Effect of the irradiation of Au ions on the negative Hall resistivity for YBCO films

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Abstract

The temperature dependence of longitudinal and transversal resistivities ($\rho_{xx}(T)$ and $\rho_{xy}(T)$, respectively) near the transition region for YBCO films have been measured before and after the irradiation of Au ions. Our results show that the peak value of the negative ρ_{xy} increases significantly at 0.5 T but remains nearly the same at 4 T after the irradiation. The power law of [$\rho_{xy} = \rho_{xx}^\alpha$] has been extracted for our films, with α ranging from 0.9 to 1.6. There is no correlation found between the magnitude of negative ρ_{xy} and the α values. The field dependence of the irradiation effect on $\rho_{xy}(T)$ suggests a complicated interplay between the magnetic field and the defects on the mechanism of the anomalous Hall effect.

1. Introduction

The studies on the anomalous Hall effect for high temperature superconductors (HTS) have attracted much attention since the observation of the sign reversal of the Hall resistivity challenging the conventional theories of flux motion. Based on BS [1] and NV [2] theories, the single vortex motion could not possibly lead to a sign reversal of the Hall resistivity ρ_{xy} . Therefore, many theories or models have been prompted to explain this phenomenon, including the use of viscous-drag force [3], backflow current [4], vortex–antivortex [5,6], thermoelectric effect [7], and others. In the theory of back flow current [4], the Hall resistivity ρ_{xy} was expressed as a function of magnetic field H and pinning force F_p explicitly; and in the theory of vortex–

antivortex [6], the pinning strength also plays an important role on the negative part of ρ_{xy} . Experimentally, it was observed that the negative ρ_{xy} showed a power-law dependence on H in the low-field and low-current region [7]; while the negative part of the Hall angle was found independent of the applied fields in the limit of free flux flow (high field and large current) [8]. The fact that different ρ_{xy} – H relations were obtained in different (H, J) regimes raises the possibility that the field dependence of ρ_{xy} may follow a complicated phase diagram of flux dynamics similar to what has been observed in magnetic studies [9].

In principle, the pinning strength should be closely related to the H dependence of ρ_{xy} owing to its direct influence on the motion of flux bundles and individual vortices. Therefore, ion irradiation (creating pinning centers) should be a good route to modify the $\rho_{xy}(H)$ behavior and provides the useful information related to

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its sign reversal. The result of Hall effect measurements on Ag^+ -irradiated Tl-2223 films [10] showed that the peak value of the negative Hall resistivity ρ_{xy} was depressed by the irradiation, thus, Budhani et al. [10] suggested that the pinning force did not play a role in the occurrence of negative Hall resistivity. On the other hand, the experiment of H^+ and Si^+ irradiation on YBCO films presented an opposite result showing an enhancement of negative ρ_{xy} by irradiation [11]. The controversy of these two results motivates us to extend our studies of the irradiation effect on the negative Hall resistivity, hoping to elucidate the role of the pinning force on the mechanism of its sign reversal.

We have performed measurements of longitudinal and transversal resistivity (ρ_{xx} and ρ_{xy} , respectively) for some un-irradiated and irradiated YBCO films with the applied field (H) ranging from 0.5 to 4 T. The irradiation of Au ions with an energy of 20 MeV and with a dosage of 10^{11} ion/cm² was employed to generate defects for our YBCO films. We will demonstrate the behavior of $\rho_{xx}(T)$ and $\rho_{xy}(T)$ at various fields before and after the irradiation. The power law [$\rho_{xy} = \rho_{xx}^\alpha$] will be also examined in this study.

2. Experiments

The YBCO film with a thickness of 1760 Å was prepared by an off-axis RF magnetron sputtering system onto SrTiO_3 (001) substrates as described in Ref. [12]. The X-ray diffraction data showed a preferred orientation with the crystal c -axis perpendicular to the plane of SrTiO_3 . The film of YBCO was patterned to the standard geometry for the Hall effect measurement. The width of the current path was 500 μm , and the applied currents were 1 and 4 mA, which are equivalent to current densities of 1.14×10^3 and 4.56×10^3 A/cm², respectively.

After the completion of the first resistivity measurement, the film was irradiated with 20 MeV Au ions generated from a 3-MeV NEC 9SDH-2 tandem accelerator. The irradiation fluence we used to create defects was 10^{11} /cm². By using the TRIM damage simulation program, the projected range of 20 MeV Au ions was calculated to be 2.11 μm , suggesting that Au ions of 20 MeV penetrated our YBCO film. This simulation also estimated the electronic energy loss rate to be ~ 9 MeV/ μm which is less than the threshold energy

(~ 20 MeV/ μm for YBCO) of creating linear tracks. Therefore the defects generated by Au ions of 20 MeV are expected to be point or cluster defects.

3. Results and discussions

The longitudinal and transversal resistivities (ρ_{xx} and ρ_{xy} respectively) were measured with current densities of 1.14×10^3 and 4.56×10^3 A/cm² for comparison. The data of $\rho_{xx}(T)$ and $\rho_{xy}(T)$ measured with these two current densities did not show any difference within our resolution. Fig. 1 displays the temperature (T) dependence of ρ_{xx} and ρ_{xy} for the un-irradiated YBCO film at $80 < T < 100$ K. In the upper panel of Fig. 1, curves a, b and c represent the $\rho_{xx}(T)$ at various fields (H) with H being 0.5, 1 and 4 T, respectively. The observed broadening of the ρ_{xx} transition with increasing H has been discussed extensively [13]. We would however like to emphasize the existence of a close relationship between $\rho_{xx}(T)$ and $\rho_{xy}(T)$. From the com-

Fig. 1. Longitudinal resistivity (ρ_{xx}) vs. T (upper panel) and transversal resistivity (ρ_{xy}) for an YBCO film at various fields (lower panel).

Fig. 2. Longitudinal resistivity (ρ_{xx}) vs. T (upper panel) and the transversal resistivity (ρ_{xy}) for the irradiated YBCO film at various fields (lower panel).

parison of the upper and lower panel, it is noted that the T range of the superconducting transition in ρ_{xx} coincides with the range of the negative ρ_{xy} . In the lower panel of Fig. 1, it is observed that the negative peak value (ρ_{xy}^p) increases with increasing H . This behavior of H -dependent $\rho_{xy}(T)$ in the transition region is similar to that found in the previous reports [14–16].

Fig. 2 shows $\rho_{xx}(T)$ and $\rho_{xy}(T)$ at various fields for the irradiated sample. The central feature of Fig. 2 is different from what has been shown in Fig. 1 since the value of ρ_{xy}^p is larger at $H=0.5$ than that at $H=1$ T. To demonstrate clearly the irradiation effect on the negative ρ_{xy} at various fields, Fig. 3 displays the $\rho_{xx}(T)$ (upper panel) and $\rho_{xy}(T)$ (lower panel) at $H=0.5$ and 4 T, with the symbols ($\square$, $+$) representing the data for the un-irradiated sample and the dashed curves being the data for the irradiated samples. In the upper panel of Fig. 3, as expected the normal-state ρ_{xx} increases slightly while the transition temperature decreases at both fields after irradiation. The lower panel of Fig. 3 shows that ρ_{xy}^p increases significantly at

0.5 T, but slightly at 4 T after irradiation. This result indicates a field dependence of the irradiation effect on the negative ρ_{xy}^p and reflects the fact that the flux motion (thus ρ_{xy}) in the mixed state is controlled by the interaction of vortices and defects. It is worthy to mention that we have observed a positive ρ_{xy}^p at 2 T for one of our films before irradiation, and this positive ρ_{xy}^p becomes negative after the irradiation of Au ions as shown in Fig. 4. It is evidential for a relevance between defects and the occurrence of negative Hall resistivity.

In the work of Budhani et al. [10], the negative ρ_{xy} diminished by the irradiation of Ag ions of 276 MeV at 1 T. In the work of Huang et al. [11], the negative ρ_{xy} was enhanced by the irradiation of 3-MeV H^+ and 3-MeV Si ions at 3 and 2 T, respectively. From the point of view of the defect-type, Ag ions of 276 MeV create column defects, and H^+ and Si ions of 3 MeV mainly generate point defects due to their low energy. If pinning plays an important role in the negative ρ_{xy} ,

Fig. 3. Comparison of $\rho_{xy}(T)$ before and after irradiation at $H=0.5$ and 4 T for an YBCO film.

Fig. 4. Sign reversal of $\rho_{xy}(T)$ at $H=2$ T after irradiation for a particular YBCO film.

it becomes controversial that the column defects suppress the negative ρ_{xy} while point defects enhance the negative ρ_{xy} (note that a column defect is more effective than a point defect as a pinning center). Au ions of 20 MeV are expected to generate a collection of point or cluster defects because their electronic energy loss rate (~ 9 MeV/ μm) is less than the threshold energy for creating linear tracks (~ 20 MeV/ μm). Our observation of an enhancement in the negative ρ_{xy} at 0.5 T agrees with the result of Huang et al., and suggests that the variation of negative ρ_{xy} with increasing defects is dependent on the type of defects as well as the magnetic field.

To further understand the effect of irradiation on the negative ρ_{xy} , it is of importance to learn whether the irradiation increases the pinning force F_p . A quantitative analysis on the variation of F_p at the transition region is difficult, since large thermal fluctuations near T_c usually suppress the contribution of F_p to the flux motion. In principle, F_p is a function of H , J_c (the critical current density), and T . It is known that $F_p(H, T)$ is proportional to $J_c(H, T)$ and J_c can be extracted from the I - V or M - H measurements, but they can be measured only at temperatures lower than T_c -offset. As reported previously by some authors [17,18], the behavior of $F_p(H)$ is strongly temperature-dependent, thus, the derived $F_p(H)$ from $J_c(H)$ at low temperature would not necessarily represent the $F_p(H)$ in the tran-

sition region. An alternative route is to derive F_p from U_0 (the thermal activation energy or pinning potential). In a thermally activated model for resistivity loss at the mixed state where $\rho \approx \exp(-U_0/kT)$ [19], it is expected that the variation in U_0 will give a quantitative description of variations in F_p . We thus plot $\ln(\rho_{xx})$ vs. $1/T$ for our YBCO films in Fig. 5. The solid and dashed curves represent the data for the sample before and after irradiation, respectively. According to the data in Fig. 5, $\ln(\rho_{xx})$ have linear relations with $1/T$ at 0.5 and 1 T, but their slopes have no detectable changes after the irradiation. It seems that irradiation of Au ions with 20 MeV did not create effective pinning centers. However, the data in Fig. 3 clearly show the significant changes of $\rho_{xy}(T)$ at 0.5 T after irradiation. We therefore conclude that either Au ions of 20 MeV do not create effective pinning centers, or the enhancement of the pinning force is not reflected in U_0 due to the nature of collective pinning [20].

It has been observed by Luo et al. [21] that there exists a power-law behavior [$\rho_{xy}(T) \propto \rho_{xx}(T)^\alpha$] at various fields with $\alpha = 1.7 \pm 0.2$. The power-law dependence was attributed to the collective vortex response in the presence of disorder. We therefore have examined the relation of ρ_{xx} and ρ_{xy} for our YBCO films. In Figs. 6 and 7, we plot ρ_{xy} vs. ρ_{xx} on a log-log scale at various fields. Fig. 6 shows the data for the un-irradiated film

Fig. 5. $\ln(\rho_{xx})$ vs. $100/T$ at various fields for un-irradiated and irradiated YBCO films.

Fig. 6. $\text{Log}(-\rho_{xy})$ vs. $\text{Log}(\rho_{xx})$ at various fields for an un-irradiated YBCO film.

with $H = 0.5, 1$ and 4 T. The linear relation is not obvious for the entire negative ρ_{xy} region but extractable in a narrow region near ρ_{xy}^p , as guided by the solid lines in Fig. 6. The α value is found to be 0.9 ± 0.1 for $H = 0.5$ T and 1.6 ± 0.1 for $H = 4$ T. Fig. 7 displays the relations between $\rho_{xx}(T)$ and $\rho_{xy}(T)$ after irradiation, showing that the power law seems to exist for a wider region of negative ρ_{xy} . The least-squares fit gives α values ranging from 1.3 ± 0.2 (at 0.5 T) to 0.9 ± 0.1 (at 4 T) for the irradiated film. It is interesting to note that the α value increases with increasing field for the un-irradiated sample, but decreases with increasing field for an irradiated sample. It was proposed earlier by Dorsey et al. [22] that the scaling of ρ_{xy} vs. ρ_{xx} occurs near the vortex-glass transition, and the exponent α equaling 1.7 was associated with a chosen exponent of particle-hole asymmetry. Later, Vinokur et al. [23] suggested a general picture for this scaling behavior, with a proper consideration of the disorder effect in the force balance equation, in which α should be an exact value of 2 and the deviation of α from 2 was attributed to the temperature dependence of a parameter controlling the Hall angle. However, both Dorsey's and Vinokur's theories did not include the field dependence of α . By examining the irradiation-induced variations in ρ_{xy}^p and α , we could not find a clear correlation between ρ_{xy}^p and α , supporting the proposition that the origins of the negative ρ_{xy} and the scaling [$\rho_{xy} = \rho_{xx}^\alpha$] may be different [21,23].

The fact that the details of the H dependence of $\rho_{xy}(T)$ in the mixed state varies with samples reveals a difference in the pinning nature of different compounds. Based on some literature [3,10,15,16,24,25], the negative ρ_{xy} exists in most HTS material including YBCO [3,15,16], EBCO [15], BSCCO [15], TBCCO [17,24] and NCCO [25], and the behavior of the H dependence of negative ρ_{xy} can be categorized into two groups. For the YBCO-type, the negative ρ_{xy} first appeared at low field, and, then, increases in magnitude with increasing field. Also the region of negative ρ_{xy} shifts to lower temperature and becomes broader with increasing field. For the BSCCO or TBCCO-type sample, the negative ρ_{xy} appears at low field, then decreases in magnitude with increasing field without a shift of its temperature range, and finally becomes positive at high field (~ 4 T). Iye et al. [15] attributed this discrepancy in the H dependence of the negative ρ_{xy} to the difference in the flux dynamics and the nature of the pinning mechanism between two materials. We therefore ascribe the field dependence of the irradiation effect on the negative ρ_{xy} to the irradiation-induced change in the density or the distribution of defects, resulting in the change of their pinning nature. Further studies are in the way for understanding the nature of the defect-related variations of the negative ρ_{xy} for

Fig. 7. $\text{Log}(-\rho_{xy})$ vs. $\text{Log}(\rho_{xx})$ at various fields for an irradiated YBCO film.

HTS, which may lead us to the origin of the negative Hall resistivity.

4. Conclusion

We have measured ρ_{xx} and ρ_{xy} for YBCO films before and after irradiation of Au ions. It has been observed that the negative peak value of $\rho_{xy}(\rho_{xy}^p)$ increases significantly at $H=0.5$ T, and remains nearly the same at $H=4$ T, indicating that the variation of the negative ρ_{xy} by ion irradiation is field dependent. The power law [$\rho_{xy}=\rho_{xx}^\alpha$] has also been examined before and after irradiation, our results show a H dependence of α values ranging from 0.9 to 1.6 instead of being a constant value as observed by Luo et al. [21]. Overall, the irradiation with Au ions of 20 MeV affects the peak value of negative ρ_{xy} at 0.5 T, and the α value at 0.5 and 4 T for our YBCO film, suggesting defects play a role in the negative ρ_{xy} . However, it requires further studies to comprehend the role of defects in the origin of the negative Hall resistivity.

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