Effect of pressure on the critical current density of YBa$_2$Cu$_3$O$_{7-\delta}$ thin films

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We have investigated the effect of pressure on the critical current density ($J_c$) at 77 K in YBa$_2$Cu$_3$O$_{7-\delta}$ thin films with an ambient $J_c$ varying from $10^4$ to $4 \times 10^5$ A/cm$^2$. The same linear enhancement of the relative $J_c$ up to ~24 percent at 16 kbar was observed for all samples. The observation can be explained in terms of the internal strain existing in the Y1:2:3 thin films.

Over the last four years, considerable effort has been focused on understanding and improving the critical current density ($J_c$) in YBa$_2$Cu$_3$O$_{7-\delta}$ (Y1:2:3) thin films. One outstanding problem is the much greater pinning strength in thin film than in bulk samples. Regardless of the various synthesis techniques, the $J_c$s of good thin films seem to converge at $6 \times 10^6$ A/cm$^2$ at 77 K, while the $J_c$s of good bulk samples seem to be between $10^4$ and $10^5$ A/cm$^2$. It was demonstrated [1] that, while the intragrain $J_c$ of thin films can be as high as $10^6$ A/cm$^2$, grain misorientations will reduce the intergrain $J_c$ to $10^5$ A/cm$^2$ or less. However, single crystals of Y1:2:3, which are supposed to be weak-link free, display a $J_c$ which is orders of magnitude lower than that of thin films. This implies that there are stronger pinning centers in thin films. Consequently, much TEM work has been devoted to the search for defects which are unique to thin films. The efforts led to some new discoveries in the microstructure of thin films [2]. However, such unique defects might not be dense enough to explain a high $J_c$ in epitaxial films [2,3]. In another model [3], an extremely high defect-density was proposed as the main reason for the high $J_c$ in thin films. However, there is no direct TEM evidence for it yet. This puzzle prompted us to study the relationship between pinning and strain. Generally, epitaxial thin films are characterized by large inhomogeneous microstrain which, in Y1:2:3, could be created by lattice misfit, differences in thermal expansion, and the orthorhombic-tetragonal phase transition. Such large internal strain has been observed by X-ray diffraction. Since the internal strain can enhance pinning in the conventional low transition temperature $T_c$ superconductors [4], it is natural to expect a similar effect for Y1:2:3. To test this conjecture, the $J_c$s and $T_c$s of Y1:2:3 thin films with an ambient $J_c$ ranging from $10^4$ to $4 \times 10^5$ A/cm$^2$ at 77 K have been measured in a hydrostatic pressure bomb up to 16 kbar. The $J_c$ was observed to increase universally with pressure by 24 percent. This suggests that there is a close relationship between the strain and the pinning.

The Y1:2:3 thin films examined in this study were prepared on SrTiO$_3$ or LaAlO$_3$ substrates by the laser ablation technique [5]. Standard X-ray rocking-
curve, pole-figure, and peak-profile analysis techniques were employed to obtain microstructural and local strain information on these thin films. A four-probe method was used to determine \( J_c \) and \( T_c \). For these measurements, 10 \( \mu m \times 1 mm \) thin film strips were patterned by the dry-etching technique [5]. Electrical Pt-leads were attached to the strips with In-contacts with a typical contact resistance of \( \sim 1 \Omega \). A 1 \( \mu V/cm \) standard was used to measure the \( J_c \).

The hydrostatic pressure was generated by the clamp technique [6], using the Fluoronitrile (3M Industrial Chemical Co.) as the pressure medium. The pressure was determined by a superconducting Pb-manometer.

By varying the deposition conditions, two types of \( c \)-oriented films of thickness \( \sim 2000 \AA \) were obtained: type A was epitaxial, single-crystal-like and type B was polycrystalline. Type A films displayed an average mosaic spread of the \( c \)-axis \( \Delta \theta \leq 0.3^\circ \) and an average alignment spread of the \( a, b \)-axis \( \Delta \theta \leq 1^\circ \). Type B films exhibited a much larger spread of \( \leq 1^\circ \). These films had a \( T_c \) between 85 and 91 K and a transition width between \( \sim 2 \) and 2 K.

Under pressure, the \( T_c \) changes negligibly for both types of thin films, with the onset \( T_c \), showing a slight increase but the zero-resistivity point showing a small decrease as shown in fig. 1. At 16 kbar, the mid-transition point was hardly shifted, i.e. \( < 0.2 \) K. Such a pressure effect is small compared to that for bulk Y1:2:3. The pressure coefficient is \( \sim 0.04 \) K/kbar [7] for bulk Y1:2:3 with \( T_c = 92 \) K and increases for samples with lower \( T_c \). The small effect observed here may be associated with the complication arising from the nonhydrostaticity of pressure due to the anisotropic nature of the thin-film/substrate sample system or arising from the large internal strain in the sample-system. On the other hand, the \( J_c \) at 77 K increases clearly with pressure for all samples, as shown in fig. 2. The \( J_c \)-enhancement normalized to the ambient \( J_c \) was found to be linear for all thin films investigated, as displayed in fig. 3. At 16 kbar, a universal 24 percent \( J_c \)-increase was detected. The temperature variation, as monitored by a thermocouple attached to the sample throughout the \( J_c \)-measurements, was less than 0.1 K.

It is known that the temperature \( T \) increases with decreasing pressure. The pressure-induced temperature \( T \) decrease at different \( J_c \) was measured. The \( J_c \) at different pressures was measured. The average \( \langle 1/J_c \rangle (dJ_c/dt) \) is proportional to the pressure-induced temperature variation which is less than \( \sim 3 \) percent for the observed \( J_c \)-enhancement.

It has been demonstrated that pressure superconducting links which can be broken by high pressures, or large-angle misorientations of pressure-induced cracks or reduce the thickness of the various layers between superconductor and substrate. \( J_c \) which has been found to decrease at high pressures. However, for a thin film, stress varies with strain or the strain length is dictated by the stiffness of the substrate.

At our maximum pressure of 16 kbar, the strain generated cannot exceed 1 percent and is expected to be even smaller in the sample which, again, can be inferred from the small links by the observed \( J_c \)-enhancement and the likelihood of the formation of links in the film samples which is less likely to be affected by pressure enhancement.

The effect of rotation on the \( J_c \)-enhancement has been previously studied. The growth of random intergranular critical currents is in agreement with the universal decreasing behavior of \( J_c \) with increasing \( \theta \) between the grain planes in the thin film samples. The intergranular \( J_c \) and/or \( f(\theta) \), which are highly dependent on the observed \( J_c \)-enhancement, are more likely that such an effect of rotation is evident in the evolution of grains and the evolution of \( f(\theta) \). Therefore, the pressure enhancement is not likely to be due to the strain effect produced by the rotation of the sample.

It has been proposed that \( J_c \)-enhancement is enhanced by a strain effect which could be associated with or elastic, and the results obtained are consistent with the idea that inelastic deformation occurs.
It is known that the $J_c$ of a sample at a fixed temperature $T$ increases as $T_c$ increases, or as the reduced temperature $t = T/T_c$ decreases. We have measured the $J_c$ at different temperatures near 77 K and found that the average temperature coefficient of $J_c$, $(d J_c / dt)$, is $\sim 0.13$. As mentioned above, the pressure-induced $T_c$-increase is less than 0.2 K at 16 kbar. The accompanying $J_c$-increase is therefore not more than $\sim 3$ percent, too small to account for the observed $J_c$-enhancement.

It has been demonstrated that the $J_c$ of high temperature superconductors is seriously limited by weak links which can be microcracks, second-phase impurities, or large-angle grain boundaries. The application of pressure certainly can close the microcracks or reduce the thickness of the second-phase layers between superconducting grains and increase $J_c$ which has been observed in ceramic samples [8]. However, for a thin film sample, the pressure-induced strain or the change of the above physical lengths is dictated predominantly by the mechanical stiffness of the substrate, such as SrTiO$_3$ or LaAlO$_3$. At our maximum pressure of 16 kbar, the maximum strain generated cannot be greater than 0.2 percent, and is expected to be uniform throughout the entire sample which, again, is too small to affect the weak links by the observed 24 percent, not to mention the unlikelihood of the large effect of microcracks in thin-film samples with $J_c > 10^6$ A/cm$^2$.

The effect of misorientation of grains on $J_c$ has been previously studied [1]. It was shown that the measured intergrain $J_c = J_{c0} f(\theta)$, where $J_{c0}$ is the intragrain critical current density and $f(\theta)$ is a universal decreasing function of the misalignment angle $\theta$ between the grains. The wide spread of $J_c$ in the thin film samples can be caused by the differences in $J_{c0}$ and/or $f(\theta)$, which arise from the different deposition conditions used. Since the pressure effect on the observed $J_c$ is reversible, it is extremely unlikely that such an effect can occur through the orientation of grains, or in other words, through change in $f(\theta)$. Therefore, our observation suggests that pressure enhances $J_c$ through a modification in $J_{c0}$.

It has been proposed [4] that pinning can be enhanced by a strain field associated with defects. The pinning potential can result from the change in volumes or elastic constants between the superconducting and the normal states. The former depends on strain ($\epsilon$) linearly, whereas the latter does quadratically. The pinning forces ($F_p$) in a one-dimensional model are then $d\epsilon / d\varepsilon$ and $d(\epsilon^2) / d\varepsilon$, respectively. In both cases, the flux pinning is proportional to the strain gradient over a length-scale comparable to the coherence length. Externally applied hydrostatic pressure will produce an additional strain ($\epsilon_\text{ext}$). For an anisotropic thin-film/substrate sample-system, such as the one studied here, one can still reasonably assume that the strain induced by the external pressure is uniform along the $a$, $b$-plane. $\epsilon_\text{ext}$ is estimated to be $\leq 0.2$ percent for Y1:2:3 thin films at 16 kbar. A uniform $\epsilon_\text{ext}$ will not affect the linear part of $F_p$ due to the volume change between the superconducting and normal states. However, the quadratic term for $F_p$ becomes $d\epsilon / d\varepsilon$ and $d(\epsilon^2) / d\varepsilon$, which are increased by an additional strain of $F_p$ where $F_p$ is the pinning force in the absence of external pressure. The linear pressure-dependence of $J_c$ observed in Y1:2:3 thin films can therefore be understood in terms of the enhanced pinning force induced by pressure associated with the elastic-constant change between the superconducting and normal states. The lattice mismatch and the difference between the thermal expansion coefficients of Y1:2:3 and the substrate, the tetragonal-orthorhombic transition, intergrowth, and anisotropy in Y1:2:3 can be causes for $\epsilon$. However, we would like to point out that the similarity of the observed $J_c$-enhancements by pressure in various Y1:2:3 thin films might imply both a nearly universal pressure effect of the intragrain-pinning ($H_{c0}$) and that the different $f(\theta)$ (which will not change under pressure) is the main cause of different $J_c$s in various thin films. Further verification and a detailed explanation are needed.

In conclusion, we have observed a linear $J_c$-enhancement by pressure in various Y1:2:3 thin films with $J_c$ ranging from $10^4$ to $4 \times 10^6$ A/cm$^2$. At 16 kbar, a $\sim 24$ percent $J_c$ increase resulted. The observation can be understood in terms of the increase in pinning associated with the quadratic strain-dependence of the pinning potential proposed [4]. However, further experiments are needed to unravel the implications of the similarity of the $J_c$-enhancement by pressure.
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References


[8] Recently, there have been reports of a large pressure effect on ceramic oxide superconductors, which might be the result of weak-link healing; see, for example, V. Svidunov et al. Mod. Phys. Lett. 4 (1990) 645.

Determination of superconducting transition temperatures in AlNiCo films from AC response

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The temperature dependence of the AC susceptibility for different AC frequencies and AC amplitudes in a bulk superconducting AlNiCo film was measured. For each AC frequency and temperature, the in-phase and out-of-phase components of the AC susceptibility were extracted from the impedance spectrum of the film. For frequencies below 5 kHz, the AC susceptibility was found to be temperature independent in the superconducting state.

1. Introduction

The AC susceptibility is widely used for characterizing the properties of high-temperature superconductors. The determination of the temperature dependence of the AC susceptibility is important for understanding the superconducting state and for applications such as magnetic field measurements. The AC susceptibility is an important quantity for characterizing the superconducting state and for applications such as magnetic field measurements. The AC susceptibility is an important quantity for characterizing the superconducting state and for applications such as magnetic field measurements. The AC susceptibility is an important quantity for characterizing the superconducting state and for applications such as magnetic field measurements.