Transport properties of $Bi_2Sr_2CuO_6$ single crystals: Possibility of interplane coupling in the weakly localized regime

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Transport properties of $Bi_2Sr_2CuO_6$ single crystals, including the electric conductivity magnetoresistance, and Hall coefficient, were measured. Characteristics of the conductivity in the weakly localized regime, which includes temperature, electric field, and magnetic field, were also measured. The coefficient of ln H was found to be much smaller than the theoretical value predicted for the weakly localized regime. Measurement of the Hall coefficient indicates that the electron-electron interaction does not play a significant role in the conductivity. Rather, interplane coupling appears to play a role in the transport properties of this system.

The nature of normal-state conduction in high-T_c superconducting cuprates remains unknown, although many years have passed since the discovery of superconducting cuprates. Previous studies reported a ln T upturn in resistance at low temperature in various kinds of cuprates, such as $La_{2-x}Sr_xCuO_{4+y}$ (Ref. 1), $Bi_2Sr_2CuO_6$ (Refs. 2,3), $Nd_{2-x}Ce_xCuO_y$ (Refs. 4,5), $Nd_2CuO_{4-x-\delta}F$ (Ref. 6), and $Pr_{2-x}Ce_xCuO_4$.[7] This upturn is thought to be due to the weakly localized regime (WLR) of Anderson localization. The reasons are that electric conduction in cuprate occurs in the two-dimensional CuO_2 plane and that the doped carriers introduce random potential into the plane. Tanda *et al.* demonstrated that the localized states of $Nd_{2-x}Ce_xCuO_y$ (Ref. 4) and $Nd_2CuO_{4-x-\delta}F$ (Ref. 6) can best be described as a disordered Fermi-liquid system, i.e., essentially the same as the localized states in conventional metal films. However, other studies have reported different phenomena in the localized state of cuprates: these differences include isotropic magnetoresistance observed in $La_{2-x}Sr_xCuO_{4+y}$ (Ref. 1) and anomalous temperature dependence of the dephasing rate, $\tau_\phi \propto T^{-1/3}$, observed in $Bi_2Sr_2CuO_6$.[3]

The present paper reports the electric-field, temperature, and magnetic-field dependences of conductivity in the localized state of $Bi_2Sr_2CuO_6$ single crystals. We also measured the Hall coefficient of the sample. Theories of localization phenomena for metal films predict these dependences, which are represented as ln T, ln H, and ln E, and the coefficients are related to each other. We observed ln T, ln E, and ln H dependences in the localized regime of the $Bi_2Sr_2CuO_6$ single crystals and found that the coefficient of ln H is much smaller than the others. One may consider that this discrepancy in the coefficient of ln H is caused by electron-electron interaction. However, the effect of the electron-electron interaction was found to be negligible, since the Hall coefficient was independent of temperature. The results suggest that interplane coupling between the conducting planes plays an important role in the transport phenomena in $Bi_2Sr_2CuO_6$.

The $Bi_2Sr_2CuO_6$ single crystals used in this study were synthesized by the self-flux method.[8] A composite powder consisting of Bi_2O_3, $SrCO_3$, and CuO was placed in an alumina crucible and the mixture was reacted in a furnace at 950 °C for 4 h. The furnace was cooled at the rate of 1 °C/h. All the processes were carried out under standard atmosphere. The resulting crystals were black and slab shaped. Typical sample size was $0.5\times1\times0.01$ mm^3. Electric conductivity of the sample was measured by the standard four-probe technique. Voltage drop across the sample was measured using a nanovoltmeter (Keithley 182). Typical current was 100 μÅ for 1 Ω measurement. Electrical contacts were fabricated by the following method: gold thin film was sputtered onto the sample, and silver wires were attached with silver paste and cured at 160 °C for 2.5 h. Resistance of the contacts was typically 10 Ω.

To prevent Joule heating from raising the temperature of the sample during *I-V* measurements, a short pulse current was applied to the sample instead of direct current.[9] A transformer was inserted between the pulse generator and sample circuit to prevent a ground loop from forming the measurement equipment. Current flowing in the circuit was determined by monitoring the voltage drop across a 10 Ω shunt resistor connected in series with the sample. Both voltage and current were measured by a digitizing oscilloscope. The sampling ratio was 256 kHz, and the sampled data were averaged 256 times in order to reduce background noise. The pulse width was 3 ms with a 1 s interval. The duty cycle of these pulse currents was 1:300. By using this arrangement, the amount of Joule heating produced by the current could be reduced to 1/300, compared with the amount of heat produced by direct current of the same strength.

Figure 1 shows the temperature dependence of the electric conductivity of the sample. Conductivity increases linearly from room temperature to 100 K. Maximum conductivity was observed around 100 K, below which conductivity decreased proportionally to ln T. In the WLR, conductance can be represented[10] as

$$\Delta\sigma(T)=\alpha p\,\frac{e^2}{2\pi^2\hbar}\ln T \qquad (1)$$

where α is a constant of an order of unity, and p is a parameter that takes into account the scattering process, $\tau_i \propto T^{-p}$. The number of CuO_2 layers stacked in the $Bi_2Sr_2CuO_6$ sample was then calculated based on sample thickness and the spacing between the layers of the sample. Given a sample

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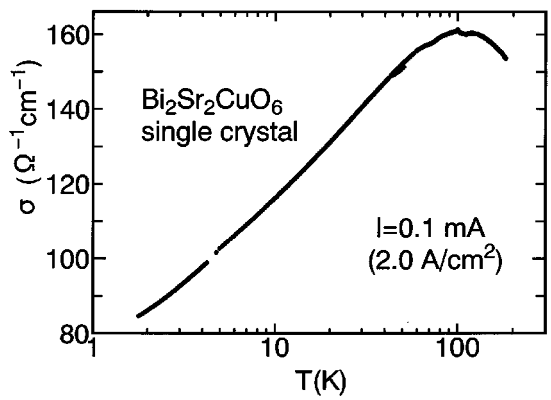

FIG. 1. Conductivity of sample decreases by ln T. The coefficient of ln T is discussed in the text.

thickness of 10 μm and a lattice spacing of 12 Å the sample was determined to contain 8000 layers. Using only the number of layers to calculate the conductance per unit sheet, we obtained $\alpha p = 0.2$.

Figure 2 shows the electric-field dependence of the resistance at 4.2 K. Dots and open circles represent dc (100% duty cycle) and pulse measurement (0.3% duty cycle), respectively. As shown in the figure, resistance R remains constant below 2 mV (corresponding to an electric field of 0.1 V/cm), and decreases by ln E above the threshold. The data from different duty cycles are in agreement. This result shows that the observed nonlinearity in resistance is not caused simply by a temperature increase due to Joule heating, but rather to the nature of $Bi_2Sr_2CuO_6$. The relation between temperature T and electric field E in the WLR has been proposed.[10] In the nonlinear resistance regime, the effective temperature of the carriers T_{eff} can be higher than the temperature of the lattice system. Effective temperature is proportional to the electric field E as

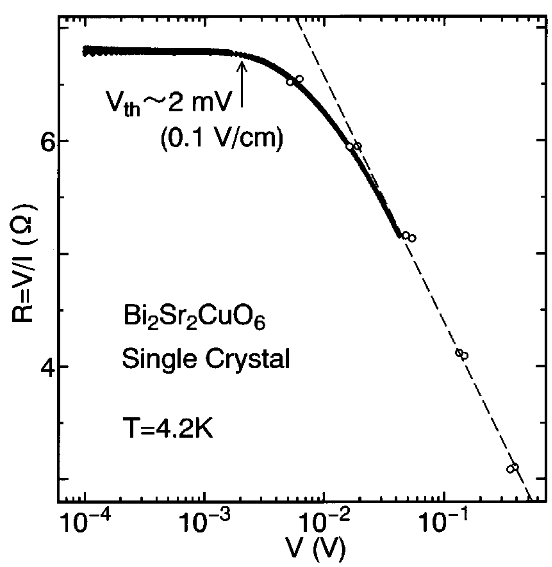

FIG. 2. I-V characteristics of the sample at 4.2 K, plotting $R(=V/I)$. Dots and open circles represent data obtained by dc and pulse measurement, respectively. Both values agree around 10^{-2} V. Resistance R remains constant below the threshold electric field, at which R begins increasing by ln T.

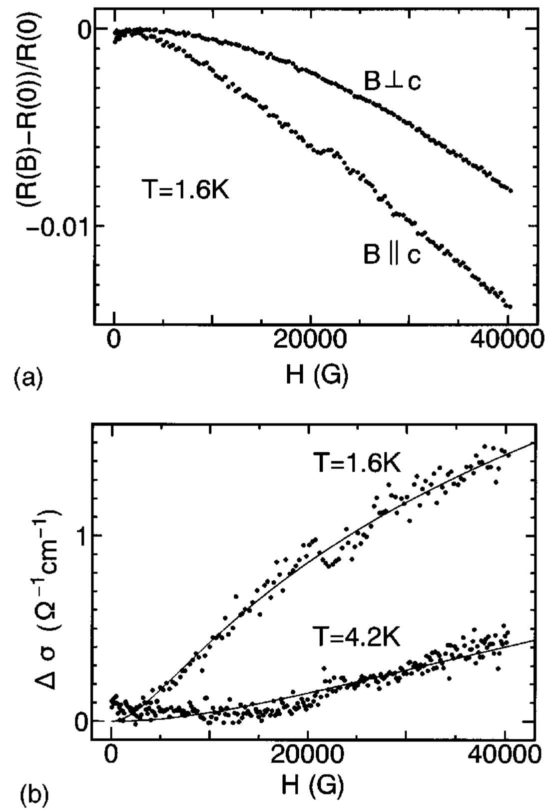

FIG. 3. (a) The transverse and longitudinal magnetoresistances of sample. Note that the sign of magnetoresistances is negative for both directions. (b) The component of orbit motion contributing to magnetoconductivity, $\Delta\sigma = -(\Delta\rho_T - \Delta\rho_L)/\rho_0^2$. Solid lines show the fit with theory.

$$T_{\mathrm{eff}}^{-p} \propto E^{-p/(1+p/2)}. \qquad (2)$$

By substituting T_{eff} for T in Eq. (1), the nonlinear conductivity can be represented as

$$\Delta\sigma(E) = \frac{\alpha p}{1+p/2} \frac{e^2}{2\pi^2\hbar} \ln E. \qquad (3)$$

From the coefficient of ln E, as shown in Fig. 2, we obtained $\alpha p/(1+p/2) = 0.1$. When it is noted that we have $\alpha p = 0.2$, the observed data yields a p value of approximately 2. This is a reasonable value and the assumption expressed in relation (2) is considered to be valid.

Figure 3(a) shows the magnetoresistance of the sample, when the magnetic field is applied parallel, and perpendicular, to the CuO_2 planes. The magnitude of the transverse magnetoresistance is about twice as large as the longitudinal value. The signs of the magnetoresistance are negative for both the parallel and perpendicular fields. Anisotropic negative magnetoresistance is a significant characteristic of the WLR. Figure 3(b) shows the orbital component of the magnetoconductivity defined by $\Delta\sigma = -(\Delta\rho_T - \Delta\rho_L)/\rho_0^2$, where $\Delta\rho_T$ and $\Delta\rho_L$ denote transverse and longitudinal magnetoresistance; and ρ_0 signifies zero-field resistivity, respectively. The magnetoconductivity in the WLR is thus given as

$$\Delta\sigma(H) = -\frac{\alpha^* e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{1}{\Omega\tau}\right) - \psi\left(\frac{1}{2}+\frac{1}{\Omega\tau_\phi}\right) - \ln\left(\frac{\tau}{\tau_\phi}\right)\right] \qquad (4)$$

TABLE I. Coefficients of logarithmic dependences for temperature, electric field, and magnetic field observed in same sample. Note small value for ln H.

	ln T	ln E	ln H
Coefficients (Ω^{-1})	2.5×10^{-6}	1.2×10^{-6}	4.8×10^{-8}
$e^2/2\pi^2\hbar$ unit	$\alpha p=0.2$	$\alpha p/(1+p/2)=0.1$	$\alpha^*=0.005$

where ψ is the digamma function, $\Omega=4eDH/\hbar$, D is the diffusion constant, and α^* is a constant of the order of unity.[11] The content between the brackets of Eq. (4) reaches an asymptotic value for ln H when H is large. Therefore,

$$\Delta\sigma(H)=\alpha^*\frac{e^2}{2\pi^2\hbar}\ln H. \tag{5}$$

By fitting the magnetoconductivity shown in Fig. 3(b) to Eq. (5), we obtained $\alpha^*=0.005$. This is much smaller than the expected value of the order of unity. Table I shows a summary of the coefficients obtained for ln T, ln E, and ln H. The discrepancy in ln H is different from the localized states of metal films. Scaling theory predicts that conductivity in the WLR is determined only by system size. At finite temperature, the system size is replaced by a cutoff length which is a function of T, E, and H, and the coefficients of these dependences must be related to each other. Therefore, the observed discrepancy in ln H is not explained in terms of the WLR theory.

We considered the effect of the electron-electron interaction. The electron-electron interaction also shows a ln T dependence in the conductivity. The coefficient of ln T attributable to this interaction is $(1-F)(e^2/2\pi^2\hbar)$, where F is the screening factor.[12] While the temperature dependence of conductivity is similar to that of localization, the interaction effect has a remarkably different magnetic-field dependence with respect to the magnetoresistance and Hall coefficient.[13] The magnetoresistance in the WLR is negative, and purely transverse for a thin film, whereas the interaction effect shows a positive magnetoresistance and is isotropic for spin splitting and transverse for the orbital part. Figure 3(a) shows that the positive magnetoresistance due to the electron-electron interaction was not observed in our sample. Moreover, the Hall coefficient of the sample also shows that the interaction contributes very little to the sample conductivity. The interaction correction for the Hall resistance R_H is proportional to the resistance increase

$$\delta R_H/R_H=2\,\delta R/R. \tag{6}$$

Figure 4 shows that the observed Hall coefficient of the sample is almost constant in the localized regime where the resistance varies 2 to 7 Ω. It is therefore reasonable to conclude that the effect of the electron-electron interaction is negligible in our sample, and that the very small value for the coefficient of ln H can not be attributed to the electron-electron interaction.

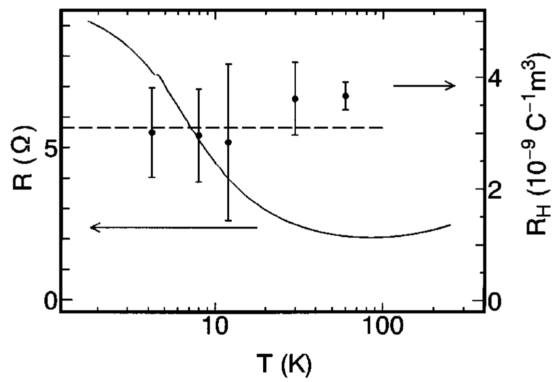

FIG. 4. Temperature dependence of Hall coefficients (solid circles) and resistance (solid line) of the sample. The Hall coefficients is almost independent of temperature (see text).

We have noted that the coefficient of ln H is significantly different from that of ln T and ln E in the localized state of $Bi_2Sr_2CuO_6$. This suggests the existence of interplane coupling between the CuO_2 planes. The interplane coupling increases the number of conducting paths, hence the conductivity might have a different value from that expected for a single plane. Moreover, since the relation (2) is valid in the nonlinear resistance regime $[T_{\mathrm{eff}}(E)>T]$, as we discussed before, both temperature and electric field play the same role in contributing to the conductivity. Hence the coefficients of ln T and ln E are still thought to be in agreement. However, the orbital component of magnetoresistance is caused by the suppression of interference between the partial wave functions of a carrier. This interference occurs independently in each plane. The magnitude of the orbital component of magnetoresistance is determined separately in each plane, hence the coefficient of ln H may possibly be different from those of ln T and ln E. In conclusion, we suggest that interplane coupling plays an important role in the electric transport properties in the localized state in $Bi_2Sr_2CuO_6$ single crystals.

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