Pressure and temperature dependence of the critical current density in $YBa_2Cu_3O_{7-\delta}$ thin films

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The transport critical current density (J_c) in *c*-oriented Y-Ba-Cu-O thin films deposited on $LaAlO_3$ was measured under hydrostatic pressure. We find the relative change of J_c under pressure substantially temperature dependent near T_c, and practically temperature independent for $T/T_c<0.8$. This behavior is discussed in terms of the empirical equation $J_c=J_{c0}(1-T/T_c^*)^\alpha$, with different factors considered to be important in two temperature regions. The change of J_c under pressure for temperatures close to T_c is dominated by the value of α and pressure derivatives of T_c^* and α and the pressure derivatives $d(\ln J_c)/dP$ are sample dependent; for low temperatures the change of J_c is dominated mainly by pressure dependence of J_{c0} and is universal for all samples under study.

INTRODUCTION

The study of different mechanisms limiting the critical current density (J_c) in high-T_c materials is important both for the understanding of the superconducting state in high-T_c compounds and for improvement of their properties for future applications. In a number of cases the analysis of the temperature dependence of the critical current density $[J_c(T)]$ (see, for example, Ref. 1) can distinguish between flux creep behavior typical for homogeneous type-II superconductors and granular-type behavior, when a superconductor may be represented as an array of Josephson-type superconductor–normal-metal–superconductor (*S-N-S*) or superconductor-insulator-superconductor (*S-I-S*) junctions. Interesting results obtained in high-pressure studies of J_c in various bulk high-T_c materials[2–4] and $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films[5] were also considered as an important test for the different theoretical models of J_c-limiting factors. However, practically all measurements under pressure in Refs. 2–5 were performed at a fixed temperature (mainly at ~77 K), which is, although technolgically important, rather arbitrary for studying $J_c(T)$ characteristics of high-T_c materials. In the present work, the pressure derivatives of the critical current density, $d(\ln J_c)/dP$, were studied at different temperatures in order to understand how universal the values of $d(\ln J_c)/dP$ measured at fixed temperatures are, and, in addition, to look for a correlation between the temperature dependence of J_c and $d(\ln J_c)/dP$ to obtain some information about J_c-limiting factors.

EXPERIMENT

The samples used in the present work were *c*-oriented YBCO thin films deposited on single-crystalline (100) oriented $LaAlO_3$ substrates by a pulsed laser ablation technique.[6] The thickness of the samples was 2000–3500 Å, and the films were patterned by the dry etching method into 10 μm×1 mm bridges with large contact pads. Films with a J_c(77 K) range $4\times10^4-1\times10^6$ A/cm^2 and T_c values 86–89 K were used in this work. The width ($0.9R_n-0.1R_n$) of the transition ΔT_c was 1.5–2 K.

Platinum wires pressed with indium to the sample (with evaporated silver pads in the case of high-J_c films) were used as contacts (typical contact resistance ~1Ω). T_c and J_c were measured by a standard four-probe dc technique. $E=1$ μV/cm criterion was used to determine the critical current from measured *I-V* characteristics. In T_c and resistivity vs temperature $[R(T)]$ measurements, a low current ($I=10^{-8}$ A, current density $j<5$ A/cm^2) was applied to the sample.

Measurements were performed in a piston-cylinder hydrostatic pressure cell with a 40:60 mineral-oil–pentane mixture as the pressure transmitting medium in a pressure range 0–13.5 kbar. The cell was enclosed in a copper can to provide a stable and uniform thermal environment and was placed over a liquid-helium bath. A Lake Shore model 805 temperature controller together with a manganin heater wound bifilarly around the surface of the cell and silicon diode in thermal contact with the exterior of the cell as the temperature sensor were used for temperature control. The temperature was stabilized with an accuracy to ±0.03 K. Possible thermo-emf contributions to the signal were excluded by alternating the direction of the current through the sample during the measurements of the *I-V* curves.

RESULTS AND DISCUSSION

The $R(T)$ dependence for all films was metallic with $R(300\text{ K})/R(100\text{ K})\sim2.3-2.7$, $\rho(290\text{ K})\sim190$ $\mu\Omega$ cm for the films with higher J_c, the resistivity of the films with lower J_c being somewhat higher. The decrease of the resistivity in the normal state was observed with the relative change generally smaller at lower temepratures. Pressure derivatives were $d(\ln\rho_{ab})/dP\sim-(0.008-0.01)$ kbar^{-1} for $T=300$ K and $d(\ln\rho_{ab})/dP\sim-(0.004-0.006)$ kbar^{-1} for $T=100$ K (the temperature dependence of the pressure in the cell, calibrated earlier in Ref. 7, was taken into account). According to the published data the relative change of resistivity under pressure in bulk 1:2:3 materials at room temperature appears to be constant. [$d(\ln\rho)/dP \sim -(0.012\pm0.001)$ kbar^{-1}, for single crystals it is referred to $d(\ln\rho_{ab})/dP$], irrespective of the sample density, oxygen content, substitution to the Y site [with the exception to the $(Y,Pr)Ba_2Cu_3O_{7-\delta}$] and Cu site and was discussed as intrinsic property.[8] The temperature dependence of the relative change of normal-state resistivity under hydrostatic pressure was also observed in YBCO single crystals,[9] but in contrast to our results for thin films, in the case of single crystals, the absolute values of $d(\ln\rho_{ab})/dP$ increases at lower temperatures. Slightly different values of $d(\ln\rho_{ab})/dP$ for bulk materials and thin films together with a qualitative difference in the temperature dependence of $d(\ln\rho_{ab})/dP$ could be understood in terms of different stress fields in bulk samples and system (film plus substrate) under hydrostatic pressure[10] and if we assume, in addition, that the stress field in the thin film changes with temperature because of the difference between the thermal expansion coefficients of the thin film and the substrate.

For the films under study, the width of the superconducting transition normally was slightly decreasing under pressure. Both slight increases and decreases of T_c under pressure were observed (Table I). Changes in T_c and J_c under pressure were reversible.

The current-voltage characteristics (CVC) for all the samples under consideration and for different pressures and temperatures were nonlinear. Their shape could be described as power-law behavior $V=CI^n$ (Fig. 1, inset) with coefficient C and exponent n dependent on temperature.[11] Both parameters are rather pressure insensitive. Close to T_c and at low temperatures the temperature dependence of the exponent n is significant, and for the intermediate temperature region it is rather weak (Fig. 1). Similar $n(T)$ behavior in I-V characteristics of YBCO thin films was observed in Ref. 12 where it was discussed in terms of spatial variations of the local critical current density throughout the sample. It is also similar to the case of power-law-shaped CVC in conventional type-II superconductors.[13] Estimations based on detailed calculations in Ref. 13(b) indicate that our values of exponents n correspond to a critical current distribution with $\delta J_c(\mathrm{FWHM})/J_c < 20\%$ (for the films with lower J_c) over the entire body of the sample, which is possible considering the presence of grain boundaries, stacking faults, and other defects that can cause inhomogeneous current flow. Spatial inhomogeneity of J_c has been directly observed in

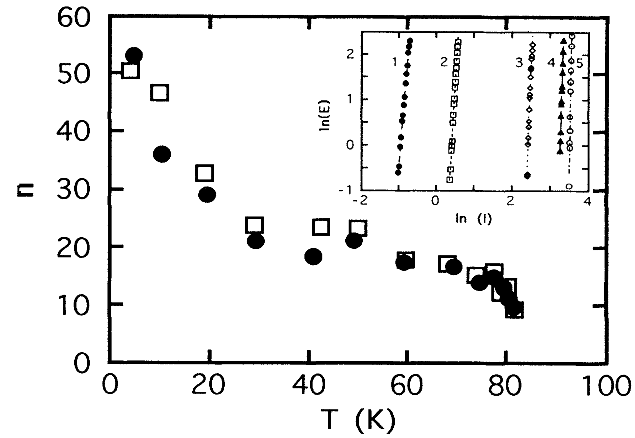

FIG. 1. Example of the temperture dependence of the exponent n (sample No. 11; ●, $p=4.2$ kbar; □, $P=8.4$ kbar). Inset: example of CVC (E in μV/cm, I in mA), $P=4.2$ kbar. Temperatures: (1) 82 K, (2) 77 K, (3) 49 K, (4) 19 K, (5) 4.8 K.

YBCO thin films by spatial imaging of the critical current density.[14] The exponent n for the films with higher J_c was somewhat higher, which corresponds to smaller values of $\delta J_c(\mathrm{FWHM})/J_c$. The insensitivity of the exponent n to the pressure probably points to the fact that the hydrostatic pressure does not change the current flow distribution substantially.

The temperature dependence of J_c for the samples under study shows upward curvature for the temperatures near T_c, and slight downward curvature at low temperatures ($T<15$–20 K). The shape of the $J_c(T)$ curve at low temperatures ($T<30$ K) and near T_c follows the temperature dependence of the exponent n (Fig. 1) and depends upon J_c criterion. (See, for example, discussion on different criteria of J_c in Ref. 15.) However, if we examine $d(\ln J_c)/dP$, our results, qualitatively, are criterion independent.

The $J_c(T)$ dependence in temperature range 40 K $< T < T_c$ may be approximated by

$$J_c = J_{c0}(1-T/T_c^*)^\alpha, \tag{1}$$

T_c^* being the critical temperature and J_{c0} the critical current density at $T=0$. T_c^* was left as an adjustable parameter in this approximation because, for the transition

TABLE I. Critical current density and T_c in YBCO thin films under pressure. Experimental results and approximations.

Sample No.	$T_c{}^a$, K	$d(\ln T_c)/dP^a$ (10^{-3} kbar^{-1})	J_c (77 K) (10^6 Å/cm^2)	$d(\ln J_c)/dP$ (77 K) (kbar^{-1})	T_c^* (K)	$d(\ln T_c^*)/dP$ (10^{-3} kbar^{-1})	α	$d(\ln J_{c0})/dP$ (kbar^{-1})
	Experimental				Approximation			
5	89.3(88.8)		0.6	−0.007	84.8	−0.2	1.23	0.026±0.009
8	86.6(85.5)	0.1(0.4)	0.039	0.023	83.4	0.8	1.15	0.024±0.003
9	86.6(85.5)	0.2(0.4)	0.038	0.02	83.2	0.4	1.24	0.006±0.001
11	86.6(85.5)	0.7(0.9)	0.05	0.037	84.5	0.4	1.27	0.029±0.003
14	89.9(88.5)	−0.2(−0.1)	1.1	0.008	86.7	−0.1	1.24	0.024±0.002

[a]For the midpoint, the data in parentheses are for the $0.1R_n$ level.

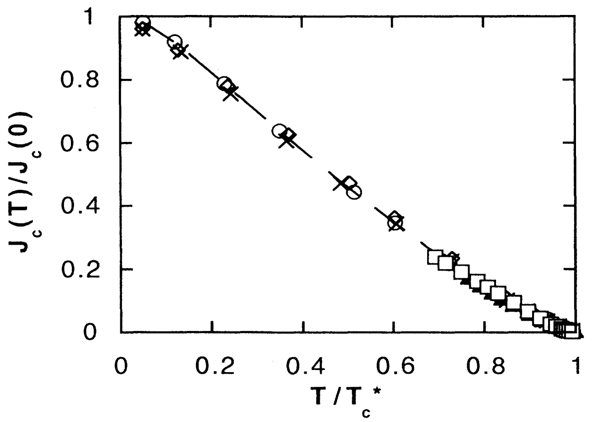

FIG. 2. Normalized $J_c(T)$ dependence for the films under study (▲, No. 5; ×, No. 8; ◇, No. 9; ○, No. 11; □, No. 14).

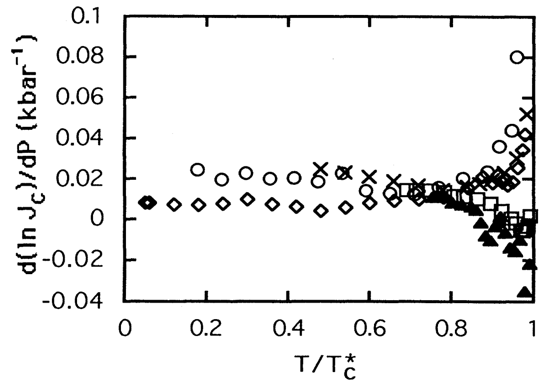

FIG. 3. Temperature dependence of the pressure derivatives for the films under study (▲, No. 5; ×, No. 8; ◇, No. 9; ○, No. 11, □, No. 14).

width $\Delta T_c \sim 1.5-2$ K the "correct" definition of T_c seems to be uncertain. As was mentioned above, Eq. (1) gives a rather good approximation of the experimental data in a limited temperture range $(0.4 < T/T_c)$, so J_{c0} gives only the upper limit of J_c at $T \sim 0$. Equation (1) gives the value of the exponent $\alpha \sim 1.15-1.3$ for all measured films. Pressure does not change the value of the exponent noticeably. The normalized temperature dependence of the critical current density has a "universal" character for all the samples used in the present work (Fig. 2): the change under pressure of the "normalized" $J_c(T)$ dependence is small. The slight difference in "normalized" $J_c(T)$ behavior for both different samples and different pressures can be noticed in the $(0.8-0.9) < T/T_c^* < 1$ temperature range. $J_c(T)$ dependencies in the films under study are in agreement with the universal temperature dependence of the transport critical current revealed for a number of thin films and superlattices and for different values and orientations of the magnetic field in Ref. 16.

$J_c(T)$ dependence is assumed to be significant for the analysis of J_c-limiting factors (see, for example, Ref. 1). Our experimental results are in contradiction with *S-N-S* model of granular superconductors, which predicts $\alpha=2$ close to T_c.[17] The observed behavior also does not appear to be described by the *S-I-S* model which gives $\alpha=1$ (Ref. 18) or $\alpha=\frac{3}{2}$ (Ref. 19) near T_c and a rather long region of downward curvature at low tempertures. It is possible to describe the observed temperature dependence of critical current by a flux creep model,[20] although the complicated form of temperature dependence of J_c in this model and the rather large number of adjustable parameters make doubtful the success of attempts to use this model to describe physical reasons of the changes of J_c under pressure. The scaling of our $J_c(T,P)$ data with the results for the films in a magnetic field[16] can also be considered as an indirect indication that J_c-limiting factors other than weak links are dominant for $J_c(T,P)$ characteristics in the films under study.

Temperature dependencies of the relative changes of the critical current density under pressure for different samples are presented in Fig. 3. Two regions are clearly seen on this plot. For the temperatures close to T_c^* $(0.8 < T/T_c^* < 1)$ the pressure derivatives $d(\ln J_c)/dP$ are substantially temperature dependent and sample dependent, with both positive and negative values of the pressure derivatives of critical current. For lower temperatures $(T/T_c^* < 0.8)$, the pressure derivatives $d(\ln J_c)/dP$ are practically temperature independent, and the values of $D(\ln J_c)/dP$ are close to each other for different samples.

It seems possible to analyze these dependencies within the scope of the empirical approximation of the temperature dependence of the critical current [Eq. (1)]. Naive differentiation of Eq. (1) gives us

$$d(\ln J_c)/dP = A + B\ln(1 - T/T_c^*) + C/(T_c^*/T - 1) , \quad (2)$$

$$A = d(\ln J_{c0})/dP, \quad B = d\alpha/dP, \quad C = \alpha[d(\ln T_c^*)/dP] .$$

Although Eq. (1) is not valid close to $T=0$, the value of $d(\ln J_{c0})/dP$ gives a reasonable estimation of the pressure dependence of critical current density at low temperatures. Experimental pressure derivatives together with the results of approximations of the experimental data by Eqs. (1) and (2) are presented in Table I.

The quality of approximation appears to be relatively insensitive to the value of T_c^*. The form of Eq. (2) shows us that the temperature dependence of $d(\ln J_c)/dP$ is determined by the second and third terms. T_c^* corresponds to the critical temperature for $J_c \sim 0$ (on the "tail" of the transition, i.e., for $R \to 0$), so T_c^* and therefore the behavior of $d(\ln J_c)/dP$ close to T_c may be determined by the properties of grain boundaries, imperfections, defects, etc. This may be one of the reasons for the difference between experimental $d(\ln T_c)/dP$ and estimations of $d(\ln T_c^*)/dP$ from Eq. (2).

The sample-dependent behavior of the normalized critical current density and its pressure derivatives for $0.8 < T/T_c^* < 1$ together with the spatial inhomogeneity of the critical current density can be considered as the effect of imperfections and defects on J_c close to the superconducting transition temperature. Additional defects (amorphous surface layers, etc.) may appear in the sample during the ion milling[21] in the dry patterning process and these defects can also be partly responsible for the behavior of J_c and its pressure derivatives near T_c^*.

In the low-temperature region ($T/T_c^* < 0.8$), the behavior of $J_c(T)$ and its pressure derivatives is "universal" and the values of $d(\ln J_{c0})/dP$ for all the samples are close to each other and seem to show the value which corresponds to the pinning properties of the superconductor itself, but is not due to boundaries and imperfections. In this issue our present results are consistent with the results of the previous work,[5] although for some samples our present data at 77 K differs from the universal pressure derivative in that work.

Comparison of the published data for pressure derivatives of J_c in bulk materials[2-4] with the results of Ref. 5 and the present work shows that the value of $d(\ln J_c)/dP$ for ceramic samples is normally substantially (about an order of magnitude) higher than for thin films, and that the results for the melt-textured material are close to that for films. This difference could be understood if the main J_c-limiting factors in thin films and melt-textured materials are different from that in ceramics, where the critical current is considered to be associated with an array of Josephson junctions.[2,4] The difference in stress fields in bulk samples and thin films under hydrostatic pressure[10] should also contribute to this.

In conclusion, the $J_c(T)$ dependence in YBCO thin films under pressure was studied. Experimental data for fixed pressures could be approximated by an empirical equation $J_c(T) = J_{c0}(1 - T/T_c^*)^\alpha$. Near T_c, the relative change of J_c under pressure is strongly temperature dependent and substantially sample dependent and is supported to be due to spatial inhomogeneity of the critical current density caused by defects and imperfections. At lower temperatures, the temperature dependence $d(\ln J_c)/dP$ is weak. It is similar for films with different J_c's and corresponds to the pinning properties of the superconductor itself. Finally, the relative change of J_c under pressure in thin films is substantially lower than that for bulk ceramic samples, in which this change is considered to be associated mainly with the changes of the properties of Josephson-type weak links.

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