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Critical current densities and irreversibility fields of a $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ sample containing $n = 6–15$ phases

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ABSTRACT

A recent report on multilayered superconductors establishes unique constant T_c although the number of inner CuO_2 plane (IP) increases. Many hypotheses proposed that the irreversibility field (B_{irr}) and critical current density (J_c) are depends on the crystal structures. We have measured the J_c and B_{irr} of the $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ sample containing $n = 6–15$ phases to investigate the effect of the number of IP's on the B_{irr} and J_c and its pinning properties. The rate of fall of J_c increases and irreversible lines (IL's) shift to lower temperatures with increasing the number of IP's, which suggests that anisotropy increases with n. The IL settled in between those for $Bi_2Sr_2CaCu_2O_y$ with high anisotropy value and $YBa_2Cu_3O_7$ with less anisotropy value. The double logarithmic plot of irreversibility field versus $[1 - (T/T_c)]$ analysis suggests that the flux line melting model is adopted. The flux pinning force density F_p ($\approx J_cB$) exhibits scaling behavior when the magnetic field B is normalized by the irreversibility field B_{irr}. Analysis of the normalized pinning force reveals that a surface pinning mechanism is dominant and reduced magnetic field $b_{max} = 0.2$ agree with surface pinning mechanism with closely spaced pins.

1. Introduction

Multilayered (ML) cuprates admit two or more crystallographically inequivalent CuO_2 planes in a unit cell: outer planes (OP) with pyramidal (five) oxygen coordination and inner planes with square (four) oxygen coordination. Multilayered cuprates are generally depicted by the formula, $MCa_{n-1}Cu_nO_{2n}$, where M is a charge reservoir layer (CRL) such as $HgBa_2O_y$, $Bi_2Sr_2O_y$, $Tl_2Ba_2O_y$, $Ba(O,F)_y$ etc. The $Ca_{n-1}Cu_nO_{2n}$ has an infinite layer structure and n means the number of CuO_2 planes between the CRL. Multilayered high-T_c cuprates, which have more than three CuO_2 planes in a unit cell, demonstrate peculiar properties because of the two types of CuO_2 planes. Evidence for the coexistent phase of superconductivity and antiferromagnetism in a unit cell has been obtained in the five-layered high-T_c superconductor $HgBa_2Ca_4Cu_5O_{12+\delta}$ [1–3]. Also our recent investigations have proposed a T_c versus n relationship for multilayered high-T_c superconductors, in which the T_c is almost constant above about $n = 5$ [4]. We explained the characteristic relationship between T_c versus n using the carrier imbalance model in multilayered cuprates shown by NMR measurements [5]. The OP can have enough carriers for superconductivity for large n even if the number of carriers in IP becomes too small to induce superconductivity.

The B_{irr} and J_c of the samples should be influenced by the n even though that the samples have the same T_c, because a coupling between the OP's is expected to be weak with increasing the number of IP's. To know the J_c and B_{irr} for large n, we used the $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ (Hg-12($n-1$)n) sample containing $n = 6–15$ phases because we have not succeeded in synthesizing single-phase samples for $n \geqslant 7$. In this report, the J_c and B_{irr} properties of the sample will be shown and compared with other superconductors.

2. Experimental

The multilayered (ML) cuprates are normally synthesized under a pressure of several GPa [6]. The details of the preparation for polycrystalline $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ sample with a nominal composition of $n = 10$ (Hg-12910) have been reported elsewhere [4]. For grain alignment, the polycrystalline sample was ground to a powder with average grain size 2–3 μm, mixed with an epoxy resin in a sample powder: epoxy resin = 1:3 weight ratio, and kept for 12 h in a high magnetic field of 7 T at room temperature. Our samples consist of a collection of single crystals embedded into a cylindrical epoxy, all crystals having the c-axis parallel to the applied

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field. In present study, the aligned sample and polycrystalline single-phase samples of $n = 4$ and 5 are used. The aligned and polycrystalline samples were characterized by powder X-ray diffraction (RINT 1100, Rigaku). Magnetic susceptibility (MPMS, Quantum Design) was measured by the field cooling method. Measurements of the isothermal magnetization $M(H)$ were made for a set of temperatures (T) from 5 to 100 K. From the DC magnetization hysteresis loops, we determined the intragrain J_c and B_{irr} (criterion 1000 A/cm^2) using Bean's critical state model, $J_c = 30\ \Delta M/d$, where 'ΔM' is the magnetization determined from M–H loops, 'd' is the grain size in polycrystalline samples.

3. Results

Fig. 1 shows the XRD pattern of the aligned Hg-12910 sample. Most peaks could be indexed as only (0 0 l) peaks. The XRD pattern shows the coexistence of the $n = 6$–15 phases of Hg-12($n-1$)n. Fig. 2 shows the temperature dependence of susceptibility of the Hg-12910 sample. The sample showed a high and sharp superconducting transition at temperature 103 K. This means that all the coexistent phases in the sample have the same T_c values, otherwise a lot of transitions would have been observed.

Fig. 3 shows the field dependence of J_c observed at various temperatures for the Hg-12910 sample. Although the J_c values are fairly high and only weakly dependent on the magnetic field at low temperatures, a rapid falling off with increasing field was observed above 30 K. Hence, strong pinning at high temperatures as observed in $YBa_2Cu_3O_7$ (Cu-1212) superconductors, seems not to be observed in the Hg-12910 sample. The J_c declines precipitously with magnetic field at moderate temperatures (>30 K) because of the weak flux pinning. The variation in the J_c values estimated at 1 T for $n = 4$, 5 and 10, plotted as the $J_c(T)/J_c(0)$ versus temperature are shown in Fig. 4. The J_c can be approximated to the temperature dependence of $J_c(T) = J_c(0)\exp(-T/T_0)$ where T_0 is a fitting parameter and provides a rough measure of the decaying speed of J_c with increasing temperature. The fitting parameter T_0 prevailed for the $n = 10$ was 5 K while for $n = 4$ and 5 are 9.5 K and 20 K, respectively. The shift of T_0 values at low temperatures with the increase in number of CuO_2 layers in a unit cell and sudden fall of J_c value with applied magnetic field suggest the increase in the anisotropy value. The T_0 values for the optimal doped other cuprates superconductors are reported previously; such as $T_0 = 14$–23 K for (Cu, C)Ba_2Ca_3-Cu_4O_y ((Cu, C)-1234) [7–9], $T_0 = 7$ K for Hg-1201 [10], $T_0 = 4$–5 K for $Bi_2Sr_2CaCu_2O_y$ (Bi-2212) [11]. In the present investigation the T_0 values of the Hg-12910 sample is established same as Bi-2212, but lower than (Cu, C)-1234. While for the $n = 4$ and 5, the T_0 values are higher than Bi-2212 but lower than Cu-1212. This proposes that the Hg-12910 pretends like highly anisotropic system like Bi-2212.

Numerous experiments probing the mixed state of cuprate superconductors have been established, the presence of a boundary in the magnetic phase diagram which separates a magnetically irreversible, zero resistance state from a reversible state with dissipative electrical transport properties [12–16]. This boundary has been suggested to be due to either depinning [13,17], to a vortex-glass formation [18], or to the flux-lattice melting [19]. The temperature dependence of IL of Hg-12($n-1$)n ($n = 4$, 5 and 10), Bi-2212 and Cu-1212 are shown in Fig. 5. It is clear that the $n = 4$, 5 and 10 samples have a steeper IL's and, therefore, a large irreversibility regions in B–T plane than those of Bi-2212 sample.

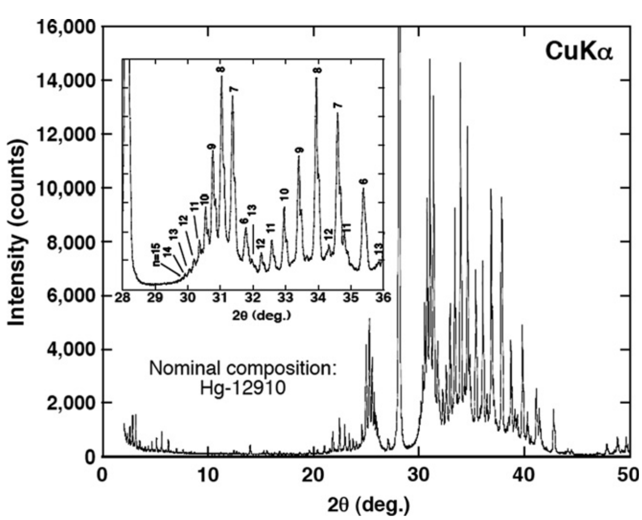

Fig. 1. X-ray diffraction pattern of the aligned $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ sample with nominal composition of $n = 10$ (Hg-12910). Inset shows the selected range from $2\theta = 28°$ to 36°. All the peaks are assigned to (0 0 l) indices from $n = 6$–15 phases as shown by numbers in the inset. The sample simultaneously contains $n = 6$–15 phases.

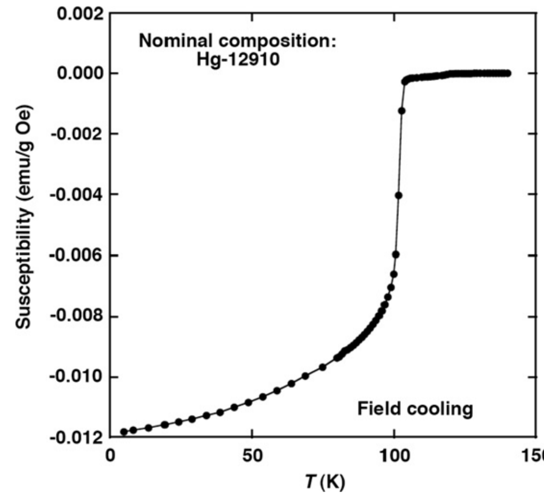

Fig. 2. Temperature dependence of the susceptibility for $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ with nominal composition of $n = 10$ (Hg-12910). Although the sample contains $n = 6$–15 phases, a one-step superconducting transition is observed at a temperature of 103 K.

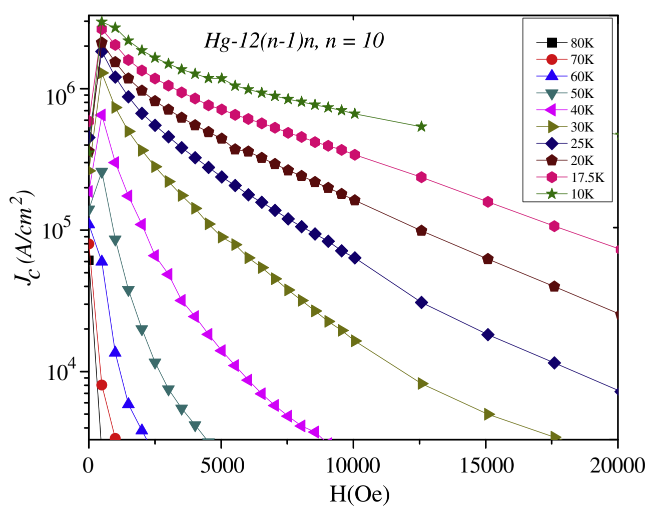

Fig. 3. Field dependence of J_c of $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ with nominal composition of $n = 10$ (Hg-12910) at various temperatures. The sample contains $n = 6$–15 phases.