Scaling behavior of the longitudinal and Hall resistivities in indium films

S. Okuma and N. Kokubo
Research Center for Very Low Temperature System, Tokyo Institute of Technology, 2-12-1, Ohokayama, Meguro-ku, Tokyo 152, Japan
(Received 22 July 1996; revised manuscript received 2 January 1997)

We have made simultaneous measurements of the longitudinal ρ_{xx} and Hall ρ_{xy} resistivities for granular films of indium with different thicknesses ($\bar{t}=12$, 20, and 60 nm) and the normal-state resistivities ($\rho_{xxn}=2-5\times10^{-5}$ Ω m) at temperatures T down to 0.5 K and in fields B up to 7 T. A striking scaling behavior expressed as $\rho_{xy}(T)=A\rho_{xx}(T)^{\beta}$ has been observed for all the films studied irrespective of $\bar{t}$ and ρ_{xxn} at fixed fields which are not close to a critical field B_C. In the mixed state ($B<B_C$ and $T<T_C$, where T_C is the transition temperature), the coefficient A and exponent β $(=2-3)$ are nearly independent of the field strength B and the film thickness $\bar{t}$. In the vicinity of the field-driven superconductor-insulator transition, we have found the *unusual* insulating region $B_{xxC}<B<B_{xyC}$, where B_{xxC} and B_{xyC} represent critical fields determined by ρ_{xx} and ρ_{xy}, respectively, which tends to grow with increasing ρ_{xxn} and/or decreasing $\bar{t}$. This region is similar to one found previously by Paalanen, Hebard, and Ruel in amorphous InO_x thin films, and the present result is consistent with their notion that the insulating region corresponds to the Bose-glass insulator. [S0163-1829(97)02625-8]

INTRODUCTION

The Hall effect in the mixed state of the type-II superconductors has attracted intense recent attention. There are two interesting problems which have not yet been clarified in detail. The first one is an anomalous sign change of the Hall resistivity ρ_{xy}, which has been observed in many of the high-T_C superconductors[1–11] (HTSC's) as well as in some of the conventional (low-T_C) superconductors,[12–14] at a temperature below the superconducting transition temperature T_C and in low magnetic fields. Several models[15,16] have been proposed to account for the finding; however, the nature of this phenomenon has not yet been fully understood. The second interesting problem is a puzzling scaling law of the Hall ρ_{xy} versus longitudinal ρ_{xx} resistivity: $\rho_{xy}\sim\rho_{xx}^{\beta}$, which has been observed for the temperature T dependence and/or for the field B dependence. This scaling behavior has been reported in various HTSC cuprates such as $YBa_2Cu_3O_{7-\delta}$ ($\beta\sim1.7$),[6,17–19] $Bi_2Sr_2CaCu_2O_x$ ($\beta\sim2$),[18,20] and $L_{2-x}Ce_xCuO_4$ ($L=$Nd,Sm) ($\beta\sim0.8$).[21,22] Dorsey and Fisher[23] (DF) have interpreted the observed scaling behavior in the framework of the glassy scaling near the vortex-glass transition. This model assumes the existence of the vortex-glass transition in a three-dimensional (3D) vortex system, and furthermore, the region where the scaling behavior is observable is restricted within a narrow regime near the vortex-glass transition. Based on an entirely different approach, Vinokur, Geshkenbein, Feigel'man, and Blatter[24] (VGFB) have calculated the effect of flux pinning on the Hall resistivity and shown a similar scaling behavior expressed as $\rho_{xy}=A(T,B)\rho_{xx}^{\beta}$, with $\beta=2$. This model considers the force balance for stationary moving vortices with disorder-dominated dynamics. The argument is universal and independent of the specific vortex state.

It is interesting to ask whether a similar scaling law is also observed in conventional superconductors other than HTSC's. In this paper we have made simultaneous measurements of the longitudinal ρ_{xx} and Hall ρ_{xy} resistivity for granular films of indium with different thicknesses and disorder. If the scaling behavior is indeed observable, this system is favorable for a detailed study of the phenomenon because (i) these films are so simple compared to high-T_C materials in which the anomalous sign change of ρ_{xy} as well as anisotropy effects must be taken into account, (ii) the dimensionality of the system can be easily altered by changing the average film thickness, and (iii) the influence of disorder on the scaling behavior can be systematically studied.

EXPERIMENT

The films used in this study were prepared by repeating the cycles of a small amount of vacuum deposition of indium and surface oxidation. The observation by transmission electron microscopy (TEM) clearly showed that thus prepared films consist of coupled superconducting particles with average grain sizes $\bar{d}=8-14$ nm. We have known from previous studies that the films with $\bar{d}<20$ nm can be viewed as a dirty superconductor rather than a Josephson network.[25] For films 1 and 2 with average thicknesses $\bar{t}$ of 20 and 12 nm, respectively, surface oxidation was performed weakly so that the resistivity in the normal state, ρ_{xxn} ($T=5$ K), was in the range $2-3\times10^{-5}$ Ω m, whereas for films 3 ($\bar{t}=60$ nm) and 4 ($\bar{t}=20$ nm) strong disorder was introduced by heating the sample. This heat treatment results in a monotonic increase in ρ_{xxn} ($T=5$ K), which is around 5×10^{-5} Ω m, and a resultant decrease in T_C and B_C as typically observed in dirty thin superconductors. In particular, we obtained film 4 by heating film 1 to 100 °C for about 3 h in air after the low-temperature measurements had been performed. Apparent structural changes have not been visible within the experimental resolution of TEM. We accordingly consider that the increase in ρ_{xxn} by heat treatment is due to the growth of a surface oxide layer and/or to a slight opening between the grains.

The longitudinal ρ_{xx} and Hall ρ_{xy} resistivities were mea-

 © 1997 The American Physical Society

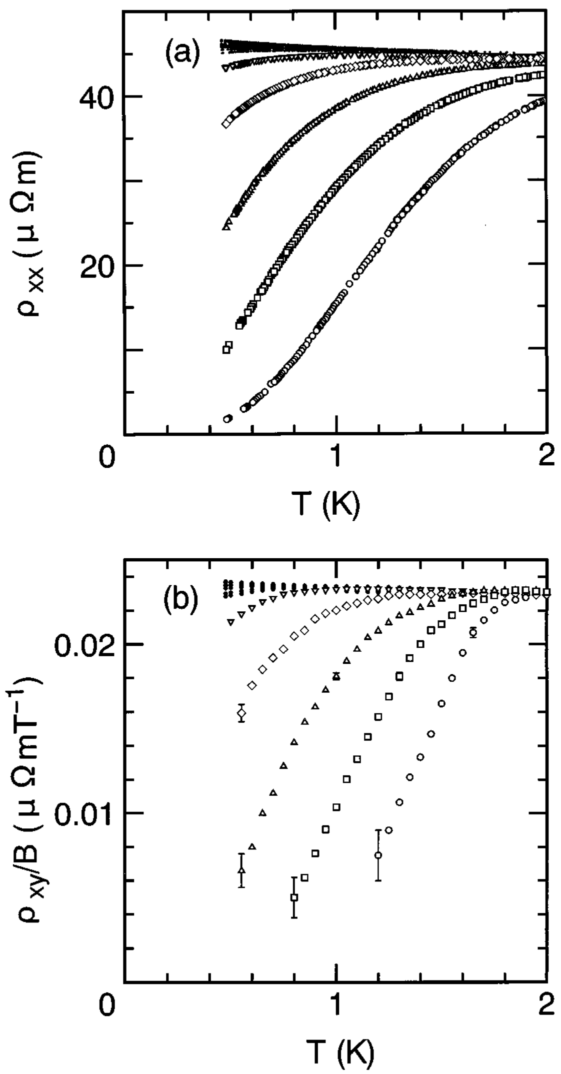

FIG. 1. Temperature dependence of (a) the longitudinal resistivity ρ_{xx} and (b) the Hall resistivity divided by the field, ρ_{xy}/B, for film 3 ($t=60$ nm) in different magnetic fields. The magnetic fields are ●, 7–4.3 T; ▽, 4.0 T; ◇, 3.5 T; △, 3.0 T; □, 2.5 T, and ○, 2.0 T (from top to bottom).

sured simultaneously by a standard dc technique as a function of the temperature at fixed magnetic fields. The Hall voltage was measured using a pair of equally spaced voltage probes which lie between pairs of equally spaced voltage probes for the ρ_{xx} measurements. The longitudinal component of the voltage arising from slight misalignment of the Hall probes was eliminated by reversing the magnetic field. Each film was directly immersed into the liquid ^{3}He or ^{4}He to achieve good thermal contact. In various magnetic fields, the temperature was measured and controlled by means of calibrated RuO_2 resistors and vapor pressure of liquid ^{3}He or ^{4}He. In this study, a magnetic field B was applied perpendicularly to the film surface.

RESULTS AND DISCUSSION

Figures 1(a) and 1(b), respectively, display the temperature dependence of ρ_{xx} and ρ_{xy}/B (ρ_{xy} divided by B) for film 3 ($t=60$ nm) at low temperatures and in various fields ranging from $B=2.0$ to 7.0 T. In zero field ρ_{xx} exhibits a decrease at $T_C\sim 3.2$ K and vanishes at around 2.2 K. One can notice that the temperature dependence of $\rho_{xx}(T)$ looks remarkably similar to $\rho_{xy}(T)/B$.[26,27] As observed in much thinner films,[26–30] when the field exceeds its critical value B_C (~ 4.6 T), a field-induced transition from a state where ρ_{xx} and ρ_{xy}/B (or ρ_{xy}) are zero to a state where ρ_{xx} and ρ_{xy}/B (or ρ_{xy}) are infinity seems to take place at $T=0$. In the normal state $[T>T_C(B)]$, ρ_{xy} is proportional to the magnetic field strength and hence ρ_{xy}/B is independent of the field strength. In the mixed state $[T<T_C(B)]$, we do not observe the sign change of ρ_{xy} in the field range studied here. Below 2 T, it is not possible to obtain a finite Hall voltage at low temperatures without great ambiguities. Qualitatively similar behaviors[27,30] of ρ_{xx} and ρ_{xy} to those shown in Figs. 1(a) and 1(b) are observed for other films.

In Figs. 2(a)–2(c) we plot the data for $\rho_{xy}(T)$ as a function of the corresponding data for $\rho_{xx}(T)$ on a log-log plot at various fields below B_C. Here the temperature T $[<T_C(B)]$ is the scanning variable. Upon lowering temperature both $\rho_{xx}(T)$ and $\rho_{xy}(T)$ in each film decrease monotonically except for the data points which lie in the vicinity of the field-induced S-I transition ($B\sim B_C$). The remarkable feature in these figures is that for each film most of the data points at different fields collapse onto approximately a single line. Deviations of the data points from the straight lines are visible in the lower parts of the curves, which may be due to less precision in determination of $\rho_{xy}(T)$. Thus most of the data presented here clearly display the striking power-law relationship expressed as

$$\rho_{xy}(T)=A\rho_{xx}(T)^{\beta}, \tag{1}$$

where an exponent β is in the range 2–3 and the coefficient A is a constant, nearly independent of the field, but dependent on the sample.

We first explore the sample dependence of A. Since the scaling law expressed as Eq. (1) does commonly hold for films 1–4 at fields up to $\sim B_C$, the coefficient A is *roughly* estimated by the normal-state resistivities ρ_{xxn} and ρ_{xyn} at $B\sim B_C$ assuming $\beta=2$. The values of A for films 1–4 thus estimated are in the range 10^2–10^3 $(\Omega\ \mathrm{m})^{-1}$, which are smaller by approximately two orders of magnitude than the values $A\sim 10^4$–10^5 $(\Omega\ \mathrm{m})^{-1}$ reported for HTSC's.[6,18,19] It is found from the data for films 1 and 4, together with the data for a previous study,[27] that ρ_{xyn} ($B\sim B_C$) increases almost linearly with ρ_{xxn} ($B\sim B_C$) by heat treatment except for the samples which lie in the vicinity of the disorder-driven S-I transition. This means that in our samples the heat treatment gives rise to a reduction of the carrier density n as well as an enhancement of the potential scattering rate (disorder). As a result, the value of A for film 4 becomes remarkably smaller than that for film 1. In contrast to the ρ_{xxn} dependence, the thickness dependence of A turns out to be very weak. This is immediately seen by comparing the data for films 1 ($t=20$ nm) and 2 ($t=12$ nm) with ρ_{xxn} (5 K) $=2$–3×10^{-5} Ω m. For the thicker films 3 ($t=60$ nm) and 4 ($t=20$ nm) with ρ_{xxn} (5 K) $\sim 5\times 10^{-5}$ Ω m, A is a weak decreasing function with respect to the thickness.

We next turn to the exponent β. In Figs. 3(a)–3(d), β for films 1–4 is, respectively, plotted as a function of the field

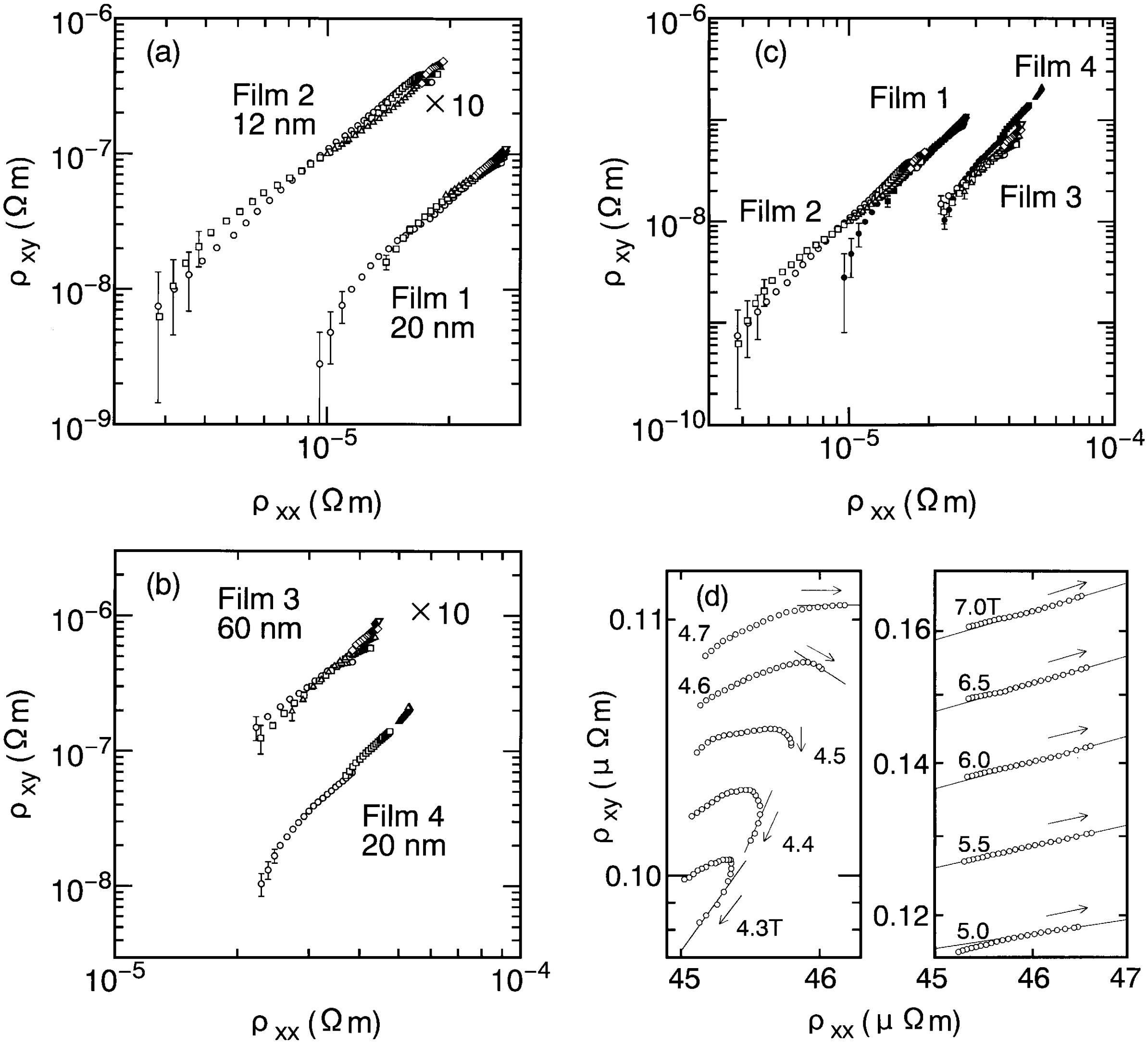

FIG. 2. ρ_{xy} vs ρ_{xx} dependences at various magnetic fields ($B<B_c$) for (a) films 1 ($\bar{t}=20$ nm) and 2 ($\bar{t}=12$ nm) and for (b) films 3 ($\bar{t}=60$ nm) and 4 ($\bar{t}=20$ nm). Data points for films 2 and 3 are suitably shifted along the vertical axis for clarity. The fields and corresponding symbols are ○, 4.0 T; □, 4.4 T; △, 4.6 T; ◇, 4.8 T; and ▽, 5.0 T for film 1; ○, 4.0 T; □, 4.5 T; △, 5.0 T; and ◇, 5.5 T for film 2; ○, 2.0 T; □, 2.5 T; △, 3.0 T; ◇, 3.5 T; and ▽, 4.0 T for film 3; ○, 3.0 T; □, 3.5 T; and △, 4.0 T for film 4. (c) All the data ($B<B_C$) for films 1–4 are plotted in the same graph. Data points for films 1 and 4 are represented by solid symbols. (d) Log-log plot of ρ_{xy} vs ρ_{xx} for film 3 at higher fields. In the vicinity of the critical field, B_{xxC} or B_{xyC}, only the data at low temperatures are used to extract the β values in Eq. (1). Arrows indicate the direction of $T\rightarrow 0$.

B. It is apparent from these figures that $\beta(B)$ in each film tends to a value which is close to 2 or more with decreasing B ($\ll B_C$), while $\beta(B)$ approaches a value which is close to 1 or more with increasing B ($\gg B_C$). As illustrated in Fig. 2(d), in the vicinity of the S-I transition ($B\sim B_C$), where the scaling behavior is observable only in a limited range, we extracted $\beta(B)$ (denoted by open circles) from the data of $\rho_{xx}(T)$ and $\rho_{xy}(T)$ at low temperatures. The abrupt change in $\beta(B)$ observed in the vicinity of B_C signals the presence of the *unusual* insulating state.[26,27] We will discuss this issue later.

In summary, we have observed a scaling behavior expressed as Eq. (1) for all the films with different thicknesses ($\bar{t}=12$, 20, and 60 nm) and resistivities ($\rho_{xxn}\sim 2-5\times 10^{-5}$ Ω m). We have known from recent studies[31] that films with average thickness $\bar{t}$ larger than 60 nm undergo a 3D vortex-glass transition, whereas a film with $\bar{t}=20$ nm exhibits a 2D vortex-glass behavior; i.e., the vortex-glass transition does not occur at finite temperatures. Therefore, we are not able to expect the scaling behavior [Eq. (1)] for films 1 ($\bar{t}=20$ nm), 2 ($\bar{t}=12$ nm), and 4 ($\bar{t}=20$ nm) according to the DF theory[23] at temperatures well above the glass temperature ($T_g\sim 0$). This is not in accordance with the present experimental results.

As a possible explanation, we interpret these results in terms of the VGFB model,[24] in which the resistivity-squared dependence of ρ_{xy} originates from a general feature of the vortex state. In the theory both A and ρ_{xx} are temperature dependent. A quadratic dependence of ρ_{xy} on ρ_{xx} ($\beta=2$) is expected at low enough temperatures where the pinning effect is relevant and transport properties are governed by thermally assisted flux flow (TAFF). In the TAFF regime, $\rho_{xx}(T)$ changes more rapidly than $A(T)$ with temperature, and hence the temperature dependence of ρ_{xy} is dominated

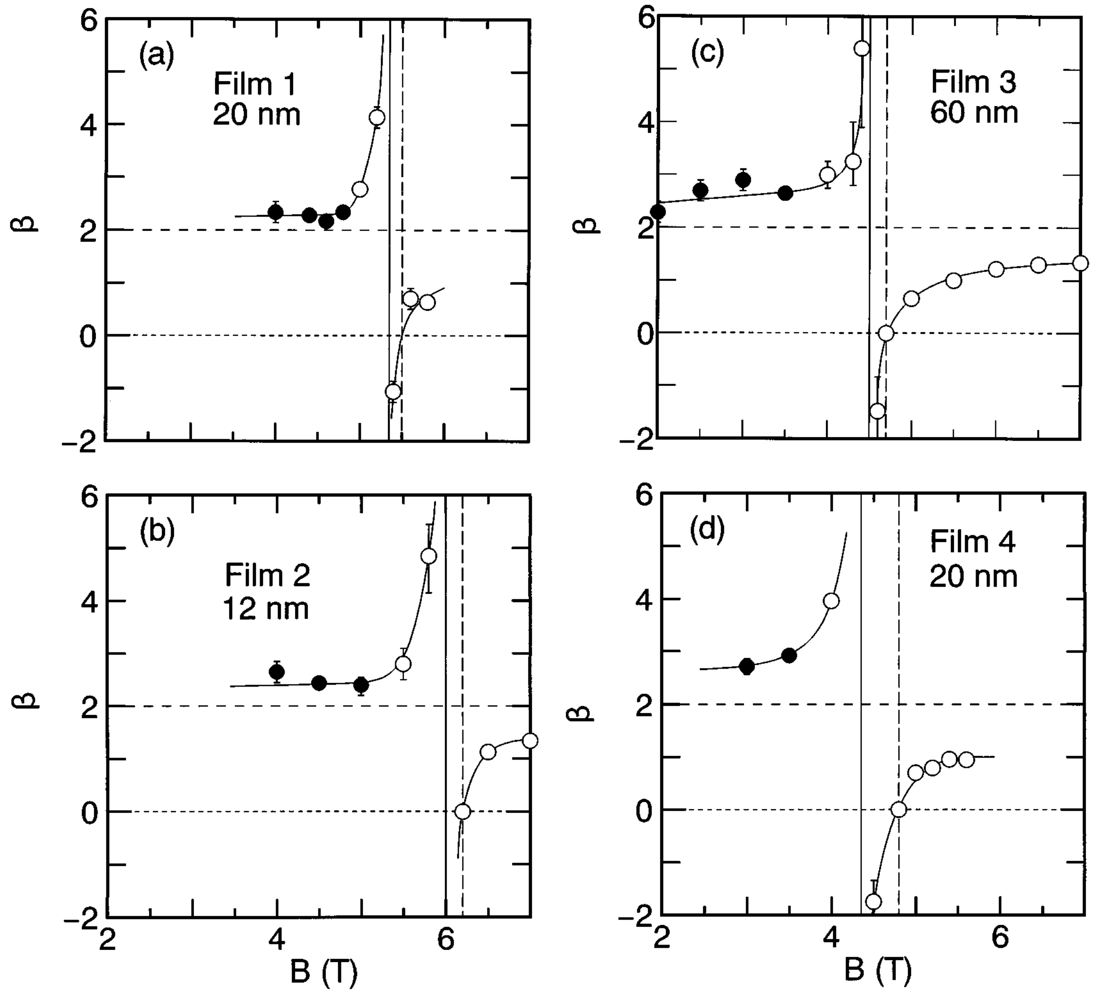

FIG. 3. Exponent β in Eq. (1) is plotted as a function of the magnetic field B for (a) film 1 ($\bar{t}=20$ nm), (b) film 2 ($\bar{t}=12$ nm), (c) film 3 ($\bar{t}=60$ nm), and (d) film 4 ($\bar{t}=20$ nm). Open circles represent the values of β extracted from data of limited range taken close to or above the critical fields, such as shown in the low-temperature data of Fig. 2(d). Vertical solid and dashed lines indicate B_{xxC} and B_{xyC}, respectively. The region $B_{xxC}<B<B_{xyC}$, where $\beta(B)$ is negative, corresponds to the *unusual* insulating phase.

by ρ_{xx}^2. In the present experiments, however, most of the data were taken at relatively higher temperatures where pinning is not so relevant and the transport is probably described by viscous flux flow (VFF) rather than thermally assisted flux flow. In the VFF regime the temperature dependence of $A(T)$ is equally important as that of $\rho_{xx}(T)$ and no simple scaling law with $\beta=2$ is expected. Deviation of β ($\sim 2-3$) from the predicted value of 2 is thus attributed to the temperature dependence of $A(T)$. The theory further predicts the independence of A on the pinning strength. Unfortunately, since we were not able to control the pinning strength, keeping other parameters constant, it was not possible to test that remarkable prediction in our films. Experimental verification for the prediction has been reported using irradiated samples of $YBa_2Cu_3O_7$ (Ref. 19) and Tl oxides.[8,19]

Another striking observation to be pointed out is that the coefficient A is nearly independent of the field strength B in each film. This has also been reported in some of the high-T_c materials and explained in the framework of the VGFB theory. As claimed by several authors,[18,20,22,24] the independence of A on the field strength is, within this approach, equivalent to the statement that the tangent of the Hall angle is proportional to the field strength, consistent with the Bardeen-Stephen theory in which the Hall effect in the mixed state is due to the normal carrier Hall effect in the vortex cores. All these findings mentioned above, together with insensitiviness of the β value to the film thickness $\bar{t}$, the applied magnetic field B (except for $B\sim B_c$), and the normal-state longitudinal resistivity ρ_{xxn}, seem to favor the view as proposed by Vinokur *et al.*[24]

Nevertheless, we are currently very careful in making a conclusive statement about the validity of the VGFB theory. This is because it is not yet clear to us whether this simple force balance model based on *single*-vortex dynamics is indeed applicable to the present system (i.e., the vortex-liquid regime in relatively high fields) where the interaction between vortices is probably important. Quite recently, the dependence of the scaling behavior on the pinning strength has been observed in irradiated twinned crystals of $YBa_2Cu_3O_7$:[32] The scaling exponent β decreases from 2 to 1.5 with increasing the defect density. It has been claimed that the experimental results are in better agreement with the theory by Wang, Dong, and Ting[33] (WDT), which explicitly includes the pinning-induced backflow effect and predicts the change in β from 2 to $\sim$1.5 with increasing the pinning strength, rather than the theory by Vinokur *et al.*[24] In our experiment, however, it appears difficult to accept the WDT theory because the values of β are always larger than 2. Anyway, more detailed theories[34] describing the vortex dynamics for the mixed-state Hall effect are called for. Also, further measurements, controlling the pinning strength, with improved ρ_{xy} resolution at even lower temperatures are challenging.

Finally, we comment on the *unusual* insulating region mentioned above. This region was first found in amorphous InO_x thin films by Paalanen, Hebard, and Ruel[26] (PHR) and later by us in In films ($t=20$ nm).[27] It was found that, in addition to a usual critical field B_{xxC} where $\rho_{xx}(T\to 0)$ diverged, another critical field B_{xyC} where $\rho_{xy}(T\to 0)\to\infty$ existed and the region $B_{xxC}<B<B_{xyC}$ became broader with increasing disorder ρ_{xxn}. Based on these findings, it was claimed that the region corresponded to the Bose-insulator phase. As suggested in Ref. 26, the analysis of the resistivity data according to Eq. (1) and the subsequent plot of β against B as shown in Fig. 3 turned out to be helpful in studying the S-I transition.[27] In what follows, we will discuss the results shown in Fig. 3 from this viewpoint. We focus on the critical fields B_{xxC} and B_{xyC}, which are represented by the vertical solid and dashed lines, respectively. In the vicinity of the S-I transition, the meaning (and validity) of the power-law dependence as well as the extracted value of β is not so clear. Nevertheless, the critical fields are well defined in Fig. 3; the vertical solid and dashed lines agree with the critical fields deduced convincingly[26,27] from the magnetic field dependence of ρ_{xx} and ρ_{xy}, respectively, at low temperatures, such as shown in Fig. 4. Comparing the data for films 1 and 4 with $t=20$ nm, one can straightforwardly confirm the previous finding that the region $B_{xxC}<B<B_{xyC}$ becomes broader with increasing ρ_{xxn}. In the case of the thickest film with $t=60$ nm (film 3), however, the corresponding region is markedly narrowed, although the film is most disordered (hence B_{xxC} is very low). This is clearly seen in Figs. 3(c) and 3(d). In contrast, for the thinnest film with $t=12$ nm (film 2) the region is not so limited, although ρ_{xxn} is lowest (hence B_{xxC} is very high). These results suggest a trend that the *unusual* insulating region ($B_{xxC}<B<B_{xyC}$) becomes more pronounced as the film becomes thinner (at fixed disorder ρ_{xxn}). This provides further experimental support for the notion[26,27] first suggested by PHR that the insulating region ($B_{xxC}<B<B_{xyC}$) corresponds to the Bose-glass insulator where quantum fluctuations of the phase enhanced in 2D play an essential role.[35]

In conclusion, we have observed a scaling behavior between the Hall (ρ_{xy}) and longitudinal (ρ_{xx}) resistivities expressed as $\rho_{xy}(T)=A\rho_{xx}(T)^{\beta}$ for indium films with different thicknesses ($t=12$, 20, and 60 nm) and the normal-state resistivities ($\rho_{xxn}=2-5\times 10^{-5}$ Ω m) for fixed fields which are not close to the critical field B_c. In the mixed state [$B<B_c$ and $T<T_c(B)$], the coefficient A and exponent β are nearly independent of the field strength B and the film thickness t. Furthermore, β is insensitive to the normal-state resistivity ρ_{xxn}. In the vicinity of the field-driven S-I transition, we have observed an *unusual* insulating region ($B_{xxC}<B<B_{xyC}$) which tends to grow with increasing ρ_{xxn} and/or decreasing t. This is consistent with the notion, as first suggested in amorphous InO_x thin films by Paalanen, Hebard and Ruel,[26] that the insulating region corresponds to the Bose-glass insulator.

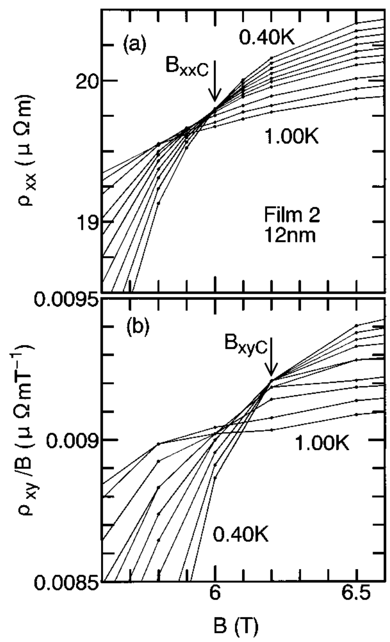

FIG. 4. Magnetic field dependence of (a) ρ_{xx} and (b) ρ_{xy}/B for film 2 ($t=12$ nm) at various temperatures. Isotherms range from 0.40 to 1.00 K in 0.05-K steps below 0.70 K and in 0.10-K steps above 0.70 K.

ACKNOWLEDGMENTS

We thank R. Ikeda for helpful discussions. This research was supported in part by Kawasaki Steel 21st Century Foundation and by a Grant-in-Aid for Scientific Research (B) from the Ministry of Education, Science, Sports and Culture. One of us (N.K.) was supported by a Grant-in-Aid from JSPS.

[1] M. Galffy and E. Zirngiebl, Solid State Commun. **68**, 929 (1988).
[2] Y. Iye, S. Nakamura, and T. Tamegai, Physica C **159**, 616 (1989).
[3] S. J. Hagen, C. J. Lobb, R. L. Greene, M. G. Forrester, and J. H. Kang, Phys. Rev. B **41**, 11 630 (1990).
[4] T. R. Chien, T. W. Jing, N. P. Ong, and Z. Z. Wang, Phys. Rev. Lett. **66**, 3075 (1991).
[5] S. J. Hagen, C. J. Lobb, R. L. Greene, and M. Eddy, Phys. Rev. B **43**, 6246 (1991).
[6] J. Luo, T. P. Orlando, J. M. Graybeal, X. D. Wu, and R. Muenchausen, Phys. Rev. Lett. **68**, 690 (1992).
[7] J. P. Rice, N. Rigakis, D. M. Ginsberg, and J. M. Mochel, Phys. Rev. B **46**, 11 050 (1992).
[8] R. C. Budhani, S. H. Liou, and Z. X. Cai, Phys. Rev. Lett. **71**, 621 (1993).
[9] M. N. Kunchur, D. K. Christen, C. E. Klabunde, and J. M. Phillips, Phys. Rev. Lett. **72**, 2259 (1994).

[10] A. V. Samoilov, Z. G. Ivanov, and L.-G. Johansson, Phys. Rev. B **49**, 3667 (1994).
[11] S. J. Hagen, A. W. Smith, M. Rajeswari, J. L. Peng, Z. Y. Li, R. L. Greene, S. N. Mao, X. X. Xi, S. Bhattacharya, Qi. Li, and C. J. Lobb, Phys. Rev. B **47**, 1064 (1993).
[12] H. Van Beelen, J. P. Van Braam Houckgeest, H. M. Thomas, C. Stolk, and R. De Bruyn Ouboter, Physica (Amsterdam) **36**, 241 (1967).
[13] C. H. Weijsenfeld, Phys. Lett. **28A**, 362 (1968).
[14] N. Usui, T. Ogasawara, K. Yasukochi, and S. Tomoda, J. Phys. Soc. Jpn. **27**, 574 (1969).
[15] A. T. Dorsey, Phys. Rev. B **46**, 8376 (1992).
[16] N. B. Kopnin, B. I. Ivlev, and V. A. Kalatsky, J. Low Temp. Phys. **90**, 1 (1993).
[17] P. J. M. Wöltgens, C. Dekker, and H. W. de Wijn, Phys. Rev. Lett. **71**, 3858 (1993).
[18] H.-C. Ri, R. Gross, F. Gollnik, A. Beck, R. P. Huebener, P. Wagner, and H. Adrian, Phys. Rev. B **50**, 3312 (1994).
[19] A. V. Samoilov, A. Legris, F. Rullier-Albenque, P. Lejay, S. Bouffard, Z. G. Ivanov, and L.-G. Johansson, Phys. Rev. Lett. **74**, 2351 (1995).
[20] A. V. Samoilov, Phys. Rev. Lett. **71**, 617 (1993).
[21] M. Cagigal, A. Seffar, J. Fontcuberta, M. A. Crusellas, J. L. Vicent, and S. Piñol, Physica C **235-240**, 3177 (1994).
[22] M. Cagigal, J. Fontcuberta, M. A. Crusellas, J. L. Vicent, and S. Piñol, Physica C **248**, 155 (1995).
[23] A. T. Dorsey and M. P. A. Fisher, Phys. Rev. Lett. **68**, 694 (1992).
[24] V. M. Vinokur, V. B. Geshkenbein, M. V. Feigel'man, and G. Blatter, Phys. Rev. Lett. **71**, 1242 (1993).
[25] S. Okuma, H. Koyanagi, and N. Nishida, J. Phys. Soc. Jpn. **60**, 4017 (1991); S. Okuma and N. Nishida, Physica C **185-189**, 1925 (1991).
[26] M. A. Paalanen, A. F. Hebard, and R. R. Ruel, Phys. Rev. Lett. **69**, 1604 (1992).
[27] S. Okuma and N. Kokubo, Phys. Rev. B **51**, 15 415 (1995).
[28] S. Okuma, Mater. Sci. Eng. B **25**, 187 (1994); S. Okuma and N. Kokubo, Solid State Commun. **93**, 1019 (1995).
[29] A. F. Hebard and M. A. Paalanen, Phys. Rev. Lett. **65**, 927 (1990).
[30] S. Okuma and N. Kokubo, in *Proceedings of the 7th International Symposium on Superconductivity*, Kitakyushu, 1994, edited by K. Yamafuji and T. Morishita (Springer-Verlag, Tokyo, 1995), p. 113.
[31] S. Okuma and H. Hirai, Physica B **228**, 272 (1996).
[32] W. N. Kang *et al.*, Phys. Rev. Lett. **76**, 2993 (1996).
[33] Z. D. Wang, J. Dong, and C. S. Ting, Phys. Rev. Lett. **72**, 3875 (1994).
[34] R. Ikeda, J. Phys. Soc. Jpn. **65,** 3998 (1996).
[35] M. P. A. Fisher, Phys. Rev. Lett. **65**, 923 (1990).