Critical current densities and irreversibility fields of high-$T_c$ superconductors AuBa$_2$Ca$_{n-1}$Cu$_n$O$_{2n+3}$ ($n = 3, 4$) prepared under high pressure

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Abstract

Critical current densities ($J_c$) and irreversibility fields ($B_{irr}$) of high-$T_c$ superconductors AuBa$_2$Ca$_{n-1}$Cu$_n$O$_{2n+3}$ [Au-12($n-1)n, n = 3, 4$] prepared under high pressure were determined from the hysteresis in DC magnetization loop. Both the $J_c$ and $B_{irr}$ values of the Au-1234 phase were larger than those of Hg- and Bi-based cuprate superconductors, but smaller than those of the Y-123 superconductor. This result suggests that the electronic structure of Au-1234 is less anisotropic compared with the Hg- and Bi-phases. The Au-1223 phase showed very small $J_c$ values corresponding to its small superconducting volume fraction.

Keywords: High-$T_c$ superconductor; Magnetic hysteresis; Critical current densities; Irreversibility field; AuBa$_2$Ca$_{n-1}$Cu$_n$O$_{2n+3}$ ($n = 3, 4$)

1. Introduction

Recently, a new series of high-$T_c$ superconductors AuBa$_2$Ca$_{n-1}$Cu$_n$O$_{2n+3}$ [Au-12($n-1)n, n = 3, 4$] were synthesized under a high-pressure/high temperature condition of 6 GPa and 1250–1300 °C as polycrystalline form [1]. These phases have layered structures with stacking of planes along the c-axis, BaO–MO–BaO–CuO$_2$– (Ca-CuO$_2$)$_n$ where the M site is occupied mainly by Au which belongs to the IB group in the periodic table as does Cu. Large $J_c$ values at the M sites have square-planar coordination, forming Au–O zigzag chains along the b-axis. In previous studies, we measured critical current densities ($J_c$) and irreversibility fields ($B_{irr}$) for various high-$T_c$ superconductors prepared under high pressure, such as (Cu,C)Ba$_2$Ca$_{n-1}$Cu$_n$O$_{2n+3}$ [(Cu,C)-12($n-1)n, n = 3, 4$], (Cu,Cr)Sr$_2$Ca$_{n-1}$Cu$_n$O$_{2n+3}$ [(Cu,Cr)-12($n-1)n, n = 2, 3$] and (Cu,V)Sr$_2$Ca$_{n-1}$Cu$_n$O$_{2n+3}$ [(Cu,V)-12($n-1)n, n = 3, 4$] in which charge reservoir M sites are partly occupied by Cu [2–4]. From relatively large $J_c$ and $B_{irr}$ values in these phases, it was concluded that the occupation of Cu on the M-site contributes to the electric conduction along the c-axis and to make the systems electrically less anisotropic, resulting in the better superconducting properties.

In present study, we have carried out magnetization measurements for bulk form of Au-12($n-1)n$ ($n = 3, 4$) samples to evaluate their $J_c$ and $B_{irr}$. The M sites of these phases are mainly occupied by Au which belongs to the IB group in the periodic table as does Cu. Large $J_c$ and $B_{irr}$ might be expected for the present system if the Au ions at the M sites contribute to the electric conduction along the c-axis. In addition, the present study is worth elucidating the effect of the Cu occupation on the M site, through the comparison with previous results for other high $T_c$ superconductors including the (Cu,M)-series of phases mentioned above. The $J_c$ and $B_{irr}$ data obtained were discussed from the view point of anisotropy in the electronic structures.

2. Experimental

Polycrystalline samples of Au-1223 and 1234 used in the present study were prepared under a high-pressure/high-temperature condition of 6 GPa and 1250–1300 °C for 2–3 h. In order to change the hole concentration and to
increase the superconducting volume fraction, the sample of Au-1223 was postannealed for 2 h at 300 °C in O2 atmosphere. Details of the sample preparation are described elsewhere [1]. The X-ray powder diffraction patterns and electron probe microanalysis (EPMA) showed that the Au-1234 and 1234 samples contained small amounts of CuO, gold metal and an unknown phase of ‘Ca2BaAuOy’, [1]. Net content of these impurity phases was estimated to be less than ~10% but no correction was applied for the magnetization hysteresis data since the exact impurity content was unknown and ~10% uncertainty does not affect the discussions given below. Onset superconducting transition temperatures (Tc) determined by magnetic susceptibility data were 30 and 99 K for Au-1223 and 1234, respectively. The Au-1234 showed a sharp superconducting transition with a large enough diamagnetism to assume bulk superconductivity, while the transition of Au-1223 was broad with weak diamagnetism even after the postannealing. These results are in good agreement with the previous report [1].

Magnetization hystereses (∆M) were measured using a SQUID magnetometer (Quantum Design) for the bulk samples with magnetic field up to 5.5 T at various temperatures. The microstructures of the samples were observed using a scanning electron microscope (SEM) to determine their average grain sizes. The grains were found to be plate-like with an average diameter of ~5 μm in both samples.

3. Results and discussion

Fig. 1 shows typical examples of magnetic hysteresis loop observed for Au-1234 at 5, 15 and 25 K. Magnetic field dependence of ∆M in high field region is small in this temperature range and temperature dependence of ∆M also looks less pronounced, suggesting that Au-1234 has high Jc and Birr values. On the other hand, ∆M is quite small in Au-1223 as given in the inset of Fig. 1. In order to estimate Jc and Brr from the ∆M data, Bean’s model [5] was used. Since the intergrain critical current density can be neglected in the present samples due to weak coupling between grains, the intragrain critical current density may be calculated as

\[ J_c = 30\Delta M/d, \]

where d means the average grain size (d = 5 μm for both Au-1223 and 1234 according to the SEM observations).

Magnetic field dependences of Jc are shown in Fig. 2(a) and (b) for Au-1223 and 1234, respectively. In the low temperature region, Au-1234 phase has high Jc values, and its magnetic field dependence is quite small. This behavior is similar to that of (Cu,V)-1234 [4], but differs from the results for (Cu,C)-12(n − 1)n (n = 3, 4) phases whose Jc values are small and decrease very rapidly with increasing magnetic field [2]. The large Jc values of Au-1234 suggest that it contains in the structure enough number of pinning centers, though it is not known which type of crystal defects work as the pinning centers. The field dependence of Jc becomes larger in Au-1234 than in (Cu,V)-1234 at temperatures near Tc [4]. On the other hand, Au-1223 shows very small Jc values probably due to the small superconducting volume fraction. According to the structural analysis, 6−8% of the Cu sites in the CuO2 layer are occupied by Au in Au-1223 [6]. This seems to be the main reason for the very broad superconducting transition and the small volume fraction of Au-1223.

The Jc at 1 T is shown in Fig. 3 for the Au-1234 phase as a function of normalized temperature, T/Tc. Data for Bi2Sr2CaCu2Oy (Bi-2212) [7], HgBa2CaCu2Oy (Hg-1223) [8] Bi2Sr2CaCu2Oy (Bi-1234) [9], YBa2Cu3O7 (Y-123) [2], (Cu,C)1234 [2] and (Cu,V)1234 [4] are also given for comparison. The Jc of Au-1234 is higher than those of Bi-2212, B-1234 and Hg-1223 for almost the entire range of the normalized temperature. At temperatures near Tc, Au-1234 shows stronger temperature dependence of Jc than Y-123, (Cu,C)1234 and (Cu,V)1234 phases, resulting in smaller Jc values near Tc.

The irreversibility field of Au-1234 was calculated from its Jc data according to the Jc = 10^5 A/cm^2 criterion. Fig. 4 shows Birr plotted against T/Tc for the Au-1234 phase compared with the various superconductors shown above. It has been elucidated that the Birr value depends strongly on electric anisotropy of the system [10]. In Fig. 4, the Birr values of Bi-2212 are quite low compared with the M-1223 or M-1234 phases. This is no doubt caused by the Bi–O double charge reservoir layers which suppress the electric conductivity along the c-axis resulting in the large anisotropy. In an M-12(n − 1)n-type structure, on the other hand, adjacent CuO2 conduction layers are connected along the c-axis through the chemical bonds, Cu–O–M–O–Cu. The electronic anisotropy of the phase is, therefore,
affected seriously by the elements which occupy the M-site. Thus, the M-12(n—1)n-type superconductors in Fig. 4 may be categorized into two groups: the first group includes (Cu,C)-1234, (Cu,V)-1234 and Y-123 in which the M sites of the charge reservoir layers are fully or partly occupied by Cu, while the second one includes Hg-1223, B-1234 phases with Cu-free M sites. As seen in Fig. 4, the former group phases have much higher $B_{\text{irr}}$ values than the latter. In the first group, 3d-orbitals of the Cu atoms at the M-sites seem to contribute to increase electric conductivity along the $c$-axis, making the system less anisotropic. This seems to be a main reason for the large $B_{\text{irr}}$ values of the former group. The electric anisotropy would be affected not only by the structure and constituent elements of the charge reservoir layer but by the carrier density of the system [10], although the former factor is more decisive. The carrier densities in the phases in Fig. 4 are not far apart from the optimum levels because their $T_c$'s are close to the highest values. The structure and constituent elements of the charge reservoir layer appears to be a key factor to understand the $B_{\text{irr}}$ data in Fig. 4.

The $B_{\text{irr}}$ vs. $T/T_c$ line of Au-1234 is located between those of the two groups, indicating that Au-1234 has an intermediate character. According to the structural analysis of Au-1223 [6], the occupation factor of Cu for the M site is only 4%. Although detailed structure refinement has not been carried out for Au-1234, its net Au/Cu ratio determined by EPMA is close to the stoichiometric value of 1/4 [1], indicating that the M sites are also mainly occupied by Au. Therefore, the Cu occupation at the M sites is not the reason for the relative enhancement of $B_{\text{irr}}$ in Au-1234. As one of the possible origins of the high $B_{\text{irr}}$ value, we suggest...
were originally given by a criterion different from that of the Au ion of Au-1234 contribute to the conduction along the c-axis to a certain extent, making the phase less anisotropic compared with the second group of phases.

4. Conclusion

We have carried out DC magnetization measurements for Au-12(n−1)n (n = 3, 4) in order to evaluate Jc and \( B_{irr} \). The Au-1234 phase has relatively large Jc values under magnetic field, while the Au-1223 phase shows quite small Jc values probably caused by a small superconducting volume fraction. The M-12(n−1)n-type cuprate superconductors can be categorized into two groups from the view point of \( B_{irr} \); the M sites of the first group phases are partially or fully occupied by Cu with less anisotropic electric structures and larger \( B_{irr} \) values while the second group phases have Cu-free M sites with smaller \( B_{irr} \) values.

The \( B_{irr} \) values of the present Au-1234 phase are located between those of the two groups. This result suggests that the 5d-orbitals of the Au ion of Au-1234 contribute to the conduction along the c-axis to a certain extent, making the phase less anisotropic compared with the second group of phases.

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