AN n-TYPE TUNABLE TWO-DIMENSIONAL FERROMAGNETIC SEMICONDUCTOR

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Motivations

- Semiconductor Spintronics: the use of the electron's spin in addition to its charge in semiconductor devices

- This holds promise of combining multiple functionalities (Storage, logic, data processing, communications) in a single chip

- Ultimate goal: quantum computation

Outline

- Ferromagnetism in (III,Mn)As
  - Growth of FM structures
  - Magneto-transport properties: hole-mediate FM
  - Electric Field control of FM
- Theory of FM in DMSs
  - Mean Field Theory and Zener's model
  - Anomalous Hall Effect
- New Structure
- Ohmic contact to $Ga_{1-x}Mn_xAs$
- Sample preparation
- Magneto-Transport Measurements
  - Electron-mediated FM with excellent gating capabilities
  - Small Anomalous Hall Effect consistent with an electron-mediated DMS
- Conclusions & Future Directions

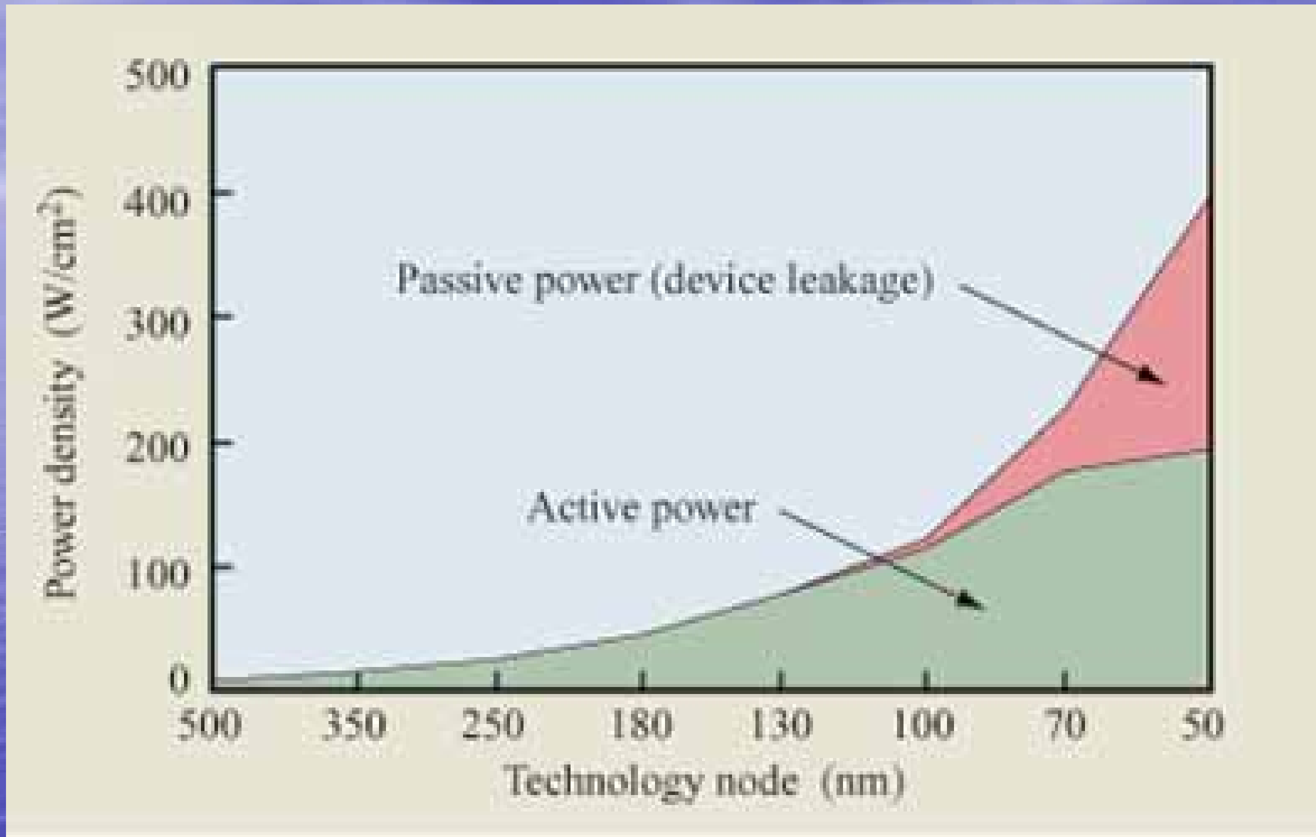
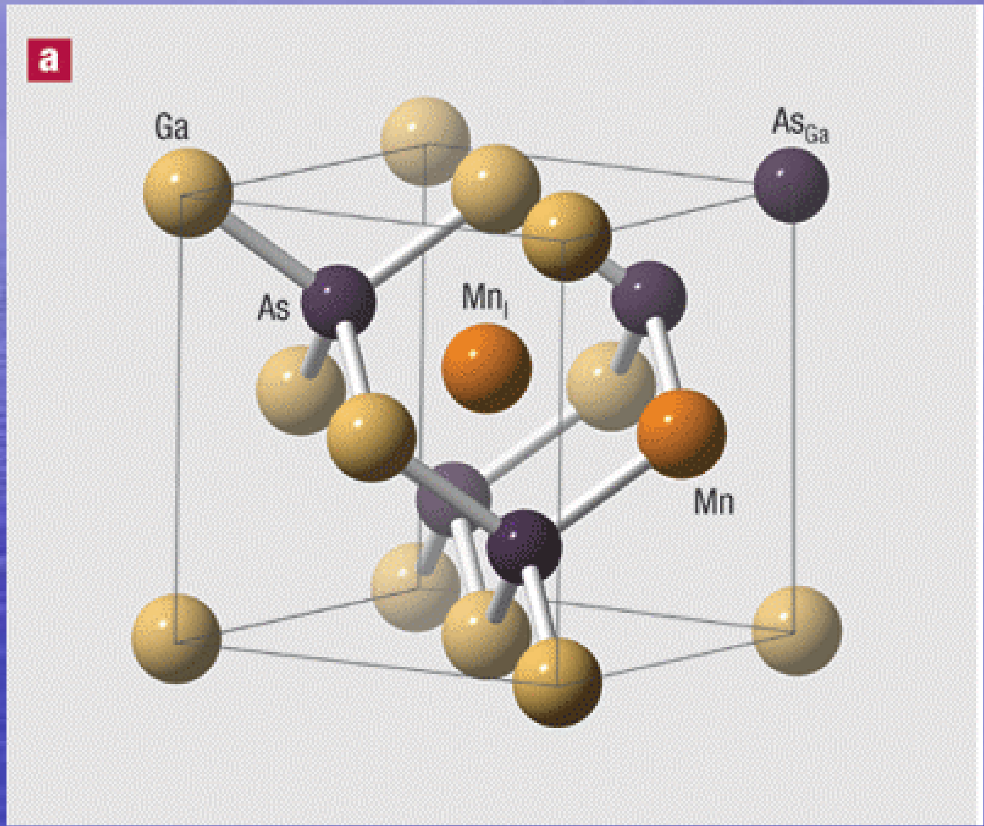
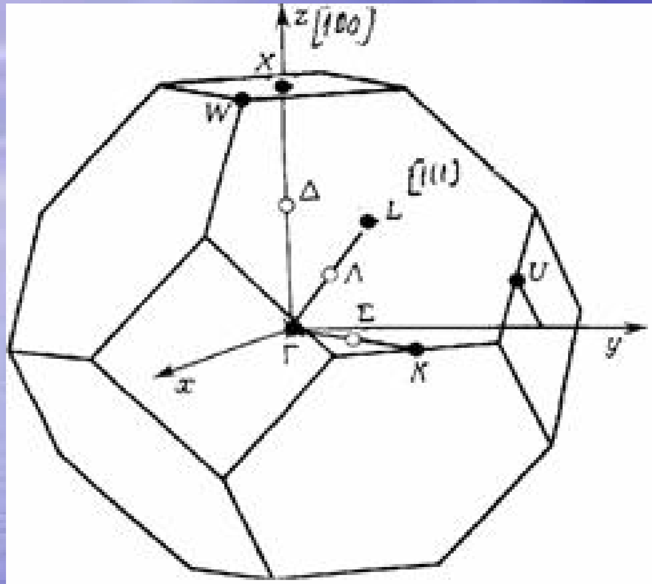

Passive power (device leakage)
Active power
Power density (W/cm²)
500
400
300
200
100
0
500
350
250
180
130
100
70
50
Technology node (nm)

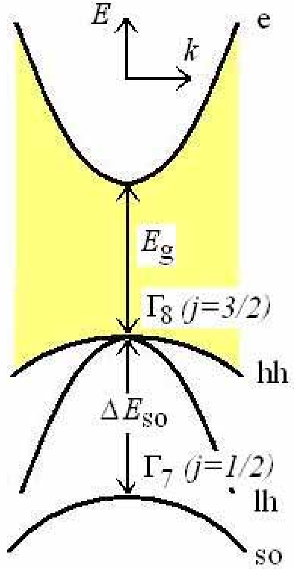
Figure 1

GaAs Crystal Structure with Mn (Zinc-blende structure)



GaAs Band Structure





Schematic electron (e), heavy hole (hh), light hole (lh), and split-off (so) bands near the center of the first Brillouin zone (k=0).

4×4 Luttinger Hamiltonian,

$$H_L = \frac{\hbar^2}{m_0}\left[\left(\gamma_1 + \frac{5}{2}\gamma_2\right)\frac{k^2}{2} - \gamma_3\left(\mathbf{k}\cdot\mathbf{J}\right)^2 + (\gamma_3 - \gamma_2)\sum_i k_i^2 J_i^2\right]$$

Bloch wave $\psi_{n\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} u_{n\mathbf{k}}(\mathbf{r})$ Periodic

$$H_{\mathbf{k}} u_{n\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{n\mathbf{k}} u_{n\mathbf{k}}(\mathbf{r}) \quad H_{\mathbf{k}} = \frac{P^2}{2m} + \frac{1}{m}\hbar\mathbf{k}\cdot\mathbf{P} + \frac{k^2}{2m}$$ +V(r)

Spin-Orbit in GaAs

$$H_{\text{eff}} = \epsilon_k + V + H_{\text{int}} + H_{\text{ext}},$$

$$H_{\text{int}} = -\frac{1}{2}\,\mathrm{b}\,(\mathbf{k}) \cdot \boldsymbol{\sigma},$$

$$H_{\text{ext}} = \lambda\,\boldsymbol{\sigma} \cdot (\mathbf{k} \times \nabla V)\,,$$

bulk inversion asymmetry

Dresselhaus term

$$H_{\mathrm{D,\,3d}} = \mathcal{B}\,k_x\left(k_y^2 - k_z^2\right)\sigma_x + \text{c.p.}$$

Quantum well (2D)

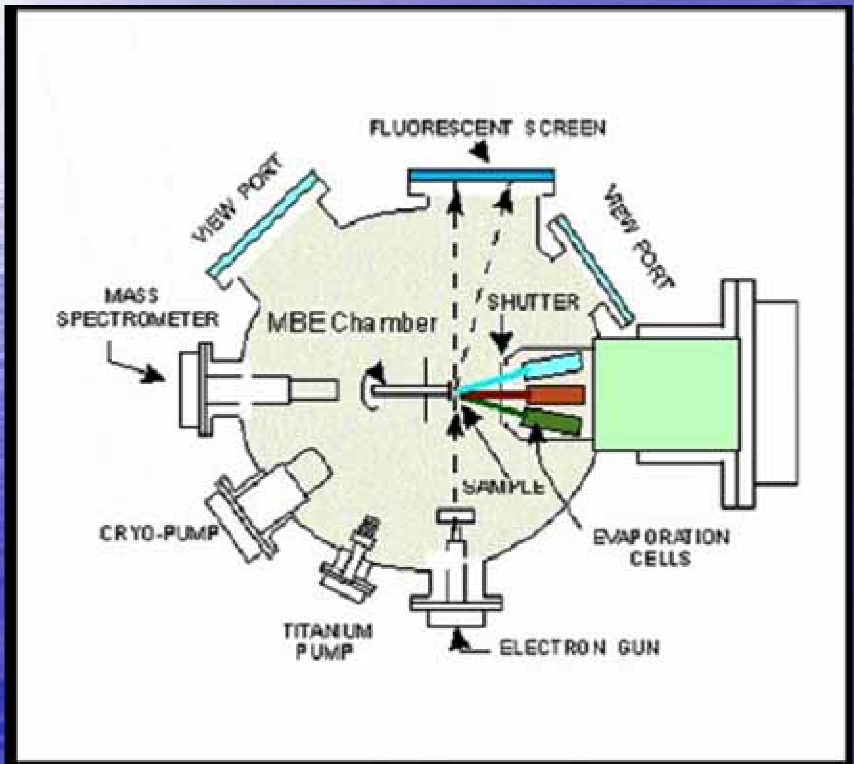
Rashba Hamiltonian

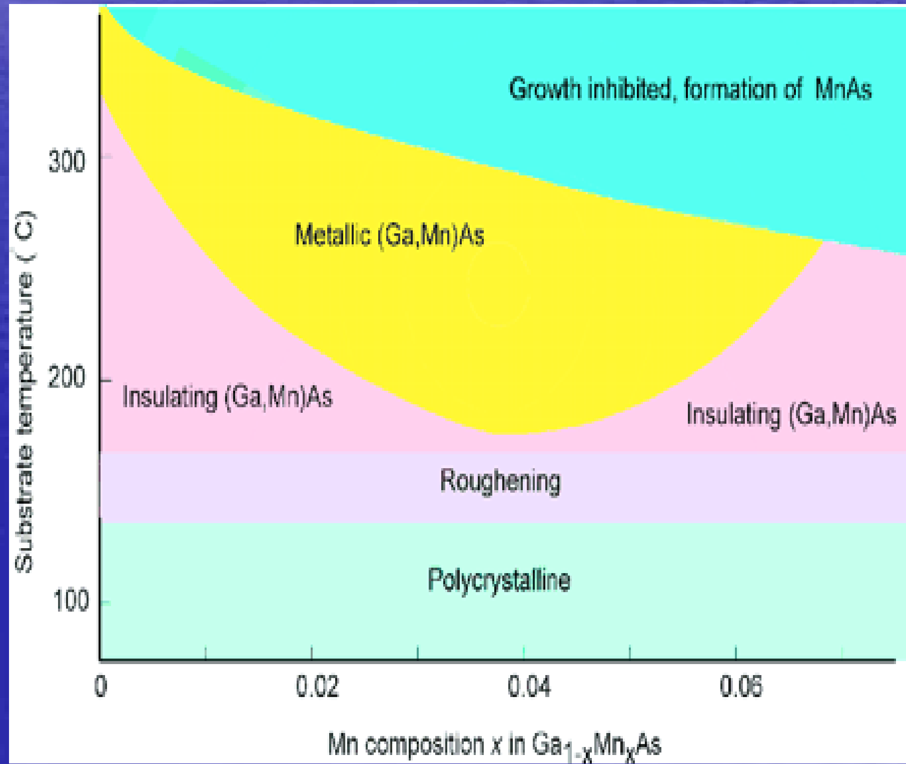
$$H_\alpha = \alpha\,(k_y\sigma_x - k_x\sigma_y) \propto \langle \nabla_z V \rangle$$

$$\mathbf{b}\,(\mathbf{k}) = 2\alpha\,\hat{\mathbf{z}} \times \mathbf{k}$$

Ferromagnetism in (III,Mn)As

- LT-MBE growth
- Phase diagram: relation between growth parameters and the properties of GaMnAs

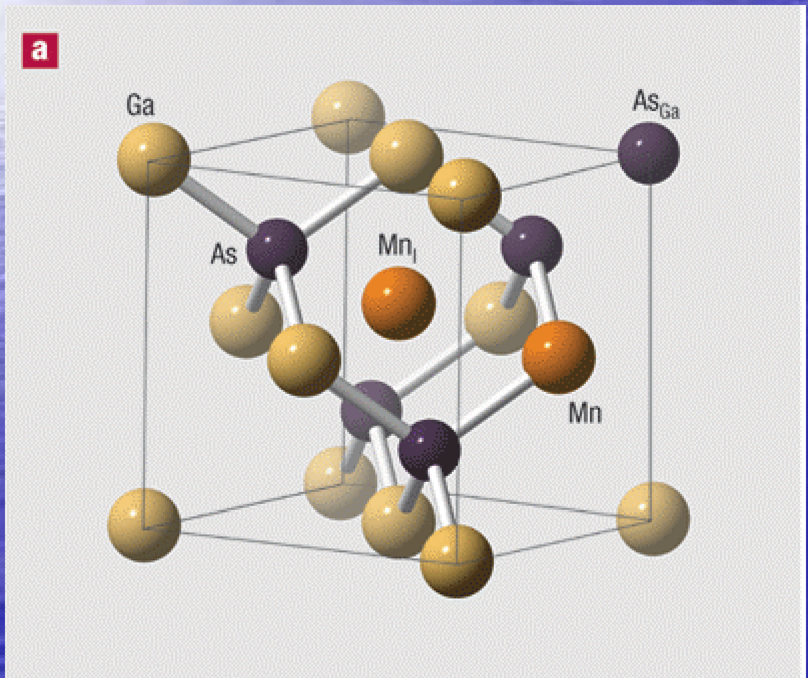




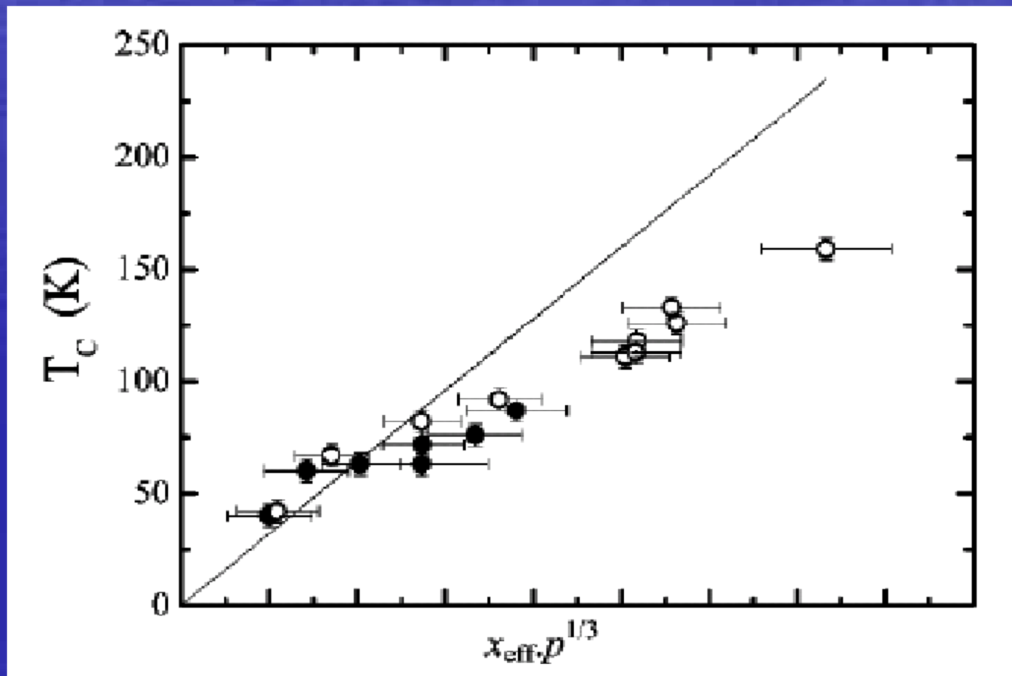
H. Ohno Science 281, 952 (1998)

Ferromagnetism in (III,Mn)As

- Substitutional Mn and growth defects
- Curie temperature increase with post-growth thermal annealing



MacDonald et al. Nature 4, 195 (2005)

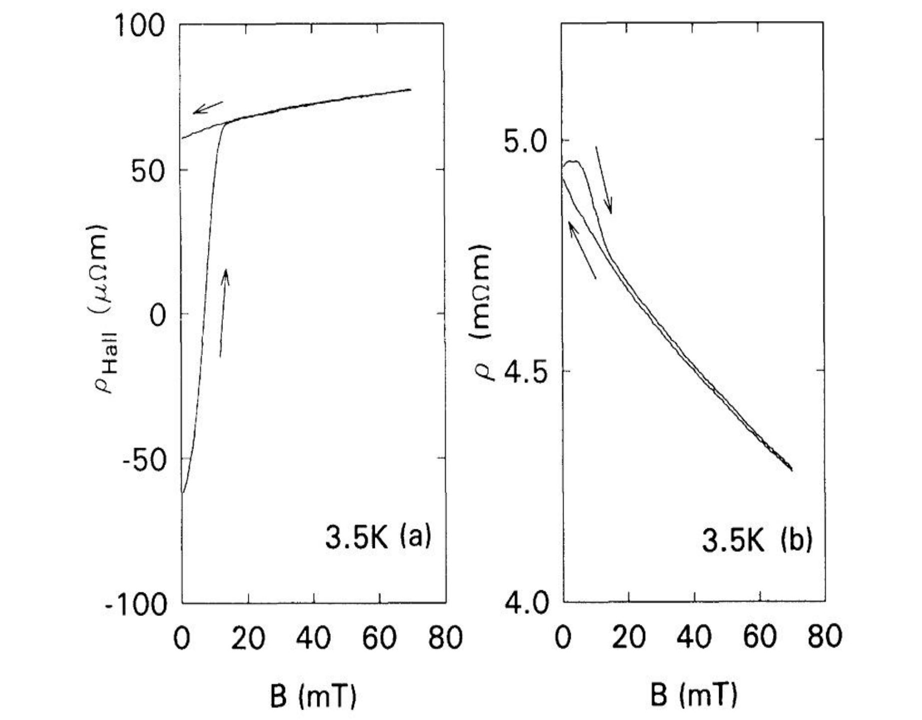


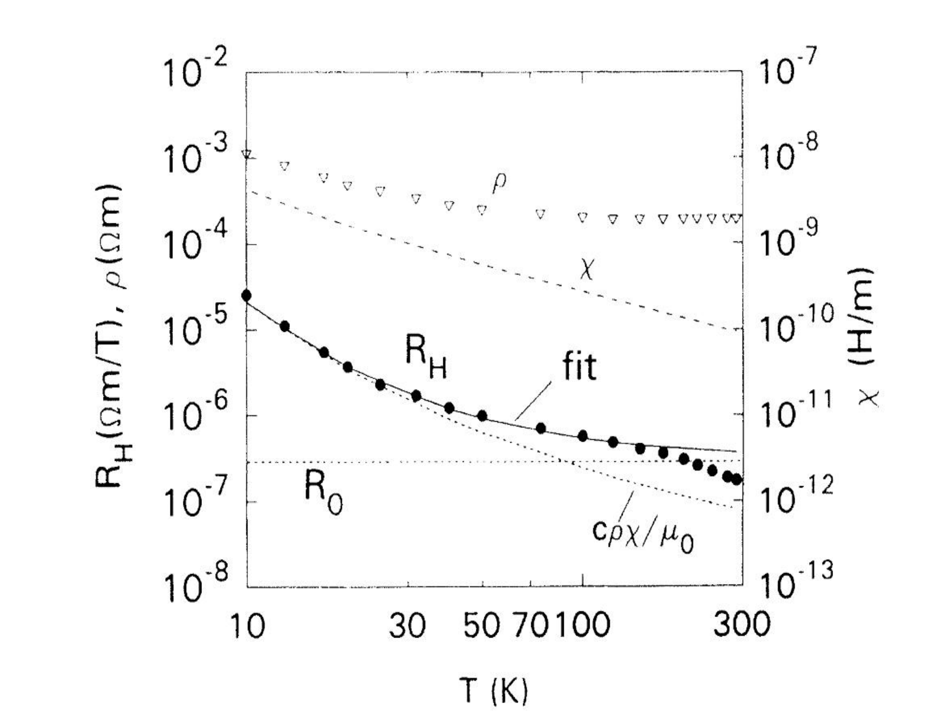
Wang et al. JAP 95, 6512 (2004)

Ferromagnetism in (III,Mn)As

- First DMS InMnAs: T_C~7.5K
- AHE in the Hall coefficient vs. temperature plot

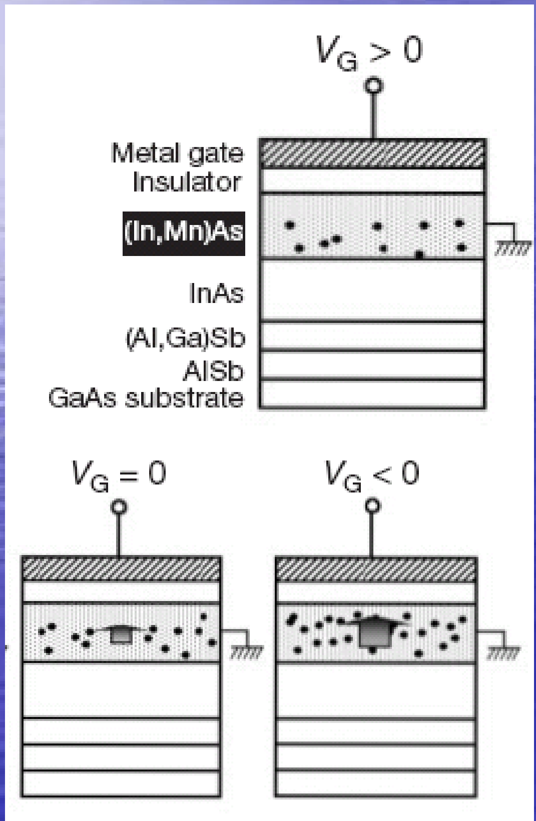
Ohno et al. PRL 68, 2664 (1992)

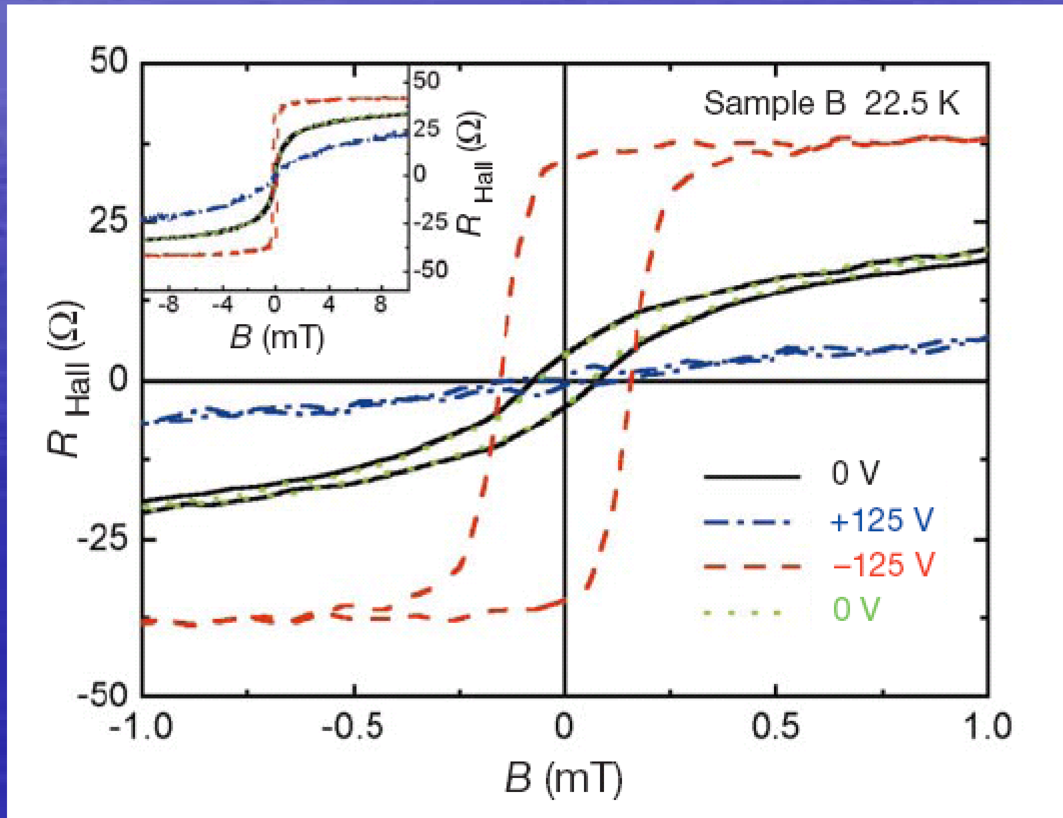




Ferromagnetism in (III,Mn)As

- Electric field control of FM

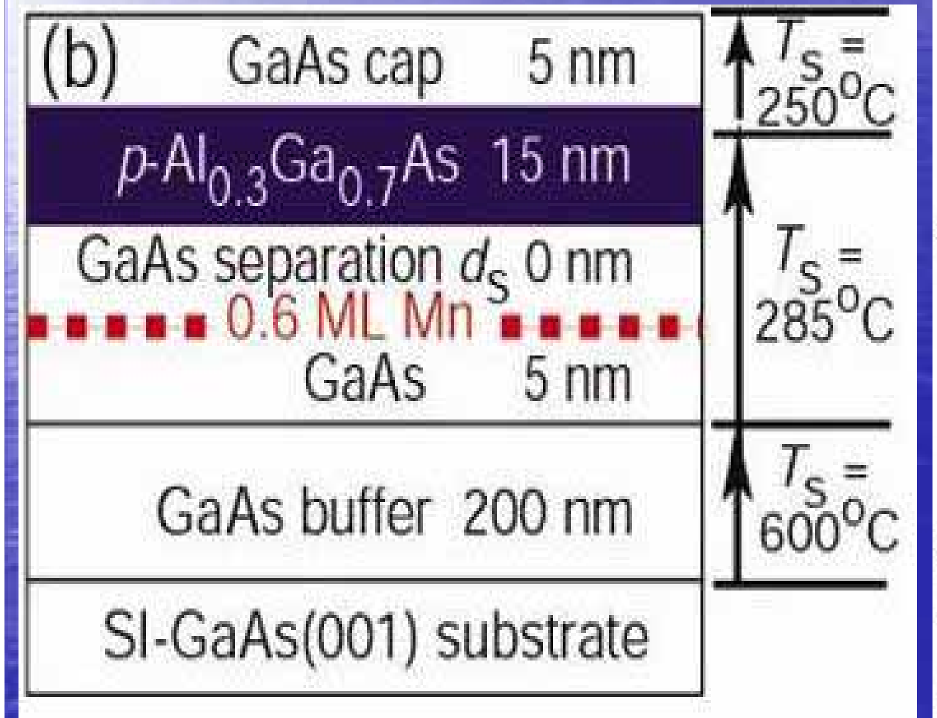


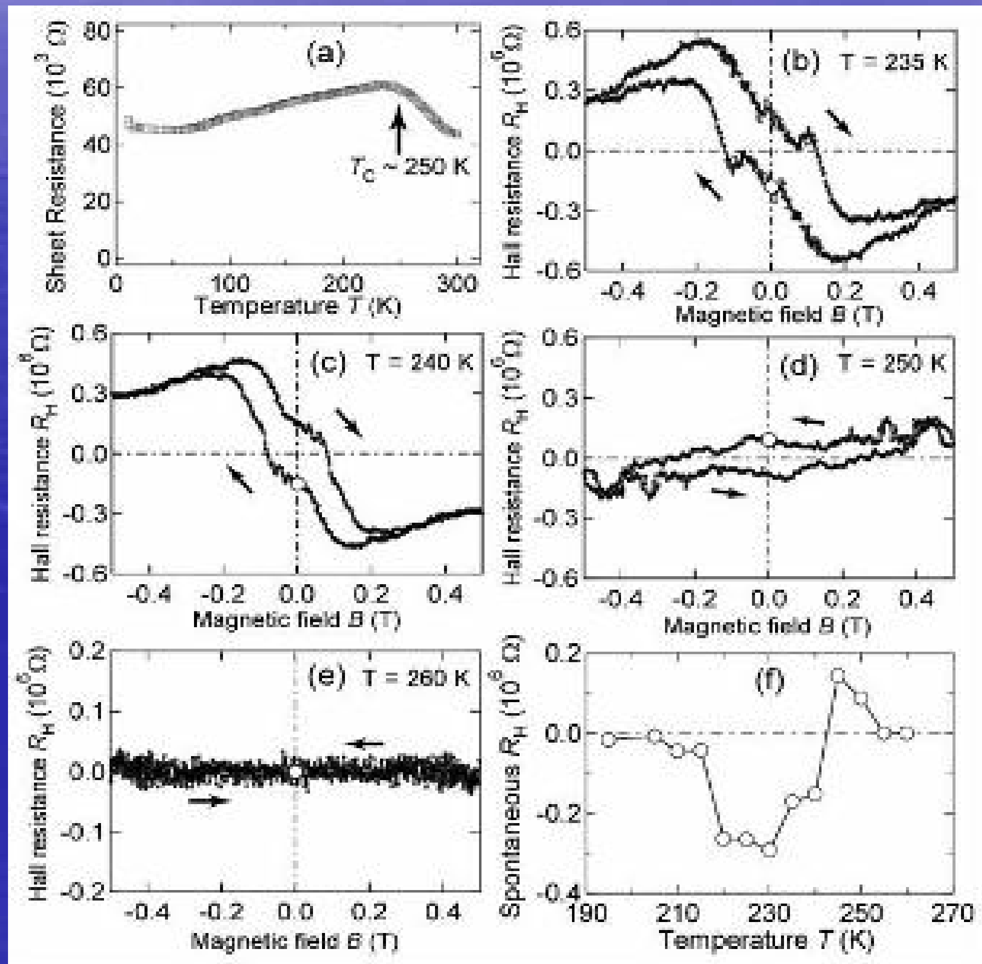


Ohno et al., Nature 408, 944 (2000)

Ferromagnetism in (III,Mn)As

- High T_C Heterostructures: T_C~250K





Nazmul et al. PRL 95, 017201 (2005)

Theory of FM in DMSs

- Mean Field Theory & Zener's model

Mn Spin Free energy: $F_s = \frac{1}{2}\,\alpha S^2$
(antiferrogmagnetic Mn-Mn int.)

Carrier's Free energy: $F_c = \frac{1}{2}\,\gamma s^2$ (kinetic energy)

Mn-Carrier Interaction: $F_{int} = -\beta\, s\, S$

Minimize $F = F_s + F_c + F_{int} \rightarrow s = (\beta/\gamma)S$

$F = \frac{1}{2}\,(\alpha - \beta^2/\gamma)S^2$

[Ferrogmagnetic when $(\alpha - \beta^2/\gamma) < 0$.]

$$H = H_{KL} + \vec{s} \cdot \vec{h}_{MF}$$ Diagonalization ---> Carrier's Free energy F_C

$$M_S = g\mu_B N_0 x_{eff} S B_S \left[\frac{g\mu_B |H_{MF}|}{k_B (T + T_{AF})} \right]$$ --> Spin's Free energy F_S

$$F = F_C[M] + F_S[M]$$

$$B_J(x) = \frac{2J+1}{2J} \coth\left(\frac{2J+1}{2J}x\right) - \frac{1}{2J} \coth\left(\frac{1}{2J}x\right)$$

$$L(x) = \coth(x) - \frac{1}{x}$$

$$x = \frac{g\mu_B J B}{k_B T}$$

Theory of FM in DMSs

- Mean Field Theory & Zener's model

$$F = F_C[M] + F_S[M]$$

Minimization with respect to M

$$M = g\mu_B N_0 x_{eff} S B_S\left[\frac{g\mu_B\left(-\partial F_c[M]/\partial M + H\right)}{k_B(T+T_{AF})}\right]$$

$$when \quad k_B T \gg g\mu_B H$$

Brillouin function Taylor expansion

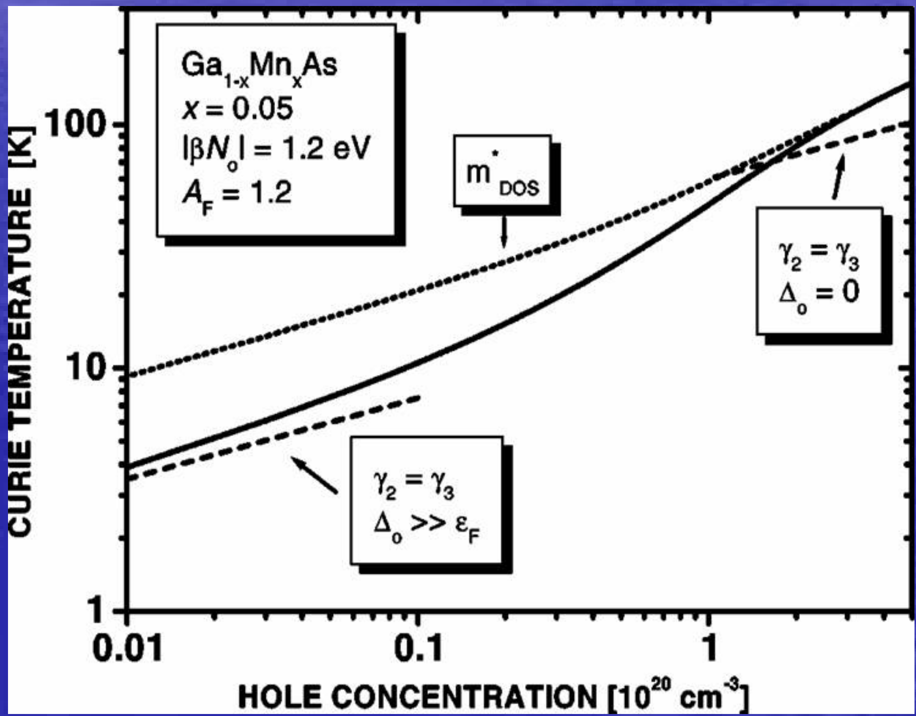
$$T_C = N_0 x_{eff} \frac{S(S+1)}{12k_B} J_{pd}^2 \rho_s(T_C) A_F - T_{AF}$$

Theory of FM in DMSs

- For a strongly degenerate carrier liquid

$$\rho_s = \frac{m^*_{DOS} k_F}{\pi^2 \hbar^2} \quad and \quad T_{AF} \sim 0$$

$$T_C \sim m^* x_{eff} n^{1/3}$$



Ohno et al., PRB 63, 195205 (2001)

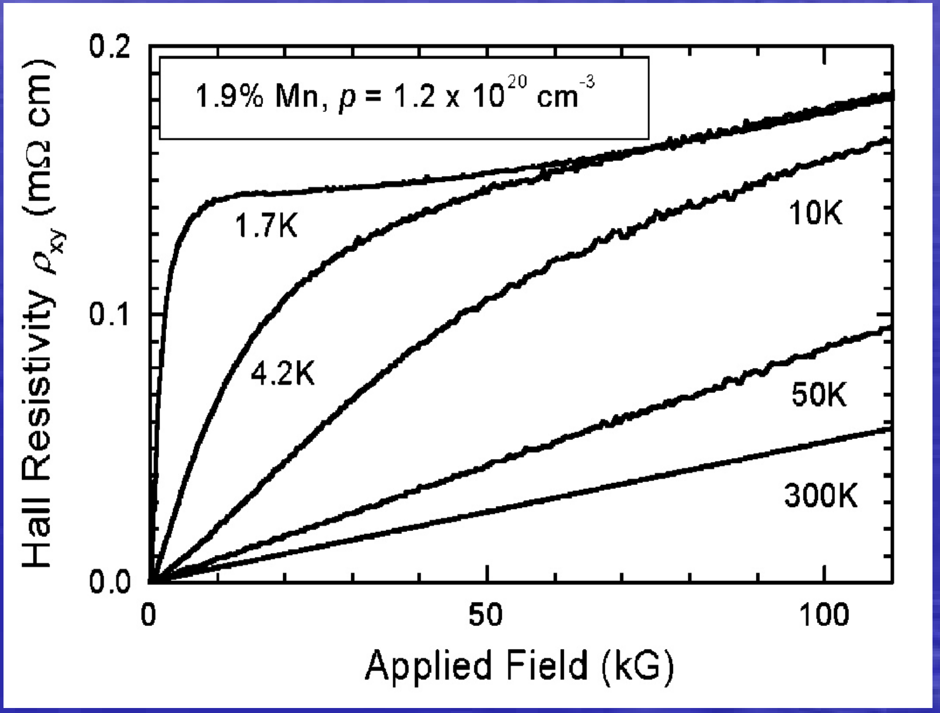
- Anomalous Hall Effect

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

$$when\ T \geq T_C \quad M = \frac{\chi B}{\mu_0}$$

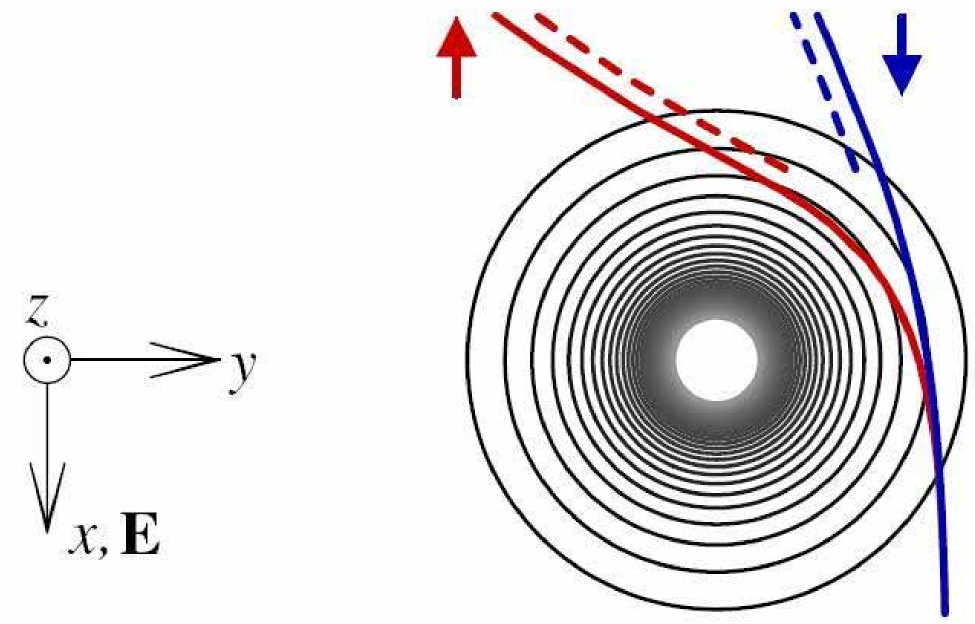
$$\chi = \frac{C}{T - T_C}$$

$$where\ C = \frac{4g^2 S_{Mn}(S_{Mn}+1)\mu_B^2 x}{3a_0^3 k_B}$$



Ferrand et al., PRB 63, 085201 (2001)

Spin-Orbit Scattering—
Skew S. and Side-jump S.



$$\mathbf{j}_{\mathrm{SH}}^{\mu} = e^{-1}(\mathbf{J}_{\mathrm{AH}}^{\uparrow} - \mathbf{J}_{\mathrm{AH}}^{\downarrow}).$$

Engle, Rashba, and Halperin, Cond-mat 2006

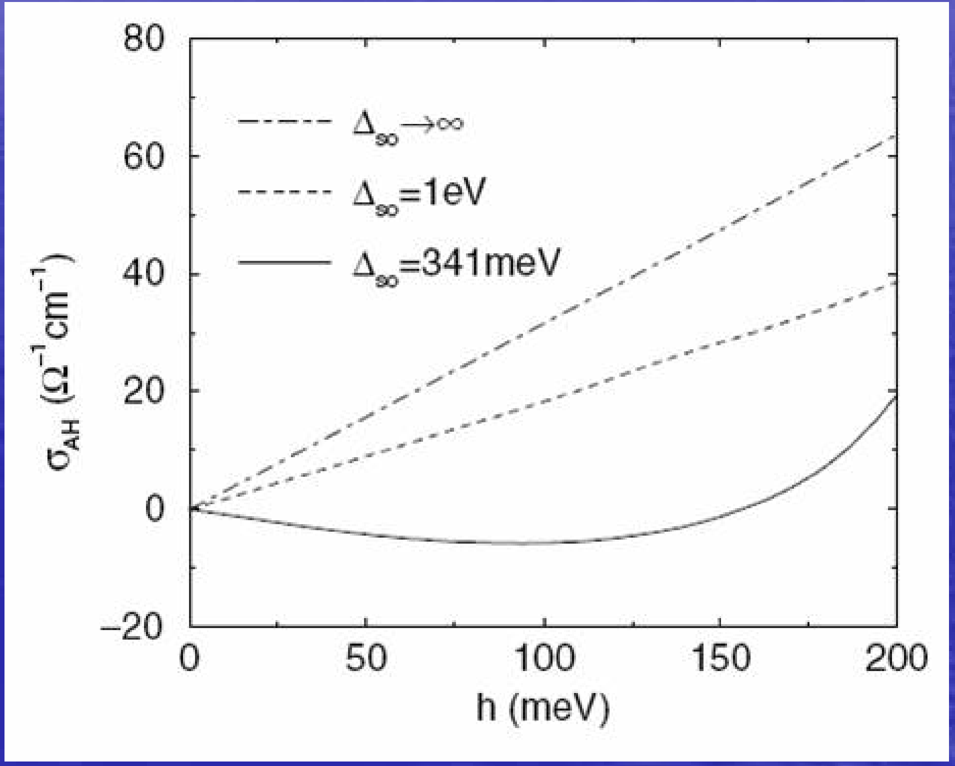
- Intrinsic AHE (Karplus & Luttinger)

$$R_s \propto \rho_{xx}^2$$

- Skew Scattering (Smit)

$$R_s \propto \rho_{xx}$$

- Intrinsic AHE + Berry phase (Jungwirth et al.)



Jungwirth et al., PRL 88, 207208 (2002)

New Structure

- Fabrication of two-dimensional devices with low carrier concentration and high mobility with the ultimate objective of making the first ferromagnetic quantum dot

- Development of a scheme for the fabrication of Ohmic contact, by thermal annealing, to buried 2D hole/electron gas

New Structure

- 2DHG Triangular QW

$$p = 2.3 \times 10^{13} cm^{-2}$$

$$\mu = 1937 cm^2 / Vs$$

GaAs (001)	Substrate
SI-GaAs	275 nm
SI-AlGaAs	57 nm
GaAlAs:Be	3.3 nm
SI-AlGaAs	11 nm
SI-GaAs	23 nm

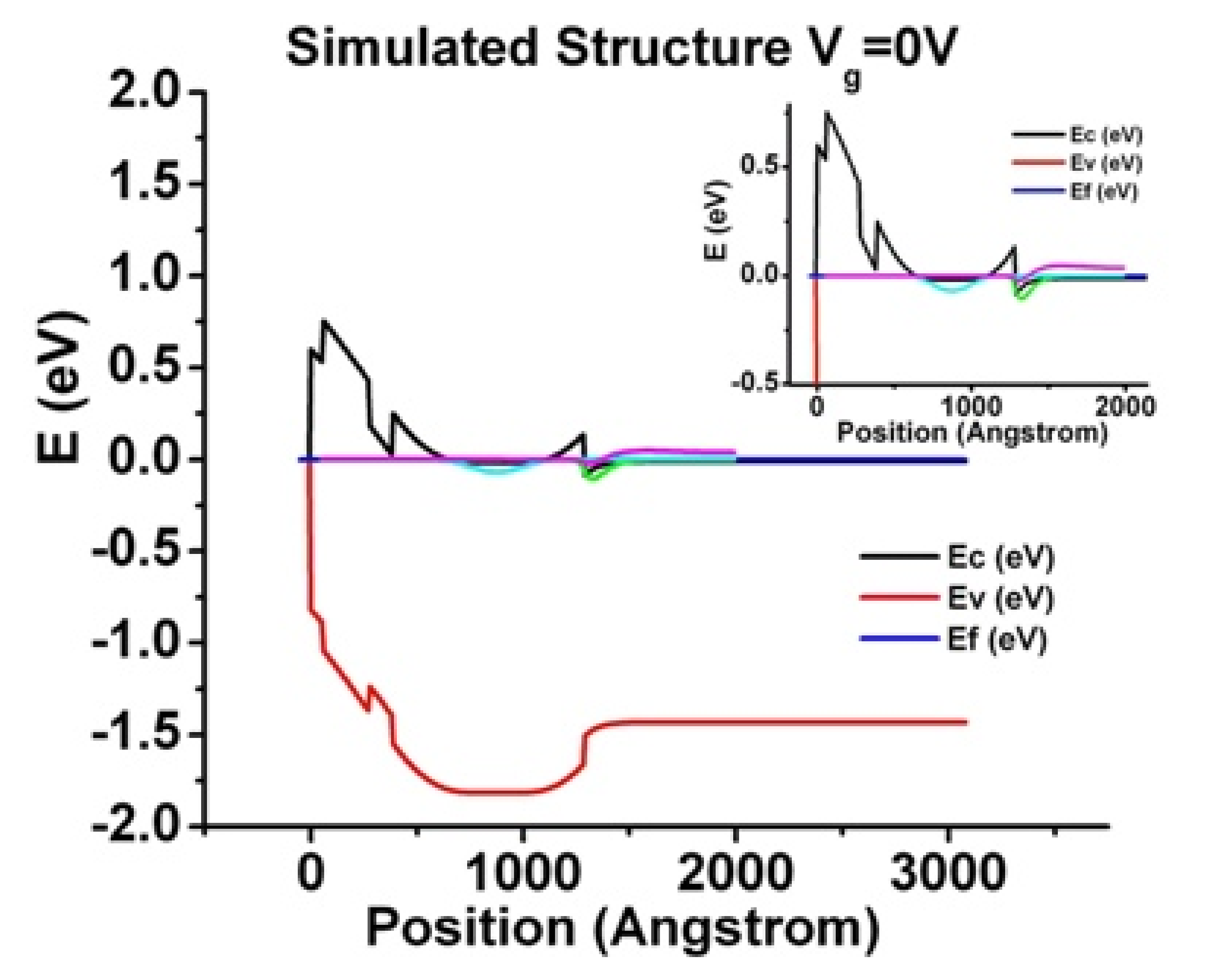
- Good control of the growth process
- Clean chamber

New Structure

- Square QW
  - Easier to grow
  - Less impurity for scattering
  - Reduced presence of Mn_I

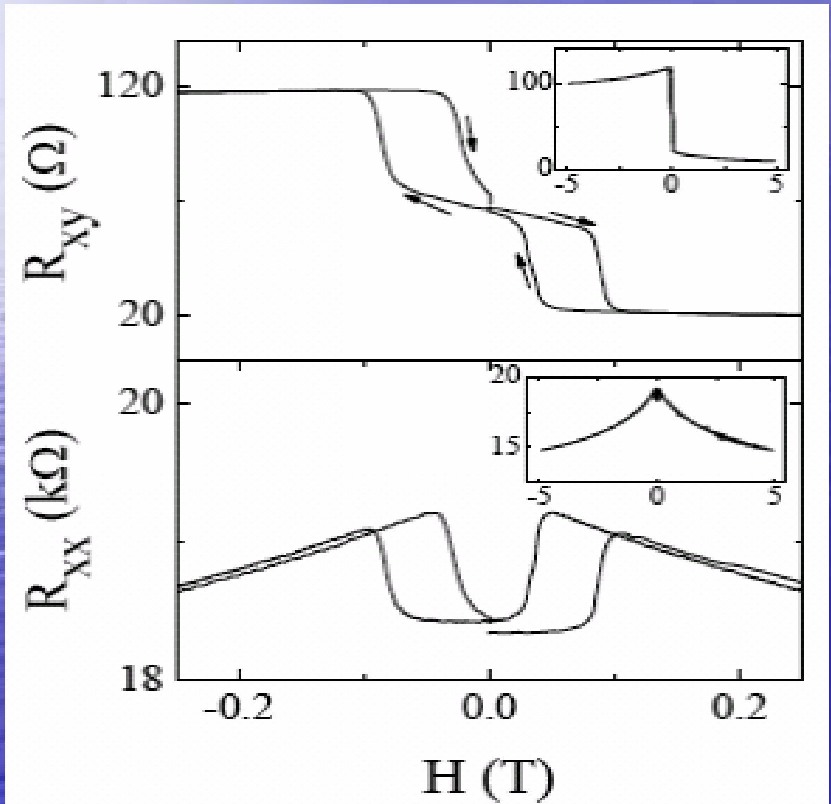
GaAs (001)	Substrate
GaAs:Si	100 nm
AlGaAs:Be	200 nm
SI-GaAs	10 nm
LT-Mn	2/3 ML
LT-AlGaAs:Be	10 nm
LT-AlGaAs	15 nm
LT-GaAs	5 nm

Simulated Band Structure

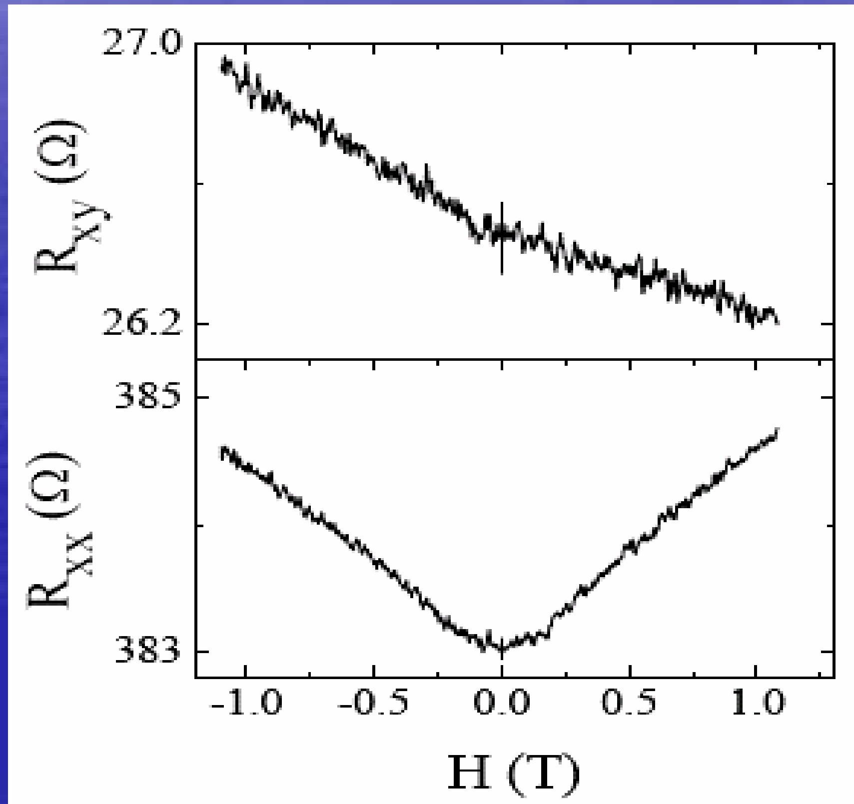


Ohmic contact to $Ga_{1-x}Mn_xAs$

- Ferromagnetism in perpendicular field



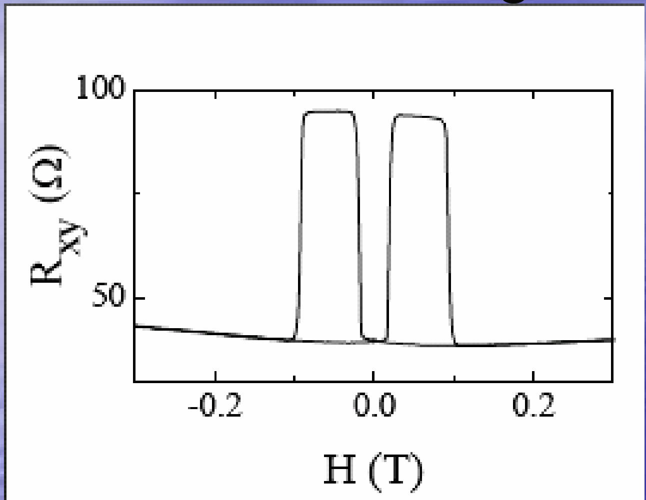
No Annealing



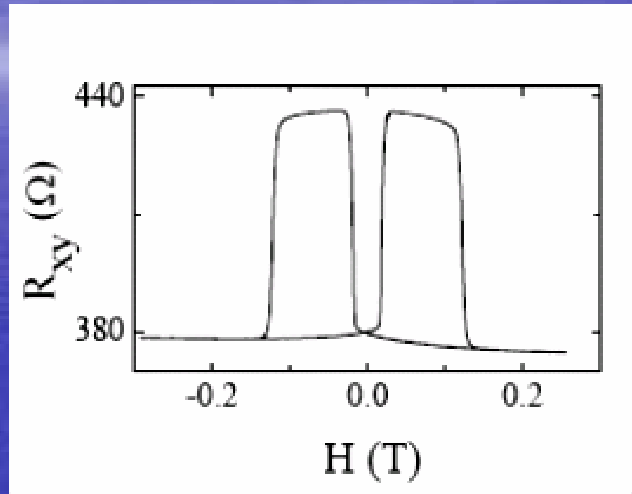
470 °C for 30 s

Ohmic contact to $Ga_{1-x}Mn_xAs$

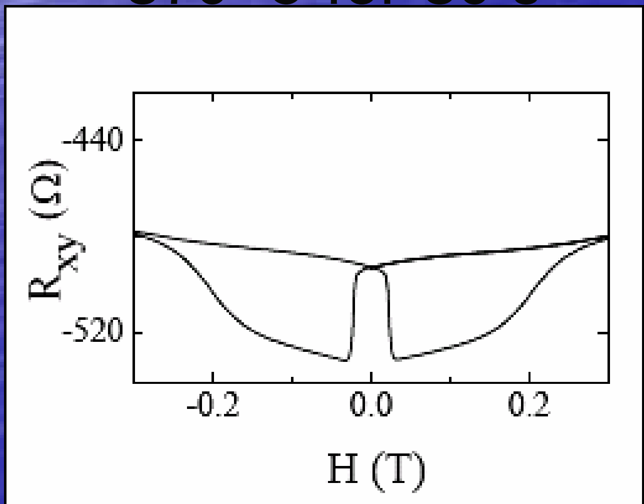
No Annealing



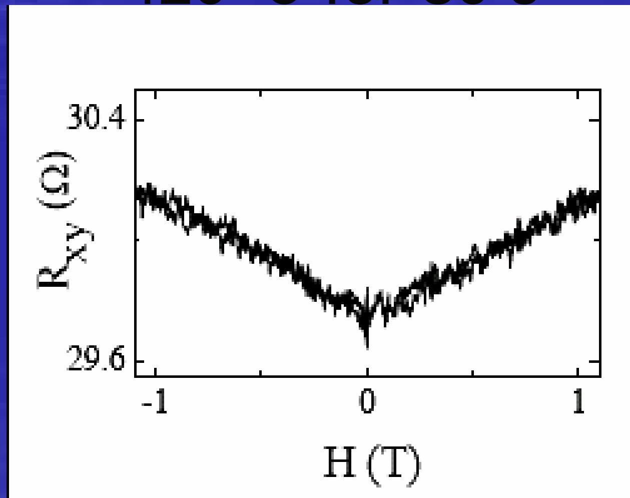
320 °C for 30 s



370 °C for 30 s

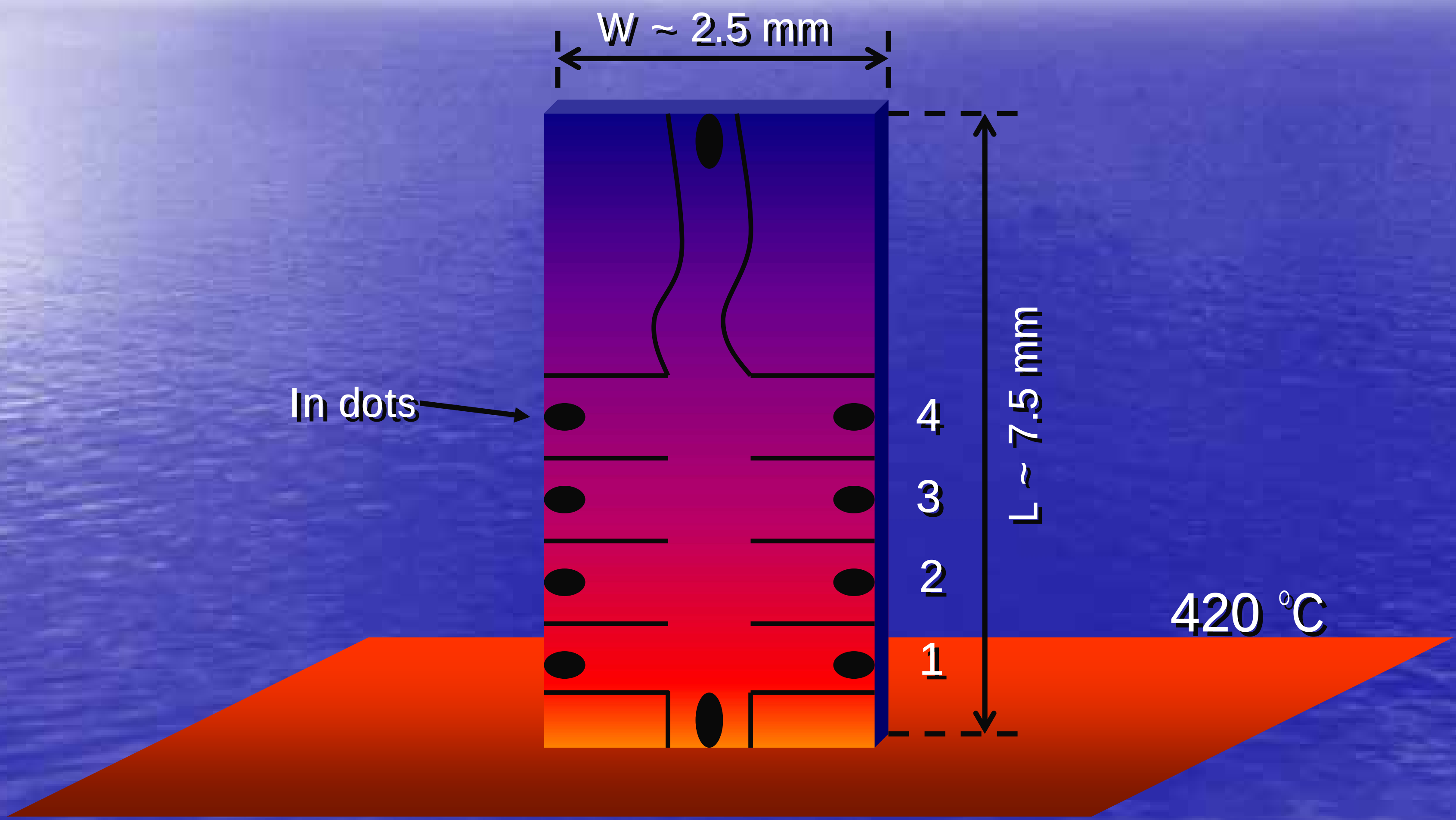


420 °C for 30 s

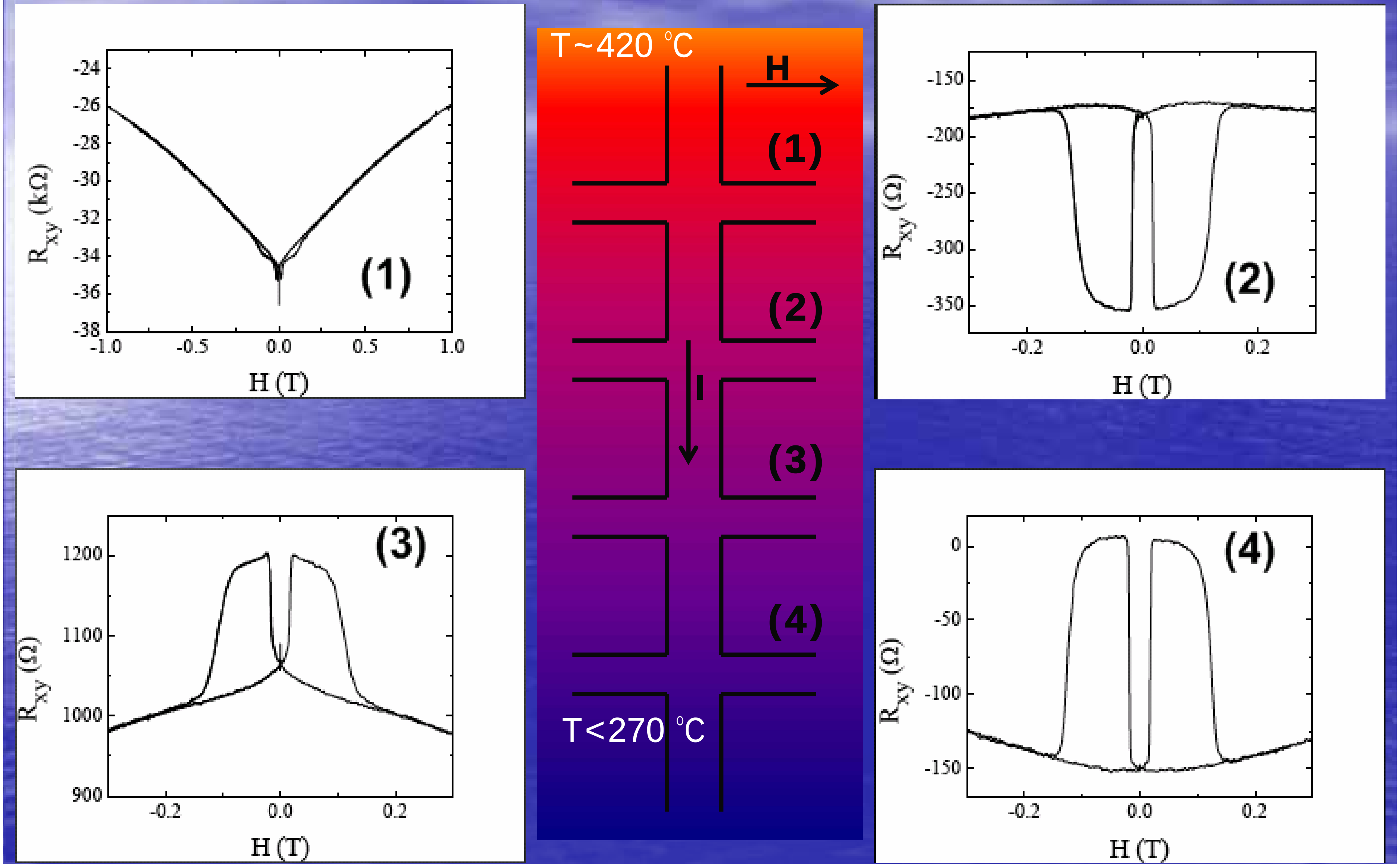


Ohmic contact to $Ga_{1-x}Mn_xAs$

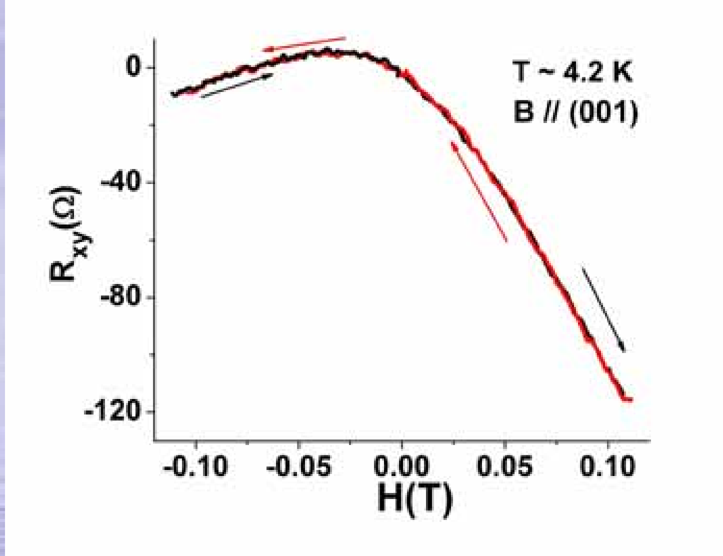
- Thermal Gradient

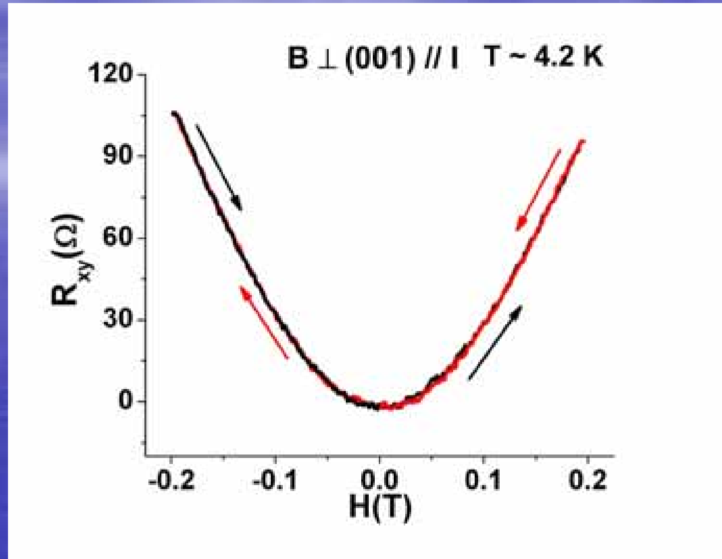


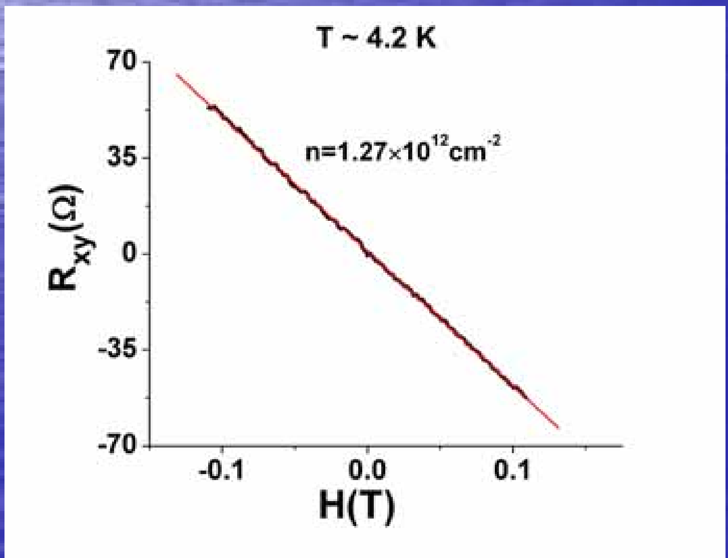
Ohmic contact to $Ga_{1-x}Mn_xAs$

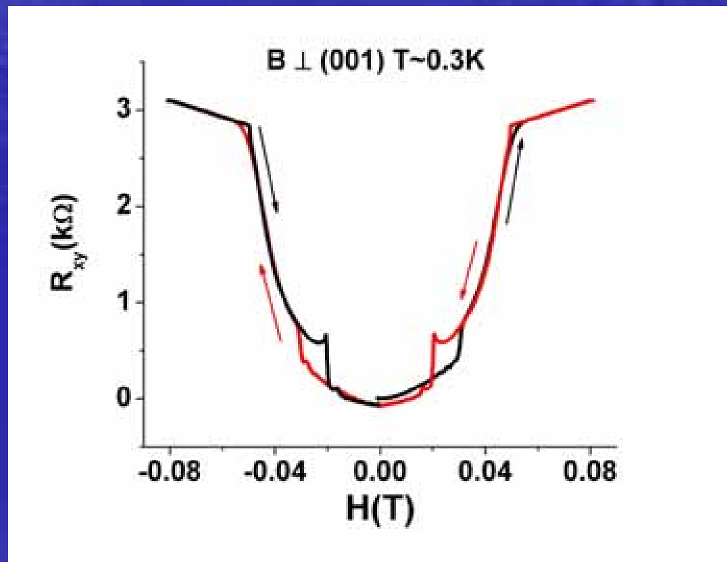


Ohmic contact to $Ga_{1-x}Mn_xAs$

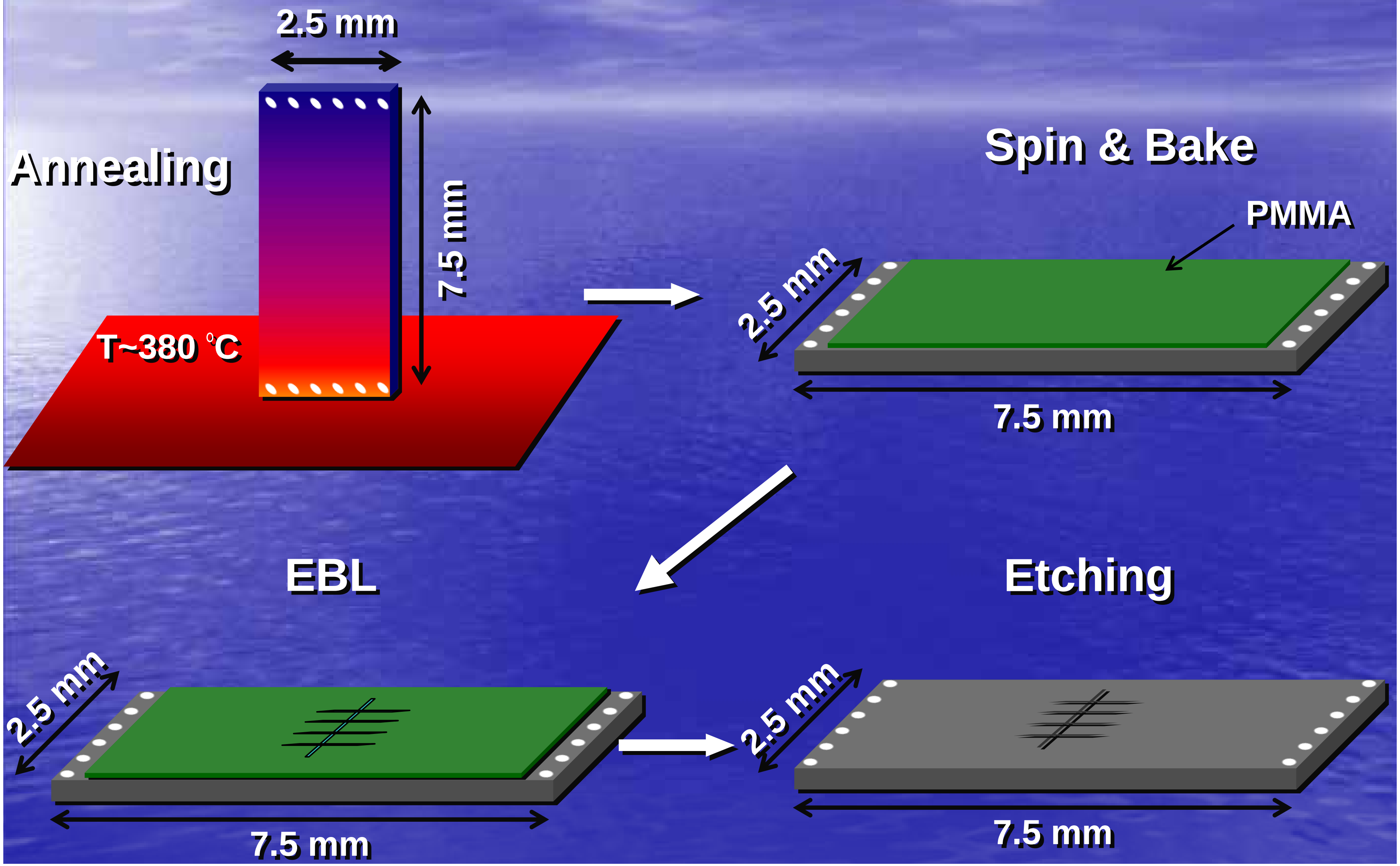






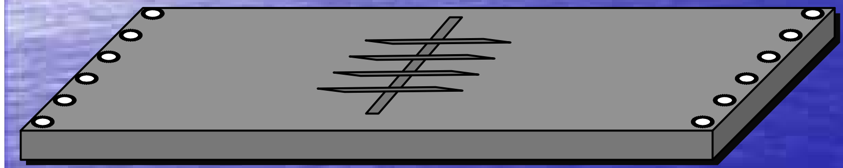


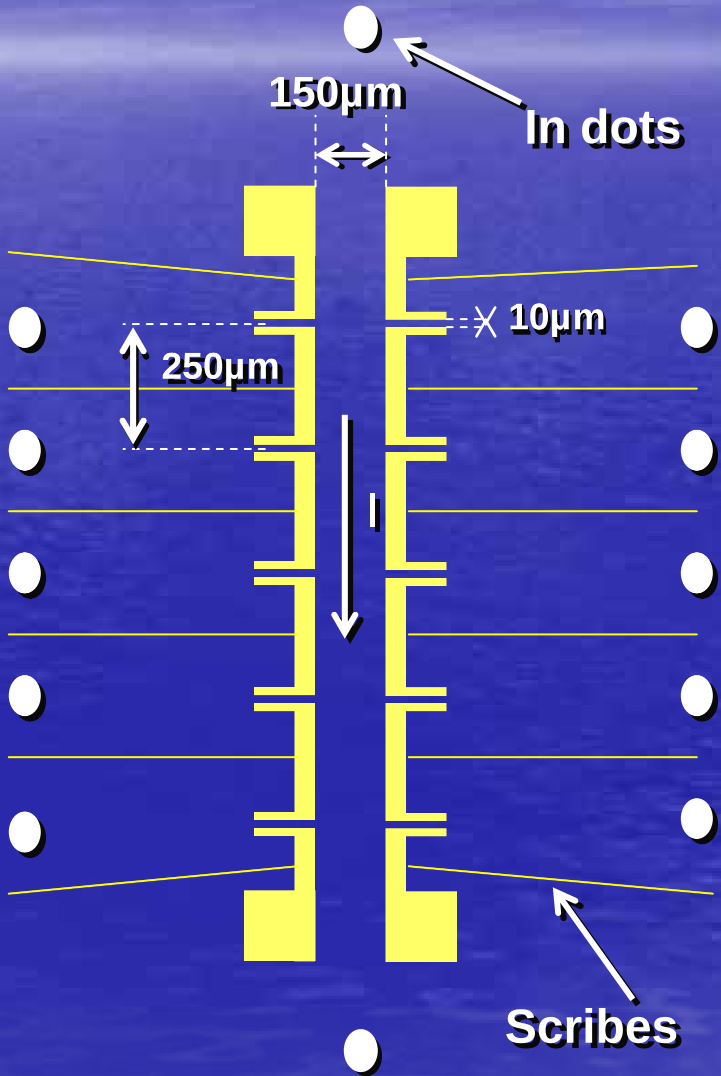
SAMPLE PREPARETION



SAMPLE PREPARATION

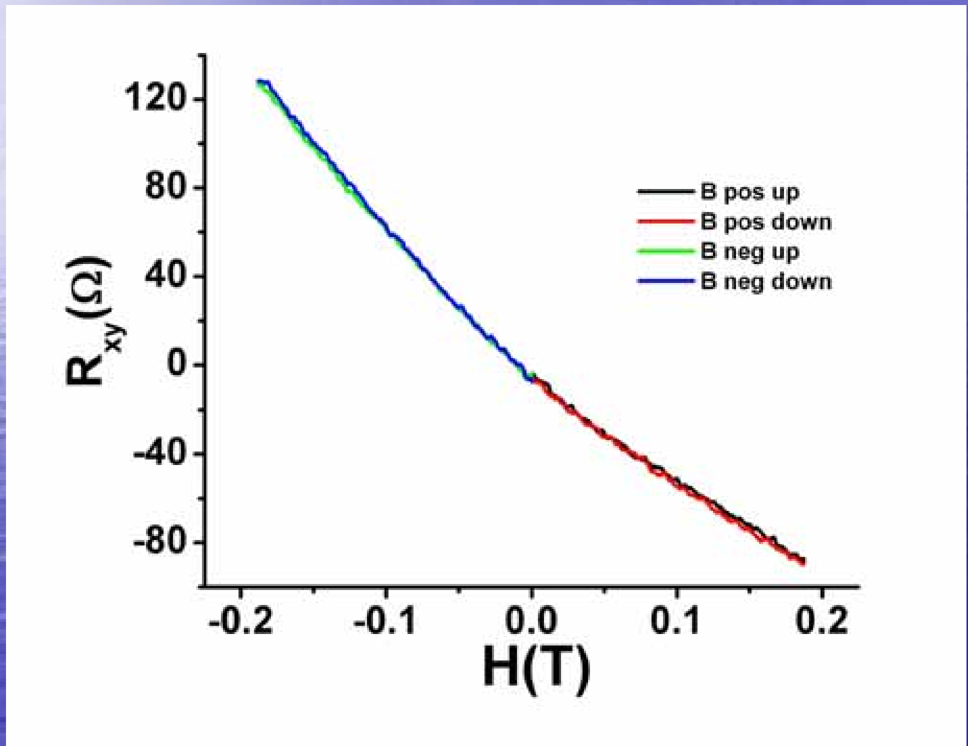
- Hall Bar Pattern

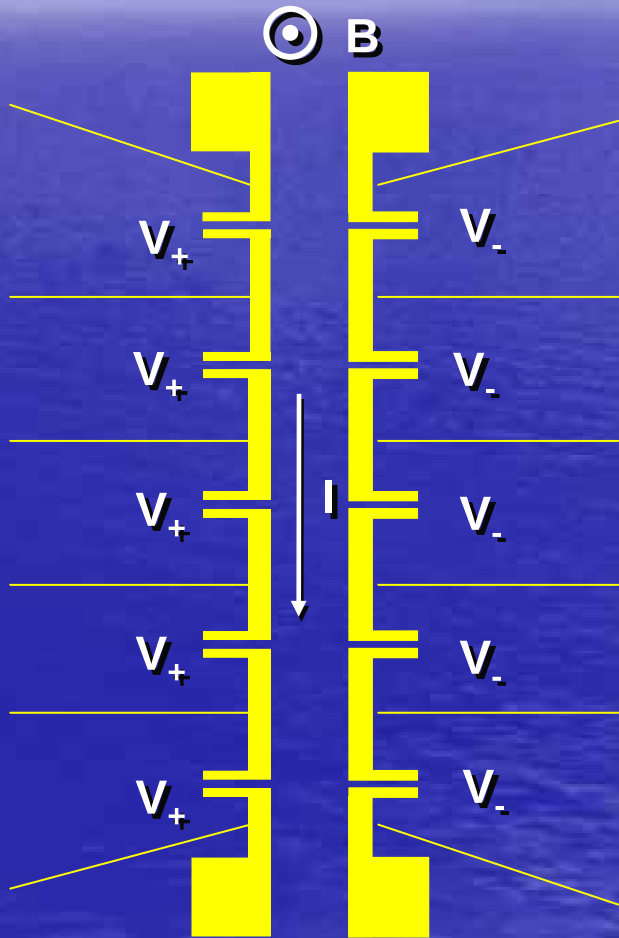




MAGNETO-TRANSPORT MEASUREMENTS

- 4.2 K Measurements





MAGNETO-TRANSPORT MEASUREMENTS

- Lag Removal

$$I_{Magnet} - I_{Ramper} = -I'\left(1 - e^{-t/\tau}\right)\tau$$

$$I_{Magnet} - I_{Ramper} = I'e^{-t/\tau}\tau$$

- Anti-symmetrization

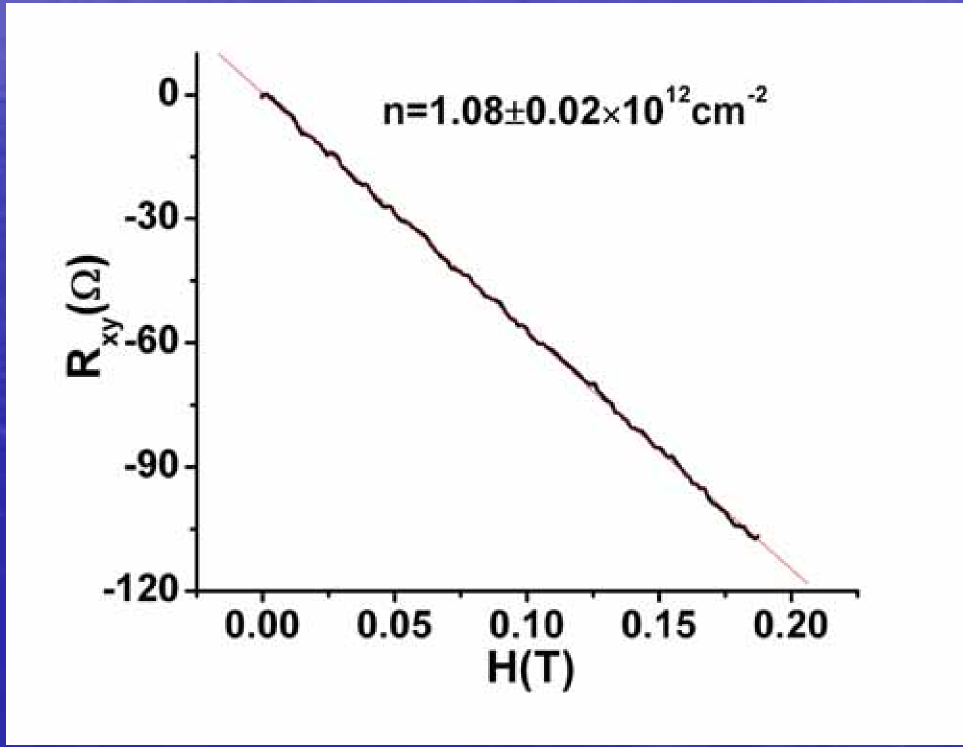
$$R_{xy}(B) = \left(R_{xy}(B+) - R_{xy}(B-)\right)/\,2$$

- Density & Mobility

$$n = 1.08 \times 10^{12}\, cm^{-2}$$

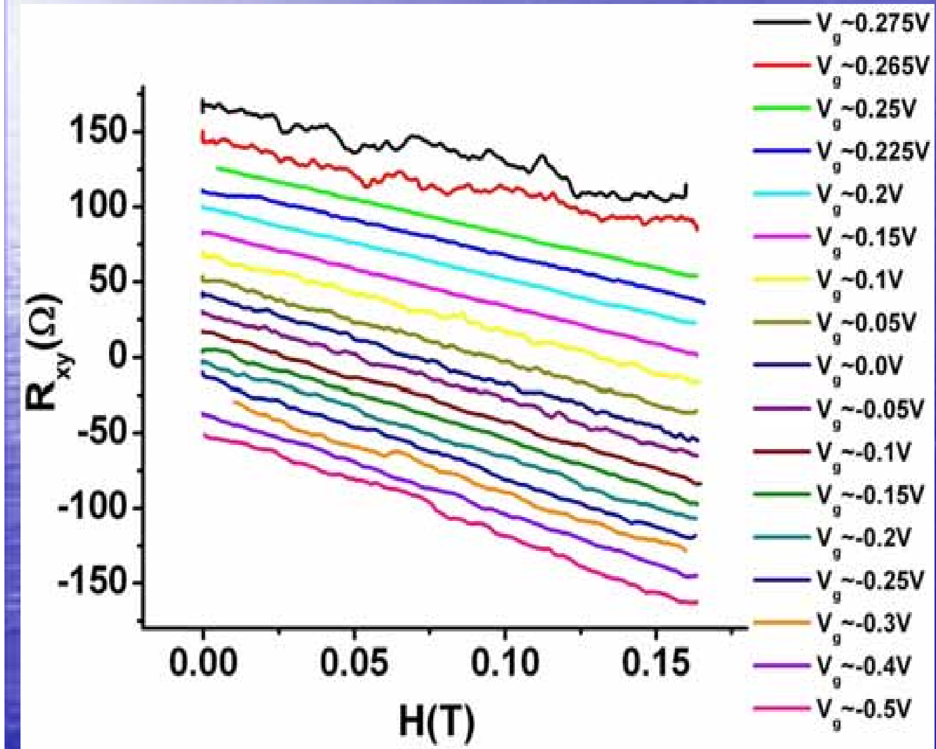
$$\mu = 575 cm^2\,/Vs$$

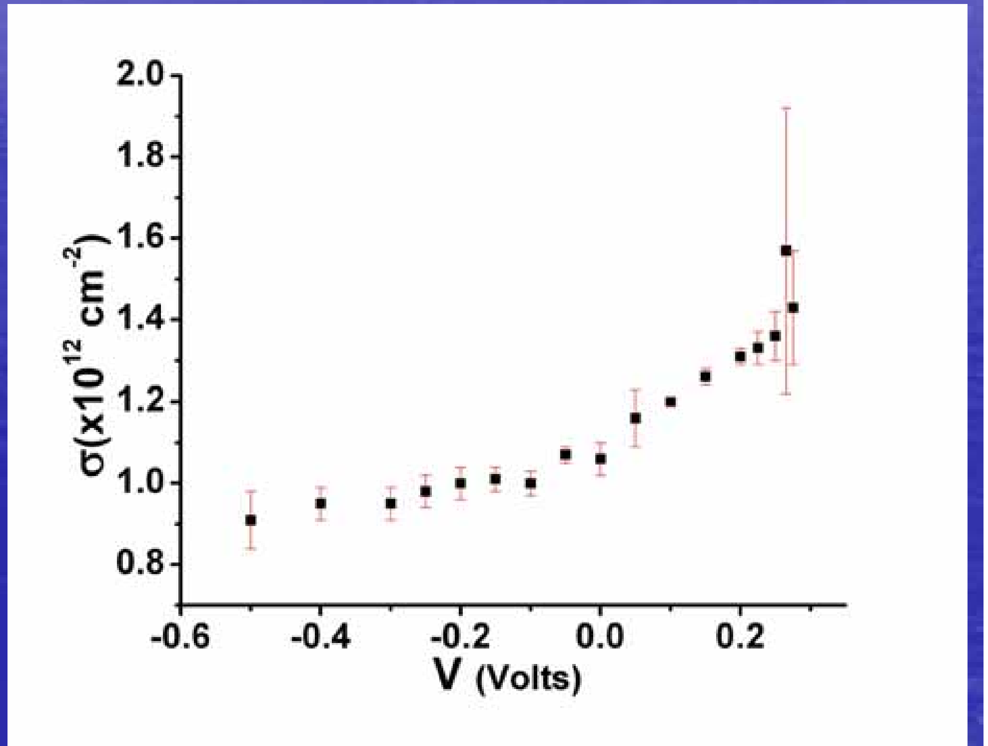
n-Type Electrons!



MAGNETO-TRANSPORT MEASUREMENTS

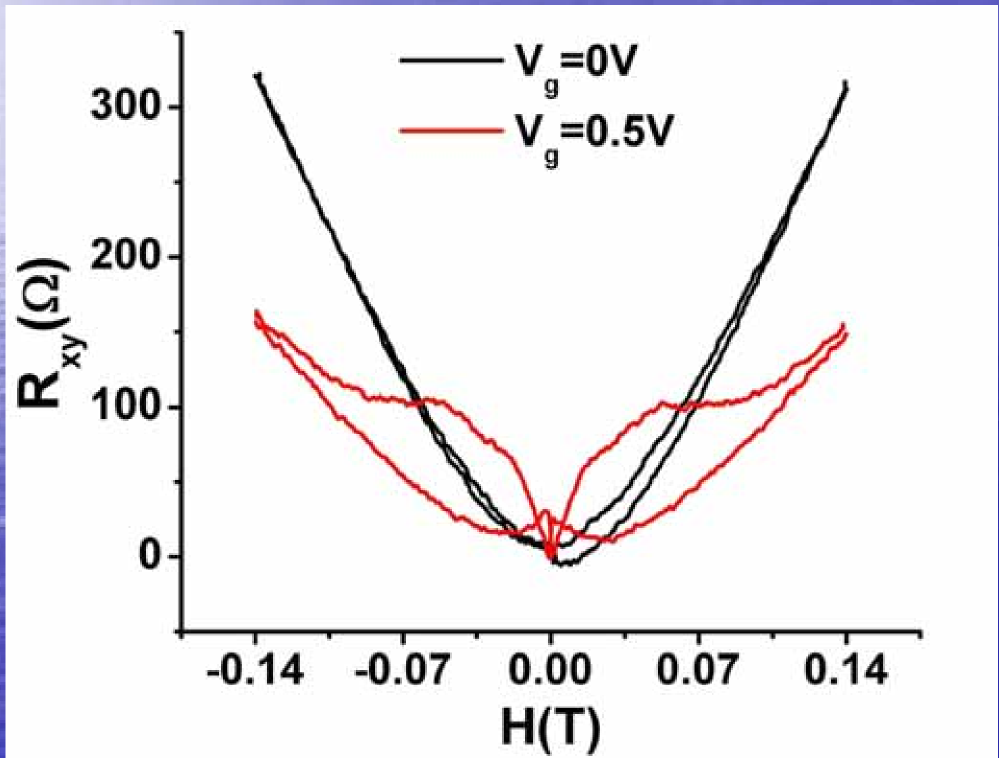
- Gating

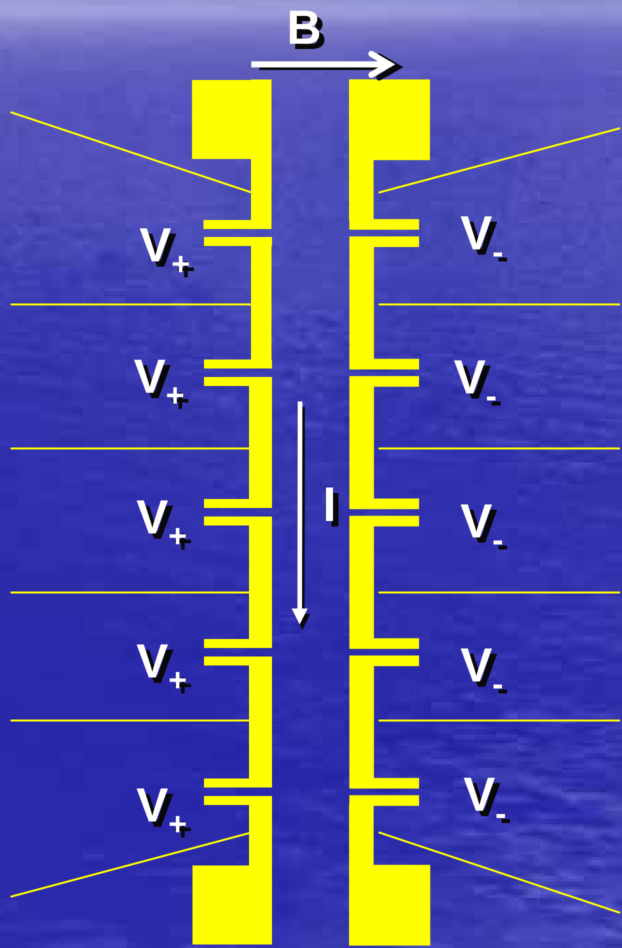




MAGNETO-TRANSPORT MEASUREMENTS

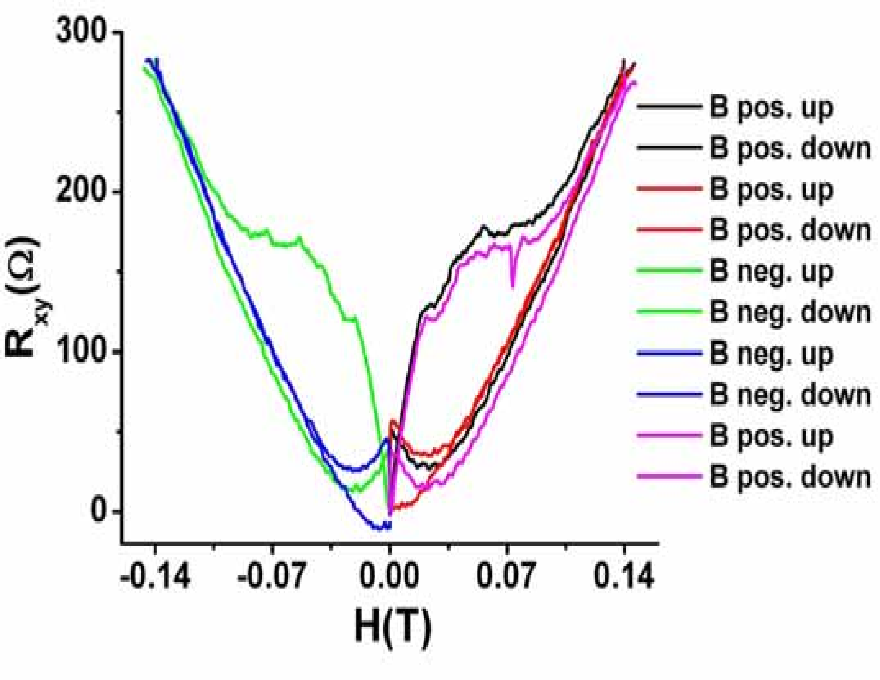
- 0.3 K Measurements

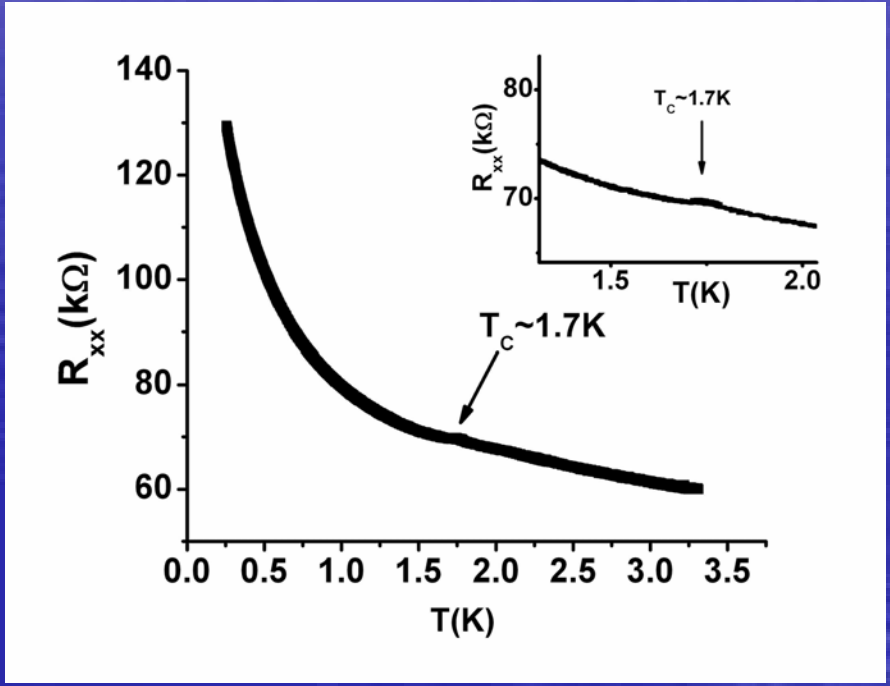




MAGNETO-TRANSPORT MEASUREMENTS

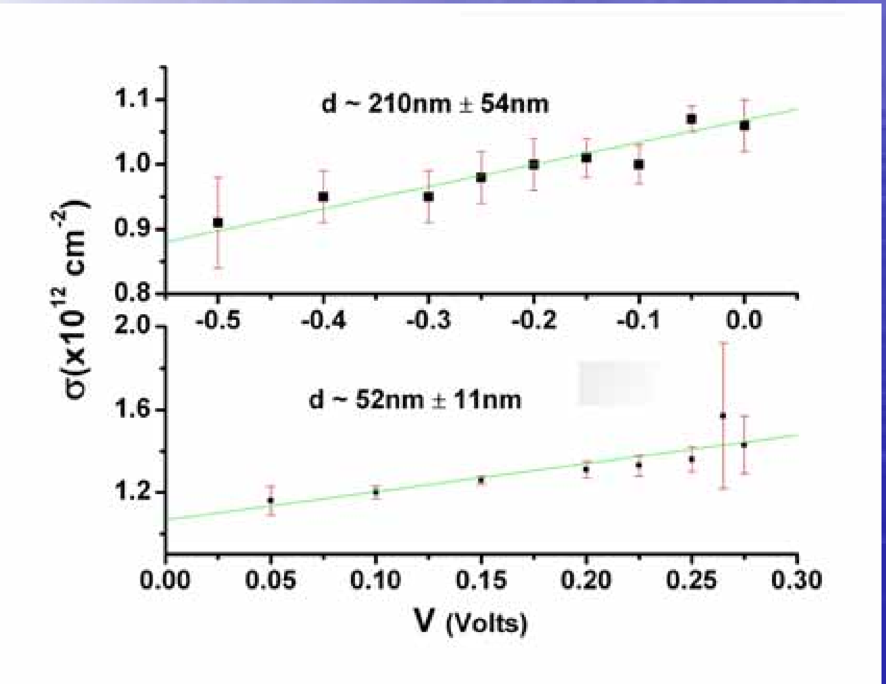
- Hysteresis
- Curie Temperature

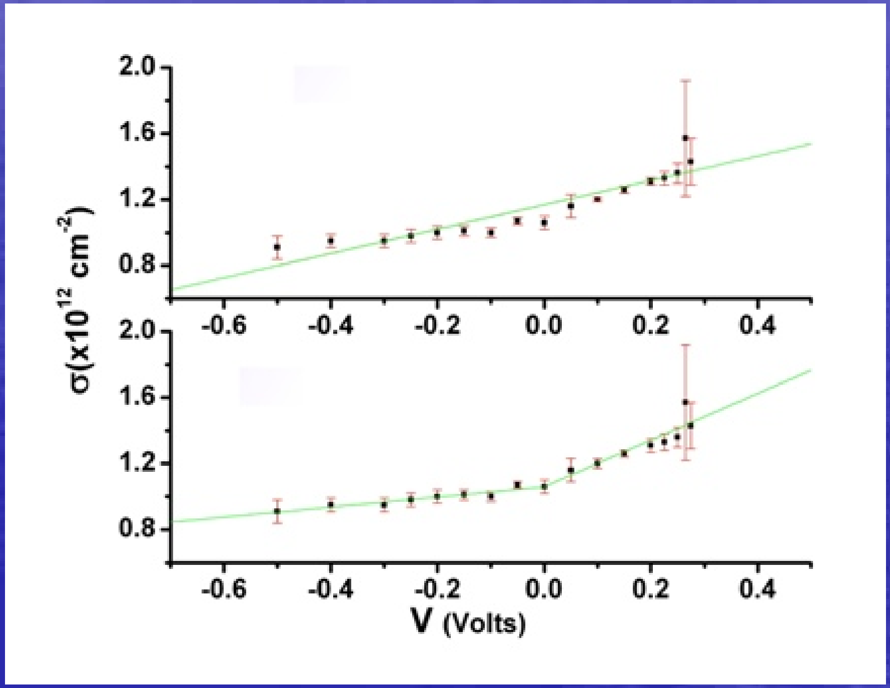




MAGNETO-TRANSPORT MEASUREMENTS

- Two slopes vs. one slope model

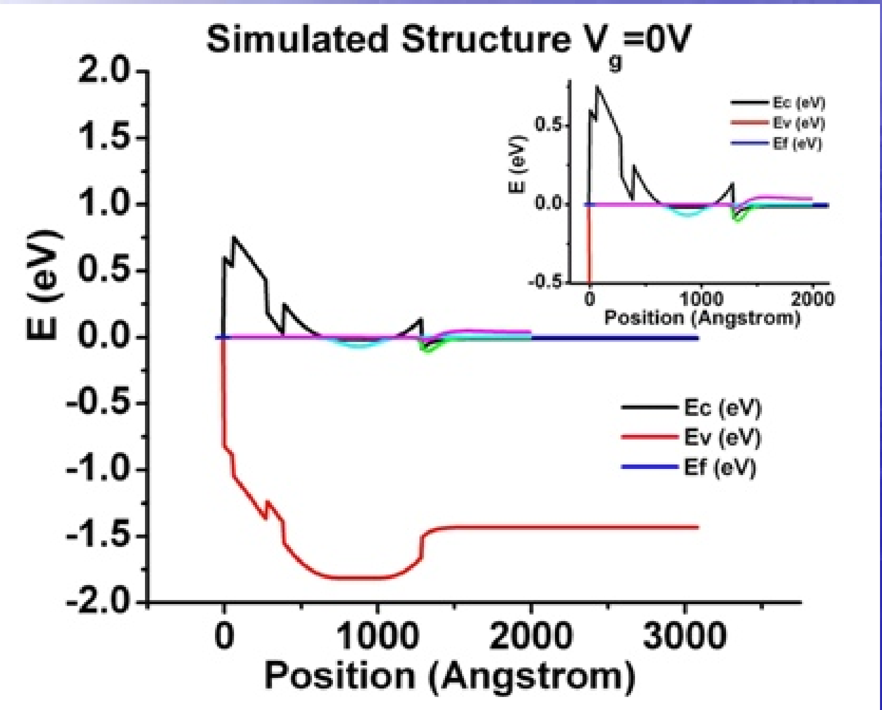


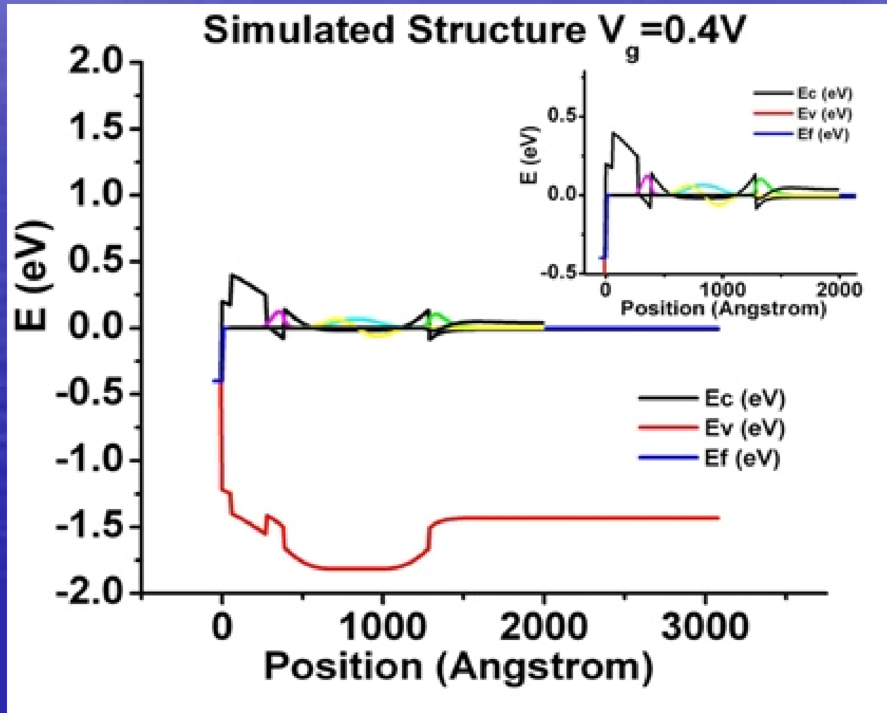


F-test confidence level greater than 99.9%

MAGNETO-TRANSPORT MEASUREMENTS

- Simulations





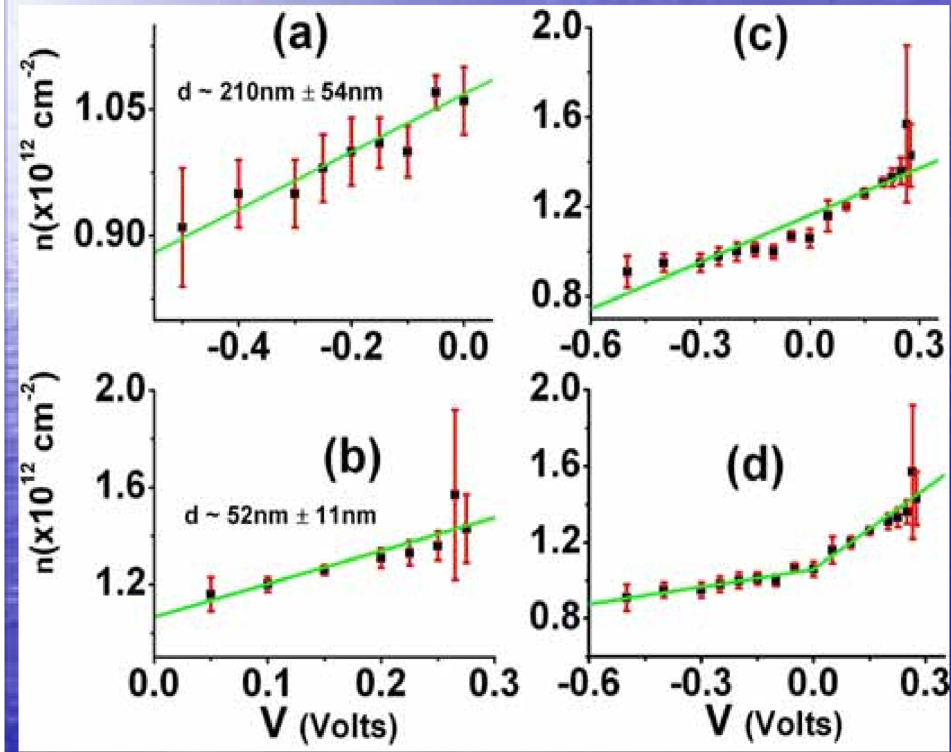
V_g=0V

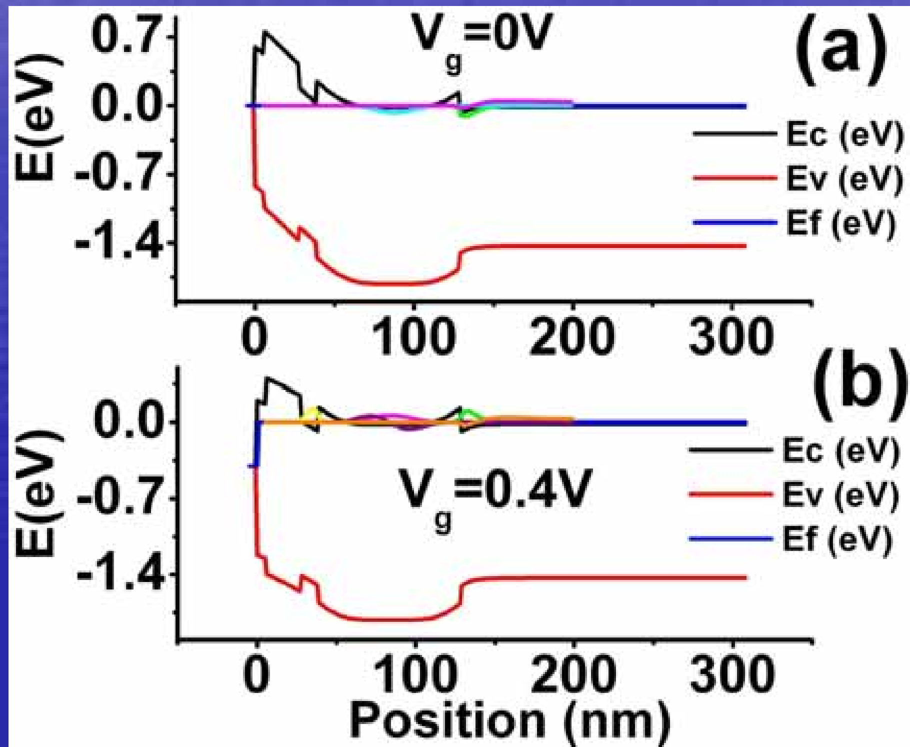
V_g=0.4V

MAGNETO-TRANSPORT MEASUREMENTS

Two slopes vs. one slope model

Simulations





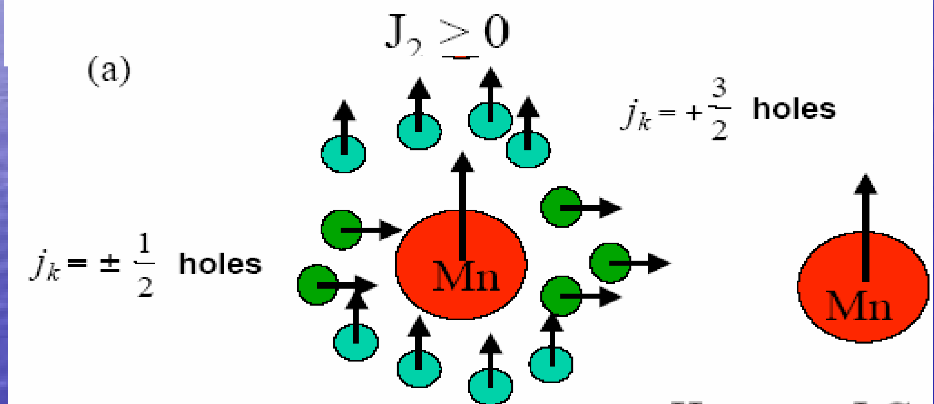
F-test confidence level greater than 99.9%

Heisenberg Exchange Anisotropy

Spin-Orbit—Second Order Perturbation

P-type

$$H_{12} = -J_1 \mathbf{S}_1 \cdot \mathbf{S}_2 + J_2 \mathbf{S}_1 \cdot \mathbf{r}_{12} \mathbf{S}_2 \cdot \mathbf{r}_{12}$$



From: Randy Fishman

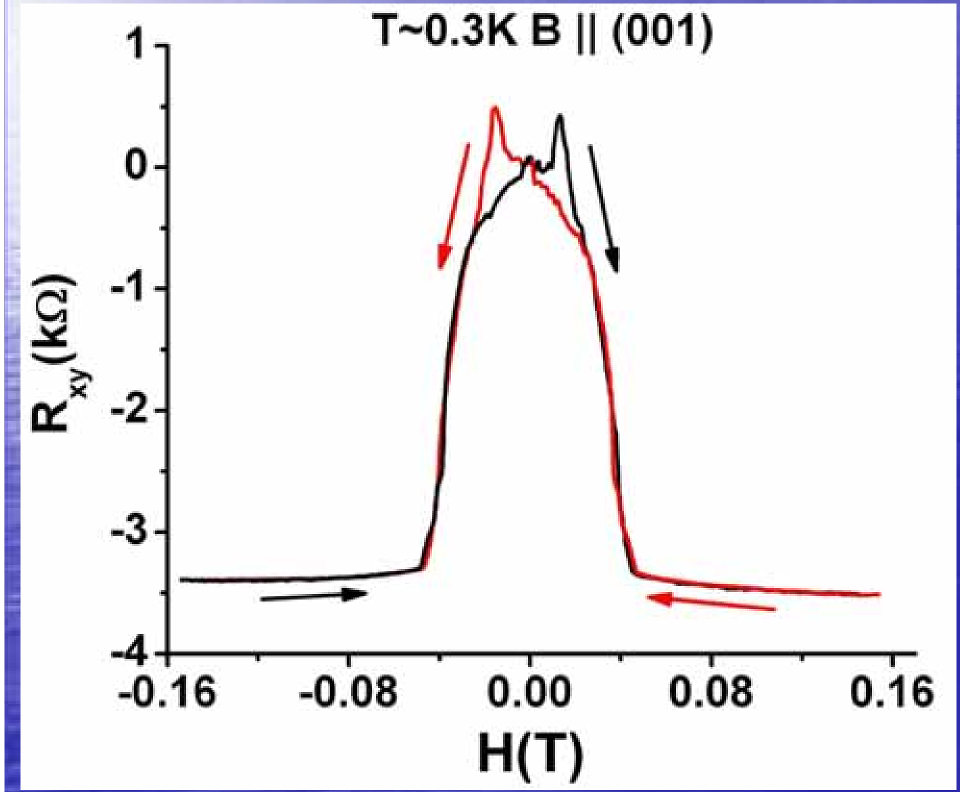
Dipole-Dipole Interaction (~ 100μev)

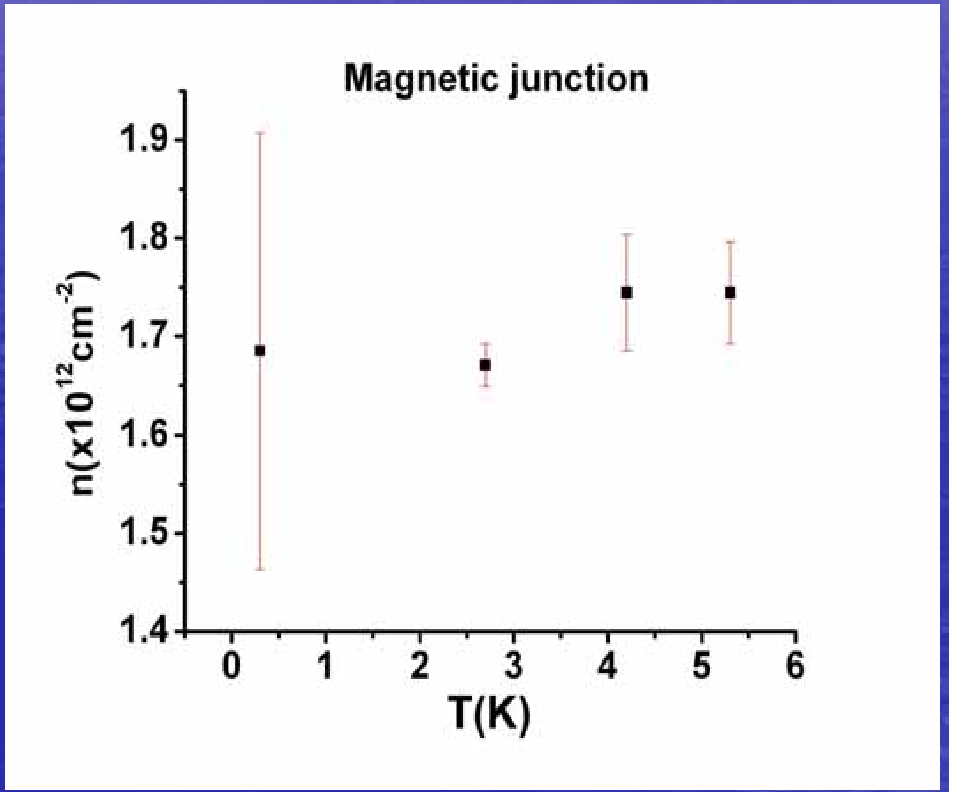
N-type

$$\mathbf{H} = -\frac{\mu_0}{4\pi r_{jk}^3}\left(3(\mathbf{m}_j \cdot \mathbf{e}_{jk})(\mathbf{m}_k \cdot \mathbf{e}_{jk}) - \mathbf{m}_j \cdot \mathbf{m}_k\right)$$

MAGNETO-TRANSPORT MEASUREMENTS

- Anomalous Hall Effect

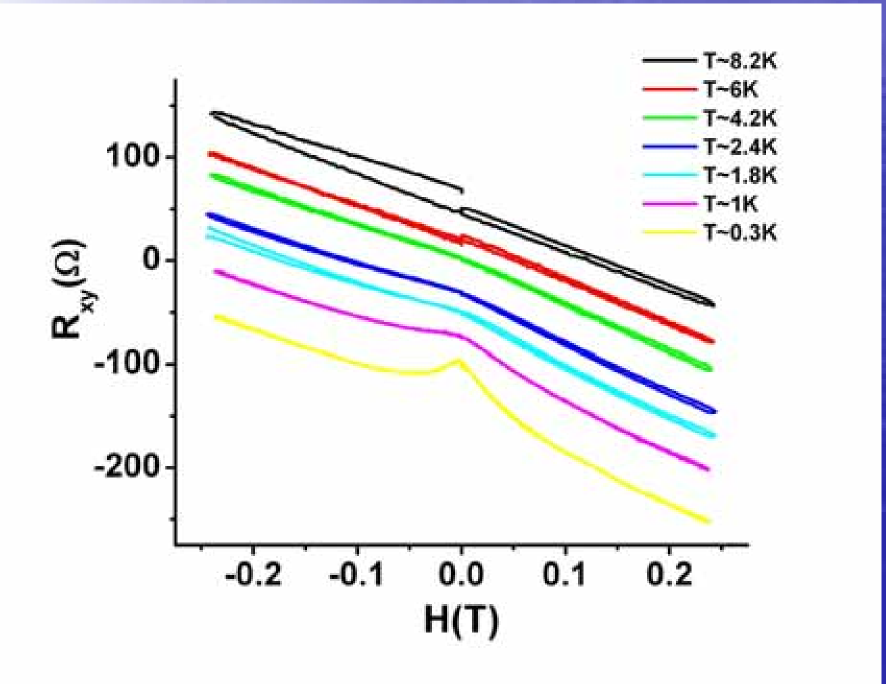


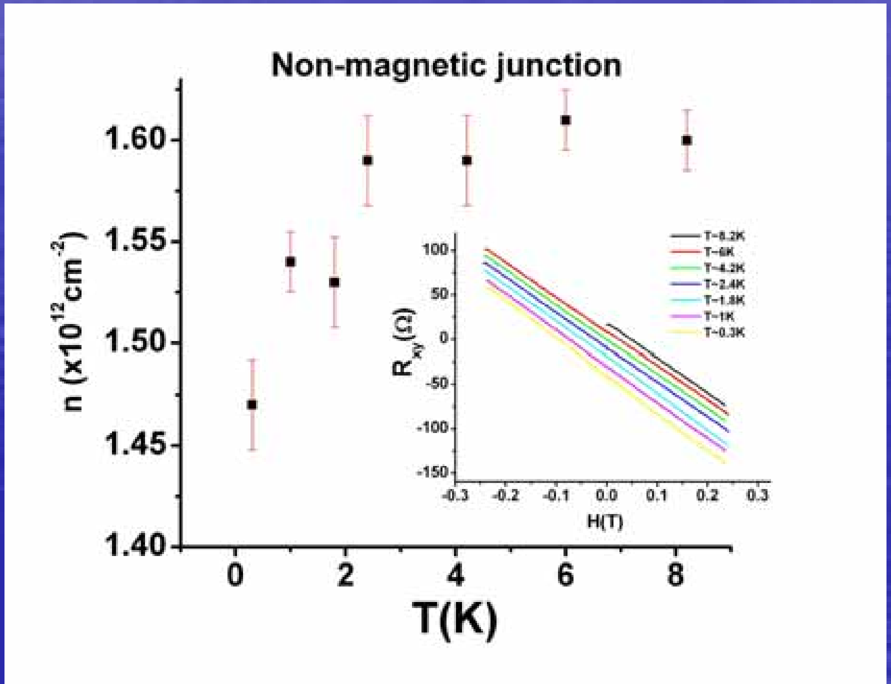


Magnetic junction

MAGNETO-TRANSPORT MEASUREMENTS

- Anomalous Hall Effect

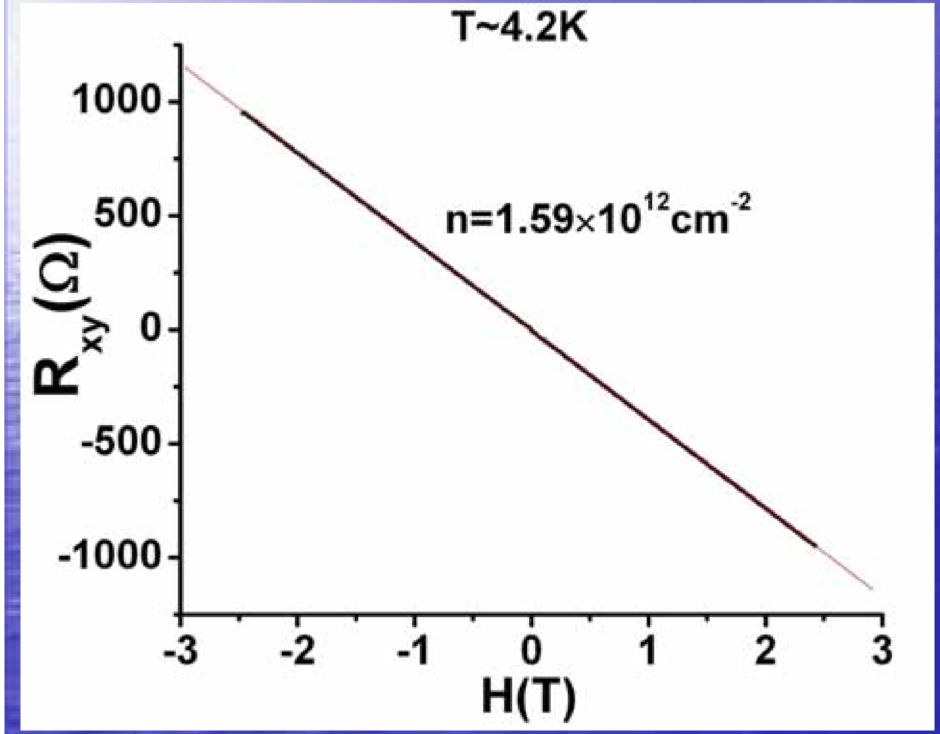


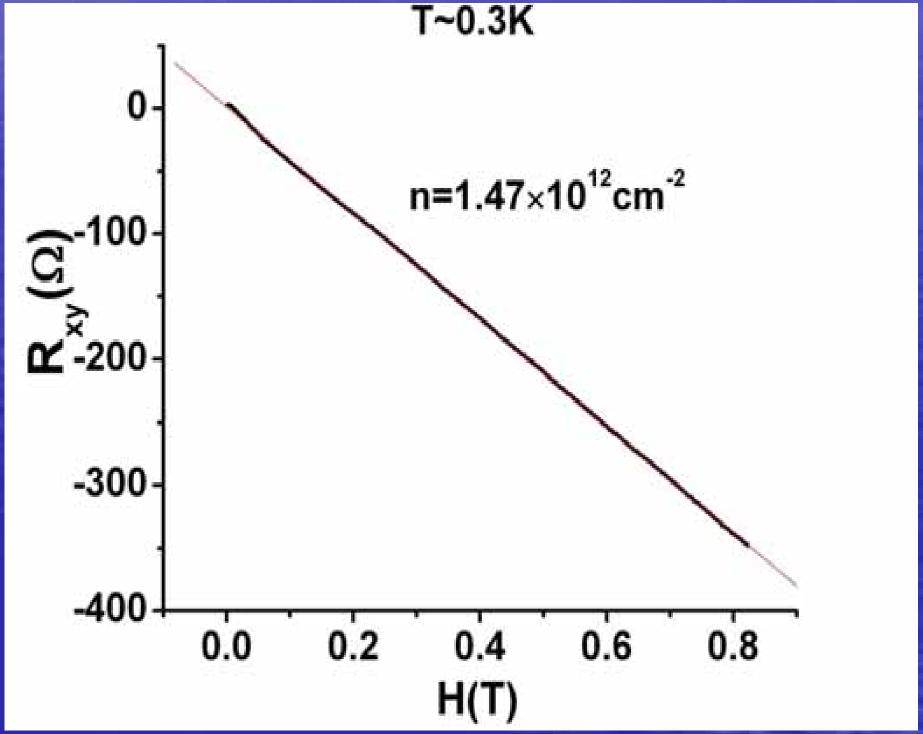


Non-magnetic junction

MAGNETO-TRANSPORT MEASUREMENTS

- Anomalous Hall Effect





Non-magnetic junction

MAGNETO-TRANSPORT MEASUREMENTS

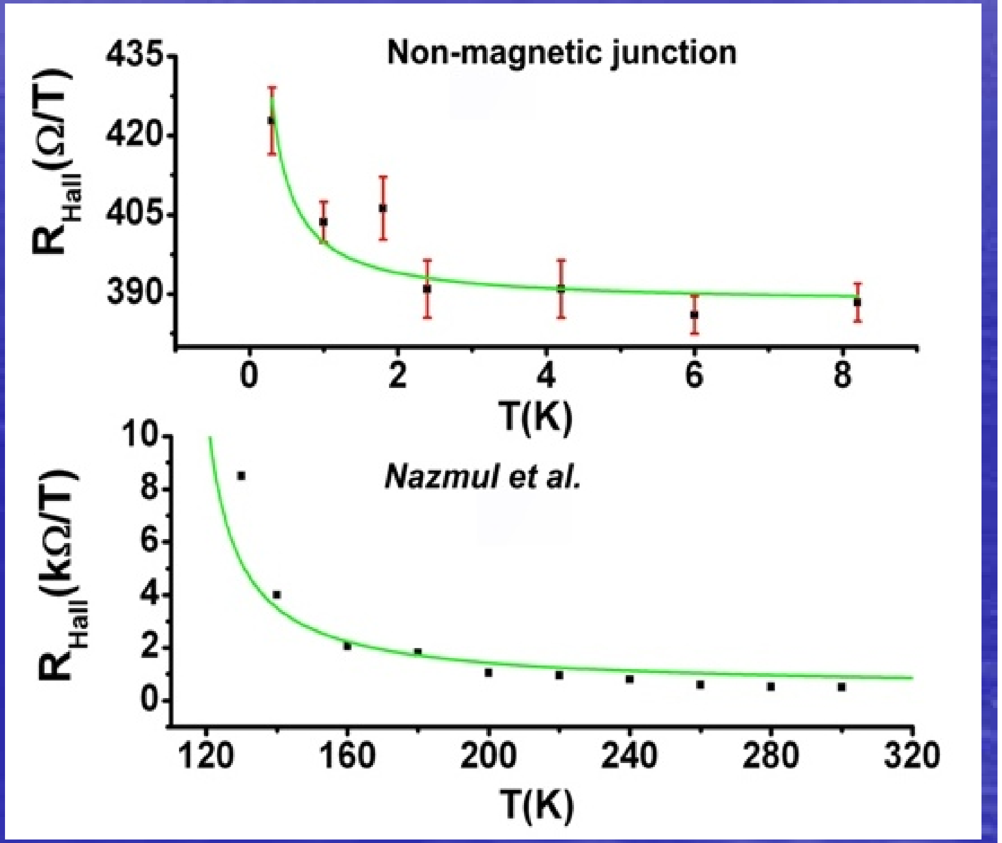
- Anomalous Hall Effect

$$R_H = R_O + R_S \frac{C}{\mu_0 (T - T_C)}$$

$$R_{S-NMJ} = 2.73 \pm 0.58 \times 10^{-11}\ \Omega / T$$

$$R_{S-Naz} = 4.46 \pm 0.76 \times 10^{-7}\ \Omega / T$$

$$r = \frac{R_{S-Naz}}{R_{S-NMJ}} \approx 16000$$



MAGNETO-TRANSPORT MEASUREMENTS

- Anomalous Hall Effect

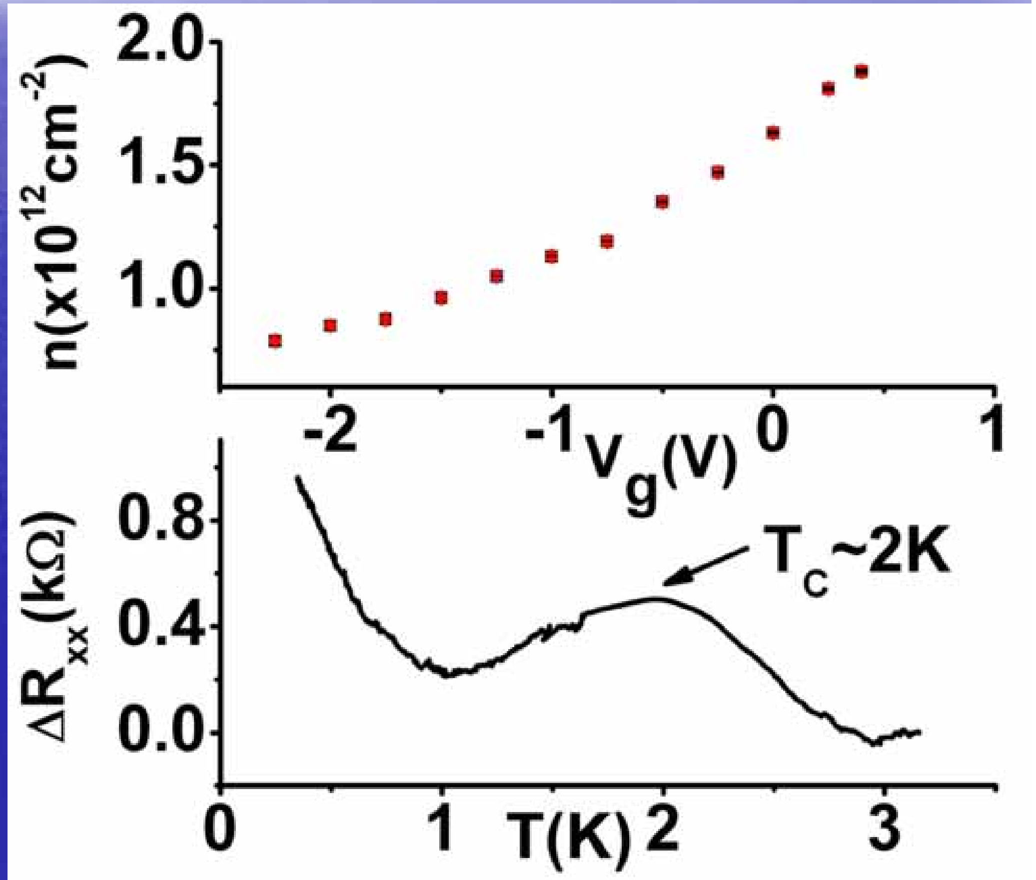
$$R_{Hall} = -\frac{1}{en_{HJ}} \frac{qr^2+1}{(qr+1)^2}$$

$$q = \frac{n_{QW}}{n_{HJ}}, \qquad r = \frac{\mu_{QW}}{\mu_{HJ}}$$

$$\frac{\partial(1/R_{Hall})}{\partial n_{QW}} = e\frac{(q^2r^4+2qr^2+2r-r^2)}{(qr^2+1)^2}$$

$$q \approx 2.5, \qquad r \approx 0.22$$

$$\frac{R_{S-Naz.}}{R_{S-NMJ}} \approx 1800$$



Conclusions & Future Directions

- We have successfully designed a 2D Ferromagnetic gas with excellent gating capabilities
- We can make ohmic contact to the 2D gas without destroying the Ferromagnetism
- We have shown the first clear evidence of electron-mediated ferromagnetism in GaMnAs
- We have set the first clear bound on the AHE in an electron mediated DMS compared to a hole mediated DMS
- Domain size study
- Simpler structure with better mobility
- First ferromagnetic quantum dot

Spin-Orbit: Skew-Scattering (extrinsic-disorder)

$$H_1 = [-\frac{\nabla^2}{2m} + V_{dis}(\mathbf{r})]\delta_{\sigma\sigma'} - M_z\tau^z_{\sigma\sigma'} - i(g_\sigma/4\pi n_\sigma)[\tau_{\sigma\sigma'}\cdot(\nabla V_{dis}\times\nabla)]$$

$$n_\sigma = (k^2_{F\sigma}/4\pi)$$

$$\sigma^{ss(0)}_{xy} = e^2\sum_\sigma \tau^z_{\sigma\sigma}D^{(0)}_\sigma N_\sigma\sqrt{w_\sigma}g_\sigma/(1+\frac{1}{2}g^2_\sigma)$$
$$= \frac{e^2}{4}\sum_\sigma \tau^z_{\sigma\sigma}\left(\frac{n_\sigma}{n_{imp}}\right)\frac{1}{\sqrt{w_\sigma}}\frac{g_\sigma}{(1+g^2_\sigma/2)^2}$$

$$\sigma^{ss(0)}_{xy}/\sigma^{(0)}_{\alpha\alpha} \simeq \left(\frac{M_z}{\epsilon_F}\right) V_0N_0 \langle g_0\rangle_\sigma$$

$$\rho_{xy} = \frac{\sigma_{xy}}{\sigma^2_{xx}+\sigma^2_{xy}} \approx \frac{\sigma_{xy}}{\sigma_{xx}}\rho_{xx}$$

Spin-Orbit: Side-Jump-Scattering

$$\mathbf{v} = \frac{d}{dt}\mathbf{r} = -i[\mathbf{r}, H_1] = \frac{\mathbf{p}}{m} + (g_\sigma / 4\pi n_\sigma)(\tau_{\sigma\sigma} \times \nabla V_{dis})$$

$$\sigma_{xy}^{sj} = (e^2/2\pi) \sum_\sigma [g_\sigma / (1 + \frac{1}{2} g_\sigma^2)] \; \tau^{\,z}_{\sigma\sigma}$$

AHE: Berry Phase (intrinsic)

$$\chi(\mathbf{k}) = -\int_c^{\mathbf{k}} d\mathbf{k}\prime \cdot \mathbf{X}(\mathbf{k}\prime)$$

$$\mathbf{X}(\mathbf{k}) = \int_{\text{cell}} d^2r \;\; u^*_{n\mathbf{k}}(\mathbf{r}) \; i\nabla_k \;\; u_{n\mathbf{k}}(\mathbf{r})$$

$$\mathbf{\Omega}(\mathbf{k}) = \nabla_k \times \mathbf{X}(\mathbf{k})$$

$$\begin{aligned} \dot{\mathbf{k}} &= e\mathbf{E} + e\dot{\mathbf{r}} \times \mathbf{B} \\ \dot{\mathbf{r}} &= \nabla_{\mathbf{k}}\epsilon_{n\mathbf{k}} - e\mathbf{E} \times \mathbf{\Omega} \end{aligned}$$

$$\mathbf{j}_H = -e^2 n \langle \mathbf{\Omega} \rangle \times \mathbf{E} \rightarrow \qquad \sigma^B_{xy} = e^2 n \quad \langle \Omega_z \rangle$$

$$\langle \mathbf{\Omega} \rangle = n^{-1} \textstyle\sum_{\mathbf{k}\sigma} \quad \mathbf{\Omega}_\sigma(\mathbf{k}) f(\epsilon_{\mathbf{k}\sigma})$$

$$\sigma_{AH} = -\frac{2e^2}{\hbar V} \sum_{n,\mathbf{k}} f_{n,\mathbf{k}} Im \left\langle \frac{\partial u_{n,\mathbf{k}}}{\partial k_x} \middle| \frac{\partial u_{n,\mathbf{k}}}{\partial k_y} \right\rangle$$