**Pressure-Induced Increase in $J_c$ across Single Grain Boundaries in YBa$_2$Cu$_3$O$_x$**

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The critical current density $J_c$ under hydrostatic pressure to 0.6 GPa is determined for melt-textured YBa$_2$Cu$_3$O$_x$ ($6.4 \leq x \leq 6.9$) 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 critical current density is estimated from the pressure temperature 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$_2$Cu$_3$O$_x$ 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. It’s also known that $J_c$ in the bulk, like $T_c$, has a large dependence on oxygen concentration $x$ and pressure. 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$_2$Cu$_3$O$_x$ ($6.4 \leq x \leq 6.9$) bicrystalline rings to investigate the $J_c$ across single [001]-tilt GBs ($0 \leq \theta \leq 31^\circ$). $J_c(T)$ as a function of temperature was determined from the change in the ac susceptibility of YBa$_2$Cu$_3$O$_x$ rings placed in a He-gas pressure cell. Figure 1 (left) displays real part of ac susceptibility versus temperature for YBa$_2$Cu$_3$O$_x$ (25° GB) cubicrystalline rings generally have vacant oxygen sites in the GB region. (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$^{-1}$).
3. Results and Discussion

Dependence of $J_c$ at 9 K and its pressure derivative $d\ln J_c/dP$ on mismatch angle $\theta$ is illustrated in Figure 2. We found that $J_c$ increases rapidly with hydrostatic pressure (the rate of 20% GPa$^{-1}$ in YBCO$_{6.9}$). 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 $J_c^{\text{GB}} = J_{c0} \exp(-2KW)$, where the decay constant $K = \sqrt{2m\phi \hbar}$. Thus, the tunnel barrier height $\phi$, the barrier width $W$, and the pressure derivative is

$$
\frac{d\ln J_c^{\text{GB}}}{dP} = -2K\alpha \left( \frac{1}{2} \cdot \frac{d\ln \phi}{dP} + \frac{d\ln W}{dP} \right)
$$

(1)

Here we put $d\ln J_{c0}/dP \simeq 0$ from experiment. Assuming $\alpha = -d\ln \phi/dP = 0$ and bulk compressibility $\kappa_b = \kappa_{\text{GB}} = -d\ln W/dP \simeq 2 \times 10^{3} \text{ GPa}^{-1}$ in Eq. (1), the estimated value of $J_c$ (approx. 0.01 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 $\theta$ is expected using $J_c(\theta)$ as

$$
d\ln J_c(\theta)/dP = \ln(J_{c0}/J_c(\theta)) \langle 2 + \kappa_{\text{GB}} \rangle
$$

$d\ln J_c/dP$ contains two contributions: relaxation effect ($d\ln J_c/dP)_\text{relax}$ and intrinsic pressure effect ($d\ln J_c/dP)_\text{intr}$. 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$_2$ 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 $\tau_{\text{GB}} = \tau_{\text{bulk}}/2$. 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 $J_c$ under GB pressure is caused by the decrease in width $W$ and in potential $\phi$ 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.