C. Malik and R.
137.
N.V. Parmon, Sov.
991) 1524.
ata, Physica C 178

A. Wareka, A. Zettl,
81 (1991) 18.
i and Y. Saito, Solid

ıs, P. Lee, Yan Gao
2) 3191.
State Commun. 74

V. Sharma, H. Clara
sc. 23 (1992) 127.
C 181 (1991) 179.
31 (1992) 257.
s. Chem. Solids 43

preparation.

Physica C 205 (1993) 307–310
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Effect of pressure on the critical current density of $YBa_2Cu_3O_{7-\delta}$ thin films

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We have investigated the effect of pressure on the critical current density (J_c) at 77 K in $YBa_2Cu_3O_{7-\delta}$ thin films with an ambient J_c varying from 10^4 to 4×10^6 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 $YBa_2Cu_3O_{7-\delta}$ (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_cs of good thin films seem to converge at 6×10^6 A/cm^2 at 77 K, while the J_cs 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 microstrains 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_cs and T_cs of Y1:2:3 thin films with an ambient J_c ranging from 10^4 to 4×10^6 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 stair 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 rockingcurve, 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 determined J_c and T_c. For these measurements, 10 μm×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 ~1 Ω. A 1 μV/cm standard was used to measure the J_c. The hydrostatic pressure was generated by the clamp technique [6], using the Fluorinert (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 ~2000 Å 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 $\Delta\theta \leq 0.3°$ and an average alignment spread of the *a*, *b*-axis $\Delta\theta \leq 1°$. Type B films exhibited a much larger spread of $\leq 1°$. These films had a T_c between 85 and 91 K and a transition width between ~1 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 ~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.

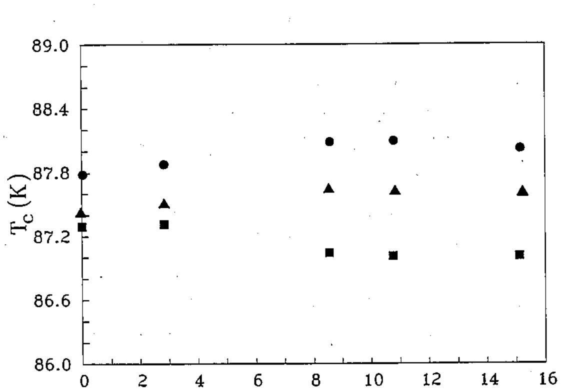

Fig. 1. T_c vs. P for a typical Y1:2:3 thin film. (●) $T_{c\,con}$, (▲) $T_{c\,mid}$, (■) $T_{c\,zero}$.

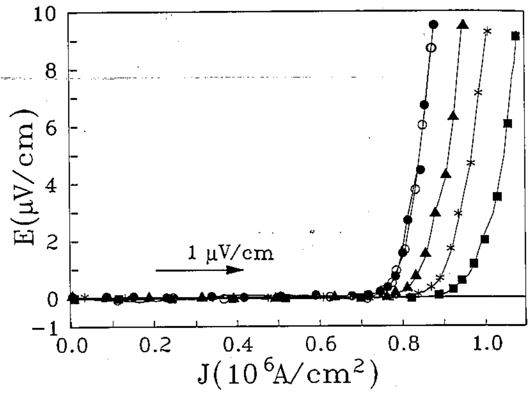

Fig. 2. E–J curves for a typical Y1:2:3 thin film ($J_c \sim 1 \times 10^6$ A/cm^2 at 77 K) under various pressures. (●) $p=0$, (▲) $p=2.84$ kbar, (∗) $p=8.55$ kbar, (■) $p=15.14$ kbar, (○) $p=0$ (release pressure).

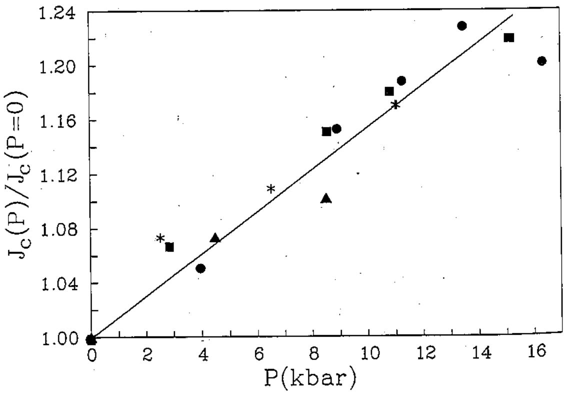

Fig. 3. The normalized J_c/J_{c0} vs. P for several films. Type I film with (●) $J_{c0}=1.6\times10^6$ and (∗) $J_{c0}=4.1\times10^6$ A/cm^2; type II film with (△) $J_{c0}=4.8\times10^4$ and (■) $J_{c0}=7.9\times10^5$ A/cm^2.

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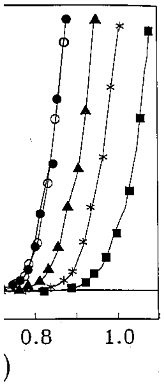

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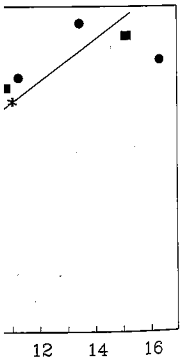

ral films. Type I film
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It is known that the J_c of a sample at a fixed temperature T increases as T_c increases, or as the reduced temperature $t=T/T_c$ decreases. We have measured the J_c at different temperatures near 77 K and found that the average temperature coefficient of J_c, $(1/J_c)(dJ_c/dt)$ 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 θ 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 (ϵ) linearly, whereas the latter does quadratically. The pinning forces (F_p) in a one-dimensional model are then $d\epsilon/dx$ and $d(\epsilon^2)/dx$, 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 (ϵ_1). 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. ϵ_1 is estimated to be ≤ 0.2 percent for Y1:2:3 thin films at 16 kbar. A uniform ϵ_1 will not affect the linear part of F_p due to the volume change between the superconducting and normal states. However, the quadratical term for F_p becomes $d(\epsilon_1+\epsilon)^2/dx = 2\epsilon_1(d\epsilon/dx) + d\epsilon^2/dx \rightarrow 2\epsilon_1(d\epsilon/dx)$, $+F_0$ where F_0 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 ϵ. 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_cs 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 4×10^6 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

[1] D. Dimos, P. Chaudhari, J. Mannhart and F.K. LeGoues, Phys. Rev. Lett. 61 (1988) 219;
D. Dimos, P. Chaudhari and J. Mannhart, Phys. Rev. B 41 (1990) 4038.

[2] See, for example, G. Gerber, D. Anselmetti, J.G. Bednorz, J. Mannhart and D.G. Schlom, Nature (London) 350 (1991) 279.

[3] T.L. Hylton and M.R. Beasley, Phys. Rev. B 41 (1990) 11669.

[4] See, for example, A.M. Campbell and J.E. Everetts, Adv. Phys. 21 (1972) 199.

[5] M.F. Davis, J. Wosik, K. Forster, S.C.Deshmukh, H.R. Rampersad, S. Shah, P. Siemsen, J.C. Wolfe and D.J. Economou, J. Appl. Phys. 69 (1991) 7182.

[6] C.W. Chu, T.F. Smith and W.E. Gardner, Phys. Rev. Lett. 20 (1968) 198.

[7] Z.J. Huang, P.H. Hor, R.L. Meng, Y.Q. Wang, L. Gao, J. Bechtold, Y.Y. Sun and C.W. Chu, APS Bull. 33 (1988) 389.

[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. Svistunov et al. Mod. Phys. Lett. 4 (1990) 645.

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