Pressure effects on the electrical resistivity of Pr$_2$Ba$_4$Cu$_7$O$_{15-\delta}$ oxide superconductor

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Abstract. The superconductivity of Pr$_2$Ba$_4$Cu$_7$O$_{15-\delta}$ (Pr247) is realized at the CuO double-chains. The oxygen deficiency $\delta$ dependence of the superconducting transition temperature $T_c$ shows the bell-like curve with the maximum of $T_c = 20.6$ K at $\delta = 0.64$. We investigated the pressure effects on the double-chain superconductivity of Pr247. The resistivity was measured under the pressure of 10 GPa produced by a modified Bridgman anvil type cell. With increasing pressure above 3 GPa, the superconductivity was suppressed and disappeared. The temperature dependence of the resistivity shows a semiconductor like behavior above 5 GPa. The x-ray diffraction using a diamond anvil cell under hydrostatic condition shows that no structural transition occurs below 10 GPa.

1. Introduction

It is well known that the Pr-substitution for Y-site in YBa$_2$Cu$_3$O$_{7-\delta}$ (Y123) with CuO single chain and YBa$_2$Cu$_4$O$_8$ (Y124) with CuO double chain dramatically suppresses the superconducting transition temperature $T_c$ and superconductivity in CuO$_2$ planes disappears [1]. The cause is still controversial, but the most widely held theory is that its superconductivity is suppressed due to the localization of carriers in the CuO$_2$ layers as a result of the hybridization of Pr-4$f$ and O-2$p$ in the CuO$_2$ layers [2]. PrBa$_2$Cu$_3$O$_{7-\delta}$ (Pr123) and PrBa$_2$Cu$_4$O$_8$ (Pr124) shows semiconductor-like and metal-like behavior, respectively. From the results of the anisotropy of the electrical resistance of a Pr124 single crystal, metal-like conductivity on Pr124 is due to the CuO double chains [3].

Recently, we have succeeded in synthesizing a Pr$_2$Ba$_4$Cu$_7$O$_{15-\delta}$ (Pr247) oxide and found that this material shows superconductivity with $T_c = 15$ K [4, 5] after reduction treatment. Pr247 has the same crystal structure as Y$_2$Ba$_4$Cu$_7$O$_{15-\delta}$ (Y247) with an alternative repetition of the single and double chains along the c-axis. As-sintered sample of Pr247 shows metallic conductivity at low temperatures owing to the conduction in the CuO double chains, such as Pr124. Reduction treatment on Pr247 caused the carrier density change by controlling the amount of oxygen deficiency in the CuO single chains. For example, the resistivity in Pr247 with a reduction
treatment at 650 °C in Ar gas for 4 days shows superconductivity with $T_c = 10$ K [4]. More recently, we have found that reduction treatment at 400°C in vacuum for 6 hours or more also can give rise to superconductivity around $T_c = 15$ K [5]. The $T_c$ depends on the oxygen deficiency $\delta$ which is estimated from the weight change during the vacuum annealing. This indicates that the superconductivity in the Pr247 emerges as a result of oxygen loss, i.e., electron doping, unlike in hole-based oxide superconductors such as Y123. Sano et al. studied the one-dimensional conduction mechanism based on Tomonaga-Luttinger liquid theory [6]. The CuO double chain on Pr247 can be treated as a one-dimensional (1D) structure and their results explained well the experimental results on Pr247 mentioned above. According to their theoretical phase diagram based on the weak coupling theory, electron-doping causes the phase transition from the normal conductive phase to the superconductive one. This agrees well with the experimental results that the electron doping on Pr247 by oxygen defects causes the superconductivity. The theory by Sano et al. suggests that applying pressure causes the undoping effects on the double chain conduction. In the present paper, we reports on the pressure effects on the Pr247 sample annealed in vacuum. Moreover, we use the modified Bridgman anvils type pressure apparatus with a Teflon capsule, which can produce the high pressure up to 10 GPa.

2. Experimental
A polycrystalline Pr247 compound was synthesized by a high-oxygen-pressure technique. The precursor was prepared using a polymerized complex method of an appropriate amount of Pr$_6$O$_{11}$, CuO, and Ba(NO$_3$)$_2$. These were decomposed at 800-880°C in air for 24 hours. It was pressed into a pellet and then reacted in pure oxygen gas of 5 atm at 973°C for 18 hours. As-sintered samples were reduced by post-annealing in vacuum at 400°C for various durations. The oxygen deficiency $\delta$ was calculated from the weight change during the annealing. The magnetic susceptibility was measured with a SQUID magnetometer (MPMS of Quantum Design Co.). The sample with $\delta = 0.71$ shows 60% volume fraction of superconductivity, which is much larger than that in our previous report [5]. As shown in Fig. 2, the $T_c$ shows the bell-shaped curve against $\delta$ with the maximum $T_c = 20.6$ K at $\delta = 0.64$.

The electrical resistance under high pressure on the $\delta = 0.26, 0.64$ and 0.79 samples was measured by a conventional 4-probe method. Pressures up to 2 GPa were produced by a piston cylinder type pressure cell made of NiCrAl and CuBe alloys [7]. Higher pressures up to 10
GPa were produced by a modified Bridgman anvil type pressure cell. The pressure cell and modified Bridgman anvils are made of CuBe and tungsten carbide, respectively [8, 9]. Both type of pressure cells were cooled with a liquid He free type 1 K and 4 K cryocoolers ((Iwatani industrial gases corp). A mixture of Fluorinert FC-70 and 77 was used as a pressure-transmitting medium in all the experiments.

3. Results and Discussion
The electrical resistivity under pressure up to 2.5 GPa was measured with the piston cylinder type pressure cell. On the sample $\delta = 0.26$, as shown in the left panel of Fig. 3, the resistivity drops at 13.1 K at ambient pressure but no zero resistivity was observed down to 5.4 K. However, as shown in Fig. 1, the negative magnetic susceptibility due to the Meissner effect was clearly observed below 15.5 K, so that, the resistivity-drop for the sample $\delta = 0.26$ at this temperature is due to the superconductivity. Moreover, with increasing pressure, the $\rho - T$ profiles become very similar with that of the as-sintered sample[5].

The sample with $\delta = 0.64$ shows the maximum value of $T_c = 20.6$ K among the present samples. From this result we consider the $\delta = 0.64$ sample as an optimum-doped sample. The center panel of Fig. 3 shows the temperature dependence of the resistivity for the sample with $\delta = 0.64$ up to 2.5 GPa. The transition temperature $T_c$ increased with increasing pressure from 22.7 K at 0 GPa to 33.1 K at 2.5 GPa. No zero resistivity was observed above 2 GPa.

The right panel of Fig. 3 shows the temperature dependence of the resistivity of the sample with $\delta = 0.64$. At 0, 1.0 and 2.0 GPa. The transition temperature $T_c$ is 23 K at 0 GPa and increased to 25.5 K at 2.5 GPa. In contrast to the other two samples, zero resistivity is still observed even in the pressure of 2.0 GPa and the change in $T_c$ with pressure is small.

We performed the resistivity measurements under high pressure above 3 GPa with a modified Bridgman anvil type pressure cell. Temperature dependence of the resistivity for the sample with $\delta = 0.64$ and 0.79 is shown in Fig. 4. For both samples, no zero resistivity was observed under pressure above 5 GPa and the $\rho - T$ profiles shows a semiconductor-like behavior.

The disappearance of the superconductivity on Pr247 by applying pressure is consistent with the theoretical study based on the 1D conduction mechanism. However, the metal-semiconductor transition cannot be explained. The high-pressure X-ray powder diffraction measurements at SPring8, BL10XU beamline at room temperature using a diamond anvil cell showed that no

Figure 3. Temperature dependence of the resistivity on Pr247 under various high pressures up to 2.5 GPa for the sample with $\delta = 0.26$, 0.64 and 0.79.

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structural transition occurs below 10 GPa. The appearance of the semiconductor-like behavior is probably due to the 1D conductive system on CuO double chain, which is easily broken by the deformation owing to applying the high pressure.

![Figure 4](image-url)

**Figure 4.** Temperature dependence of the resistivity on Pr247 under various high pressures up to 10 GPa for the sample with $\delta = 0.64$ and 0.79.

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