CONF-900817--1

Submitted for presentation at the LT19-19th International Conference on Low Temperature Physics, Brighton, United Kingdom, August 16-22, 1990, and to be published by Elsevier in a special edition of *Physica B*.

CONF-900817--1

DE90 009415

Evidence of Weak Pair Coupling in the Penetration Depth of Bi-Based High-T_c Superconductors*

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*Research supported by the Division of Material Sciences, U.S. Department of Energy under contract no. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

EVIDENCE of WEAK PAIR COUPLING in the PENETRATION DEPTH of Bi-BASED HIGH-T_c SUPERCONDUCTORS

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The magnetic penetration depth $\lambda(T)$ has been investigated in Bi(Pb)SrCaCuO high-T_c compounds having 2- and 3-layers of copper-oxygen per unit cell. Studies of the magnetization in the vortex state were employed and the results were compared with weak and strong coupling calculations. The temperature dependence of λ is described well by BCS theory in the clean limit, giving evidence for weak pair coupling in this family of materials. For the short component of the λ tensor, we obtain values of 292 and 220 nm (T=0) for Bi-2212 and (BiPb)-2223, respectively.

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1. INTRODUCTION and EXPERIMENTAL ASPECTS

Intensive investigation of high temperature superconductors (HTSC) during the past three years has revealed many properties of these materials, yet the fundamental mechanism whereby valence electrons are formed into superconducting pairs remains controversial. One physical property that provides some insight into this important question is the temperature dependence of the magnetic penetration depth $\lambda(T)$. The functional form of $\lambda(T)$ differs, depending on whether the pair coupling is weak BCS-like or strong, and if the limit is clean or dirty. Our investigation of $\lambda(T)$ in several Bi-based HTSC materials shows that in every case studied, the experimental results are accurately described by BCS theory, implying that the coupling is weak in this family of layered Cu-oxide superconductors. In addition, we find that agreement with clean limit theory is better. This result is highly plausible, since this case is appropriate when the electronic mean free path lengths exceed the corresponding coherence lengths, which are generally quite short in HTSC's.

In this work, we have investigated Bi-based superconducting compounds containing two and three Cu-O layers per unit cell. Two-layer sintered specimens processed differently had midpoint resistive T_c's of 81.0, 81.8 and 73.5 K. These and a three-layer, sintered sample of $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ (T_c=108 K) were highly textured from pressing. Preliminary results have been obtained for a single crystal of Bi-2212. In all cases, X-ray diffraction analysis indicated little extraneous phase content.

The magnetic investigations were performed in a commercial SQUID magnetometer and a vibrating sample magnetometer. Both instruments were equipped so as to maintain the sample in a homogeneous, monotonically varying field environment. In general, the magnetization M(H,T) was studied at fixed temperature T as a function of field H < 50 kG, applied normal to the basal plane in the (textured) polycrystalline materials. Measurements at T > T_c were used for background corrections.

2. THEORETICAL BASIS and EXPERIMENTAL RESULTS

In the vortex state of a uniaxial superconductor, Kogan et al. [1] have obtained the result in the London limit that

$$dM/d(\ln[H]) = \phi_o/(32\,\pi^2\,\lambda_{eff}^2) \qquad (1)$$

where ϕ_o is the elementary flux quantum and λ_{eff} is an appropriate penetration depth. This expression is valid for fields H where $H_{c1} \ll H \ll H_{c2}$, provided that M is reversible. For an anisotropic single crystal, we define λ_i as the penetration depth for fields screened by supercurrents in the i-th direction. In a layered compound like BSCCO, the independent components of the penetration depth tensor are λ_c and λ_a, where any basal plane anisotropy is neglected. With H//c-axis in a single crystal, one has $\lambda_{eff}^2 = \lambda_a^2$ and with H//ab, then $\lambda_{eff}^2 = \lambda_a\lambda_c$. In a randomly oriented polycrystal, an angular average of Eq. 1 leads to the result that $\lambda_{eff}^2 = (\lambda_a\lambda_a\lambda_c)^{2/3}g(\gamma)/2$, where $g(\gamma)$ is a function that varies roughly logarithmically with the anisotropy parameter $\gamma = (m_c/m_a)^{1/2} = (\lambda_c/\lambda_a)$. [1]

The effective penetration depth was determined from measurements of M vs ln[H] at various temperatures. Figure 1 presents typical results for Bi-2212. For all samples, similar data were obtained in the H-T plane where the materials were magnetically reversible. Using the general Ginzburg-Landau relation that $\lambda^{-2} \propto (T_c - T)$ near T_c, we obtained a value for the transition temperature T_c appropriate to the penetration depth as the temperature at which $\lambda^{-2} = 0$. This procedure is important, since choosing a value for T_c is problematical, especially in Bi-based materials where the transition tends to be rather broad. The values so obtained were close to the midpoint values of the resistive transitions and the 10% onset in the magnetic transition, but the

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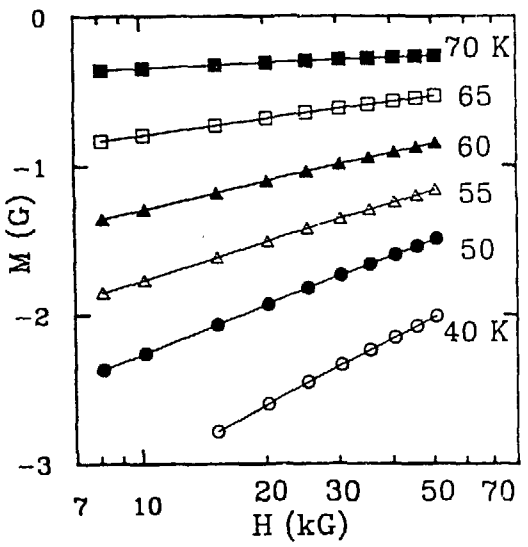

Figure 1. Vortex state magnetization M vs ln(H), for Bi-2212 at temperatures shown. Slopes are proportional to $(1/\lambda_{eff}^2)$ and yield T_c=72.4 K.

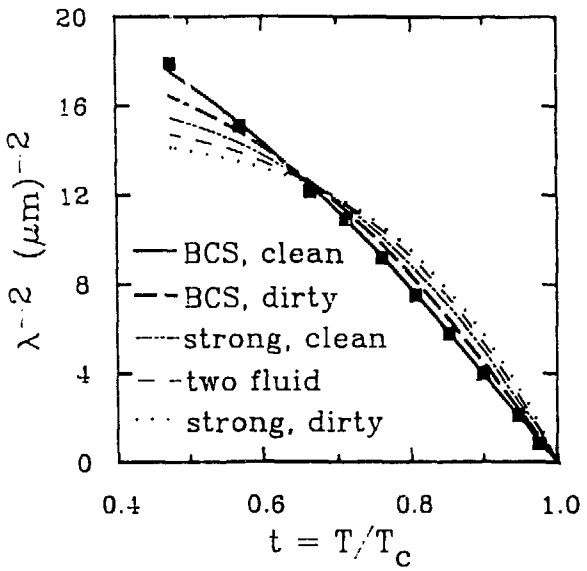

Figure 2. The penetration depth λ_{eff} vs reduced temperature t, for (BiPb)-2223 (T_c = 106 K). Lines show least-squares fits of theoretical dependencies to experimental data (squares).

procedure outlined is a far more satisfactory method [2].

Theoretical dependencies for the penetration depth $\lambda(t)$ as a function of reduced temperature $t=(T/T_c)$ include BCS results in the clean and dirty limits [3] and the empirical two fluid model with $\lambda(t) = (1-t^4)^{-1/2}$. For the strong coupling cases, recent calculations by Rammer [4] are used. We have made least-squares fits of each of these forms to the experimental data, where the only free parameter is the value $\lambda(0)$ at T=0.

Figure 2 presents experimental results for the 3-layer compound as a function of t. First, one notes that near T_c the experimental points for λ^{-2} follow the linear G-L variation ($T-T_c$) rather well. Second, BCS theory in the clean limit provides an excellent description of the experimental results. As is quite evident in the figure, the quality of the description steadily deteriorates as one goes from weak to strong coupling, and from the clean to the dirty limit. Results similar to these were obtained for all of the Bi-based materials investigated, as well as for aligned Tl-2223 HTSC materials.[2]

For the (BiPb)-2223 sample, this analysis yielded $\lambda_{eff}(0)$ = 220 nm, while for the sintered Bi-2212 samples, an average value $\lambda_{eff}(0)$ = 292 nm was obtained. Due to the strong texture of the samples, we regard these results as the "basal plane-shielded" depth λ_a. The latter value is very similar to that reported [5] for single crystal Bi-2212 with H//c, $\lambda_a(0)$ = 300 nm. Our preliminary results on single crystal Bi-2212 with both field orientations, H//c and H//ab, have yielded $\lambda_a(0)$ = 266 nm and for $\lambda_c(0)$, a lower bound of 3700 nm. The corresponding anisotropy parameter is γ = 14, compared with recently reported value of 17 [6], 3 [7], and 60 [8]. Details will be reported in a later paper. In summary, the temperature dependence of the penetration depth $\lambda(T)$ for these Bi-based materials indicates that they are weak coupling superconductors, as suggested by Little [9].

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