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Scaling behavior of mixed-state hall effect in MgB_2 thin films

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Abstract

The Hall resistivity (ρ_{xy}) and the longitudinal resistivity (ρ_{xx}) in *c*-axis-oriented superconducting MgB_2 thin films have been investigated in extended fields up to 18 T. We have observed a scaling behavior between the Hall resistivity and the longitudinal resistivity, $\rho_{xy} = A\rho_{xx}^{\beta}$, where the exponent ($\beta$) is observed to be independent of the temperatures and the magnetic fields. For a wide magnetic field region from 1 to 18 T and a wide temperature region from 10 to 28 K, a universal power law with $\beta = 2.0 \pm 0.1$ was observed in *c*-axis-oriented MgB_2 thin films. These results can be well interpreted by using recent models.

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Keywords: MgB_2 thin film; Hall effect; Hall scaling; Scaling behavior

1. Introduction

Since the first observation [1] of the Hall effect in the superconducting state, numerous experimental results have been reported for type II superconductors [2–8]. However, the origin of the Hall effect due to vortex motion still remains an unresolved subject [8–11] for more than three decades. In this situation, the fully convincing empirical law of vortex matter is required as an important breakthrough for understanding vortex dynamics. When a type II superconductor in a magnetic field is cooled down from a normal state to a superconducting state, quantized magnetic fluxes are created inside the superconducting medium. If a transport current is applied, the vortices move perpendicular to the current direction due to the Lorentz force $\mathbf{F}_L = \mathbf{J} \times \mathbf{B}$, where $\mathbf{J}$ is the applied current density and $\mathbf{B}$ is the average magnetic induction. In this scenario, we cannot detect the Hall voltage, as was speculated before 1965, because the electric field caused by the vortex motion is parallel to the current direction according to the Josephson relation $\mathbf{E} = \mathbf{B} \times \mathbf{v}$, where $\mathbf{v}$ is the average velocity of the vortices. In order to reconcile this inconsistency, Nozieres and Vinen [12] suggested the Magnus force as a possible origin of the longitudinal component of the vortex velocity, whereas Kopnin et al. [13] considered the vortex-traction force by a transport supercurrent.

In the meanwhile, an interesting Hall scaling behavior has been observed by several groups [2–7]. Furthermore, a scaling behavior between ρ_{xy} and ρ_{xx} has been found in most the high-temperature superconductors (HTS). The power law, $\rho_{xy} = A\rho_{xx}^{\beta}$, with $\beta = 2$ has been observed for $Bi_2Sr_2CaCu_2O_8$ crystals and $Tl_2Ba_2Ca_2Cu_3O_{10}$ films. Other similar studies have reported $\beta = 1.5$–2 for $YBa_2Cu_3O_7$ (YBCO) films, YBCO crystals, and $HgBa_2CaCu_2O_6$ films.

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Even $\beta = 1$ was reported for heavy-ion-irradiated $HgBa_2CaCu_2O_6$ thin films.

A number of theories have been proposed to explain the scaling behavior between ρ_{xy} and ρ_{xx}. A phenomenological model was put forward by Vinokur et al. [10]. They claimed that in the flux-flow region, β should be 2 and independent of the pinning strength. Their result was consistent with the observed exponent in Bi-, Tl- and Hg-based superconductors only for the Hall data measured in high magnetic fields [14]. Another phenomenological model was proposed by Wang et al. [11], who claimed that β could change from 2 to 1.5 as the pinning strength increased, which agreed with the results reported for YBCO crystals [5] and $HgBa_2CaCu_2O_6$ films [6].

The Hall scaling behavior, therefore, is a complicated phenomenon, which seems strongly depend on the type of superconductors. However, from the experimental Hall data reported in previous papers, one can found a general trend [14]. At higher fields, the scaling range of a magnetic field and a temperature is wide and shows a universal value of $\beta = 2$, which is independent of the field, the temperature, and the pinning strength. At lower fields, the scaling range is relatively narrow so that the precise measurements of β could not be easy.

The MgB_2 superconductor is a very interesting sample for investigating the flux dynamics [15]. Different from HTS, MgB_2 shows no Hall sign anomaly in the mixed-state and has a rather simple vortex phase diagram [15,16]. The absence of sign anomaly implies that the hydrodynamic contribution is very small or negligible [13,15]. Thus, the MgB_2 compound is probably the best candidate for probing whether the Hall scaling is universal or not because we need only consider the quasiparticle term of the Hall conductivity, which is consistent with the universal Hall scaling theory [10].

In this paper, we report the demonstration of a universal scaling behavior of the Hall resistivity in *c*-axis-oriented MgB_2 thin films for extended range of magnetic fields up to 18 T, and the results can be well described using recent theories [10]. Based on our results, we will discuss that the universal Hall scaling law is also valid for HTS in high fields in case where the hydrodynamic contribution in the Hall effect is negligibly small.

2. Experimental

The fabrication process and the normal-state transport properties of MgB_2 thin films used in this study are described in detail elsewhere [17,18]. The X-ray diffraction patterns indicated highly *c*-axis-oriented thin films perpendicular to the substrate surface. The critical current density at 15 K and under a self-field condition was observed to be on the order of 10^7 A/cm^2. Standard photolithographic techniques were used to produce Hall-bar patterns, which consisted of a rectangular strip (1 mm × 3 mm) of MgB_2 film with three pairs of sidearms. The narrow sidearm width of 0.1 mm was patterned so that the sidearms would have an insignificant effect on the equipotential. Using this 6-probe configuration, we were able to measure simultaneously the ρ_{xy} and ρ_{xx} at the same temperature and magnetic field. To achieve good ohmic contacts, we coated Au film on the contact pads after cleaning the sample surface by using Ar-ion milling. The magnetic field was applied perpendicular to the sample surface by using a superconducting magnet system. We applied very high current density of 10^4 A/cm^2 in order to obtain ρ_{xy} and ρ_{xx} data for wide range of magnetic fields and temperatures.

3. Results and discussion

Fig. 1 shows the temperature dependence of ρ_{xx} for MgB_2 thin films grown on Al_2O_3 substrates for applied current density of 10^4 A/cm^2. The inset is a magnified view near the critical temperature region. At zero field, the onset transition temperature (T_c) was 39 K and had a narrow transition width of ~0.1 K, as judged from the 10% to 90% superconducting transition. The normal-state resistivity at 290 K was ~23 μΩ cm, indicating an intermetallic nature with a relatively high charge carrier density.

Fig. 2 shows the magnetic field dependence of ρ_{xx} for MgB_2 films at various temperatures from 10 to 34 K and at a current density of 10^4 A/cm^2. A very small and positive magnetoresistance can be observed above an upper critical field. At lower temperatures, the superconducting transitions of ρ_{xx} became broad, indicating that vortices move easily for wide magnetic field ranges due to the strong Lorentz force by applying a very high current density. As the magnetic field was increased, ρ_{xx} grew gradually up to an upper critical field, which is different from the previous observation measured with low current density in MgB_2 [16].

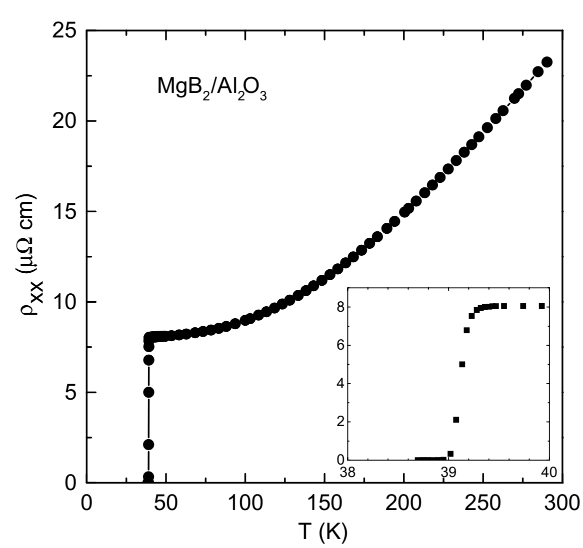

Fig. 1. Temperature dependences of ρ_{xx} for MgB_2 thin films at current density of 100 A/cm^2. Inset shows a magnified view near a superconducting transition region.