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# TRANSPORT AND TUNNELING IN $Bi_2Sr_2CaCu_2O_{8-x}$

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We have measured the resistivity, TEP, Hall coefficient, and tunneling characteristics of single crystals of $Bi_2Sr_2CaCu_2O_{8-x}$ (BSCCO). Simple empirical expressions were found for the normal state transport coefficients that hold true for different crystal directions, oxygen contents, and even for different classes of high $T_c$ oxides. Tunneling measurements on BSCCO single crystals suggest an anisotropic or modulated gap below $T_c$ with $2\Delta_{ab}/k_BT_c \approx 6$-7 and $2\Delta_c/k_BT_c \approx 3$-4.

We have investigated the normal state resistivity, thermoelectric power (TEP), and Hall coefficient of single crystal $Bi_2Sr_2CaCu_2O_{8-x}$ (BSCCO) as functions of crystal direction and oxygen/defect configuration. We have also studied the anisotropic properties of BSCCO in the superconducting state through tunneling measurements using point contact and break junction configurations. Just as with other classes of high temperature superconductors (HTSC), the normal state properties of BSCCO are strongly influenced by oxygen configuration. The temperature dependence of the anisotropic thermopower, ab-plane resistivity, and Hall coefficient all follow simple empirical expressions which hold also for other classes of HTSC. These results provide a framework with which to evaluate various models of normal state transport in the layered perovskites. The tunneling data suggests the existence of an anisotropic or modulated gap in BSCCO with a zero temperature value of $2\Delta_0/k_BT_c \approx 6$-7 and 3-4 along the ab-plane and c-direction respectively.

The oxygen configuration (i.e. actual oxygen content with possible associated defect structure) of crystalline BSCCO was (reversibly) altered by annealing crystals in different pressure environments. X-ray studies show no multiple phase inclusions.

The resistance and TEP were measured for samples with three different oxygen configurations denoted by "High Oxygen" (HO), "Freshly Prepared" (FP), and "Low Oxygen" (LO). HO samples were annealed in $O_2$ at one atm. (1.5 hr at 650°C, followed by a 5 hr ramp to 25 °C), FP samples were taken directly from the crucible with no additional anneals, and LO samples were annealed in a rough vacuum (same temperature cycle as the HO samples). From previous thermograviometric studies[1] we infer that HO samples have approximately 0.08 more oxygen per formula unit than LO samples.

Fig. 1 shows that the temperature dependence of the resistance for the HO, FP, and LO samples follows closely the empirical fit:

$$R(T) \sim T^{\alpha} \exp(\Delta/kT), \qquad (1)$$

where $\alpha \approx 0.7$ and $\Delta$ increases from 0 to 23 meV with increasing oxygen deficiency. Fig. 1 also shows the c-axis resistance of $YBa_2Cu_3O_{7-\delta}$ (YBCO) under ambient pressure and under uniaxial stress,[2] and the c-axis resistance of a needle-like $Bi_{0.1}Sr_{2.2}Ca_{1.1}Cu_{6.5}O_y$ crystal. In each case, the resistivity data is well fitted by Eq. (1) for $\alpha \approx 0.7$,

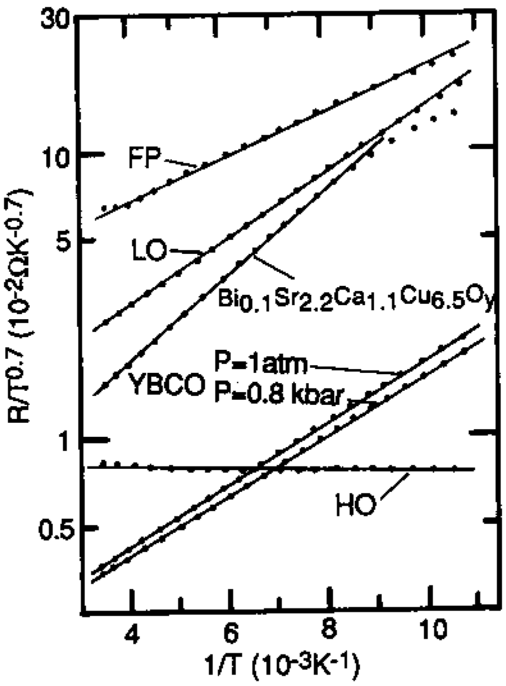


FIGURE 1
Resistivity for various high $T_c$ oxides plotted according to Eq. (1) (see text).

raising the possibility that similar conduction mechanisms are involved in the different crystal directions for both rare earth based and Bi-based HTSC's.

The TEP of BSCCO is very dependent on oxygen configuration. Fig. 2 shows the ab-plane resistance and anisotropic TEP of BSCCO crystals having different oxygen configurations. Figure 2(a) shows both the resistance and ab-plane TEP of the FP (slightly oxygen deficient) crystal. The ab-plane TEP of this sample is positive over the whole temperature range and follows the simple empirical expression:

$$S=A+BT \quad (2)$$

where $A=23\mu V/K$ and $B=-0.05\mu V/K^2$, before flattening off at ≈150K and dropping to zero at $T_c$.

Figure 2(b) shows the resistance and ab-plane TEP of the HO crystal. The resistance looks metallic, but the TEP has a substantial shift of $14\mu V/K$ compared to the FP sample, and now gives a negative value at room temperature. The temperature dependence of the TEP, however, still follows Eq. (2) with only a change in the parameter A. Annealing crystals in oxygen causes the TEP to simply shift downwards while essentially preserving the slope. This same behavior of the ab-plane TEP can be inferred for YBCO from previous (seemingly contradictory) measurements. Analogous behavior occurs in $La_{2-x}Sr_xCuO_4$ where the ab-plane TEP increases considerably and changes its temperature dependence upon removal of Sr.[3]

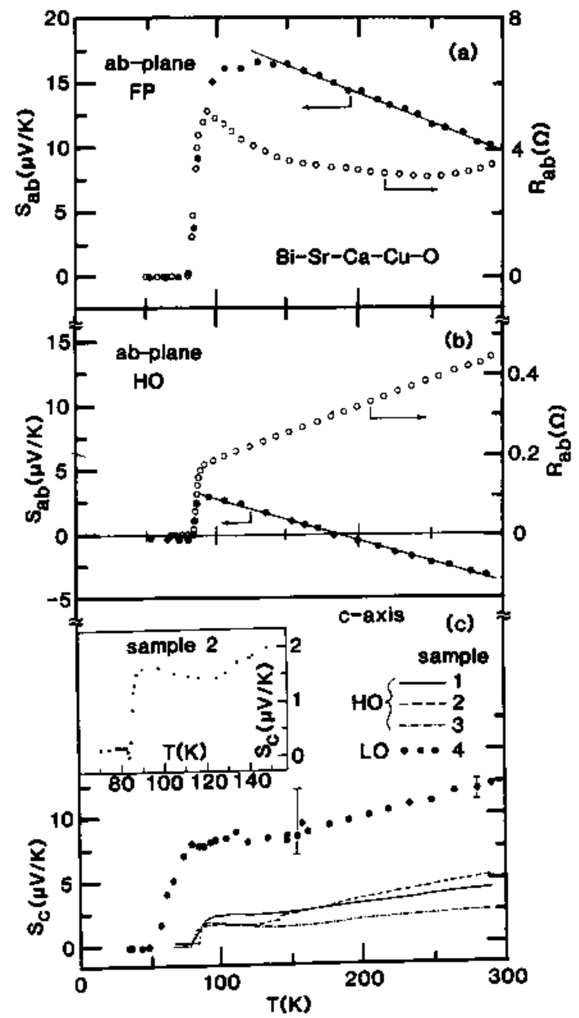


FIGURE 2
ab-plane R and anisotropic TEP for BSCCO crystals having different oxygen configuration (see text).

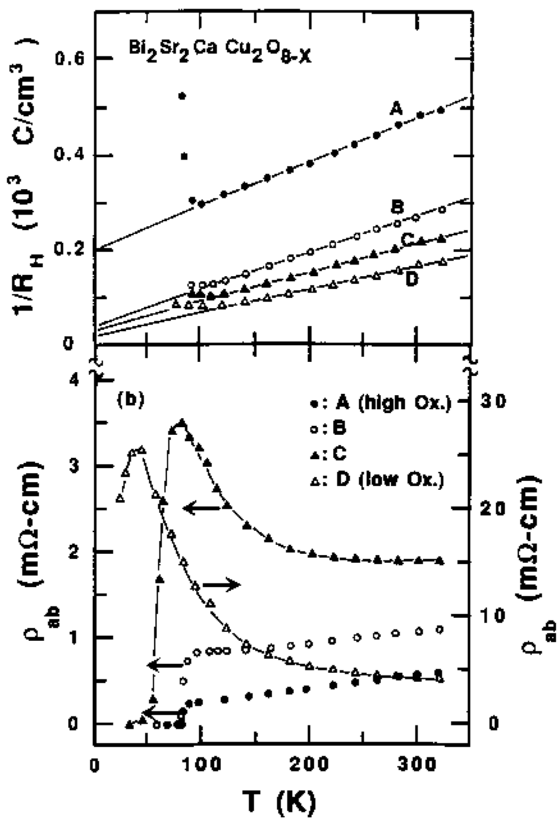


FIGURE 3
$1/R_H$ and resistivity for ab-plane of BSCCO for different oxygen configurations (see text).

Figure 2(c) shows the temperature dependence of the c-axis TEP for three HO BSCCO samples and one LO sample. All three of the HO crystals have a c-axis TEP that is fairly linear with a positive slope down to 130K before turning up in a manner reminiscent of phonon drag (inset). The HO curves look similar to c-axis TEP data from YBCO[4] and more recent measurements performed on Ba-K-Bi-O[5]. As with the ab-plane TEP on LO samples, the c-axis TEP is shifted upwards with only a slight change in slope for a LO sample. Similar behavior has been seen in oxygen deficient samples of YBCO.[4] Thus, Eq. (2) has validity even in the c-direction for different high $T_c$ oxides.

Fig. 3 shows the inverse ab-plane Hall coefficient (measured with a 1T field aligned parallel to the c-axis) and the ab-plane resistivity of a particular BSCCO crystal for four different oxygen configurations. The A (HO) curve is for the crystal following an initial high oxygen anneal (5h at 650°C, followed by a 12h ramp to 25°C, in $O_2$ flow). Curves B,C and D (LO) were obtained after annealing the crystal for 5h at 325°C, 345°C and 375°C respectively, followed by a 12h ramp to 25°C, all at ~10mtorr $O_2$. As has been observed by several groups for YBCO[6], and BSCCO[7], the high oxygen data was found to obey the simple empirical expression

$$1/R_H=C+DT \qquad (3)$$

while the resistivity is linear and metallic. This expression for the inverse Hall coefficient still held after oxygen was removed, even though the resistivity changed from metallic to semiconductor-like. A large offset ocurred in $1/R_H$ from anneal A to anneal B, the latter which still shows metallic behavior and no significant change in $T_c$.

Anisotropy shows up not just in normal state transport measurements, but also in superconducting tunneling measurements. Break junction and point junction tunneling data reveal evidence for an anisotropic gap in BSCCO. Fig. 4 shows a typical I-V curve obtained from a break junction across the ab-plane of a BSCCO single crystal immersed in liquid He. The junction is highly hysteretic at low voltages, but the maximum slope occurs reproducibly near ±45mV. If this value is associated with $2\Delta_{ab}$, we find $\Delta_{ab}$=22.5meV at 4.2K. This value was confirmed by dV/dI measurements performed at different temperatures on a superconductor- insulator-normal (SIN) junction between an indium tip and the edge of a BSCCO crystal. The inset to Fig. 4 shows the position of the local differential conductivity maximum in the SIN measurements as a function of temperature. The solid line is the BCS gap, fit to the T=4.2K and T=76k data points. The fit suggests $\Delta_{ab}(T=0)$=22.5meV and $T_c$=85.4K, where the relation $\Delta(T)/\Delta(0)=1.74[1-T/T_c]^{1/2}$ was used near $T_c$.

To investigate the energy gap structure along the

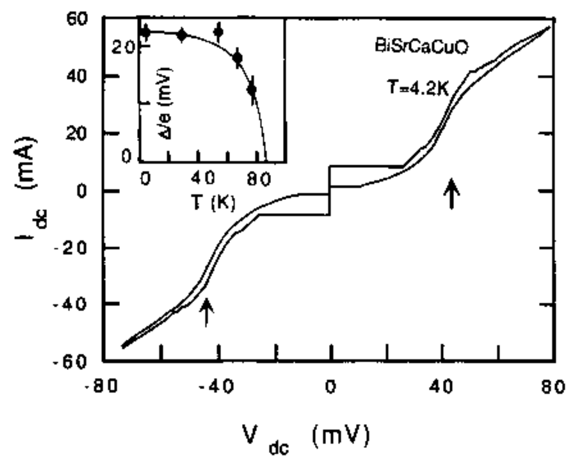


FIGURE 4
I-V characteristic for BSCCO break junction. Arrows identify gap (2Δ) structure. The inset shows the T dependence for gap structure in SIN tunneling

c-axis, we employed a "differential" tunneling configuration: well characterized BSCCO crystals were mounted and cleaved such that tunneling would take place from the ab-plane direction of one crystal into the c-axis direction of another crystal. The junction was thus of the $S_1$-I-$S_2$ type. The dV/dI characteristic of the differential tunnel junction showed two distinct features, which we identify as corresponding to the sum and differences of the energy gaps in the ab-plane and c-axis directions. Again taking the local maximum in the differential conductance as the relevant energy, we find $\Delta_{ab}+\Delta_c$=35meV and $\Delta_{ab}-\Delta_c$=11meV. From this we infer $\Delta_{ab}$=23meV and $\Delta_c$=12 meV. The value for $\Delta_{ab}$ is in good agreement with that determined above, 22.5meV. Again with $T_c$=85K, we find $2\Delta_c/k_BT_c$=3.3±0.3, thus suggesting an energy gap anisotropy in BSCCO at low temperatures of about a factor of two. Alternatively, the low c-axis gap value may not reflect the gap anisotropy, but rather a (proximity effect) depressed gap in the Bi-O layer regions.

Disorder may play an important role in the physics of HTSC's. Our transport data is not consistent with variable range hopping or a soft coulomb gap, but a physical explanation for Eq. (1) may be found within Phillips' model of "quantum percolation".[8] In this context, the activated term could arise from the difference in energy between the fermi level and low lying extended states, while the $T^\alpha$ term comes from a temperature dependent mobility. Using the (possibly problematical) Mott formula for thermo- power, $S \sim T(d\ln\sigma/dE)_{Ef}$, the empirical expression for the resistivity given in Eq. (1) yields Eq. (2), the observed temperature dependence of the thermo- power. The decrease in temperature dependence of the Hall mobility (deduced from Fig. 3) as oxygen is removed coincides with what one might expect for a system undergoing increased localization.

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