High-Pressure Effect on $T_c$ of HgBa$_2$Ca$_3$Cu$_4$O$_{10+\delta}$ up to 30 GPa

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Abstract. In order to investigate the pressure dependence of $T_c$ of the Hg-based cuprates, we performed the electrical resistance measurements of high purity HgBa$_2$Ca$_3$Cu$_4$O$_{10+\delta}$ (Hg-1234) synthesized under pressure. We used a diamond-anvil cell to generate high pressure up to 30 GPa. In this work, two Hg-1234 samples with different hole concentration ($T_c = 125$ K for optimaldoped sample and $T_c = 124$ K for underdoped one at ambient pressure) were measured. With applying pressure $T_c$ of underdoped sample increased ($dT/dP = +0.6$ K/GPa) and passed through a peak with 143 K at ~30 GPa and decreased drastically at higher pressure. This behavior was different from previous works for Hg-1234 and Hg-1223, in which the $T_c$ saturates above the pressure giving the maximum $T_c$.

1. Introduction

Since superconducting transition temperature ($T_c$) reached 164 K in HgBa$_2$Ca$_3$Cu$_2$O$_{8+\delta}$ (Hg-1223) under pressure[1][2], there is no report that $T_c$ exceeds 164 K though extensive investigations have been made on the different cuprate families, such as LSCO, YBCO, the Bi-, Tl-, Hg-based compounds, and many of other new materials might be synthesized and measured under pressure.

Generally, $T_c$ depends on the carrier concentration ($N_h$), the number of CuO$_2$ planes and the crystal structure. External pressure is a powerful tool to control of $N_h$ and crystal structure. For example, $T_c$ of Hg1223 increases with applying pressure by +1.0 K/GPa. In order to investigate the pressure dependence of $T_c$ of the Hg-based cuprates in wide pressure range, we performed the electrical resistance measurements of high purity HgBa$_2$Ca$_3$Cu$_3$O$_{10+\delta}$ (Hg-1234) synthesized under pressure up to 39 GPa.

2. Experimental

In this work, two Hg-1234 samples with different hole concentration; ($T_c = 125$ K for optimaldoped sample and $T_c = 124$ K for underdoped one at ambient pressure) were prepared by high pressure and at high temperature. The optimaldoped sample was synthesized at about 1000 °C under a pressure of 3.5 GPa for 6 h. The underdoped sample was obtained by annealing the optimaldoped sample at 280 °C in a vacuum for 24 h. Though it is difficult to synthesize single-phase samples of multilayered cuprates,
these samples are polycrystal revealed as single phase by powder X-ray diffraction. We used a diamond-anvil cell (DAC), made of CuBe, to generate high pressure. Pressure was determined by a ruby fluorescence method at near temperature $T_c$. Nonmagnetic stainless steel of SUS310S and Rhenium (Re) were used for a gasket material. The electrical resistance measurements were performed using the standard four-probe technique. Four copper (Cu) films of 2-3 $\mu$m thickness were placed in contact with the sample (excluding underdoped sample run2 at 13.3 GPa of three probe measurement). The c-BN with epoxy resin was used for electrical insulation between electrical probes and the gasket material.

3. Results and Discussion
We performed the electrical resistance measurements of high purity Hg-1234 which are different hole concentration under high pressure up to 30 GPa (39 GPa for underdoped sample). The temperature dependences of the samples at several pressure are displayed in Fig.1. Zero resistance was not obtained in this measurement; which may be due to intergrain boundaries because they are not superconducting. The pressure dependences of $T_c$ of both samples are displayed in Fig. 2. To compare with previous works[3], we defined $T_c$ as $T_{cd}$ and $T_{ct}$ displayed in Fig. 3. At the underdoped sample, we observed that $T_c$ increased with pressure monotonically ($dT_c/dP = +0.6$ K/GPa) and passed through a peak with 143 K at $\sim$30 GPa and decreased drastically at higher pressure. On the other hand, at the optimaldoped sample, we measured the electrical resistance up to $\sim$30 GPa. $T_c$ increased monotonically with applying pressure ($dT_c/dP = +0.6$ K/GPa) and reached 143 K at $\sim$30 GPa. We note that in higher pressure region above $\sim$20 GPa superconducting transition became broad and behavior of normal state above $T_c$ seems semiconductive. Particularly, at underdoped sample there is very large difference between $T_{cd}$ and $T_{ct}$. Even at 39 GPa electrical resistance increased like semiconductor below $T_c$ as temperature decreased as well as superconducting transition was broad.

The results that the $T_c$ of Hg-1234 increased monotonically with pressure are similar to previous works, however, different in pressure value of maximum $T_c$, enhancement value of $T_c$, and $T_c$ at ambient pressure. Our measurements revealed that this behavior is intrinsic to sample and the pressure dependence of $T_c$ in higher pressure region. Superconducting transition became broad, this might indicate that disorder of the crystal structure invited by shear stress of pressure. To investigate the relation between crystal structure and $T_c$, it is necessity to measure electrical resistance and X-ray diffraction simultaneously.

![Figure 1](image_url)  
Fig. 1. Temperature dependence of electrical resistance of (a) Hg-1234 (underdoped) and (b) Hg-1234 (optimaldoped) at different pressures. Electrical resistances are normalized with respect to their values at 160 K.
4. Conclusion
We performed electrical resistance measurements of high-purity Hg1234 samples with different hole concentration under high pressure. The $T_c$ of both samples reached 143 K at ~30 GPa.

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