PHYSICAL REVIEW B VOLUME 41, NUMBER 13 1 MAY 1990

High-pressure study of $Bi_2Sr_2CaCu_2O_8$ single crystals

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(Received 21 September 1989; revised manuscript received 12 January 1990)

We report measurements of the in-plane resistivity (ρ_{ab}) and out-of-plane resistivity (ρ_c) on a $Bi_2Sr_2CaCu_2O_8$ high-temperature superconducting single crystal under hydrostatic pressure up to 20 kbar. ρ_{ab} has an initial derivative $d(\ln\rho_{ab})/dP$ of -0.75% kbar^{-1}, while ρ_c depends much more strongly on pressure, $d(\ln\rho_{ab})/dP \approx -4.0\%$ kbar^{-1}. The superconducting transition temperature (T_c) in both configurations increases monotonically by +0.15 K/kbar in the pressure range covered.

Soon after the discovery of high-temperature oxide superconductors, it was realized that the investigation of the normal-state properties under high pressure can supply valuable information on the mechanism for superconductivity. The strong pressure dependence of T_c of La-Ba-Cu-O (Ref. 1) lead to the idea of substituting La with the smaller Y atom, simulating the application of pressure chemically. This substitution has resulted in the 90-K superconductor $YBa_2Cu_3O_7$.[2] Since then many papers have been published on the pressure dependence of T_c. However, the results are far from being coherent: even for the same compound, positive and negative values of dT_c/dP were found.[3]

Some of the discrepancies in the pressure dependence of T_c come from varying sample quality. In order to obtain reliable results one needs measurements on high-quality single crystals which can also give relevant information on the pressure dependence of the resistivity in different crystallographic directions, in addition to dT_c/dP.

Here we report measurements on the in-plane (ρ_{ab}) and out-of-plane (ρ_c) resistivity in $Bi_2Sr_2CaCu_2O_8$ single crystals[4] and examine the response of the transition temperature to the applied pressure.

High-quality single crystals of $Bi_2Sr_2CaCu_2O_8$ (hereafter 2:2:1:2) were obtained by the flux method. CuO was used as flux, so the starting stoichiometry was 2:2:1:3. The mixture of respective oxides was heated to 1030 °C, stirred for 30 min and cooled down to 760 °C with 2 °C/h speed, and then furnace cooled. The single crystals were in the form of shiny, black, flat pyramids with a strong tendency to cleave in the a-b plane. Within the accuracy of microanalysis ($\sim 1\%$) the composition stoichiometry was 2:2:1:2. Resistivity has been measured in a four-probe configuration. Contacts were made by silver epoxy fired on 750 °C. Contact resistances were 1 Ω and they were stable during temperature and pressure cyclings. Typical sample dimensions for ρ_{ab} were $1.0\times0.5\times0.002$ mm^3. We have checked ρ_{ab} for 20 samples and have chosen one which had a single, sharp transition, ρ (300 K) = 150 μΩ cm, a linear resistivity in the 140–300-K range, and a low intercept at $T=0$ K, ρ (0 K) = 20 μΩ cm. For ρ_c measurement the sample dimensions were $0.57\times0.32\times0.02$ mm^3. Because of the large anisotropy $\rho_c/\rho_{ab} = 4\times10^4$ in our samples, we could perform a direct four-probe measurement of ρ_c, without applying the Montgomery method. Contact geometry is sketched in Fig. 3. (The current was injected in the c direction and the voltage was measured on the other pair of contacts. For current injection in the a-b plane on this sample, no detectable voltage drop was observed on the other side of the crystal). Our ρ_c value is in the same range as that of Ref. 4 obtained by the Montgomery method. The samples were mounted in a steel pressure chamber with a clamped piston rod. The pressure fluid was a 50%-50% mixture of n-pentane and izopentane. The pressure was applied at room temperature, then the piston was sealed and the chamber was put into a cryostat for the low-temperature measurements. The temperature was monitored with a Pt thermometer fixed on the pressure chamber at the sample height. The reproducibility between cooling and heating cycles was ≈ 0.03 K. The pressure was measured in the whole temperature range by means of an InSb (Ref. 5) calibrated resistor. The pressure loss on cooling was about 3 kbar.

Experimental results. Figure 1 shows the temperature dependence of ρ_{ab} at ambient pressure and at 20 kbar. For the sake of clarity the presentation of the intermediate pressures has been omitted. The resistivity decreases, T_c shifts up in temperature, and the extrapolated value of ρ_{ab} to $T=0$ K decreases under pressure. The transition region is magnified in Fig. 2, and data for all pressures are shown here. One can see that there is no structure in the transition and that the transition width does not increase with pressure [$\Delta T_c \equiv T(90\%R_N) - T(10\%R_N) = 6.2$ K for 1 bar and 6.0 K for 16 kbar, where R_N is the linearly extrapolated normal resistance value at T_c].

The out-of-plane resistivity ρ_c versus temperature is shown in Fig. 3 for several pressures. It shows a nonmetallic temperature dependence at all pressures and its magnitude is in the Ω cm range. The resistivity decreases strongly with pressure while T_c goes up. The transition region is enlarged in Fig. 4. One can indeed observe steps corresponding to a weak distribution of T_c, however, it does not disturb the evaluation of dT_c/dP. In this direc-

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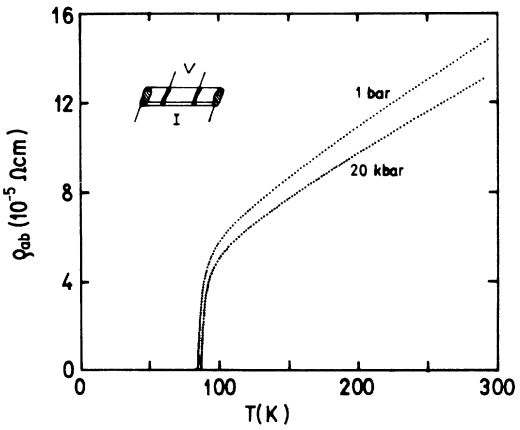

FIG. 1. Temperature dependence of ρ_{ab} for ambient pressure and for 20 kbar. Intermediate pressures are omitted for clarity. Sketch of contact geometry is also shown.

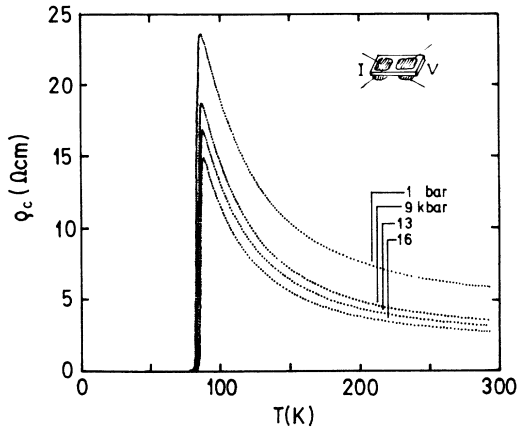

FIG. 3. Temperature dependences of ρ_c for all applied pressures. Sketch of contact geometry is also shown.

tion there is probably no influence of superconducting fluctuations and ΔT_c is narrower than for ρ_{ab}, despite the distribution of T_c; ΔT_c is 2.6 K at 1 bar and 2.3 K at 16 kbar. We have obtained T_c as a function of pressure from the $\rho_{ab}(P,T)$ curves using the usual criteria of 90%, 10%, and 50% transition points of R_N, and all these values are plotted as $T_c(P)-T_c(0)$ versus pressure in Fig. 5. One can see that dT_c/dP does not depend on the definition of T_c and has the value $dT_c/dP=0.15\pm0.02$ K/kbar.

For comparison with theory it can be useful to know the pressure dependence of the normal-state resistivity ρ_{ab} and ρ_c. Figures 6 and 7 show, respectively, $\rho_{ab}(P)/\rho_{ab}(0)$ and $\rho_c(P)/\rho_c(0)$ versus pressure at different temperatures [ρ_{ab} and ρ_c data have been interpolated so that they refer to the same reduced temperatures $T/T_c(P)=$const]. This interpretation is useful for discussing possible effects which scale as T_c, however, since $d\ln T_c/dP$ is small, it only has a minor effect on the $\rho(P)/\rho(0)$ curves. The temperatures noted on the figures correspond to $\rho(T,1$ bar). The initial slope of $d\rho_{ab}/dP$ at 300 K is -0.75% kbar^{-1}, but it increases in absolute value on decreasing temperature, e.g., at 90 K it is -1.25% kbar^{-1}. The initial slope of the pressure derivative of ρ_c is much stronger if it is -4% kbar^{-1} at 300 K and decreases in absolute value to -2.5% kbar^{-1} at 90 K.

Discussion. For the Bi-Sr-Ca-Cu-O superconductors there are already some reports on the pressure dependence of T_c performed on polycrystalline[6,7] and single-crystal[8] samples. The samples from this family are usually multiphased and of lower quality with a very broad transition, which further broadens with pressure making it difficult to evaluate the relevant transition temperature. Hence dT_c/dP was found to be negative in Ref. 6, positive in Ref. 7, and in the measurements of Goldstein *et al.*[8] it is nonlinear, that is, T_c increases up to 10 kbar and then it decreases above this pressure.

Our results for dT_c/dP do not show any nonlinearity and we can try to give a description within the conventional BCS theory. Following the analysis of Sundquist[9] and Griessen and co-workers[3,10] applied to $YBa_2Cu_3O_7$ one gets $d\ln T_c/d\ln V=-\gamma+g(\lambda,\mu^*)d\ln\lambda/d\ln V$, where γ is the Gruneisen parameter and g is a complex function of

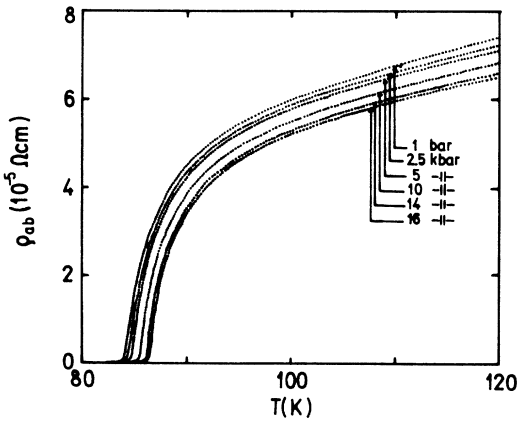

FIG. 2. Enlarged transition region of ρ_{ab} for all applied pressures.

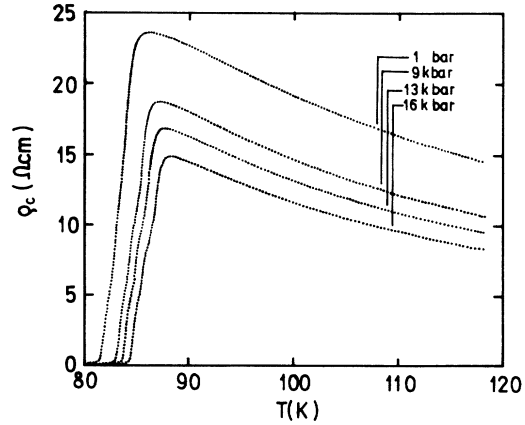

FIG. 4. Enlarged transition region of ρ_c for all applied pressures.

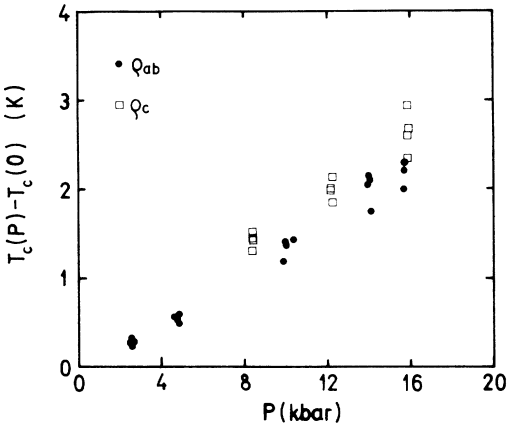

FIG. 5. Pressure dependence of the transition temperature for current flow in the a-b plane and in the c direction. The transition temperature is defined as the temperature at which the resistivity equals 90%, 50%, and 10% of the extrapolated normal resistivity.

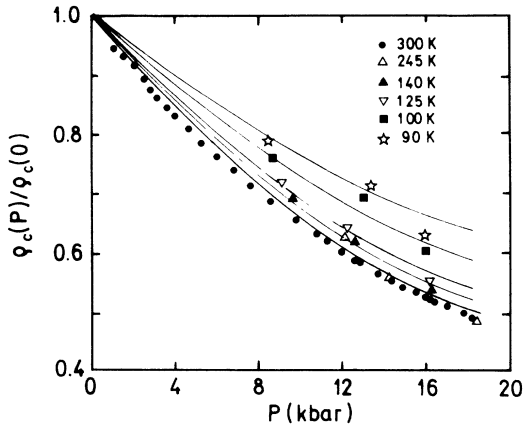

FIG. 7. Pressure dependence of normalized resistivity for current in c direction and for several temperatures. Contrary to Fig. 6 the initial slope of the curve increases slightly with temperature.

λ and μ^*, the Coulomb pseudopotential. In Griessen's[3] analysis $g(\lambda,\mu^*)\approx 0.4+1/\lambda$. $d\rho_{ab}/dP$ give $d\ln\lambda/d\ln V = 13-q$, where $q=d\ln\omega_p^{-2}/d\ln V$ (ω_p being the plasma frequency).

In order to account for the measured value of $d\ln T_c/d\ln V=-3$ (even taking $\lambda=10$), for $\gamma=4$ unrealistically strong pressure dependence of the plasma frequency is needed, $q=11$, or with a reasonable $q=2$, we need $\gamma=9$, which is also unlikely. This discrepancy between $d\ln T_c/d\ln V$ and $d\ln\lambda/d\ln V$ suggest that the resistivity probably is not limited by electron-phonon scattering, or one has to treat the results in a two-band model, considering that the above derivatives are determined by different bands.

One possible way to account for the experimental results is to evoke the model of Tesanovic[11] and Ihm and Yu,[12] where T_c depends mainly on the interaction between the CuO_2 planes. They propose a similar BCS-like expression for $T_c:T_c\sim\exp(\lambda_V+\lambda_W)^{-1}$, where λ_V is the inplane and λ_W the interplane interaction parameter. Looking at the crystalline structure one could expect the lattice to be much softer in the c direction so the interplane interactions could vary more with pressure than the in-plane interactions. This model can qualitatively account for the large scatter of the $d\ln T_c/d\ln V$ results in the literature on Y-Ba-Cu-O.[3] It is known that ρ_c varies from sample to sample and can show metallic or semiconductor temperature dependence, which is influenced by the oxygen content and probably by disorder in the oxygen sublattice. This disorder, which can be present even at the level of the unit cell, can reduce the interplane coupling. Samples may also vary in phase purity (intergrowths, e.g., 2:2:2:3 layers; inclusions, e.g., $SrCuO_2$ layers) which can also influence dT_c/dP. The importance of the interplane couplings has also been noticed by Crommie *et al.*[13] by measuring the effect of uniaxial stress on the c-axis resistivity of $YBa_2Cu_3O_{7-x}$ single crystals.

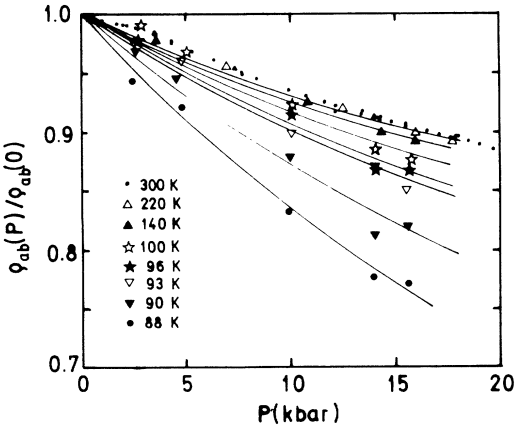

FIG. 6. Pressure dependence of normalized resistivity for current in the a-b plane and for several temperatures. Initial slope of the curve decreases with temperature.

Another interesting point is the temperature dependence of the $\rho_{ab}(P)/\rho_{ab}(0)$ vs P curves: Below 140 K the pressure dependence of ρ_{ab} increases with decreasing temperature (Fig. 5). Looking at the ρ_{ab}-T curve, one can realize that below this temperature ρ_{ab} decreases faster than linearly with temperature. This "extra conductivity" (σ) is usually treated as a three-dimensional Aslamazov-Larkin fluctuating superconducting contribution above T_c. Our results show that pressure increases this term. If pressure favors the superconducting pairing above T_c, it means that the number of normal carriers which can hop in the c direction is decreased, so $d\rho_c/dP$ has an opposite, weaker temperature dependence than $d\rho_{ab}/dP$, as observed (Fig. 7).

In conclusion, the pressure dependence of ρ_{ab} and ρ_c of $Bi_2Sr_2CaCu_2O_8$ single crystals give a monotonic increase of T_c with pressure. This can be explained in a model where T_c is controlled by a Josephson-like coupling of CuO_2 planes. The strong and opposite temperature dependence of $d\rho_c/dP$ and $d\rho_{ab}/dP$ below 140 K could be due to the strong pressure dependence of the superconducting fluctuations.

The high-pressure chamber loaned by the Budapest group and useful discussions with J. R. Cooper are gratefully acknowledged. This work has been partly supported by the Foundation for the Scientific Cooperation of the European Community and Yugoslavia.

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