Novel Pressure-induced Phenomena in Condensed Matter Systems
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Pressure-Induced Increase in J_c across Single Grain Boundaries in $YBa_2Cu_3O_x$

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The critical current density J_c under hydrostatic pressure to 0.6 GPa is determined for melt-textured $YBa_2Cu_3O_x$ ($6.4 \leqslant x \leqslant 6.9$) rings containing single [001]-tilt grain boundaries (GBs) with artificial mismatch angles. We found that J_c increases rapidly under pressure at the rate 20 to 40 % GPa^{-1}. Such a large enhancement cannot be explained by a simple tunneling model where the GB width is compressed under pressure. The intrinsic pressure dependence of J_c is estimated from the temperature pressure hysteresis to be 15 to 25 % GPa^{-1}, revealing a substantial relaxation effect in the GB. Both intrinsic and relaxation effects make important contributions to the large pressure dependence of J_c observed in the present experiments. $YBa_2Cu_3O_x$ bicrystalline rings generally have vacant oxygen sites in the GB region. Filling such sites with oxygen anions should lead to further enhancement in J_c.

KEYWORDS: Superconductivity, YBCO, Grain boundary, Pressure

1. Introduction

Applications of ceramic high-T_c superconductors are difficult to achieve because the critical current density J_c observed in bulk polycrystalline materials is low. It has been known for many years that the main factor for poor J_c originates from grain boundaries (GBs) that are inevitably present in bulk materials. But the value of J_c in polycrystals is enhanced by reducing GB mismatch angles.[1)] It's also known that J_c in the bulk, like T_c, has a large dependence on oxygen concentration x and pressure.[2,3)] We examined the behavior of J_c across the GB with various mismatch angles in both nearly optimally doped and underdoped YBCO bicrystals under hydrostatic pressure to 0.6 GPa.

2. Experimental

We used melt-textured $YBa_2Cu_3O_x$ ($6.4 \leq x \leq 6.9$) bicrystalline rings to investigate the J_c across single [001]-tilt GBs ($0 \leq \theta \leq 31°$). $J_c(T)$ as a function of temperature was determined from the change in the ac susceptibility of $YBa_2Cu_3O_x$ rings placed in a He-gas pressure cell.[5–7)] Figure 1 (left) displays real part of ac susceptibility χ' versus temperature in the single 25° GB (4mm OD× 2mm ID× 5mm) under 0 and 0.6 GPa pressure. In both measurements, the amplitude H_{ac}=10 G ($H(t) = H_{ac} \sin \omega t$) is applied to the ring at 1 Hz from outside of the pressure cell. When flux begins to enter in the ring core through the GB, as shown in Figure 1 (top), the temperature of kink $T_{\rm kink}$ in $\chi(T)'$ is seen at 67 K under ambient pressure. The kink shifts to higher temperature under high pressure. The ring current I equals to the critical current I_c at the kink. In the single-turn solenoid approximation, the induced current I in a ring is given using $I = D \cdot H_{ac}$ (D is the average of the inner and outer ring diameters). J_c is estimated by $J_c(T_{\rm kink}) = D \cdot H_{ac}/A$ (cross-section area A). $J_c(T)$ under 0 and 0.6 GPa is plotted in Figure 1 (right), where J_c is seen to rapidly increase with pressure. This $d \ln J_c/dP$ is much higher than the decrease in transition temperature $d \ln T_c/dP$ ($\sim -25 \times 10^{-4}$ GPa^{-1}).

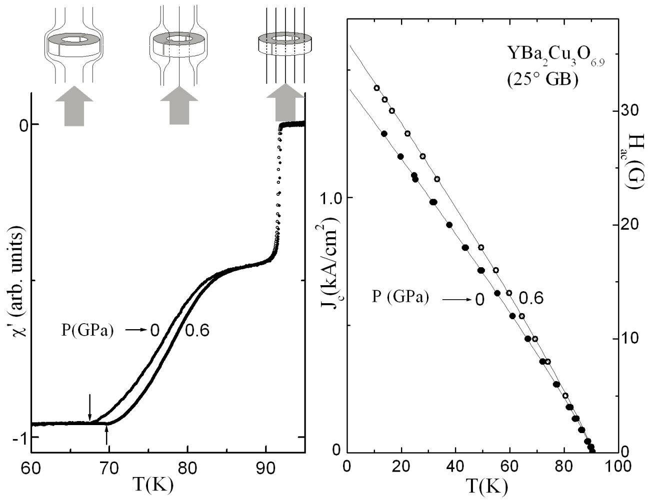

Fig. 1. (left) Real part of ac susceptibility versus temperature for a nearly optimally doped YBCO bicrystalline ring with 25° GB. (right) Temperature dependence of J_c under ambient and high pressure. (top) Illustration of flux lines in a bicrystalline ring for temperature ranges $T < T_{\rm kink}$, $T_{\rm kink} < T < T_c$ and $T > T_c$, respectively. Transition temperature $T_c \simeq 91.84$ K (midpoint of χ') at ambient pressure.

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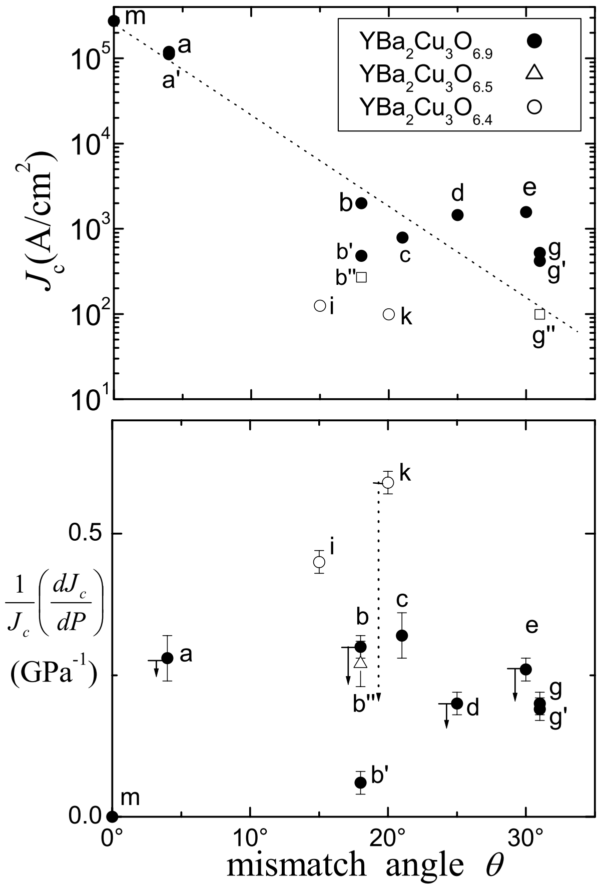

Fig. 2. (top) Dependence of J_c at 9 K and (bottom) the pressure derivative of J_c on mismatch angle in both nearly optimally doped (•), underdoped $x = 6.4$ (○) and $x = 6.5$ (△) $YBCO_x$ rings. The length of arrows show the values of $d(\ln J_c/dP)_{\rm relax}$. Each lower-case letter labels a ring with a specific GB mismatch angle θ: m-0°, a-4°, i-15°, b-18°, k-20°, c-21°, d-25°, e-30°, g-31°.

3. Results and Discussion

Dependence of J_c at 9 K and its pressure derivative $d\ln J_c/dP$ on mismatch angle θ is illustrated in Figure 2. We found that J_c increases rapidly with hydrostatic pressure (the rate of 20 % GPa^{-1} in $YBCO_{6.9}$).[6) On the other hand, the J_c in the ring without GB has no pressure change. Simply supposing the GB is a tunneling junction, the J_c behavior in conduction layers (CuO_2 plane) can be estimated by WKB approximation as $J_c^{\rm GB} = J_{c0}\exp(-2KW)$, where the decay constant $K = \sqrt{2m\phi}/h$, the tunneling barrier height ϕ, the barrier width W.[8) Thus, the pressure derivative is

$$\frac{d\ln J_c^{\rm GB}}{dP} = -2Ka\left\{\frac{1}{2}\cdot\frac{d\ln\phi}{dP} + \frac{d\ln W}{dP}\right\} \qquad (1)$$

Here we put $d\ln J_{c0}/dP \simeq 0$ from experiment. Assuming $\alpha = -d\ln\phi/dP = 0$ and bulk compressibility $\kappa_a \approx \kappa_{\rm GB} = -d\ln W/dP \simeq 2\times10^3\ \mathrm{GPa}^{-1}$ in Eq. (1), the estimated value of J_c ($\approx 0.01\ \mathrm{GPa}^{-1}$) is 20 times less than the experimental values. Therefore, a large potential reduction may arise under pressure so that $\alpha \neq 0$. It's also thought that dependence of the pressure derivative J_c on mismatch angle θ is expected using $J_c(\theta)$ as $dJ_c(\theta)/dP = \ln(J_{c0}/J_c(\theta))(\alpha/2 + \kappa_{\rm GB})$.

$d\ln J_c/dP$ contains two contributions: relaxation effect $(d\ln J_c/dP)_{\rm relax}$ and intrinsic pressure effect $(d\ln J_c/dP)_{\rm intr}$. The pressure induced relaxation effects of J_c through GB were observed as well as T_c. The estimated relaxation effect contributes 20% to the large increase in J_c under pressure in nearly optimally doping and 60% in underdoped $YBCO_{6.4}$. The relaxation effect in T_c has been known to arise from the rearrangement of oxygen atoms in CuO_δ chains under pressure. So, it's expected that oxygen atoms in GBs (defects and dislocation) have significantly higher mobility and rearrange easily even at optimal doping. The exponential time-dependent relaxation behavior in J_c at 9 K led to the GB relaxation time $\tau_{\rm GB} = \tau_{\rm bulk}/2$. This is evidence that the oxygen mobility in GB is faster than in the bulk. It's also expected that the relaxation time decreases with GB mismatch angle. But, in the present measurements, we cannot see large relaxation time difference between 25° and 30° rings.

4. Summary

J_c across [001]-tilt GBs with mismatch angle from 4 to 31° is found to increase under hydrostatic pressure at the rate 20 to 40 % GPa^{-1}. It's thought that the increase of J_c across GB under pressure is caused by the decrease in width W and in potential ϕ of tunnel barrier. Filling empty sites with additional oxygen anions would increase the hole carrier concentration and thus further enhance J_c across the GB.

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