{pg} obtained from the above method.

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 $k_B T_c \simeq \frac{1}{2} g\mu_B H_p$, 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_{c2}^N. (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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[*] Present address: National High Magnetic Field Laboratory, Tallahassee, FL 32310, USA

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