Anomalous Hall/Nernst Effects in Magnetic Semiconductors and Magnetic Insulators

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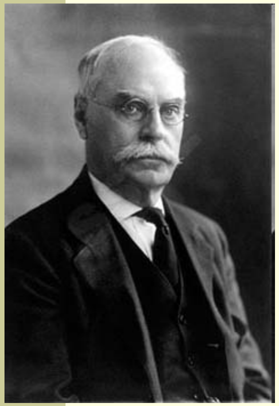
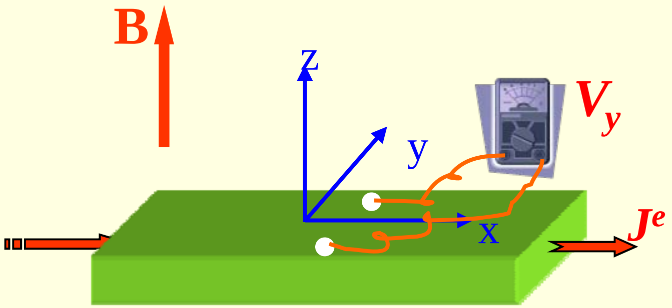
Outline

- Introduction
  - Anomalous Hall effect (AHE)
  - Anomalous Nernst effect (ANE)
- GaMnAs: Dilute Magnetic Semiconductor (DMS)
  - AHE/ANE in absence of B-field
  - Validity of Mott relation with n=2
  - Hole-mediated ferromagnetism, probably via impurity band
- Fe_3O_4: Ferrimagnetic Insulator (FMI)
  - Robust AHE power-law scaling with n=0.3
  - Preliminary ANE data: absence of ANE
- Summary

Anomalous Hall Effect (AHE)



In ferromagnets, ρ_{xy} contains two parts:



Normal or ordinary Hall effect (OHE)

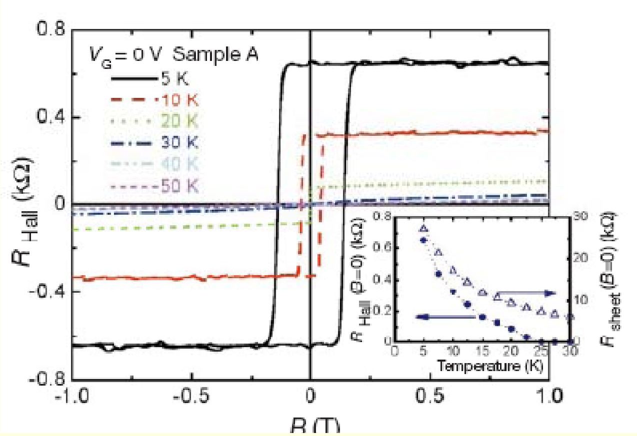
$$\rho_{xy} = R_0 B + R_s M$$

ρ_{AH}: anomalous or extraordinary Hall effect (AHE)

- ρ_{xy} exists even if B=0
- AHE is more than an order greater than OHE

→ $\rho_{xy} \sim \rho^{AH}$

AHE is not caused by magnetic field, but by spin-orbit coupling (SOC)

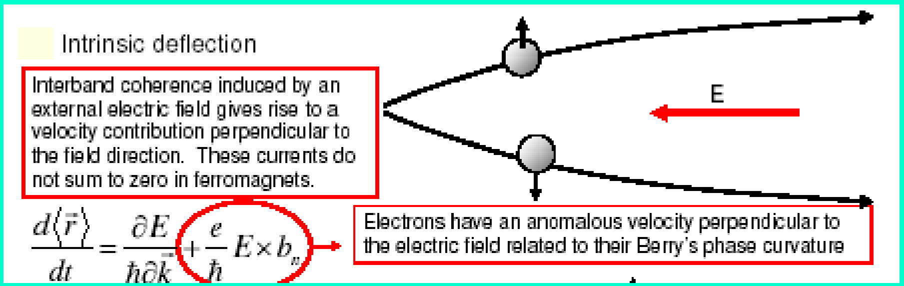


AHE from 5 nm-thick (In, Mn)As layer

Physical Origin of AHE

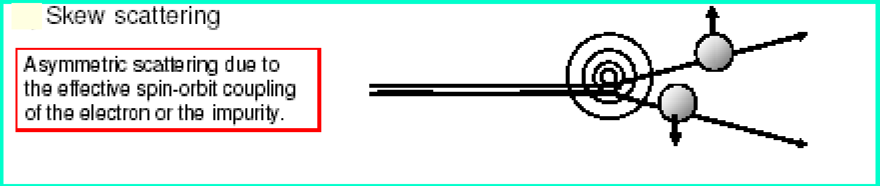
Spin-orbit effect: extrinsic (scattering) or intrinsic (band structure)

❖ Karplus & Luttinger (intrinsic: inter-band effect)

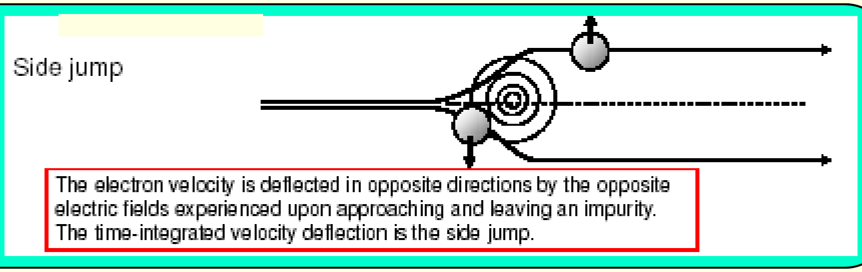


See excellent review articles: N.A. Sinitsyn, J. Phys.: Condens. Matter (2008); N. Nagaosa et al., Rev. Mod. Phys. (2010).

❖Smit (extrinsic: skew scattering)



❖Berger (extrinsic: side-jump)



❖Niu & MacDonald (intrinsic: Berry's phase)

Power-Law

Power-law: $$R_s = \lambda \rho_{xx}^n$$

- Exponent n=2:

$$\sigma_{xy} \sim \rho_{xy} / \rho_{xx}^2$$ ($\rho_{xx} >> \rho_{xy}$)

→ independent of $1/\tau$!

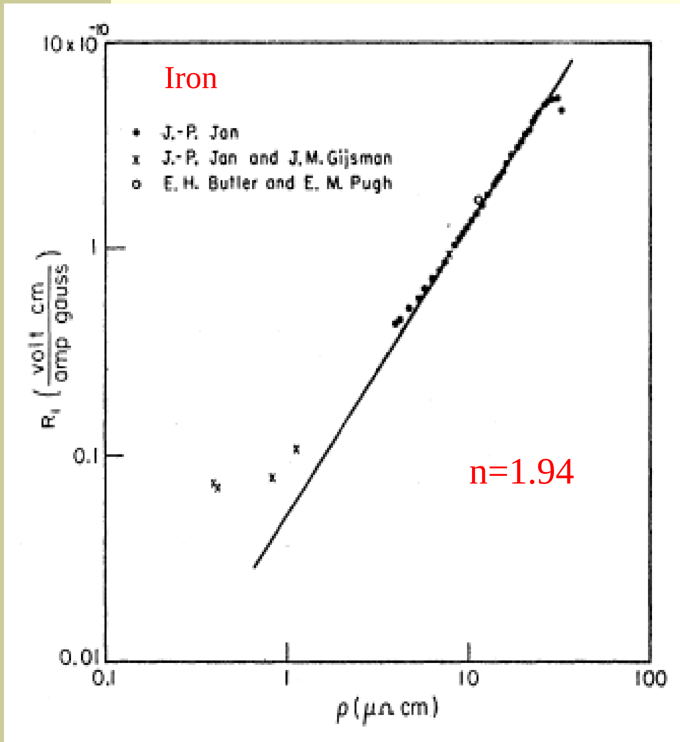
→ Special Hall current: $J_H = \sigma_{xy} E_x$

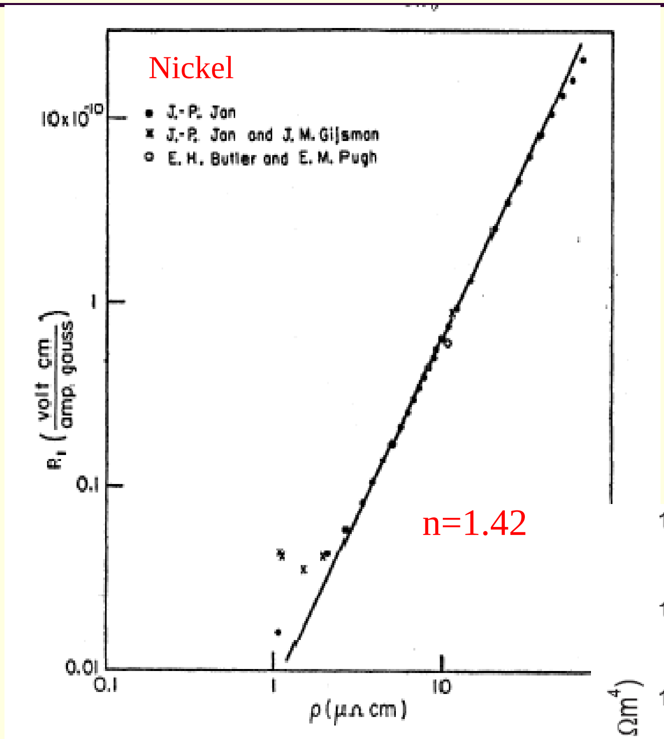
- Exponent n=1:

$$\sigma_{xy} \sim \sigma_{xx}$$

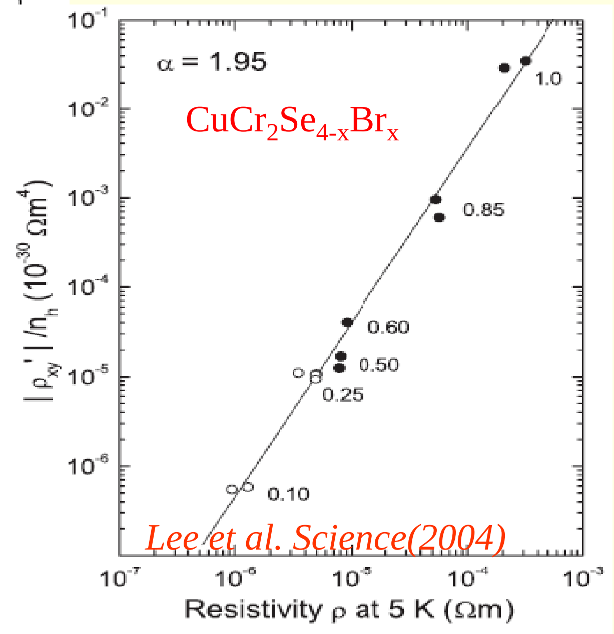
skew scattering (extrinsic)

Experimental Data





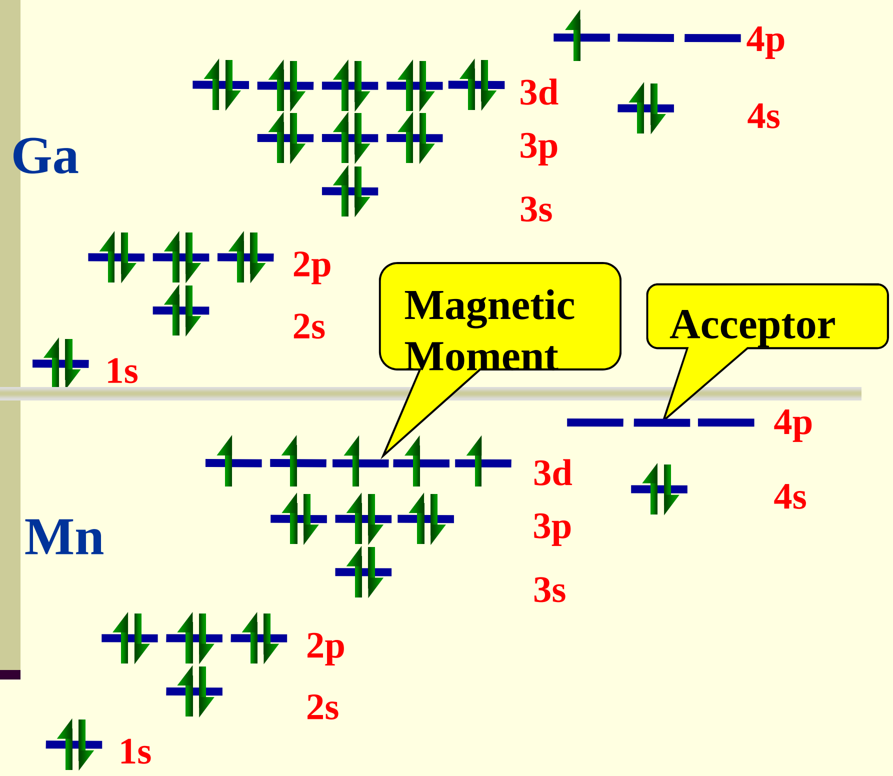
Pure metals are not ideal



- Scattering rate can be tuned by impurity, temperature or magnetic field
- Semiconductors or alloys are preferred

Dilute Magnetic Semiconductors (DMS)

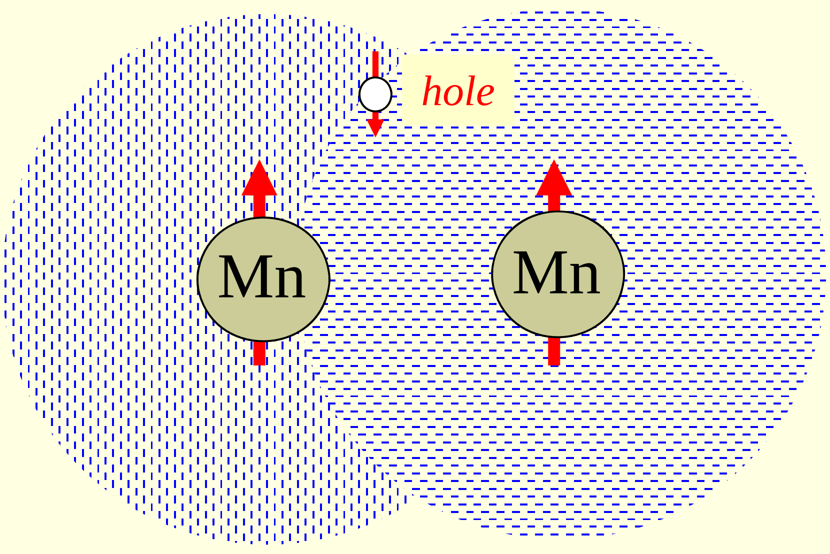
$Ga_{1-x}Mn_xAs$: most studied DMS



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

- Carrier-mediated interaction

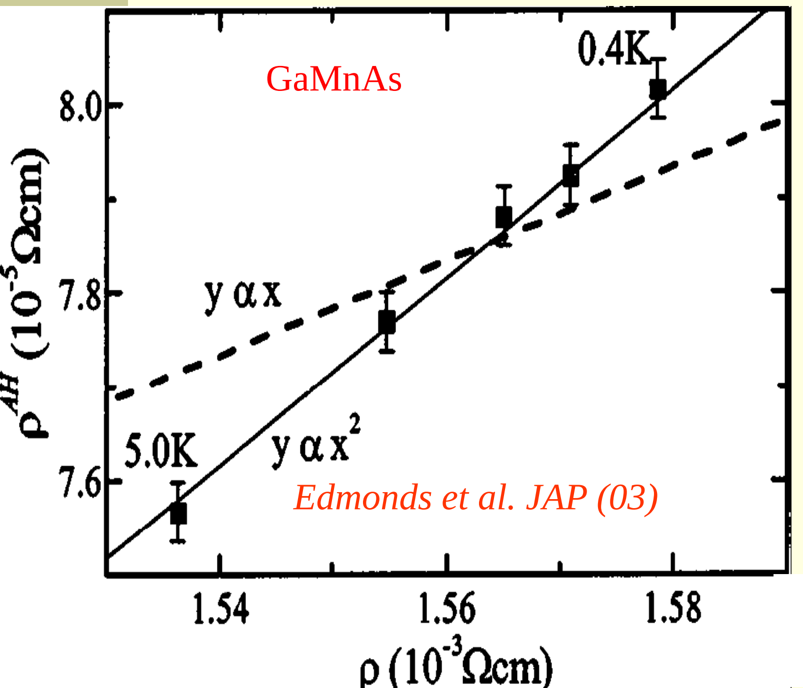
Zener model: $T_c \sim x^*p^{1/3}$

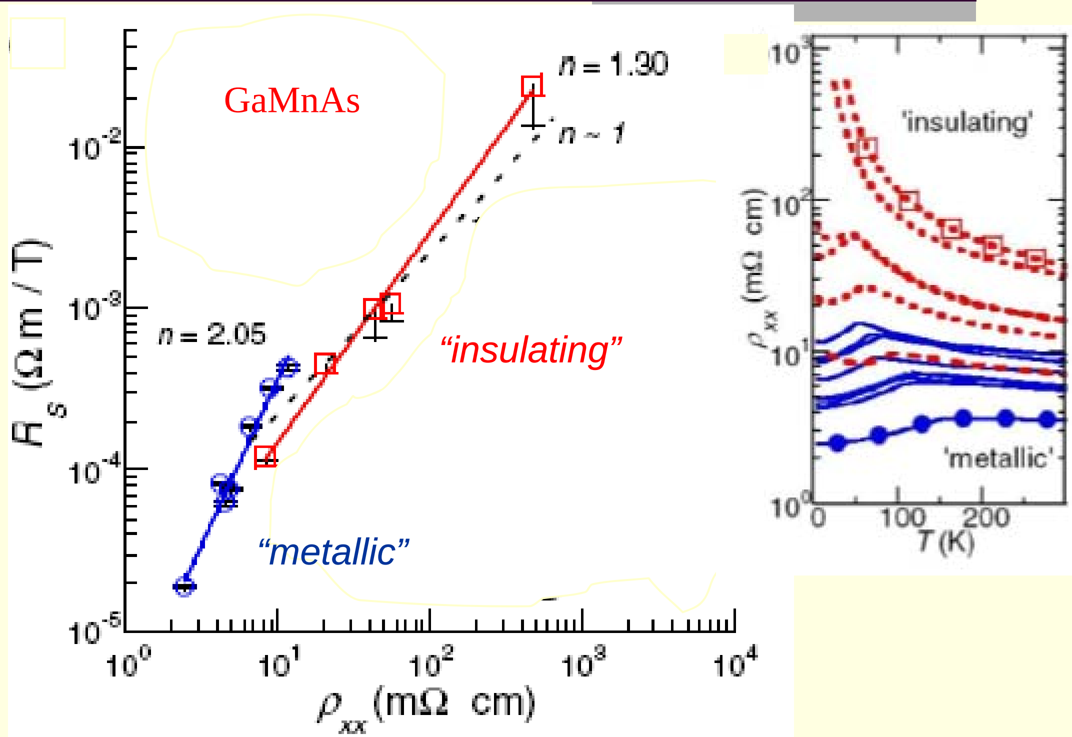


Highest T_c ~ 150 K!

- Strong SOC for holes in GaAs
- Strong impurity scattering

AHE in DMS





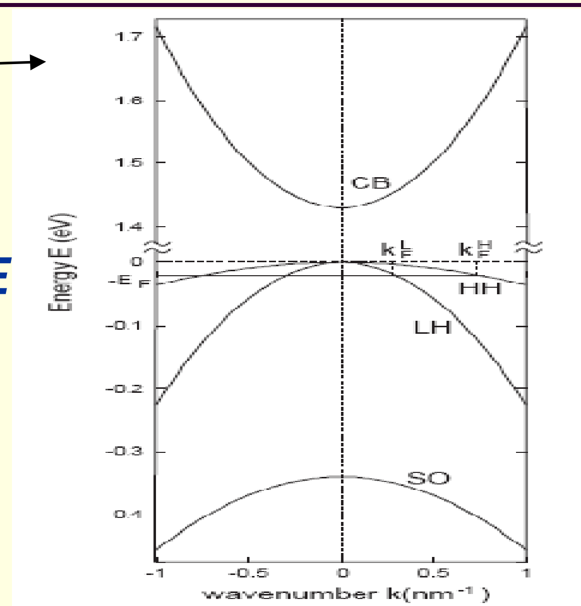
Chun et al., PRL (07)

Results support intrinsic mechanism (but the resistivity range is too narrow)

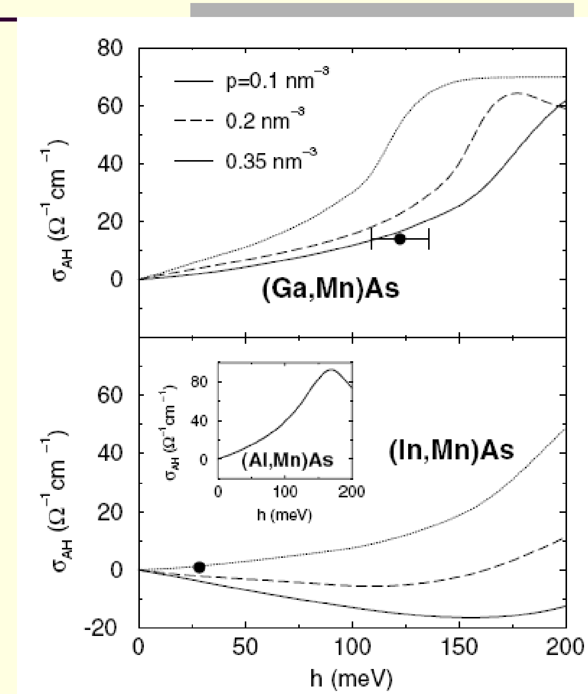
n~ 2 and AHE's carrier density dependence in "metallic" regime → intrinsic origin

DMS: Intrinsic AHE

GaAs band structure →



- ➢Spin-orbit coupling
- ➢External electric field ***E***

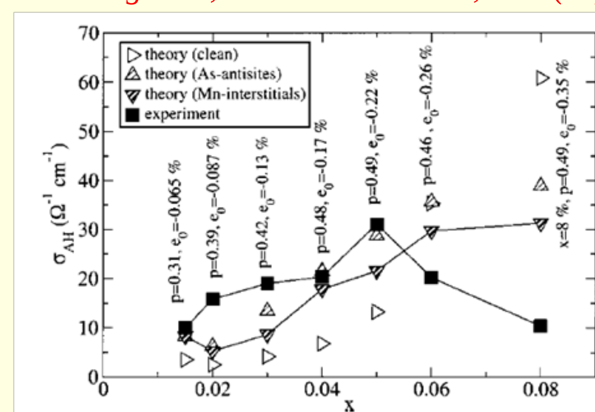


Jungwirth, Niu and McDonald, PRL (02)

Electron wavepackets acquire additional velocity:

$$\dot{x}_c = \frac{\partial \epsilon}{\hbar \partial \vec{k}} + \underline{(e/\hbar)\vec{E} \times \vec{\Omega}}\,.$$

Anomalous velocity

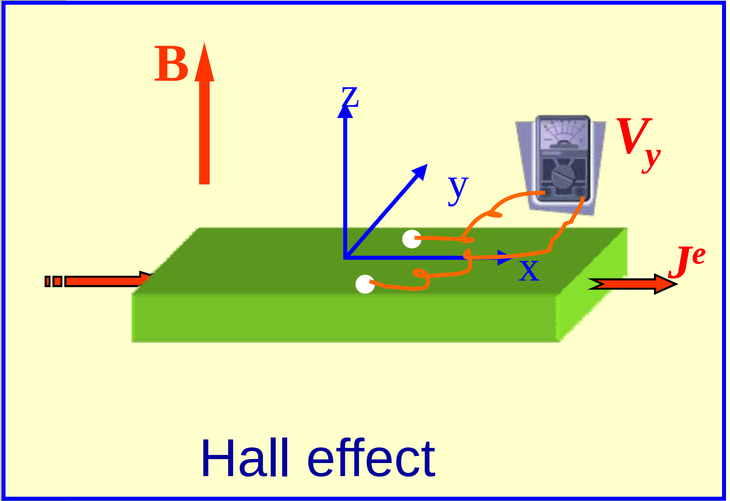


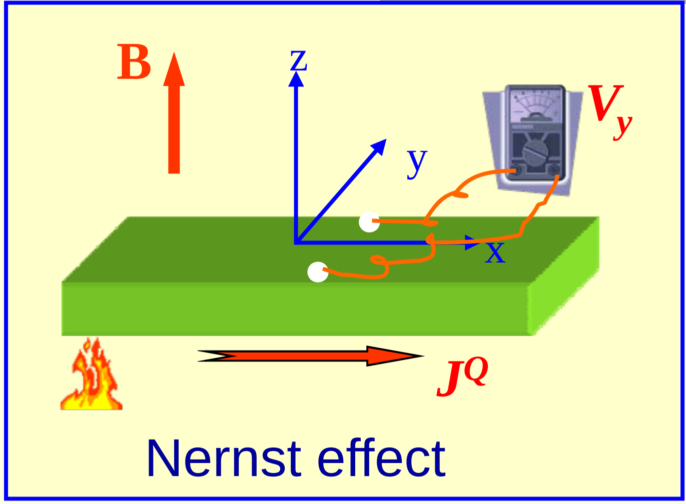
Jungwirth et al. APL (03)

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

→ Intrinsic origin of AHE in DMS

Nernst Effect





$$\sigma_H = \frac{E_y}{J_x}$$

$$S_N = \frac{E_y}{(\nabla T)_x} = -\frac{\Delta V_y}{\Delta T_x} \cdot \frac{L}{W}$$

- Normal Hall Effect

$$\sigma_H \propto B$$

- Anomalous Hall Effect (AHE)

$$\sigma_{AH} \propto M$$

- Normal Nernst Effect

$$S_N \propto B$$

- Anomalous Nernst Effect (ANE)

$$S_{AN} \propto M$$

Other Transport Effects

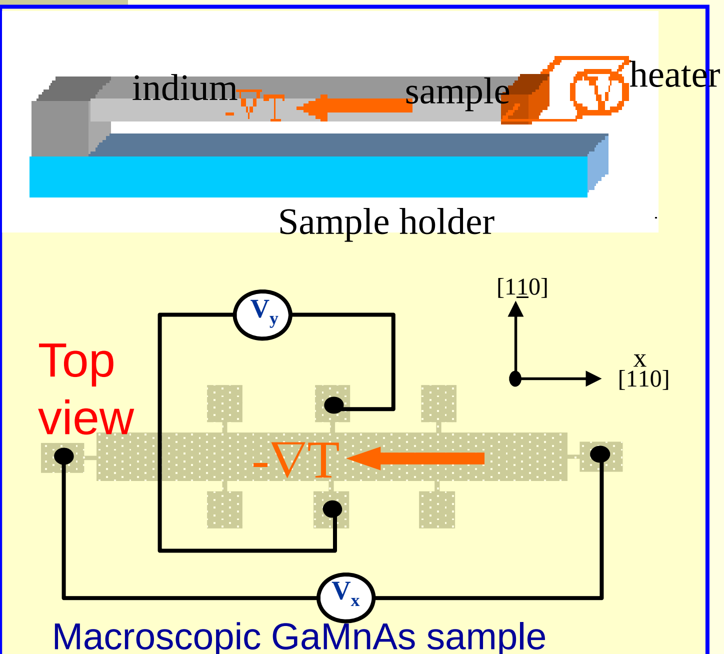
Stimulus: ΔV_x or ΔT_x
Response: → I_x, I_x^Q and I_x, I_x^Q if there is B or M.

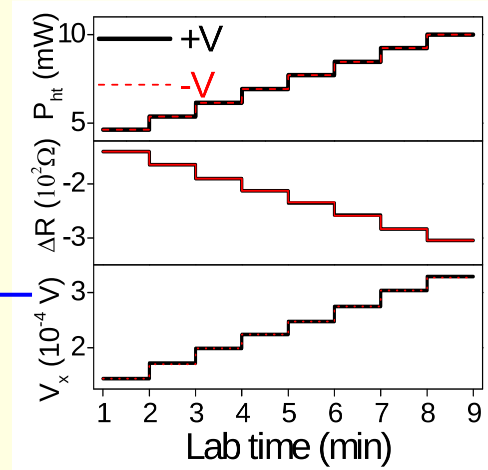
Open-circuit condition: measuring ΔV instead of I; ΔT instead of I^Q

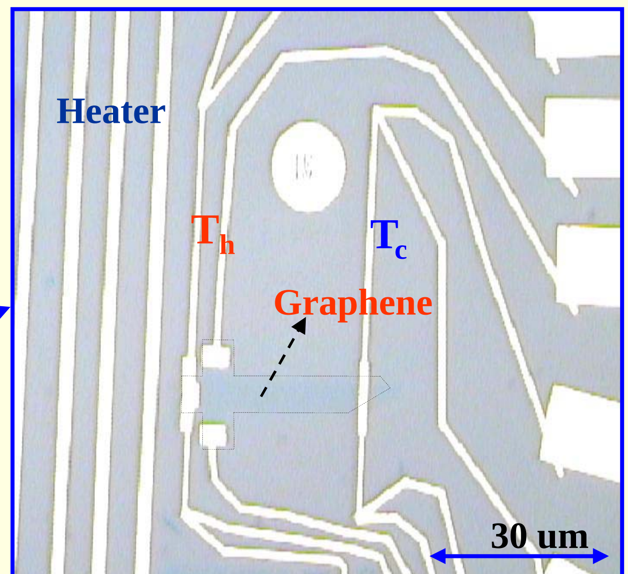
Response / Stimulus	I_x	I_y	I_x^Q or ΔT_x	I_y^Q or ΔT_y
ΔV_x	Conductivity	Hall effect	Peltier effect	Ettingshausen effect
ΔT_x	Seebeck effect	Nernst effect	Thermal conductivity	Righi-Leduc effect

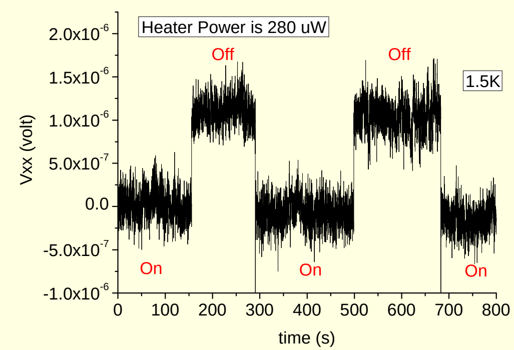
Various coefficients are connected by Onsager relations and other relations (e.g. Wiedemann-Franz law, Mott relation, etc.)

Thermoelectric Measurements



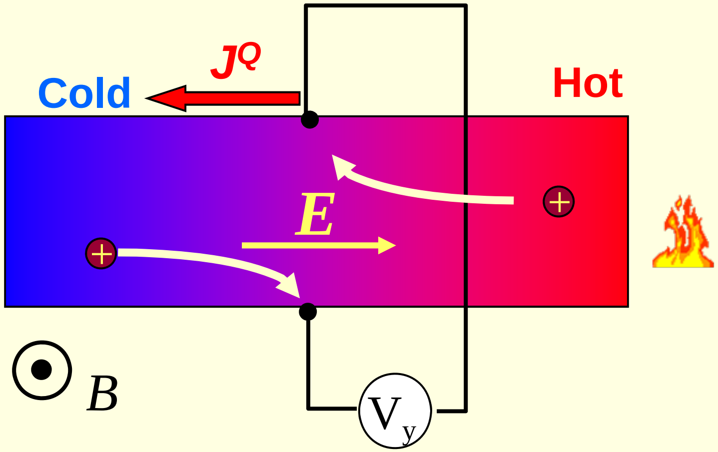






Typical ΔT ~ 50 mK; ΔT is measured by microfabricated thermometers.

Nernst Effect



Open circuit voltage (J_x and $J_y=0$)

$$\vec{J} = \sigma\vec{E} + \alpha(-\nabla T)$$

diffusion *drift*

$$S_{yx} = \frac{1}{\sigma_{xx}}(\alpha_{yx} - \sigma_{yx}S_{xx})$$

Nernst current Hall current

- Nernst effect is a net effect resulting from both Hall current (drift) and Nernst current (diffusion). In metals, it is a very small effect.

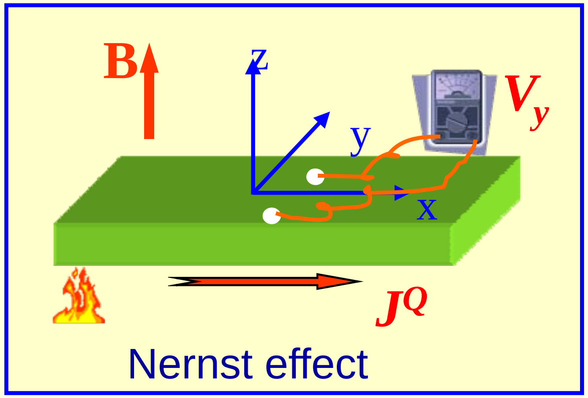
Mott relations

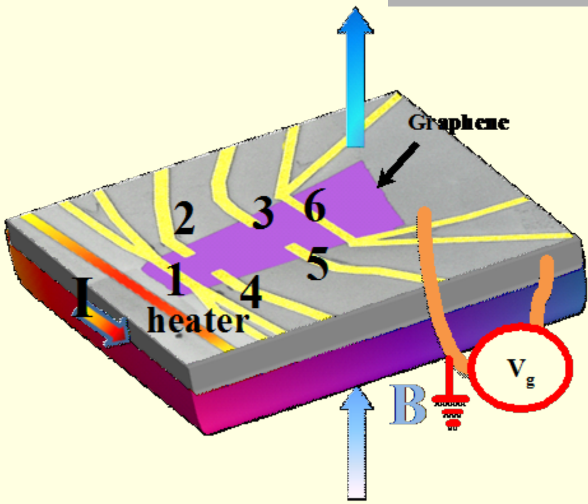
$$\alpha_{xx} = \frac{\pi^2 k_B^2 T}{3e}\left(\frac{\partial \sigma_{xx}}{\partial \varepsilon}\right)_{\varepsilon_F}$$

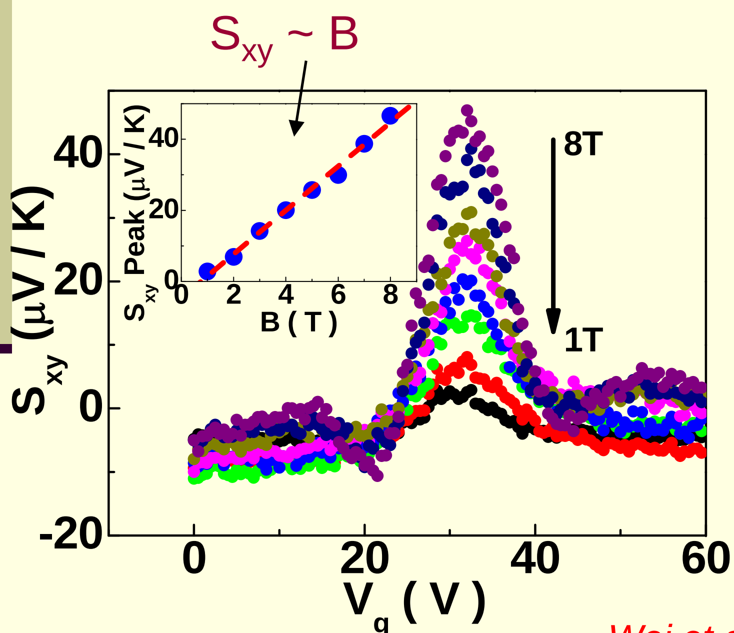
$$\alpha_{yx} = \frac{\pi^2 k_B^2 T}{3e}\left(\frac{\partial \sigma_{yx}}{\partial \varepsilon}\right)_{\varepsilon_F}$$

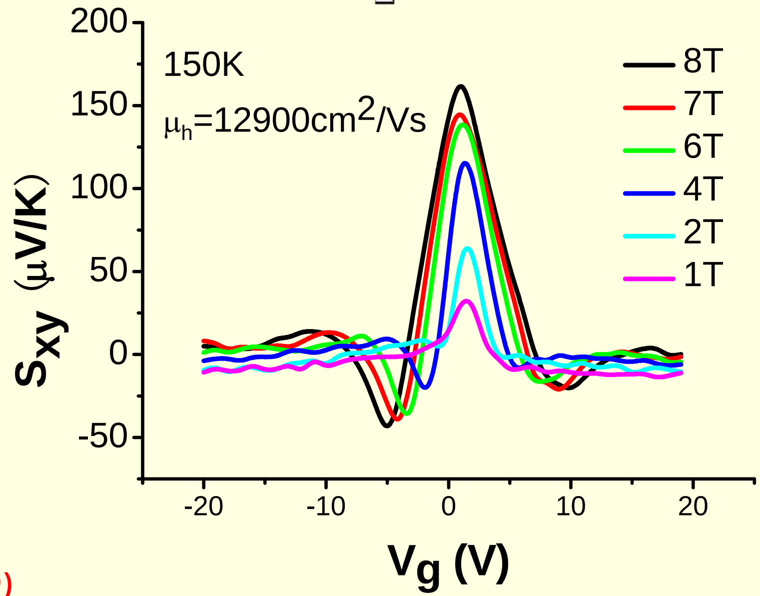
$$S_{yx} = \frac{\pi^2 k_B^2 T}{3e}\left[\arctan\left(\frac{\sigma_{yx}}{\sigma_{xx}}\right)\right]' = \frac{\pi^2 k_B^2 T}{3e}\left(\frac{\partial \Theta_H}{\partial \varepsilon}\right)_{\varepsilon_F}$$

Normal Nernst Effect in Graphene









Wei et al. PRL (09)

Why Anomalous Nernst Effect?

- Does ANE exist if AHE is caused by intrinsic effect?
  - Only statistical force (no E-field)

$$\dot{x}_c = \frac{\partial \epsilon}{\hbar \partial \vec{k}} + (e/\hbar)\vec{E} \times \vec{\Omega}.$$

  - If l does not depend on Fermi energy, there will be no ANE

$$\rho_{AH} = \lambda \rho_{xx}^2 M_z \longrightarrow \sigma_{AH} = \lambda M_z$$

Finite $S_{AN} \rightarrow \lambda = \lambda(\varepsilon_F)$!

- How are AHE and ANE related?
  - Validity of Mott relation (D. Xiao PRL 07)
  - Does ANE help us understand physical origin of AHE

- What can we learn about ferromagnets?
  - Spin-orbit coupling, magnetic ordering

Subtleties with DMS

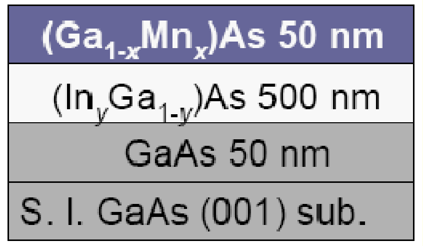
- Films with in-plane anisotropy often require high magnetic fields to obtain finite AHE (i.e. M_z). To completely saturate M_z, it requires magnetic fields in excess of 10 T!
- Normal Hall/Nernst signals become large at high fields.
- High magnetic fields cause significant magneto-resistance (i.e. change in ρ_{xx}), even when AHE saturates.
- In DMS, all spins contribute to magnetization, but only those in hole-rich regions contributes to AHE; therefore, it is difficult to separate these two for $\rho_{AH} = \lambda \rho_{xx}^2 M_z$.

Solutions:

• DMS films with perpendicular anisotropy (no need to have B-field)

• ANE and AHE measured simultaneously from the same area (no need to measure M)

GaMnAs with Perpendicular Anisotropy

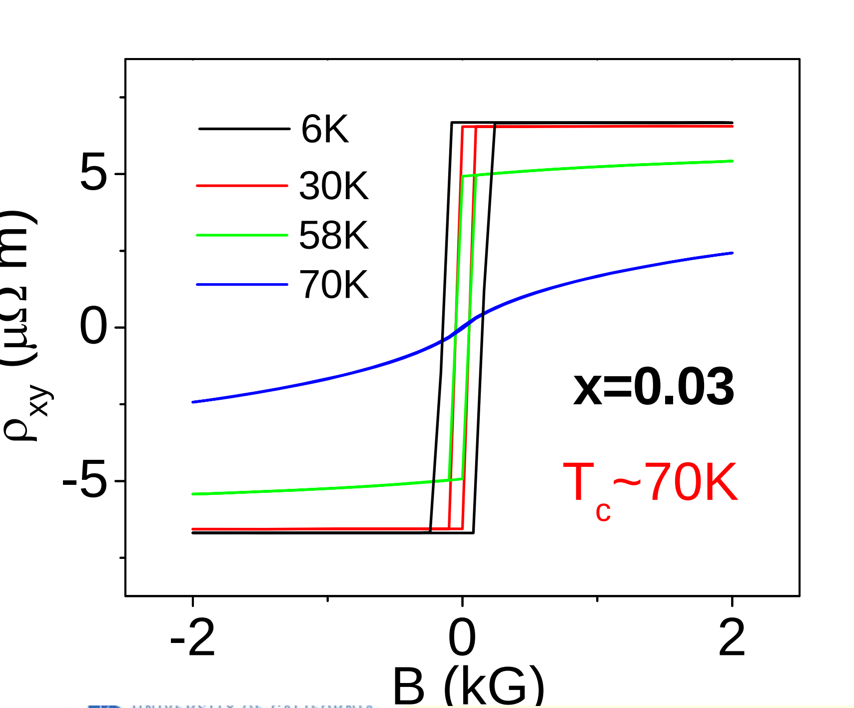


InGaAs buffer layer → tensile strain
→perpendicular anisotropy

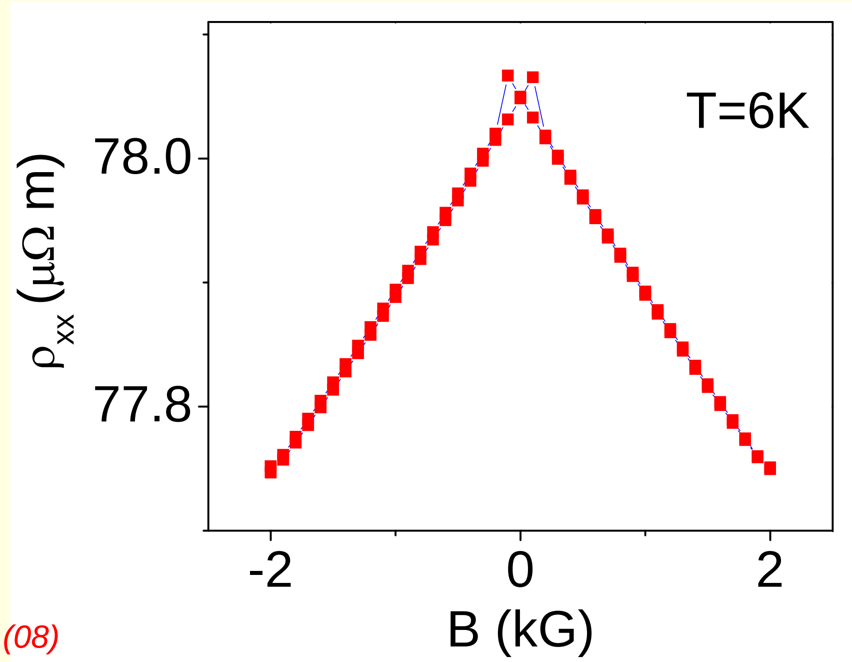
"B=0" is a special field

A set of films with different Mn, so different T_c's.

AHE (OHE is negligible)



Longitudinal resistivity



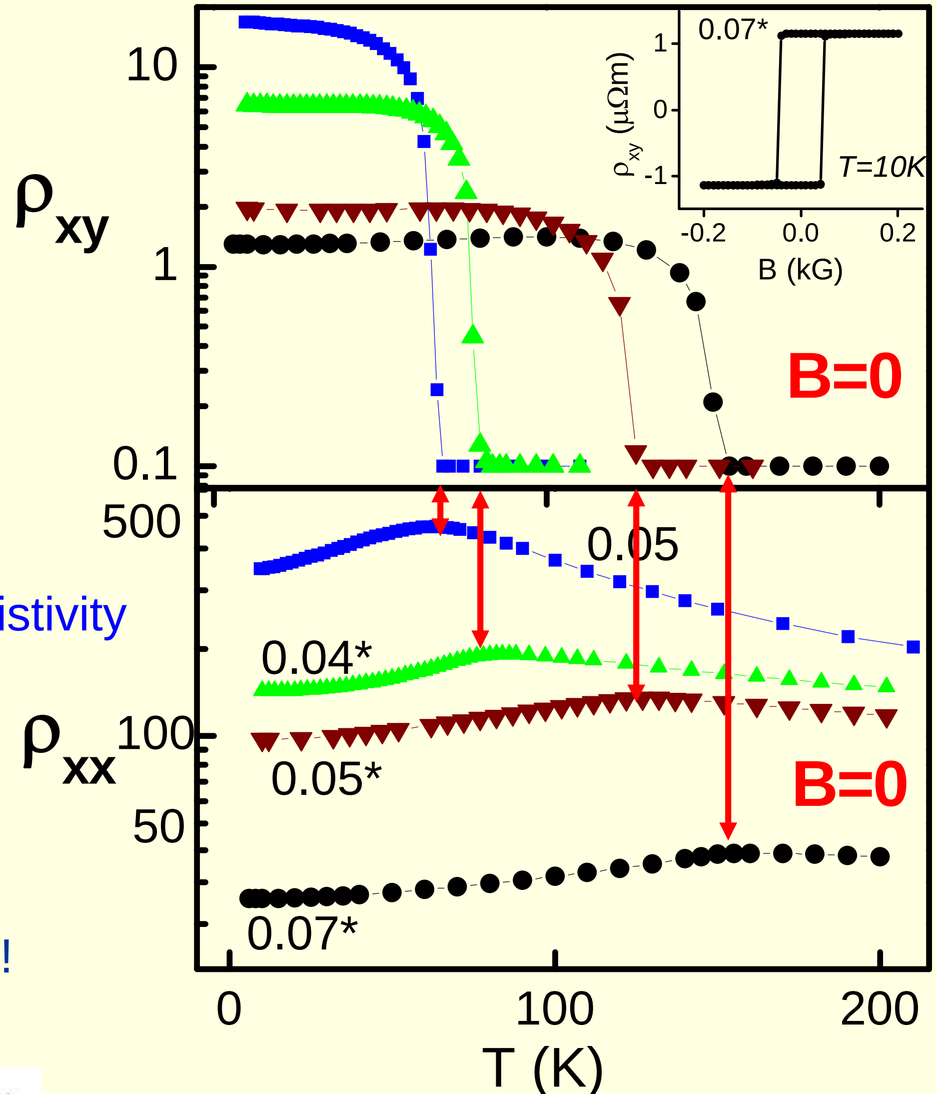
Pu et al. PRL (08)

AHE in GaMnAs

Hall resistivity

Longitudinal resistivity

All “metallic”!

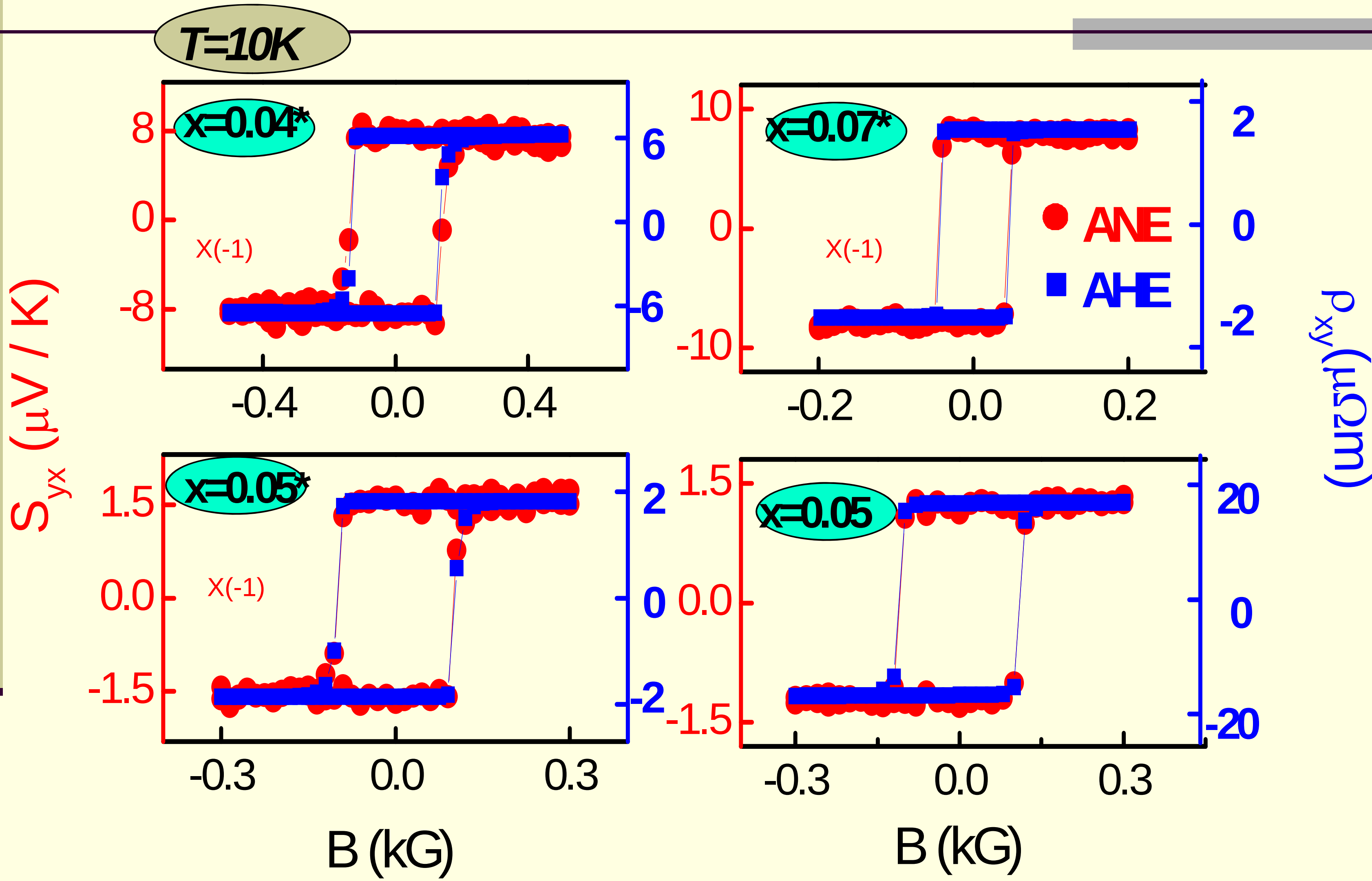


AHE remains positive below T_c

x=0.04*, 0.05*, and 0.07* are annealed but x=0.05 is not.

Usual power-law analysis is highly unreliable because of uncertainty in determining M

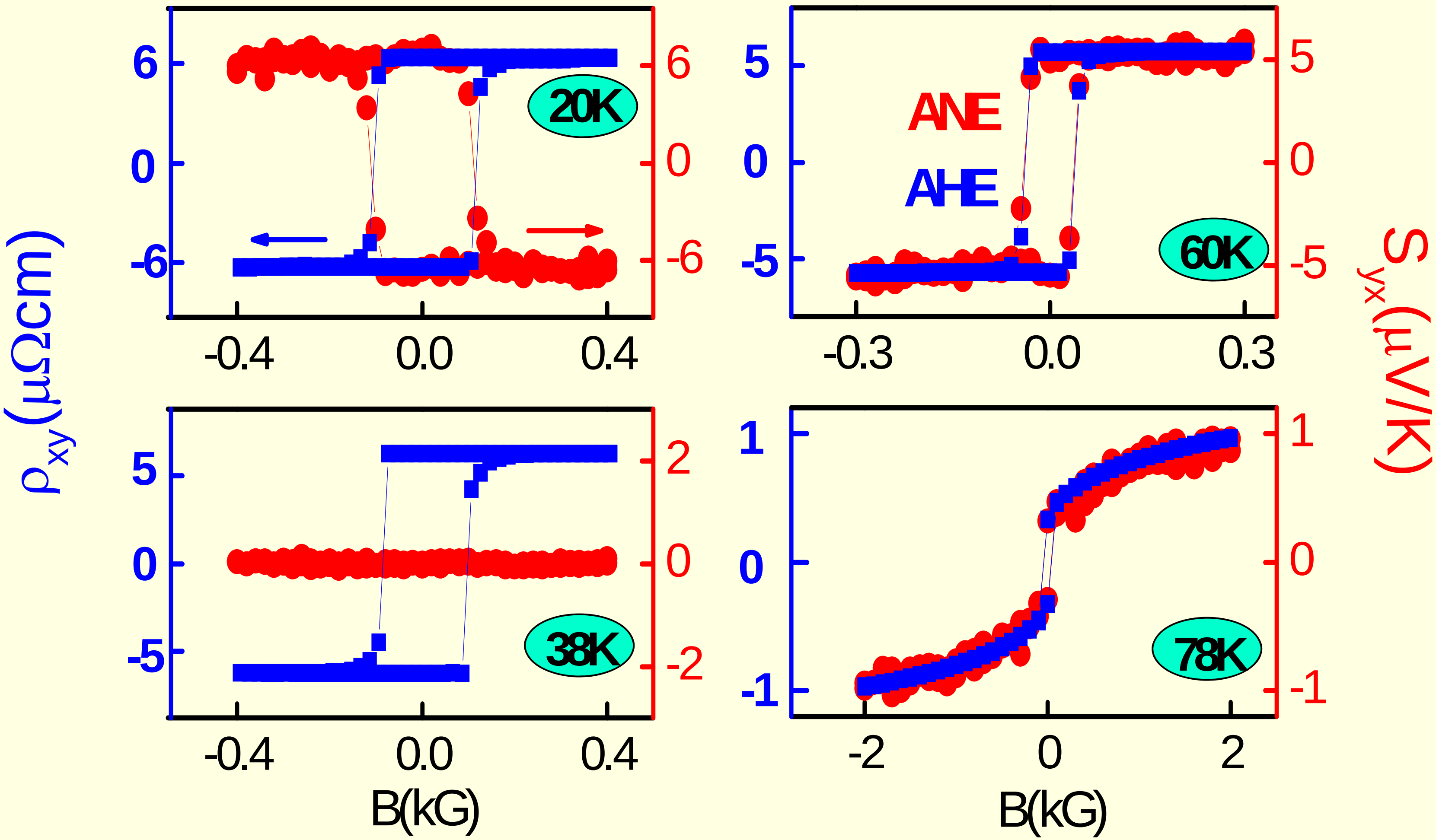
AHE & ANE in Different Samples



No ordinary Nernst effect is visible; S_{yx} goes with ρ_{xy}

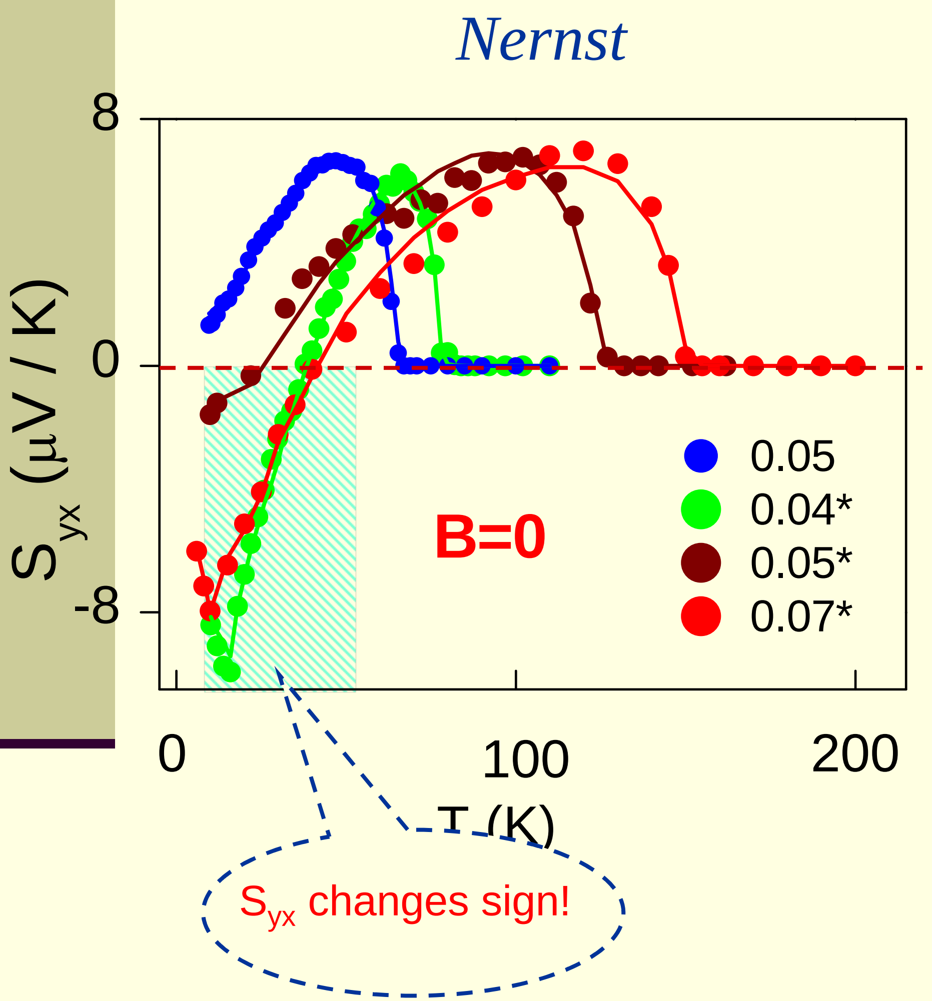
AHE & ANE at Different Temperatures

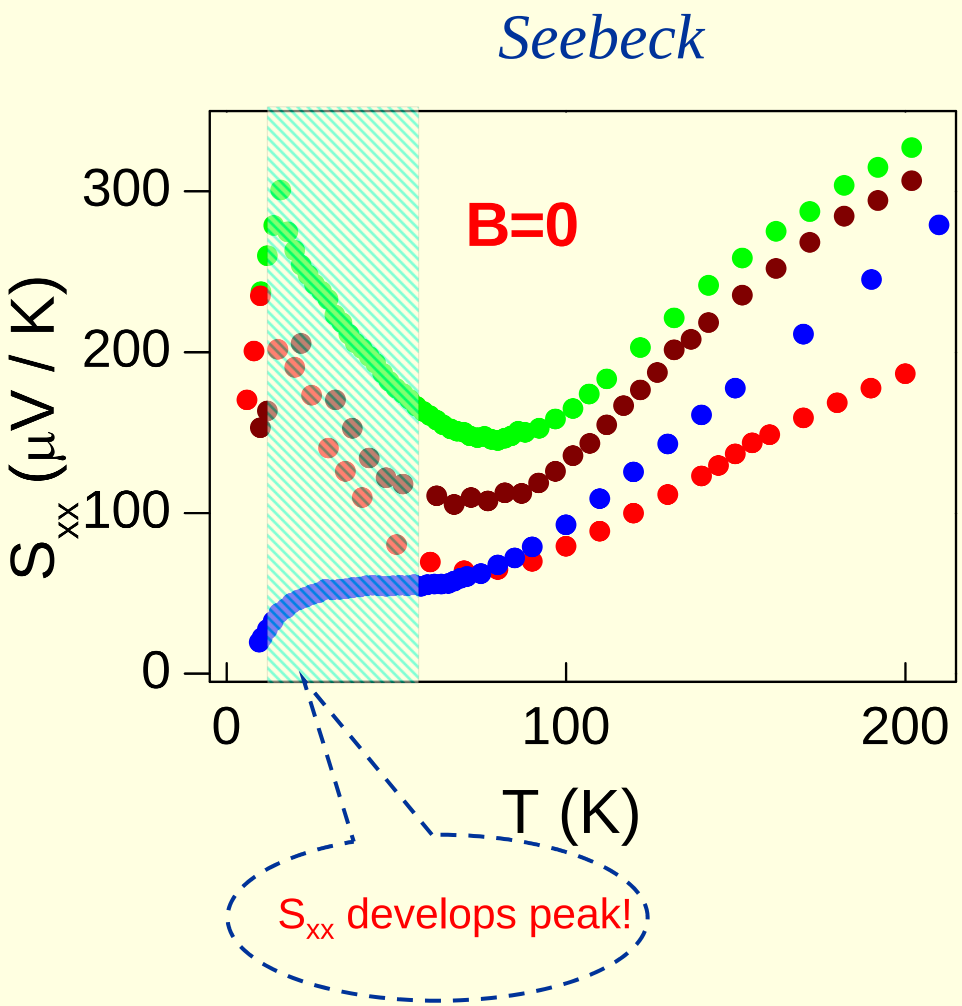
- x=0.04* (annealed)



• Except for sign, AHE and ANE scale with each other → share the same physical origin!

Zero-Field S_{xx} and S_{yx}





Mott Relation

$$\rho_{xy} = \lambda M \rho_{xx}^{n}$$

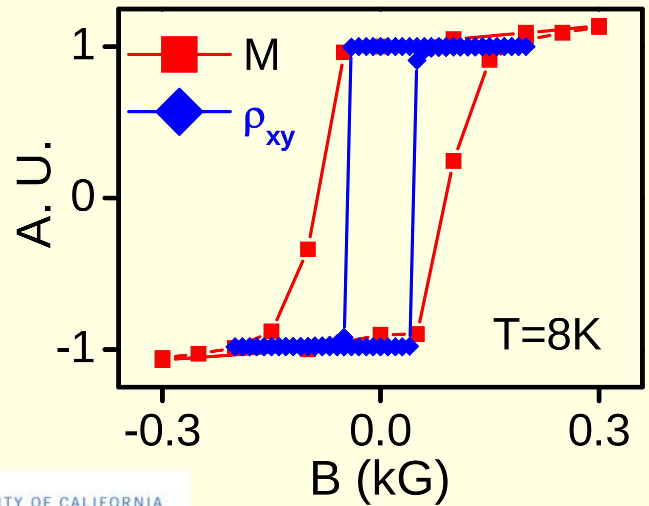
Mott relation →

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

Replace M by σ_{xx} & σ_{xy} by reusing the power-law

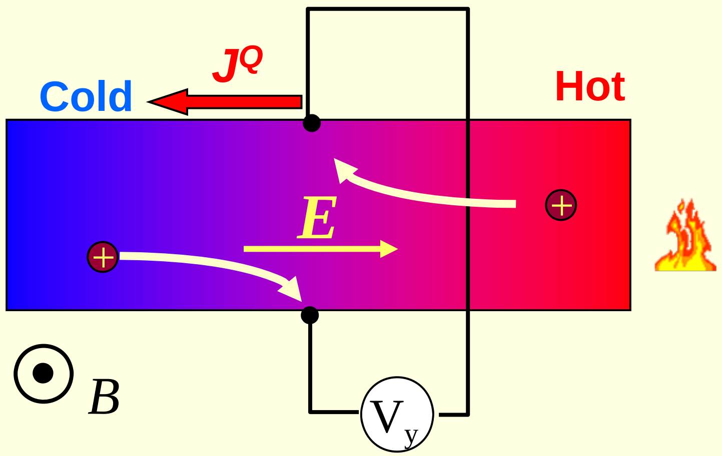
We have

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



- No longer need to measure M independently → removing uncertainty in M measurements
- All transport coefficients are from exactly the same region (Hall bar cross)

S_{yx} Sign Change



Open circuit voltage (J_x and $J_y=0$)

Nernst current:

$$J_y = \alpha_{yx}(-\nabla T)_x$$

Nernst current   Hall current

$$S_{yx} = \left(\frac{\sigma_{xy}}{\sigma_{xx}}\right)' = \frac{1}{\sigma_{xx}}\left(\alpha_{yx} - \sigma_{yx} S_{xx}\right)$$

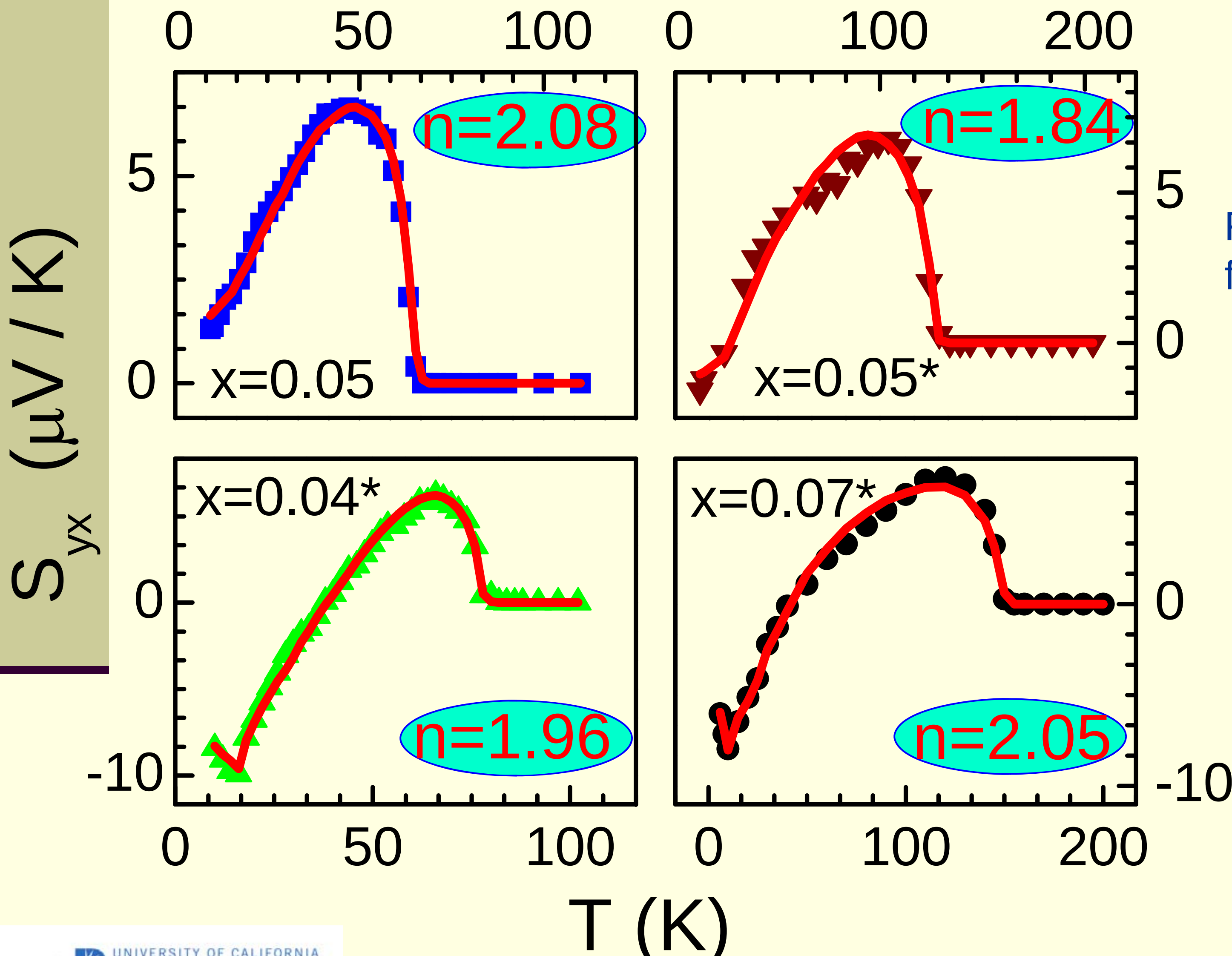
$$S_{yx} = \frac{\rho_{xy}}{\rho_{xx}}\left(T\frac{\pi^2 k_B^2}{3e}\frac{\lambda'}{\lambda} - (n-1)S_{xx}\right)$$

Nernst current   Hall current

Sign change is only possible if n > 1, → NOT skew scattering!

At low-T where S_{xx} is large, Hall current exceeds Nernst current → Sign Change!

Exponent "n"



Red solid lines are fits to Mott relation

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

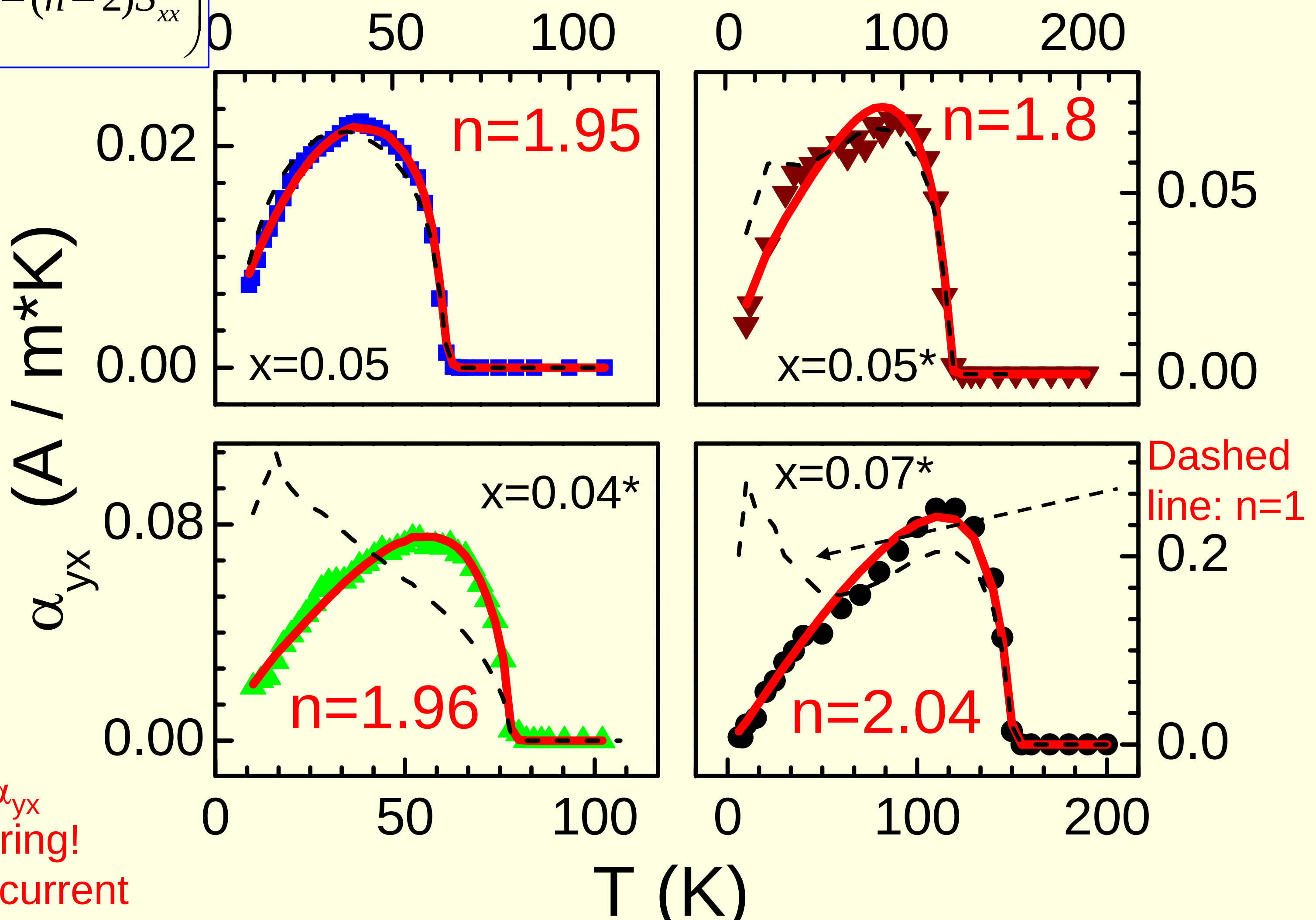
Mott relation works well for n=2!

Nernst Current: J_N

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

Nernst current:

$$J_N = -\alpha_{yx}(\nabla T)_x$$



n=2 → nothing in α_{yx}
depends on scattering!
→ intrinsic Nernst current

Intrinsic vs. Side Jump

- n=2 → intrinsic or side jump (SJ)

In GaMnAs,

❖ Intrinsic mechanism can account for most of AHE magnitude

❖ SJ displacement $\Delta y < 0.1$ nm, and MFP is about ~ 20 nm.
Hall angle $\Theta_H < 0.05$ for SJ; observed Hall angle $\Theta_H \sim 0.1$

❖ AHE/ANE is likely dominated by intrinsic mechanism

Mott relation holds for AHE/ANE with intrinsic (Berry's phase) mechanism.

Meaning of λ / λ'

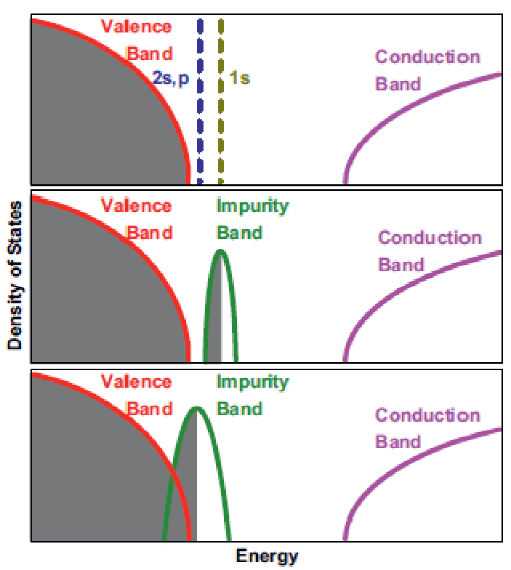
- λ depends on Fermi energy
- We obtain the value of λ / λ'

	#4*	#5	#5*	#7*
n	1.96	1.95	1.8	2.04
λ/λ'(eV)	0.046	0.049	0.040	0.096

For small ε_F, we assume $\lambda \propto \varepsilon_F^{\alpha}$

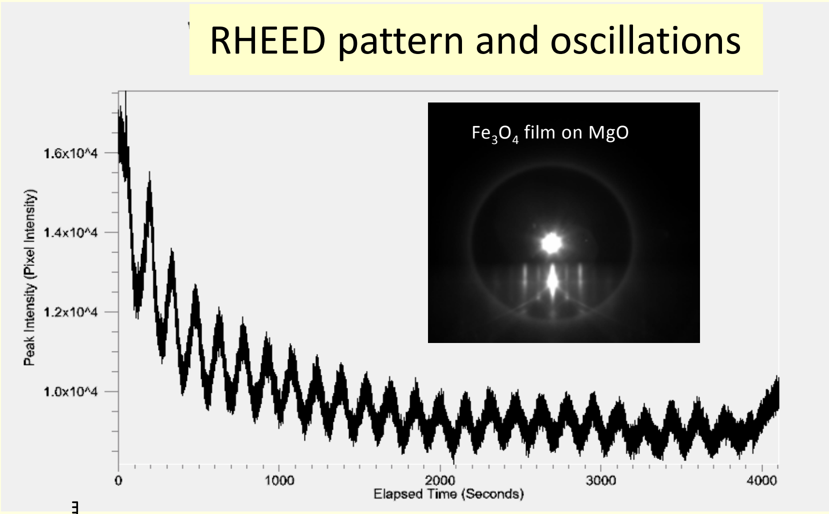
$$\frac{\lambda}{\lambda'} = \frac{\varepsilon_F}{\alpha} \approx 0.05 - 0.1eV$$

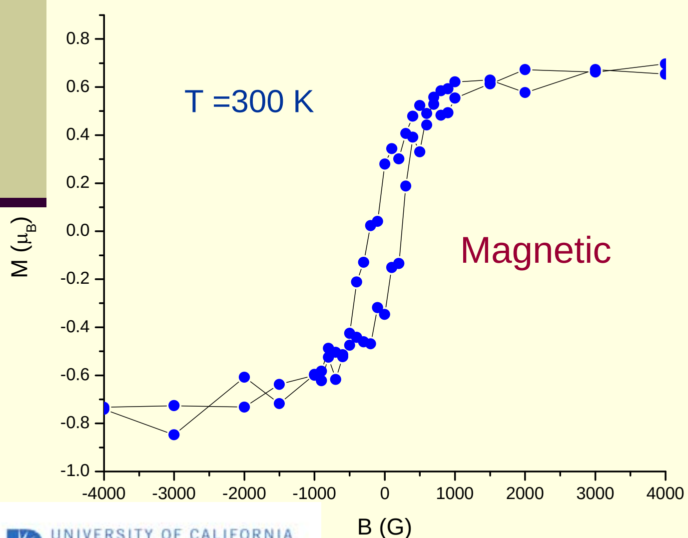
For p~ 10^{19}cm^{-3}, obtained ε_F is an order smaller than expected from valence band, suggesting the impurity band picture.

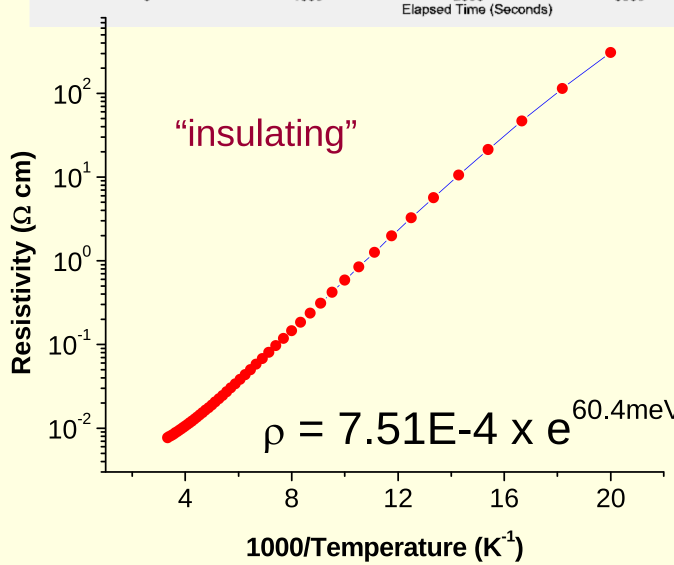


Magnetic Insulator Films: Fe_3O_4/MgO (001)

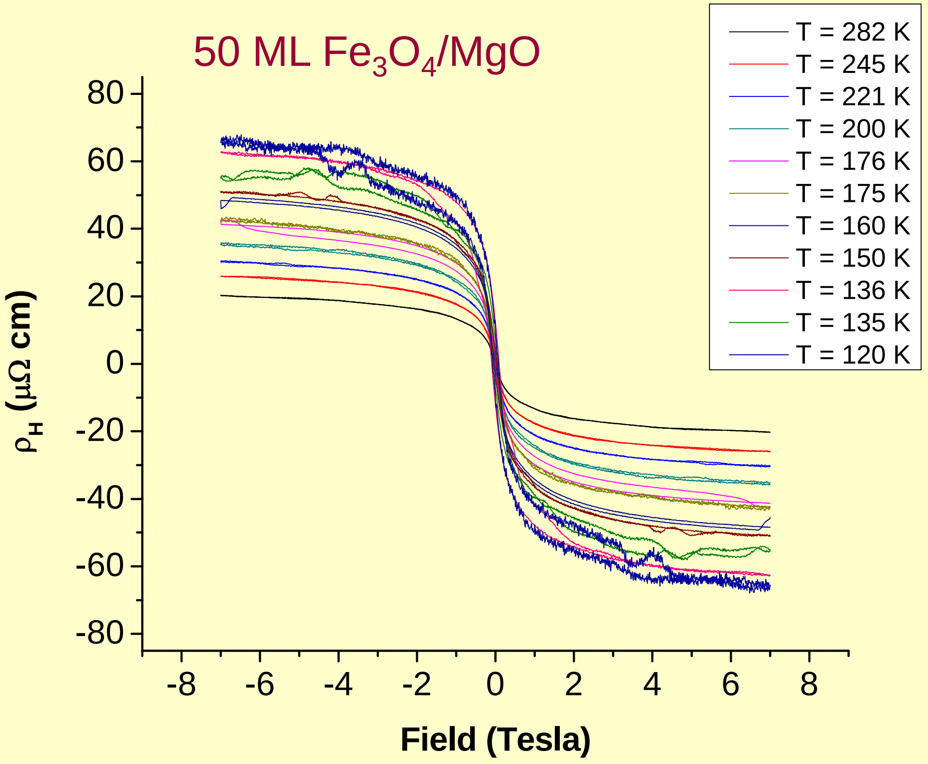
- Fe_3O_4 films are epitaxially grown with laser MBE

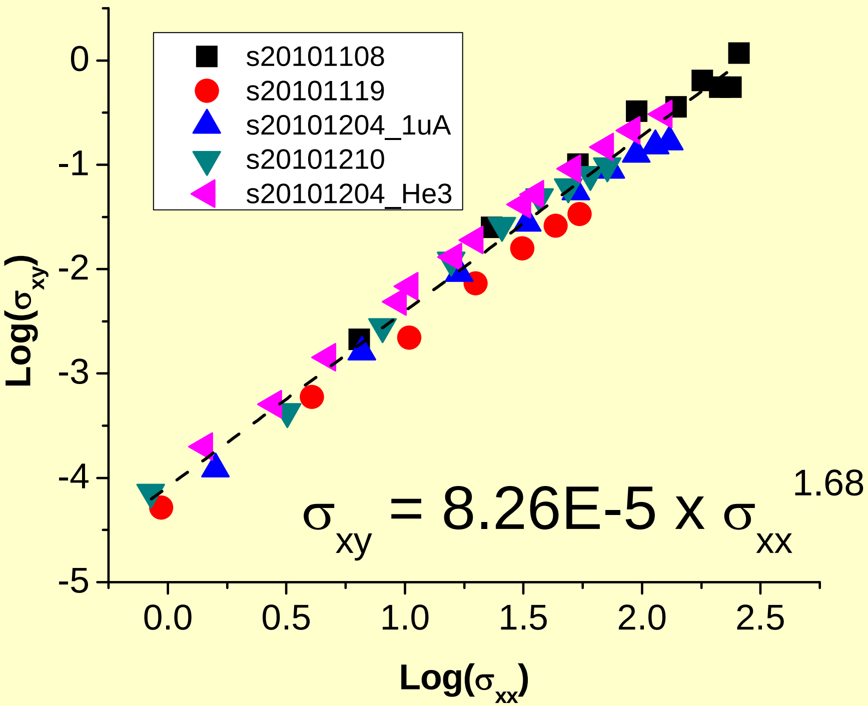






Power-Law Scaling

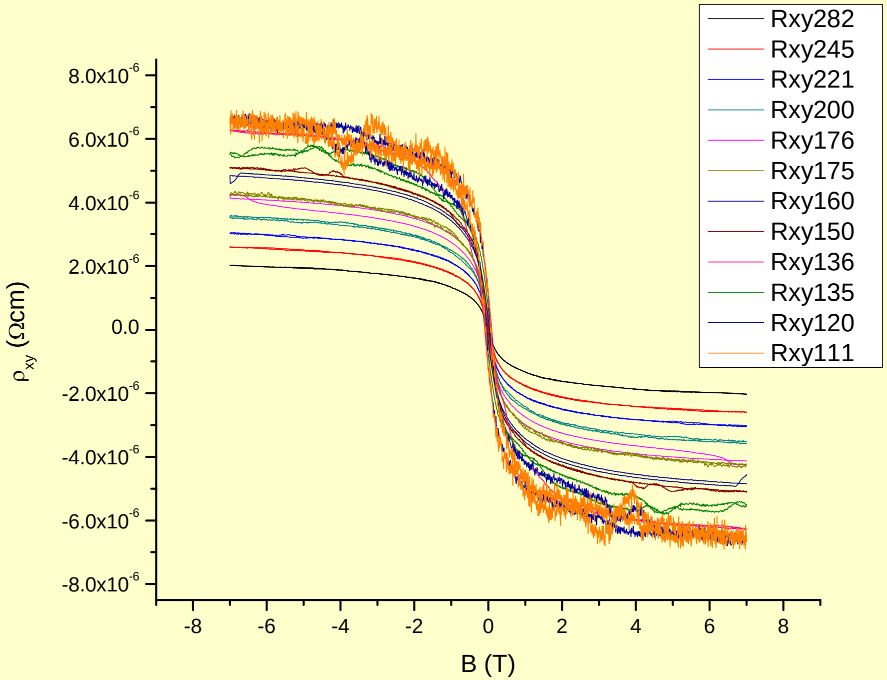


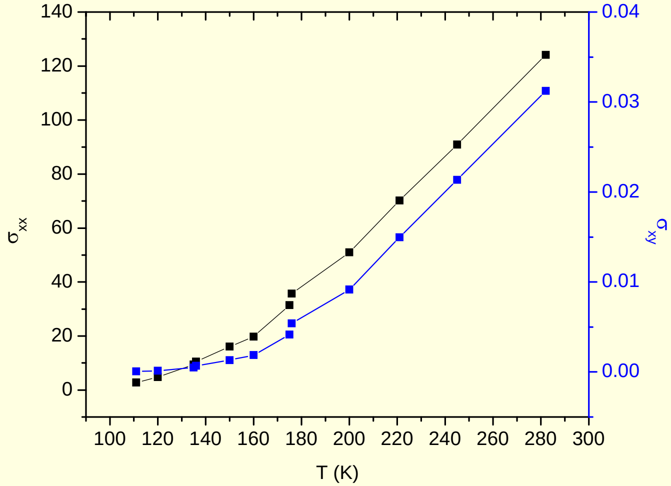


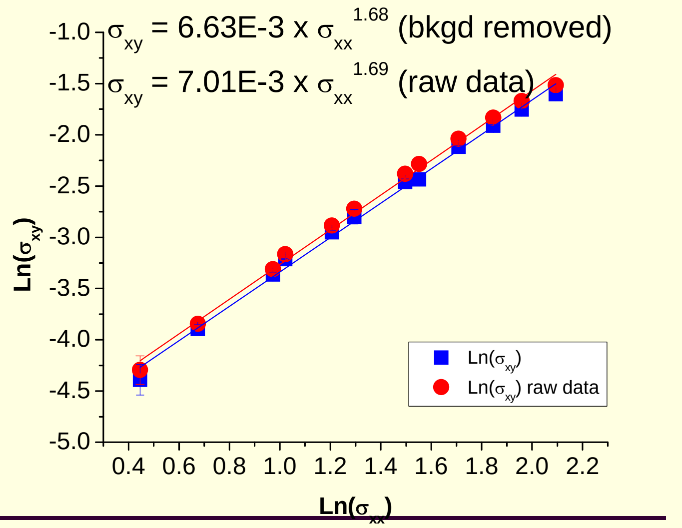
AHE signal above Verwey temperature

A much smaller n=0.32!
Consistent with other reported value.

AHE and Power-Law

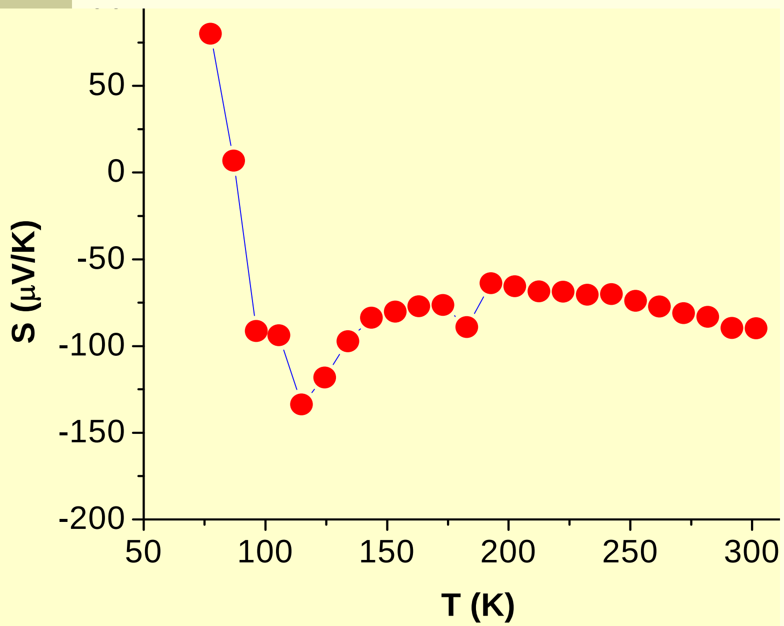


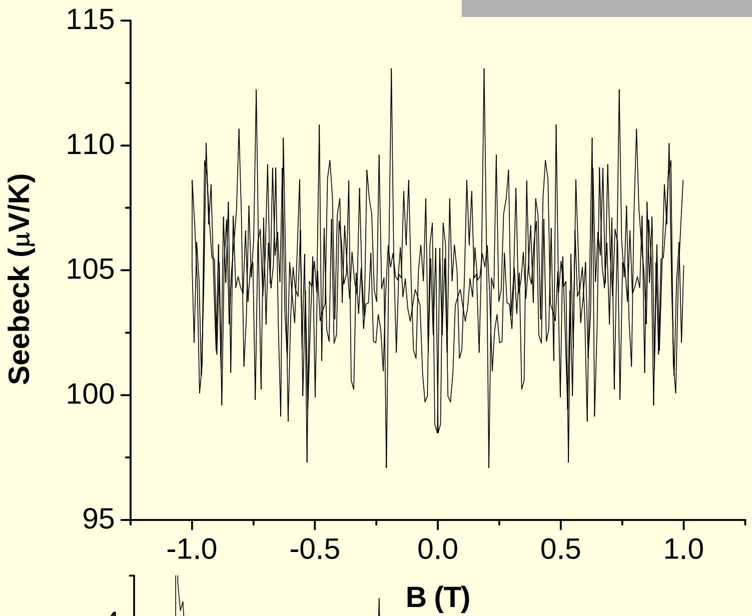


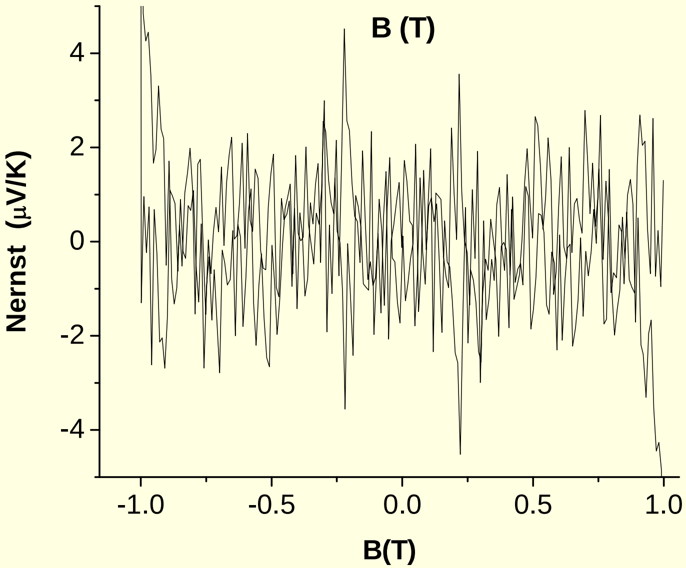


Thermoelectric Measurements

Zero-field Seebeck





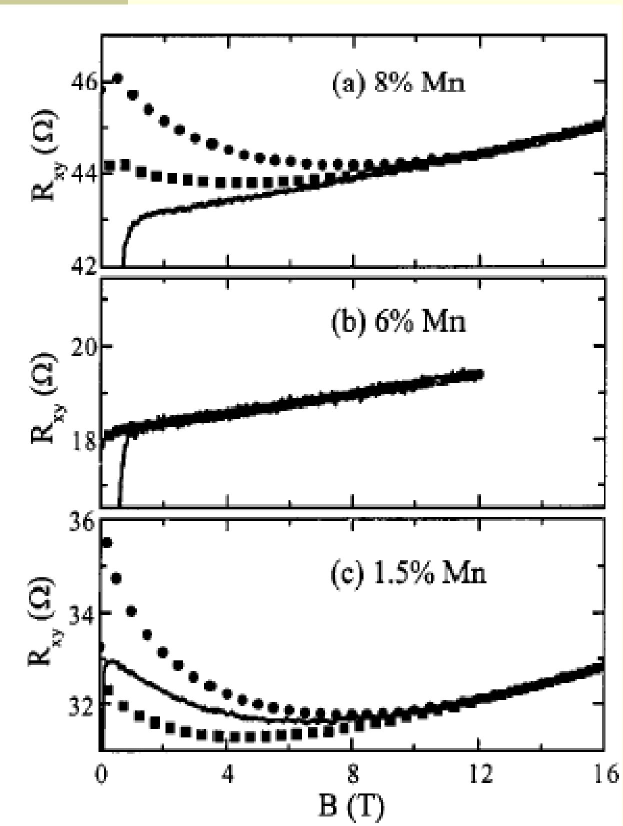


Summary

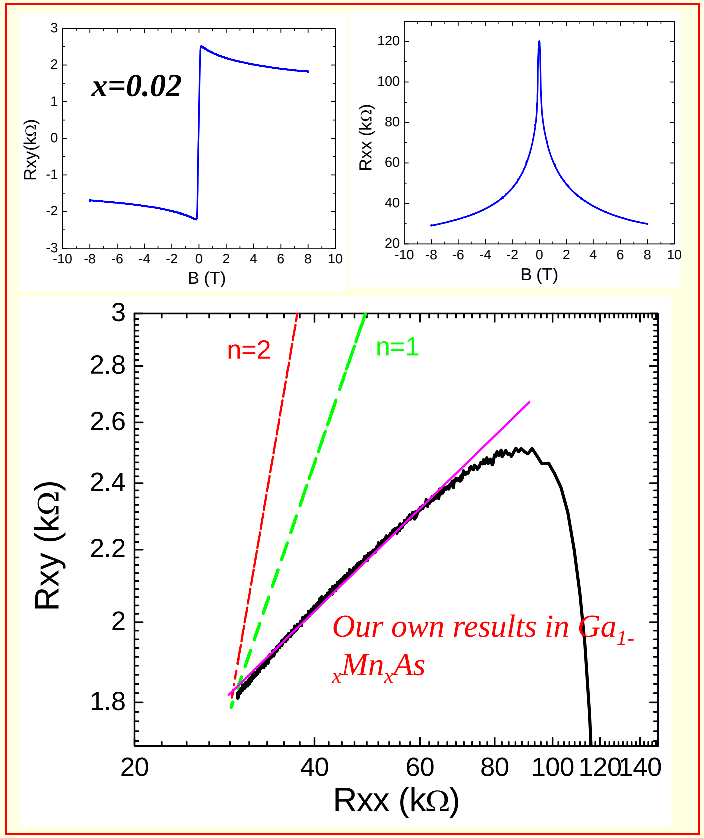
- Large ANE is observed in GaMnAs [$\lambda=\lambda(\varepsilon_F)$].
- AHE and ANE share the same physical origin.
- “n=2” is obtained from zero-field AHE and ANE without uncertainty in magnetization measurements.
- Our results suggest intrinsic Nernst current J_N.
- Mott relation is experimentally validated for scattering rate-independent anomalous transport.
- Small magnitude of λ/λ' suggests impurity band picture.
- “n=0.3” is found in epitaxial Fe_3O_4 films, but ANE has not been observed.

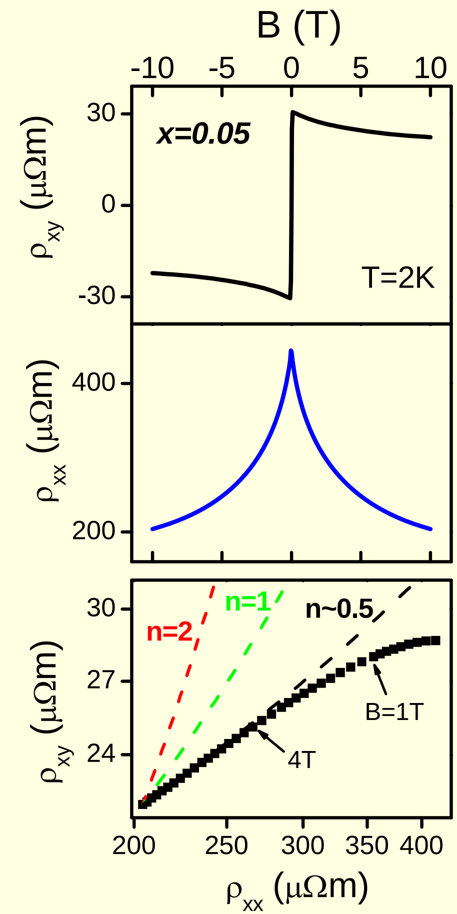
Discussion: 1. Effect of High B-Field

- 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?

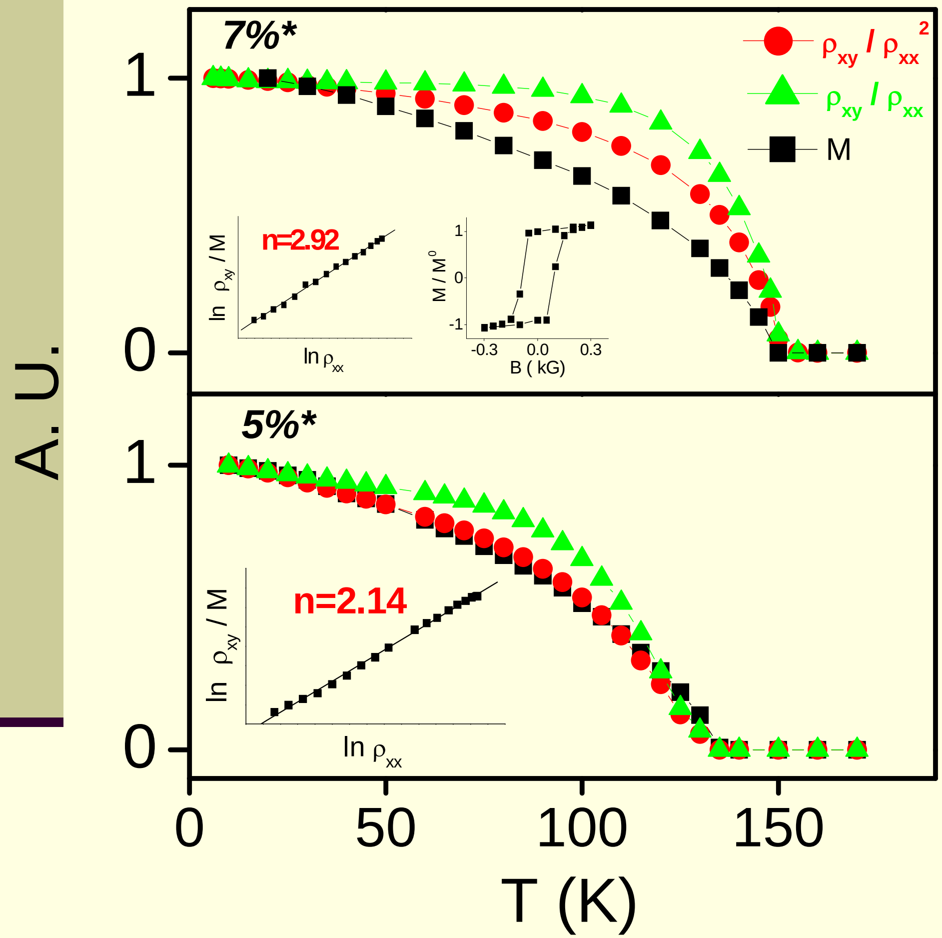


Edmonds et al. JAP (03)





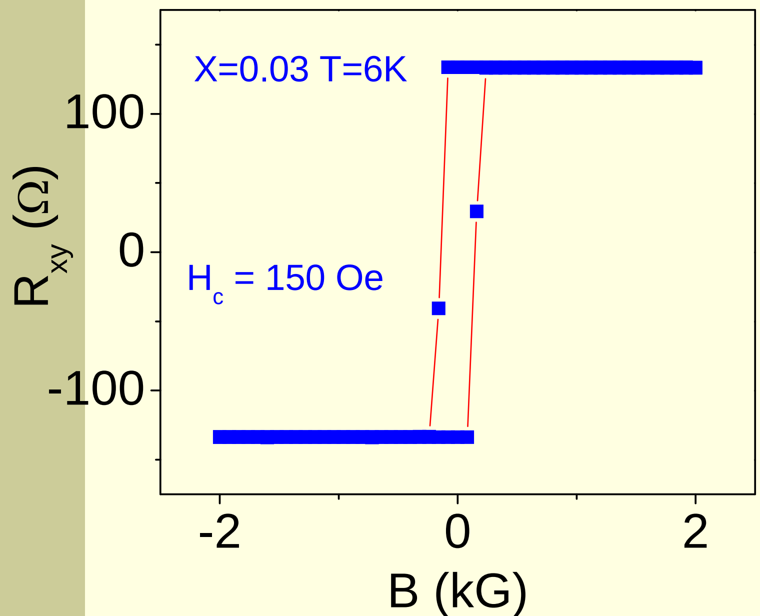
Find Exponent n



- Exponent is not always one or two
- Separate magnetization measurement is needed
- Hall loops are different from MH loops

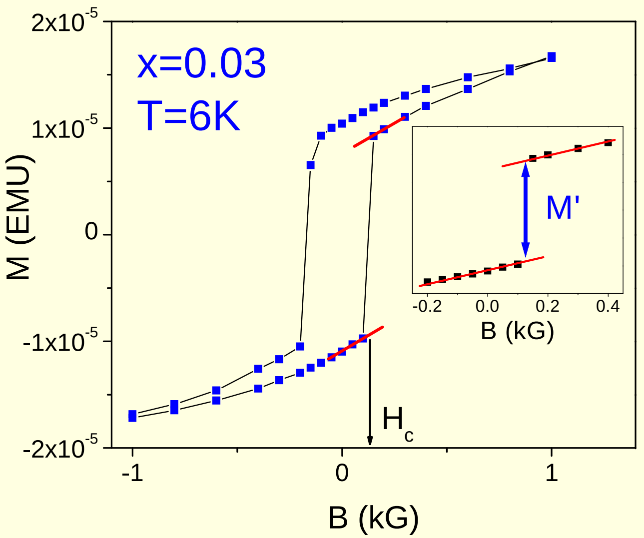
R_{xy} and M Measurements

Transport



Magnetization

Good



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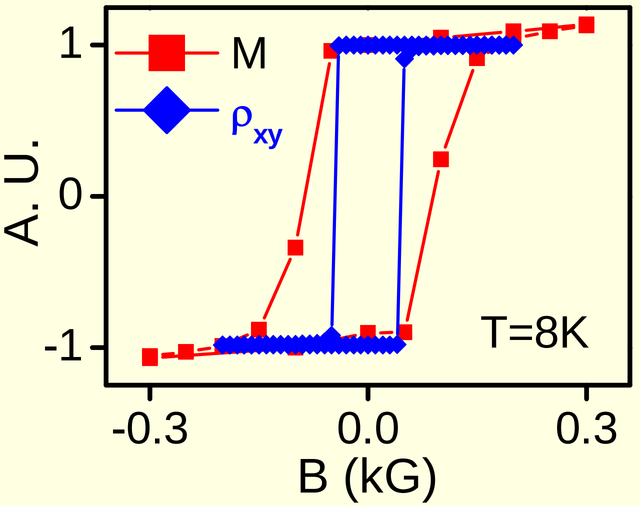

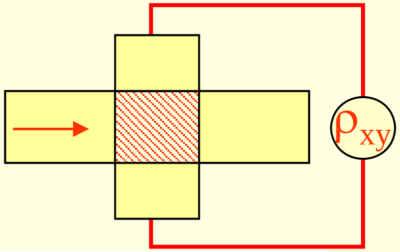

Probing area ~ $(100\ \mu m)^2$