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Scaling of the anomalous Hall effect in low Mn concentration (Ga,Mn)As

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We present magnetotransport in a series of $Ga_{1-x}Mn_xAs$ ($x\sim 0.014$) films. Both ordinary and anomalous Hall resistivities are analyzed in high magnetic field (up to 18.0 T) at various temperatures. The unique scaling behavior $n\sim 0.5$ is found for the entire series, which is not compatible with existing scattering theories. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2838477]

III-V-based diluted magnetic semiconductors are of interest due to their ability for controlling the spin degree of freedom, and consequently their potential for applications in spintronic devices.[1–3] However, certain fundamental properties of these alloys—e.g., the basic nature of their conduction—still hold many unexplained questions.[4] In this context magnetotransport measurements on $Ga_{1-x}Mn_xAs$—and especially the anomalous Hall effect (AHE)—have played a major role in clarifying these issues.[5–8] While most efforts for identifying the mechanisms of conduction—impurity band with weak localization[9,10] versus true disordered metal with delocalized holes[11,12]—have so far been focused on $Ga_{1-x}Mn_xAs$ with high Mn concentrations,[13] relatively little attention has been given to the case of insulating samples, where impurity band conduction is certain to occur.[14]

In this work we have carried out AHE measurements on $Ga_{1-x}Mn_xAs$ epilayers with low Mn concentration ($x=0.014$) in high magnetic fields (up to 18.0 T), where aligning all Mn spins along the field direction makes it possible to extract the ordinary Hall coefficient from the Hall data.[15,16]

The $Ga_{1-x}Mn_xAs$ films were grown on semi-insulating (001) GaAs substrates in a Riber 32 R&D dual-chamber (III-V and II-VI) molecular beam epitaxy system. Prior to $Ga_{1-x}Mn_xAs$ deposition a 400 nm ZnSe buffer layer was grown at 330 °C in the II-VI chamber. The substrate was then moved to the III-V chamber for the growth of a 300 nm layer of $Ga_{1-x}Mn_xAs$ around 250–280 °C. In samples used in this work the Mn concentration x was kept at the same level (~ 0.014), but the compensation level (and therefore the conductivity of the samples) was varied by varying the growth temperature and/or by Be codoping.[17] The parameters of the samples used in this study are summarized in Table I.

The transport measurements were carried out at the National High Magnetic Field Laboratory. A superconducting magnet with a variable temperature insert enabled us to sweep the field up to 18.0 T at various temperatures (2.0–200 K). The (Ga,Mn)As samples were cleaved into standard Hall bars with dimensions of $0.6\times 2\ \text{mm}^2$. The field was always applied perpendicular to the plane of the film.

The total Hall resistivity ρ_{xy} in an itinerant ferromagnet can be described by

$$\rho_{xy} = \rho^{\text{OH}} + \rho^{\text{AH}} = R_0B + R_SM_z, \tag{1}$$

where R_0 and R_S are the ordinary and the anomalous Hall coefficients, respectively. Usually AHE is ascribed to a scattering anisotropy induced by the spin-orbit interaction. Such scattering mechanisms can explain most of the qualitative features of the AHE observed in ferromagnets, including linear[18] and quadratic[19] correlations

$$R_S = a\rho_{xx} + b\rho_{xx}^2, \tag{2}$$

where ρ_{xx} is the longitudinal resistivity. The two terms on the right are known as skew and side-jump contributions, respectively. Recently a k-space Berry-phase theory of AHE (Ref. 11) with $R_S\propto\rho_{xx}^2$ has also been proposed and applied specifically to $Ga_{1-x}Mn_xAs$ in the metallic transport regime. On the other hand, an emerging model for the AHE in the hopping regime suggests that the Hall resistivity $\rho_{xy}\sim\rho_{xx}$ as a function of temperature, i.e., it diverges as $T\to 0$.[20]

In this work we will use a scaling relation $R_S=c\rho_{xx}^n$ (where n is a scaling factor) to investigate magnetotransport in the impurity band regime in $Ga_{1-x}Mn_xAs$ films. As a first step we take logarithm of both sides of Eq. (1):

$$\log(\rho_{xy} - R_0B) = \log cM_z + n\log\rho_{xx}. \tag{3}$$

Since in our experiments $\rho_{xy}\gg R_0B$, we obtain

$$\log\rho_{xy} \cong \log cM_z + \frac{1}{\ln 10}\frac{R_0B}{\rho_{xy}} + n\log\rho_{xx}. \tag{4}$$

At $T<T_C$, M_z will be saturated (all Mn spins are aligned along the z direction) and have therefore insignificant temperature dependence when a sufficiently strong magnetic field (e.g., >10 T) is applied, and we can then determine R_0, c, and n simultaneously from a logarithmic plot of ρ_{xy} versus ρ_{xx}.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 shows the longitudinal and transverse resistivities ρ_{xx} and ρ_{xy} of sample D (see Table I) at 2, 5, 10, 15, 20,

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TABLE I. Mn concentration x, longitudinal resistivity ρ_{xx}, scaling factor n, ordinary Hall coefficient R_0, Curie temperature T_C, and magnetization M at $B=2$ T and $T=2$ K for five $Ga_{1-x}Mn_xAs$ samples studied. Hall effect cannot be properly measured in samples A–C below 10 K due to very high resistivity.

Sample	Mn (x)	ρ_{xx} (20 K) (Ω cm)	n <10 K	n ~20 K	R_0 (20 K) (Ω cm/T)	T_C (K)	M (emu/cm^3)
A	1.4%	3.926		0.264	0.317	16	7.03
B	1.4%	0.906		0.292	0.157	18	6.81
C	1.4%	0.321		0.424	0.138	20	8.88
D	1.4%	0.045	0.914	0.508	0.026	24	8.81
E	1.6%	0.014	0.946	1.575	0.028	26	9.55

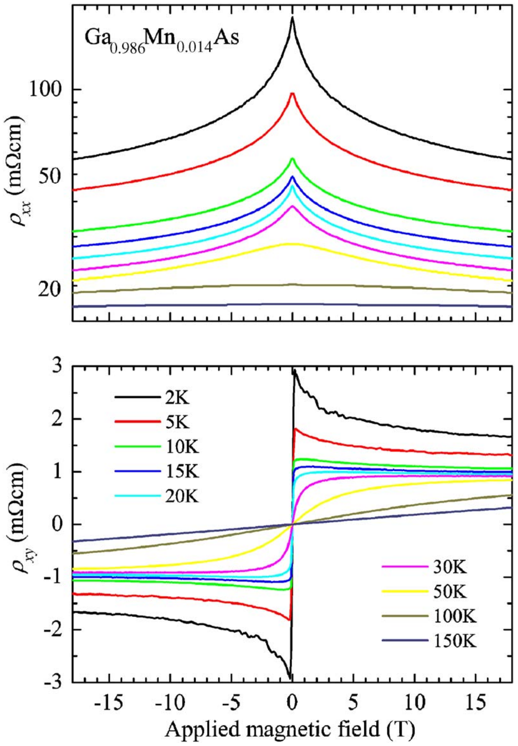

FIG. 1. (Color online) Field dependence of longitudinal resistivity ρ_{xx} (upper panel) and transverse resistivity ρ_{xy} (lower panel) obtained at various temperatures (from 2.0 up to 150 K) for sample D.

30, 50, 100, and 150 K. Above $B>0.05$ T a large negative magnetoresistance (MR) is observed at all temperatures and is especially distinct at low temperatures in the upper panel of Fig. 1. Note that in the high field region (~18 T) ρ_{xx} decreases with increasing field at a much slower rate, but never saturates.

The Hall resistivity ρ_{xy}, on the other hand (shown in the lower panel of Fig. 1), shows distinctly different field dependences for low and high temperatures (essentially below and above $T_C=24$ K). In the low temperature range ρ_{xy} starts with a rapid increase with field, reaching its maximum value around $B=0.09$ T. At higher fields ρ_{xy} drops continually (showing a negative slope that is characteristic of *electronlike* conduction). In contrast, for $T>T_C$ our results show that ρ_{xy} *always* increases with B, more steeply in the low field region and at a slower rate at high field, but the slope of the ρ_{xy} curve is always being positive (*holelike*). Thus the slope of ρ_{xy} at high fields experiences a sign change from negative to positive as the temperature rises. While such behavior could suggest that the conduction mechanism is changing with temperature from electronlike to holelike, we believe this to be unlikely. Considering the scaling relation $R_S=c\rho_{xx}^n$, we attribute this phenomenon to the competition between AHE and the ordinary Hall resistivity. Therefore, due to large and unsaturated negative MR, the ordinary Hall co-

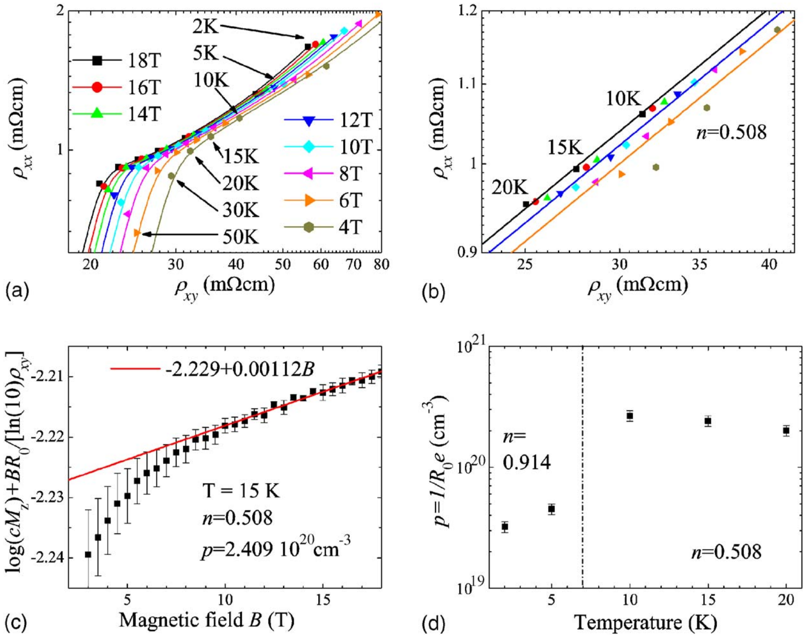

FIG. 2. (Color online) (a) Logarithmic plot of ρ_{xy} vs ρ_{xx} at various temperatures (2, 5, 10, 15, 20, 30, and 50 K) and magnetic fields (4.0–18.0 T) for sample D. (b) Linear fits with scaling factor $n=0.508$ at 10, 15, and 20 K for $B=6$, 12, and 18 T. (c) Magnetic field dependence of $\log(cM_z)+BR_0/[\ln(10)\rho_{xy}]$, and a linear fit for $B>10$ T from which the ordinary Hall coefficient R_0 is extracted. (d) Hole concentrations $p=1/R_0e$ at different temperatures; the vertical dashed line indicates a phase transition. Note that the scaling factor n is fixed at 0.914 for $T<10$ K and 0.508 for 10 K$<T<$20 K.

efficient R_0 and the anomalous Hall coefficient R_S cannot be determined directly from the intercept and the slope of the Hall response at high fields.

Equation (4), however, provides a straightforward approach for determining R_0, c, and n simultaneously from a logarithmic plot of ρ_{xy} versus ρ_{xx}. As shown in Fig. 2(a), such logarithmic plot shows ρ_{xy} to have a nearly linear relation with ρ_{xx} for $T < 30$ K. As the temperature increases, however, the curve begins to deviate from the linear behavior due to the fact that magnetization no longer saturates in the available field range. For 10, 15, and 20 K shown in Fig. 2(b) we find very good linear fits with a scale factor $n = 0.508$ for $B > 10$ T, but not at low fields [see fit for $B = 6$ T in Fig. 2(b)]. The similar relation is also found for ρ_{xx} and ρ_{xy} at 2 and 5 K but with different scale factor ($n = 0.914$, see Table I).

The linear fits in Fig. 2(b) clearly show a field dependent shift. From Eq. (4) we notice that the intercept of the linear fit line, $(\log cM_z + 1/\ln 10 \times R_0 B/\rho_{xy})$, is a function of B. In Fig. 2(c) we plot this intercept as a function of B for $T = 15$ K. At low field ($B < 10$ T) the intercept increases rapidly with field, demonstrating the variation of the unsaturated magnetization. On the other hand, at high field ($B > 10$ T) the plot clearly demonstrates a linear dependence on the field, indicating that all Mn ions in the sample are aligned along the field direction. Using this fixed slope we can extract $R_0 = \text{slope} \times \ln 10 \times \rho_{xy}$. In the metallic case one can then obtain the carrier concentration p by the relation $R_0 = 1/pe$, assuming a holelike conduction.

By applying the procedure to various temperatures (below T_C) where saturated magnetization can be achieved, we can obtain n, R_0, and p at a given temperature. The result is illustrated in Fig. 2(d), which shows temperature dependences (below T_C) of the scaling factor n and the calculated hole concentration $p = 1/R_0 e$. Note that the distinct jumps of n and p occurring between 5 and 10 K suggest the existence of an unknown phase transition below T_C. Furthermore, due to the nature of impurity conduction, the relation $p = 1/R_0 e$ is not really valid in the insulating regime. The apparent jump in the hole concentration might therefore indicate that such phase transition is related to a change of the mechanism of conduction in (Ga,Mn)As around 10 K.

In Table I we have listed the calculated results for all five samples studied. Based on the temperature dependences of ρ_{xx}, we see from the table that around the Curie temperature (20 K), as ρ_{xx} decreases, the samples change from insulating (A) to metallic (E). This is accompanied by increases in the scaling factor n and the T_C, and a decrease in R_0.

Finally, since $\rho_{xx} \gg \rho_{xy}$, we calculated the anomalous Hall conductivity σ_{xy} using the relation $\sigma_{xy} = \rho_{xy}/\rho_{xx}^2$. We plot σ_{xy} for all five samples listed in Table I as a function of ρ_{xx} in Fig. 3 for temperatures below T_C. The plot shows a reasonably good linear fit and we obtain a relation $\sigma_{xy} \propto \rho_{xx}^{-1.5}$, which also means that $\rho_{xy} \propto \rho_{xx}^{0.5}$ or $R_s \propto \rho_{xx}^{0.5}$, giving a scaling factor $n = 0.5$. Note that if we examine every sample in this plot separately, we will obtain a different value of n (from 0.2 to 1.0, as indicated in Table I) for each sample. However, it is interesting to have a universal scaling factor for all studied samples (whose resistivity varies by more than two orders of magnitude, from 0.008 to 3.0 Ω cm). Note that this result is surprisingly consistent with results obtained from digital ferromagnetic heterostructures (which have a scale factor of $0.4 < n < 0.6$).[14] Thus, although a value of $n < 1$ is not predicted by any existing models, our results present one of the characteristics of impurity band conduction in (Ga,Mn)As.

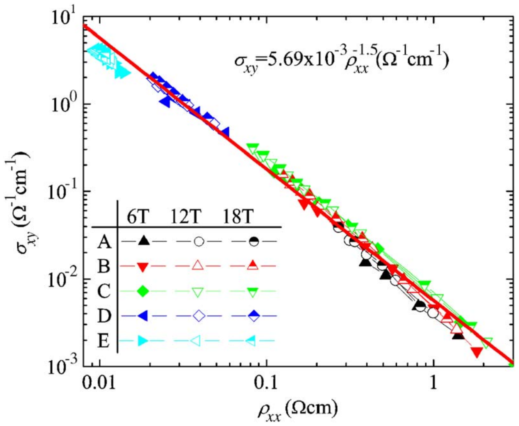

FIG. 3. (Color online) σ_{xy} as the function of ρ_{xx} for five samples studied in this paper. For each sample the experimental data are taken at three magnetic fields (6, 12, and 18 T) and at various temperatures below T_C.

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