Two-Dimensional Behavior and Critical-Current Anisotropy in Epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ Thin Films

P. Schmitt,[(1),(2)] P. Kummeth,[(2)] L. Schultz,[(1)] and G. Saemann-Ischenko[(2)]
[(1)]*Siemens AG, Research Laboratories, Erlangen, Germany*
[(2)]*Physikalisches Institut, Universität Erlangen-Nürnberg, Erlangen, Germany*
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The critical-current anisotropy $j_c(B,T,\Theta)$ of epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ films has been measured in detail. Below 70 K, the measured $j_c(B,T,\Theta)$ can be fully accounted for by the assumption that only the field component $B_\parallel = B\cos\Theta$ influences j_c, as has been proposed by Kes *et al.* Above this temperature, a 2D-to-3D dimensional crossover results in additional dissipation. By comparison with results on polycrystalline samples, evidence is given for the absence of any influence of the grain boundaries on $j_c(\Theta)$.

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One of the fundamental questions concerning the mechanism of superconductivity in high-temperature superconductors (HTSC) is related to the dimensionality of these systems at low temperatures. According to Lawrence and Doniach [1], a dimensional crossover from 3D to 2D occurs in layered superconductors on the condition that the coherence length ξ_c perpendicular to the superconducting layers is small compared to the distance of these layers. This condition is met by all HTSC at sufficiently low temperatures. Tachiki and Takahashi derived an intrinsic pinning mechanism from this fact [2] and calculated the $j_c(\Theta)$ anisotropy [3] as measured by Roas, Schultz, and Saemann-Ischenko [4] for epitaxial $YBa_2Cu_3O_{7-\delta}$ films. The flux lines are pinned between the CuO_2 planes in this model [5]. The experimental data of Roas, Schultz, and Saemann-Ischenko [4] and Kuwasawa *et al.* [6] are well described by this model at low temperatures and high magnetic fields. Christen *et al.* [7] demonstrated that an approach focusing on the effective-mass anisotropy $\gamma(\Theta)$ fails to explain $j_c(\Theta)$ in the case of $YBa_2Cu_3O_{7-\delta}$, whereas a special kind of vortex state has been shown to be in qualitative agreement with the experimental data of Ref. [4] by Ivlev and Kopnin [8]. In the case of $Bi_2Sr_2CaCu_2O_{8+x}$, ξ_c becomes much smaller than d_{CuO}, resulting in an extremely weak coupling between the superconducting CuO_2 layers. For this reason, according to Kes *et al.* [9], this material represents a 2D Josephson-coupled system. They deduce the following proposals from this model: (i) In external magnetic fields, only the field component perpendicular to the layers should give rise to a dissipative behavior and (ii) for the external magnetic field B aligned along the CuO_2 planes, B should not influence superconductivity as long as the temperature is below the crossover temperature T_0 from 3D to 2D behavior. These assumptions have been shown to provide a good description of the different experiments cited by the authors. In this Letter, we will demonstrate that for $T < 70$ K the anisotropy $j_c(\Theta)$ of $Bi_2Sr_2CaCu_2O_{8+x}$ epitaxial thin films can be fully accounted for by this model.

Epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ films have been reproducibly prepared on (100) $SrTiO_3$ by pulsed laser deposition using a Siemens XP 2020 excimer laser (XeCl, 308 nm) and have $T_c \approx 80$ K and $j_c(4.2\text{ K}, B=0) > 2\times10^6$ A/cm^2. Details of the preparation have been reported elsewhere [10]. Contrary to the procedure described there, after deposition, the films were kept at the deposition temperature in $p_{O_2} = 1$ mbar for 1 h. The films were cooled to room temperature within 1 h by switching off the heater without changing the oxygen pressure, resulting in an improvement of both T_c and the inductively measured transition width ΔT_c. The epitaxial growth of the films has been confirmed by TEM investigations [11], revealing a twinning of the films as well. The FWHM of the (0010) rocking curve ranges from 0.35° to 0.43° indicating some scatter of the c axis. Rutherford-backscattering-channeling experiments yielded a X_{min} of 0.34, which is consistent with the FWHM of the rocking curve.

The films were patterned mechanically by scratching 1-mm-long and typically 0.1-mm-wide strip lines along the a or b axis of the film using a plotter equipped with a stainless-steel needle. The critical-current density $j_c(B,T,\Theta)$ of 100–300 nm thin films has been measured as a function of temperature T, magnetic field B, and the angle Θ between the c axis of the film and the magnetic-

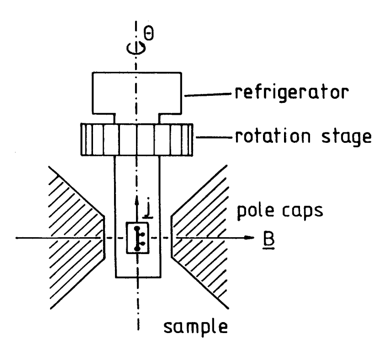

FIG. 1. Schematic of the setup used for the $j_c(B,T,\Theta)$ measurements defining the angle Θ between the magnetic-field direction and the c axis of the film. $\Theta=0$ corresponds to the **B**$\parallel$**c** direction.

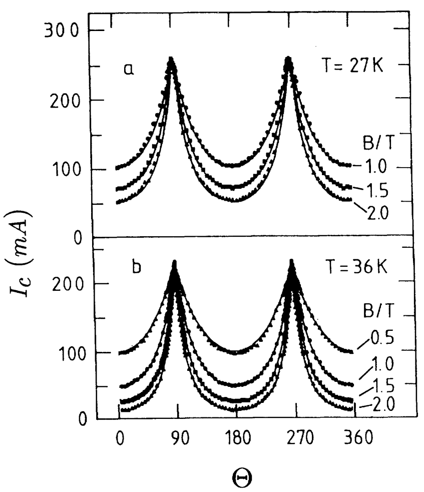

FIG. 2. Critical current of two epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ films at (a) 27 K and (b) 36 K, respectively, as a function of the angle Θ between magnetic field and c axis. Symbols represent experimental data, and solid lines have been calculated using Eq. (2).

field direction, keeping magnetic field and current perpendicular to each other. A voltage criterion of 3.5 μV (Figs. 2–4) or 0.5 μV (Figs. 5–7) corresponding to an electrical field criterion of 35 or 5 μV/cm, respectively, has been adopted for the j_c measurements. The angular resolution of the setup used in these experiments (Fig. 1) was about 0.01° with the absolute angle being accurate to 1° or 2°. The sharp maxima, which appear for the $\mathbf{B}\perp\mathbf{c}$ direction, were used for the calibration of the absolute Θ value. During the $j_c(\Theta)$ measurements, the samples were kept at constant temperature. As evident from the results, frozen-in magnetic flux did not effect the measured j_c values.

The $j_c(\Theta)$ dependence is shown for several magnetic fields and temperatures in Figs. 2 and 3. The symbols represent the measured values, and the solid lines have been calculated from the $j_c(\mathbf{B}\|\mathbf{c})$ dependence following a model proposed by Kes *et al.* [9]. According to these authors, in the case of $Bi_2Sr_2CaCu_2O_{8+x}$ the CuO_2 planes completely decouple for temperatures below the 3D-to-2D crossover temperature $T_0=\{1-[2\xi_{ab}(0)/d_{CuO}]^2\}/\Gamma$, where ξ_{ab} is the coherence length within the CuO_2 planes and d_{CuO} is their separation; $\Gamma=m_z/m_{xy}$ is the effective-mass anisotropy [1]. At this temperature, ξ_c becomes smaller than half the distance of the CuO_2 planes, assuming the usual temperature dependence $\xi(T)=\xi(0)(1-T/T_c)^{-1/2}$. The decoupling of the CuO_2 planes results in a 2D description with an almost vanishing order parameter in between the CuO_2 planes. Following Kes *et al.*, a magnetic field parallel to the CuO_2 planes penetrates, as if the material is "magnetically transparent." For arbitrary field directions only the perpendicular component will have to be considered.

Concerning the $j_c(\Theta,B)$ measurements, this model

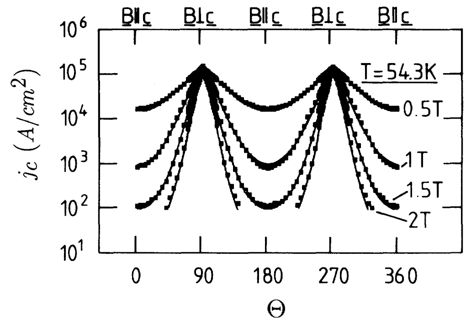

FIG. 3. Critical-current density $j_c(\Theta)$ of an epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ film at 54.3 K. Equation (2) has been used for the calculation of the solid lines, and experimental data are represented by symbols.

suggests that only the component $B_\|=B\cos\Theta$ gives rise to a decrease of j_c in a magnetic field B declined by an angle Θ with respect to the $\mathbf{B}\|\mathbf{c}$ direction, whereas in the $\mathbf{B}\perp\mathbf{c}$ direction j_c should be independent of B. Defining $j_{c\|}(B):=j_c(B)$ for $\mathbf{B}\|\mathbf{c}$ and $j_{c\perp}(B):=j_c(B)$ for $\mathbf{B}\perp\mathbf{c}$, the relation

$$j_c(\Theta,B)=j_{c\|}(B\cos\Theta) \tag{1}$$

should therefore hold. As an experimental fact, however, $j_{c\perp}(B)$ is not completely field independent, especially at high temperatures. For the following, $j_c\perp(B)$ is used as a cutoff parameter for $j_c(\Theta,B)$. Equation (1) is therefore rewritten

$$j_c(\Theta,B)=\min[j_{c\perp}(B),j_{c\|}(B\cos\Theta)]\,. \tag{2}$$

The solid lines drawn in Figs. 2 and 3 have been calculated using this expression for $j_c(\Theta,B)$, which contains no adjustable parameters. In order to check consistency of this model, we also calculated $j_{c\|}(B)$ from $j_c(\Theta,B)$ using relation (1), which will be erroneous only for very small fields B as a result of releasing the minimum condition. Each curve $j_c(\Theta,B)$ gives a curve for $j_{c\|}(B)$. Figure 4

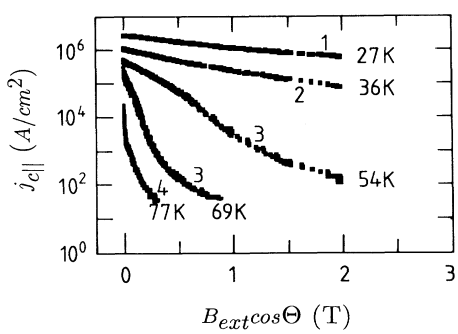

FIG. 4. Magnetic-field dependence $j_{c\|}(B)$ of different samples (1–4) at different temperatures as calculated using Eq. (1). Each curve is deduced from at least four $j_c(\Theta)$ curves measured at different magnetic fields B for each temperature.

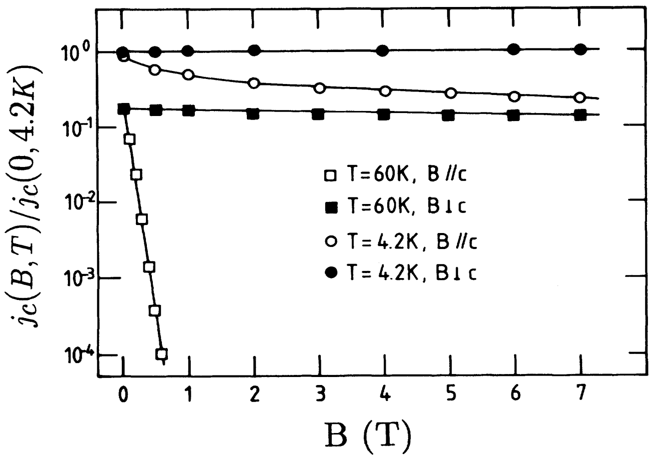

FIG. 5. Magnetic-field dependence of j_c for an epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ film for the **B**||**c** and **B**⊥**c** directions at 4.2 and 60 K. At 60 K, $j_{c\perp}(B=7\text{ T})$ is only 20% smaller than the zero-field value, whereas at 4.2 K, $j_{c\perp}$ is completely field independent up to 7 T.

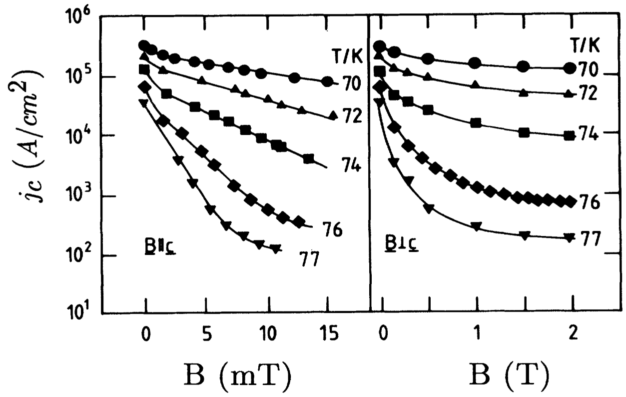

FIG. 6. Magnetic-field dependence of j_c for an epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ film for the **B**||**c** and **B**⊥**c** directions for different temperatures close to $T_c=80$ K.

shows the calculated $j_{c\parallel}(B)$ dependence of four samples for different temperatures using at least four $j_c(\Theta,B)$ curves at each temperature measured in different applied magnetic fields B. If the functional dependence [Eq. (1)] were not a proper description of the experimental data, the calculated $j_{c\parallel}(B)$ curves would not coincide at a given temperature.

In the following, we discuss the field independence of j_c in the **B**⊥**c** direction proposed for temperatures below T_0 [9]. For magnetic fields up to 7 T and temperatures up to 60 K, $j_{c\perp}$ indeed is almost field independent for epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ films, as evident from Fig. 5. Of course, the model will only hold for perfect single crystals with the CuO_2 planes lying exactly parallel to each other throughout the strip line. In real single-crystalline films, there is, however, some mosaic spread to the c axis as evident from the width of the rocking curve. In fact, the HWHM of the rocking curve $\Delta\Theta$ of a (001) peak may be interpreted as the mean deviation of the c axis from the ideal direction, causing a mean-field component $B^*=B_{\text{ext}}\sin\Theta^*$ parallel to the c axis and, as a consequence, a decrease of j_c with B also for optimized alignment, where Θ^* is expected to be close to but not necessarily identical with $\Delta\Theta$. Therefore, $j_{c\perp}(B^*)$ should be identical to $j_{c\parallel}(B)$ with B^* as defined above. Figure 6 shows the measured $j_c(B)$ dependence for both directions at different temperatures close to $T_c=80$ K. Special care has been taken to align the magnetic field parallel to the mean a-b plane for the $j_c(\mathbf{B}\perp\mathbf{c})$ measurements to within 0.03°. In Fig. 7, $j_{c\parallel}(B)$ has been redrawn from Fig. 6 (open symbols), whereas $j_{c\perp}(B)$ has been transformed to $j_{c\perp}(B^*)$ using $\Theta^*=0.23°$, which is very close to the HWHM of the (0010) rocking curve $\Delta\Theta=0.2°$ (solid symbols). Obviously, for temperatures close to T_c, the functional dependence $j_{c\perp}(B^*)$ deviates strongly from $j_{c\parallel}(B)$ with j_c decreasing faster than expected from the model of Kes *et al.* [9] for the **B**⊥**c** direction. With decreasing temperature, this difference gets smaller and almost vanishes at 70 K. These results may be interpreted in terms of a 3D-to-2D transition in the following way: (i) At 70 K, the observed $j_{c\perp}(B)$ behavior is consistent with the model of a 2D Josephson-coupled superconductor, and (ii) at higher temperatures, due to the increase of ξ_c, coupling of the CuO_2 planes as measured by ξ_c/d_{CuO} becomes stronger, resulting in a dissipative behavior for in-plane fields due to $H_{c2}(T)$, and therefore in a 3D behavior.

In conclusion, the critical-current anisotropy $j_c(B,T,\Theta)$ has reduced to the magnetic-field dependence of j_c in the **B**||**c** direction for epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ films below about 70 K. As a consequence, extrinsic pinning defects like twin boundaries and surface pinning effects,

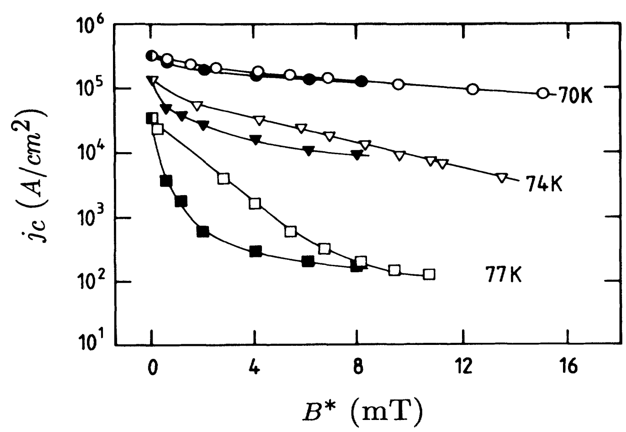

FIG. 7. j_c as a function of the reduced field B^* with $B^*=B$ for the **B**||**c** direction (open symbols) and $B^*=B\sin\Theta^*$, $\Theta^*=0.23°$, for the **B**⊥**c** direction (solid symbols).

which have been shown to play an important role for $j_{c\perp}(B)$ in $YBa_2Cu_3O_{7-\delta}$ films [4,12], will, in the case of $Bi_2Sr_2CaCu_2O_{8+x}$, influence only $j_{c\parallel}(B)$. It is remarkable that the model of Kes *et al.* [9] has been applied successfully to polycrystalline $Tl_2Sr_2Ca_2Cu_3O_{10+x}$ thin films by Nabatame *et al.* [13] as well as to polycrystalline $Bi_2Sr_2CaCu_2O_{8+x}$ thin films by Raffy *et al.* [14]. In addition, $j_{c\perp}$ has been shown to scale with $j_{c\parallel}$ with a temperature-independent effective texture angle $\Theta^* = 10°$ in the case of textured $Bi_2Sr_2CaCu_2O_{8+x}$ bulk samples [15]. By comparison with our results on epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ films, this gives evidence for the absence of any influence of grain boundaries on $j_c(\Theta)$ in these materials.

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