Anomalous Nernst Effect in GaMnAs: What Do We Learn from It?

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Outline

- Introduction
  - Transport coefficients
  - Anomalous transport: anomalous Hall effect (AHE) & anomalous Nernst effect (ANE)
  - Origin of AHE
- AHE and ANE in GaMnAs
  - Importance of B=0
  - Validating Mott relation without measuring magnetization
  - Scattering rate-independent Nernst current
- Summary
Various Transport Effects

If $\Delta V_x$ or $\Delta T_x$ is present, there will be both charge and heat currents in $x$- and $y$- directions (with out-of-plane B-field). In open-circuit geometry, voltages and temperature drops are measured.

<table>
<thead>
<tr>
<th>Effect</th>
<th>$V_x (I_x)$</th>
<th>$V_y (I_y)$</th>
<th>$\Delta T_x (\dot{Q}_x)$</th>
<th>$\Delta T_y (\dot{Q}_y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cause</td>
<td>$\Delta V_x (I_x)$</td>
<td>Resistivity</td>
<td>Hall effect</td>
<td>Peltier effect</td>
</tr>
<tr>
<td></td>
<td>$\Delta T_x (\dot{Q}_x)$</td>
<td>Seebeck effect</td>
<td>Nernst effect</td>
<td>Thermal conductivity</td>
</tr>
</tbody>
</table>

Hall effect

$nernst effect$

\[
S_{xx} = \frac{E_x}{(\nabla T)_x} = -\frac{\Delta V_x}{\Delta T_x}
\]

\[
S_{yy} = \frac{E_y}{(\nabla T)_x} = -\frac{\Delta V_y}{\Delta T_x}
\]

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Thermoelectric Measurements

- Seebeck leads
- BiTe Nanowire
- Nemst leads
- Top view
- Macroscopic GaMnAs sample
- Sample holder

Typical $\Delta T \sim 50$ mK; $\Delta T$ is measured by microfabricated thermometers.
In open-circuit geometry, $J_x = J_y = 0$; $\Delta T$ is along $x$-direction.

$$J_x = \sigma_{xx} E_x + \sigma_{xy} E_y - \alpha_{xx} \partial_x T - \alpha_{xy} \partial_y T = 0$$

$$J_y = \sigma_{yx} E_x + \sigma_{yy} E_y - \alpha_{yx} \partial_x T - \alpha_{yy} \partial_y T = 0$$

We experimentally determine $S_{xx}$ and $S_{xy}$ by, $S_{xx} = E_x / \partial_x T$, $S_{xy} = E_y / \partial_y T$

Mott relations:

$$\alpha_{xx} = \frac{\pi^2 k_B^2 T}{3e} \sigma_{xx} \quad \text{and} \quad \alpha_{xy} = \frac{\pi^2 k_B^2 T}{3e} \sigma_{xy}$$

$$S_{xx} = \frac{\pi^2 k_B^2 T}{3e} \left[ \ln \sqrt{\sigma_{xx}^2 + \sigma_{xy}^2} \right] \approx \frac{\pi^2 k_B^2 T}{3e} \left( \ln \sigma_{xx} \right)$$

$$S_{xy} = \frac{\pi^2 k_B^2 T}{3e} \left[ \arctan \left( \frac{\sigma_{xy}}{\sigma_{xx}} \right) \right] = \frac{\pi^2 k_B^2 T}{3e} \Theta_H$$

Nernst coefficients are fundamentally related to resistivity and Hall coefficient!

Longitudinal: equ unaltered by B-field!

Transverse: proportional to energy derivative of Hall angle
Anomalous Hall Effect (AHE)

In ferromagnets, $\rho_{xy}$ contains two parts:

$$\rho_{xy} = R_0 B + R_s M$$

$\rho_{AH}$: anomalous or extraordinary Hall

AHE has been used to study ferromagnetism in ultra-thin magnetic films whose magnetic moment is too small to be detected by magnetometry

*AHE from 5 nm-thick (In, Mn)As layer*
Physical Origin of AHE

Spin-orbit effect: extrinsic (scattering) or intrinsic (band structure)

- Karplus & Luttinger (intrinsic: inter-band effect)
- Smit (extrinsic: skew scattering)
- Berger (extrinsic: side-jump)
- Niu & MacDonald (intrinsic: Berry’s phase)

See excellent review articles: J. Phys.: Condens. Matter by N.A. Sinitsyn; Rev. of Mod. Phys. by J. Sinova; Rev. of Mod. Phys. by N. Nagaosa et al.

Power-law:

\[ R_s = \lambda \rho_{xx}^n \]

- n=2: \( \sigma_{xy} \sim \rho_{xy}/\rho_{xx}^2 \) (\( \rho_{xx} \gg \rho_{xy} \)) \( \to \) independent of \( 1/\tau \)!

\( \Rightarrow \) Special Hall current: \( J_H = \sigma_{xy} E_x \)

- n=1: skew scattering (extrinsic)
Power-Law Behavior

- Iron: $n=1.94$
- Nickel: $n=1.42$
- CuCr$_2$Se$_{4-x}$Br$_x$

- Consensus is lacking
- Semiconductors or alloys are preferred


Mn substitutes Ga in GaAs: introducing spin and charge carriers!

Dilute Magnetic Semiconductors (DMS)

- Carrier-mediated interaction

Ferromagnetic with Tc ~ 150 K!
AHE in GaMnAs

- Spin-orbit coupling
- External electric field \( E \)

Electron wavepackets acquire additional velocity:

\[
\dot{x}_c = \frac{\partial \epsilon}{\hbar \partial k} + \left(\frac{e}{\hbar}\right) \vec{E} \times \vec{\Omega}.
\]

Anomalous velocity

Under broken time reversal symmetry, this Berry phase effect alone gives rise to AHE comparable with experimental values

→ Intrinsic origin of AHE in DMS

Jungwirth, Niu and McDonald, PRL (02)

Jungwirth et al. APL (03)
Experimental Difficulties with DMS

\[ \rho_{xy} = R_0 B_z + R_s M_z = R_0 B_z + \lambda \rho_{xx}^n M_z \]

- In-plane anisotropy films often require high magnetic fields to obtain finite AHE (i.e. \( M_z \))
- High magnetic fields cause significant magnetoresistance (i.e. change in \( \rho_{xx} \))
- Magnetization does not go hand-in-hand with AHE signal
- Does ANE exist in DMS if AHE is caused by intrinsic mechanism (see PRL by D. Xiao)?
Goals and Approaches

- To demonstrate ANE in DMS (not been done)
- To carry out experiments at B=0 (not been done)
- To experimentally establish Mott relation for *intrinsic* ANE (not obvious; theory by D. Xiao PRL 07)
- To investigate nature of AHE using four transport coefficients (not trivial: difficult M measurements, requirement of high-fields for in-plane sample, but MR is large!…)

\[ S_{xy} \propto \Theta'_H \approx \left( \frac{\rho_{xy}}{\rho_{xx}} \right)' = \left( \lambda M \rho^{n-1}_{xx} \right)' \]

Find “n” using all four transport coefficients!
Ordinary Nernst Effect and Mott Relation

- Ordinary Nernst effect does exist
- Mott relation is applicable

Ordinary Nernst effect in graphene:

\[ S_{xy} \sim B \]
GaMnAs with Perpendicular Anisotropy

InGaAs buffer layer → tensile strain → perpendicular anisotropy

Sharp hysteresis → zero-field AHE and resistivity well-defined

$AHE$

Long. MR

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AHE & ANE in GaMnAs

No ordinary Nernt effect is visible; $S_{yx}$ goes with $\rho_{xy}$
AHE & ANE

- $x=0.04^*$ (annealed)

\[ \rho_{xy} (\mu\Omega cm) \]

\[ S_{xy} (\Omega m/K) \]

\[ B(kG) \]

- There is a sign change in $S_{xy}$
- AHE and ANE scale with each other $\rightarrow$ share the same physical origin!
Zero-Field $S_{xx}$ and $S_{yx}$

- $S_{yx}$ changes sign where $S_{xx}$ shows peak at low temperatures
- $S_{xx}$ is always positive $\rightarrow$ hole conduction
- Annealing enhances low-T $S_{xx}$ peak
Testing Mott Relation

\[ \rho_{xy} = \lambda M \rho_{xx} \]  
\[ \text{Mott relation} \rightarrow \]

\[ S_{yx} = \lambda M \rho_{xx}^{n-1} \left( T \frac{\pi^2 k_B^2}{3e} \frac{\lambda'}{\lambda} - (n-1)S_{xx} \right) \]

We have

\[ S_{yx} = \frac{\rho_{xy}}{\rho_{xx}} \left( T \frac{\pi^2 k_B^2}{3e} \frac{\lambda'}{\lambda} - (n-1)S_{xx} \right) \]

Replace M by \( \sigma_{xx} \) & \( \sigma_{xy} \) by reusing the power-law

- No longer need to measure M separately \( \rightarrow \) removing uncertainty in M measurements
- All transport coefficients are from exactly same region (Hall cross)
$S_{yx}$ Sign Change

\[ S_{yx} = \frac{1}{\sigma_{xx}} \left( \alpha_{yx} - \sigma_{yx} S_{xx} \right) \]

\[ S_{yx} = \frac{\rho_{xy}}{\rho_{xx}} \left( T \frac{\pi^2 k_B^2}{3e} \frac{\lambda'}{\lambda} - (n-1)S_{xx} \right) \]

If \( n=1 \), \( S_{yx} \) is determined by the first term. However nothing in 1\textsuperscript{st} term can change sign.

Sign change is only possible if \( n > 1 \), \( \rightarrow \) NOT skew scattering!

Sign change \( \rightarrow \) rule out \( n=1 \) qualitatively; but to quantitatively determine exponent \( n \) we need to fit \( S_{xy} \) data.

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Testing Mott Relation

Red solid lines are fits to Mott relation

Mott relation works for $n=2$!

$S_{yx}$ ($\mu$V/K)

$T$ (K)
Intrinsic Nernst Current: $J_N$

$$\alpha_{yx} = \frac{\rho_{xy}}{\rho_{xx}^2} \left( T \frac{\pi^2 k_B^2}{3e} \frac{\lambda'}{\lambda} - (n-2) S_{xx} \right)$$

Nernst current:

$$J_N = -\alpha \nabla T$$

$n=2 \rightarrow$ nothing in $\alpha_{yx}$ depends on scattering!

$\rightarrow$ intrinsic Nernst current
Summary

- Anomalous Nernst effect (ANE) is observed in GaMnAs
- AHE and ANE share the same physical origin
- “n=2” is obtained from zero-field AHE and ANE
- Using all transport coefficients, no magnetization is needed → we have reliably determined the nature of AHE
- Our results suggest intrinsic Nernst current $J_N$
- Mott relation is experimentally validated for scattering rate-independent anomalous transport
Discussion: 1. Effect of High B-Field

In most experiments with in-plane anisotropy samples, high magnetic fields are used, but the effect of B-field on the power-law scaling is unclear. Which field is the proper one?

Our own results in Ga$_{1-x}$Mn$_x$As
Find Exponent $n$

- Exponent is not always one or two
- Separate magnetization measurement is needed
- Hall loops are different from MH loops
$R_{xy}$ and M Measurements

Transport

$X = 0.03 \ T = 6K$

$H_c = 150 \text{ Oe}$

Magnetization

$x = 0.03 \ T = 6K$

$m'$

Probing area $\sim (100 \ \mu m)^2$

$H_c = 150 \text{ Oe}$

$T = 8K$