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SIGN REVERSAL OF HALL COEFFICIENTS NEAR T_c IN HIGH- T_c YBa₂Cu₃O_y FILMS

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Hall coefficients and resistivities of YBa₂Cu₃O_y films in superconducting mixed state have been measured at T near T_c . A sign reversal of Hall coefficients in superconducting mixed state is accounted for in terms of the induced electric field, $\mathbf{E}_{\text{ind}} = \mathbf{B} \times \mathbf{v}_L/c$. $\mathbf{E}_{\text{ind}}$ occurs as a result of the motion of the flux-vortex; $\mathbf{B}$ the magnetic induction; $\mathbf{v}_L$ the resultant velocity of the flux vortex; and c the speed of light. The normal carriers were driven to one side of the sample by the transverse component $\mathbf{E}_{\text{ind},y}$ (perpendicular to the transport current $\mathbf{j}_s$). In a steady state, an electric field $\mathbf{E}_{\text{acc},yx}$ would be developed by the accumulated charge carriers and the direction of the $\mathbf{E}_{\text{acc},yx}$ is opposite to that of the Hall electric field in the normal state. A sign reversal of Hall coefficient would occur if $\mathbf{E}_{\text{acc},yx}$ dominates in the transverse electric fields. This picture explains both p -type and n -type superconductors.

FLUX MOTION in the superconducting in the mixed state has been a subject of strong current interest [1–3]. Hall measurements in the superconducting mixed state single crystals [4, 5], thin films [6–8], have recently revealed an unexpected sign reversal of the Hall voltage in low magnetic field and at temperatures close to, but below, the superconducting transition temperature. The anomalous Hall coefficients have postulated to probably result from the following: two types of charge carriers [9], thermomagnetic effect [10] drag forces acting on vortices [7], the force acting on vortices due to quasiparticle scattering [11] and the back flow current which arises as a result of pinning [3]. A possible mechanism for the sign reversal of Hall coefficient in the superconducting mixed state based on the induced electric field $\mathbf{E}_{\text{ind}} = \mathbf{B} \times \mathbf{v}_L/c$, owing to the flux motion is presented in this study, where $\mathbf{v}_L$ is the resultant velocity of the vortices; $\mathbf{B}$ is the magnetic induction which is perpendicular to the sample surface; and c is the speed of light. Sign reversal of

Hall coefficient for YBa₂Cu₃O_y (YBCO) films, for example, was used to illustrate this model.

YBCO films were prepared by sputtering a stoichiometric YBCO target with an off axis configuration. The films were grown on SrTiO₃(100). The sputtering gas was a mixture of Ar and O₂. YBCO films were grown at 650–700°C. After growth, one atmosphere of O₂ was introduced to the chamber and the film was cooled down to room temperature at a rate of 5°C min^{−1} and the film was kept at 600°C for an hour. A detailed description of the growth of YBCO films was reported in [12]. The as grown YBCO films were black and shining. The X-ray diffraction peaks demonstrated a preferred orientation with the crystal c -axis perpendicular to the plane of the substrate. Several samples were investigated. Typical results for a YBCO film were presented as an example to illustrate this model in this study.

The resistivity and Hall coefficients are shown in Fig. 1 as a function of temperature for a YBCO film of 200 nm thick in magnetic fields. This sample shows

Fig. 1. (a) Resistivity and (b) Hall coefficient as a function of temperature for a YBCO film. The applied fields were 1, 2 and 4 T.

T_c onset at 90 K and $T_{c, \text{zero}}$ at 87.5 K. In the electrical resistivity and Hall measurements, the samples were patterned to a conventional five-leads Hall geometry by the photolithography technique. Resistivity in magnetic fields shows a broadening and Hall coefficient of the YBCO film shows a sign reversal, in similarity to other observations. Negative Hall coefficient occurs in the flux flow regime and flux creep regimes.

Understanding the mechanisms of negative Hall coefficient of high- T_c oxides in the superconducting mixed state is important. The motion of the vortices taken up is considered here when the Lorentz force is greater than the pinning force in the mixed state, so the vortices become detached from the pinning centers. The magnetic field is perpendicular to the plane of the page (along the positive z -direction). Realizing that the magnitude and the direction of the force acting on these cores are different when they are in motion from when they are pinned in materials is important. Because the viscous drag exerted by the

Fig. 2. Geometrical configuration used to illustrate the sign reversal of Hall coefficient for a YBCO film in (a) the normal state and (b) superconducting mixed state. The transport current j_s is along the positive x -direction. The induced electric field, $E_{ind} = B \times v_L/c$, is due to the motion of the flux-vortex, the magnetic induction B is perpendicular to the film. E_{ind} makes an angle θ with j_s . Positive signs indicate that holes accumulated on side B of the sample; these holes produce an electric field $E_{acc,yx}$ along the negative y -direction.

materials on the vortices would not move as fast as the transport current carrier (hole in YBCO), but only with some lower velocity. In addition to the Lorentz force and the viscous drag, a Magnus force acted on a force on the normal core. In equilibrium, the resultant velocity v_L of vortices therefore makes an angle θ with the direction of the transport current density j_s as shown in Fig. 2.

An electric field, E_{ind} , would be induced whenever the cores move across the sample with a velocity, v_L , in a magnetic field perpendicular to the surface of the film (along the z -direction), and the magnitude and the direction of E_{ind} is given by [13, 14]

$$E_{ind} = B \times v_L/c \tag{1}$$

as shown in Fig. 2. E_{ind} has a component $E_{ind,y}$ along the positive y -direction. This electric field would apply a force, $eE_{ind,y}$, to holes, so holes move along

Fig. 3. Geometrical configuration used to illustrate the sign reversal of Hall coefficient for a Nd_{0.5}Ce_{1.5}CuO₄ film in (a) the normal state and (b) superconducting mixed state. The transport current is along the positive x -direction. The induced electric field, $\mathbf{E}_{\text{ind}} = \mathbf{B} \times \mathbf{v}_L/c$, is due to the motion of the flux-vortex, the magnetic induction $\mathbf{B}$ is perpendicular to the film. Negative signs indicate that electrons accumulated on side B of the sample; these electrons produce an electric field $\mathbf{E}_{\text{acc},yx}$ along the positive y -direction.

the positive y -direction. Holes, which cannot move out of the y -direction, would then become accumulated on side B of a YBCO film as indicated by the cross symbol (+) in Fig. 2(b); those holes would generate an electric field $\mathbf{E}_{\text{acc},yx}$ along the negative y -direction. The direction is opposite to that of the Hall field in the normal state. In equilibrium, $e\mathbf{E}_{\text{ind},y} = e\mathbf{E}_{\text{acc},yx}$. The effect of $e\mathbf{E}_{\text{ind},y}$ is equivalent to that of $q\mathbf{v} \times \mathbf{B}$ in the normal state which causes the Hall electric field to occur. A sign reversal in the Hall electric field would occur because $\mathbf{E}_{\text{acc},yx}$ is along the negative y -direction. The dissipative electric field, $\mathbf{E}_{\text{ind},x}$, notably occur. Since there is a transport current $\mathbf{j}_s$ flowing along the positive x -direction, so the detected voltage along that direction is the resistive voltage corresponding to $\mathbf{E}_{\text{ind},x}$.

It should be pointed out that the only detected voltage is $\mathbf{E}_{\text{acc},yx}$ in the transverse Hall measurement

because there is no transport current along the y -direction in a steady state. This is opposite to that of $\mathbf{E}_{\text{ind},x}$, where there is a transport current $\mathbf{j}_s$ flowing along the positive x -direction. The effect of $\mathbf{E}_{\text{ind},y}$ is to apply a force $q\mathbf{E}_{\text{ind},y}$ to the holes in the superconducting mixed state and this force is balanced by $q\mathbf{E}_{\text{acc},yx}$, where q is the charge of holes. The force $q\mathbf{E}_{\text{ind},y}$ is equivalent to the Lorentz force $q\mathbf{v} \times \mathbf{B}$ which driving holes in the normal state to side A as shown in Fig. 1(a).

The model mentioned above applies also to the electronic superconductors, for example, Nd_{1.5}Ce_{0.5}CuO₄ oxide compounds. Figure 3(a) shows the geometrical configuration of Hall effect for an electronic superconductor in the normal state. The applied field $\mathbf{B}$ is along the z -direction (perpendicular to the plane of the page). The direction of the transport current $\mathbf{j}_s$ is along the positive x -direction. In the superconducting state a Lorentz force, $\mathbf{F}_L = \mathbf{j}_s \times \mathbf{B}/c$, acts a force on vortices, because of the viscous drag and the Magnus force, vortices will move along a direction shown in Fig. 3(b) (electrons in Nd_{1.5}Ce_{0.5}CuO₄ move in a direction opposite to that of YBCO films). There is an induced electric field $\mathbf{E}_{\text{ind}} = \mathbf{B} \times \mathbf{v}_L/c$ due to the flux motion. The component of $\mathbf{E}_{\text{ind}}$ along the negative y -direction; which will apply a force $-e\mathbf{E}_{\text{ind},y}$, on electrons (normal carriers in the mixed state in the two-fluid model) along the positive y -direction. In equilibrium, electrons will accumulate on side B , so an electric field, $\mathbf{E}_{\text{acc},yx}$, caused by these electrons would point along the positive y -direction; which is opposite to that of the Hall electric field in the normal state, so $\mathbf{E}_{\text{acc},yx}$, would cause a sign reversal of Hall coefficient for Nd_{1.5}Ce_{0.5}CuO₄ films in the superconducting mixed state. Since there is a transport current $\mathbf{j}_s$ flowing along the positive x -direction, so the detected voltage along the x -direction is the resistive voltage corresponding to $\mathbf{E}_{\text{ind},x}$. Indeed, a sign reversal of Hall coefficient for Nd_{1.5}Ce_{0.5}CuO₄ films has been reported recently by Hagen *et al.* [15].

Figure 4 shows θ as a function of temperature for a YBCO film at T near T_c in magnetic fields of 1, 2, and 4 T. In a magnetic field of 4 T, for instance, θ varies from 0.6° at $T = 95$ K to -0.95° at $T = 83$ K, where a local minimum in Hall coefficient occurs and reverts to about 0° at $T = 80$ K. Vortices move essentially along a direction perpendicular to the direction of the transport current $\mathbf{j}_s$.

In an ordinary picture for the occurrence of a sign reversal of Hall coefficient in a YBCO film, it is necessary to have $\mathbf{v}_L$ move upstream against the direction of the supercurrent as pointed out, e.g. by Hagen *et al.* [16]. Wang and Ting [3] considered a back flow current caused by a strong pinning so that

Fig. 4. θ as a function of temperature for a YBCO film in magnetic fields of 1, 2, and 4 T.

v_L moves upstream against the direction to explain the sign reversal of the Hall-voltage in a YBCO film. Recently, Budhani *et al.* [17] performed Hall measurement in Ag⁺ (276 MeV) irradiated Tl₂Ba₂Ca₂Cu₃O_y films. They found that a strong pinning reduced the negative Hall coefficients, not enhanced the negative Hall coefficient in contradiction to that predicted by Wang and Ting [3]; that a stronger pinning force should enhance the negative Hall coefficient. In the present model for the negative Hall coefficient to occur in YBCO film, it is necessary to have v_L move upstream with v_{Lx} parallel to the direction of j_s [see Fig. 2(b)] whereas in Nd_{1.5}Ce_{0.5}CuO₄ film it is necessary to have v_L move upstream against the direction of the supercurrent [see Fig. 3(b)].

In summary, a possible mechanism in the sign reversal of Hall coefficient in superconducting mixed state of high- T_c oxides was presented in the present work. Moving vortices, which generate an electric field, $E_{ind} = B \times v_L/c$, is essential for the occurrence of the sign reversal of Hall coefficients of high- T_c oxides in superconducting mixed state. Since there is a current flowing along the x -direction, so the detected voltage along the x -direction is the resistive voltage corresponding to $E_{ind,x}$. On the other hand, the electric field $E_{ind,y}$ would apply a force, $eE_{ind,y}$, to holes (in YBCO films), so holes move along the positive y -direction. Holes, which cannot move out of the y -direction, would then become accumulated on side B of a YBCO film as indicated by the cross

symbol (+) in Fig. 2; those holes would generate an electric field $E_{acc,yx}$ along the negative y -direction [see Fig. 2(b)]. The detected Hall-field is $E_{acc,yx}$ which is along the negative y -direction opposite to that of the YBCO film in the normal state. It is noted that in the superconducting mixed state, normal carriers were driven by $qE_{ind,y}$ while in the normal state above T_c , normal carriers were driven by $qv \times B$; so there is an analogy between $qE_{ind,y}$ and $qv \times B$. The present explanation of the sign reversal of Hall-voltage in high- T_c oxide compounds is within the framework of the two-fluid model. This model applies both to the p -type and n -type high- T_c superconductors.

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