Bloch-Grüneisen behavior for the in-plane resistivity of $Bi_2Sr_2CuO_x$ single crystals

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The temperature dependence of the in-plane resistivity of $Bi_2Sr_2CuO_x$ single crystals with a superconducting critical temperature $T_c \simeq 3$ K has been investigated. The observed linear temperature dependence in the resistivity at high temperatures saturates below 40 K towards a constant residual resistivity. Such a behavior can be described by the conventional Bloch-Grüneisen theory for the influence of electron-phonon scattering in the resistivity.

In view of the question if a conventional Fermi-liquid description can be used for the high-T_c superconductors, the understanding of unusual normal-state properties of the cuprates is of crucial importance.[1,2] A complication for such investigations lays in the fact that, unlike the situation in the superconducting coherent ground state, the properties in the normal state are usually very sensitive to the sample quality. Among the unusual normal-state properties, the observed linear temperature dependence of the electrical resistivity extending from the critical temperature T_c up to very high temperatures remains a puzzling question.[3–8] This problem is strongly related to the understanding of the mechanism of high-T_c superconductivity. It is of importance to know if this linear dependence can be understood in terms of the electron-phonon interaction or has to be described with some other interaction mechanism in these strongly correlated systems. The $Bi_2Sr_2CuO_x$ system (2201 phase) is very attractive for such a study in the cuprates because the low critical temperatures ($\leq$ 10 K, depending on the Bi/Sr ratio) allow to follow the in-plane resistivity in the normal state down to temperatures much lower than the Debye temperature. In the present investigation we have measured a conventional Bloch-Grüneisen behavior in the temperature-dependent resistivity for $Bi_2Sr_2CuO_x$ single crystals with critical temperatures below 5 K.

In normal-state transport experiments on $Bi_2Sr_2CuO_x$ single crystals (ratio Bi/Sr=1) with superconducting transition temperature $T_c = 6.5 - 8.5$ K a linear temperature dependence of the *ab*-plane resistivity $\rho_{ab}(T)$ has been observed from just above T_c up to 700 K.[4] More recently, measurements of the anisotropy in the resistivity of 2201-phase single crystals (ratio Bi/Sr=1.05) with T_c up to 7.5 K have been reported.[8] The *ab*-plane resistivity increased approximately linearly with temperature between 10 and 300 K, but a deviation from linearity occurred below 40 K. These linear dependencies in the electrical resistivity down to very low temperatures[4,8] cannot be explained in terms of the electron-phonon interaction in the usual way yielding an unclear situation for the possibility of a phonon-mediated pairing mechanism in the superconducting state.

We report here normal-state resistivity measurements on high-quality single crystals of $Bi_2Sr_2CuO_x$. The $Bi_{2+x}Sr_{2-(x+y)}Cu_{1+y}O_z$ single crystals with a high deficiency of Sr were obtained from a solution melt in KCl.[9] Superconducting crystals could be grown in the temperature range $830 - 845°$ C with the ratio Bi/Sr $= 1.6 - 1.7$ provided the Cu content was increased up to $1.1 - 1.3$. For Bi/Sr ratios higher than 2, nonsuperconducting crystals are formed. The sizes of the investigated crystals were around 0.6–2.5 mm × 0.4–0.7 mm × 3–10 μm. The T_c values measured by dc-resistivity and ac-susceptibility methods ranged from 3 to 13 K. For the resistivity measurements low resistance contacts were made to the crystals by using fired-on gold films. A four-probe contact configuration with symmetrical positions of the contacts on one side of the sample was used for the measurements of the in-plane resistivity ρ_{ab} with an analysis according to the Montgomery method.[10]

The transition curves of crystals with the onset for superconductivity between $7 - 13$ K were broadened up to

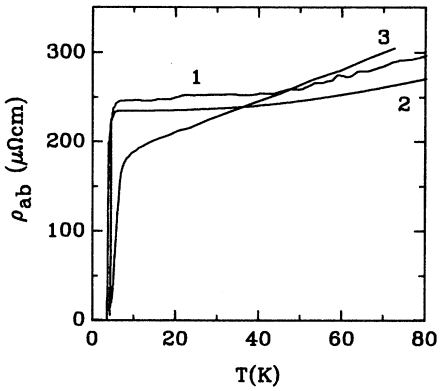

FIG. 1. In-plane resistivity ρ_{ab} of $Bi_2Sr_2CuO_x$ (2201 phase) single crystals. The crystals with lowest T_c show a saturating (nonlinear) temperature dependence for decreasing temperatures.

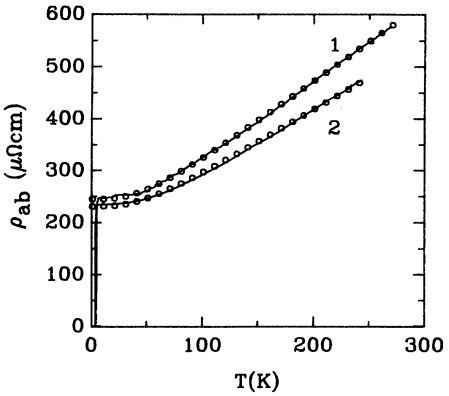

FIG. 2. In-plane resistivity ρ_{ab} of $Bi_2Sr_2CuO_x$ (2201 phase) single crystals with lowest T_c. The data points have been obtained from a Bloch-Grüneisen dependence according to Eq. (1).

4 K (10 and 90 % points of the transition). These crystals showed the approximately linear temperature dependence of resistance with the previously reported deviations from linearity just above T_c.[8] An example of the temperature dependence of the *ab*-plane resistivity for such a sample has been plotted in Fig. 1 (sample No. 3). There exists no satisfactory explanation for the anomalous decrease (with respect to linearity) in the temperature region just above T_c. The decrease in resistance cannot be explained in terms of fluctuation-induced superconductivity as encountered in the high-T_c superconductors, because the critical temperature is far too low with respect to the temperature range where the anomalous decrease in the resistivity is observed.

For samples with T_c below 5 K, the observed superconducting transition was very narrow with the width defined by the 10 and 90 % points of the transition equal to 1 K or even lower (0.3–0.4 K). X-ray rocking curves of these crystals showed that the crystals consisted of blocks with a relative misorientation in the *ab* plane not larger than three-tenths of a degree and a high homogeneity of the crystal supercell was found. Such a crystallographic analysis for the crystals with a higher T_c showed larger misorientation and inhomogeneity. The observed correlation between composition, supercell parameters, and superconducting properties from resistivity and magnetization data suggests that the broadening of the transitions is related to the crystal inhomogeneity.[9] Moreover, magnetoresistance measurements up to 10 T showed for our samples with a higher T_c indications for multiple superconducting transitions.

In the following we will concentrate on experimental data for the single crystals with $T_c = 3 - 5$ K with a narrow superconducting transition. In Fig. 1 we display the in-plane transition curves of $\rho_{ab}(T)$ not far from T_c for two crystals with a low-T_c value. The curves exhibit a saturating residual resistivity ρ_0 which lies between 230 and 250 $\mu\Omega$ cm. For this cuprate material a clear indication of a residual resistivity is found. Moreover, the observed saturation of the resistivity for decreasing temperatures resembles the usual behavior in metals and contrasts previous results for the 2201 phase.[4,8] In Fig. 2 we have plotted the resistivity data for samples No. 1 and No. 2 on a more extended temperature scale. For the slope $\Delta\rho_{ab}/\Delta T$ of the in-plane resistivity at high temperatures we obtain 1.47 and 1.26 $\mu\Omega$ cm/K for, respectively, samples No. 1 and No. 2.

The obtained values for the residual resistivity are a factor 2–3 larger than the values reported by Martin *et al.*[4] (70–100 $\mu\Omega$ cm) and Hou *et al.*[8] (91 $\mu\Omega$ cm). The observed saturating behavior at low temperatures in our samples could therefore be related to an inhomogeneous sample composition and the mixing with other phases showing semiconducting-type of behavior in the resistivity. As mentioned above, x-ray analysis showed a better crystalline quality for the crystals with a sharper superconducting transition. Particularly, by measuring the in-plane (along *a* axis) component of the modulation vector one can determine the excessive oxygen concentration and thereby it is found that the fraction of nonsuperconducting phases is smaller than the accuracy (3%) of such a determination.[9]

The differences in the absolute values of the resistivity are also influenced by the experimental procedure for obtaining these values. It has been previously found in Tl compounds that the resistivity values obtained with a Montgomery method are roughly a factor 2 larger than the values obtained by means of the Van der Pauw method.[11] For sample No. 1 we have observed a similar effect without any change in the functional temperature dependence of the resistivity. Moreover, due the strong anisotropy of the investigated material, the current distribution parallel to the *ab* planes is probably not totally homogeneous in our contact configuration.[12] The above cited works showed also a smaller slope for the linear resistivity data [0.71–1.06 $\mu\Omega$ cm/K (Ref. 4) and 0.58 $\mu\Omega$ cm/K (Ref. 8)]. Comparing data on a normalized scale $(d\rho/dT)/\rho$ would decrease the observed differences between the different data sets.

We will analyze our data of the temperature depen-

dence of the in-plane resistivity $\rho_{ab}(T)$ for our 2201 single crystals in terms of the electron-phonon scattering mechanism. Using Matthiessen's rule the scattering rate $1/\tau$ of the electrons in ordinary metals can be described as a superposition of scattering by impurities and phonons. This determines the resistivity $\rho_{ab} = \rho_0 + \rho_{ep}(T)$, where ρ_0 is the residual resistivity governed by impurity scattering and $\rho_{ep}(T)$ by the electron-phonon interaction. The temperature-dependent resistivity is proportional to the electron-phonon transport scattering rate $1/\tau_{ep}$ which can be estimated theoretically from the Bloch-Grüneisen formula[13]

$$\hbar/\tau_{ep} = 4\pi k_B T \int_0^{\omega_{max}} \frac{d\omega}{\omega} \alpha^2_{tr} F(\omega) \left[\frac{\hbar\omega/2k_BT}{\sinh(\hbar\omega/2k_BT)}\right]^2 . \quad (1)$$

The transport Eliashberg function $\alpha^2_{tr}F(\omega)$ differs slightly from the Eliashberg function $\alpha^2F(\omega)$ for the spectrum of the electron-phonon interaction with respect to the efficiency of scattering processes on the electrical resistance.

At temperatures larger than the characteristic Debye temperature Θ_D (in practice about 0.25 Θ_D), a linear $\rho_{ab}(T)$ dependence is expected from the electron-phonon interaction. For the high temperature limit of Eq. (1) it follows readily $\hbar/\tau_{ep} = 2\pi\lambda_{tr}k_BT$. The parameter $\lambda_{tr} \equiv 2\int \frac{d\omega}{\omega}\alpha^2_{tr}F(\omega)$ is determined by the transport Eliashberg function in analogy to the electron-phonon-interaction parameter λ which determines T_c in a strong-coupling theory. From a simple Drude analysis follows a relation $\lambda_{tr} = (\hbar\omega_p^2\Delta\rho_{ab}/\Delta T)(\epsilon_0/2\pi k_B)$ between the electron-phonon-interaction parameter and the resistivity slope,[3,14] where $\omega_p = \sqrt{ne^2/\epsilon_0 m}$ is the plasma frequency. Taking the plasma energy $\hbar\omega_p = 1$ eV,[4,8] we obtain $\lambda_{tr} = 0.33$ from the average slope of 1.36 $\mu\Omega$ cm/K of samples No. 1 and No. 2. Realizing that $\lambda_{tr} \simeq \lambda$,[14] the calculated λ_{tr} value represents a moderate electron-phonon interaction which seems to be consistent with the low T_c value of our samples. Because of the uncertainty in the plasma energy (a problem related to the electronic band structure), an estimate for the critical temperature using a McMillan formula lacks accuracy.

Using a numerical inversion of Eq. (1) an attempt has been made to obtain the function α^2F_{tr} from the experimental temperature-dependent resistivity data. Allowing for a minimum number of nonzero positive values of α^2F_{tr} with a 2 meV resolution, an optimized solution of the inversion problem could be found in a least-squares iteration with a standard deviation smaller than of 1 $\mu\Omega$ cm (comparable to the accuracy of the measurements) between calculated and experimental resistivity. In Fig. 3 we show the result for the obtained electron-phonon-interaction function α^2F_{tr} from the experimental data of samples No. 1 and No. 2. To test the stability of the used algorithm for the inversion of the resistivity data with respect to the experimental error, we have repeated the procedure with the experimental data disturbed by randomly distributed noise with a variance equal to the experimental accuracy. It was found that for these changed input data, the obtained peak positions for α^2F_{tr} changed as little as 2 meV. In our analysis the found α^2F_{tr} function is certainly not the real α^2F_{tr} function but the peak positions are determined by the positions of maximal curvature on the experimental $\rho_{ab}(T)$ curve. The maxima at the highest energy are not well defined due to broadening at higher temperatures. Because no inelastic neutron data are available for the $Bi_2Sr_2Cu_1O_x$, we have plotted for comparison in Fig. 3 the phonon density of states $F(\omega)$ of $Bi_2Sr_2CaCu_2O_x$.[15] From this comparison it is important to note that the range of phonon energies in our obtained α^2F spectrum lays well within that for the expected phonon density of states.

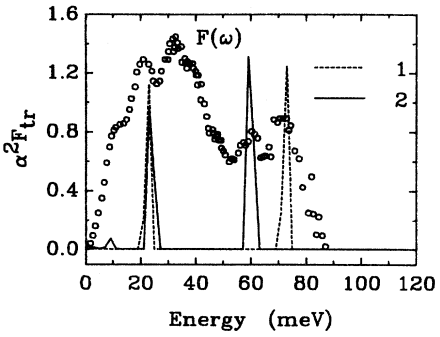

FIG. 3. The electron-phonon-interaction function α^2F_{tr} obtained from a numerical inversion of the resistivity data in Fig. 2 using Eq. (1) for two $Bi_2Sr_2CuO_x$ (2201 phase) crystals. For comparison, the data points represent the phonon density of states $F(\omega)$ for $Bi_2Sr_2CaCu_2O_x$ (2212 phase) obtained from inelastic neutron-scattering experiments (Ref. 15).

In conclusion, we have found that the in-plane resistivity of the low-T_c 2201 phase of the Bi cuprates can be described from $T_c \simeq 3$ K up to 300 K by the conventional Bloch-Grüneisen formula for the electron-phonon interaction. The deviations from linearity show a saturating behavior for temperatures below 40 K resulting in a clear residual resistivity at the lowest temperatures.

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