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Anomalous Behavior of Resistivity and Mobility of $La_{2-x}Sr_xCuO_4$ Bulk Material and Film

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The resistivity measurement of the bulk material of $La_{2-x}Sr_xCuO_4$ reveals the following phenomena. (a) The x dependence of the resistivity $\rho(x)$ shows remarkable decrease at $x \approx 1/4^N$ ($N = 1, 2, 3, \cdots$). The decrease takes place from low temperature up to room temperature. (b) The superconductivity appears at low temperature in the doping range $1/4^2 \le x \le 1/4$. By way of the Hall measurement on bulk and film specimens, the resistivity decrease is found to be due to the anomalous carrier-mobility increase on the special doping levels.

1.INTRODUCTION

When we think of the application of the high temperature superconductors (HTS) concerning three-terminal-devices like FET to be used as the elements of integrated circuits, a problem may be found as to their operation speed and sensitivity. The switching operation speed of a FET depends on the transition time between ON-OFF states, which is known to be inversely proportional to the carrier mobility μ. Besides, the transconductance g_m of FET is known to be proportional to μ. However, the normal carriers of HTS is found to have considerably smaller μ in comparison with that of semiconductor carriers. Near the critical temperature ($\sim$100[K]) μ(HTS) $\sim 10^{-3}$ (m^2/Vs). On the other hand, μ(Si)$\sim 10^{-1}$ (m^2/Vs) at room temperature, and μ(Si)$\sim 10^{1}$ (m^2/Vs) at $\sim$100[K]. This means that in a similar device structure the operation speed and g_m of FET(HTS) at $\sim$100[K] are 10^{-2} smaller than that of FET(Si) at room temperature. In spite of the merit that ON resistance $R_{ON}=0$ owing to superconductivity, HTS FET with both the slow speed and the low sensitivity will find very restricted to application in future electronics field.

This research is made to clarify the anomalous feature of a HTS where its conductivity (and μ) reveal considerable increase at special doping levels. Using this effect, one may acquire the possibility to elevate μ(HTS) much higher than semiconductor mobility not only at low temperature but also at room temperature. Moreover this research may make a substantial contribution to the HTS physics, because the anomalous conduction property directly reflects the anomalous normal carrier state of HTS.

2. THE ANOMALOUS RESISTIVITY DECREASE EFFECT OF $La_{2-x}Sr_xCuO_4$

Based on the data of resistivity measurement on the bulk material of $La_{2-x}Sr_xCuO_4$ by Uchida group [1], one of the authors (Sugahara) found the effect of the normal resistivity depression around special Sr doping level $x \approx 4^{-N}$ (N= integer) [2], and proposed a "hole-pair" model to explain the effect. The experiment made by our group [3,4] reproduced clearly the resistivity depression. This effect gives the possibility of "room-temperature zero resistivity", and the applicability HTS to three-terminal devices with high speed and high sensitivity. We at first summarize the experiment on the anomalous Sr-doping-level (x) dependence of $La_{2-x}Sr_xCuO_4$ resistivity on the bulk specimens.

We measured the temperature (T) dependence of resistivity ρ of carefully-made high-quality sintered bulk material of $La_{2-x}Sr_xCuO_4$ of various x values. From the data the x dependence of ρ is obtained as shown in Fig. 1.

It is known by Hall measurement that the Hallcarrier is supposed to be "hole", and in the latter range "electron". We tentatively call former

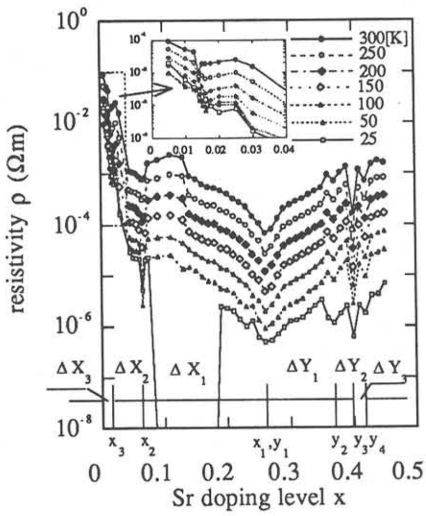


Fig.1. ρ -x relationship in the temperature range T=25~300[K]. In order to avoid the superposition of data points, the ordinates values of data points are plotted by $\rho \times C(T)$, where $C(25)=2^0$, $C(50)=2^1$, $C(100)=2^2$, ..., $C(300)=2^6$.

"hole region", and the latter "electron region". From the experimental data of Fig. 1 and other data [3,4], the following properties are found.

In the "hole region"

(i) The zero-resistivity due to superconductivity is found to take place in x range 0.085<x<0.175 at T=25[K]. At T=4.2[K], the range is 0.064< x< 0.24, which is nearly equal to $1/4^2 < x < 1/4$. (ii) General tendency of ρ -x relation is found to be $d\rho/dx < 0$. (iii) Sharp decrease of ρ is found on carrier levels x=1/4, $1/4^2$ and $1/4^3$. (iv) ρ -x relation in the range $1/4^2<x<1/4$ appears to be repeated nearly cyclically in the range $1/4^3<x'<1/4^2$. (v) Besides the sharp resistivity drops at $x=1/4^N$, steep changes of $d\rho/dx$ are observed around x=1/8=(1/4)/2 and $1/32=(1/4^2)/2$ where the drop of transition temperature is known to take place.[6]

In the "electron region"

(i) General tendency of ρ -x relation is found to be $d\rho/dx < 0$. A symmetrical character with respect to the straight line x=0.25 appears to be found between the general tendency in this region and that in the "hole region" .

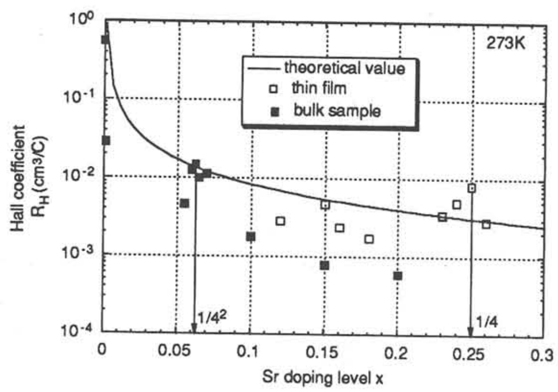
(ii) The x levels giving the resistivity drop in this region make an array in a way which is different from the array in the "hole region". If one puts as seen in Fig. 1 the anomalous levels in the "hole region" $x=x_n$, and $x=y_n$ in the "electron region", and write the separation between neighboring levels $\Delta X_n \equiv x_n - x_{n+1}$ and $\Delta Y_n \equiv y_{n+1} - y_n$ respectively, it is found that $\Delta X_n \approx 1/4^n - 1/4^{n+1}$ and that $\Delta Y_n \sim (1/4^n - 1/4^{n+1})/2$. The fact that ΔY_n is about a half of ΔX_n may reveal that the carriers in the "hole region " forming hole pairs [2),3)], and the carriers in the "electron region" are in the state of single electron.

(iii) In the high doping region x>0.25, the carrier density decreases due to oxygen deficiency which is said to be unavoidable. The tendency of $d\rho/dt > 0$ in the"electron" region in Fig. 1 might be attributed by the oxygen deficiency. However, we believe that the effect of oxygen deficiency on the material characteristic is not decisive in our measurement range, because c-axis length is nearly constant through the range, and because the resistivity of our polycrystalline specimens remains less than 5 times of ρ_{ab} of single crystal specimens[7)] which values may be regarded to be within the resistivity range supposed for good polycrystalline specimens.

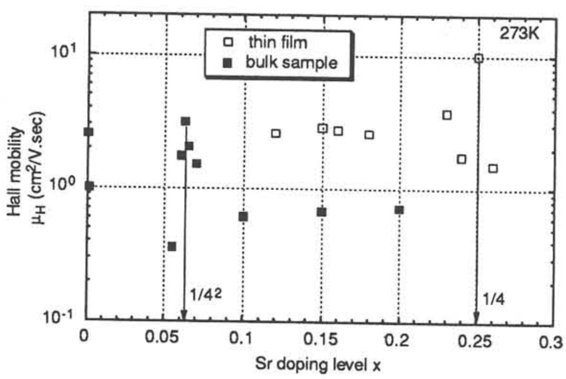
3. THE HALL MEASUREMENT OF $La_{2-x}Sr_xCuO_4$ BULK AND FILM SPECIMENS

The resistivity drop noted in Sec. 2 can either be attributed to (a) increase of carrier density or to (b)increase of carrier mobility, because conductivity is proportional to both the carrier density and the mobility. In order to clarify the question, we conduct a Hall measurement by which carrier density and mobility are measured separately . Van der Pauw method is employed for relatively thin bulk specimens of size 4×2.5×0.4 [mm^3]. Thin films of thickness 400 [nm] are made by magnetron sputtering and then patterned by ion etching in the form of the Hall bridge with a length/width ratio l/w =2[mm]/0.8[mm]. Until now the measured x range is restricted within the "hole region".

Fig. 2 is shown the measured results of the two types of specimens at 273[K]. The x dependence of Hall coefficient R_H is shown in Fig. 2(a). The solid curve is the hypothetical value when the carrier number is supposed to be the Sr dopant number. In general the discrepancy between observed data and the hypothetical value falls within 1 order. Observed R_H reveals some increase around x=1/4 and 1/16. On the



(a)



(b)

Fig. 2. The results of Hall measurement. (a) R_H-x relationship. (b) μ_H--x relationship.

other hand, the Hall mobility μ_H appears to have no general x dependence except the anomalous levels. Sharp increment of μ_H is observed around x=1/4 and 1/16. These results show that the anomalous resistivity decrease is related to the μ increase.

4. CONCLUSION

We experimentally showed that anomalous increase of conductivity occurs at $x \approx 4^{-N}$ in $La_{2-x}Sr_xCuO_4$. By way of Hall measurement using bulk and film specimens, increase of carrier mobility is confirmed at $x \sim 1/4$ and 1/16. This new effect suggests the possibility that high-temperature oxide superconductor is usable as the material of high speed electronics devices.

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