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AC susceptibility studies on Bi–Sr–Ca–Cu–O system

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Abstract. We report the low field a.c. susceptibility data $\chi'(T, H_{rms})$, $\chi''(T, H_{rms})$ for the newly prepared superconducting system $Bi_xSr_4Ca_2Cu_4O_y$ ($x = 0{\cdot}5, 1{\cdot}0$ and $1{\cdot}5$) containing Bi at concentrations lower than that in the conventional Bi-based system. Our experimental results are discussed in the light of existing theories.

Keywords. AC susceptibility; Bi–Sr–Ca–Cu–O; bulk superconductivity; eddy currents.

1. Introduction

AC susceptibility (ACS) experiment has been widely used to investigate the physical properties of high temperature superconductor (HTSC), particularly the study of magnetic field (a.c.) dependence on $\chi'(T)$, $\chi''(T)$ can provide information like bulk superconductivity, dimensionality, effect of particle size, preparation condition; to distinguish between the sintered, powdered sample, and also the glassy state behaviour to compare with spin-glass like state (Hein 1986; Goldfarb *et al* 1987; Rao *et al* 1987; Gregory 1973). For example, it has been shown that the a.c. field of 0·01 Oe is required to obtain perfect diamagnetism and 1 Oe is sufficient to distinguish the above parameters of HTSC sample (Goldfarb *et al* 1987; Rao *et al* 1987).

In ACS experiment the general features one can find is that the χ'' reaches a maximum corresponding to the inflexion point in χ', showing the coincidence of the Meissner effect. Hence we believe that χ'' is equally important even though the observable quantity of χ'' in real experiment is small, should be analysed to bring out the features of the superconducting state like bulk superconductivity, filamentary type etc, a fact which has not received enough attention in the study of HTSC.

The reasons cited above motivated us to undertake a systematic study of χ', χ'' at low fields (0·2 Oe to 20 Oe) around $T \leqslant T_c$ for the superconducting phase in newly-synthesized low-bismuth superconducting system $Bi_xSr_4Ca_2Cu_4O_y$ ($x = 0{\cdot}5, 1{\cdot}0$ and $1{\cdot}5$). The present system is different from the conventional Bi-based superconductors, with respect to the bismuth concentration.

2. Experiment

2.1 *$Bi_xSr_4Ca_2Cu_4O_y$ ($x = 0{\cdot}5$, $1{\cdot}0$ and $1{\cdot}5$) system*

It has been shown by us (Chatterjee *et al* 1989) that the bismuth deficiency in this $Bi_xSr_4Ca_2Cu_4O_y$ system compared with $Bi_4Sr_4Ca_2Cu_4O_{16}$ (4424) causes a change in symmetry, even though the unit cell dimensions are the same. The important result is that the Ca atom of the body centred, tetragonal structure of 4424 system is missing in $Bi_xSr_4Ca_2Cu_4O_y$. Thus we believe the present composition is different structurally from 4424 phase. The detailed X-ray data, together with preparation procedure is presented in Chatterjee *et al* (1989).

2.2 *ACS experiment*

ACS of the samples $x = 0{\cdot}5, 1{\cdot}0$ and $1{\cdot}5$ was measured using the home-made cryostat, L'ATNE mutual inductance bridge coupled with a microprocessor Z-80 for automation, under different fields in the range of 0·2 Oe to 20 Oe at 433 Hz. The sensitivity of our system is $1\,\mu H = 2{\cdot}14 \times 10^{-5}$ emu at 4 Oe, with a resolution of $0{\cdot}05\,\mu H$.

3. Results and discussion

The resistivity studies show (Chatterjee *et al* 1989) that the zero resistance state for $x = 0{\cdot}5$ is achieved at $T_c \sim 66$ K, for $x = 1{\cdot}0$ at $T_c \sim 74$ K, for $x = 1{\cdot}5$, $T_c \sim 78$ K. The ACS data namely χ', χ'' with T under various fields for different bismuth concentrations are shown in figures 1 and 2 in the vicinity of T_c at 433 Hz. We found as mentioned in the reference (Goldfarb *et al* 1987) that one would expect a positive χ'' from zero when the magnetic field exceeds H_{c1}. Further the critical temperature can be accurately estimated by identifying the temperature corresponding to the peak in $\chi''(T)$ rather than the inflexion point in $\chi'(T)$. T_c corresponding to the peak in χ'' at 0·8 Oe are 57·8 K for $x = 0{\cdot}5$, 69 K for $x = 1{\cdot}0$. For $x = 1{\cdot}5$, no peak was discernible in the temperature range investigated. Also, we found that as we increase the field, the $\chi''(T)$

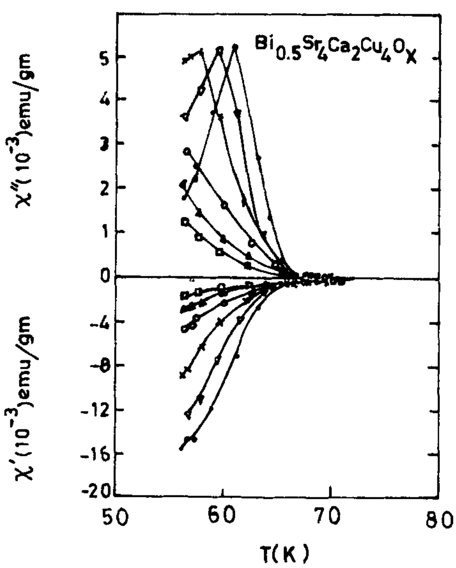

Figure 1. χ', χ'' with T for $Bi_{0{\cdot}5}Sr_4Ca_2Cu_4O_y$ under different fields. (●) 0·2 Oe; (▽) 0·4 Oe; (×) 0·8 Oe; (○) 2·0 Oe; (▲) 4·0 Oe; (□) 8·0 Oe.

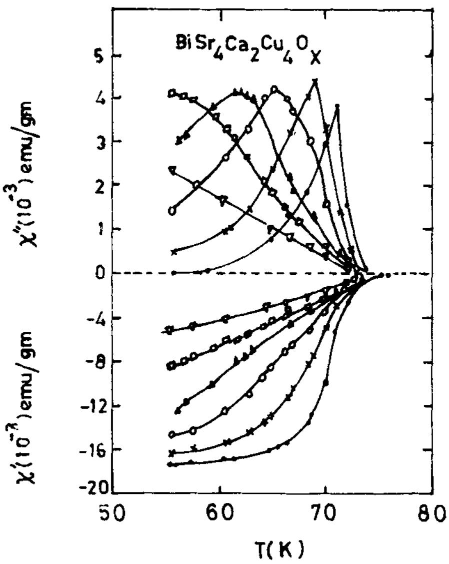

Figure 2. χ', χ'' with T for $BiSr_4Ca_2Cu_4O_y$ under different fields. (▽) 20 Oe and other notations same as in figure 1.

peak shifts to the lower temperature side. For example for $x = 0{\cdot}5$ sample, T_c varies from 61·2 K to 57·8 K with variation of the field from 0·2 Oe to 0·8 Oe. For $x = 1{\cdot}0$ sample T_c varies from 71·2 K to 61·6 K, for the field from 0·2 Oe to 4 Oe. We have restricted our present study of χ', χ'' with field dependence, even though in the ACS experiment one can study the χ', χ'' with frequency also. It should be mentioned here that there are some contradictory reports. For example, Mehdauli *et al* (1987) claimed the frequency dependence of χ' for temperature below T_c for YBaCuO, whereas Goldfarb *et al* (1987) found that there is no indication of the above behaviour, even though in both cases the onset of superconducting transition is independent of frequency. Thus for a superconductor a change in χ' with T corresponds to Meissner effect and one would also expect that the frequency cannot significantly change the onset of T_c. Thus the field dependence study is preferable rather than the frequency dependence. In order to analyse our χ', χ'' data, we have plotted the χ' with χ'' (magnitude only) for all fields and temperature, for $x = 1{\cdot}0$ sample as shown in figure 2. It may be interesting to note that χ'' reaches a maximum value with χ' irrespective of the field and temperature. In order to bring out this significance and also the physical significance of the peak in $\chi''(T)$, we invoked different theories. Here we report some of our preliminary investigation for our data.

Khoder (1983), on the basis of bulk superconductivity using BCS approach, explained the χ', χ'' behaviour in ACS experiment near T_c, including the peak in $\chi''(T)$. He attributed this peak to either the acceleration of the supercurrent or the reduction of field due to Meissner effect in the superconducting materials. According to his argument that χ' is so sensitive, the width of the superconducting transition is almost zero. Hence the plot of χ' with χ'' is preferable to test the applicability of his theory. We found that the plot of χ' with χ'' seems to follow the same behaviour as we show from our experimental data (figure 3). According to Khoder's calculation the value of χ', corresponding to the maximum value of χ'' is 0·0318 emu/cc which

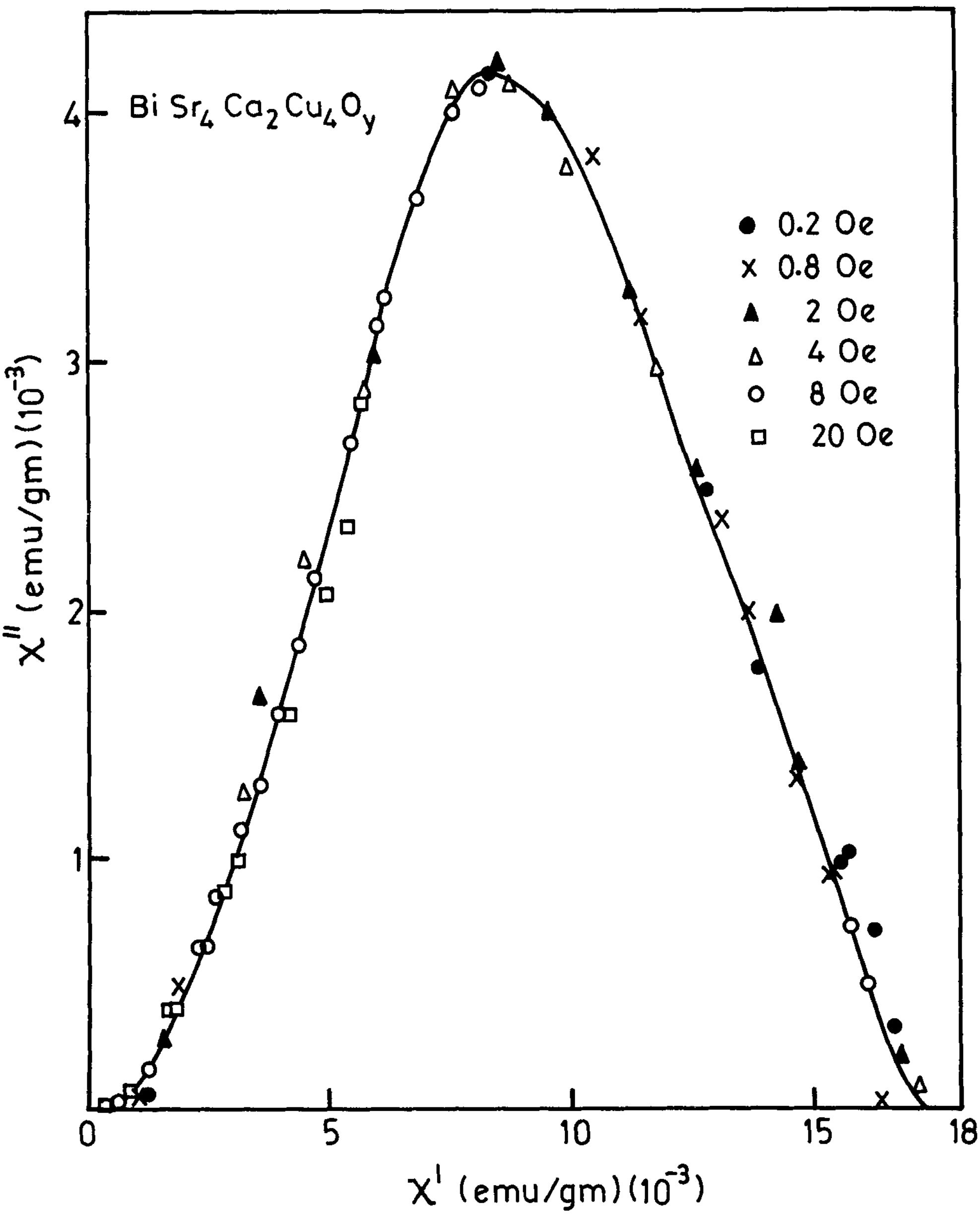

Figure 3. χ' with χ'' for $BiSr_4Ca_2Cu_4O_y$ for different temperatures and fields.

is in agreement with our value of χ' 0·0306 emu/cc. In order to check the consistency we have carried out the ACS experiment for YBaCuO, where the χ' value is of the same order 0·03 emu/cc. Thus it seems Khoder's approach may explain ACS data for HTSC.

However, different theories like eddy current model (Gregory 1973; Hein 1986), filamentary structure of superconducting phase (Maxwell and Strongnin 1963), can also explain the peak in $\chi''(T)$.

According to Gregory, if the applied frequency is less than the cut-off frequency, f_c, one would expect a peak in $\chi''(T)$ which is a normal state property. The cut-off frequency f_c is such that,

$$f_c = (1{\cdot}8/a)^2(10^9\rho/4\pi^2).$$

Here a is the radius of the sample, ρ the resistivity. For our $x = 1{\cdot}0$ sample $a = 0{\cdot}101$ cm at $\rho(300\,\mathrm{K}) \approx 14{\cdot}74\,\mu\Omega$cm, we found $f_c \sim 118$ kHz. Also at $\rho(90\,\mathrm{K}) \approx 5{\cdot}8\,\mu\Omega$cm, just before the onset of T_c, $f_c \sim 47$ kHz. Thus as a consequence of the high resistivity in HTSC, the cut-off frequency is of the order of tens of kHz, whereas for typical type-1 Pb supercondutor $f_c \sim 5$ Hz. Since the present experiments were carried out at 433 Hz, we required the data at higher frequencies to study this model in detail. On the other hand Maxwell and Strongnin (1963) showed that the enhancement of χ'' is due to the increase of conductivity ascribed to filamentary structure of superconductor. ACS studies on Pb–Sn (type II) confirmed this model where a/δ is less than 1·8 at $T > T_c$ and as one approaches normal to superconducting transition δ must decrease so that $a/\delta > 1{\cdot}8$. Here a is the radius of the sample in cm, δ is the normal state skin depth. We found that for our cylindrical sample $x = 1{\cdot}0$, a/δ is always less than 1·8 both at 100 K and at 76 K namely, 0·163 and 0·485 respectively. δ can be calculated using the equation

$$\delta^2 = (10^9\rho/4\pi^2 f)$$

where ρ is the resistivity in Ωcm, f is in sec^{-1}, δ is in cm. Therefore, the peak in $\chi''(T)$ is not possibly due to the filamentary structure proposed by Maxwell and Strongnin.

4. Conclusion

We have studied the χ', χ'' near T_c through ACS experiment for the low bismuth superconducting system, which is different from the conventional bismuth-based system. On the basis of T_c data we found that the effect of bismuth concentration in $Bi_xSr_4Ca_2Cu_4O_y$ is to increase T_c from 66 K to 78 K, when x varies from 0·5 to 1·5. We also found that the samples ($x = 0$) i.e. $Sr_4Ca_2Cu_4O_y$ is an insulator. The doping of bismuth system turns it to metallic. The onset temperature also shifts to higher temperature as x is increased from 86 K to 92 K. It is well known that 4424 phase (here $x = 4$) the onset temperature is 110 K. It is significant to recall the recent study (Mc Elfresh *et al* 1989) in $Sr_{14}Cu_{24}O_{14}$, which exhibits a semiconducting behaviour.

Regarding the physical significance of the peak in $\chi''(T)$, it seems Khoder's approach can explain our data. However, more experiments like conductivity as a function of frequency, careful observation of ACS on different system is required to support the above approach to HTSC.

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