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Paraconductivity of Ga-doped BiPbSrCaCuO

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Abstract. Thermal treatment of Bi, Pb, Ga, Sr, Ca and Cu oxides mixed to the nominal composition $Bi_{1.8}Pb_{0.1}Ga_{0.1}Sr_2Ca_2Cu_3O_y$ produces a superconducting material with a transition at 72–74 K. X-ray data indicate only the (2212) orthorhombic phase with lattice constants $a = b = 5.4$ Å and $c = 31$ Å. Resistance data of polycrystalline samples of this material show quasi-two-dimensional paraconductivity effects. The effective thickness of the superconducting electronic sheet, $d = 53$ Å, is comparable to the value of 30 Å found for the coherence length from the magnetoresistance data. As in other Bi-based high-T_c materials, this compound shows a substantial dissipation in the presence of an external magnetic field.

1. Introduction

Two-dimensional (2D) paraconductivity corrections proposed by Aslamazov and Larkin (1968) have been reported recently by Martin *et al* (1989) for single crystals of BiSrCaCuO. Vidal *et al* (1988) and Poddar *et al* (1989) studied these effects in polycrystalline samples of Bi-based, high-T_c compounds. Hikita and Suzuki (1989) studied the reduction of fluctuation corrected BCS critical transition temperature T_c^0, as a function of an applied magnetic field. Gridin *et al* (1990) have reported the field dependence of T_c^0 in the Pb-doped BiSrCaCuO polycrystalline material.

In this paper, we report a magnetoresistance study of the Ga-doped BiPbSrCaCuO polycrystalline material in which we interpret quasi-2D paraconductivity effects in the vicinity of the superconducting transition which occurs at 72–74 K.

Studying T_c^0 as a function of magnetic field we derive the value of the mean coherence length, $\xi(0)$. Paraconductivity effects at zero field give the effective thickness, d, of the superconducting electronic sheet. We find that there is a simple relation between d and $\xi(0)$, namely $d/\xi(0) = \sqrt{\pi}$. The application of a magnetic field results in considerable dissipation in this material, as in other Bi-based, high-T_c systems.

2. Discussion of experimental results

The samples were prepared by the solid state reaction method described by Statt *et al* (1988). Powders of Bi, Pb, Sr, Ca, Ga and Cu were mixed to yield the nominal

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composition of $Bi_{1.8}Pb_{0.1}Ga_{0.1}Sr_2Ca_2Cu_3O_y$. The mixture of powders was pelletized and thermally treated in air for 120 h at 850 °C. This was followed by a slow cooling at the rate of 0.2 °C min^{-1} in the temperature range 850 °C $< T <$ 400 °C and at 0.4 °C min^{-1} from 400 °C to room temperature. Thermal treatment of $T >$ 860 °C produced material that was not superconducting. The DC susceptibility of the superconducting material is shown in figure 1. The onset of diamagnetism begins at 71 K for a field of 34 Oe. The analysis of the x-ray patterns indicates that only the (2212) superconducting phase exists. The indexation of the peaks presented in figure 2 was performed for the orthorhombic unit cell with the lattice constants $a = b = 5.4$ Å and $c = 30.7$ Å (Veal *et al* 1988). Resistivity measurements were made with a four-probe technique. The samples for the resistivity study had a rectangular shape with dimensions $L(x) \times L(y) \times L(z) = 1.27 \times 0.20 \times 0.09$ cm^3. The external magnetic field H was oriented parallel to the smallest sample side, $L(z)$, and the current was applied along the $L(x)$ direction.

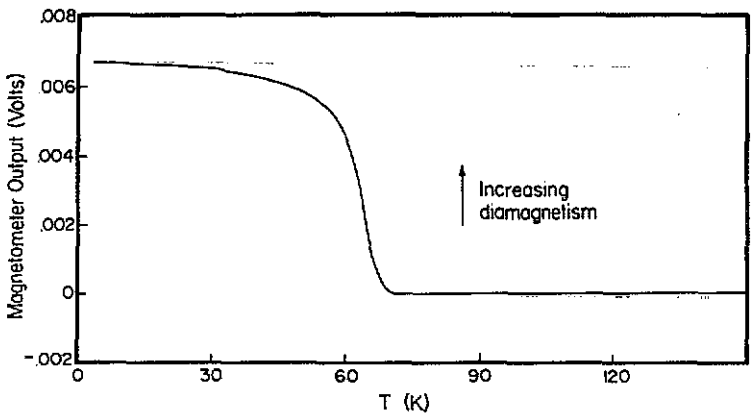

Figure 1. Temperature dependence of the DC susceptibility at $H = 34$ Oe.

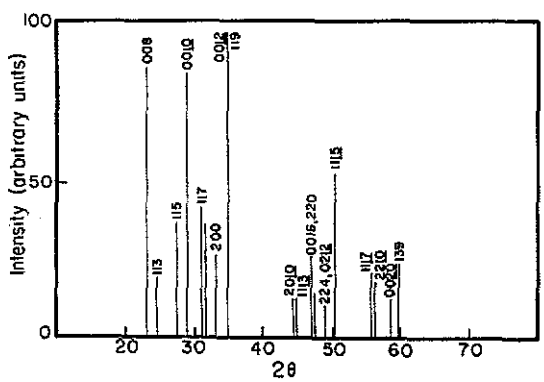

Figure 2. X-ray pattern. The peaks are indexed on the basis of the (2212) orthorhombic unit with $a = b = 5.4$ Å and $c = 30.7$ Å. Note the highly textured structure indicated by the enhanced $(00m)$ intensities.

The study of the x-ray diffraction patterns from powdered and pelletized samples show that the $(00l)$ peaks are always enhanced. The enhancement is stronger for the

pelletized, as-grown samples. This suggests that there is a textured morphology in our polycrystalline material. The samples for the transport study were always cut in such a way that the thinnest, $L(z)$, side was oriented along the preferred c axis. The cross-sectional area to length ratio, p, of our samples is 0.018 cm. The resistance, R, and resistivity, ρ, are related according to $R = \rho/p$.

The temperature dependence of the normalized resistance $R(H,T)R^*$ for $H = 0$ and 1.0 T is presented in figure 3. The resistance of the samples is normalized to the resistance R^* measured at 300 K. The major magnetoresistance occurs below 80 K. The resistance in figure 3 extrapolates to a value at $T = 0$ which is approximately 40% of the 90 K value. This implies a substantial contribution to the resistance from grain boundaries. However, we do not believe that grain-boundary effects are important in our analysis because we consider effects well above the critical temperature where the coherence length is finite and the mean field regime exists. Here, the effective size of the fluctuations is of the order of the coherence length and is small relative to the size of the grain boundaries. Also, the intergrain resistance may be considered as temperature independent near the mean-field transition temperature and the paraconductivity in the resistivity of the grains can be observed (Veira *et al* 1989).

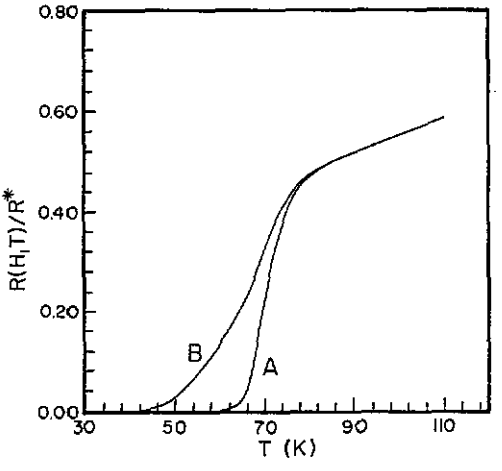

Figure 3. The temperature dependence of the normalized electrical resistance $R(H,T)/R^*$. A: for zero field, B: for $H = 1.0$ T. R^* is the resistance at 300 K with a typical value of 42 mΩ.

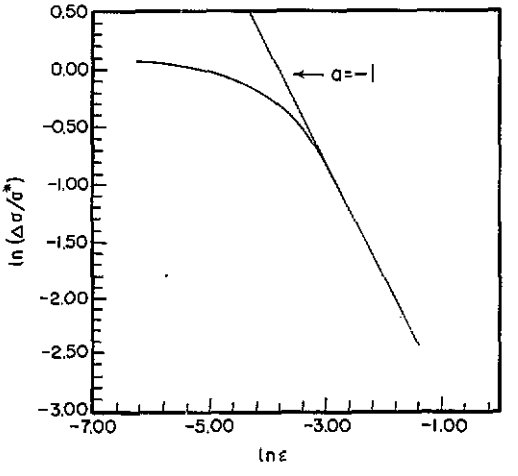

Figure 4. The natural logarithm of the left-hand side of (1) versus ln ϵ for the zero-field data normalized to the room-temperature conductivity, σ^*. The temperature region in which a deviates from $a = -1$ (straight line) was used to evaluate the coherence length, $\epsilon_\perp(0)$, by means of (3).

We now turn to the analysis of the paraconductivity effects. The single-layer relation derived by Aslamazov and Larkin (1968) for the enhanced conductivity at $T > T_c^0$, where T_c^0 is the Ginzburg–Landau mean-field theory transition temperature is:

$$\Delta\sigma = A\epsilon^a. \tag{1}$$

For the 2D case $a = -1$ and $A = e^2/16\bar{h}d$; for 3D $a = -1/2$ and $A = e^2/32\bar{h}\epsilon(0)$. $\epsilon = (T - T_c^0)$, d is the layer thickness and $\epsilon(0)$ is the coherence length at $T = 0$ K.

In (1), $\Delta\sigma = \sigma - \sigma_N$ where $\sigma_N = 1/\rho_N$ is the normal-state conductivity background which has to be determined by extrapolation from temperatures above $2T_c$ to lower temperatures in order to fit the paraconductivity term, $\Delta\sigma$.

Lawrence and Doniach (1971) considered a multi-layer superconducting structure and found that the modified paraconductivity with an interlayer coupling is:

$$\Delta\sigma = (B/\epsilon)(1 + v/\epsilon)^{-1/2} \tag{2}$$

where $B = e^2/16\hbar d$ and $v = [2\epsilon_\perp(0)/d]^2$. $\epsilon_\perp(0)$ is the coherence length in the stacking direction of the multi-layer structure. Other quantities in (2) have the same meaning as in (1). The value of $\epsilon_\perp(0)$ is expected to be comparable to $\epsilon_c(0)$ for the Bi-based single-crystal data that have been reported by Klee *et al* (1988), Palstra *et al* (1988) and Naughton *et al* (1988). For two limiting cases, $v \ll 1$ and $v \gg 1$ one obtains that (2) yields the 2D and 3D single-layer terms of (1), respectively. Therefore, we find first the principal temperature dependence of $\Delta\sigma$ by using the form of (1).

In figure 4 we plot the natural logarithm of the left-hand side of (1) versus ln ϵ. Following the procedure described by Poddar *et al* (1989) who varied T_c^0 and a to obtain the best least-mean-square fit to the data, we get $a = -0.99 \pm 0.03$ and $T_c^0 = 72.4 \pm 0.2$ K for the zero-field case. The value of a is that expected for 2D paraconductivity. Also, one observes that the single-layer, 2D term does not hold for $T < 76$ K.

Lawrence and Doniach (1971) pointed out that even in the 2D case 3D effects are expected for temperatures close enough to T_c. Using their estimate for the characteristic temperature interval that separates these two regimes

$$\Delta T \sim T_c^0 v \tag{3}$$

we can evaluate $\epsilon_\perp(0)$ and d for our material in the interval 76 K $-T_c^0 = 3.5$ K. Assuming that $T > 76$ K and $a = -1$, we apply another useful construction suggested by Fiory *et al* (1983) for finding T_c^0 and d. This is presented in figure 5, where $(1/r - 1/r_N)^{-1}$ is plotted as a function of T. Here r and r_N are the resistance and the normal background resistance normalized to the room-temperature resistance R^*. The slope, b, of the straight line gives d according to

$$d = bR^* pe^2 T_c^0/16\hbar \tag{4}$$

and the extrapolation of the line to the T-axis yields T_c^0. We find that $T_c^0 = 72.5 \pm 2$ Å. Inserting $d - 53$ Å and $\Delta T = 3.5$ K into (3) yields $\epsilon_\perp(0) = 5.8 \pm 0.2$ Å.

In figure 5 we also present the use of this construction for finding the field dependence of T_c^0. In figure 6 we plot the empirical relation found for this dependence for our material:

$$H = C(1 - t)^z \tag{5}$$

with $C = 3.47 \pm 0.5$ T and $z = 1.3 \pm 0.1$; $t = T_c^0(H)/T_c^0(0)$. Hikita and Suzuki (1989) used the field dependence of T_c^0 for an estimation of the coherence length, $\epsilon(0)$. They applied the analysis of Kapitulnik *et al* (1988) who pointed out that in the critical region there is the following relation between H_{c2} and t:

$$H_{c2} = D(1 - t)^q \tag{6}$$

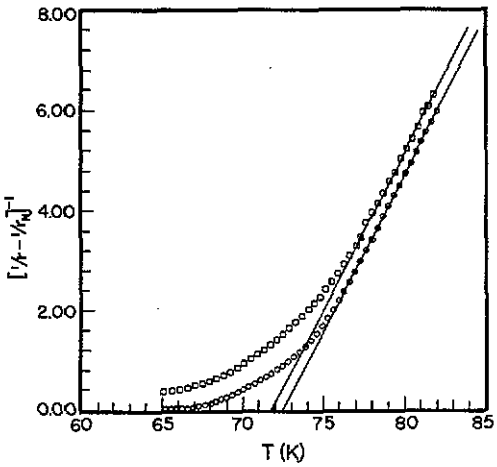

Figure 5. Construction for the evaluation of T_c^0 and d by means of (1) and (4) for the 2D case: $a = -1$. Squares and circles are for $H = 1.0$ T and $H = 0$ T data, respectively. $T_c^0 = 71.8 \pm 0.1$ K and $T_c^0 = 72.5 \pm 0.1$ K for the former and latter case, respectively. $d = 53 \pm 2$ Å. See (5) and (6) for discussion. The full line corresponds to the best power-law fit.

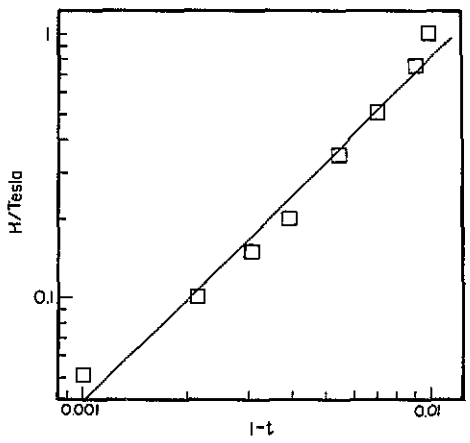

Figure 6. The field dependence of $1 - t, t = T_c^0(H)/T_c^0(0)$. See (5) and (6) for discussion. The full line corresponds to the best power-law fit.

here $D = \phi/2\pi\epsilon^2(0)$; ϕ is the flux quantum. Comparing C and D of the last two equations we get $\epsilon(0) = 30$ Å, which represents a reasonable mean value for textured polycrystalline samples with $d = 53$ Å. The value of $q = z = 1.3 \pm 0.1$ agrees satisfactorily with the finding of Hikita and Suzuki (1989). We note that $\epsilon(0)$ is expected to differ from the estimate for $\epsilon_\perp(0)$ given above, since the field orientation was chosen to be along the preferred orientation of our textured samples so that $\epsilon(0)$ was closer to $\epsilon_\parallel(0)$.

As a final remark we note that while the values of d and $\epsilon(0)$ might differ by as much as 7% from sample to sample there is a simple relation between these two quantities for the same sample:

$$\pi/[\epsilon(0)/d]^2 = 1.01 \pm 0.03. \tag{7}$$

Our previous data on $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_y$ material with $T_c = 113$ K reported by Gridin *et al* (1990) also support this observation. Since the effective size of the superconducting sub-unit is d^2 and $\pi/\epsilon^2(0)$ for zero field and $H \neq 0$ cases, respectively, the observation presented by (7) would result from the normalization condition of the wave-function describing this sub-unit.

In summary, the Ga-doped, Bi-based polycrystalline material studied here shows quasi-2D paraconductivity effects. The out-of-plane coherence length derived from the zero-field data is of the order of 5.6 Å for this (2212) phase material. The mean coherence length obtained from the magnetoresistance data is $\epsilon(0) = 30$ Å. There is a simple relation between the effective thickness, d, of a superconducting sheet and $\epsilon(0)$: namely, $d^2 = \pi/\epsilon^2(0)$. This material shows a substantial increase in dissipation, for $H \neq 0$, as do other Bi-based, high-T_c compounds.

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