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Mixed-state Hall Angle in Hg-based Superconducting Thin Films

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Abstract

The mixed-state Hall angle has been measured in Hg-based superconducting thin films as functions of magnetic fields (H) up to 18 T. The temperature dependence of the Hall angle shows a peak (T*) at low temperature, which is consistent with a crossover point from the thermally activated flux flow (TAFF) to a critical region (CR). At low fields below 10 T, T* shifts to low temperature with increasing fields. Interestingly, however, we found that T* is independent of fields above 10 T, suggesting unusual vortex state. A physical implication of H – T* line will be discussed.

Keywords: Hall effect, Hg-based superconductors, thin film, vortex phase diagram

I. Introduction

One of the most striking features in the superconductivity is the mixed-states Hall effect, [1-8] which has been remained an unsolved problem for more than 30 years. When a type II superconductor in a magnetic field is cooled down from a normal state into a superconducting state a quantized magnetic flux (vortex) is created inside the superconducting medium. If we apply a transport current the vortices move perpendicular to the current direction due to the Lorentz force $\mathbf{F}_L = \mathbf{J} \times \mathbf{B}$, where **J** is the applied current density and **B** is the average magnetic induction. In this scenario, we can not detect the Hall voltage as one speculated before 1965, [5] because the electric field arising by vortex motion is parallel to the current direction according to the Josephson relation $\mathbf{E} = \mathbf{B} \times \mathbf{v}_L$ with $\mathbf{v}_L$ being average velocity of vortices. In order to solve this inconsistency, Nozieres and Vinen (NV) [6] considered the Magnus force, as a possible origin of the longitudinal component of vortex velocity while Kopnin, Ivlev, and Kalatsky, [7] recently, proposed vortex-traction force by the transport supercurrent. Another unusual phenomenon of the mixed-state Hall effect is a sign anomaly, which is believed to be strongly relevant to the Hall force, but this is not well understood yet.

Since the first observation [5] of the Hall effect in the mixed state of the Nb single crystal, where the ratio of ρ_{xy}/ρ_{xx} is a function of the magnetic field, many studies have been done to understand this effect. The Hall effect for the case of free flux-flow without pinning was studied by Bardeen and Stephen (BS) [8] and by NV using slightly different models. Both groups derived the same flux-flow resistivity, $\rho_{xx} = \rho_n H / H_{c2}$, where ρ_n is the normal resistivity; however, they obtained different Hall resistivities, $\rho_{xy} = (e\tau / m) \rho_n H^2 / H_{c2}$ for the BS model and $\rho_{xy} = (e\tau / m) \rho_n H$ for the NV model. Therefore, the magnetic field dependence of the Hall angle for BS and NV model is given by

$$\tan\Theta = \frac{eH}{m}\tau \quad , \qquad (1)$$

$$\tan\Theta = \frac{eH_{c2}}{m}\tau \ , \qquad (2)$$

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respectively, where τ is the relaxation time.

For the high-temperature superconductors (HTS), however, the Hall angle is not as simple as predicted by BS and NV. According to the Kopnin's theory based on the time dependent Ginzburg-Landau theory, the Hall angle can be described by tanΘ(H) = a(T) + b(T)H, which is partially consistent with the experimental data in $Tl_2Ba_2CaCu_2O_8$ thin films [9].

In this paper, we report results for the behavior of tanΘ (H) for $HgBa_2CaCu_2O_6$ (Hg-1212) and $HgBa_2Ca_2Cu_3O_8$ (Hg-1223) thin films as a function of the magnetic field up to a considerably high field of 18 T. From the field dependence of tanΘ, we found a new feature, a crossover point (H*), which divides the tanΘ vs. H curve into two parts, CR and TAFF region and is consistent the peak temperature of tanΘ vs. T data. More interestingly, we find that T* is independent of H above 10 T. We will propose a plausible vortex phase diagram.

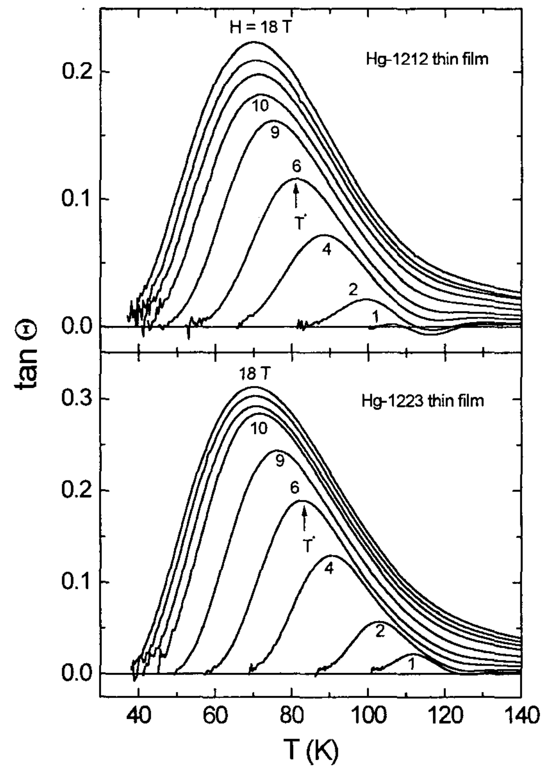

Fig. 1. Temperature dependence of the Hall angle for th Hg-1212 (top) and Hg-1223 (bottom) thin films as func tions of various magnetic fields up to 18 T.

II. Experimental

The transport properties and fabrication process of Hg-based superconducting thin films are described in detail elsewhere [10], [11]. The Tl-2212 thin films are commercially available. 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 and the Hg-1212 were observed 132 and 127 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 was found to be less than 2 K. The values of ρ_{xy} and ρ_{xx} were simultaneously measured using a two-channel nanovoltmeter (HP34420A) and the standard five-probe dc method. 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.

III. Results and Discussion

Fig. 1 shows the temperature dependence of tanΘ for the Hg-1212 (top) and Hg-1223 (bottom) thin films as functions of various magnetic fields up to 18 T. For the low field data, we observe negative dip near T_c, indicating the double sign reversal as ob-

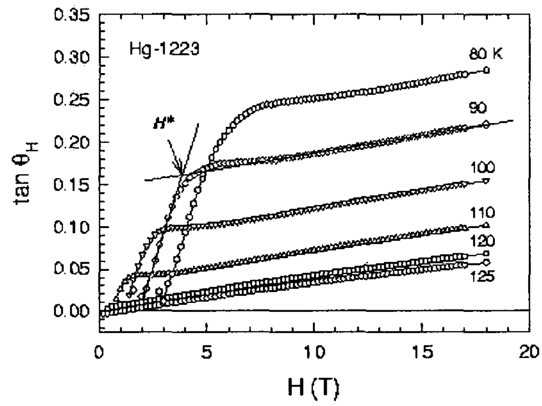

Fig. 2. Magnetic field dependence of the Hall angle i Hg-1223 thin film for various temperatures.

served in the high anisotropic HTS, such as Bi- and Tl-based compounds. Note that the peak (T*) at low temperature. For both Hg-1212 and Hg-1223 data, as the fields increase the T* shifts to lower temperature below 10 T, but does not change its location above 12 T. This has not been observed for any high-T_c superconductors mainly because detailed measurements have not yet been done. This result is our main finding and will be discussed later.

In Fig. 2, we plot the $\tan\Theta$ as a function of magnetic field up to 18 T. A crossover field H* divides the $\tan\Theta$ curve into two parts having different slopes. In this figure, the arrow denotes H* at T = 90 K. In our previous work [12], [13] we interpreted the physical implication of H* based on the Yeshurun and Malozemoff's theory. From the resistivity measurement, we analyze the temperature dependence of the effective activation energy and find that the H* is coincides with the crossover temperature from CR and TAFF region. More interestingly, we find that T* is consistent with H*.

In Fig. 3, we made a phase diagram based on the field dependence of T* in Fig. 1 and the irreversibility field H_{irr}, which is determined from the temperature at $\rho_{xx} = 10^{-9}$ Ω cm of ρ_{xx} – T curves for various fields. For the low field below 8 T, we find that the T* is the crossover point from CR to TAFF region, which is well agreed to the analyses obtained from the $\rho_{xx}(T)$ and $\tan\Theta(H)$ measurements. Here, CR implies the transition region from TAFF to the vortex grass phase, in which the temperature dependence of pinning strength is much stronger than that of TAFF region.

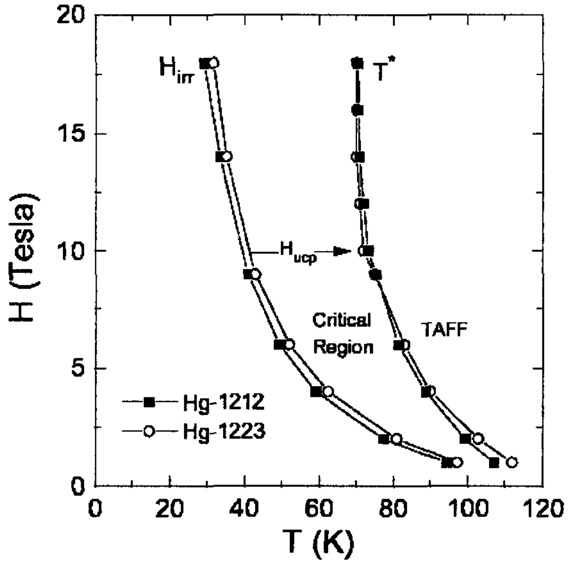

Fig. 3. Phase diagram for the Hg-1212 (■) and Hg-122 (O) thin films

Now, the remained question in this phase diagram is the physical meaning of the region between H_{irr} and T* lines above the upper crossover point (H_{ucp}), where T* is independent of magnetic fields. As a plausible scenario, we can consider decoupled (2D like) vortex liquid state. With very high anisotropy nature of HTS, it is well known that vortex line (3D vortex) changes into pancake vortex (2D vortex) with increasing magnetic fields. When a magnetic field increases, the vortex-vortex interaction becomes stronger because the distance between vortices is closer. If vortex-vortex interaction is much stronger than the interlayer coupling strength, then the vortices are decoupled into pancake vortices. Thus, the T* is independent of magnetic field above H_{ucp}, as shown in Fig. 3. The H_{ucp} depends on the interlayer coupling strength. The lower crossover point (H_{lcp}) of 3D-2D vortex was observed 0.5 T in the Hg-1223 thin films [11]. If we consider various kind of disorders (pinning sites), such as point defects, crystal dislocations, and natural linear defects, we may understand the wide range of crossover fields from 0.5 T to 10 T.

IV. Summary

Using Hg-based superconducting thin films, we have measured the mixed-state Hall angle in the magnetic fields up to 18 T. The temperature dependence of the Hall angle shows a peak at low temperature, which is consistent with a crossover point from the CR to TAFF region. For the first time, we find the upper critical field (H_{ucp} = 10 T), where T* is independent of magnetic fields. We believe that H_{ucp} is the crossover field from 2D vortex liquid to mixed 2D-3D vortex liquid.

Acknowledgements

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