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Reversible magnetization and irreversibility line of tri-layer superconductor $Ba_2Ca_2Cu_3O_6(O,F)_2$ with $T_c \sim 108$ K[☆]

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Abstract

We report magnetization measurements of grain-aligned $Ba_2Ca_2Cu_3O_6(O,F)_2$ with $T_c \simeq 108$ K. The interlayer distance of the material is the shortest among known tri-layer superconductors. Unexpectedly, the magnetization data show that the coupling strength between CuO_2 layers is rather weak. A direct reflection of the weak coupling is highly suppressed irreversibility line, i.e. a broad reversible region in *H–T* plane. The decoupling field obtained from the irreversibility line is less than 0.1 T, which is comparable with that of quasi two-dimensional superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$. Comparison of data with the Hao–Clem model gives characteristic parameters [$\xi_{ab}(0)$ and $\lambda_{ab}(0)$] and the critical fields [$H_c(0)$ and $H^c_{c2}(0)$]. A large value of penetration depth, $\lambda_{ab}(0) = 240$ nm reflects a small carrier concentration in CuO_2 planes, and explains the reason of the weak interlayer coupling.

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1. Introduction

For high-temperature superconductors (HTSC), charge carriers in the con-ducting CuO_2 planes are supplied from insulating charge-reservoir block (CRB). For instance, $YBa_2\ Cu_3O_{7-\delta}$ (Y-123) can be doped by the oxygen O_δ in $YBa_2O_{2+\delta}$ block. However, the function of the CRB, beyond carrier supplier, is not yet completely clear. One can presume that CRB plays role to reduce the layer-by-layer coupling, since the physical extension of CRB widens the space between the CuO_2 planes. The strong anisotropic nature of HTSC is known to come from a weak interlayer coupling.

Previously, a number of group synthesized a new homologous series Ba_2 (or Sr_2)$Ca_{n-1}Cu_nO_y$ (02 ($n-1$)n).[1–11] Structurally, 02 ($n-1$)n is akin to Hg-based homologous series $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ (Hg-12($n-1$)n). The cardinal difference in the two series is structure of CRB. For Hg-based superconductors, the CRB consists of double rocksalt-like block $HgBa_2O_{2+\delta}$ and the hole concentration in CuO_2 planes is determined by the

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interstitial oxygen defects in the HgO_δ plane. On the other hand, for 02 $(n-1)n$ single rocksalt block formed by two adjacent BaO layers plays role of CRB. The charge concentration in the CuO_2 planes can be controlled by partially substituted ions at the apical-oxygen sites. The thickness of CRB for 02 $(n-1)n$ is about 7.4 Å, which is significantly smaller than 9.5 Å for Hg-12 $(n-1)n$. Since, the thinner CRB makes the spacing between CuO_2 layer blocks shorten, one would expect a strong interlayer coupling in 02 $(n-1)n$.

In this work, we explore the effect of a thinner CRB for the interlayer coupling in tri-layered $Ba_2Ca_2Cu_3O_6(O,F)_2$ (0223F) with $T_c \simeq 108$ K. The apical oxygen in the sample is partially substituted by fluorine. In F-free case, the phase easily transforms to a derivative phase by reacting with H_2O and CO_2 in the air. (This means that the pristine phase essentially prefers an under-doped state) The substitution of F^{-1} for the apical O^{-2} makes the system to be in an under-doped state, and hence it prevents such a transformation or degradation [9].

Here we measure the mixed-state magnetization of 0223F. The data are compared with the Hao–Clem model [12,13] and the high-field scaling law proposed by Ullah and Dorsey [14]. Also, the irreversibility line $H_{irr}(T)$ is analyzed in framework of the vortex fluctuation model [15–17]. These results consistently show that interlayer coupling in 0223F is not enhanced in comparison with the same tri-layered $HgBa_2Ca_2Cu_3O_{8+\delta}$ (Hg-1223; $T_c \simeq 135$ K), even though the thickness of the CRB is much smaller than that of Hg-1223.

2. Experiments

Details of sample preparation are given in Refs. [9–11]. Nearly single-phase sample of $Ba_2Ca_2Cu_3O_6(O,F)_2$ (nominal composition of $Ba_2Ca_2Cu_3O_{6.225+\delta}F_{1.4}$) was synthesized at the temperature of 950 °C under the pressure of 4.5 Gpa using a cubic-anvil-type apparatus. X-ray diffraction result reveals that the compound has a tetragonal symmetry ($I4/mmm$) with lattice parameters $a = 3.866$ Å and $c = 27.42$ Å.

To obtain a c-axis-aligned sample, the Farrell method [18] was employed. The sample powder was passed through a fine sieve to remove possible intergrain coupling. This fine powder was aligned in a commercial epoxy with an external magnetic field of 7 T. After alignment, only the (00l) reflections were seen in the XRD pattern. The composite of the sample powder and epoxy is approximately 6 mm in length and 4 mm in diameter.

The magnetization was measured as a function of temperature by using a superconducting quantum interference device magnetometer (MPMS-XL, Quantum Design). The background contribution from epoxy and impurities was subtracted from the observed values.

3. Results and discussion

As a preliminary, the magnetic susceptibility of the aligned sample, $4\pi\chi(T) = 4\pi M(T)/H_{ext}$ was measured for the external field $H_{ext} = 10$ Oe parallel to the c axis, as shown in Fig. 1. The superconducting transition occurs at $T \simeq 108$ K. At $T = 5$ K, the nominal shielding fraction, $|4\pi M|/H_{ext}$, is about 0.65.

Fig. 2 shows magnetization curves, $4\pi M(T)$, measured in the external field range 1 T $\leq H_{ext} \leq$ 5 T parallel to the c axis. Roughly, the magnetization in this field range is reversible for $|4\pi M| < 50$ G, where the magnetization does not show hysteresis with respect to field or temperature. The inset of Fig. 2 shows $M(T)$ around the transition region. A crossover of the magnetization curves is clearly seen at $T = T^* \simeq 104$ K, which is a reflection of the thermal distortion of the two-dimensional (2D) vortex pancakes out of the straight stacks [19]. This feature means that the $M(T)$ curves highly deviate from the standard London behavior, [20] and hence T_c drop with H, expected in the mean-field theory, is indiscernible.

To describe the reversible magnetization data, we use the Hao–Clem model [12,13] based on the Ginzburg–Landau (GL) theory. The model considers not only the electromagnetic energy outside of the vortex core, but also the kinetic and condensation energy change arising from suppression of the order parameter in the vortex core. This model permits a reliable description of the magnetization in the entire mixed state and an accurate determination of thermodynamic parameters such as the critical field, $H_c(0)$.

In the Hao–Clem model, the reversible magnetization being expressed in dimensionless form, $4\pi M'(H')$, is a universal function for a given value of the GL parameter, κ, and is temperature independent. Here, the magnetization and external field are defined as $4\pi M' \equiv 4\pi M/\sqrt{2}H_c(T)$ and $H' \equiv H\sqrt{2}H_c(T)$ [12,13]. At a fixed temperature, the ratio $4\pi M_i(H_i)/H_i$ ($i = 1, 2, \ldots$) in experimental data corresponds

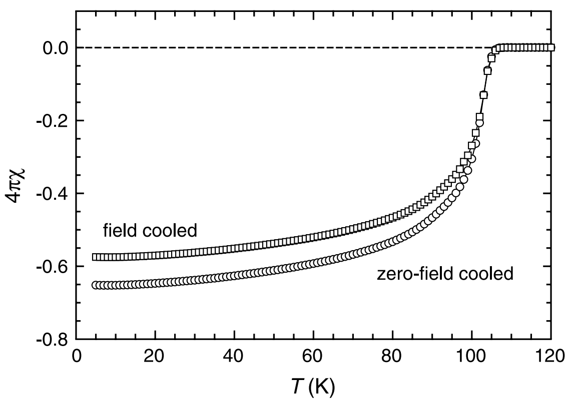

Fig. 1. Low-field susceptibility, $4\pi\chi(T)$, of c-axis aligned $Ba_2Ca_2Cu_3O_6(O,F)_2$ measured for $H = 10$ Oe parallel, to the c axis. Upper and lower curves represent field-cooled (Meissner) and zero-field-cooled (shielding) $4\pi\chi(T)$'s, respectively.