Critical current density and upper critical field of YBa$_2$Cu$_3$O$_7$ thin films

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Epitaxial YBa$_2$Cu$_3$O$_7$-thin films with the c-axis oriented perpendicular to the film plane were prepared by dc-sputtering from a single stoichiometric target on (100) SrTiO$_3$-substrates. Typical values of the inductively measured superconducting transitions were about 90 K with a width less than 0.5 K. Critical current densities were measured on 5 to 10 μm wide strips as function of magnetic field and temperature. The temperature dependences of $j_c$ follow a universal function $j_c(B, T) = j_c^*(T=0, B) \cdot (1 - T/T_c(B))^\alpha$ with $\alpha = 1.5 \pm 0.1$. For $B=0$ and $T=77$ K we obtained $j_c = 4 \cdot 10^6$ A/cm$^2$. The field dependence of the resistive transitions was measured with the magnetic field parallel to the c-axis. The slope of the upper critical field $B_{c2}(T)$ was determined for different criteria. The carrier concentration evaluated from Hall-effect measurements was found to decrease linearly from one per unit cell at 240 K with decreasing temperature extrapolating nearly through zero for $T=0$. Highly resolved angular dependent measurements of the critical current density with $B$ perpendicular to the current but tilted from the c-axis show a very strong and sharp enhancement of $j_c$ for the magnetic field parallel to the (CuO$_2$)-layers ($B \perp c$). Additionally to this phenomenon, which is caused by an intrinsic pinning mechanism due to the layered structure of high-$T_c$-superconductors the influence of the anisotropy of the upper critical field on $j_c(B, T, \varphi)$ is evident near $T_c$.

1. Introduction

Detailed transport measurements in the normal and superconducting state are of great interest for an understanding of the intrinsic properties of high-$T_c$-superconductors. For applications the temperature and magnetic field dependence of the critical current density $j_c(B, T)$ is of crucial importance. Epitaxial thin films are especially suitable for transport measurements in two aspects: first the results are not affected by grain boundary effects in contrast to polycrystalline material. Second films can be easily patterned into appropriate geometries for quantitative measurements contrary to single crystals.

Therefore we prepared high-quality $c$-axis oriented YBa$_2$Cu$_3$O$_7$-films on SrTiO$_3$ by high pressure oxygen sputtering for measurements of resistivity $\rho(T)$, Hall-coefficient $R_H(T)$, upper critical field $B_{c2}(T)$ and critical current density $j_c(B, T)$ on the same film.

As it is well known that $B_{c2}(T)$, and $j_c(B, T)$ are lowest for $B$ oriented perpendicular to the CuO$_2$-layers we concentrate in this paper on measurements in this orientation in order to establish a lower limit [1, 2].

Additionally we measured the angular dependence $j_c(B, T, \varphi)$ for $T$ close to $T_c$ in order to study the intrinsic pinning mechanism due to the layered structure as proposed by Tachiki and Takahashi [3].

2. Experimental details

The films were deposited by high pressure dc-sputtering ($3 hPa$) in pure oxygen atmosphere from a stoichiometric target onto heated SrTiO$_3$ substrates held at $T_{sh} = 900 \degree C$ by a Pt-substrate holder [4]. After deposition the films were in situ annealed at $T_{sh} = 575 \degree C$ in 1 bar oxygen. This annealing step is required to transform the tetragonal YBa$_2$Cu$_3$O$_{7-\delta}$-phase into the orthorhombic YBa$_2$Cu$_3$O$_{7-\delta}$ ($\delta \approx 0.1$)-phase. The structural quality of the films in respect of phase purity, oxygen content (c-lattice parameter), c-axis orientation and epitaxy (rocking curves) was investigated by X-ray diffraction in Bragg-Brentano geometry using Cu-K$_\alpha$ radiation. The superconducting critical temperature and the transition width of the fully coated substrates were determined by ac-susceptibility measurements, which is a far more stringent quality test than measurements of resistive transitions. The computer controlled inductive measurements were carried out with a mutual inductance bridge especially suited for thin films and a PAR 5210 two-phase Lock-In-amplifier, detecting real and imaginary part of the susceptibility simultaneously. Low resistance contacts with
typical resistance values of 10 mΩ were fabricated by evaporating silver onto the film. Standard photolithographic techniques were used to pattern the films into an 8-probe geometry. This structure consists of a 2 mm long and 0.2 mm wide strip and a 100 µm long and 10 µm wide microbridge. On the wider strip there are contacts for resistivity and Hall effect measurements and the microbridge can be used for measurement of the critical current density and resistivity. Further details concerning the above described steps have been reported earlier [5]. The resistive transition curves of the microbridge and the 0.2 mm wide strip of up to four samples were obtained in one run fully computer controlled with an IBM-AT-compatible computer connected via IEEE-Bus to a programmable current source (Keithley 224) and a scanner voltmeter (Keithley 199).

The samples were mounted with Apiezon-N on a copper block, which contained thermometers and heater. For resistance measurements a current density of 1000 A/cm² was applied. As temperature sensors Pt-resistors (T > 40 K) and carbon glass resistors (T < 40 K) were used. Measurements in magnetic fields up to 12 T were made in a NbTi/NbSn-hybrid magnet (Oxford Instruments) with a 52 mm diameter bore. Except for the measurements of the angular dependence of the critical current density j_c(B, T, ϕ) all experiments in this paper were carried out with the magnetic field oriented perpendicular to the film surface, i.e. parallel to the c-axis of the YBa_2Cu_3O_7-crystal structure. The Hall effect data were taken by reversing the current and the magnetic field in order to eliminate thermovoltage and resistive contributions respectively. The Hall voltage measured up to 3 T was linearly increasing with magnetic field. A 1 µV criterion over the 100 µm long microbridge was applied for the j_y(B, T) measurements. The voltage was detected by a nanovoltmeter (Keithley 181) with a resolution of 10 nV. Angular resolved measurements of the critical current density were carried out by rotating a copper block, on which the substrate was mounted, with a wormgear. The angular resolution of the device is 0.04° and the film can be tilted without warming to room temperature from its original orientation fully 360°.

3. Results and discussion

By the above described method films with thicknesses between 100 and 1000 nm and smooth and highly reflective surfaces were prepared. In X-ray diffraction patterns only the (00 l)-peaks of YBa_2Cu_3O_7 could be detected except for substrate peaks. Rocking curves of the (005)-peaks show linewidths (FWHM) of less than 0.4°. In all cases the c-axes of the films were oriented exactly parallel to substrate axis within experimental error of 0.1°. The extremely narrow linewidth and the perfect alignment are clear indications of epitaxial growth. The correlation between substrate materials and film growth was subject of a previous publication [6]. Inductively measured T_c-values were between 89 K and 90 K for films with a thickness of about 100 nm and around 91 K for thicker films. The transition-widths (10%–90%) were below 0.5 K. The onsets of the inductive transitions coincide with the end-points of the resistive transitions (T_c0). The resistive measurements were taken on the narrow and the wide bridge simultaneously and exhibit the same transitions, suggesting that the films are homogeneous. The temperature dependence of the resistivity ρ(T) shows metallic behaviour from room temperature down to 100 K and extrapolates linearly to zero for T=0. The resistivity is about 100 µΩ cm at 100 K. The influence of a magnetic field applied parallel to the c-axis of the film is displayed in Fig. 1. As found generally for high-T_c-superconductors with (CuO_2)-layers the onset of the transition is only weakly shifted by the magnetic field, but the transition is significantly broadened in contrast to the behaviour of conventional superconductors. The determination of the upper critical field B_c2(T) is not unambiguous in high-T_c superconductors due to thermally activated flux flow. Following the derivation of B_c2(T) in the framework of the Ginzburg-Landau theory for the meaning of a nucleation field for superconductivity which then should be reflected by the onset of the resistive transition. The onset of the transition cannot be evaluated in a satisfactory manner due to significant superconductive fluctuations. If we calculate instead the initial slope at 0.9 ρ* with ρ* being the resistivity at 95 K just above the main part of the transition we obtain B_c2(0.9 ρ*) = \left(\frac{dB_c}{dT}\right)_{\rho*} = -10.9 T/K.

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