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The Hall effect of the superconducting oxides $(Bi, Pb)_2Ca_2Sr_2Cu_3O_y$

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Abstract. The temperature dependence of the Hall coefficient R_H has been measured between 50 and 250 K for the superconducting compounds with nominal compositions $Bi_2Ca_2Sr_2Cu_3O_y$ and $Bi_{1.6}Pb_{0.4}Ca_2Sr_2Cy_3O_y$. It is found that the Hall number, n_H, is linearly T-dependent and field-independent in the normal state and decreases rapidly on doping with lead. This result is quite in agreement with the recent theoretical calculation proposed by Xing and co-workers. A large anomaly in R_H is observed around T_c, which is discussed in terms of the intergranular structure of this material.

1. Introduction

The Hall effect in both ceramic and single-crystal superconducting $ReBa_2Cu_3O_{7-y}$ compounds has been investigated by many groups. The data show strong anisotropies and unusual temperature dependence of electronic properties. These may be helpful in understanding the novel mechanism for high-T_c superconductivity. An important question is whether or not the extraordinary properties are common characteristics for all oxide cuprates, which have different crystalline and electronic structures. In particular, the newly discovered Bi-site compounds without any rare-earth elements exhibit many different features compared to those of previously known 90 K superconductors; there are neither Cu–O chains nor Cu–O bonds linking the Cu–O planes in them. Does this act on their transport properties in the normal state? In this paper, we make a contribution towards answering this question through a study of Hall effect in the Pb-doped BiCaSrCuO system.

2. Experimental details

Samples with nominal compositions $Bi_2Ca_2Sr_2Cu_3O_y$ and $Bi_{1.6}Pb_{0.4}Ca_2Sr_2Cu_3O_y$ were selected for the study of the Hall effect. Their synthesis, phase and crystalline structure features were presented and discussed by Chen *et al* (1988). Their basic superconducting properties are reproduced in figure 1. The zero resistance temperature T_{ce} of the unleaded sample is 75.5 K. A small drop in resistance at about 110 K is observed; this

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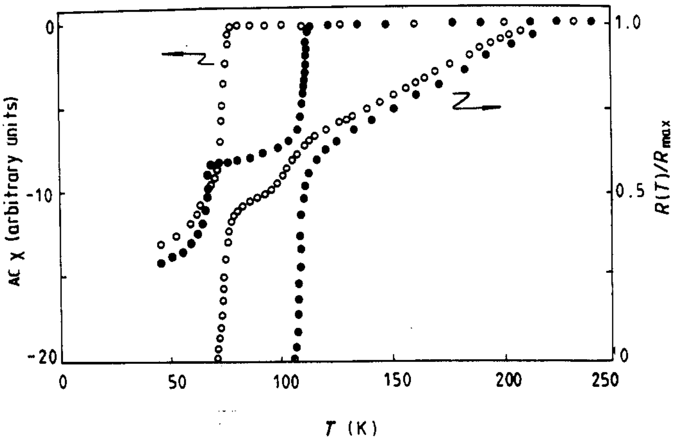

Figure 1. Temperature dependence of the resistivity and AC magnetic susceptibility for $Bi_2Ca_2Sr_2Cu_3O_y$ (○) and $Bi_{1.6}Pb_{0.4}Ca_2Sr_2Cu_3O_y$ (●).

means the sample includes a little of the higher-T_c superconducting phase in addition to the main 80 K phase. The T_{ce} of the Pb-doped sample is as high as 107 K, and the measurement of the AC susceptibility indicates that the amount of the higher-T_c (107 K) superconducting phase is much larger than that of the lower T_c (67 K) one.

The samples were cut into bars of $12 \times 4 \times 0.7$ mm^3; four silver electrodes were evaporated in a standard Hall configuration and copper leads were soft-soldered to the electrodes. This procedure ensures low contact resistances of less than 10^{-4} Ω cm^{-2}. The temperature dependences of the Hall voltage (V_H) were measured in a magnetic field of 3 T, and the field dependences of V_H were obtained in the fields of from 1 to 5 T at 135 K only. To avoid errors due to the non-symmetry of the Hall potential probes, the Hall coefficient was calculated for both magnetic-field and measuring-current directions. The sample temperature was controlled to within 2 mK during the collection of the Hall voltage data. The measuring current density is about 2 A cm^{-2}, and the voltage resolution is better than 10^{-8} V.

3. Results and discussion

3.1. The anomaly in $R_H(T)$ and its explanation

The Hall coefficient R_H against temperature curves for both samples probably do have some common characteristics, as shown in figure 2. R_H is positive in the normal state, and increases slowly as the temperature drops down to the T_c onset, then, via an anomalous region, decreases to zero, as expected for a superconductor. To a certain extent, this behaviour is similar to that in ceramics of $YBa_2Cu_3O_{7-y}$ and $La_{1.85}Sr_{0.15}CuO_4$, as reported by Zhao *et al* (1987) and Hundley and Zettl (1987), respectively. Therefore, it would seem that the anomaly of $R_H(T)$ around T_c is a common feature in the high T_c superconducting ceramics. We propose that it is associated with the complex microstructure of the ceramic materials, that is, that the valleys of $R_H(T)$ below T_c originate from grain boundaries.

If such an anomalous phenomenon is really related to the grain boundaries, it should not occur in a single crystal. Recent work on both ceramic and single crystal

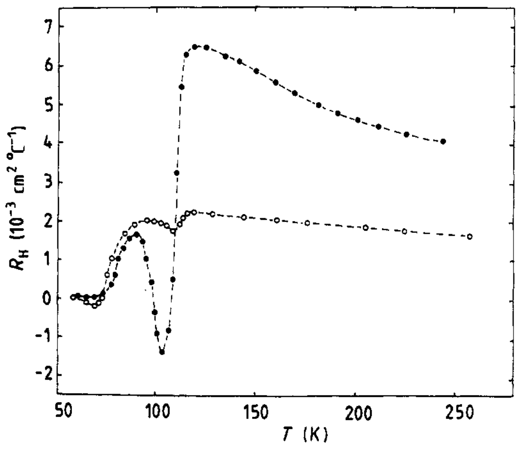

Figure 2. Temperature dependence of the Hall coefficient for both samples: ○, $Bi_2Ca_2Sr_2Cu_3O_y$; and ●, $Bi_{1.6}Pb_{0.4}Ca_2Sr_2Cu_3O_y$.

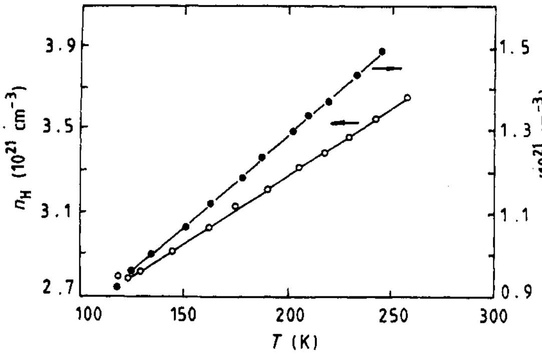

Figure 3. The variation of Hall number against temperature: ○, $Bi_2Ca_2Sr_2Cu_3O_y$; and ●, $Bi_{1.6}Pb_{0.4}Ca_2Sr_2Cu_3O_y$.

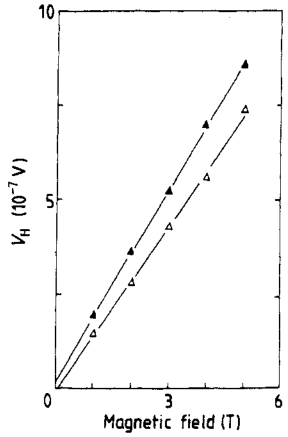

Figure 4. The dependence of Hall voltage on the applied magnetic field at 135 K; △, $Bi_2Ca_2Sr_2Cu_3O_y$; and ▲, $Bi_{1.6}Pb_{0.4}Ca_2Sr_2Cu_3O_y$.

$YBa_2Cu_3O_{7-y}$ compounds reported by Thier and Winzer (1988) has strongly supported our proposition. No valley on $R_H(T)$ below T_c was observed on the single crystal, but there is a large one on the bulk samples.

3.2. *The Hall number, n_H*

The Hall number $n_H = 1/eR_H$ is linearly temperature dependent in the normal state (as shown in figure 3). The formula $n_H(T) = n_0(1 + aT)$ is well satisfied for both samples, where n_0 and a are 0.38×10^{21} cm^{-3} and 0.012 K^{-1} respectively for the sample of $Bi_{1.6}Pb_{0.4}Ca_2Sr_2Cu_3O_y$; and 1.95×10^{21} cm^{-3} and 0.0034 K^{-1} for $Bi_2Ca_2Sr_2Cu_3O_y$. The n_H at 250 K is 1.49×10^{21} cm^{-3} for Pb-doped sample and 3.66×10^{21} cm^{-3} for the other one. Obviously, the carrier concentration is reduced by doping with lead.

The experimental results, e.g. T-dependence of the Hall number, are in good agreement with the two-band model with an extra carrier source proposed by Xing and Ting (1988) recently. In this model, the Hall number can be described by the equations

$$n_H(T) = n_0(0)(1 + T/T^*) \tag{1}$$

$$T^* = \pi d N_1/(m_e + m_h) \tag{2}$$

where N_l represents the density of the localised states provided by oxygen vacancies, d the lattice parameter along the c-axis, and spacing m_e and m_h the effective mass of electron and hole, respectively. From these formulae, and assuming m_e and m_h to be identical for both samples, it is quite reasonable to suppose that the Hall number declines with doping lead due to the partial substitution of Pb^{4+} for Bi^{3+} leading to a decrease of vacancies in this oxygen-deficient material. In addition, we deduce that $dn_H(T)/dT$ is proportional to $1/N_l$ or a, which agrees qualitatively with the experimental result.

It must be pointed out that the linear T-dependence, and even the magnitude and the sign of Hall number n_H coincide with that of $ReBa_2Cu_3O_{7-y}$ compounds reported by Zhang *et al* (1987) and Tanaka *et al* (1987). This coincidence may imply that there are similar band structures that originate from the conductive tunnels of these materials. Indeed, the electronic structure proposed by Massidda *et al* (1988) for $Bi_2CaSr_2Cu_2O_8$ indicates that the band structure and $N(E_F)$, the density of states at E_F, even for the highly 2D-Fermi surface that is closely related to the transport process as well as to the superconductive mechanism, do not essentially change compared with the $ReBa_2Cu_3O_{7-y}$ compounds except for the Bi–O planes, which play a role similar to that of the Cu–O chains. On the other hand, a weak T-dependence on Hall coefficient was observed by Hundley and Zettl (1987) in $La_{1.85}Sr_{0.15}CuO_4$. The T_{ce} of this material is only 36 K, but the Hall number n_H at room temperature reaches 6×10^{21} cm^{-3}. This is much larger than that of the other two kinds of high-T_c oxide superconductors. Perhaps, this means that the electron–phonon interaction in the latter is much stronger than that in K_2NiF_4 type compounds, and implies that some novel scattering mechanisms exist in the present materials.

3.3. Relationship between the Hall voltage and the applied magnetic field

The Hall voltage against the applied magnetic fields curves for both samples at 135 K are reproduced in figure 4. It can be seen that the V_H is proportional to the magnetic field. This means that the Hall coefficient or the carrier concentration in a magnetic field of up to 5 T is field-independent in the normal state. It is possible that this observation may rule out certain asymmetric magnetic scattering mechanisms.

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