a-b anisotropy of the normal-state resistivity of untwinned $YBa_2Cu_3O_{7-\delta}$

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The *a-b* anisotropy of the normal-state resistivity ρ_a/ρ_b of untwinned $YBa_2Cu_3O_{7-\delta}$ has been studied on six crystals using the Montgomery method. ρ_a/ρ_b increases with increasing temperature and reaches a (sample-dependent) value of 1.2–1.85 near room temperature. The wide variation of this value is attributed to the high sensitivity of the chain resistance to oxygen disorder. The temperature dependence of ρ_a/ρ_b can be modeled by a parallel circuit of metallic chains and superconducting planes with excess conductivity due to superconducting fluctuations in the planes at temperatures below 150 K.

The orthorhombic structure of $YBa_2Cu_3O_{7-\delta}$ is characterized by two features: the corrugated CuO_2 planes sandwiching the Y sites and the one-dimensional Cu-O chains along the **b** direction in the basal plane. The CuO_2 planes, which are the probable location of the superconducting carriers, give rise to large anisotropies of the normal state and superconducting properties between the **c** direction and the basal plane. The presence of the chains introduces additional *a-b* anisotropy in the elastic constants,[1] whereas superconducting properties (penetration depth,[2] upper critical field,[3] magnetic torque,[4] flux pinning[5]) appear almost isotropic in the basal plane.

With the availability of untwinned $YBa_2Cu_3O_{7-\delta}$ crystals of sufficient size, measurements of the *a-b* anisotropy of the resistivity in the normal state are now possible. Band-structure calculations[6] predict an enhanced conductivity along **b** due to the presence of a one-dimensional band along this direction. Recent measurements of infra-red (IR) reflectivity[7,8] on detwinned $YBa_2Cu_3O_{7-\delta}$ seem to confirm this prediction.

Here we present low-frequency measurements of the anisotropy ρ_a/ρ_b of the normal-state resistivity on six detwinned crystals of various quality. We find the resistivity along **a** to be larger in all cases than along **b** and that ρ_a/ρ_b is temperature dependent, reaching values ranging from 1.2 to 1.85 at room temperature. The results are discussed in a model of a parallel circuit of planes and chains.

Measurements of the *a-b* anisotropy of the resistivity were performed on six $YBa_2Cu_3O_{7-\delta}$ crystals grown by a self-flux method.[9] In order to keep the shape anisotropy, small crystals of almost square geometry were selected. They were detwinned by annealing under uniaxial stress.[3] The anisotropy of the resistivity ρ_a/ρ_b in the *a-b* plane was measured using the Montgomery method.[10] Four small contacts were attached to the corners of the top *a-b* surface of the crystals in two steps. First, four dots of silver paste were placed and sintered to the surface at 420 °C in flowing oxygen. Then gold wires were glued to the dots with silver paste. This resulted in contacts with less then 1 Ω resistance. In order to obtain absolute values for the resistivity the contacts on two crystals were extended to the conventional four-probe geometry after completing the measurements of ρ_a/ρ_b.

Within the Montgomery method ρ_a/ρ_b is determined from the relation

$$\sqrt{\rho_a/\rho_b}=(l_a/l_b)(l_b'/l_a') \ . \tag{1}$$

Here l_a' (l_b') is the distance between contacts along **a** (**b**), and l_a (l_b) refers to equivalent points on an isotropic crystal. l_a/l_b is determined through the resistance ratio R_a/R_b. $R_{a,b}$ are the resistances as determined from the voltage measured between the two contacts along **a** (**b**) on one side of the crystal while the current is passed through the contacts on the opposite side. Since R_a/R_b was found in all cases to be smaller than about 50, neither the sample thickness nor the resistivity in the **c** direction plays a significant role in the derivation of ρ_a/ρ_b.[10]

The temperature dependence of R_a and R_b for crystal no. 3 is shown in Fig. 1. At high temperatures a linear temperature dependence[11] is observed, whereas at temperatures below 150 K deviations from linearity are found. Similar behavior has been observed on twinned crystals and has been interpreted as excess conductivity due to superconducting fluctuations.[12] The results on our detwinned crystals indicate that the deviations from linearity are more pronounced in the **a** direction than in **b**. This difference between **a** and **b** direction leads to a temperature-dependent anisotropy of the resistivity as

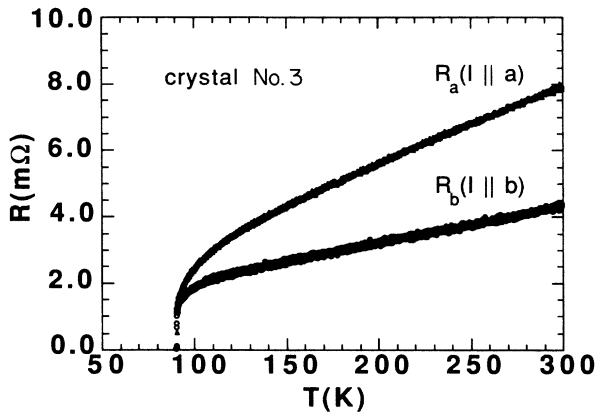

FIG. 1. Temperature dependence of the resistance of crystals no. 3 measured along **a** and **b**.

shown in Fig. 2. At temperatures higher than 250 K, ρ_a/ρ_b seems to saturate at a value between 1.2 and 1.85 for the different crystals. That is, the resistivity along **a** is higher than along **b**. This result is in agreement with recent measurements of infrared reflectivity[7,8] and band-structure calculations,[6] which indicate additional metallic conductivity along **b**. Reasons for the wide variation of ρ_a/ρ_b will be discussed below. Also included in Fig. 2 are the results for a twinned crystal. The temperature-independent value of 1.05 for ρ_a/ρ_b confirms that the Montgomery method gives reliable results. The difference between the measured value and the expected value of 1.00 is due to uncertainties in the distance between contacts.

Figure 3 shows the temperature dependence of the resistivity along the two orientations for a crystal with $\rho_a/\rho_b=1.8$ (no. 2) and with $\rho_a/\rho_b=1.35$ (no. 4). ρ_b has been measured after extending the contacts to the conventional geometry, whereas ρ_a has been calculated from the data in Fig. 2. In a simple model it is assumed that along the **a** direction the resistivity due to the planes is measured, whereas along **b** a parallel circuit consisting of the planes and the chains is measured. With the additional assumption that the plane contribution is isotropic, the chain contribution ρ_{ch} can then be calculated from

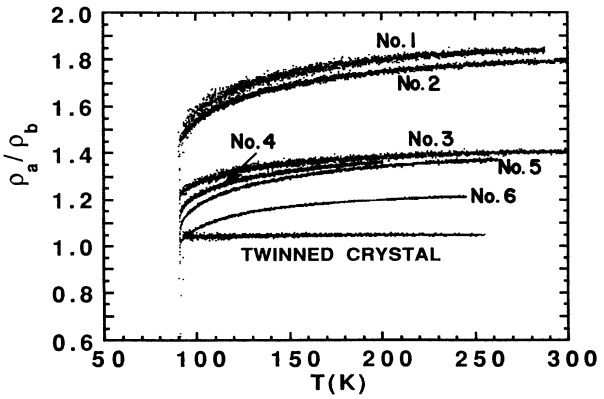

FIG. 2. Temperature dependence of the resistivity anisotropy ρ_a/ρ_b for the six detwinned crystals and the twinned crystal.

$$\rho_{ch}=\rho_b/(1-\rho_b/\rho_a)\,, \tag{2}$$

which is also shown in Fig. 3. This model does not include the conduction path along the bridging oxygen O(4) sites which allows charge to be transferred between the chains and planes. However, since there are O(4) on all four edges of the unit cell, this contribution is assumed to be isotropic in the *a*-*b* plane.

For the crystal with the large value of ρ_a/ρ_b, ρ_{ch} is of comparable size to ρ_a and ρ_b and shows a metallic temperature dependence. Down to temperatures very close to T_c, ρ_{ch} is linear in T. In contrast, for the crystal with $\rho_a/\rho_b=1.35$, ρ_{ch} is about a factor of 5 larger than ρ_a,ρ_b, and shows the tendency to saturation below 120 K. The absence of a downturn in the chain resistivity strongly suggests that fluctuations occur only in the planes, a conclusion supported by ir data[7] showing normal-state behavior in the chains below 90 K. Indeed, the temperature dependence of the anisotropy can be understood qualitatively by assuming fluctuations only in the planes. Using the parallel resistor formula and a linear temperature dependence for the chains ($\rho_{ch}=c_0+c_1T$) and planes ($\rho_a=a_0+a_1T$), we obtain

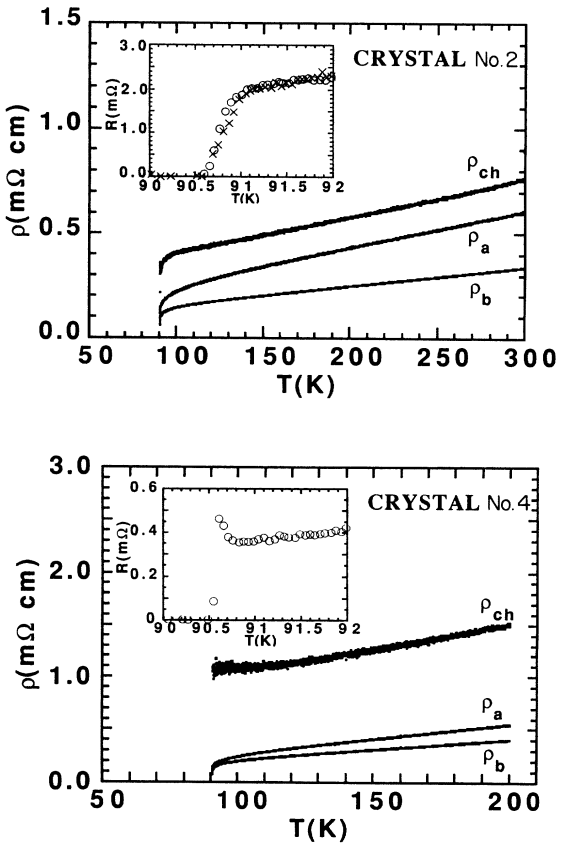

FIG. 3. Temperature dependence of the resistivity along the crystallographic axes and of the chain contribution for crystal no. 2 (upper panel) and crystal no. 4 (lower panel). The insets show details of the superconducting transition for both Montgomery configurations in crystal no. 2 and the *b* configuration in crystal no. 4. (The other configuration of crystal no. 4 does not fit on the same scale.)

TABLE I. Comparison of the resistivity anisotropy ρ_a/ρ_b with other parameters describing the crystal. T_c (onset) is the onset temperature of the resistive transition, ΔT_c the transition width, RR the resistivity ratio taken between the values at 250 and 100 K. Resistive transition describes whether the transition shows structures (see inset of Fig. 3 for examples).

Crystal no.	ρ_a/ρ_b	T_c (onset) (K)	ΔT_c (K)	RR	Resistive transition
1	1.85	93.1	0.2	4.4	clean
2	1.8	91	0.4	2.2	clean
3	1.4	90.9	0.5	2.8	structure
4	1.35	91	0.4	2.2	structure
5	1.35	91.1	0.3	3.0	structure
6	1.2	90.5	0.2	3.1	structure

$$\frac{\rho_a}{\rho_b}=1+\frac{1/(c_0+c_1T)}{1/(a_0+a_1T)+\sigma_{fl}},$$

where σ_{fl} is the fluctuation conductivity. For large T, ρ_a/ρ_b will saturate at $1+a_1/c_1$ (which for crystals no. 2 and no. 4 is 2 and 1.6, using linear fits to the high-temperature values of ρ_a and ρ_{ch} in Fig. 3), while at T_c ρ_a/ρ_b will drop sharply to 1 since σ_{fl} diverges. This model also explains why the downturn due to fluctuations in ρ_b is more pronounced in crystal no. 4 with large ρ_a/ρ_b than in crystal no. 2 with a small ρ_a/ρ_b: The low chain resistivity more effectively shorts out the changes in the plane resistivity due to fluctuations. This picture of superconductivity confined to the planes with metallic chains acting as reservoir of charge is consistent with the absence of anisotropy in H_{c2} between **a** and **b** (Ref. 3) and IR data[7] finding no superconducting gap in the chains at 35 K, as well as with the anisotropy normal-state resistivity reported here.

In Table I the observed values of the anisotropy are compared with other parameters characterizing the crystals. It appears that a high value of ρ_a/ρ_b implies, in addition to a high T_c, a clean, sharp superconducting transition, whereas structures in the superconducting transition are associated with low values of ρ_a/ρ_b. Examples for these two cases are shown in the insets of Fig. 3. Since structure in the transitions is probably caused by inhomogeneities of the oxygen content or oxygen disorder, we attribute the variations of the measured ρ_a/ρ_b to interruptions of the chains due to oxygen vacancies. This might also account for some differences between our results and those reported recently[13] which were obtained from an alternate analysis. Intrinsic parameters of the chains like density of states and scattering times will be accessible only in nearly perfect crystals. It therefore appears that the values of ρ_a/ρ_b are a sensitive measure of the degree of chain disorder.

In conclusion, the conductivity along **b** is larger than along **a** for all temperatures and all crystals studied here. These results are in agreement with band-structure calculations and IR reflectivity measurements. The anisotropy ρ_a/ρ_b increases with increasing temperature and saturates at values ranging from 1.3 to 1.85 near room temperature. The wide variation of this value is attributed to the high sensitivity of the chain resistance to oxygen disorder, and the temperature dependence of ρ_a/ρ_b can be described by a parallel circuit of planes and chains.

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