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Mixed-state Hall effect in Hg- and Tl-based superconducting thin films

수은 및 탈륨계 초전도박막에서 혼합상태의 홀효과

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We have investigated the mixed-state Hall effect in $HgBa_2CaCu_2O_6$, $HgBa_2Ca_2Cu_3O_8$, and $Tl_2Ba_2CaCu_2O_8$ thin films as functions of the magnetic field up to 18 T. At high fields and low temperatures, the scaling exponent in $\rho_{xy} = A\rho_{xx}^{\beta}$ shows a universal behavior, $\beta = 1 \pm 0.1$, regardless of the field, the number of CuO_2 layers, the types of defects, and even the types of compounds. At low fields and high temperatures, $\beta = 1 \pm 0.1$ also appears as a universal number although the observed field range is rather limited. These observations show the universal scaling of Hall resistivity in the regions of the clean and the moderately clean limit, consistent with a theory based on the midgap states in the vortex core.

1. Introduction

When a type II superconductor is cooled down from a normal state into a superconducting state, the Hall effect shows very unusual features, which have been a long-standing problem and have remained as unresolved issues for more than three decades. The sign reversal of the Hall effect below the superconducting transition temperatures is one of the most interesting phenomena in the flux dynamics for high-T_c superconductors (HTS) and has attracted both experimental and theoretical interest. Furthermore, a scaling behavior between ρ_{xy} and ρ_{xx} has been found in most HTS [1]-[6]. The puzzling scaling relation, $\rho_{xy} = A\rho_{xx}^{\beta}$, with $\beta \sim 2$ has been observed for $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) crystals [2] and $Tl_2Ba_2Ca_2Cu_3O_{10}$ (Tl-2223) films [3]. Other similar studies have found $\beta = 1.5 - 2.0$ for $YBa_2Cu_3O_7$ (YBCO) films [1], YBCO crystals [4], and $HgBa_2CaCu_2O$ (Hg-1212) films [5]. Even more interestingly, $\beta \sim 1$ was observed in the Hg-1212 thin films [6] after heavy-ion irradiations.

To interpret this scaling behavior, a number of theories have been proposed. The first theoretical attempt was presented by Dorsey and Fisher [7]. They showed that near the vortex-grass transition, ρ_{xy} and ρ_{xx} could be scaled with an exponent $\beta = 1.7$, and they explained the experimental results of Luo *et al.* for YBCO films [1]. A phenomenological model was put forward by Vinokur *et al.* [8]. They claimed that in the thermally assisted flux-flow (TAFF) region, β should be 2 and independent of the pinning strength. Their result was consistent with the observed exponent in Bi-2212 crystals and Tl-2223 films only for high fields. Another phenomenological model was proposed by Wang *et al.* [9]. They showed that β could change from 2 to 1.5 as the pinning strength increased, which agreed with the results reported for YBCO crystals [4] and Hg-1212 films [5]. However, all these theories fail to explain the wide range of β from 1 to 2 observed in ion-irradiated Hg-1212 films [6].

Recently, a more detailed theory based on localized states in vortex cores was developed by Kopnin and Lopatin (KL) [10] for the clean limit (CL) and the moderately clean limit (MCL). Due to the short coherence lengths, HTS change from the MCL to the CL as the temperature decreases from T_c. KL showed that $\sigma_{xy} = \rho_{xy}/\rho_{xx}^2$ was universal in the CL whereas the tangent of the Hall angle was universal in the MCL. This implies that β can change from 1 to 2 with decreasing temperature, which is consistent with previous work on ion-irradiated Hg-1212 [6]. This theory also well describes the recent observation of a triple Hall sign reversal in Hg-1212 thin films containing a high density of columnar defects [11]. Localized core states have been observed in HTS by using various experimental setups, such as far-infrared spectroscopy [12] and scanning tunneling spectroscopy [13], and they are in good agreement with the theoretical predictions [14]. Furthermore, in the MCL case, Kopnin and Volovik [15] showed that σ_{xy} for d-wave superconductors was very similar to the result [10] for s-wave superconductors. On the other hand, Frantz and Tesanovic [16] claimed that a bound state does not exist in the vortex core of a d-wave superconductor.

In this paper, we report the first demonstration of the universal scaling behavior of the Hall resistivity in the CL and the MCL regions for Tl- and Hg-Based Superconductors, and the results can be well described by the recent KL theory. In the present study, by using a low-noise preamplifier prior to a nanovoltmeter, we were able to expand the sensitivity of the Hall voltage up to one order of magnitude compared to the sensitivities in previous works. This high sensitivity was crucial to finding the accurate scaling behavior when the Hall signal was very small, and we were able to confirm the universality of the Hall scaling behavior for an extended field range up to 18 T.

2. Experimental

The transport properties and fabrication process of Hg-based superconducting thin films are described in detail elsewhere [17], [18]. The Tl-2212 thin films are commercially available [19]. The typical dimensions of the thin films were 5 mm × 10 mm × 0.5 – 1 μm. The mid-resistance temperature T_c in zero field for the Hg-1223, the Hg-1212, and the Tl-2212 films were 132, 127, 106 K, respectively. The X-ray diffraction patterns indicated highly oriented thin films with the c axes normal to the plane of the substrate and phase purities of more than 95 %. The transition width, judged from 10 – 90 % of the normal-state resistivity, was found to be less than 2 K. The heavy-ion irradiation of the Tl-2212 films was performed along their c axes by using 1.4–GeV U ions. The irradiation dose was 6×10^{10} ions/cm^2, which corresponded to a matching field, B_ϕ, of ~ 1.2 T. The Hg-1212 films were irradiated at a dose of 5×10^{10} ions/cm^2 ($B_\phi \sim 1$ T) along the c axes by using 5–GeV Xe ions [6]. The values of ρ_{xy} and ρ_{xx} were simultaneously measured using a two-channel nanovoltmeter (HP34420A) and the standard five-probe dc method. A low-noise preamplifier (N11, EM Electronics Inc.) was installed prior to the nanovoltmeter in order to increase the sensitivity of the Hall voltage at low fields. The applied dc current density was 100 – 250 A/cm^2. Both ρ_{xx} and ρ_{xy} were Ohmic at the current levels used in these measurements. The magnetic field was applied parallel to the *c* axes of the thin films. The value of ρ_{xy} was extracted from the antisymmetric part of the Hall voltages measured under opposite fields.

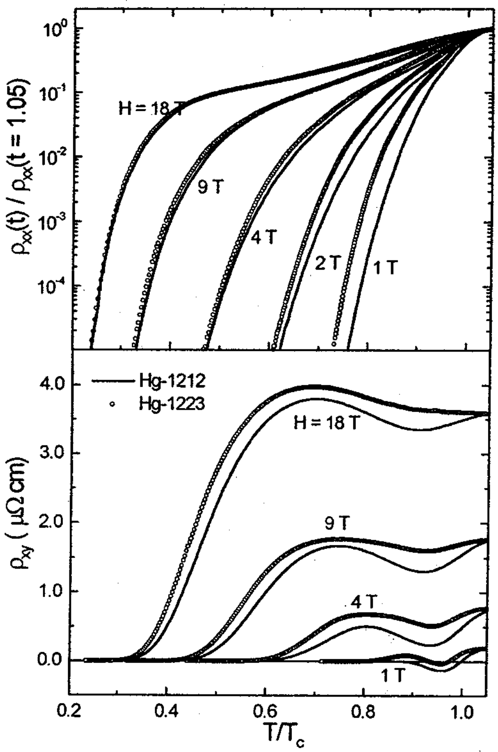

Fig. 1. Reduced-temperature dependences of ρ_{xx} (top) and ρ_{xy} (bottom) curves for Hg-1212 (solid lines) and for Hg-1223 (open circles) thin films.

3. Results

Figure 1 shows the temperature dependences of ρ_{xx} and ρ_{xy} for Hg-1212 and Hg-1223 thin films for various magnetic fields up to 18 T. In order to compare ρ_{xx} and ρ_{xy} for different samples, we use a reduced-temperature scale, T/T$_c$, rather than a real-temperature scale. At low fields, the difference in ρ_{xx} between Hg-1212 and Hg-1223 is clearly visible and decreases with increasing field up to 18 T, showing that the addition of one CuO_2 layer increases T$_c$ but weakens the pinning strength at low fields. Interestingly, the behavior of ρ_{xy} is different from that of ρ_{xx}. A significant difference in ρ_{xy} can be observed even at 18 T, suggesting that the flux-flow ρ_{xy} is more sensitive than the flux-flow ρ_{xx} to the number of CuO_2 layers. A comparison of the physical properties for those two samples may provide an interesting explanation for the role of the CuO_2 layers [20] in the homologous series of $HgBa_2Ca_{n-1}Cu_nO_{2n+2}$ superconductors with n = 1– 6. The ρ_{xx} and ρ_{xy} data for heavy-ion irradiated Hg-1212 are shown in Ref. 6.

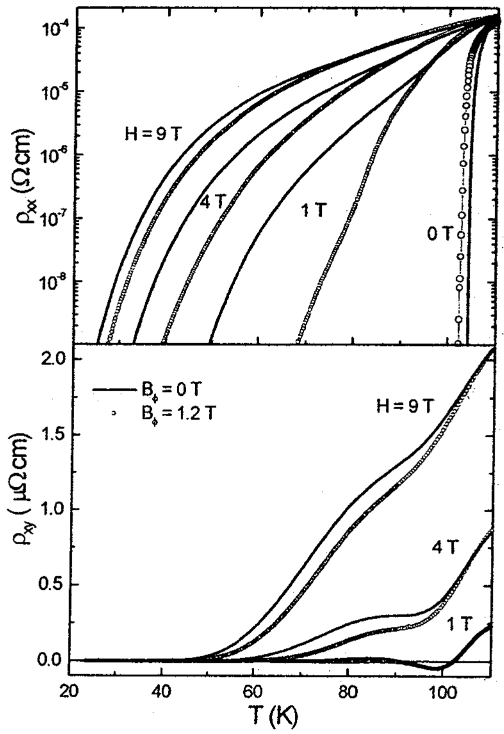

Fig. 2. Temperature dependences of ρ_{xx} (top) and ρ_{xy} (bottom) curves for Tl-2212 thin films before (solid lines) and after (open circles) ion irradiations.

In Fig. 2, we show the temperature dependences of ρ_{xx} and ρ_{xy} for Tl-2212 thin films before and after irradiations. Although T_c at zero field decreases by ~ 2 K after irradiation, the large enhancement of T_c in magnetic fields due to the strong pinning by columnar defects is clearly observed. This agrees with previous observations [3] for irradiated samples. The scaling behaviors between ρ_{xy} and ρ_{xx} for Hg-1212 and Hg-1223 films for various magnetic fields up to 18 T are plotted in Fig. 3. The corresponding data for Tl-2212 films before and after irradiations are shown in Fig. 4. Since ρ_{xy} below H = 2 T is negative in a certain temperature region, we plot the absolute value $|\rho_{xy}|$. The β in $|\rho_{xy}| = A\rho_{xx}^{\beta}$ is extracted from the slope of the solid lines, as shown in Figs. 3 and 4. Hall scaling is observed over roughly two decades of ρ_{xy}, and even four decades in high fields. This scaling relation is valid in the TAFF region. Note that the TAFF region expands to lower temperatures at high fields due to a huge resistive broadening in the magnetic fields for these materials. Thus, we can investigate the Hall behavior in the clean limit by applying high magnetic fields [21]. On the other hand, the low-field data correspond to the moderately clean limit since the TAFF region in this case is limited to near T_c.

The field dependence of the Hall scaling is clearly demonstrated by the above data, and the results, including previously observed data for irradiated Hg-1212 films, are summarized in Fig. 5. As the field increases, β changes from 1.4 to 1.9 for Hg-1212, from 1.3 to 1.9 for Hg-1223, from 1.0 to 1.9 for the pristine Tl-2212, from 1.0 to 1.9 for the irradiated Tl-2212, and from 1.0 to 1.9 for the irradiated Hg-1212 [6]. Note that at higher fields, H $\geq$ 8 T, the scaling exponent $\beta = 1.9 \pm 0.1$ shows a universal behavior, regardless of the field, the number of CuO_2 layers, the types of defects, and even the types of compounds. More strikingly, at low fields, $\beta = 1 \pm 0.1$ also appears as a universal number although the observed field range is rather limited. The scaling exponent is independent of field below H = 0. 3 T for pristine Tl-2212 and below H = 1.2 T for irradiated Tl-1212 and Hg-1212 films. This universal behavior of the scaling is our principal finding, and this observation has serious implications for the physics of the Hall behavior, as discussed below.

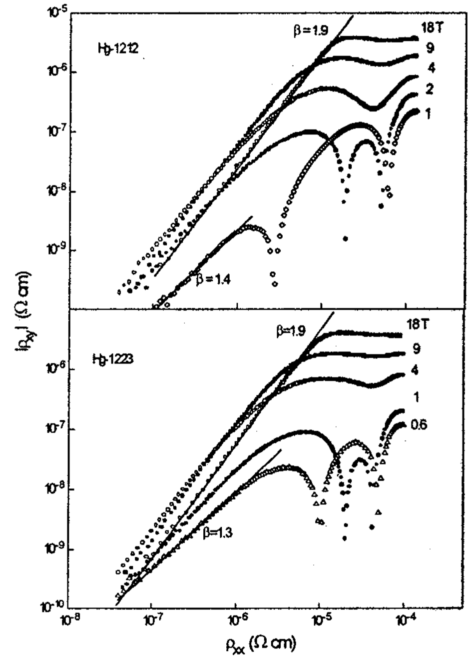

Fig. 3. Scaling behaviors between ρ_{xy} and ρ_{xx} for Hg-1212 (top) and Hg-1223 (bottom) thin films.

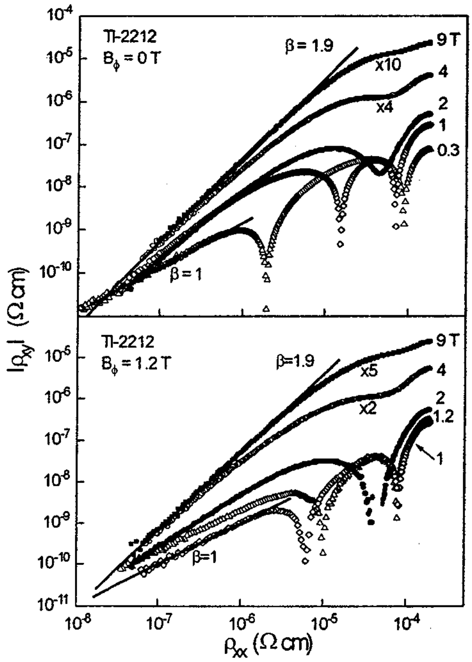

Fig. 4. Scaling behaviors between ρ_{xy} and ρ_{xx} for Tl-2212 thin films before (solid lines) and after (open circles) ion irradiations.

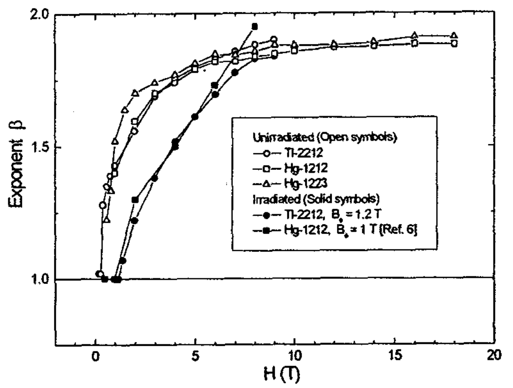

Fig. 5. Field dependences of the scaling exponent β for various Hg- and Tl-based HTS before (open symbols) and before (solid symbols) ion irradiations. The fact that the universal power law has β = 1.9 above H = 8 T and β = 1.0 at low fields, which are independent of magnetic fields, is clearly visible.

4. Discussion

With short coherence lengths and large energy gaps in HTS, the discrete nature of the energy levels, ω_o, in the vortex cores has been observed experimentally [12], [13] and has been interpreted theoretically [14]. Considering these localized states and an additional force induced by the kinetic effects of charge imbalance relaxation, KL [10] calculated the Hall and the longitudinal conductivities in the CL and the MCL regions. According to this theory, the mixed-state Hall conductivity can be described by three terms: $\sigma_H = \sigma_H^{(L)} + \sigma_H^{(D)} + \sigma_H^{(A)}$, where $\sigma_H^{(L)}$, $\sigma_H^{(D)}$, and $\sigma_H^{(A)}$ are the contributions from localized excitations, delocalized excitations, and an additional force, respectively. The additional force is determined by the energy derivative of the density of states at the Fermi surface. Since $\sigma_H^{(A)}$ dominates over $\sigma_H^{(L)}$ and $\sigma_H^{(D)}$ near T_c, the Hall anomaly can take place, as observed in most HTS. $\sigma_H^{(D)}$ originates from the density of quasiparticles outside the vortex core; thus, $\sigma_H^{(D)}$ is comparable to the normal-state Hall conductivity very near T_c, but is very small at low temperatures compared to $\sigma_H^{(L)}$. Due to this, we can neglect $\sigma_H^{(A)}$ and $\sigma_H^{(D)}$ in the low-temperature region. Note that the Hall scaling behavior is observed in the TAFF regions, which correspond to temperature regions below the positive peaks in the ρ_{xy} – T curves. In the TAFF regions, therefore, σ_H and the longitudinal conductivity σ_L can be expressed by [10]

$$\sigma_H \sim \frac{Ne}{B}\frac{(\omega_0\tau)^2}{1+(\omega_0\tau)^2}, \qquad (1)$$

$$\sigma_L \sim \frac{Ne}{B}\frac{\omega_0\tau}{1+(\omega_0\tau)^2}, \qquad (2)$$

where N is the density of charge carriers and τ is the relaxation time. It has been found [10, 21] that the tangent of the Hall angle, tanΘ = $\sigma_H/\sigma_L \sim \omega_o\tau$, is very small (<< 1) in the dirty region near T_c while it is very large (>> 1) in the superclean region T << T_c. According to Eqs. (1) and (2), there are two distinct scaling regions. For the low-temperature (CL) region with $(\omega_o\tau)^2 >> 1$, Eq. 1 becomes $\rho_{xy} \sim (Ne/B)\rho_{xx}^2$, resulting in a universal scaling law of β = 2, which is also predicted by the phenomenological models proposed by Vinokur *et al.* [8] and Wang *et al.* [9]. However, at relatively high temperatures (MCL) with $(\omega_o\tau)^2$ << 1, we obtain $\rho_{xy} \sim (\omega_o\tau)\rho_{xx}$; thus, a universal scaling law with β = 1 ± 0.1 should be observed since ρ_{xx} is an exponential function of temperature while $\omega_o\tau$ is a slowly varying function of temperature [21]. These features are explicitly consistent with our present results shown in Fig. 5. In other words, a universal values of β = 2 and β = 1 are found for the CL and the MCL, respectively. In the crossover regions from the MCL to the CL, 1 < β < 2 is found. These observations were possible because of the large resistive broadening in the magnetic fields for Hg- and Tl-based compounds and were partially due to the enhanced sensitivity of the measurement. For the irradiated samples, the universal regions shifted to higher fields, indicating that the MCL and the CL regions moved to lower temperature due to the impurity effect of the columnar defects.

In the case of YBCO, however, the Hall scaling [1, 4] could be different from those observed for Hg- and Tl-based superconductors. Since the Hall scaling in YBCO takes place for $\rho_{xy} < 0$, where $\sigma_H^{(A)}$ is comparable to $\sigma_H^{(L)}$, the Hall scaling can be modified by the temperature dependence of $\sigma_H^{(A)}$. Furthermore, because $\sigma_H^{(A)}$ is more pronounced with increasing temperature, the scaling range of ρ_{xy} is narrower than those observed in Tl- and Hg-based superconductors. This is a possible explanation why $\beta = 1$ has not been observed in YBCO.

5. Summary

The universal Hall scaling behaviors between ρ_{xy} and ρ_{xx} in Hg-1212, Hg-1223, and Tl-2212 thin films were investigated as functions of the magnetic fields. We found the universal behavior of the Hall scaling for the CL and the MCL regions. Within the context of a recent theory [10] based on the localized states in vortex cores, this universal behavior was explicitly understood. However, this behavior is valid only if $\sigma_H^{(L)}$ is the main contribution to the Hall effect.

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