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Angular dependence of the Hall conductivity in $YBa_2Cu_3O_x$ films with columnar defects

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We have studied the role of strong pinning on the Hall conductivity by measuring the angular dependence of the longitudinal and the Hall resistivity of $YBa_2Cu_3O_x$ films with columnar defects. The resulting Hall conductivity $|\sigma_{xy}|$ of irradiated films shows a sharp increase with decreasing temperature when an external magnetic field is aligned parallel to the columnar defects, a strong pinning configuration, whereas $|\sigma_{xy}|$ of unirradiated films shows a broad minimum in the same orientation. This distinctive difference demonstrates the pinning dependence of the Hall conductivity. [S0163-1829(98)04446-4]

One interesting scientific issue regarding the role of columnar defects on the transport properties of high-T_c superconductors is whether the Hall conductivity σ_{xy} depends on vortex pinning.[1–6] A theory by Vinokur *et al.*[7] suggests that the Hall conductivity σ_{xy} should be independent of pinning. According to this model, the Hall behavior obeys a scaling relation $\rho_{xy}=A\rho_{xx}^2$ in the thermally assisted flux-flow region, where ρ_{xx} is the longitudinal resistivity and ρ_{xy} is the Hall resistivity. The coefficient A is assumed to be pinning independent and the scaling exponent β to be 2 regardless of pinning. Since the Hall conductivity is given as $\sigma_{xy} \approx \rho_{xy}/\rho_{xx}^2=A$, it is suggested that pinning is irrelevant to the Hall conductivity. In order to test the role of pinning, several researchers have studied the Hall conductivity before and after heavy-ion irradiation. Budhani *et al.*[1] reported that the scaling behavior remains unaffected after Ag-ion irradiation on $Tl_2Ba_2Ca_2Cu_3O_{10}$ films and Samoilov *et al.*[2] also reported that the Hall conductivities of $YBa_2Cu_3O_x$ (YBCO) single crystals and $Tl_2Ba_2CaCu_2O_x$ films are not changed after introducing the columnar defects. However, both results have been reinterpreted favoring the pinning dependence.[3,8]

Wang *et al.*[9] proposed a model that the scaling behavior as well as the Hall conductivity can be modified by strong pinning by taking account of the backflow current effect due to pinning. In this case, the scaling exponent may change from 2 to 1.5 and σ_{xy} becomes more negative as the pinning strength increases. Ao[10] also suggested that the scaling exponent varies between 1 and 2 depending on the details of a sample by considering the motion of vacancies in a pinned flux lattice. Experimentally, a systematic study of YBCO single crystals by Kang *et al.*[3] showed that the scaling behavior as well as the Hall conductivity changes after heavy-ion irradiation. Even in unirradiated YBCO/PBCO superlattices[11] and $HgBa_2CaCu_2O_x$ films[8] it is found that the scaling exponent changes with increasing magnetic field. Since the vortex pinning decreases with increasing field, it is argued that this field dependence of the scaling exponent is not consistent with the pinning-independent model by Vinokur *et al.*[7] In this work, we present the *angular* dependence of the Hall conductivity in YBCO epitaxial films before and after heavy-ion irradiation, which unambiguously shows the pinning dependence of the Hall conductivity. We also find that it is important to measure the angular dependence of σ_{xy}, not just the dependence for one orientation of the magnetic field, in order to test the role of enhanced pinning.

Epitaxial YBCO films were grown on $LaAlO_3$ substrates using off-axis sputtering. Transition temperatures T_c determined in zero field by the peak of $d\rho_{xx}/dT$ were 90.2 and 89.7 K before and after irradiation, respectively. The transition width (10–90 % transition) was found to be less than 1 K. The columnar defects were formed along the c axis of the YBCO films by 1.3-GeV uranium-ion irradiation. The total planar density of the defects was 5×10^{10} cm^{-2}, which corresponds to the matching field of $B_\phi\approx1$ T. We chose to study films instead of single crystals to enhance the experimental resolution because the difference in σ_{xy} before and after irradiation is often not clearly larger than the measurement accuracy.[5] In order to reduce sample-to-sample variation, half of each film was covered during the irradiation so that a direct comparison between the Hall behavior of unirradiated and irradiated samples was possible. Additional films from the same batch were irradiated with a crossed defect configuration in which columnar defects were oriented ±10° relative to the c axis. ρ_{xx} and ρ_{xy} are measured simultaneously using an ac lock-in technique while rotating the samples in magnetic fields. The angular position is determined by the Hall signal of a GaAs sensor attached to the sample block.

The angular dependence of ρ_{xx} and ρ_{xy} of the unirradiated film for $H=1.74$ T at several reduced temperatures $t=T/T_c$ is shown in Figs. 1(a) and 1(b). The angular position θ corresponds to the angle between the applied magnetic field and the c axis of the sample. The curves of ρ_{xx} versus θ are

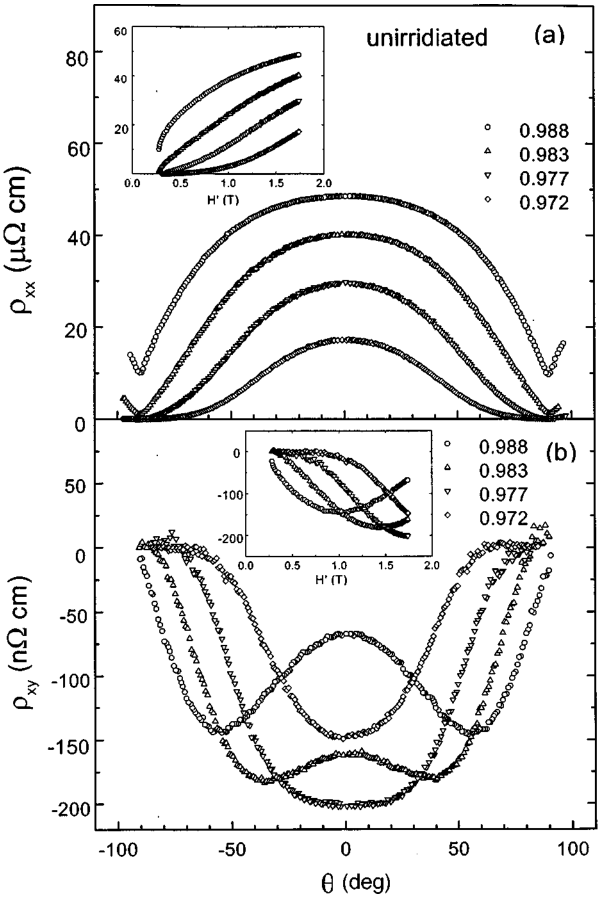

FIG. 1. The angular dependence of ρ_{xx} (a) and ρ_{xy} (b) of the unirradiated film for $H=1.74$ T at several reduced temperatures 0.988, 0.983, 0.977, and 0.972. $\theta=0°$ corresponds to $H\|c$. The insets are the same data sets replotted as a function of scaled magnetic field H' determined by Eq. (1).

consistent with typical results for unirradiated samples. A complicated shape of ρ_{xy} is a result of its nonmonotonic dependence on magnetic field. With increasing θ, the effective magnetic field for the transverse component of the transport properties H'

$$H'=H\cos\theta\sqrt{1+\Gamma^{-1}\tan^2\theta} \tag{1}$$

decreases. Here Γ is the effective mass anisotropy. The decrease in H' is explained by Geshkenbein and Larkin[12] as a result of the anisotropic nature of YBCO. The plots of ρ_{xx} and ρ_{xy} as a function of H' with $\Gamma=40$ are shown in the insets of Fig. 1. This figure of ρ_{xx} and ρ_{xy} agrees well with published work on YBCO (Refs. 13 and 14), where ρ_{xx} and ρ_{xy} versus magnetic field are measured with H parallel to the c axis, confirming the validity of the anisotropic mass model in unirradiated films. It should be noted that the angular scaling of σ_{xy} in unirradiated single crystals of YBCO using Eq. (1) has been demonstrated by Harris *et al.*[15]

The case of an irradiated film is shown in Figs. 2(a) and 2(b) for $H=1.74$ T. At the same reduced temperatures, the magnitudes of ρ_{xx} and ρ_{xy} for $H\|c$ are smaller than those of unirradiated films, consistent with previous work.[2,3] We note that the pinning of the columnar defects is found to be effective up to a magnetic field a few times its matching field.[1,3] A noticeable difference is that a dip of ρ_{xx} develops at $\theta=0°$ ($H\|$ columnar defects) below $t=0.977$ due to the onset of vortex pinning by columnar defects. In case of the Hall resistivity shown in Fig. 2(b), a corresponding diplike feature of $|\rho_{xy}|$ appears at $\theta=0°$ below $t=0.977$ instead of a broad minimum observed in the unirradiated case. This diplike feature is quite different in nature from the broad minimum observed in $|\rho_{xy}|$ at $t=0.983$ and 0.988; the former can be understood as the suppression of $|\rho_{xy}|$ in the presence of strong pinning, while the latter comes from the nonmonotonic dependence on magnetic field as in the unirradiated case. The scaled-field-dependent behaviors of ρ_{xx} and ρ_{xy} shown in the inset are also different from those of the unirradiated films; ρ_{xx} is roughly linear dependent on H' except for very high and very low θ where intrinsic pinning or pinning by columnar defects plays a dominant role. The shape of ρ_{xy} with increasing field is likewise changed. On the other hand, in a separate measurement with field applied parallel to the c axis on this film, we find that there is no distinguishable difference between the overall field dependence of ρ_{xx} and ρ_{xy} and those of unirradiated films (insets of Fig. 1), except that the magnitudes are smaller.

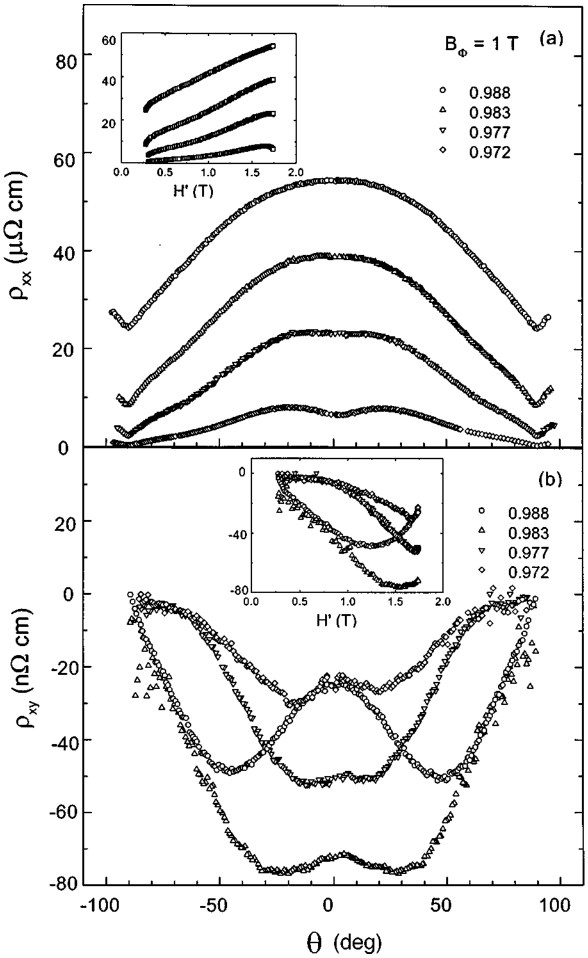

FIG. 2. The angular dependence of ρ_{xx} (a) and ρ_{xy} (b) of the irradiated film for $H=1.74$ T at the same reduced temperatures as in Fig. 1. The insets show the same data replotted as a function of scaled magnetic field as in Fig. 1. The effect of pinning by the columnar defects appears as a diplike feature centered at $\theta=0°$.

The angular dependence of σ_{xy} is calculated using the

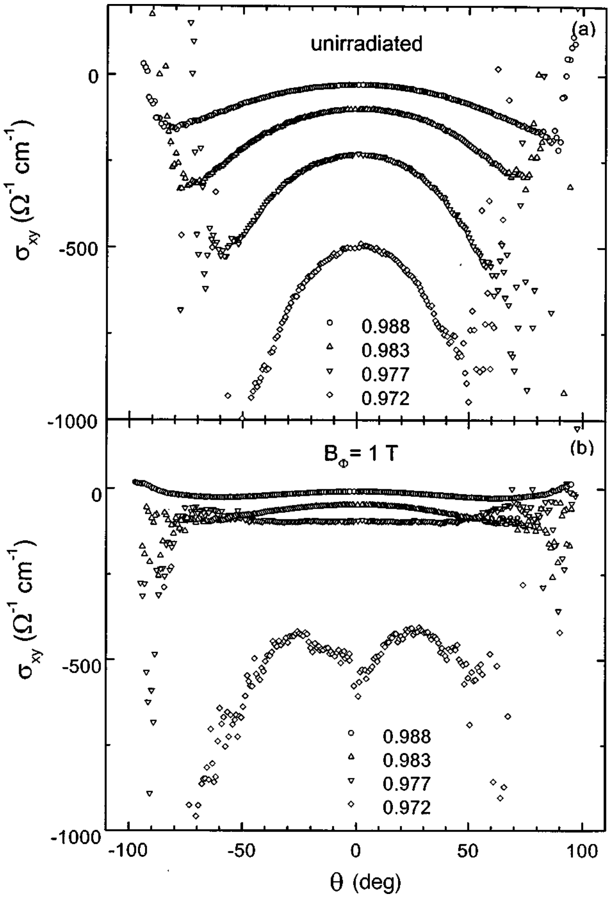

FIG. 3. The angular dependence of σ_{xy} of the unirradiated (a), and the irradiated YBCO film (b). The difference between two sets of data in the region of strong pinning ($t=0.977$ and 0.972) is obvious, indicating the pinning dependence of the Hall conductivity.

relation $\sigma_{xy}=\rho_{xy}/\rho_{xx}^2$ and the results are shown in Fig. 3. Here the effect of columnar defects on σ_{xy} is unambiguously observed. The Hall conductivity of the unirradiated film shows an apparent maximum at 0° for all temperatures below $t=1$ as shown in Fig. 3(a), whereas the angular dependence of σ_{xy} of the irradiated film changes with decreasing temperature as shown in Fig. 3(b). We note that a dip in this figure in fact corresponds to a peak in $|\sigma_{xy}|$ since σ_{xy} is negative in this temperature region. $|\sigma_{xy}|$ becomes a maximum at 0° for $t=0.977$, clearly different from the unirradiated case. This broad maximum of $|\sigma_{xy}|$ develops in to an apparent peak at $t=0.972$, which is an obvious manifestation of the effect of enhanced pinning by columnar defects on the Hall conductivity.

Figure 4 shows the angular dependence of σ_{xy} of the film with *crossed* columnar defects of ±10°. $B_\phi\approx 1$ T and T_c in zero field is 89.3 K. In a separate study,[16] it was found that the critical current density of YBCO films with ±10° configuration is higher than in the case of parallel pins. The qualitative features are very similar to the case of parallel defects: a maximum of $|\sigma_{xy}|$ at $\theta=0°$ starts to develop at $t=0.977$, but the peak at $t=0.972$ is broader than in Fig. 3(b), presumably due to the fact that the accommodation angle is larger for the crossed defects configuration. This

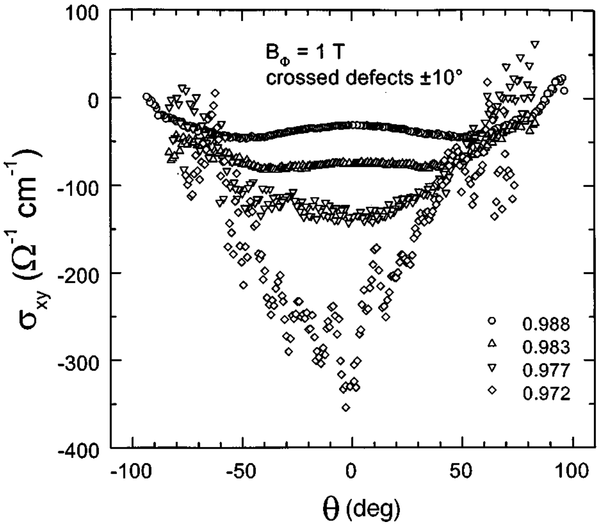

FIG. 4. The angular dependence of σ_{xy} of a YBCO film irradiated with crossed columnar defects of ±10°. The qualitative features are very similar to the case of parallel defects in Fig. 3(b), but the peak centered at $\theta=0°$ is broader due to the larger accommodation angle in this defect configuration.

result together with the one shown in Fig. 3 clearly indicates that the strong vortex pinning indeed modifies the Hall conductivity.

In previous work,[2,3] σ_{xy} has been measured only for fields applied parallel to the columnar defects, the configuration for most effective pinning. However, such results sometimes have not been conclusive enough in determining the role of columnar defects, especially in single crystal samples.[2,5] Figure 5 shows the temperature dependence of σ_{xy} before and after irradiation for $H=1.74$ T applied parallel to the c axis. The difference is quite noticeable in the slopes of σ_{xy} with respect to reduced temperature: $|\sigma_{xy}|$ in the irradiated film

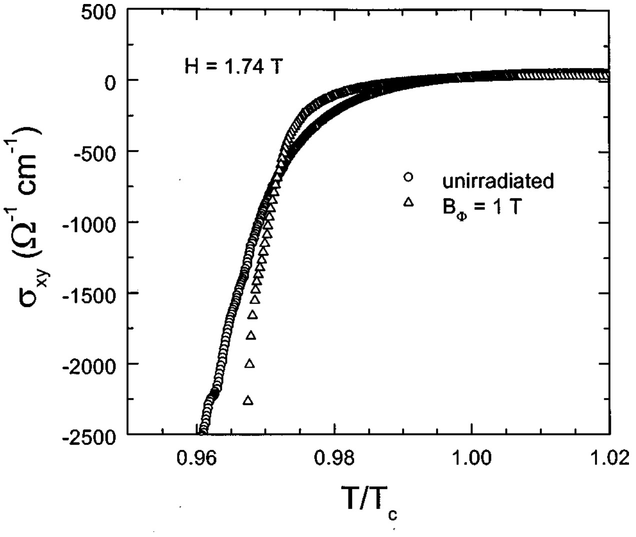

FIG. 5. The temperature dependence of σ_{xy} before (circle) and after irradiation (triangle) measured in YBCO film with parallel pins as a function of reduced temperature for $H=1.74$ T applied parallel to the c axis. The rapid increase of $|\sigma_{xy}|$ with decreasing t in the irradiated film for 1.74 T is related to the development of a peak at $\theta=0°$ in Fig. 3(b).

increases more rapidly with decreasing temperature for $\sigma_{xy} < -300\ \Omega^{-1}\ \mathrm{cm}^{-1}$, and this large slope is related to the development of the peak in $|\sigma_{xy}|$ in Fig. 3(b). Finally we examined the scaling behavior $\rho_{xy} = A\rho_{xx}^{\beta}$ in two samples, and found that β is reduced after irradiation from 1.8 ± 0.2 to 1.6 ± 0.2 for $H = 3.18$ T, consistent with the previous single crystal work.[3] The smaller reduction in β may be related to the high density of inherent defects such as oxygen deficiencies or dislocations in films compared to single crystals. Those defects may promote flux line wandering from the columnar pins.

Often, successful scaling of the angular dependence of σ_{xy} (Ref. 15) or the transport entropy[17] in unirradiated YBCO has been interpreted to support the pinning independent model.[5] In this work based on samples containing columnar defects, however, it is found that not only does the angular scaling based on the anisotropic mass model break down, but the model of the pinning independence of the Hall conductivity also fails when the magnetic fields are parallel to the columnar defects. This implies that vortex dynamics, and particularly the Hall behavior in the strongly pinned system, requires additional treatment.

In summary, we have demonstrated the pinning dependence of the Hall conductivity by measuring its angular dependence. σ_{xy} after irradiation shows a large change compared to the unirradiated case. In addition, the modification of the temperature dependence of σ_{xy} and the reduction of the scaling exponent β after irradiation are found to be consistent with the pinning dependence of the Hall behavior.

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