Double Sign Reversal of the Hall Voltage in $Bi_2Sr_2CaCu_2O_{8+\delta}$ Thin Film

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ABSTRACT

Hall measurement was done on a $Bi_2Sr_2CaCu_2O_{8+\delta}$ liquid phase epitaxy (LPE) thin film. The Hall voltage, V_H, was obtained using the method of magnetic field direction reversal. Below the critical temperature, it was found that V_H changes sign from positive to negative until it reaches a negative dip, after which it increases again to become zero and undergo a second sign change. With decreasing applied magnetic field, this dip was observed to become more prominent and greater in magnitude and to shift to lower temperatures. The sign change is explained by considering that the Hall field consists of two anti-parallel components: one is attributed to the deflection of the charge carriers by the Lorentz force, and the other is attributed to the dynamic motion of vortices in the mixed state.

Key words: Hall effect, Hall voltage, sign reversal, vortex motion

INTRODUCTION

The anomalous Hall effect for $Bi_2Sr_2CaCu_2O_{8+\delta}$ thin films, and generally for high-temperature superconductors continues to be an interesting scientific issue mainly because it goes against known and conventional theories. It contradicts models such as the Bardeen-Stephen model that predicts the Hall coefficient and voltage to have the same sign, both in the normal and superconducting states (Tinkham, 1996).

Several attempts have been made to explain the sign reversal. It has been proposed that vortex pinning or the dimensionality of the vortex pinning disorder is responsible for the sign change. That is, pinning affects the counterflow in the vortex core that may result in a more pronounced sign anomaly as the pinning strength increases (Kopnin et al., 1999). This notion was later refuted by the argument that the Hall conductivity is independent of pinning (Lang et al., 1999). Others attempted to show that the anomaly can be understood based on the vortex vacancy motion in a pinned vortex lattice and is a property of the vortex many-body correlation rather than that of an individual vortex (Ao, 1998).

One tentative explanation, which is presented in this paper, is to consider that the Hall field consists of two components that are anti-parallel to each other. One component has the same sign and magnitude in the normal and superconducting states, and is associated with the Lorentz force. The other component, associated with the movement of the vortices, causes the sign reversal.

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At temperatures above T_c, the main driving force behind the Hall effect for high-temperature superconductors is the Lorentz force. When an external magnetic field is applied perpendicular to the flow of current, the Lorentz force deflects the charge carriers. These charge carriers drift away from the direction of the current toward the side of the superconductor resulting to an induced electric field transverse to the direction of both the current and the applied magnetic field as shown in Fig. 1. This, in turn, results to a potential drop across the two sides of the sample called the Hall voltage.

However, the case is different when the superconductor undergoes a transition from the normal to the superconducting state. Below T_c and above the lower critical field, $Bi_2Sr_2CaCu_2O_{8+\delta}$ and other Type II superconductors allow partial penetration of magnetic flux through vortices and is said to be in the mixed state. As the vortices penetrate a sample, they interact with the transport current $\vec{J}$ causing these vortices to move at a velocity $\vec{v}_\phi$. This vortex velocity, however, is limited by the frictional drag force, $\beta\vec{v}_\phi$, while the Magnus force, $\alpha n_s e(v\mathrm{x}\Phi_0)$, shifts the direction of this motion through an angle Θ_ϕ away from the direction perpendicular to $\vec{J}$, as shown in Fig. 2.

By Faraday's law, the motion of the vortices transverse to the current density induces a time-averaged macroscopic electric field E (Fig. 2), which is given by Eq. (1).

$$E = -\vec{v}_\phi \times \vec{B}_{in} \qquad (1)$$

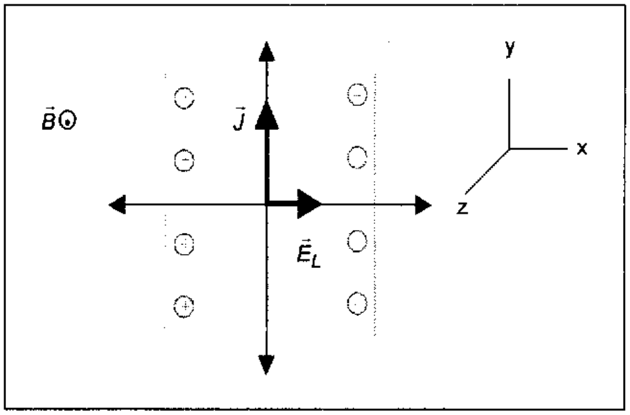

Fig. 1. Lorentz force. Deflection of the charge carriers by the Lorentz force, which produces an electric field perpendicular to the direction of current and magnetic field.

The component of this electric field along the current-flow direction produces a voltage drop along this direction. The other component of the induced electric field, $E_x = E\sin\Theta_\phi$, produces a Hall field as illustrated in the Fig. 3. Combining this with the electric field due to the Lorentz force gives the total induced transverse electric field, or the Hall field.

As shown in Fig. 4, the Hall field could be considered as consisting of two anti-parallel components. The

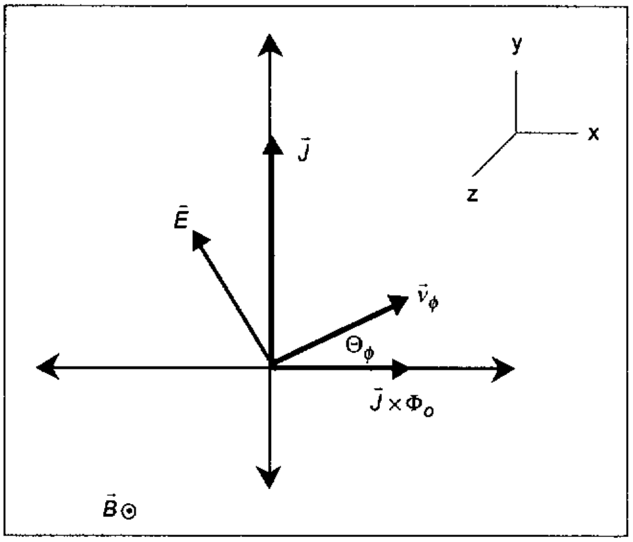

Fig. 2. Electric field $\vec{E}$ induced by the motion of a vortex moving at a velocity $\vec{v}_\phi$ through an applied magnetic field B_{app} directed upward from the page.

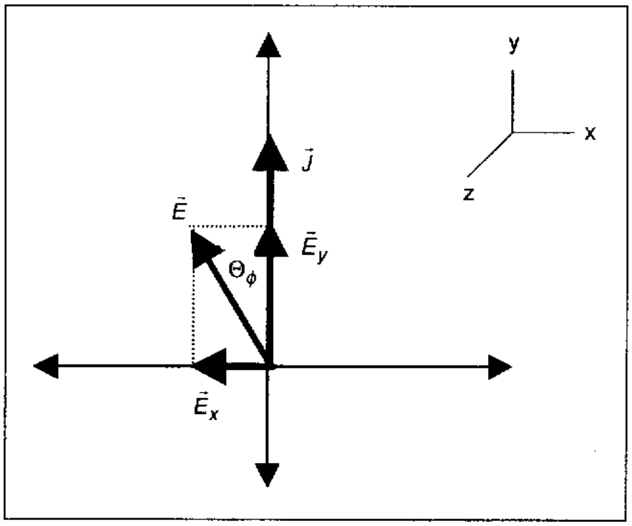

Fig. 3. Resolution of the induced electric field into transverse (E_x) and longitudinal (E_y) components.

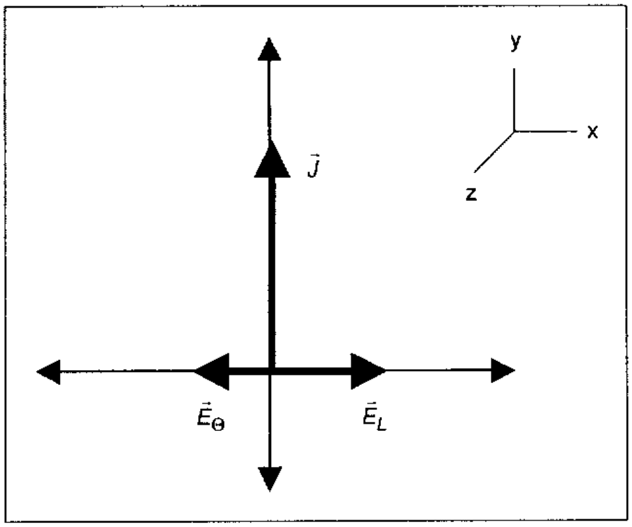

Fig. 4. The two anti-parallel components of the Hall field: $\vec{E}_\Theta$ (the field associated with vortices) and $\vec{E}_L$ (the field associated with the Lorentz force).

contribution due to the Lorentz force, $\vec{E}_L$, is constant because the current density and the applied magnetic field are kept constant. However, the second component, $\vec{E}_\Theta$, is dynamic and is dependent on temperature and the applied field. To investigate how this component changes with temperature, one should consider the behavior of the vortex motion in this regime. One model that describes the movement of these vortices in this regime is the Anderson-Kim Flux Creep Theory. This model assumes that flux creep occurs by bundles of flux lines jumping between adjacent pinning points and that the movement of these flux lines is an activation process directed by thermal energy.

In this paper, the Hall voltage for a $Bi_2Sr_2CaCu_2O_{8+\delta}$ thin film was measured and was observed to change sign twice at temperatures below T_c. The behavior of the Hall voltage is explained by considering its two anti-parallel components.

METHODOLOGY

The sample used is a *c*-axis oriented $Bi_2Sr_2CaCu_2O_{8+\delta}$ thin film grown by liquid phase epitaxy. The film was cut into a rectangle having a dimension of 4 mm x 7 mm. For the longitudinal and Hall measurements, the standard four-point probe method was utilized (Fig. 5). Indium-bonded gold wires were used as contacts and leads. A current of 10 mA was passed through contacts 1 and 2, while the transverse voltage was measured between contacts 3 and 4.

The sample was placed inside a cold head, which is connected to a closed-cycle helium refrigerator. It was cooled down to 15 K, and then allowed to warm up to room temperature while voltage measurements were conducted.

For the Hall measurement, an external magnetic field was applied parallel to the *c*-axis of the sample. Different magnetic field strengths were used, ranging from 0.01 T to 0.5 T.

To compensate for the misalignment of the transverse contacts 3 and 4, which adds a significant longitudinal component to the Hall voltage, the magnetic field reversal method was used (Raven & Wan, 1999). Two sets of measurements were conducted: (1) using positive magnetic fields; and (2) using negative magnetic fields. The Hall voltage is obtained using the equation:

$$V_H = \left[\frac{V_{(B+)} - V_{(B-)}}{2}\right] \qquad (2)$$

where $V_{(B+)}$ is the transverse voltage taken with positive magnetic fields (magnetic field applied towards the $+z$ axis, as in Fig. 5) and $V_{(B-)}$ is the transverse voltage measured using negative magnetic fields (along the $-z$ axis). This expression eliminates the longitudinal offset due to the misalignment of contacts 3 and 4.

RESULTS AND DISCUSSION

Fig. 6 shows the temperature dependence of the resistance measurement taken at zero magnetic field. From the profile, the critical temperature of the sample was determined to be 75 K with a transition width of 25 K.

Fig. 7 shows the transverse voltage measurement across contacts 3 and 4 for positive and negative magnetic fields. The fields used were 0.01 T, 0.1 T, and 0.5 Tesla. As the magnetic field was increased, the transition region broadens. This is attributed to the increase in the number of vortices (Tinkham, 1996).

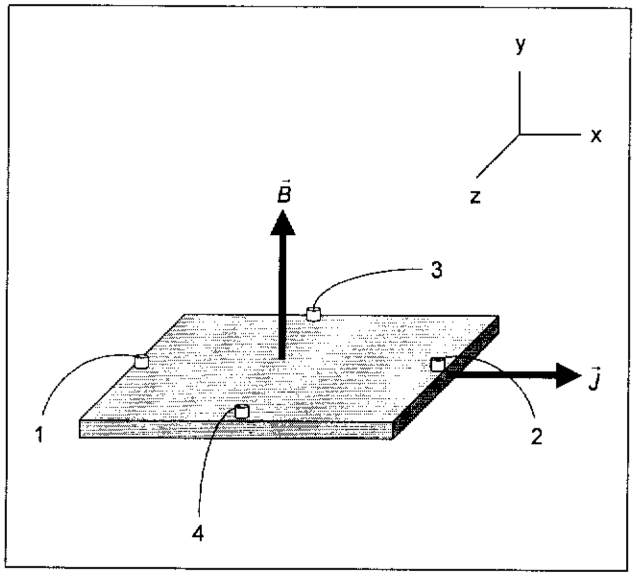

Fig. 5. Contact configuration of the sample. The magnetic field is applied perpendicular to the direction of current.

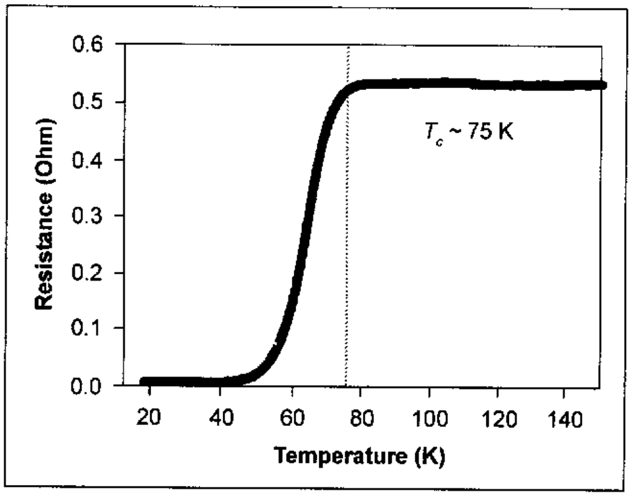

Fig. 6. Longitudinal resistance at $\vec{B}=0$.

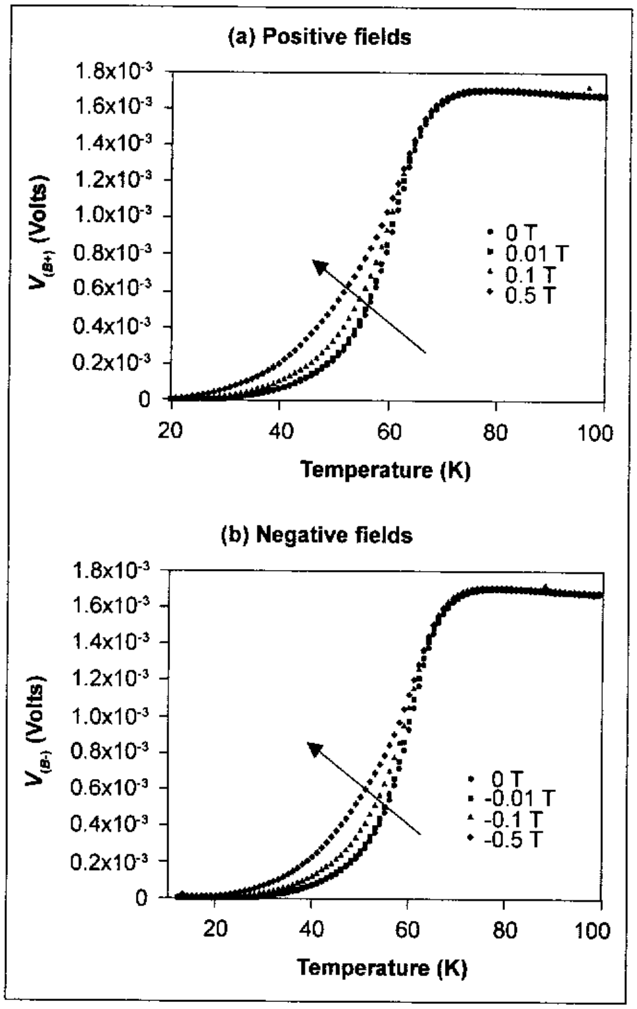

Fig. 7. Transverse voltage at (a) positive magnetic fields and (b) negative magnetic fields.

Superimposed plots of $V_{(B+)}$ and $V_{(B-)}$ shows a cross-over of the transverse voltages near the transition region, and at lower temperatures (Fig. 8). The temperatures at which the cross-overs occur are different for each magnetic field. This cross-over marks the sign change in the Hall voltage (Raven & Wan, 1999). To verify this, the Hall voltage is extracted using Eq. (2) and is plotted in Fig. 9.

Fig. 9 shows that at the cross-over temperatures, the Hall voltage for each magnetic field strength, indeed, changes sign. It becomes negative until a minimum is reached, after which it increases again to become zero and undergo a second sign change at a lower temperature. Also, in the presence of decreasing applied magnetic field, the position of the dip shifts to lower temperature. The sign change is also observed to become more prominent at lower magnetic fields. That is, at low magnetic fields, the magnitude of the negative dip is greater. Similar observations have been reported on other Hall measurements on high temperature superconductors. Lang, in their work on $Bi_2Sr_2CaCu_2O_3$, also reports a double sign reversal that is only observed in moderate magnetic fields of about $B < 6$ T and becomes prominent in smaller magnetic fields (Lang et al., 2001).

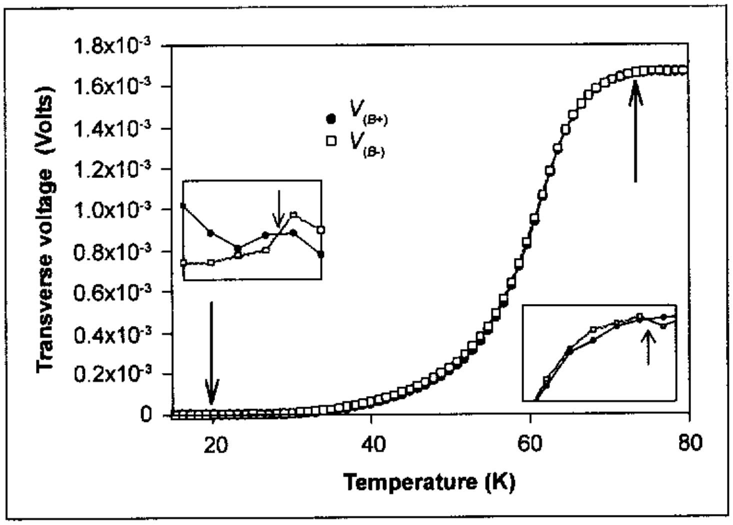

Fig. 8. Cross-over of the $V_{(+0.01\,T)}$ and $V_{(-0.01T)}$ indicating start of sign change. Inset: magnified view of the cross-overs.

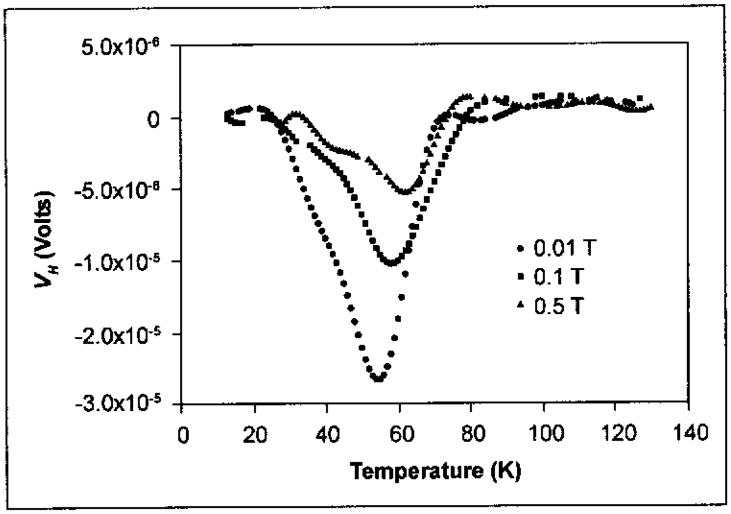

Fig. 9. Sign reversal of the Hall voltage below the critical temperature.

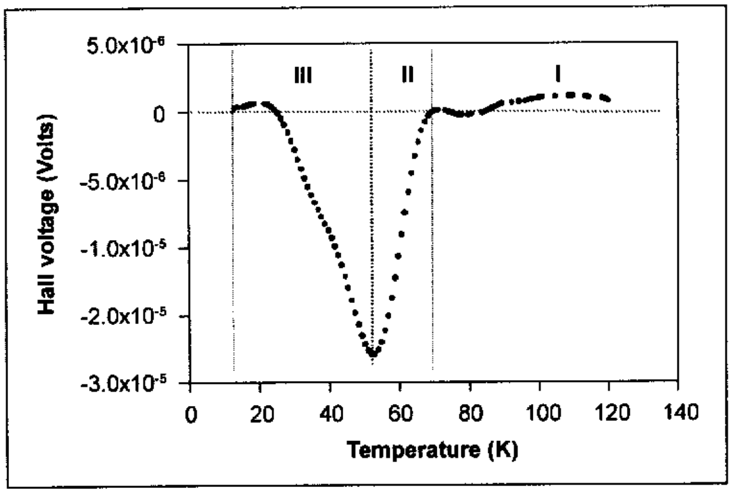

Fig. 10. Hall voltage sign reversal for Bi-2212 thin film. Region I: the Lorentz force is the only component of the Hall effect; Region II: vortices are thermally activated, causing an increase in the induced electric field due to vortices; Region III: vortices are pinned down and frozen, resulting to a decrease in the contribution to the Hall field due to vortices.

As has been mentioned, key to the understanding of the Hall effect, and consequently, the sign reversal of the Hall voltage, is vortex dynamics. The Anderson-Kim Flux Creep Model predicts that as the temperture is decreased below T_c, vortices penetrating the superconductor experiences thermal activation. When this happens, the vortices are depinned from their pinning centers and start to move. From Eq. (1), this thermally-activated motion induces a transverse Hall electric field, $\vec{E}_\Theta$, due to the vortices, which increases as the vortices become more mobile. However, as the temperature is lowered, the thermal vibration between flux lines decreases and the behavior of the vortices favors a transition from the vortex liquid state to the vortex solid state—the vortices penetrating the sample starts to be pinned down, and is characterized to have no considerable motion. When this happens, $\vec{E}_\Theta$ decreases as well.

Fig. 10 shows the Hall voltage measurement for the Bi-2212 sample, taken at 0.01 T. In Region I, the sample is still in the normal state and has a positive Hall voltage. The Lorentz force is the only component of the Hall effect in this region. Below T_c, vortices start to penetrate the sample and undergo thermal activation. They become more mobile, resulting to an increase in the electric field $\vec{E}_\Theta$. The sign reversal of the Hall voltage occurs when $\vec{E}_\Theta$ becomes greater in magnitude than the field due to the Lorentz force. When this happens, a negative net Hall field and, consequently, a negative Hall voltage are obtained (Region II). As the temperature is decreased further, thermal activation becomes less dominant. The vortices are pinned down and frozen resulting to the decrease in the contribution to the Hall field due to the vortices (Region III).

SUMMARY

The Hall voltage for a $Bi_2Sr_2CaCu_2O_{8+\delta}$ thin film was measured using the magnetic field reversal method. The study showed that below the critical temperature, the Hall voltage changes sign from positive to negative. After reaching a negative minimum, it increases once again and undergoes a second sign reversal at a lower temperature. It was observed that the magnitude of the negative dip increases as the externally applied magnetic field decreases.

The sign change of the Hall voltage was explained by considering that the Hall field is composed of two anti-parallel components: one component is due to the deflection of the charge carriers by the Lorentz force, while the other is attributed to the dynamic motion of vortices in the mixed state.

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