Pressure effect on quasi-one-dimensional charge transport in $PrBa_2Cu_4O_8$: Magnetotransport study

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The electrical resistivity and the magnetoresistance of $PrBa_2Cu_4O_8$ have been measured under hydrostatic pressure up to 1.0 GPa. It was found that magnetoresistance is sensitive to the applied pressure below 100 K where the resistivity shows metallic behavior. This suggests that the interchain hopping energy is increased by pressure, which makes the low-temperature electronic state more two dimensional. [S0163-1829(99)01505-2]

Electric and magnetic properties of low-dimensional electron systems have attracted much attention since the discovery of high-T_C superconductors. Of these, a one-dimensional (1D) metallic chain is of particular interest. Because of the simplicity of the models, the exact solution is available for some 1D Hamiltonians such as the 1D Hubbard model,[1] which can directly be compared with the experimental results of the appropriate model compounds. Theoretically, a 1D metal is not a conventional Fermi liquid unlike the systems with higher spacial dimensions but a so-called Luttinger liquid where the spin and charge degrees of freedom can move separately in space. This has promoted an experimental survey of the systems with conducting chains to investigate experimentally how the Luttinger-liquid state is different from the Fermi-liquid state.

$PrBa_2Cu_4O_8$ (Pr124) is one of the promising candidates for the 1D metal with self-doped CuO chains.[2,3] Pr124 is a nonsuperconductor like $PrBa_2Cu_3O_{6+\delta}$ (Pr123), but is quite different from Pr123 in that Pr124 shows a metallic conduction at low temperatures.[2–4] Since the CuO_2 plane in Pr124 show antiferromagnetism below $T_N \sim 220$ K,[5,6] as is similar to Pr123, it will not participate in the metallic conduction at low temperatures. Hence, the metallic behavior should be assigned to the CuO double chain, which is the only difference in the crystal structure from Pr123 with the single CuO chain. It is plausible that the oxygen vacancies in the CuO chain, which may prevent Pr123 from being metallic, are less important in Pr124 than in Pr123 because Pr124 is stoichiometric. The metallic nature of the CuO double chain in Pr124 is further supported by the anisotropic in-plane resistivity in the isostructural $YBa_2Cu_4O_8$.[7]

Terasaki *et al.* have measured the temperature (T) dependence of the resistivity, Hall coefficient, magnetoresistance, and thermoelectric power at ambient pressure.[4] All of these quantities were found to depend strongly on temperature, which is quite different from the behavior of high-T_C cuprates or conventional metals. They proposed that the unusual T dependence of the transport parameters arises essentially from the 1D nature of the conducting path along the CuO double chain modulated by a small interchain hopping energy $t_\perp$. The existence of $t_\perp$ results in the crossover from the quasi-1D to the quasi-two-dimensional (2D) electronic state at a certain T where $t_\perp$ exceeds the thermal fluctuation energy k_BT (i.e., $t_\perp \gg k_BT$). The crossover is evidenced by a rapid increase of the Hall coefficient and the magnetoresistance, and the small thermoelectric power below 100 K.

It is quite attractive to study how such an anisotropic electronic system behaves under pressure because a variety of electronic states such as superconducting and density-wave states, and a transition between them could be realized in 1D conductors.[8] Even in the absence of such an ordered ground state, applying pressure is one of the promising experimental techniques to change dimensionality of the system through the shrinking of the lattice, and can be used as an external probe to elucidate essential features of the low-dimensional electron systems. In this paper, we report measurements of the transverse magnetoresistance (MR) of $PrBa_2Cu_4O_8$ under hydrostatic pressure up to 1.0 GPa. We found that the transverse MR strongly depends on the applied pressure especially in the low-T metallic region, namely, the T dependence of the MR is weakened by pressure. This is consistent with the dimensional crossover from 1D to 2D in the metallic CuO double chain, and indicates that the system becomes more 2D under high pressure.

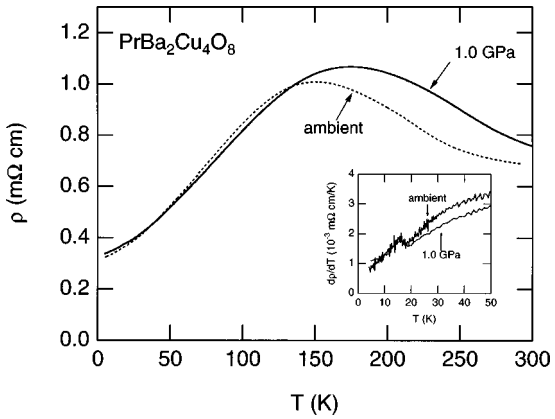

FIG. 1. Temperature dependence of the resistivity ρ of $PrBa_2Cu_4O_8$. The inset shows the temperature derivative of ρ as a function of temperature.

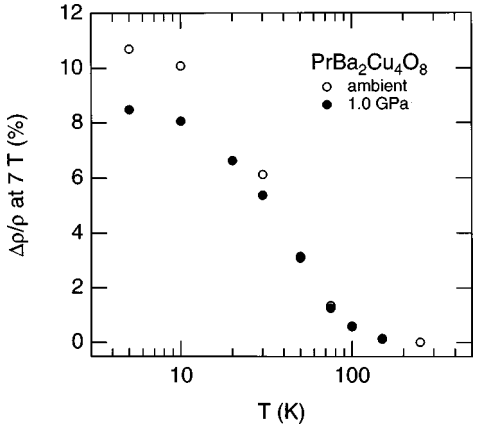

FIG. 2. Temperature dependence of the transverse magnetoresistance $\Delta\rho/\rho$ under the applied field of 7 T.

Polycrystalline samples of Pr124 were prepared by the solid-state reaction technique as described in Ref. 2. Electrical resistivity and the magnetoresistance were measured by conventional four-probe method in magnetic fields (H) up to 7 T. External fields were applied perpendicular to the current direction ($H \perp I$) so that the transverse MR can be measured. Hydrostatic pressure was applied by using a BeCu piston-cylinder cell which is designed to keep the applied pressure constant even at low temperatures. A mixture of Fluorinate (FC70:FC77=1:1) was used as a pressure-transmitting fluid. Absolute values of the applied pressure were calibrated by using the superconducting transition temperature of Pb metal. All the measurements were performed on the same ceramics with the above-mentioned high-pressure cell (even at ambient pressure) to minimize possible instrumental errors and sample-dependent factors.

Figure 1 shows the T dependence of the resistivity (ρ) in Pr124 at ambient pressure and 1.0 GPa. The observed pressure dependence of ρ is consistent with the previous study by Matsushita *et al.*[9] As shown in Fig. 1, a broad maximum is observed around 150 K at ambient pressure and 170 K at 1.0 GPa, below which ρ exhibits a metallic T dependence. A major effect of applying pressure on ρ is to increase its magnitude in the high-T semiconducting region, and to shift the broad maximum toward higher T. As a clear contrast, the resistivity does not change appreciably with pressure at low T where the metallic behavior is observed. The resistivity below ~70 K (~80 K at 1.0 GPa) is roughly expressed as $\rho=\alpha T^{1.5}+\rho_0$ with an increase (~5%) of ρ_0 and a decrease (~11%) of α under pressure. The T dependence of ρ at low T is quite different from that of the resistivity of the CuO chain in $YBa_2Cu_4O_8$ which shows clear T^2 dependence.[7] The difference in powers of T might be intrinsic to Pr124, although a possibility that it is merely an effect of in-plane contribution cannot be ruled out.

The origin of a broad maximum in ρ is not clear at present. One possible explanation for this is to regard the conducting paths in Pr124 as a parallel circuit composed of the metallic CuO chain and the semiconducting CuO_2 plane.[3,4,9] In this picture, the temperature T_{max} where ρ exhibits a maximum corresponds to temperature where the resistivities of chain and plane, ρ_{chain} and ρ_{plane}, respectively, becomes comparable, and the CuO_2 plane is responsible for the semiconducting behavior above T_{max}. If this is the case,

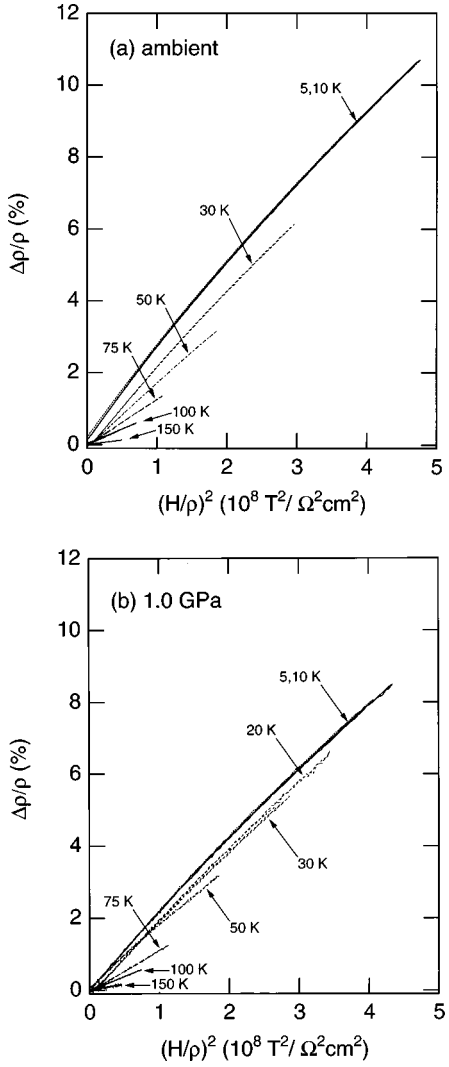

FIG. 3. Transverse magnetoresistance $\Delta\rho/\rho$ plotted as a function of $(H/\rho)^2$ where H and ρ are the applied field and the zero-field resistivity, respectively. (a) $\Delta\rho/\rho$ at ambient pressure, and (b) $\Delta\rho/\rho$ at 1.0 GPa.

the pressure dependence of T_{max} indicates that ρ_{plane} is increased appreciably by applying pressure while ρ_{chain} is not. As for the increase of ρ_{plane} under high pressure, it is plausible that the number of charge carriers in the CuO_2 plane decreases due to increased hybridization between Pr $4f$ and O $2p$ orbitals.[10] Measurement of the in-plane anisotropy of ρ using single crystals is highly desirable to examine the validity of the above model.[11]

We have observed a small hump in the $d\rho/dT$ versus T curve around 20 K as is shown in the inset of Fig. 1. The hump is visible even at an ambient pressure which indicates that this anomaly is not induced by pressure. The temperature is very close to temperature where the bulk magnetic susceptibility shows a knee, which is believed to be accompanied by long-range magnetic ordering of Pr $4f$ moments.[2,3] Therefore, it seems reasonable to attribute the anomaly in $d\rho/dT$ to Néel order of Pr moments as well. Since the metallic conduction at low T is considered to occur along the CuO double chain, the existence of such an anomaly suggests finite magnetic couplings between Pr $4f$ moments and the conduction-electron spins in the CuO

double chain. The change of the Brillouin zone due to the antiferromagnetic order of Pr moments is also a possible candidate for the origin of the anomaly in $d\rho/dT$.

The pressure dependence of the magnetoresistance (MR) makes a clear contrast to the results at zero external magnetic field, in a point that the MR in the low-T metallic region is rather sensitive to the applied pressure. As is shown in Fig. 2, the T dependence of MR is characterized by a rapid increase below about 100 K, which is indicative of the 1D-2D crossover.[4] Since in an ideal 1D conductor the Lorentz force cannot bend the trajectories of mobile carriers across the conducting chain to give no MR, vanishingly small MR suggests that the high-T electric conduction is essentially 1D even under high pressure.

Figures 3(a) and 3(b) are the plots of MR at various T as a function of $(H/\rho)^2$. The MR is positive and is almost linear in H^2, indicating that the observed MR is classical MR, i.e., MR being caused by the change in the trajectories of mobile carriers induced by the Lorentz force.[12] It is known that classical MR in metals is roughly equal to $(\omega_c\tau)^2$, where ω_c and τ are the cyclotron frequency and the scattering time, respectively, and follows a scaling function of $(H/\rho)^2$.[13] Below 10 K, the dependence of MR on $(H/\rho)^2$ merges into a single curve. This implies that the scaling, or Kohler's rule, holds in the low-T limit. However, at higher T where MR varies strongly with temperature, MR does not scale to any universal functions of $(H/\rho)^2$. This can be understood within the framework of the 1D-2D crossover by introducing the T-dependent ω_c which is vanishingly small in the high-T ($k_BT \gg t_\perp$) 1D region and finite in the low-T ($k_BT \ll t_\perp$) 2D region as suggested by Terasaki *et al.*[4]

The qualitative feature of the violation of Kohler's rule with increasing T does not change by applying pressure, which suggests that the crossover scenario even holds under high pressure. It should be emphasized, however, that under high pressure the deviation of MR from the low-T scaling curve remains small compared with that under ambient pressure. As shown in Fig. 3, decrease of MR at 50 K relative to MR at 5 K amounts to $\sim$43% for the value of $(H/\rho)^2 = 1.8 \times 10^8\ \mathrm{T}^2/\Omega^2\mathrm{cm}^2$ [which is the largest value of $(H/\rho)^2$ that can be reached at 50 K] at ambient pressure, whereas at 1.0 GPa, a relative decrease of MR from 5 to 50 K is at most $\sim$22% for the same value of $(H/\rho)^2$ [see Fig. 3(b)] aside from a small shift near $H=0$ observed for the 5 K data.[14] This suggests that pressure widens the temperature range where Kohler's rule is valid to higher temperatures. In other words, the low-T quasi-2D electronic state is stabilized by applying pressure. This may arise from the increase of $t_\perp$ or more rigorously, the increase of the ratio of $t_\perp$ to the intrachain hopping energy $t_\parallel$ under high pressure, which is expected from the decrease of the lattice spacing.

In summary, the magnetoresistance of $PrBa_2Cu_4O_8$ is found to depend strongly on the applied pressure in the low-T metallic region. The T dependence of the magnetoresistance is weakened by pressure, which is consistent with the 1D-2D crossover in the charge transport occurring in the CuO double chain. The main effect of applying pressure is to stabilize the low-T quasi-2D electronic state, which is likely to come from the increase of the interchain hopping energy as a consequence of shrinking of the lattice under high pressure.

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[11] To our knowledge, no one has succeeded in preparing single crystals of Pr124 at present.

[12] We also measured MR in a longitudinal configuration $H \| I$ to check whether MR is isotropic or not and found that longitudinal MR is smaller in magnitude than transverse MR. This indicates MR is anisotropic, which is consistent with our assignment that the observed MR is classical.

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[14] One may notice that for the MR data at 5 and 10 K shown in Figs. 3(a) and 3(b), there is a sharp raise of MR near $H=0$ followed by an H^2 law. This may arise from the AF order of Pr moments because it is not observed for the data above 20 K.