Anderson-like Insulator - Metal Transition in Rare Earth doped $Bi_2Sr_2(Ca_z\,RE_{1-z})Cu_2O_{8+y}$

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Abstract

The transition from the insulating compounds $Bi_2Sr_2RE_1Cu_2O_{8+y}$ (RE=rare earth) to the High-Temperature superconductor $Bi_2Sr_2Ca_1Cu_2O_{8+y}$ was studied. The substitution of Ca^{2+} for RE^{3+} has two effects : It introduces hole-like carriers and creates local disorder. The disorder causes localization of the electronic states in the tails of the conduction band and thus an Anderson-like transition. The carrier density scales with the rare earth valence and concentration justifying a simple chemical picture. For low Ca-content the samples are insulating and charge is transported by hopping processes. By increasing the Ca-concentration the hole density increases which leads to an insulator-metal transition at a critical concentration z_c. The RE-ions show Curie-Weiß like magnetic susceptibility and are coupled to each other through the delocalized carriers.

1. Doping and carrier density

In $Bi_2Sr_2RECu_2O_{8+y}$ a transition from an insulating to a metallic and superconducting phase can be introduced by substituting trivalent rare earth (RE)-ions through divalent Ca [1]. In the following we will focus on the case of $RE=Y^{3+}$. Doping Ca^{2+} for Y^{3+} introduces hole like carriers and lowers the resistivity. Fig. 1 shows the hole concentration for different metallic samples. The hole concentration p(T) was taken from the Hall coefficient R_H using a single band model

$$R_H = \frac{1}{p \cdot e} \tag{1}$$

The hole concentration is weakly temperature dependent. For a given temperature it increases approximately linearly with the Ca-content z. The dashed lines are fits to the linear temperature dependence
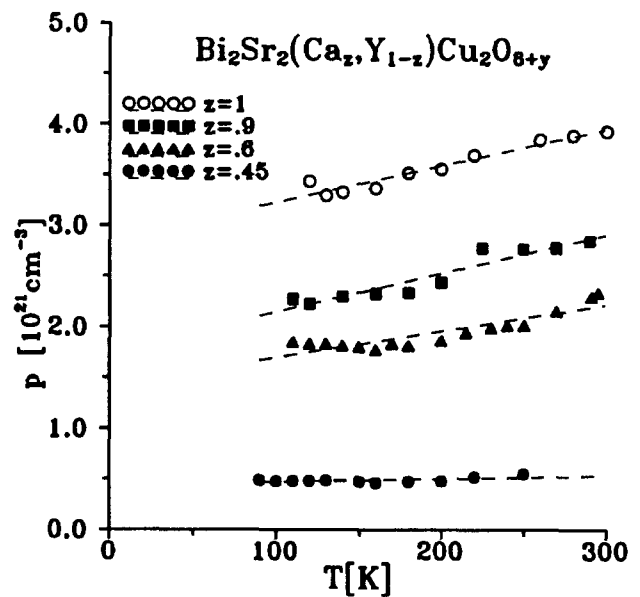
$$p(T) = a + b \cdot T \tag{2}$$

Fig.1 Carrier density p vs. temperature for metallic samples with different Ca-content z.

which is common to all HTSC [2]. The temperature dependence is strongest for the samples with high Ca-content and almost absent for the sample with z=0.45. The fact that the hole concentration is

proportional to the Ca-content supports the simple chemical picture of doping with ions of different valence. In the following we will therefore assume that the carrier density p is proportional to the Ca-content z. For low Ca-content, i.e. low carrier density, the system is an insulator $(\partial\rho\{T\rightarrow 0\}/\partial T < 0)$. This behavior changes at a critical concentration z_c. For $z > z_c$ the system becomes a metal $(d\rho/dT > 0)$ and at the same time a superconductor. Metallic samples show the well known $\rho \sim T$ behavior and superconducting transition temperatures (T_c) up to 92K $(z=.8)$.

2. Electrical resistivity and disorder

Fig. 2 shows the electrical resistivity $\rho(T)$ for three samples of the Y-based system with Ca-content z below the critical value $z_c = (0.43 \pm .02)$. The samples are insulators $(\partial\rho\{T\rightarrow 0\}/\partial T < 0)$ at low
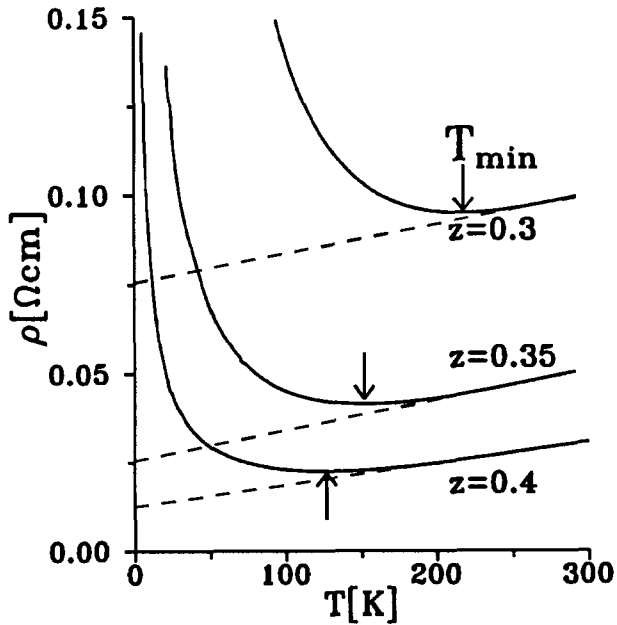

Fig.2 Resistivity vs. temperature for samples of $Bi_2Sr_2[Y_{1-z},Ca_z]Cu_2O_{8+y}$. The crossover from insulating to metallic behavior at T_{min} is marked by arrows.

temperatures while above a crossover temperature T_{min} they become metallic and have $\rho \sim T$. In addition to the well established concentration dependent transition there is therefore also a temperature dependent transition at T_{min}. The resistivity at $T < T_{min}$ is not thermally activated but of the hopping type (for details see [3])

$$\rho(T) = \rho_0 \exp[T_0/T]^{\alpha}. \tag{3}$$

The value for α varies between $\alpha = (0.5 \pm 0.05)$ at $z=0$ and $\alpha = (0.2 \pm 0.02)$ at $z=0.4$. The characteristic temperature T_0 is related to the localization radius a_H by [3]

$$a_H(z) \sim T_0(z)^{(\alpha/(\alpha-1))}. \tag{4}$$

The slope of the linear resistivity ρ_{lin} also changes with z. It is lowest for the metallic samples $(z > z_c)$ and highest for the insulating samples $(z < z_c)$. The crossover between hopping transport at low temperatures and metallic transport at high temperature can be understood if the disorder caused by the random substitution of RE- sites by Ca is taken into account. This random occupation leads to non periodic fluctuations in the potential and therefore to a localization of the electronic states in the tail of the conduction band $(E > E_c)$. Whether the system is an insulator or a metal depends on the position of E_F relative to the mobility edge E_c. If E_F sits in the localized region $(E_F > E_c)$ the samples will be insulating, whereas they will be metallic if E_F is in the delocalized part $(E_F < E_c)$. Insulating samples $(\partial\rho\{T\rightarrow 0\}/\partial T < 0)$ can become metallic if the thermal energy $k_B T$ becomes larger then the separation between delocalized states and E_F. The relation

$$k_B \cdot T_{min} \simeq (E_F - E_c) \tag{5}$$

is therefore a reasonable approximation. To understand the nature of the insulator-metal transition it is interesting to investigate the behavior of the localization radius a_H and the linear resistivity $\partial \rho_{lin}/\partial T$ at the transition. The localization radius a_H is the decay length of the localized carrier state in the insulating compounds. The temperature coefficient of the linear resistivity $\partial \rho_{lin}/\partial T$ on the other hand characterizes the delocalized states in the metallic compounds. Fig. 3 shows both quantities versus the Ca-content z. While a_H
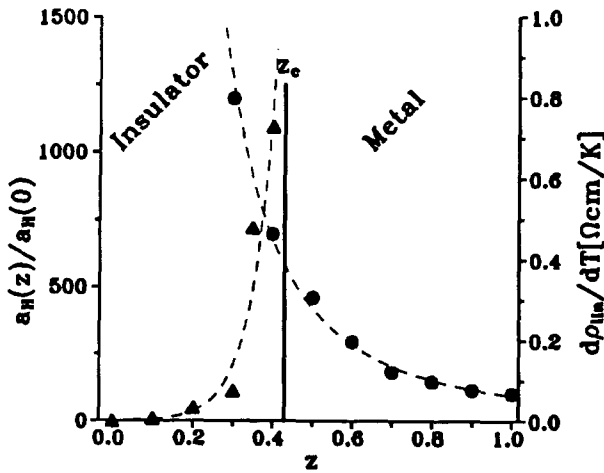

Fig.3 Localization radius a_H and coefficient of linear resistivity $\partial \rho_{lin}/\partial T$ vs. Ca-content z for $Bi_2Sr_2[Y_{1-z},Ca_z]Cu_2O_{8+y}$. The solid line marks the insulator-metal transition.

diverges at z_c, $\partial \rho_{lin}/\partial T$ is continuous. The divergence of a_H implies that the transition to the metallic state is caused by an increased diameter of the doped carrier states. At the critical concentration a_H diverges and therefore the carrier states extend over the whole crystal in the metallic compounds. The continuity of $\partial \rho_{lin}/\partial T$ at z_c on the other hand shows that the linear resistivity above T_{min} is caused by the same electronic states in both the insulating and the metallic samples. As

the states are the same we can conclude that the transition is indeed caused by disorder and of the Anderson-type. A Mott-type transition would involve different states in the metallic and the insulating samples and therefore $\partial \rho_{lin}/\partial T$ would have to change discontinuously at z_c.

4. Scaling law

If the insulator-metal transition is indeed of the Anderson type one expects to find a scaling law for the conductivity

$$\sigma(z) = \sigma_0 \left\{ \frac{z - z_c}{z_c} \right\}^{\eta}. \tag{6}$$

We therefore show the conductivity $\sigma = 1/\rho$ versus the reduced concentration $(z-z_c)/z_c$ in a double logarithmic plot in Fig.4. Because the conductivity at T=0 is not accessible and extrapolations are made difficult because of the occurrence of superconductivity at rather high temperatures we
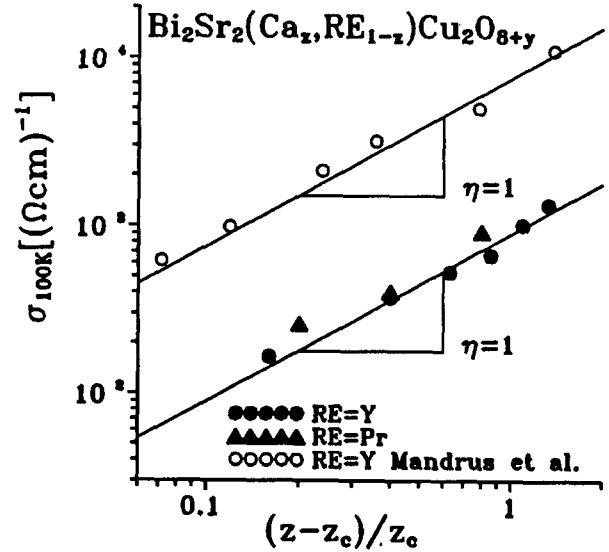

Fig.4 Double logarithmic plot of $\sigma(100K)$ vs. reduced concentration $(z-z_c)/z_c$ showing the scaling behavior with a critical exponent $\eta = 1.0$ at the insulator metal transition (closed symbols polycrystals, open symbols single crystals Ref. [4]).

use the conductivity at T=100K. Shown are our data for polycrystalline samples with RE =Y (z_c=(0.43 ± 0.02)) and RE=Pr ((z_c=(0.50 ± 0.02)) together with single crystal data of Mandrus et al. (z_c=(0.42 ± 0.02)) [4]. Both sets clearly show a scaling law with the same exponent η=1.0. The exponent is the same for poly- and single crystals and independent of both the critical concentration and the RE-ion. This is proof that the observed scaling law is an intrinsic property of the $Bi_2Sr_2[RE_{1-z}, Ca_z]Cu_2O_{8+y}$ system. The critical exponent of η=1.0 is the same as is observed in amorphous metals such as Nb:Si whereas η=0.5 is observed in highly doped semiconductors like Si:P [5]. This underlines the importance of disorder in the insulator- metal transition of HTSC.

5. Coupling between local moments

The magnetic susceptibility of the samples containing magnetic RE-ions obeys a Curie-Weiß law

$$\chi(T) = \frac{3 \cdot N}{k_B} \mu_{eff}^2 \cdot \left(\frac{1}{T + T_{CW}}\right). \qquad (7)$$

The effective moments agree well with the Hund's rule values and are independent of the RE-concentration within 10%. The coupling between them is antiferromagnetic. Fig. 5 shows $T_{CW}(z)$ for the light magnetic RE-ions Pr and Nd. The light RE-ions have 4f-states close to E_F and therefore hybridize strongly with the delocalized carriers. Contrary to the naive expectation $T_{CW}(z)$ is not largest for z=0 where the RE-concentration is highest. Instead it is smallest there and increases with the Ca-content z. This shows that the magnetic coupling is mediated by the delocalized carriers. In the insulating samples these are almost absent and therefore the coupling is small despite
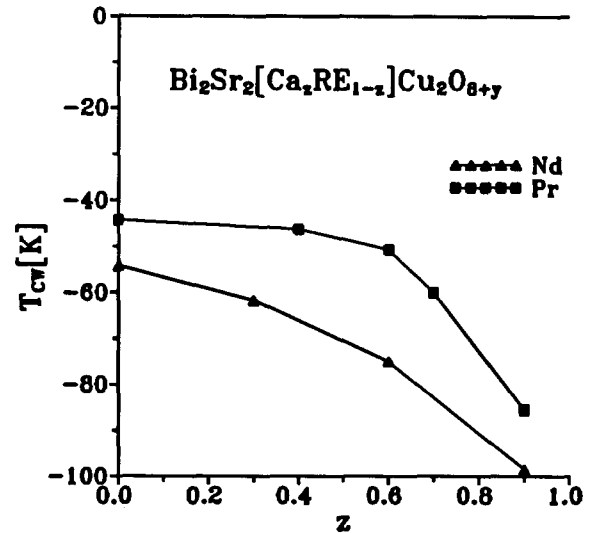

Fig.5 Curie-Weiß temperature T_{CW} vs Ca-content z for light magnetic RE-ions.

the small separation between the RE-ions. The dependence of $T_{CW}(z)$ on the carrier density shows that the coupling is of the RKKY-type and therefore that there is a finite density of delocalized carriers at the RE-site. Therefore the carriers are not completely confined to the CuO_2-plane and the electronic system is not purely 2-dimensional.

References

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