Pseudogap closing field of the overdoped Bi$_{1.79}$Pb$_{0.37}$Sr$_{1.86}$CuO$_{6+\delta}$ investigated by the out-of-plane resistivity in pulsed magnetic fields up to 40 T

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Abstract.
We have measured the out-of-plane resistivity $\rho_c$ of Pb-doped Bi2201 in strong magnetic fields up to 40 T. $\rho_c$ measurements in 40 T have confirmed the existence of two kinds of pseudogap, namely the field-insensitive pseudogap PG1 and the sensitive PG2 which have been suggested from previous $\rho_c$ measurements in 15 T. In the overdoped sample with the superconducting transition temperature $T_c = 4$ K, we have succeeded in the complete suppression of PG2. The temperature dependence of $\rho_c$ in 40 T has indicated that the nonmetallic $\rho_c(T)$ appears without PG2 on account of the existence of PG1 and/or the charge-confinement in the $ab$-plane.

1. Introduction
As for the pseudogap phenomena in high-$T_c$ cuprates, both theoretical and experimental aspects are classified into two groups, such as the precursor of the superconductivity and the competing energy gap or hidden order parameter to the superconductivity[1]. The pseudogap should be suppressed by the application of a magnetic field if it relates to the superconductivity; so that its magnetic-field response must provide a significant information for the clarification of the origin. The magnetic field dependence of the pseudogap has been investigated by using the nonmetallic temperature dependence of the out-of-plane resistivity $\rho_c$[2, 3, 4, 5]. The magnetic field response of the nonmetallic $\rho_c(T)$ directly yields that of the pseudogap, because the nonmetallic $\rho_c(T)$ is caused by the decrease in the tunneling probability between CuO$_2$ layers on account of the pseudogap-formation around $(\pm \pi, 0)$ and $(0, \pm \pi)$ on the Fermi surface at low temperatures below $T^*$. In Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$[2], Bi$_2$Sr$_{2-x}$La$_x$CuO$_{6+\delta}$[3] and Bi$_{1.79}$Pb$_{0.37}$Sr$_{1.86}$CuO$_{6+\delta}$[4, 5], the negative magnetoresistance has been observed in the nonmetallic $\rho_c(T)$, and these results have indicated that the pseudogap is suppressed in magnetic fields, leading to the precursor scenario of the pseudogap-origin. However, the field dependence of the pseudogap has still been controversial. $\rho_c$ measurements in Bi2212 have suggested that magnetic field sensitive pseudogap is formed at $T^*$ below which the nonmetallic $\rho_c(T)$ develops with decreasing temperature [2], while two kinds of pseudogap have been indicated in Bi2201, where the magnetic field sensitive
pseudogap PG2 formed at another temperature $T^{**}$ located at a lower temperature than $T^*$ below which field-insensitive PG1 is formed[3, 4, 5]. Such controversial arguments arise from insufficient magnetic fields compared with the superconducting temperature $T_c$ and $T^*$. In this study, therefore, we have measured $\rho_c$ of Pb-doped Bi2201 ($T_c^{\text{max}} \sim 20$ K) in strong magnetic fields up to 40 T, and determined which field dependence of the pseudogap is more appropriate through the trial to suppress the magnetic field sensitive pseudogap completely.

2. Experimental

Single crystals of Bi$_{1.79}$Pb$_{0.37}$Sr$_{1.86}$CuO$_{6+\delta}$ were grown by the floating-zone method[4, 5]. Crystals were annealed under vacuum, flowing Ar and O$_2$ atmosphere to control the doping levels. The superconducting transition temperature $T_c$ was determined by measuring the magnetic susceptibility. Samples measured are the heavily underdoped sample HUD ($T_c = 0$ K), the underdoped sample UD ($T_c = 13.5$ K) and overdoped samples OD1 ($T_c = 15$ K), OD2 ($T_c = 12$ K), OD3 ($T_c = 10$ K), OD4 ($T_c = 4$ K) and OD5 ($T_c = 0.7$ K). $\rho_c$ was measured by a standard DC four-terminal method in $H \leq 27$ T and 40 T, using a hybrid magnet (HFLSM, IMR, Tohoku Univ.) and a pulsed magnet (ISSP, Tokyo Univ.), respectively.

3. Results and Discussion

Figure 1 shows the magnetic field dependence of $\rho_c$ in $H \leq 27$ T parallel to the $c$-axis. Broken curves drawn in low fields are guides for eyes. In superconducting (SC) samples OD1 and OD2, as shown in figures 1(b) and 1(c), $\rho_c$ increases with increasing magnetic field and exhibits a peak at $T < T_c$. At high magnetic fields, $\rho_c(H)$ in these samples shows a negative slope, which is attributed to the recovery of the density of states at Fermi surface caused by the suppression of the pseudogap in magnetic fields. Such a negative slope is also observed at $T > T_c$ due to the existence of the pseudogap. In the nonsuperconducting (nonSC) sample HUD, on the other hand, the negative slope of $\rho_c(H)$ does not appear, though the nonmetallic $\rho_c(T)$ indicative of the pseudogap-formation has been observed in HUD as well as OD1 and OD2[4, 5]. The result indicates that the suppression of the pseudogap in magnetic fields occurs only in SC samples, and supports the existence of two kinds of pseudogap, namely the field-insensitive PG1 and the sensitive PG2. Previous reports on $\rho_c$ measurements in 15 T[3, 4, 5] have already shown that PG1 is observed in the wide doping levels from heavily underdoped nonSC to heavily overdoped nonSC samples while PG2 is formed only in SC samples. The present results reveal that the PG1 remains field-insensitive even in a magnetic field of 27 T.

Figure 1. Magnetic field dependence of $\rho_c$ of Bi$_{1.79}$Pb$_{0.37}$Sr$_{1.86}$CuO$_{6+\delta}$ in $H \leq 27$ T parallel to the $c$-axis for (a) HUD ($T_c = 0$ K), (b) OD1 ($T_c = 15$ K), (c) OD2 ($T_c = 12$ K) and (d) OD5 ($T_c = 0.7$ K). The arrow in the inset indicates $H_{pg}$. Broken curves are guides for eyes.
The pseudogap closing field $H_{\text{pg}}$ is determined above which the negative slope of $\rho_c(H)$ terminates. Such a magnetic field is observed in OD5. As shown in the inset of figure 1(d), $\rho_c(H)$ at 4 K ($> T_c$) changes its slope from negative to positive at $H_{\text{pg}} = 4$ T indicated by the arrow. At $T < T_c$, the negative slope is not detected in OD5, suggesting that PG2 is already closed when the resistive state emerges. In OD1 and OD2, on the other hand, the negative slope survives even in 27 T, because the PG2 is larger than the energy of the applied magnetic fields.

In order to discuss the temperature dependence of $H_{\text{pg}}$, $\rho_c(H)$ should be measured in strong magnetic fields using samples with larger pseudogap than that of OD5. Figure 2 shows the magnetic field dependence of $\rho_c$ in $H \leq 40$ T parallel to the c-axis. In UD and OD3, the negative slope of $\rho_c(H)$ survives in 40 T, as shown in figures 2(a) and 2(b). The magnetic field of 40 T remains insufficient in these samples to completely suppress PG2. In OD4, on the other hand, the complete suppression of PG2 is observed at high magnetic fields. With increasing magnetic field, the negative slope becomes weak and exhibits a saturation, as shown in figure 2(c).

For clarity, the enlarged figure is shown in figure 3, where $H_{\text{pg}}$ are defined below which $\rho_c(H)$ deviates from a horizontal broken line with decreasing magnetic field and indicated by arrows. Compared with the previous estimation of $H_{\text{pg}}$ in Bi$_{1.79}$Pb$_{0.37}$Sr$_{1.86}$CuO$_{6+\delta}$[6] and Sm$_{2-x}$Ce$_x$CuO$_{4-\delta}$[7], the present estimation may be more precise, because $H_{\text{pg}}$ in these systems has been determined from still changing $\rho_c$ as a function of the magnetic field. Temperature dependence of $H_{\text{pg}}$ is shown in figure 4(d). With increasing temperature, $H_{\text{pg}}$ is shifted to lower magnetic fields. Though $H_{\text{pg}}$ at $T > 20$ K cannot be determined due to the the experimental accuracy, the linear extrapolation of $H_{\text{pg}}(T)$ seems to approach zero around 50 K.

Figures 4(a)-4(c) show the temperature dependence of $\rho_c$ in $H \leq 40$ T. Temperatures $T^*$ and $T^{**}$ correspond to onset temperatures of PG1 and PG2, which are defined at the local minimum of $\rho_c(T)$ and the 0.1 % deviation temperature of $\rho_c(H, T)$ from its zero-field values, respectively. $T^*$ is field-independent, and $T^{**}$ is distinct from $T^*$ even in 40 T. Both results support the existence of two kinds of pseudogap. Positions of $T^*$ and $T^{**}$ seem close in overdoped samples, but this is consistent with the hole concentration dependence of these temperatures[3, 4, 5]. In addition, $T^{**}$ (45 K) in OD4 is in rough agreement with the vanishing temperature of $H_{\text{pg}}$ (50 K). Such coincidence confirms that the magnetic-field sensitive pseudogap is not PG1 but PG2.

In the pseudogapless normal state, a metallic $\rho_c(T)$ is naively expected. However, $\rho_c(T)$ in OD4 actually remains nonmetallic in 40 T where PG2 is completely suppressed, as shown in figure 4(c). The result indicates that the nonmetallic $\rho_c(T)$ is conserved on account of the tunneling nature due to the field-insensitive PG1 and/or the charge-confinement in the $ab$ plane. It is noted that the nonmetallic $\rho_c(T)$ is not attributed to the disorder due to the substitution of Pb for Bi and/or the distribution of the excess oxygen, because the heavily overdoped nonSC
sample exhibits a metallic $\rho_c(T)$ down to 1.5 K\cite{4, 5}.

4. Conclusion
We have measured the out-of-plane resistivity $\rho_c$ of Pb-doped Bi2201 in strong magnetic fields up to 40 T. The obtained two kinds of field response in $\rho_c$ have supported the existence of two kinds of pseudogap, namely the field-insensitive pseudogap PG1 and the sensitive PG2. The complete suppression of PG2 has been succeeded in the overdoped sample ($T_c = 4$ K) in magnetic fields up to 40 T. The temperature dependence of $\rho_c$ in 40 T has indicated that the nonmetallic $\rho_c(T)$ appears without PG2 on account of the existence of PG1 and/or the charge-confinement in the ab-plane.

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