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Superconductivity above 250 K in $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ at high pressure

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The pressure dependence of the superconducting transition temperature T_c (onset) of $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ (Tl-2223) has been measured under quasi-hydrostatic pressure (QHP) up to 5.0 GPa. The T_c increases with increasing pressure at a relatively high rate and reaches a maximum at 255.4 K and pressure of about 4.3 GPa. This is the highest T_c yet observed for any high-T_c superconductor. The total change in T_c from ambient condition (T_c = 129 K) to the high pressure applied can be greater than 126 K. The T_c above 200 K was replicated several times in our experiments. The site of the maximum of T_c and the value of dT_c/dP = 1.7 K/GPa (at P = 0) agree with previous results obtained by D. Tristan Jover et al. [1] and J. G. Lin et al. [2], respectively.

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1. Introduction

High pressure has played an important role in identification of new materials and mechanisms in high-temperature superconductivity [1–3]. The pressure dependence of the critical temperature of high-temperature superconductors has been studied extensively. For example, L. Gao et al. [3] obtained a much higher value of T_c (164 K) at a pressure of up to 31 GPa in the high-T_c superconductor Hg-Ba-Ca-Cu-O (1223). D. D. Berkley et al. [4] observed a maximum T_c of 131.8 K at 7.4 GPa in single crystals of $Tl_2Ba_2Ca_2Cu_3O_{10-\delta}$. Tristam Jover et al. [1] obtained the superconducting transition temperature in $Tl_2Ba_2Ca_2Cu_3O_{10+\delta}$, which increased from 128.5 K to 133 K with increasing pressure from 0 to 13 GPa. The maximum value of T_c (onset) in this compound was found at pressure of about 4.0 GPa. A systematic study of the pressure effects on the superconducting transition temperatures of Tl-based family has been made by J. G. Lin et al [2], who obtained dT_c/dP = 2.5 K/GPa for Tl-2223 samples at a pressure of only up to 2 GPa.

From their plot of T_c vs P for a Tl-based compound system, it seems that for Tl-2223 and Tl-2122 compounds the T_c may be further enhanced. In view of these circumstances and based upon our previous experience in high-pressure experiments, we have carried out some experiments on Tl-2223 compounds.

Here we report our investigation on the superconductivity of $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ compound under high pressures up to 5.0 GPa. We found that T_c changes rapidly with applied high pressures, especially in the range of pressures from 3.0 to 4.0 GPa. The $T_c(P)$ is observed to increase from 129 K at atmospheric pressure to 255.4 K at 4.3 GPa.

2. Experimental

The samples were prepared by using the ordinary solid reaction technique. After the powders of Tl_2O_3 , CaO, BaO, and CuO had been thoroughly mixed and ground, they were pressed into pellets with a diameter of ~ 12 mm and thickness of ~ 2 mm, and then sintered at 890 °C for 5 h in flowing oxygen gas. The samples prepared in this way were then put into quartz cells, which were evacuated to 10^{-4} Torr, sealed, heat treated at 750 °C for 250 h, and finally air-quenched to room temperature [5]. Samples ($30\times50\times300\ \mu m^3$) used for measurements under quasihydrostatic pressure (QHP) up to 5.0 GPa were cut from the above pellet.

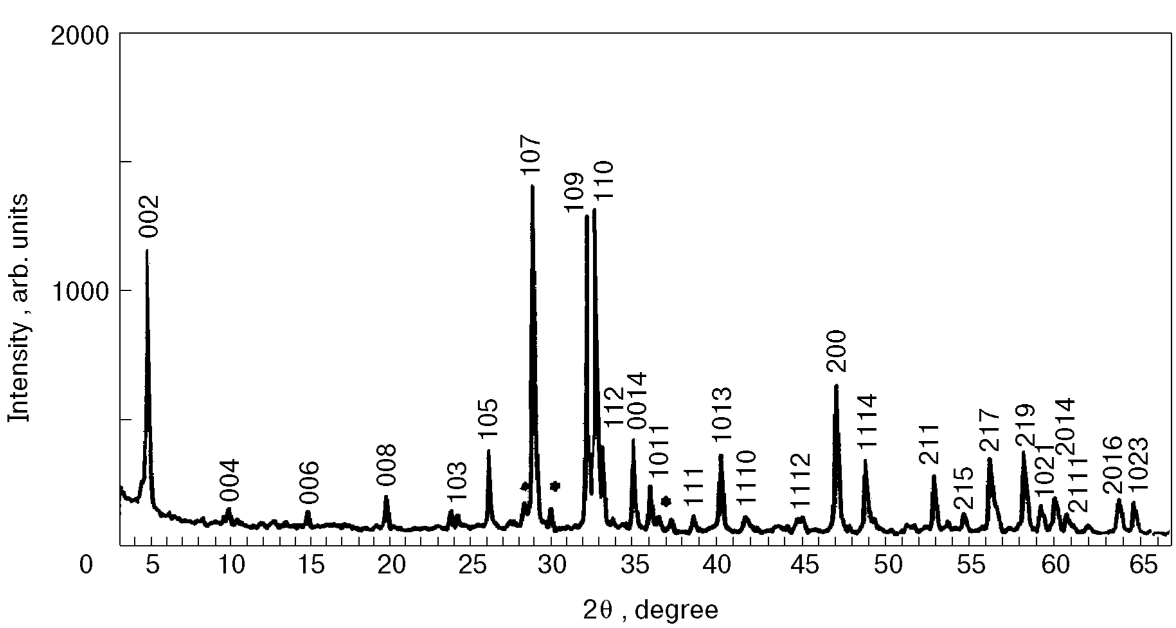

Fig. 1. Powder X-ray diffraction pattern of the as-prepared $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ sample.

The QHP was generated in a high-pressure chamber by a special system to compress the planes of Bridgman anvil made of tungsten carbide, which was fitted into a cylinder made of fully hardened beryllium copper alloy, with the diameter of the plane 1.2 mm. A thin disk made by pressing the Fe_2O_3 powder was used as the pressure transmitting medium, which had a diameter equal to that of the anvil plane. The gasket was made of Fe_2O_3 and talc powder mixture compressed into a thin ring (~ 10–15 μm thick). Pressures in the cells were calibrated against the various phase transitions of bismuth at room temperature and by using the superconducting Pb manometer at low temperature in separate calibration runs; however, the pressure was not directly measured *in situ* during the experimental cycles. The overall uncertainty in QHP was estimated to be ± (10–15%) at different temperatures.

Superconducting transition of the $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ sample under pressure was determined electrically by the four-probe technique, with thin platinum strips (~ 20 μm thick) used as electrical leads. The measuring direct current of (100 ± 0.2) μA was held constant in the whole range of pressures and temperatures. Sample temperature was measured using a rhodium-iron thermometer (Calibrated by Cryogenic Laboratory, CAS, China), which was inserted into the high-pressure cell and placed 10 mm from the sample. All of the $T_c(P)$ curves were measured during droping and rising of temperature and recorded by a X-Y recorder.

3. Results and discussion

The X-ray powder diffraction patterns for an as-prepared sample $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ measured with a RAX-10 X-ray diffractometer (Fig. 1) show a nearly perfect single phase of Tl-2223 with a tetragonal unit cell with parameters $a = 3.85$ Å and $c = 35.70$ Å.

The dc magnetization was measured using a SQUID magnetometer (quantum design). The ZFC magnetization as a function of temperature for the $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ sample in a field of $H =$ $= 5$ Oe and at ambient pressure shows a sharp single-phase superconducting transition at 129 K and antimagnetic factor of 19% (Fig. 2).

In order to determine the uncertainty of the temperature measurements, the system was put into a liquid LN2, of 77.4 K and the ice water of 273.15 K, respectively. Under this condition the temperature uncertainties are shown in Table 1.

Table 1

$\Delta T(K)$ – temperature difference between the sample and the thermometer which is located 10 mm from the sample

Sample temperature	Temperatures were measured by rhodium-iron thermometer 5#			
	$P = 0$ GPa	$\Delta T(K)$	$P = 3.5$ GPa	$\Delta T(K)$
77.4 K	77.44 K	0.04	77.43 K	0.03
273.15 K	273.65 K	0.5	272.55 K	0.6

We have measured the $R(T, P)$ curves for the cooling and warming processes. In this paper we gave all the curves of th

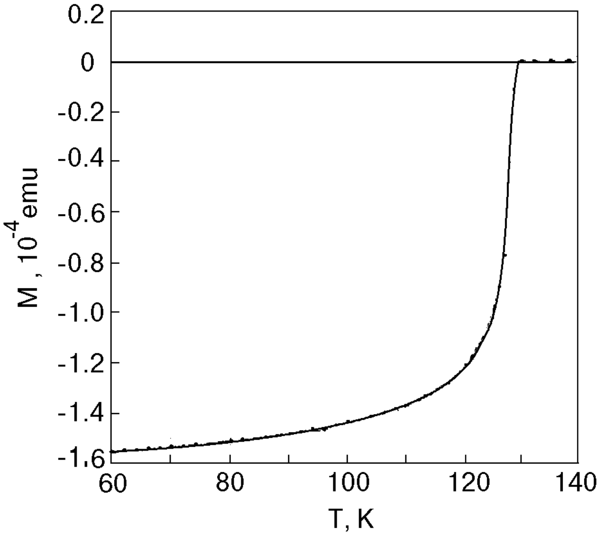

Fig. 2. Temperature dependence of magnetization of the pellet sample at ambient pressure in zero-field cooling (ZFC) at $H = 5$ Oe.

e superconducting transition during the warming processes, because the warming rate could be made as small as ~ 0.2 K/min, and steady state can easily be achieved, even though we found that the superconducting transition occurs at considerable higher temperatures in both processes.

The temperature dependence of normalized resistance with respect to the resistance values measured at T_c under different pressures up to 4.3 GPa for one sample $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ is shown in Fig. 3. The pressures were applied slowly and continuously from zero to 5 GPa. It can be seen that the T_c (onset) is clearly shifted upward with the increase of the applied pressure. When the pressure increases continuosly, the T_c rises rapidly and reaches 255.4 K at pressure of 4.3 GPa. The total change in T_c from ambient condition to the high pressure applied can be greater than 126 K. As the pressure is further increased to 4.8 GPa, the $R(T, P)$ curve changes, the behavior of the temperature dependence becomes semiconducting, and there is a marked drop of transition temperature (T_c ~ 206 K).

From Fig. 3 we can also see that the resistance (R) of the sample decreases with the increase of pressure, which, however, does not reach zero in the range of pressures applied, by analogy with the previous study of superconducting cuprates at high pressure [6,7]. The reason for the nonzero behavior of $R(T, P)$ may be attributed to possible defects and microcracks generated in the sample, as reported by C. W. Chu, et al. [6], but we think it may also come from the possible pressure gradient generated in the anvils, especially at low and very high pressures for the

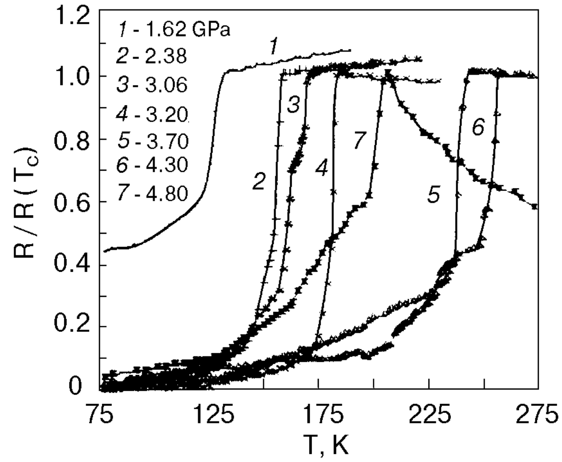

Fig. 3. Temperature dependence of normalized resistance of the $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ (Tl-2p4) sample under different pressures.

QHP system. The maximum value of the resistances of the sample is about ~ 3 Ω at the normal state and under high pressures.

To verify the reproducibility of the effect of high pressure, we have also carried out experiments with decreasing pressure. The results are summarized in Fig. 4, where the transition temperatures T_c are plotted versus pressure for both increasing and decreasing pressures. We found that $T_c(P)$ is a reversible nonlinear function of pressure. The location of the maximum of T_c and the value of $dT_c/dP = 1.7$ K/GPa (at $P = 0$) agree with the previous studies of Tristan Jover et al. [1] and J. G. Lin et al. [2], respectively.

To test the reliability of the above results, we have repeated our experiments several times with other samples cut from the same pellet which was described above. We obtained similar results, one of which is shown in Fig. 5. It can be seen that at a pressure of 3.2 GPa T_c rises to 250 K, while the resistance drops sharply to 13.5% (at 80 K) in comparison with its maximum value. For yet another sample we have obtained T_c (onset) = 153.7 and 235 K at pres

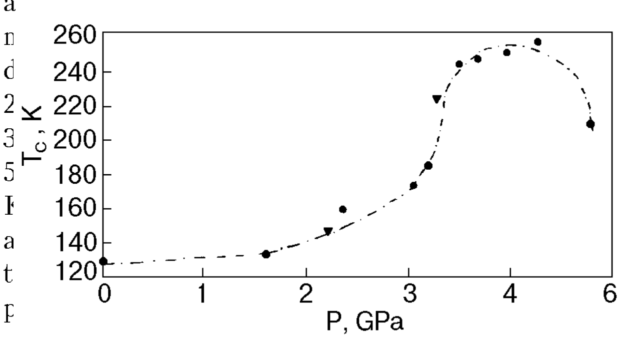

Fig. 4. Superconducting transition temperature T_c (onset) of $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ (Tl-2p4) as a function of pressure: ● — as pressure is increased; ▼ — as pressure is decreased.

sures 1.9 and 3.4 GPa, respectively, which are not shown in the figure.

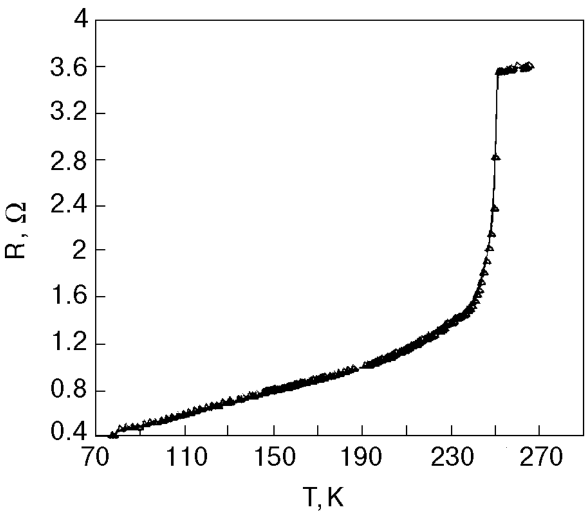

Fig. 5. Temperature dependence of the resistance of $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ (Tl-2p7) at a pressure of 3.2 GPa.

In summary, the pressure dependence of the superconducting transition temperature in the compound of $Tl_{1.8}Ba_{2.0}Ca_{2.6}Cu_{3.0}O_{10+\delta}$ has been determined: the T_c (onset) increases with increasing pressure at a relatively high rate and reaches a maximum value of 255.4 K at a pressure of about 4.3 GPa. External pressure greatly enhances the critical temperature of the oxide superconductor sample. The basic physical reason for this phenomenon is the stronger coupling between the CuO_2 planes and the change in free charge concentrations in the superconducting CuO_2 layers caused by external pressure. Our experimental investigation on the effect of high pressure on T_c of another pellet of Tl-2223 superconductor is continuing.

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