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Nanoscale Engineering: Tailored Transport Properties by Self-Organization in $YBa_2Cu_3O_{7-\delta}$ Thin Films

T. Haage,[a] J. Zegenhagen,[a] Ch. Jooss,[b] R. Warthmann,[b] J.Q. Li,[a] H.-U. Habermeier[a] and M. Cardona[a]

[a]Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany

[b]Max-Planck-Institut für Metallforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany

We have grown $YBa_2Cu_3O_{7-\delta}$ (YBCO) films on vicinal $SrTiO_3(001)$ surfaces. Scanning tunneling microscopy reveals that their morphology is reminiscent of the regular array of steps on the substrate surface. The resultant film microstructure leads to a pronounced in-plane anisotropy of the resisitivity and the critical current density j_c. We observe a substantial enhancement of j_c up to 8×10^{11} A/m^2 in the nanoscale engineered films.

The nature of flux pinning in high-temperature superconductors (HTSC's) is of fundamental and technological interest. It is well-known that epitaxial $YBa_2Cu_3O_{7-\delta}$ (YBCO) films exhibit a critical current density j_c which is at least one order of magnitude larger than that of twinned single crystals. But despite enormous efforts, the strong pinning sites generated during film growth have not yet been identified.

Here we demonstrate the generation of an array of dislocations acting as strong pinning centers with a predefined density via self-organization of the YBCO on vicinal $SrTiO_3(001)$ grown by pulsed laser deposition [1]. Crucial for the control of the transport properties and the enhancement of the flux pinning is the tailoring of the substrate surface. Our recent scanning tunneling microscopy (STM) studies reveal that, with a miscut towards [010], carefully annealed $SrTiO_3(001)$ surfaces exhibit extremely straight step edges along [100]. As shown in Refs. [2] and [3], the surface of 1.2° and 10° miscut $SrTiO_3(001)$ displays, respectively, $\approx$ 18 nm and $\approx$ 2.3 nm wide terraces separated by steps, mostly $a_{STO} = 0.39$ nm high.

The substrate steps directly produced by vicinal off-cut (with different vicinal angles θ) drastically affect the migration of adsorbed particles and consequently the growth mode [3]. If the spacing of the regular $SrTiO_3$ steps falls below the surface diffusion length, deposited particles form a layer of uniform thickness without reaching a supersaturation sufficient for the nucleation of islands on the terrace and thus, in the beginning, a replica of the substrate surface, a process we call self-organization. Note that the film grows in all cases with the c-axis parallel to $SrTiO_3$ [001].

As an example, the surface of a 120 nm thick YBCO film on 1.2° miscut $SrTiO_3(001)$ displays 100-130 nm wide terraces (see Fig. 1a) that are about six times larger than those of the clean substrate surface, indicating a tendency to overgrow a fraction of substrate steps. The surface of a 120 nm thick YBCO film on 10° miscut $SrTiO_3(001)$ exhibits almost straight step edges spaced 4-7 nm apart and growth steps of different heights, all less than $c_{YBCO} = 1.17$ nm (see Fig. 1b). This finding implies that growth fronts which nucleate out of registry with one another on adjacent terraces are shifted vertically and thus form a dislocation during coalescence. Transmission electron microscopy indeed reveals numerous antiphase boundaries [2,3] which are frequently terminated by a stacking fault after a few unit cells in YBCO films on 10° miscut $SrTiO_3(001)$. The density of these defects is reduced with increasing substrate terrace width and correspondingly decreasing vicinal angle θ.

The 120 nm thick films on 1.2° and 10° miscut $SrTiO_3(001)$ exhibit a resistive transition temperature of 89 K and 87 K, respectively. The temperature dependence of the resistivity $\rho(T)$ was

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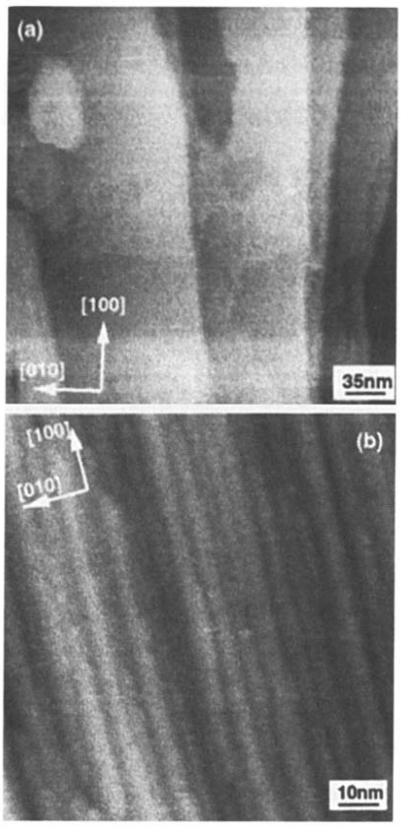

Figure 1. 350 nm × 350 nm UHV-STM images of 120 nm thick YBCO films grown on (a) 1.2° and (b) 10° miscut $SrTiO_3$(001).

measured by a four-probe method on 100 μm wide microbridges, patterned by standard lithography. As can be seen from Fig. 2, the films exhibit a resisitvity anisotropy between the directions transverse (T=[010]) and longitudinal (L=[100]) to the film step edges. At 100 K, we observe an anisotropy ratio $A_\rho = \rho_T/\rho_L$ which increases from $A_\rho \approx 1.3$ with $\theta = 1.2°$ to $A_\rho \approx 5.5$ with $\theta = 10°$. We have to take into account that the CuO_2 planes are tilted with respect to the macroscopic film surface, since the c-axis of the film grows parallel to $SrTiO_3$ [001]. However, studying $\rho(T)$ as a function of film thickness and modelling electrical conductivity as a combination of in-plane and out-of-plane transport modified by defect scattering, we find that the dominant contribution to the resistivity anisotropy results from

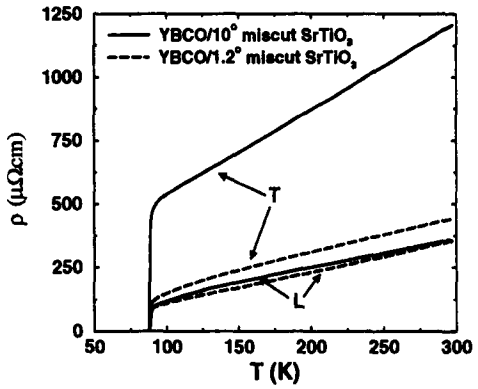

Figure 2. Resisitivity versus temperature for 120 nm thick YBCO films on 1.2° and 10° miscut $SrTiO_3$(001) transverse (T) and longitudinal (L) to the direction of regular step edges on the film surface (see Fig. 1).

the defect microstructure [2].

Furthermore, we observe anisotropic critical current densities $j_{c,T}$ and $j_{c,L}$. The current distribution is computed from the local magnetic induction above the film surface measured by means of the magneto-optical Faraday effect at 4.2 K with an external magnetic field of $\approx$ 50 mT [4,2]. With $\theta = 1.2°$, $j_{c,L}(4.2K) = 2.2 \times 10^{11}$ A/m^2 is two times larger than $j_{c,T}(4.2K)$. In YBCO films on 10° miscut $SrTiO_3$(001), we obtain an exceptionally large critical current density $j_{c,L}(4.2K) = 8 \times 10^{11}$ A/m^2, whereas $j_{c,T}(4.2K) = 1.1 \times 10^{11}$ A/m^2 exhibits a magnitude typically observed in YBCO films.

In summary, we have generated substrate surfaces ideally suited to introduce strong pinning centers via the growth mechanism itself. The results indicate that a tailoring of the transport properties in YBCO films can be achieved.

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