Current-voltage characteristic and critical currents in weak magnetic fields in $YBa_2Cu_3O_{7-\delta}$

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Pulsed laser sputtering is used to obtain thin (1000–2000 Å) superconducting $YBa_2Cu_3O_{7-\delta}$ films with zero-resistance temperature 85–91.5 K and critical current density $j_c \sim 5 \cdot 10^6$ A/cm^2 at 78 K. The temperature dependence of the current-voltage characteristics of the films and the effect of weak magnetic fields (<0.1 T) on j_c are investigated. It is shown that if there are no weak intercrystalline bonds in the film its critical current is close to that determined by the elementary Abrikosov-vortex pinning force.

INTRODUCTION

Our purpose was to study the physical limitations on the current-carrying capacity of the compound $YBa_2Cu_3O_{7-\delta}$, which has a superconducting transition at $T \sim 90$ K (Ref. 1). It is desirable to use in such investigations the "purest" samples, i.e., those that carry a minimum of individual information. Obviously, these properties are possessed to the fullest extent by single crystals. However, since its oxygen content is not fixed, a bulk single crystal can be a complex object with properties that vary with depth. It is more realistic to obtain uniform samples in the form of films, and an exposed surface offers a possibility of controlling the structure and vary by design their properties. Using lithography it is possible to prepare samples with the required pattern and readily make provisions for connecting them to the measuring apparatus.

This paper comprises three articles independently written by representatives of staffs most familiar with the techniques and procedures of the corresponding measurements. The first reports an investigation of the temperature dependence of the volt–ampere (I-V) characteristics of $YBa_2Cu_3O_{7-\delta}$ films and the behavior of the critical current density in weak magnetic fields. The second deals with the mechanisms that determine the critical current in strong magnetic fields $H \leqslant H_{c2}(T)$, and the third with the microstructure and its influence on the anisotropy and values of the electrophysical characteristics of the $YBa_2Cu_3O_{7-\delta}$ (YBCO) films.

RESULTS

The films were produced by depositing on the hot surfaces of $SrTiO_3$, GaAs, Al_2O_3, or Si the evaporation products of YBCO targets irradiated by pulsed lasers.[2] To prevent the growing film from interacting with the Al_2O_3, GaAs, and Si substrates, the latter were coated beforehand with a barrier layer of polycrystalline ZrO_2. A typical film thickness was 1000–2000 Å.

The film structure was investigated by electron diffraction and by high-resolution electron microscopy.[3]

The typical structure has platelike YBCO grains elongated along the substrate plane and oriented predominantly in a direction normal to the $\bar{\mathbf{c}}$ axis. The grain size depends strongly on the film growth conditions and can vary in the range 0.05–10 μm. In the latter case [films formed on oriented $SrTiO_3$ (100) substrates] the $\bar{\mathbf{c}}$ axis of the platelike grains is oriented strictly normal to the film surface. A film made up of smaller crystallites ($\lesssim 1000$ Å) can comprise a layered structure with disorientated $\bar{\mathbf{c}}$ axis of grains located in layers far from the surface.

The resistive and current-carrying characteristics of the films were measured by the four-contact method on formed photolithographic structures in the form of strips 10–100 μm wide. Silver films were sputtered on the contact areas. The superconducting transition of $\rho(T)$ was measured in a cryostat. The temperature was recorded with a TPK thermal transducer accurate to ± 0.05 K.

Typical transition characteristics (Fig. 1) show that the temperature T_0 corresponding to zero film resistance exceeds 85 K for substrates of all types. Higher values are reached on $SrTiO_3$ substrate, with the temperature T_0 and the transition width ΔT (90–10%) dependent on their structural perfection. The value of T_0 of polycrystalline films on $SrTiO_3$ (100) substrates does not exceed 89 K, with $\Delta T = 1$–2 K; the better single-crystal layers, on the other hand, had the record values $T_0 = 91.5$ K and $\Delta T \leqslant 0.5$ K. In the 300–100 K range the resistance of the polycrystalline films decreased nearly linearly, with a parameter $\gamma = \rho(300\ \mathrm{K})/\rho(100\ \mathrm{K}) = 2.5$–3, a value typical of films whose $\bar{\mathbf{c}}$ axis is oriented along the normal to the substrate.[4] Single-crystal films had $\gamma = 4$–5. The resistivity of the films near the transition is $(1\text{–}2) \cdot 10^{-4}\ \Omega \cdot \mathrm{cm}$.

The resistive-transition width ΔT is indicative of the inhomogeneity of the film with respect to the values of T_{0i} of its constituent crystallites. The parameters T_0 and ΔT depend substantially both on the film growth regime and on the degree of its saturation with oxygen (the value of δ). Films formed with an oxygen shortage have a "semiconductor" $\rho(T)$ behavior, but their properties could be reversibly changed by suitable annealing in oxygen, and the superconductivity restored to $T_0 > 85$ K.

Figure 2 shows a family of $\rho(j)$ plots of a film with $T_0 = 87$ K with a broad transition ($\Delta T \approx 3$ K), for which one can track the modification of the $\rho(j)$ characteristic in the transition region ($T - T_0 < \Delta T$), as well as of a film with $\Delta T \approx 0.7$ K and a higher current-carrying capacity. In the normal (N) state $T = 100$ K, $\rho = \mathrm{const}(j)$, and the I-V characteristic is linear. When the temperature is lowered into the transition region $T - T_0 < \Delta T$ the resistance decreases but remains finite for an arbitrarily low current den-

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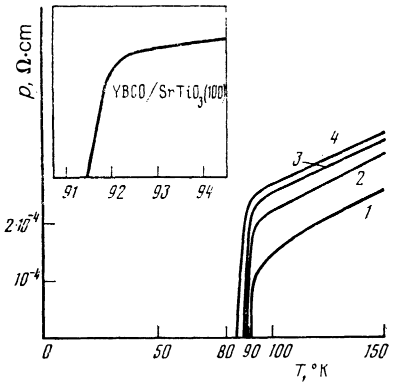

FIG. 1. Transition characteristics of single-crystal (*1*) and polycrystalline (*2, 3, 4*) YBCO films on the following substrates: *1,2*—SrTiO$_3$; *3*—GaAs; *4*—Al$_2$O$_3$, Si.

sity, since there is no continuous chain of superconducting (S) crystallites. The film is a composite of S-regions separated by N-gaps, and has at sufficiently low current density ($j<j_1\approx10^2$ A/cm^2) a linear IVC and $\rho=$ const. The transition characteristic $\rho(T)$ (Fig. 1) at $j<j_1$ is practically independent of the measuring-current level up to $\rho\geqslant10^{-3}\rho_N$, but the film resistance in this state is sensitive to weak ($B<0.1$ T) magnetic fields (Fig. 2). For $j>j_1$ their resistivity $\rho\neq$ const (j), while as $T\to T_0$ it tends to $\rho\sim j^{3/2}$.

At $T\leqslant T_0$ the $\rho(j)$ characteristic changes qualitatively; there exists a characteristic value $j=j_c$ such that at $j<j_c$ the resistance decreases rapidly to below the sensitivity level of the measuring system. As seen from Fig. 2, j_c tends to zero at $T=T_0$ (the temperature at which the S chain is formed).

At $T<T_0$ a typical $\rho(j)$ plot consists of three sections. At $j\approx j_c$ we have $\rho\neq0$ and the film becomes resistive with $\rho\ll\rho_N$. The transition is described by the exponential dependence $\rho\sim\exp(j/j_0)$, $j_0\approx0.05j_c$ up to the level $\rho\approx10^{-4}\rho_N$. For larger ρ a power-law dependence $\rho\sim j^n$ sets in with an exponent n that depends on the cryostat temperature; $n=4$–6 for $T=78$ K. With further increase of the resistance a power sufficient to change the temperature is released in the film and the power-law $\rho(j)$ dependence becomes distorted.

Greatest interest attaches to the maximum density of the nondissipative current j_c. We have determined j_c at a level $\rho(j_c)=10^{-9}$ Ω·cm, since the $\rho(j)$ plot is steep and j_c is little sensitive to the choice of the level. The characteristic value of j_c (78 K) of the better films is $>10^6$ A/cm^2, with the largest obtained value $\sim7\cdot10^6$ A/cm^2.

Further research is necessary to identify the factors that determine the large value of j_c in laser-sputtered films. It is clear, however, that one of the principal factors is the high density of the film and the absence of weak bonds between its crystallites. It is known that the low values of j_c for the YBCO ceramic are due to the breaking of the weak bonds between the grains by a transport current or by a magnetic field.[5,6] Even in weak fields $B<0.03$ T the value of j_c can change by several orders. Interest attaches in this connection to the $j_c(B)$ dependence of a set of films having different values of $j_c(B=0)$ (Fig. 3). A field $B=0$–0.15 T was applied in a direction normal to the substrate plane. It can be seen that an appreciable decrease of j_c (for certain films) takes place in the 0–0.05 T range, and a tendency of $j_c(B=0)$ to increase can be tracked for films less sensitive to the field. Thus, just as in ceramics, the degree of decrease of j_c in weak fields can serve as an indicator of the number of weak bonds in the films. The critical current of samples with sufficiently high values of j_c ($>10^6$ A/cm^2) in a magnetic field ~0.1 T decreases by only 10–20%, i.e., there are practically no weak bonds in them and the cross section through which the transport current flows is not altered by the field.

It is clear from Fig. 2 that the general $\rho(j)$ dependence of the film is not changed in a magnetic field, but is shifted along the current axis, while the exponent $n=n(B)$ decreases.

According to present notions concerning the current-carrying capacity of type-II superconductors, their departure from the S state with $\rho=0$ is due to the onset of Abrikosov-vortex motion. A vortex transports a magnetic-flux quantum $\Phi_0=2\cdot10^{-15}$ Wb of field produced either by an

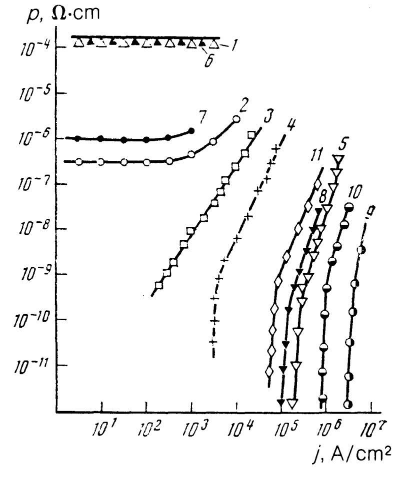

FIG. 2. Resistivity vs transport-current density for a film with $T_0=87$ K and $\Delta T=3$ K at the temperatures (K): *1*—100; *2*—88; *3*—87; *4*—84; *5*—78 ($B=0$); *6*—100; *7*—88; *8*—78 ($B=0.15$ T) and for a film with $\Delta T=0.7$ K at temperatures (K): *9*—78; *10*—86; *11*—89.2 ($B=0$).

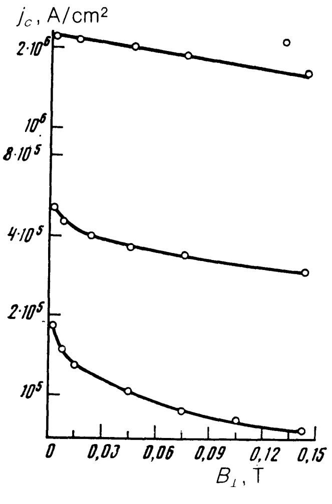

FIG. 3. Critical current density of three YBCO/SrTiO$_3$ films vs the external magnetic field at $T=77$ K.

external source or by the transport current itself. The force $f=j\Phi_0$ applied to the vortices by the current in the case of a defect-free superconductor produces viscous vortex flow at arbitrarily small j, and an energy dissipation characterized by a resistivity $\rho_f\approx\rho_N B/B_{c2}$, where B is the average field in the film and B_{c2} is the second critical field. If the film contains defects that restrain the vortices with a force f_p (pinning centers), the critical current j_c corresponding to the start of the vortex motion and to the transition to the resistive state with $\rho=\rho_f$ is given by the equilibrium condition

$$f(j_c)=f_p,\quad j_c=\Phi_0^{-1}f_p. \tag{1}$$

The principal pinning centers in YBCO films with oriented $\bar{c}$ axis can apparently be assumed to be the grain boundaries.[6,7] Theory yields for the elementary force of the pinning due to electron scattering by electrons on the grain boundaries the value

$$f_p\approx A\mu_0^{-1}B_c^2\xi_0, \tag{2}$$

where B_c is the thermodynamic critical field, ξ_0 is the coherence length in the direction transverse to the vortex, and A is a parameter that depends on the electronic properties of the superconductor (its maximum is $A_m=0.2$, Ref. 7). Taking into account the temperature dependence

$$B_c(T)=B_c(0)\left[1-(T/T_0)^2\right], \tag{3}$$

we obtain from (1) and (2) the critical current

$$j_c(T)=A\mu_0^{-1}\Phi_0^{-1}\xi_0B_c^2(0)\left[1-(T/T_0)^2\right]^2. \tag{4}$$

The value of ξ_0 is usually calculated from the relations

$$B_{c2}^{\perp}(0)=\Phi_0/2\pi\xi_0^2,\quad B_{c2}^{\perp}(0)=0.69\left|(dB_{c2}^{\perp}/dT)\right|T_0,$$

by using the experimental data on $dB_{c2}^{\perp}/dT$. For numerical estimates, we assume an average second critical field $B_{c2}^{\perp}(0)\approx 45$ T (Refs. 8–10), which yields $\xi_0=27$ Å. The values given by different workers for the YBCO thermodynamic critical field $B_c(0)$ vary greatly—from 0.8 T (Ref. 11) to 2.7 T (Ref. 8). This uncertainty is due to the difficulty of measuring B_{c1}, since B_c is calculated from the relation

$$B_c=(B_{c2}^{\perp}B_{c1}^{\perp}/\ln k_{\parallel})^{1/2},\quad 2k_{\parallel}^2/\ln k_{\parallel}=B_{c2}^{\perp}/B_{c1}^{\perp}.$$

Recent measurements of B_{c1} of a YBCO single crystal[12] yield $B_{c1}^{\perp}(0)\approx 0.22$ T and accordingly $B_c(0)=1.87$ T [at $B_{c2}^{\perp}(0)=45$ T]. Assuming for the estimates that this is the value of $B_c(0)$, we obtain from (2) a maximum pinning force f_p (78 K) $=1.5\cdot 10^{-3}$ N/m or from (4) a critical current density j_c (78 K) $=6\cdot 10^6$ A/cm^2. Calculation for $T=4$ K yields j_c (4 K) $=7\cdot 10^7$ A/cm^2.

When comparing these estimates with the experimental values of j_c it must be noted that j_c in Eq. (1) has the meaning of the maximum nondissipative-current density in the absence of fluctuation-induced breaks of the vortices away from the pinning centers at $j\leqslant j_c$. Within the framework of the thermally-activated vortex-creep model, this quantity corresponds to the value of j at which the exponential section of $\rho(j)$ goes over into the viscous-flow section $\rho=\rho_f$. A distinctive feature of the $\rho(j)$ characteristics of Fig. 2 is the absence of the last section, which corresponds at $B\approx 0.01$ T to a level $\rho\sim 10^{-7}$ $\Omega\cdot$cm, but the slope of the $\rho(j)$ curve permits a correct comparison of the value of j_c measured at $\rho=10^{-9}$ $\Omega\cdot$cm with the estimate (2).

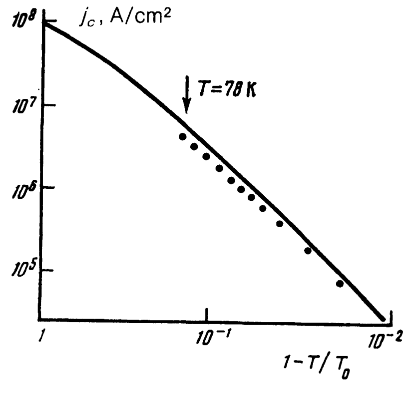

FIG. 4. Critical current density vs temperature. $B=0.05$ T, $j_c\sim(1-T/T_0)^2$. Curve—calculated according to (4), points—experimental results.

The experimental values of j_c (78 K) of YBCO films lie in the range $3\cdot 10^5$–$5\cdot 10^6$ A/cm^2, and the scatter of the values is determined mainly by the influence of extended defects (steps, scratches) on the substrate surface. The highest values j_c (78 K) $>2\cdot 10^6$ A/cm^2 were obtained for microbridges measuring 10×100 μm^2. Figure 4 shows the experimental $j_c(T)$ dependence for a film with $T_0=91$ K and j_c (78 K) $=4.5\cdot 10^6$ A/cm^2 and the calculated curve (4). Equation (4) is seen to describe the experiment quite well quantitatively and qualitatively. The critical current density increases like $(1-T/T_0)^2$ near T_0. Note that in non-oriented films, where the principal role can be assumed by pinning on the grain boundaries with different $\bar{c}$ axis orientations, the theory yields the relation $j_c\sim(1-T/T_0)^{3/2}$ (Ref. 7).

Equation (1) is valid, obviously, only for magnetic fields that are weak enough, since it does not allow for the collective interaction of the vortices with one another and with the pinning centers. In stronger fields, $j_c=j_c(B)$ and is characterized by a bulk pinning force $F_p=j_cB$ (Ref. 13).

There is at present no agreement concerning the nature of the nonlinear $\rho(j)$ characteristics in the region of the resistive state $j\gtrsim j_c$, $\rho<\rho_N$. The exponential section of the IVC contains information on the spectrum of the pinning centers and on the peculiarities of the vortex motion, and calls for a detailed analysis. The mechanism responsible for the power-law section $\rho\sim j^n$ is not clear, but it is apparently not connected with the influence of the overall heating of the sample, since it is observed also when the $\rho(j)$ characteristics are obtained by a pulsed method. The transition to the region $\rho>\rho_f$ may be due to formation of a superconducting texture when the weak bonds are broken by the current, as in ceramic samples.[14]

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