DC-transport properties of ferromagnetic (Ga,Mn)As semiconductors

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We study the dc transport properties of (Ga,Mn)As diluted magnetic semiconductors with Mn concentration varying from 1.5% to 8%. Both diagonal and Hall components of the conductivity tensor are strongly sensitive to the magnetic state of these semiconductors. Transport data obtained at low temperatures are discussed theoretically within a model of band-hole quasiparticles with a finite spectral width due to elastic scattering from Mn and compensating defects. The theoretical results are in good agreement with measured anomalous Hall effect and anisotropic longitudinal magnetoresistance data. This quantitative understanding of dc magneto-transport effects in (Ga,Mn)As is unparalleled in itinerant ferromagnetic systems.

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Progress toward the realization of room-temperature ferromagnetism in semiconductors has motivated intensive research on (Ga,Mn)As and other transition metal doped III-V semiconductors. Improvements in growth techniques for (Ga,Mn)As diluted magnetic semiconductors (DMSs) continue to yield ever higher conductivities and transition temperatures [1, 2]. The magnetic properties of these ferromagnets have been successfully modeled using an effective Hamiltonian description of the exchange coupling between valence band hole spins and Mn local moments [3]. For example, non-trivial magneto-crystalline anisotropy effects have been explained [4, 5] using the simplest mean-field version of this model [6], together with the dependence on doping and carrier concentration of the ferromagnetic transition temperature [7], domain structure [8], and magneto-optical properties [4, 9].

In this Letter we establish that the mean-field theory, combined with a Born approximation description of impurity scattering, can describe the low-temperature dc magnetotransport properties on a quantitative level. In the first part of the Letter we discuss the anomalous Hall conductivity of a series of (Ga,Mn)As samples with varying Mn and hole densities and different lattice-matching strains. In the second part we compare the measured and calculated anisotropic magnetoresistance data.

Details of the sample preparation and measurement procedures are given elsewhere [1, 10]. All the experimental results presented are for a temperature of 4.2 K. The samples are metallic and show very weak isotropic magnetoresistance at this temperature. This enables us to obtain values for the hole densities with an accuracy of about 10% from the normal Hall coefficient, assuming that the magnetization is saturated in the range of fields from 10 to 16 Tesla. The greatest uncertainty in the analysis of the data stems from the unknown density of defects and their distribution in the lattice. In our theoretical model we neglect any inhomogeneity that may have resulted, e.g. along the growth direction, from the non-equilibrium, low-temperature MBE growth. The only acceptors assumed in the calculations are substitutional Mn ions that provide one hole per impurity which is exchange coupled to the Mn local moment $S = 5/2$. We report on calculations based on two extreme scenarios that are consistent with the Mn acceptor compensation we observe and hopefully bracket the situations achievable in experimental samples. The first scenario assumes compensation only by Mn-interstitial defects that act as double-donors whose local moments are magnetically decoupled from the itinerant-hole and Mn moments, while the second assumes compensation only by non-magnetic As-antisite defects which also act as double-donors [11]. In the former case, the densities of substitutional and interstitial Mn ions used in the calculations are obtained from the experimental total (nominal) Mn density and the measured itinerant hole density, while in the latter model the density of the substitutional Mn ions is equal to the nominal Mn density.

One of the key tools used to characterize and study itinerant ferromagnetic metals is the anomalous Hall effect (AHE) [12, 13, 14], a contribution to the Hall coefficient due to spontaneous magnetization. The AHE occurs because of spin-orbit interactions. In metals [14] the standard assumption has been that the AHE occurs because of a spin-orbit coupling component in the interaction between band quasiparticles and crystal defects, which can lead to skew scattering [13] and side jump scattering [15] that give Hall *resistivity* contributions proportional to ρ and ρ^2 respectively. Our AHE theory differs fundamentally from this standard picture because the effect arises from spin-orbit coupling in the Hamiltonian of the perfect crystal which implies a finite Hall *conductivity* even without disorder.

The approach we use has its roots in the first theoretical study of the AHE by Karplus and Luttinger [12] who considered a band Hamiltonian with spin-orbit coupling, whose eigenstates are translationally-invariant Bloch waves of non-interacting electrons. A **k**-space Berry's phase interpretation of this *intrinsic* contribution to the anomalous wave-pocket velocity term is given in our previous semiclassical study [16] of the AHE in ferromagnetic semiconductors. For clean systems, the same anomalous Hall conductivity expression can be obtained starting from the Kubo formula [17]. The Kubo formula has been used, e.g., to analyze the AHE in layered 2D ferromagnets such as $SrRuO_3$ or in pyrochlore ferromagnets [18] and has been recognized [17] as a natural starting point to address infrared magneto-optic effects such as the Kerr and Faraday effects. The quantum-mechanical approach provides a convenient way to approximately include band-dependent quasiparticle broadening in the theory expressions.

In Fig. 1 we plot theoretical anomalous Hall conductivities calculated using the disorder-free, semiclassical Berry's phase formula [16]

$$\sigma_{AH} = -\frac{2e^2}{\hbar}\sum_{n'}\int\frac{d\vec{k}}{(2\pi)^3}f_{n',\vec{k}}\mathrm{Im}[\langle\partial u_n/\partial k_y|\partial u_n/\partial k_x|\rangle] \tag{1}$$

or the equivalent [17] Kubo formula

$$\begin{aligned}\sigma_{\mathrm{AH}} &= \frac{e^2\hbar}{m^2}\int\frac{d\vec{k}}{(2\pi)^3}\sum_{n\neq n'}(f_{n',\vec{k}}-f_{n,\vec{k}}) \\ &\times\frac{\mathrm{Im}[\langle n'\vec{k}|\hat{p}_x|n\vec{k}\rangle\langle n\vec{k}|\hat{p}_y|n'\vec{k}\rangle]}{(E_{n\vec{k}}-E_{n'\vec{k}})^2}.\end{aligned} \tag{2}$$

The clean-system data are compared with results obtained from the modified Kubo formula

$$\begin{aligned}\sigma_{\mathrm{AH}} &= -\tfrac{e^2\hbar}{m^2V}\textstyle\sum_{\vec{k},n\neq n'}(f_{n',\vec{k}}-f_{n,\vec{k}}) \\ \times\ &\mathrm{Im}[\langle n'\vec{k}|\hat{p}_x|n\vec{k}\rangle\langle n\vec{k}|\hat{p}_y|n'\vec{k}\rangle]\tfrac{\Gamma^2_{n,n'}-(E_{n\vec{k}}-E_{n,\vec{k}'})^2}{((E_{n\vec{k}}-E_{n'\vec{k}})^2+\Gamma^2_{n,n'})^2},\end{aligned} \tag{3}$$

which accounts for the finite lifetime broadening of the quasiparticle states. The effective lifetime for transitions between bands n and n', $\tau_{n,n'}\equiv\hbar/\Gamma_{n,n'}$, is calculated by averaging quasiparticle scattering rates calculated from Fermi's golden rule including both screened Coulomb and exchange potentials of randomly distributed substitutional Mn and compensating defects [9, 11]. In Fig. 1 we assume that compensation is due entirely to As-antisite defects. The valence band hole eigenenergies $E_{n\vec{k}}$ and eigenvectors $|n\vec{k}\rangle$ in Eqs. (1)-(3) were obtained by solving the six-band Kohn-Luttinger Hamiltonian in the presence of the exchange field, $\vec{h} = N_{Mn}SJ_{pd}\hat{z}$ [5]. Here $N_{Mn} = 4x/a^3_{DMS}$ is the Mn density in the $Mn_xGa_{1-x}As$ epilayer with a lattice constant a_{DMS}, the local Mn spin $S = 5/2$, and the exchange coupling constant $J_{pd} = 55$ meV nm^{-3} [19].

Fig. 1 demonstrates that whether or not disorder is included, the theoretical anomalous Hall conductivities are of order 10 Ω^{-1} cm^{-1} in the (Ga,Mn)As DMSs with typical hole densities, $p\sim 0.5$ nm^{-1}, and Mn concentrations of several per cent. On a quantitative level, disorder tends to enhance σ_{AH} at low Mn doping and suppresses AHE at high Mn concentrations where the quasiparticle broadening due to disorder becomes comparable to the strength of the exchange field. The inset in Fig. 1 also indicates that the magnitude of the AHE in both models is sensitive not only to hole and Mn densities but also to the lattice-matching strains between substrate and the magnetic layer, $e_0 = (a_{substrate} - a_{DMS})/a_{DMS}$.

A systematic comparison between theoretical and experimental AHE data is presented in Fig. 2. The results are plotted vs. nominal Mn concentration x while other parameters of the seven samples studied are listed in the figure legend. The measured σ_{AH} values are indicated by filled squares; triangles are theoretical results obtained in the clean limit or for a disordered system assuming either the As-antisite or Mn-interstitial compensation scenario, described above. In general, when disorder is accounted for, the theory is in a good agreement with experimental data over the full range of studied Mn densities from $x = 1.5\%$ to $x = 8\%$. The effect of disorder, especially when assuming Mn-interstitial compensation, is particularly strong in the $x = 8\%$ sample shifting the theoretical σ_{AH} much closer to experiment compared to the clean limit theory. The remaining quantitative discrepancies between theory and experiment can be attributed to inaccuracy in experimental hole and Mn densities, and to approximations we made in modeling disorder in these samples.

In addition to the AHE, strong spin-orbit coupling in the semiconductor valence band leads also to anisotropies in the longitudinal transport coefficients. In particular, the in-plane conductivity changes when the magnetization **M** is rotated by applying an external magnetic field stronger than the magneto-crystalline anisotropy field. In Fig. 3 we plot theoretical and experimental AMR coefficients, $AMR_{op} = [\sigma_{xx}(\mathbf{M}\parallel\hat{z}) - \sigma_{xx}(\mathbf{M}\parallel\hat{x})]/\sigma_{xx}(\mathbf{M}\parallel\hat{x})$ and $AMR_{ip} = [\sigma_{xx}(\mathbf{M}\parallel\hat{y}) - \sigma_{xx}(\mathbf{M}\parallel\hat{x})]/\sigma_{xx}(\mathbf{M}\parallel\hat{x})$, for the seven (Ga,Mn)As samples discussed above. Here $\hat{z}$ is the growth direction. The theoretical results were obtained using the same linear response and Born approximation framework as in the AHE case [11]. Results of the two disordered system models, one assuming As-antisite and the other one Mn-interstitial compensation, are plotted in Fig. 3. As in the AHE case, the theoretical results are able to account semi-quantitatively for the AMR effects in the (Ga,Mn)As DMSs studied, with somewhat better agreement obtained for the model that assumes Mn-interstitial compensation. Note, that the absolute longitudinal conductivities we obtain from

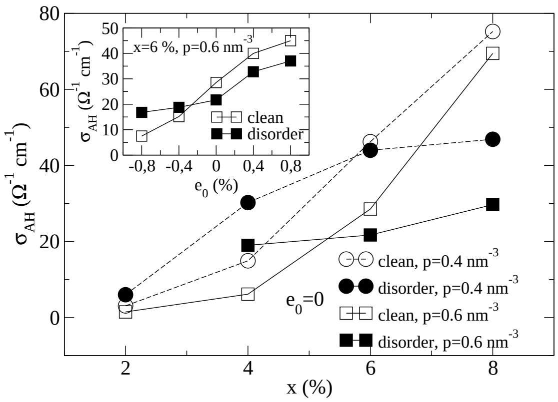

FIG. 1: Theoretical anomalous Hall conductivity of $Mn_xGa_{1-x}As$ DMS calculated in the clean limit (open symbols) and accounting for the random distribution of Mn and As-antisite impuriries (filled symbols).

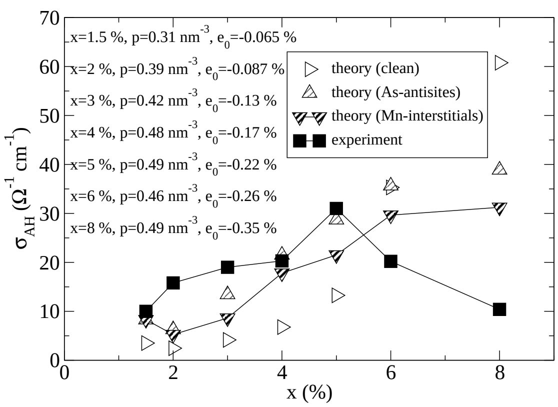

FIG. 2: Comparison between experimental and theoretical anomalous Hall conductivities.

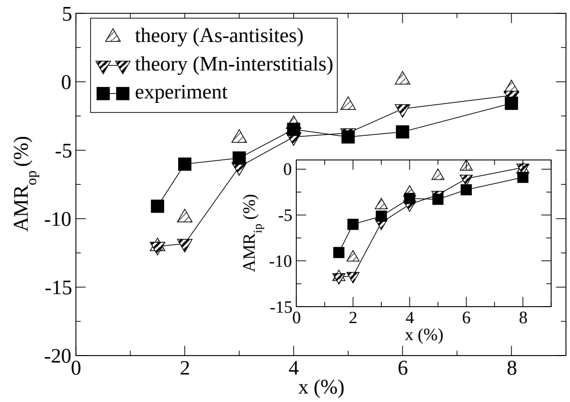

FIG. 3: Experimental (filled symbols) AMR coefficients and theoretical data obtained assuming As-antisite compensation (open symbols) and Mn-interstitial compensation (semi-filled symbols). See text for definitions of AMR_{op} and AMR_{ip}.

these calculations are several times larger than observed values. This likely demonstrates that our simple treatment of disorder effects doesn't produce accurate values for quasiparticle scattering amplitudes off particular defects. However, the magnetotransport effects discussed above are relatively insensitive to scattering strength, reflecting instead mainly the strong spin-orbit coupling in the valence band of the host semiconductor.

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[1] K. Edmonds, K. Wang, R. Campion, A. Neumann, N. Farley, B. Gallagher, and C. Foxon, Appl. Phys. Lett. **81**, 4991 (2002).

[2] K. C. Ku, S. J. Potashnik, R. F. Wang, M. J. Seong, E. Johnston-Halperin, R. C. Meyers, S. H. Chun, A. Mascarenhas, A. C. Gossard, D. D. Awschalom, et al., con-mat/0210426.

[3] T. Dietl, H. Ohno, F. Matsukura, J. Cibert, , and D. Ferrand, Science **287**, 1019 (2000).

[4] T. Dietl, H. Ohno, and F. Matsukura, Phys. Rev. B **63**, 195205 (2001).

[5] M. Abolfath, T. Jungwirth, J. Brum, and A. H. MacDonald, Phys. Rev. B **63**, 054418 (2001).

[6] T. Jungwirth, W. Atkinson, B. Lee, and A. MacDonald, Phys. Rev. B **59**, 9818 (1999).

[7] T. Jungwirth, J. Konig, J. Sinova, J. Kučera, and A. MacDonald, Phys. Rev. B **66**, 012402 (2002).

[8] T. Dietl, J. Konig, and A. MacDonald, Phys. Rev. B **64**, R241201 (2001).

[9] J. Sinova, T. Jungwirth, S.-R. E. Yang, J. Kučera, and A. H. MacDonald, Phys. Rev. B **66**, 041202 (2002).

[10] K. Wang, K. Edmonds, R. Campion, L. Zhao, A. Neumann, C. Foxon, B. Gallagher, and P. Main, cond-mat/0211697.

[11] T. Jungwirth, M. Abolfath, J. Sinova, J. Kučera, and A. H. MacDonald, Appl. Phys. Lett. **81**, 4029 (2002).

[12] R. Karplus and J. Luttinger, Phys. Rev. **95**, 1154 (1954).

[13] J. Smit, Physica (Amsterdam) **21**, 877 (1955).

[14] in *The Hall Effect and Its Applications*, edited by C. Chien and C. R. Westgate (Plenum, New York, 1998).

[15] L. Berger, Phys. Rev. B **2**, 4559 (1970).

[16] T. Jungwirth, G. Niu, and A. MacDonald, Phys. Rev. Lett. **88**, 207208 (2002).

[17] J. Sinova, T. Jungwirth, and A. MacDonald, to be published.

[18] M. Onoda and N. Nagaosa, J. Phys. Soc. Jpn. **71**, 19 (2002).

[19] H.Ohno, J. Magn. Magn. Mater. **200**, 110 (1999).