Magnetic and magnetoransport properties of 2D DMS structures

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Outline

Motivation, introduction.

2D DMS structure .

1. Transport properties.

2. Mechanisms of FM ordering.

3. Anomalous Hall effect.

4. Magnetization, magnetic structure and noise.

5. Conclusion.

Motivation

Application

Incorporation of magnetism into modern electronics - spintronics

Basic Research

Incorporation of magnetism into physics of semiconductors

Coulomb interaction, disorder, e-e interaction, electron – phonon interaction, electron - photon interaction

+

exchange interaction

Mechanism of the exchange interaction;

Effects of the disorder, Coulomb and exchange interactions interplay;

Peculiarities of the 2D quantum effects in the presence of the ferromagnetism;

AHE origin;

Magnetic structure.

Brief history

Dilute magnetic semiconductors (DMS) are semiconductors, in which transition or rare-earth metal atoms randomly replace a fraction of atoms in the matrix.

The discovery by Ohno (1992) of ferromagnetic ordering in manganese doped InAs with the 7.5K Curie temperature fuelled DMS studies that resulted in fabrication of (Ga,Mn)As compounds with the 180K Curie temperature.

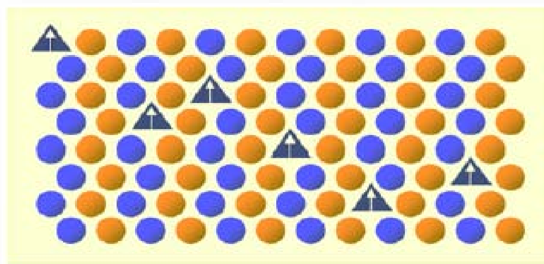
Dilute magnetic semiconductors (DMS) III-Mn-V

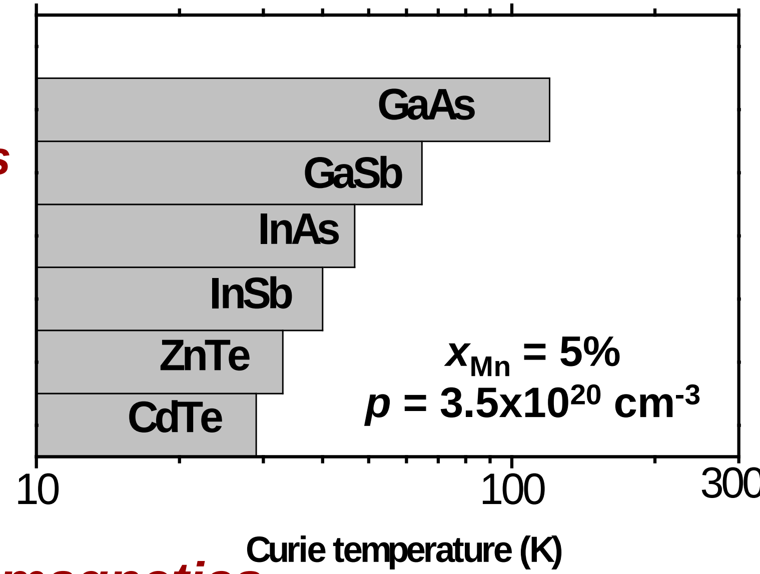
Mn – ***antiferromagnetic***

Intrinsic DMS – random ***antiferromagnets***

Cd1-xMnxTe

Zn1-xCoxO





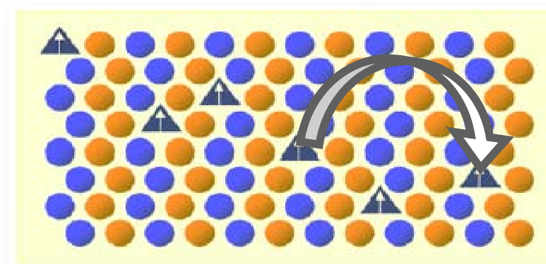
- **p$^+$-type DMS – Zener/RKKY** ***ferromagnetics***

IV-VI: p-$Pb_{1-x-y}Mn_xSn_yTe$

Story et al., PRL'86

III-V: $In_{1-x}Mn_xAs$ ***Ohno et al., PRL'92***

$Ga_{1-x}Mn_xAs$ ***Ohno et al. , APL'96***

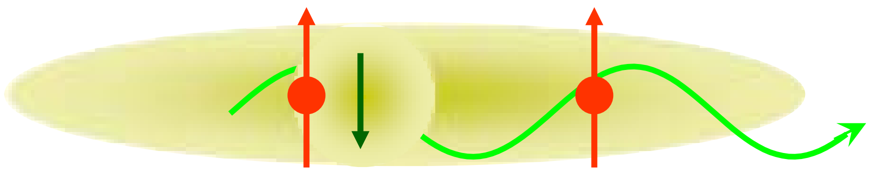


$T_C \approx$ 100 K for x = 0.05

II-VI: $Cd_{1-x}Mn_xTe/Cd_{1-x-y}Zn_xMg_yTe$:N QW ***Haury et al., PRL'97***

$Zn_{1-x}Mn_xTe$:N ***Ferrand et al., Physica B'99, PRB'01***

Possible interaction mechanism

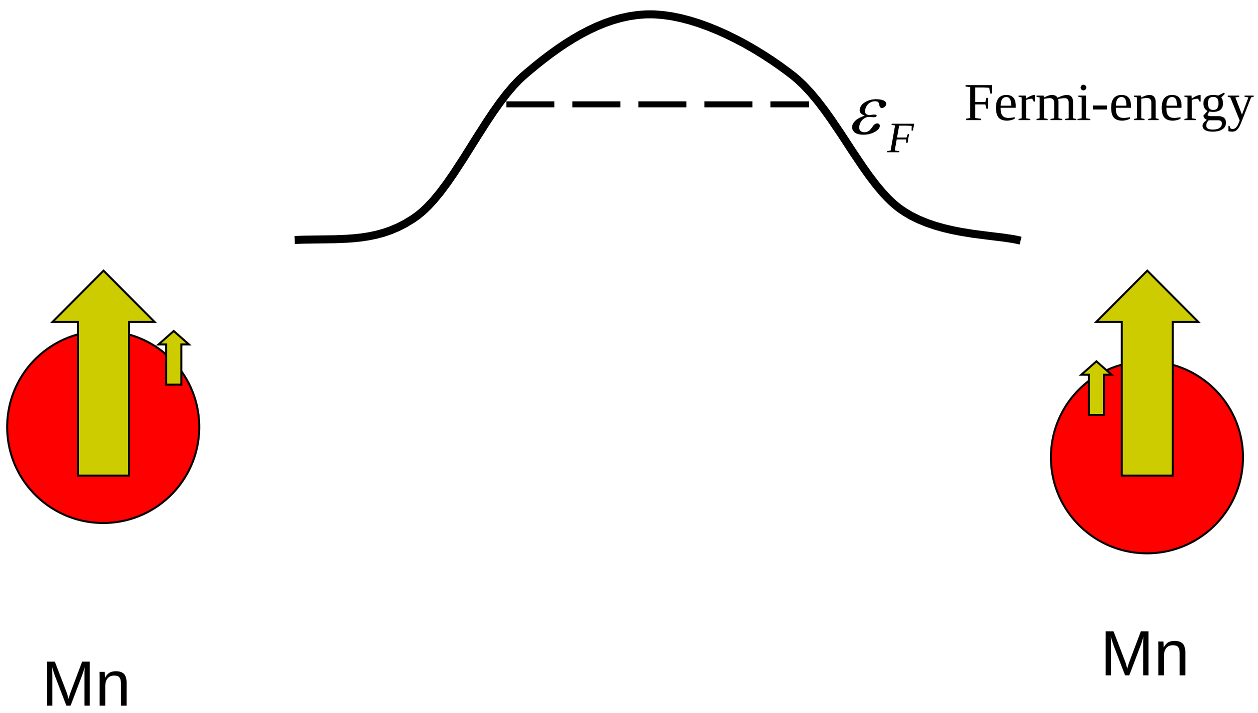


Exchange via free holes

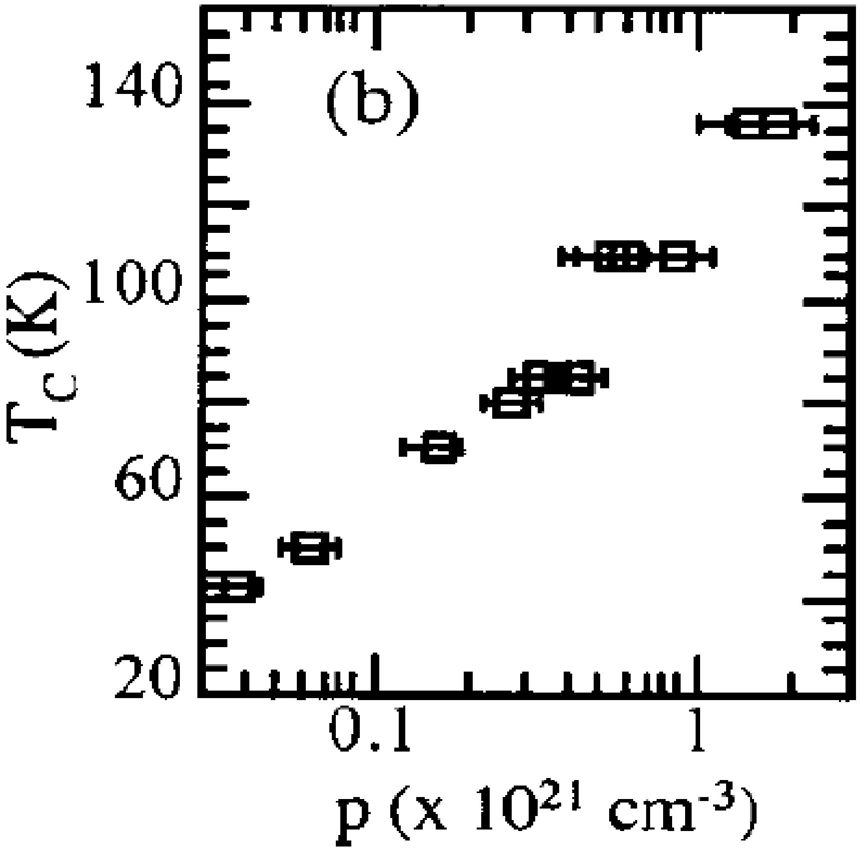
RKKY interaction

Indirect exchange via empty states above the Fermi energy in the heavy hole band. Impurity spins are parallel. Hund rule favors the exchange.

Zener



Ferromagnetism in III-Mn-V DMS as the function of hole concentration



K. C. Ku *et al.*, APL **82**, 2302 (2003).

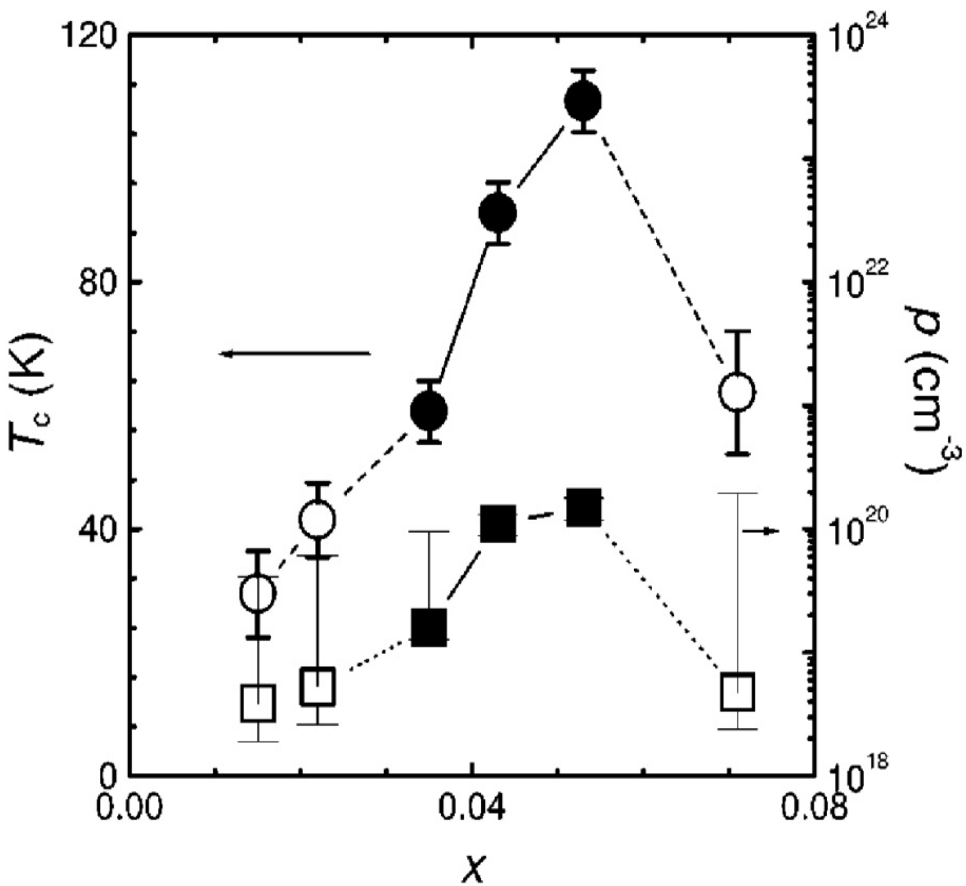
mean field theory predicts

$$T_C = C N_{Mn} \beta^2 m^* p^{1/3}$$

N

N_{Mn} – concentration of uncompensated Mn spins;
β -- exchange interaction constant between localized Mn spins and the holes (so-called *p-d* coupling),
m* -- hole effective mass,
p – hole concentration.

Ferromagnetism in III-Mn-V DMS as the function of composition



H. Ohno. J. Magn. Magn. Mater. **200,** 110 . (1999) , F. Matsukura et al., PRB **57**, R2037 (1998)

The equilibrium solubility of Mn is very low (10^{19}cm^{-3}), it is not enough for high Curie temperature.

To reach high manganese concentration (10^{21}cm^{-3}), III-V DMS have to be grown under non-equilibrium conditions. Mostly molecular beam epitaxy at low temperatures of the order of 250 °C has been used.

•Mn enters the III-V lattice to replace group-III atoms as a di-valent Mn^{++} ion.

• it brings into the lattice a magnetic moment;

• at the same time it acts as an acceptor (a source of holes).

Why does the Mn content exceed the hole concentration?
Compensation; structural disorder

T_C in (Ga,Mn)As

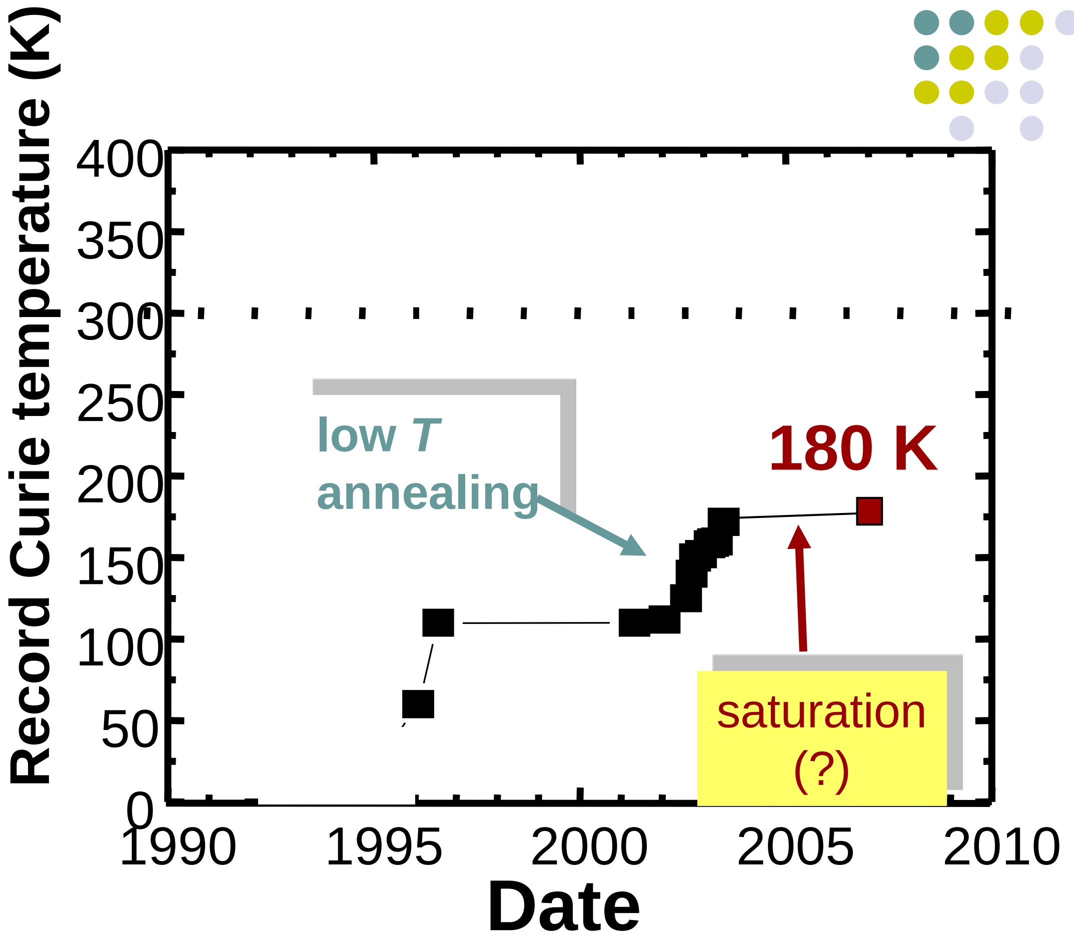
Mn substituting Ga - acceptor

Mn in interstitial site – donor

Mn could form complexes and MnAs grains, T_c= 318K

Role of Mn interstitials in limiting (reducing) T_C

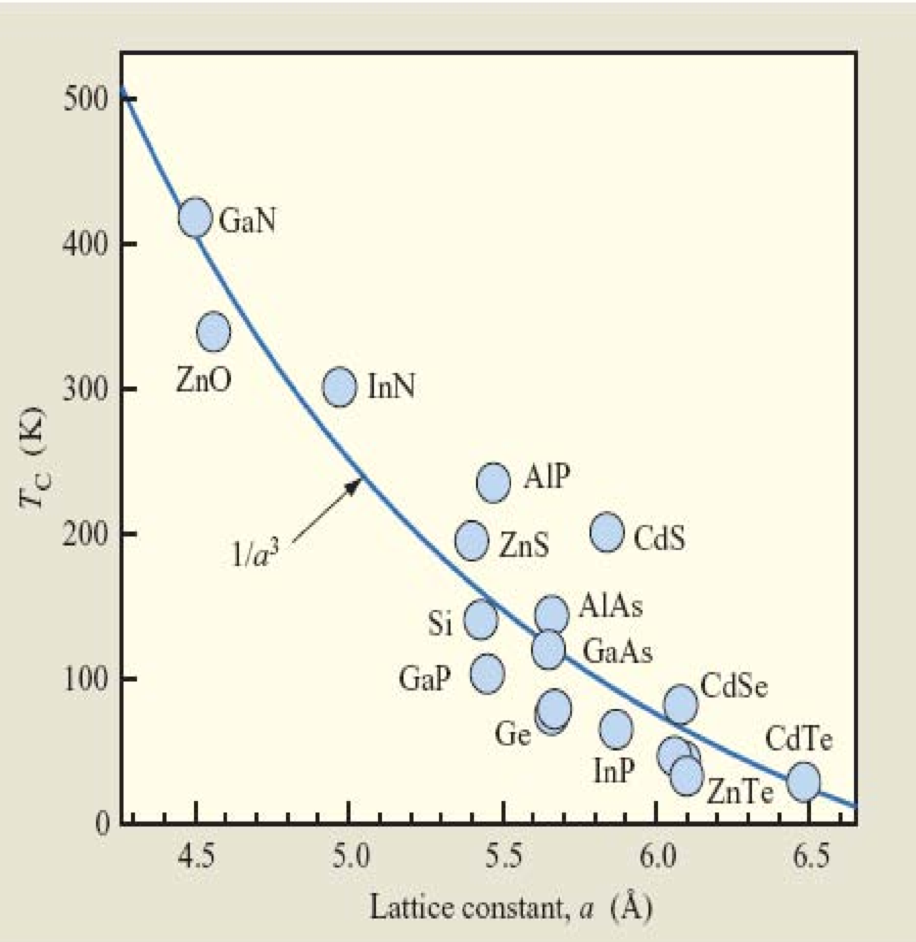
Electrical compensation by interstitial MnI leads to a reduction of the hole concentration (and $T_C \sim p^{1/3}$)
Mn_I donors tend to drift toward Mn_{III} to form Mn_{III}-Mn_I pairs in $III_{1-x}Mn_xV$ alloys
Such Mn_{III}-Mn_I pairs then couple antiferromagnetically



The progress due to increase of *p* by low temperature annealing ➔ ***out diffusion of Mn_I:***
Máca and Mašek PRB'02, Yu et al. PRB'02; APL'04
Edmonds et al. PRL'04 , Oleinik et al. cond-mat/08

T_C in (Ga,Mn)As

T. Dietl, H. Ohno, and F. Matsukara, (2001).

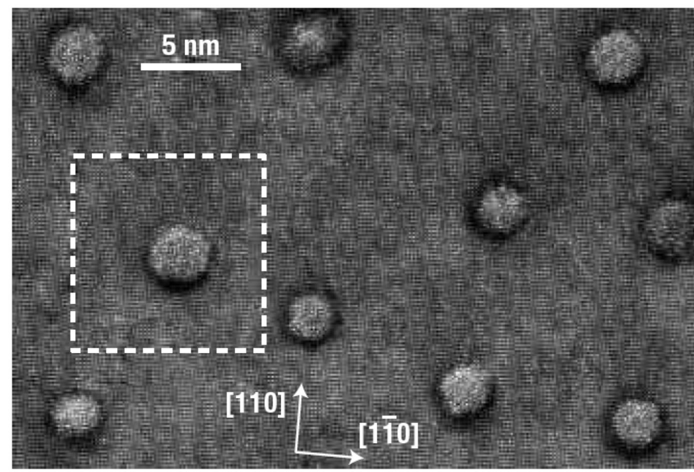


Strategies:

-- increasing *p* and/or *x* in existing ferromagnetic DMS (Ga,Mn)As

-- searching for DMS with greater coupling constant $x\beta^2\rho(E_F)$ (nitrides, oxides)

-- ferromagnetic inclusions (nanocolumns, nanograins).

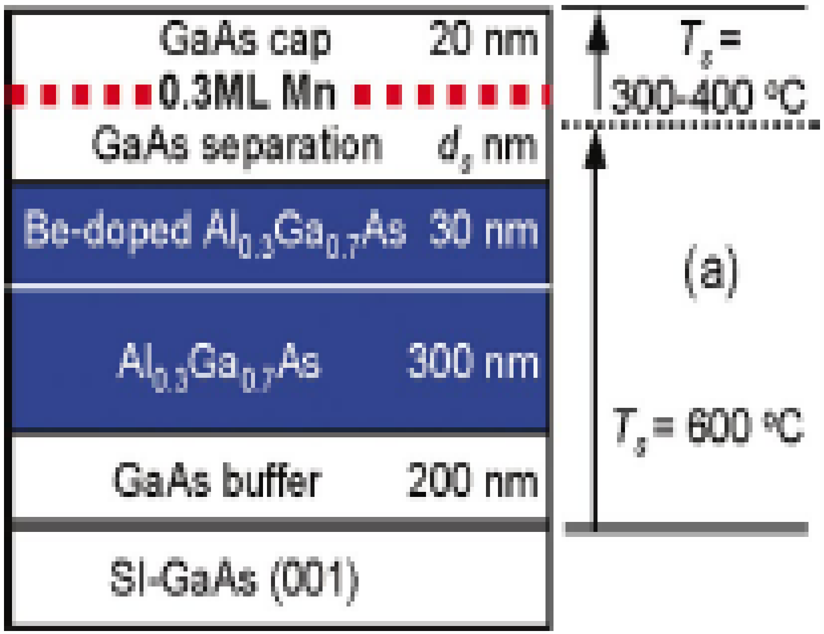


Jamet et al. Nature Mat. '06
BA et al. JETP 05

Quasi 2D DMS ?

A.M. Nazmul, M. Tanaka et al.; T. Wojtowicz, J.K. Furdyna et al.

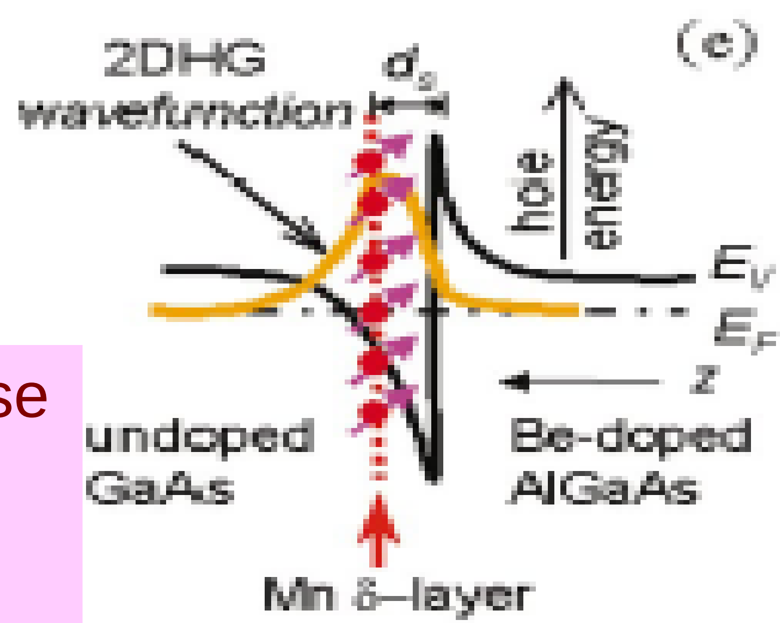
Low mobility structures (< 5 $cm^2/(V\ s)$)



GaAs/*p*-AlGaAs heterostructure, Mn δ -layer in the 2D channel :

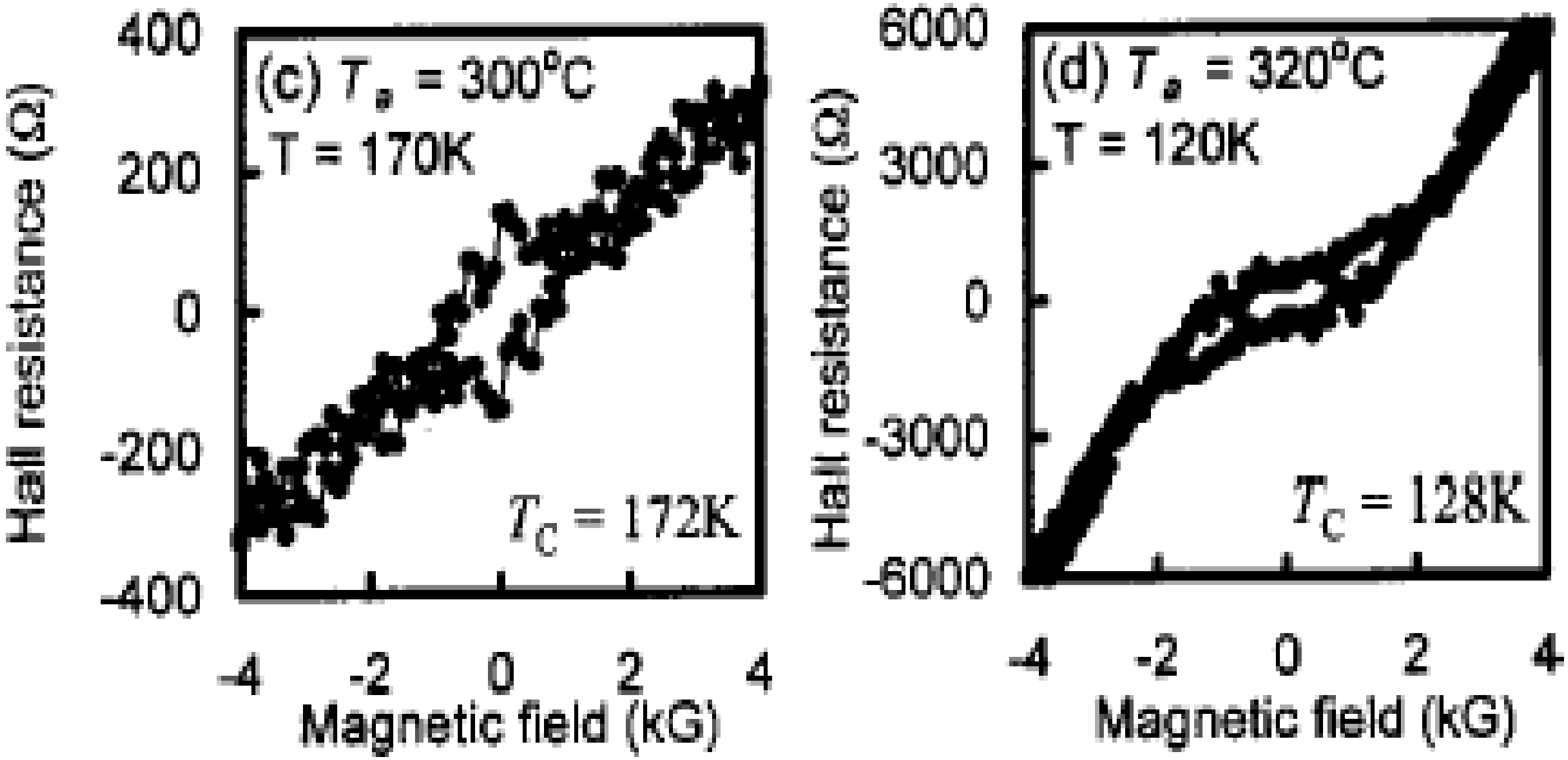
T_c = 172 K (A.M. Nazmul et.al. Phys. Rev. B **67**, 241308R (2003)) .

$$\Delta E = \hbar / \tau \approx 200 meV$$



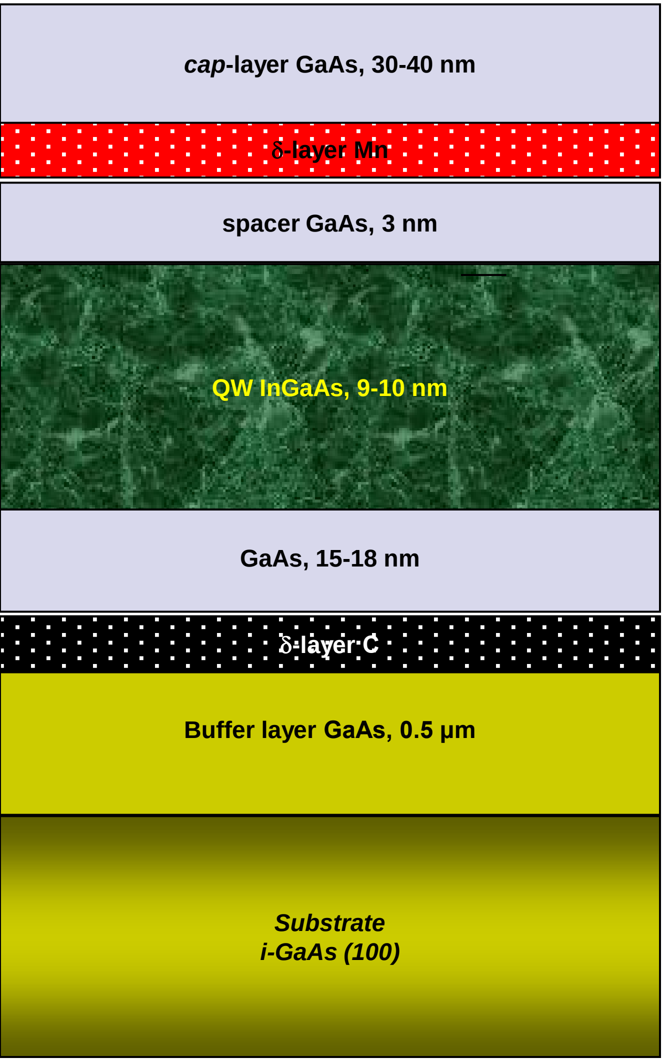
To increase mobility one should use selective doping.
Quantum well with remote Mn delta layer

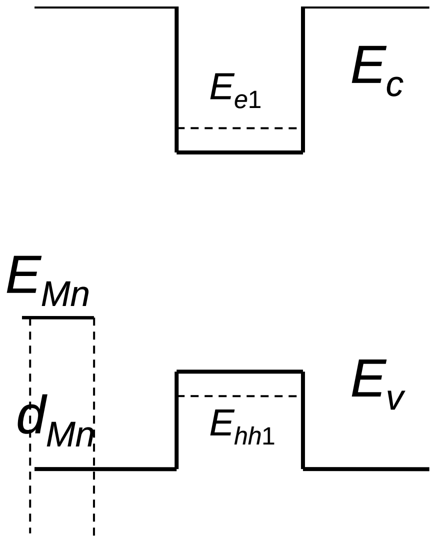
Effect of gate voltage



2D structures

Quantum well with Mn delta layer





Structure parameters

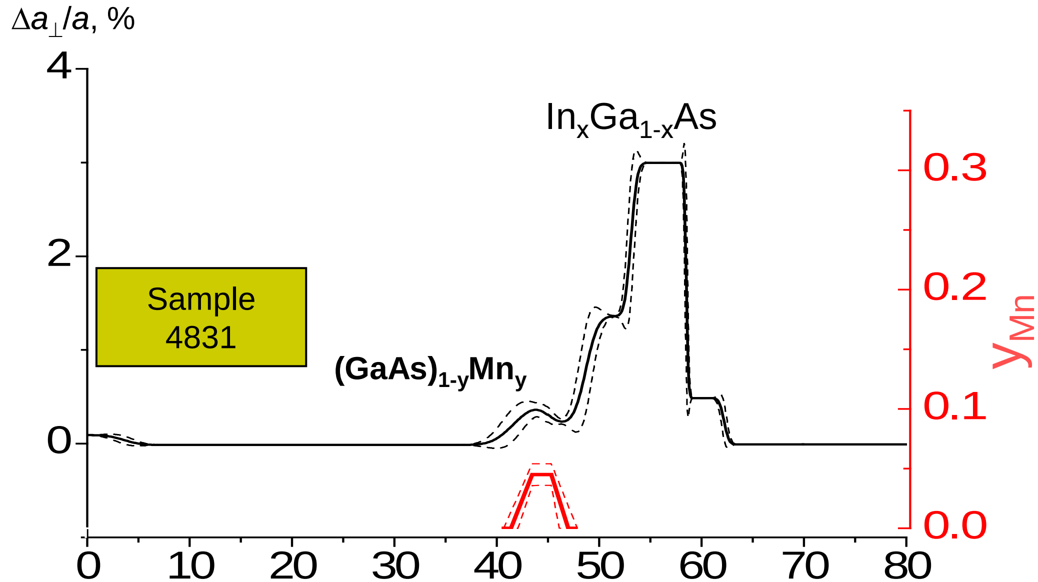
structure	d_{Mn}, ML	300K		77K	
		μ_{eff}, см^2/В·с	$p_s \cdot 10^{-12}$, см$^{-2}$	μ_{eff}, см^2/В·с	$p_s \cdot 10^{-12}$, см$^{-2}$
4831; M	0.5	176	10	1860	2
4834; I	1.2	158	14,3	1350	1,8
C; I	0	270	1,3	1598	0.5

2D

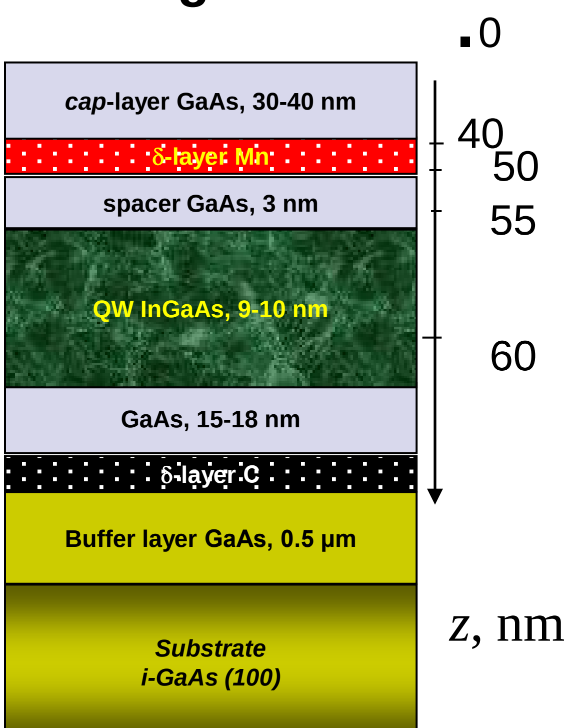
Crystal structure

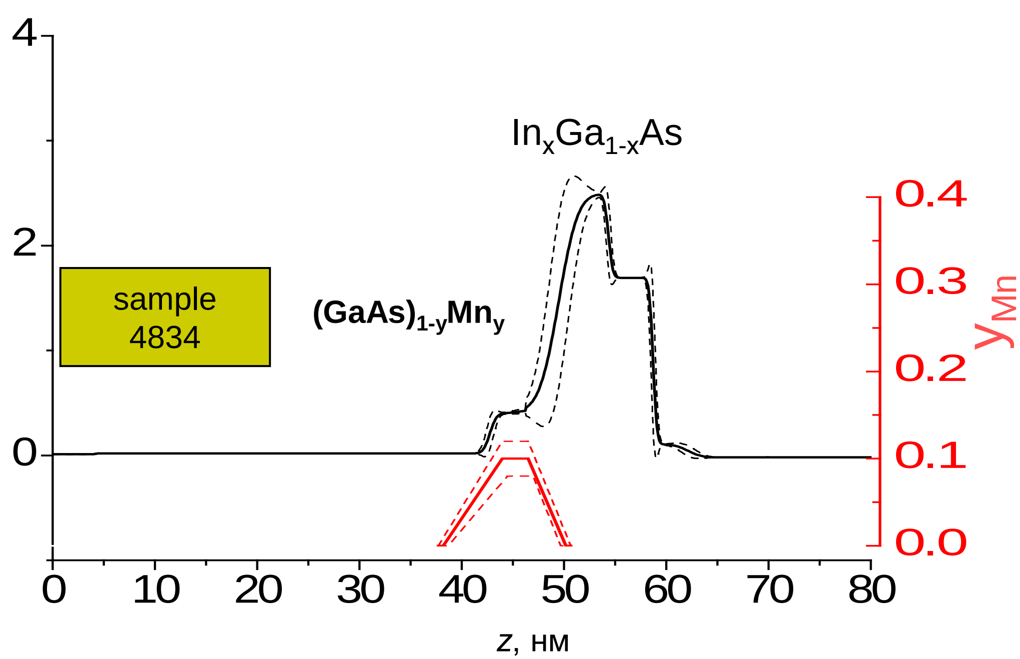
X- Ray characterization

Depth (*z*) profiles of the lattice mismatch related to GaAs evaluated from fitting the experimental X-ray rocking curves.



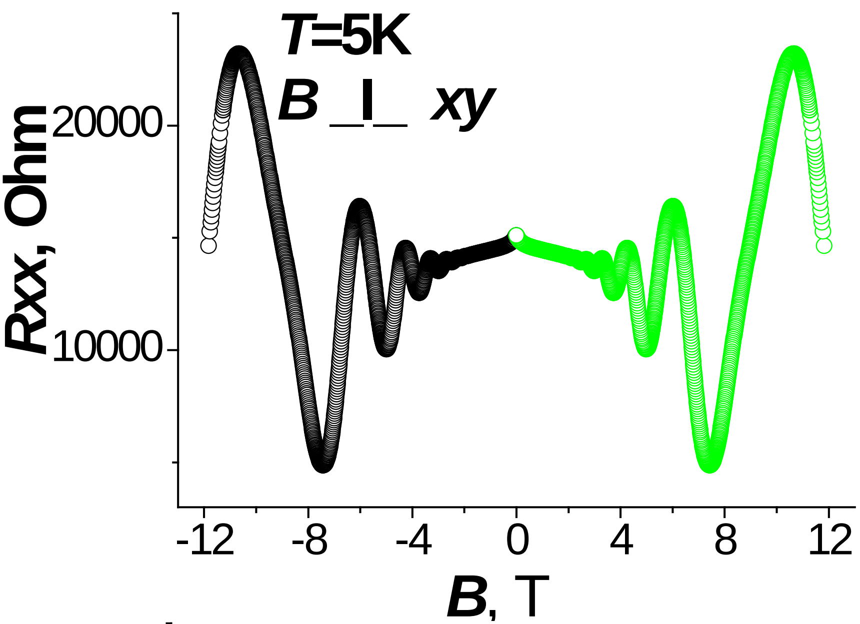
Mn content

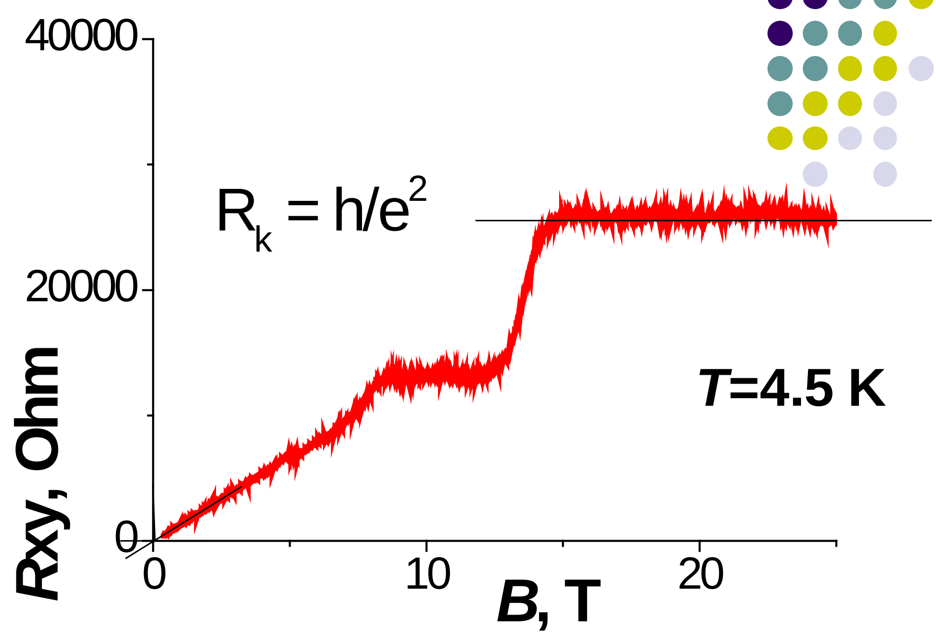


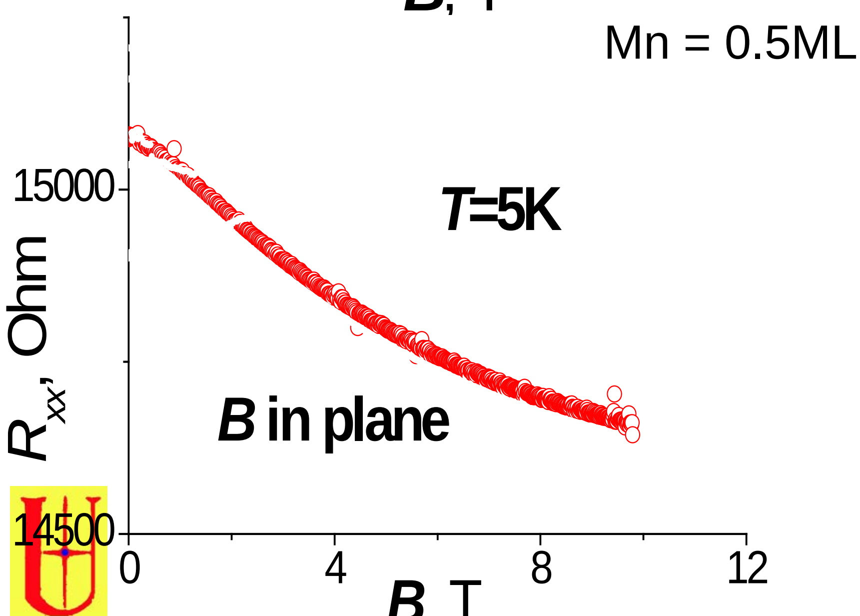


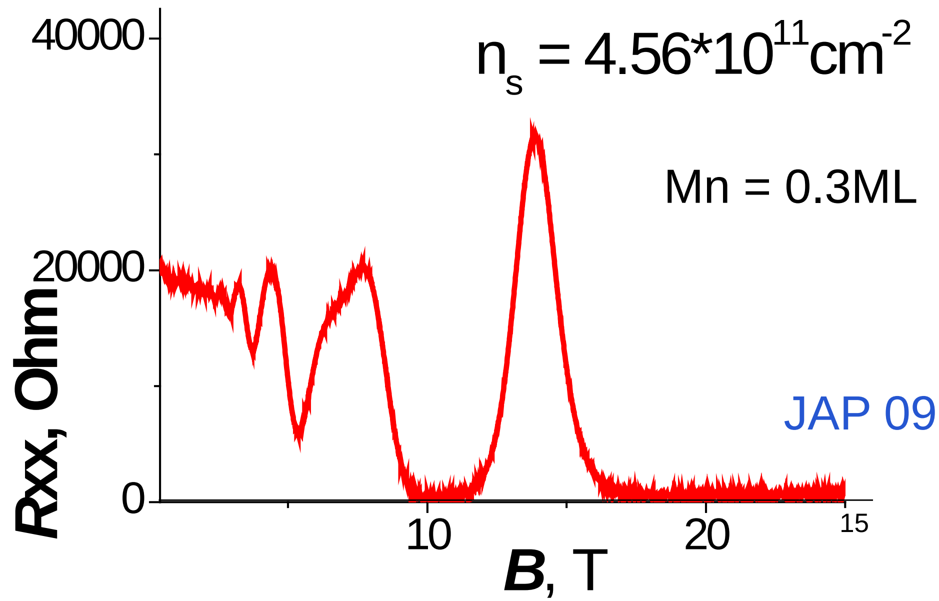
JAP 09.

2D


T=5K
B _I_ xy
Rxx, Ohm
20000
10000
-12
-8
-4
0
4
8
12
B, T

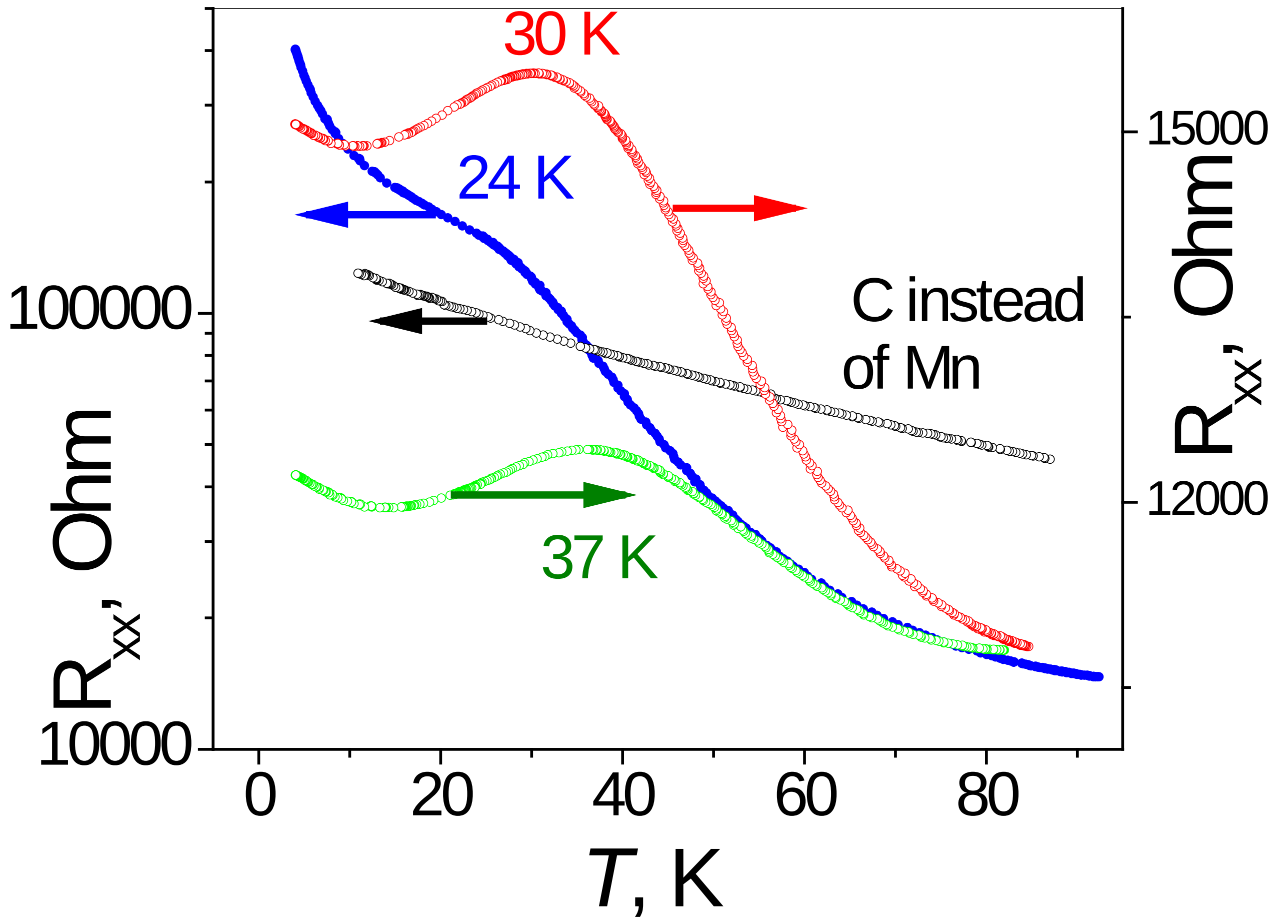

40000
20000
0
$R_k = h/e^2$
T=4.5 K
Rxy, Ohm
0
10
20
B, T


Mn = 0.5ML
15000
14500
T=5K
B in plane
R_{xx}, Ohm
0
4
8
12
B, T


40000
20000
0
$n_s = 4.56*10^{11}cm^{-2}$
Mn = 0.3ML
JAP 09.
Rxx, Ohm
10
20
B, T

Temperature dependence of the sample resistance

TR

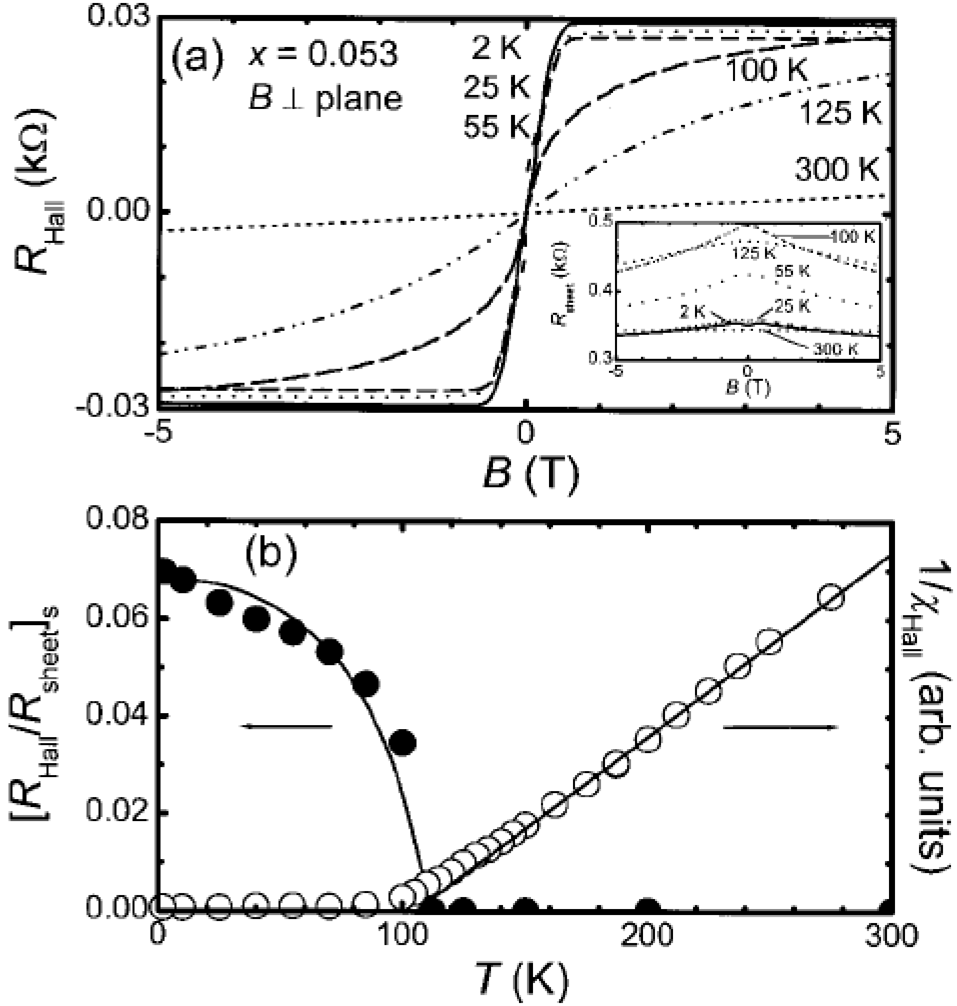


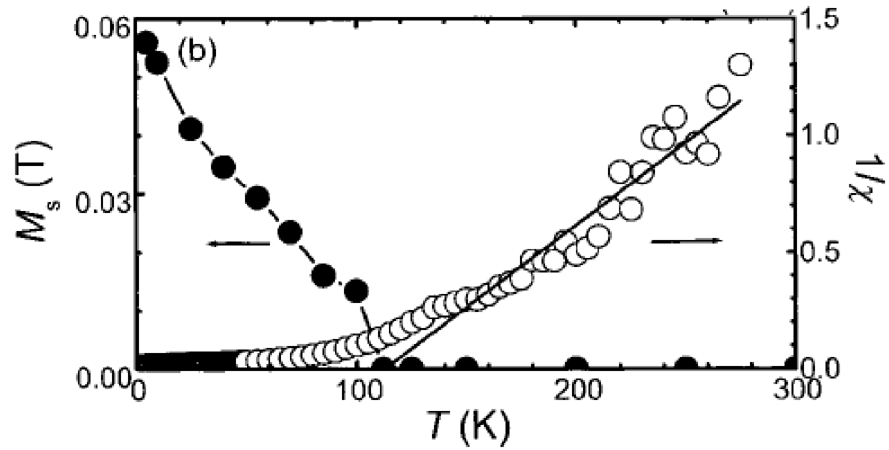
Main feature – Hump or Shoulder.
Mn doped samples only.

JAP 09.

AHE for magnetic ordering investigations

H. Ohno, F. Matsukura / Solid State Communications 117 (2001) 179–186





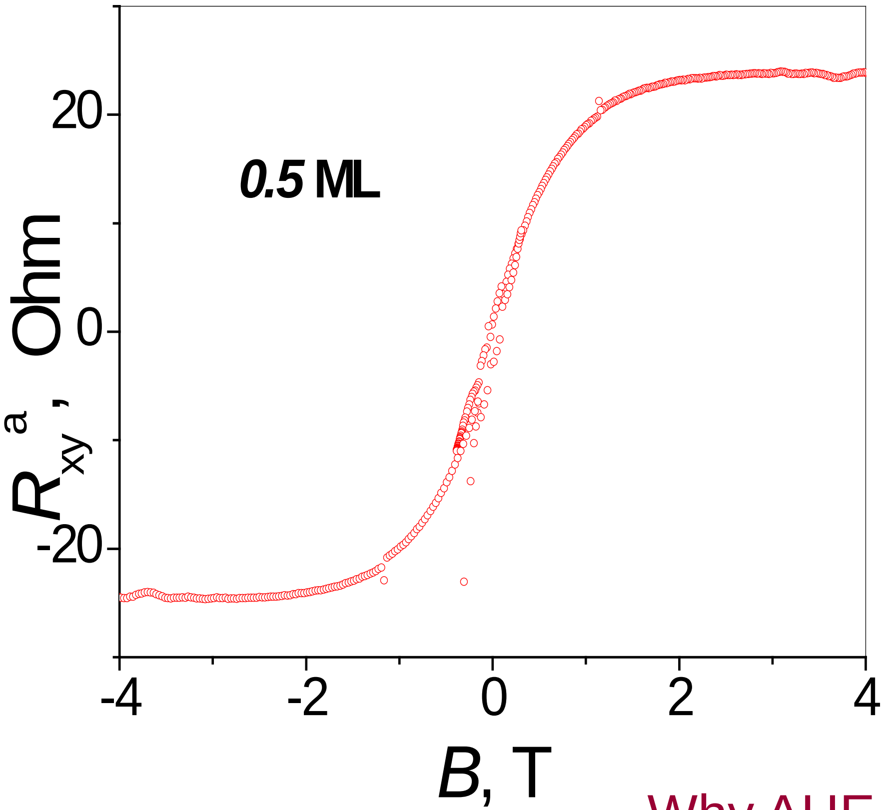
Determination of Curie temperature by measurements of magnetization for GaMnAs (x=0.053).

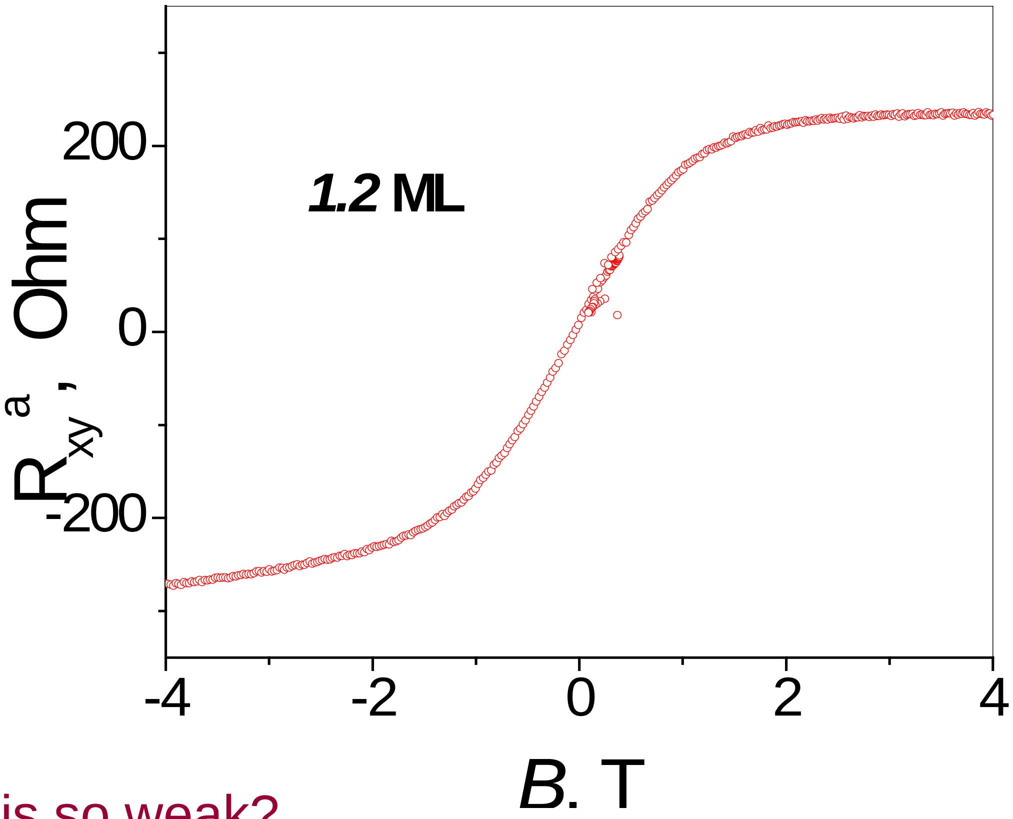
Determination of Curie temperature by AHE measurements for GaMnAs (x=0.053)

Anomalous Hall Effect

The Hall resistance *$R_H d = \rho_{yx} = R_0 B + R_s M$*

Anomalous Hall Effect is proportional to magnetization. *AHE depends on the strength of the S-O interaction and spin polarization of carriers.*

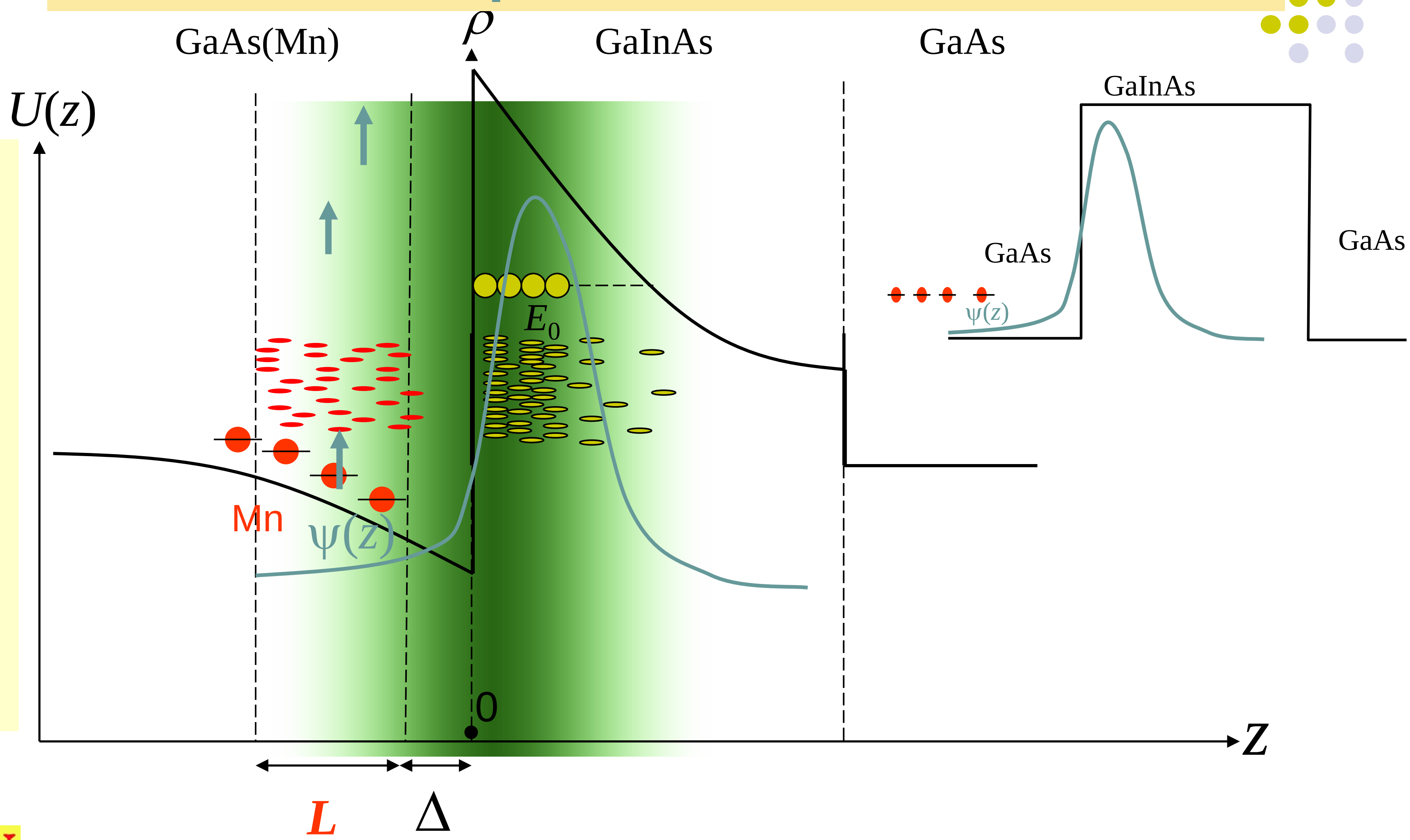




Why AHE is so weak?
What is the main AHE mechanism in the case?

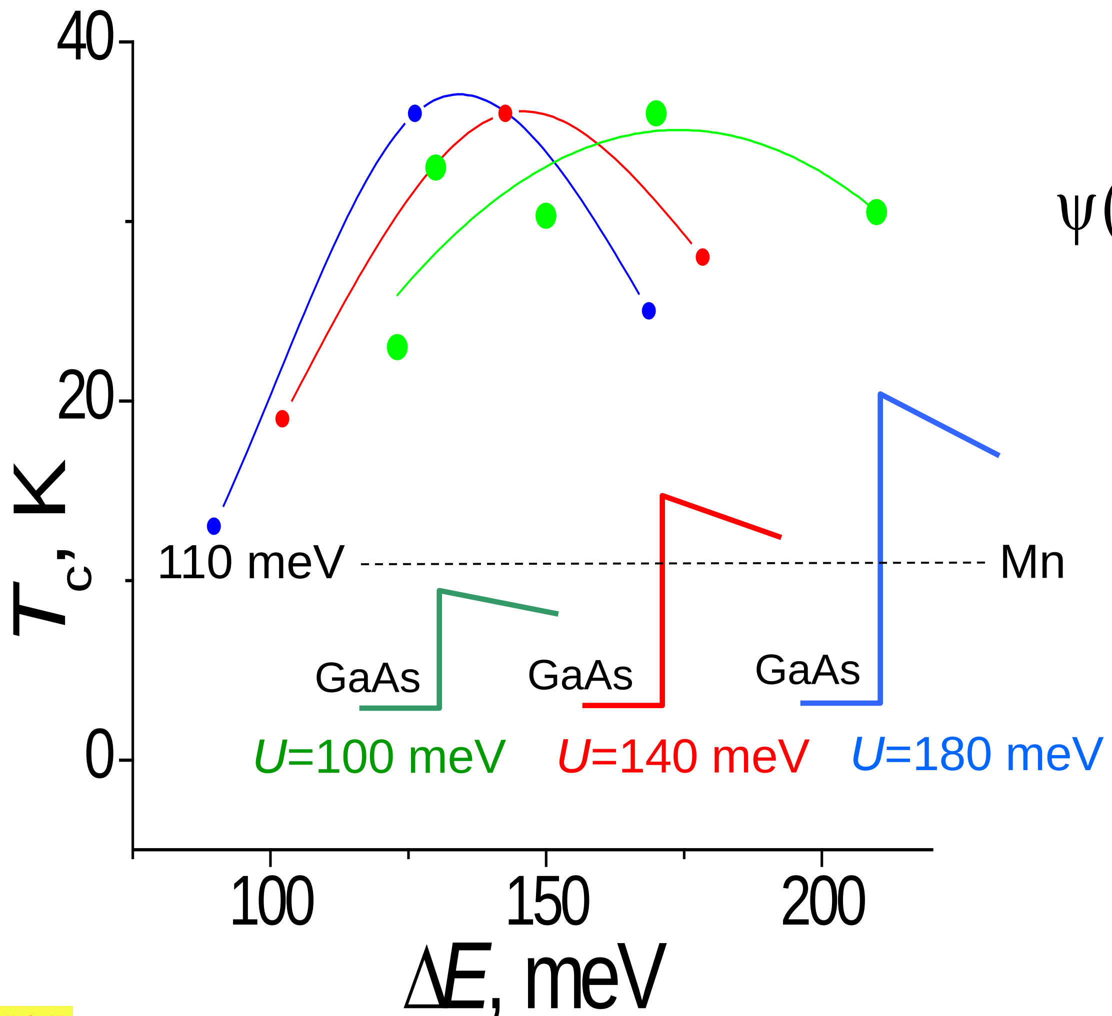
J. Phys. Cond. Matt. 2008

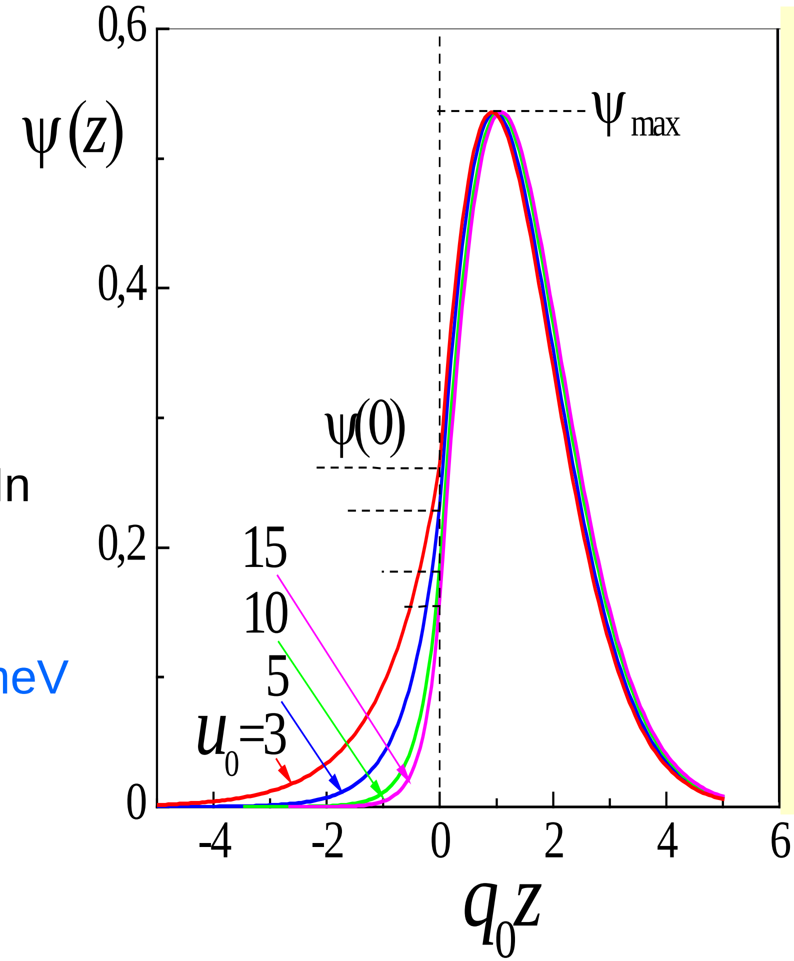
Carrier-mediated FM via carriers in the quantum well.



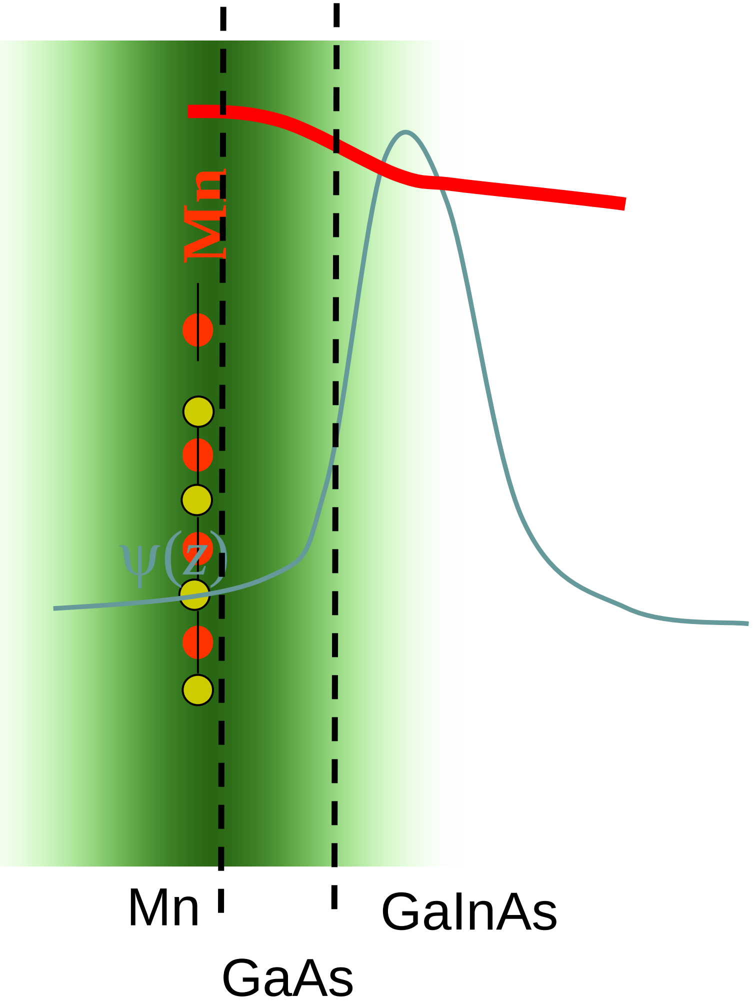
E.Z. Meilkhov and R.M. Farzetdinova,
JETP Letters (2008)

Curie temperature dependence on the depth of quantum well





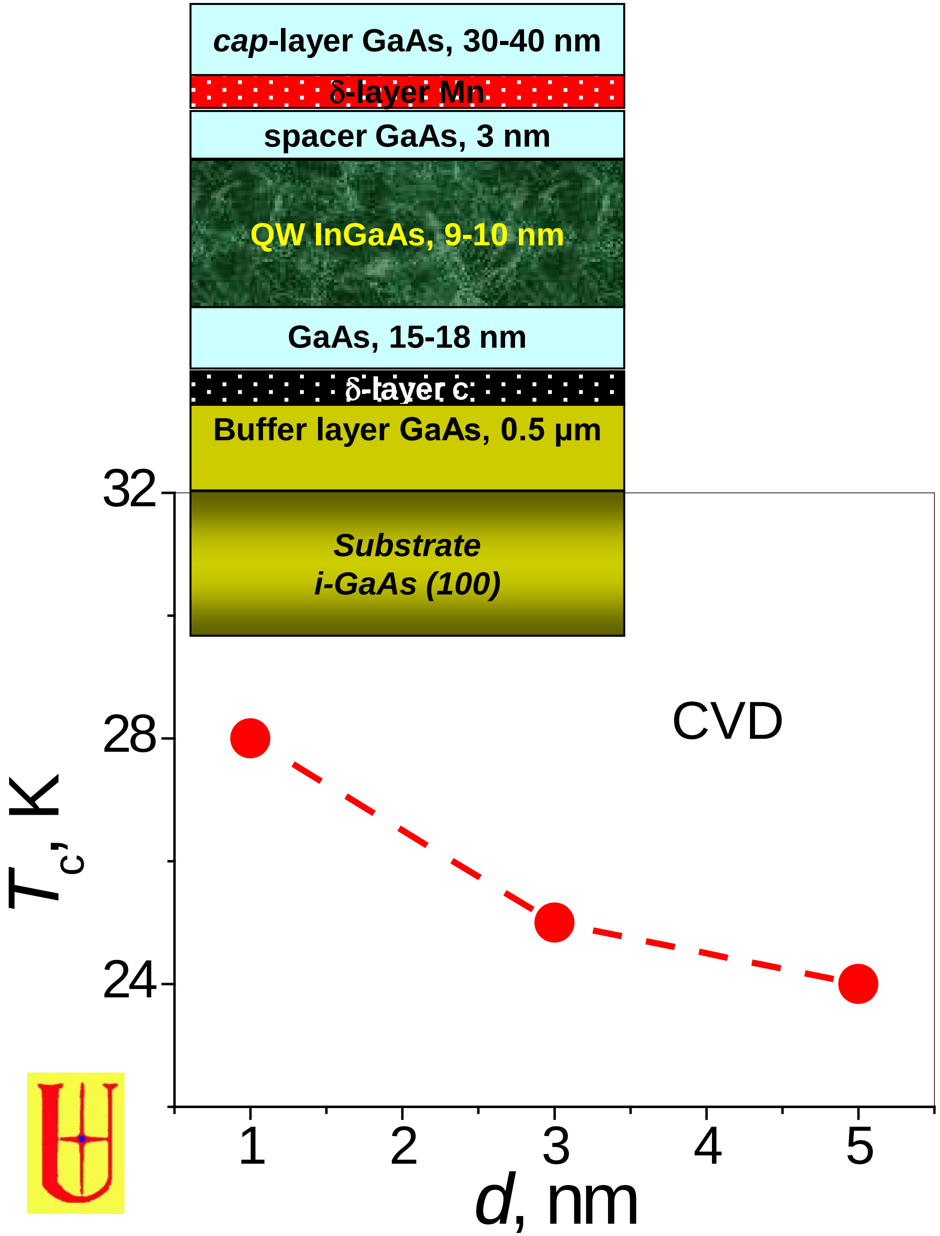
FM ordering inside Mn layer

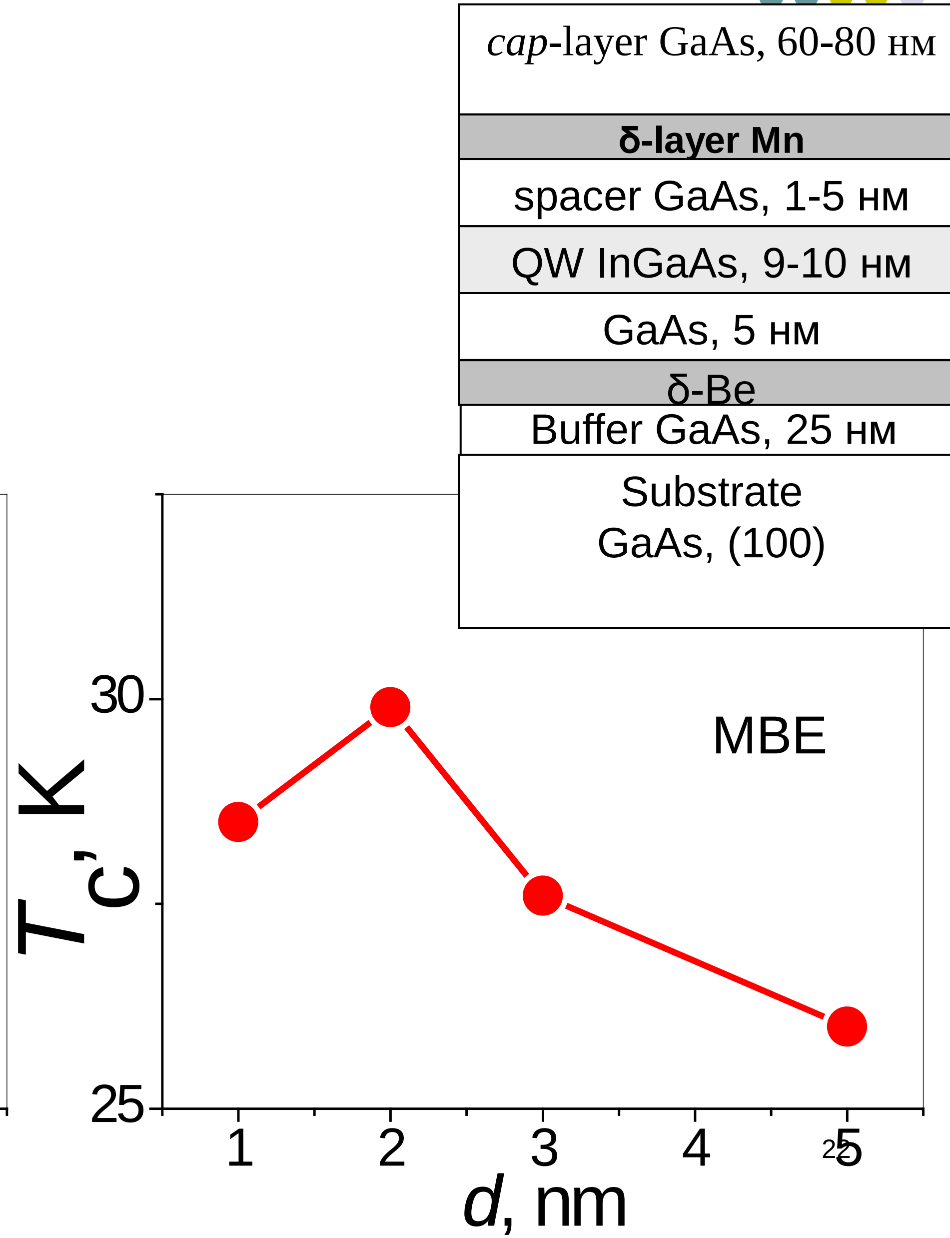


FM ordering occurs in в слое GaMnAs layer due to itinerant mechanism. Carriers in the quantum well do not invoolved. V.V. Tugushev et al. PRB (2009)

There is 2D spin – polarized collective state in the GaMnAs aria. The corresponding wave function is expanded inside quantum well and acts on carriers causing their spin-polarization.

Curie temperature dependence on the spacer thickness





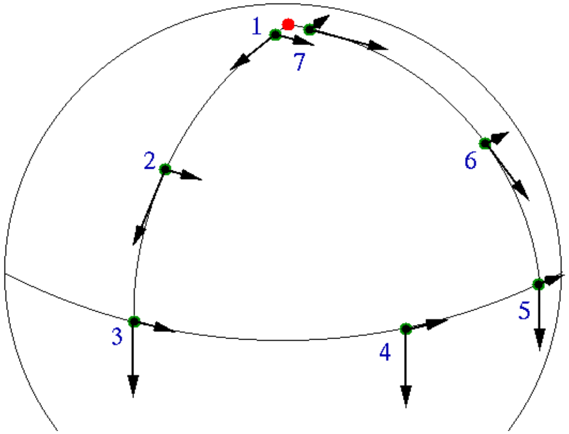
Anomalous Hall Effect

The Hall resistance $R_H d = \rho_{yx} = R_0 B + R_s M$

AHE is proportional to magnetization and is due to S-O interaction .

skew–scattering: $R_s \propto R^1_{xx}$; side-jump: $R_s \propto R^2_{xx}$

For both mechanisms AHE depends on the strength of the S-O interaction and spin polarization of carriers.



AHE current arises due to scattering asymmetry

Berry phase

$\boldsymbol{v}(\boldsymbol{k}) = \text{grad}\,[\varepsilon(\boldsymbol{k})]/h + (e/h)\boldsymbol{E}\times\boldsymbol{\Omega}(\boldsymbol{k})$

$\Omega_z(k) = 2\text{Im}[<\partial u/\partial k_y|\partial u/\partial k_x>]$

σ - does not depend on scattering

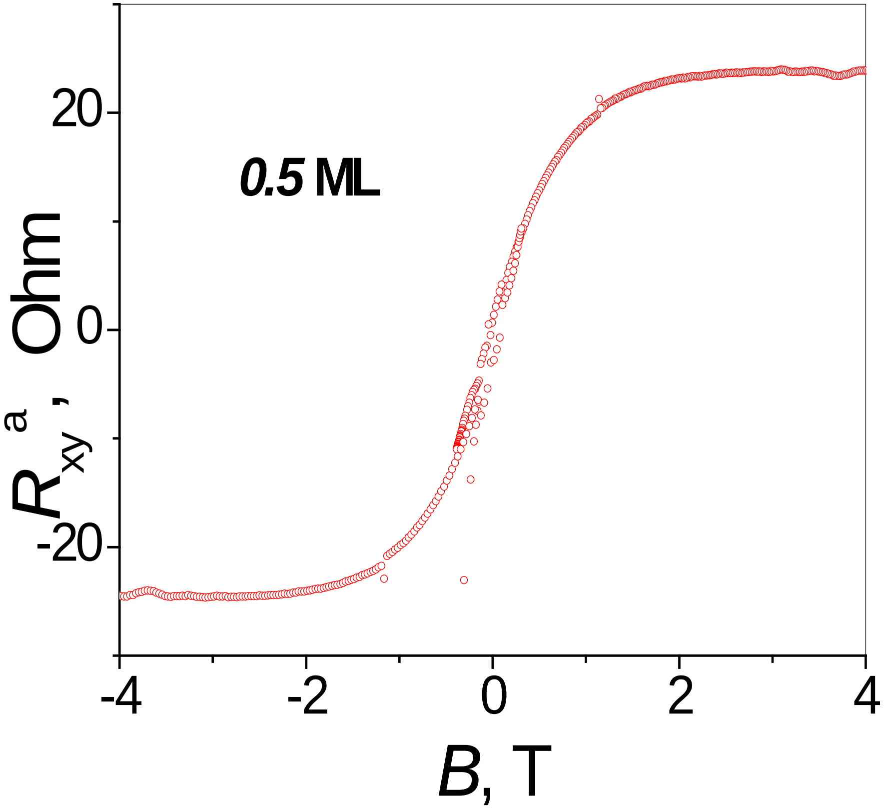
Renewed interest in AHE nature

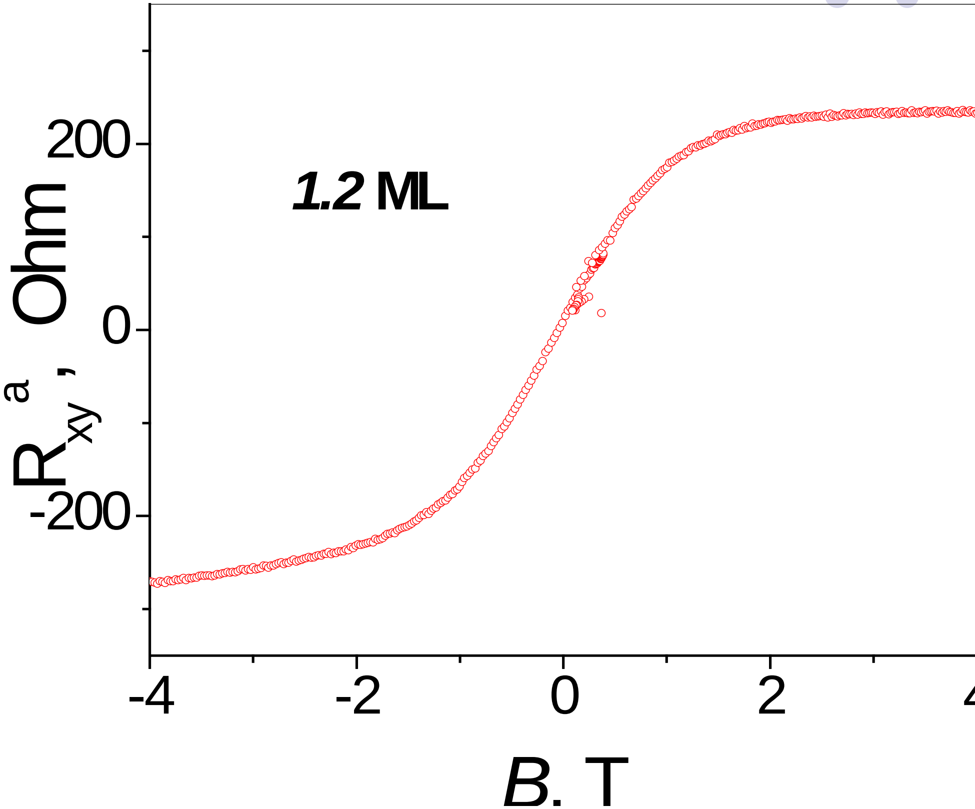
T. Jungwirth et al.(2002), T. Dietl et al.(2003), A.A. Burkov et al. (2003)

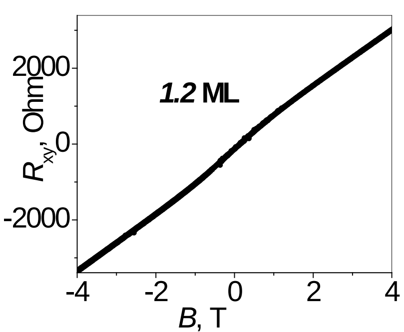
2D case: S.Y. Liu et al. (2005), V.K. Dugaev et al. (2005)

Anomalous Hall Effect

The Hall resistance $R_H d = \rho_{yx} = R_0 B + R_s M$
Anomalous Hall Effect is proportional to magnetization. *AHE depends on the strength of the S-O interaction and spin polarization of carriers.*







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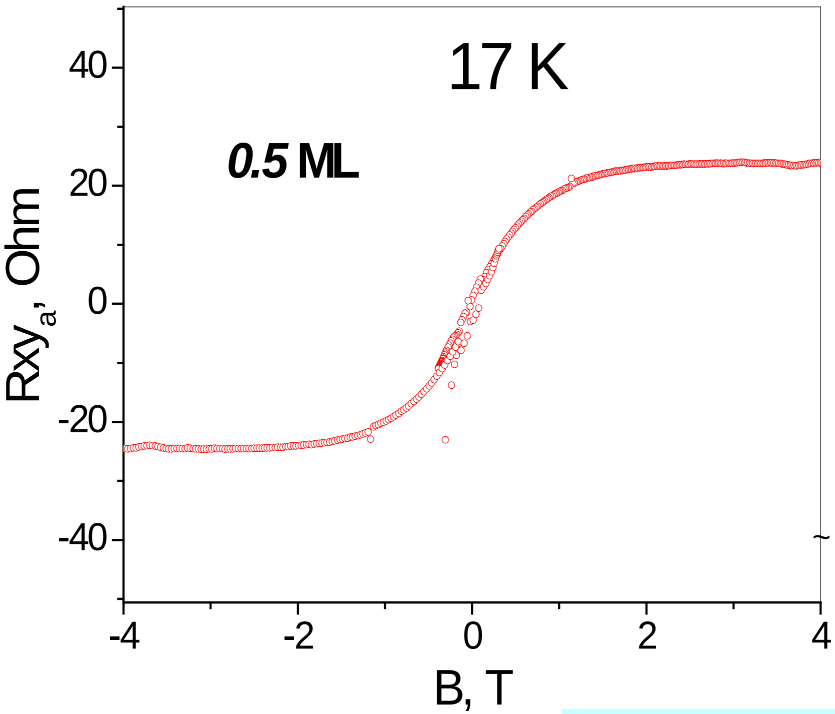
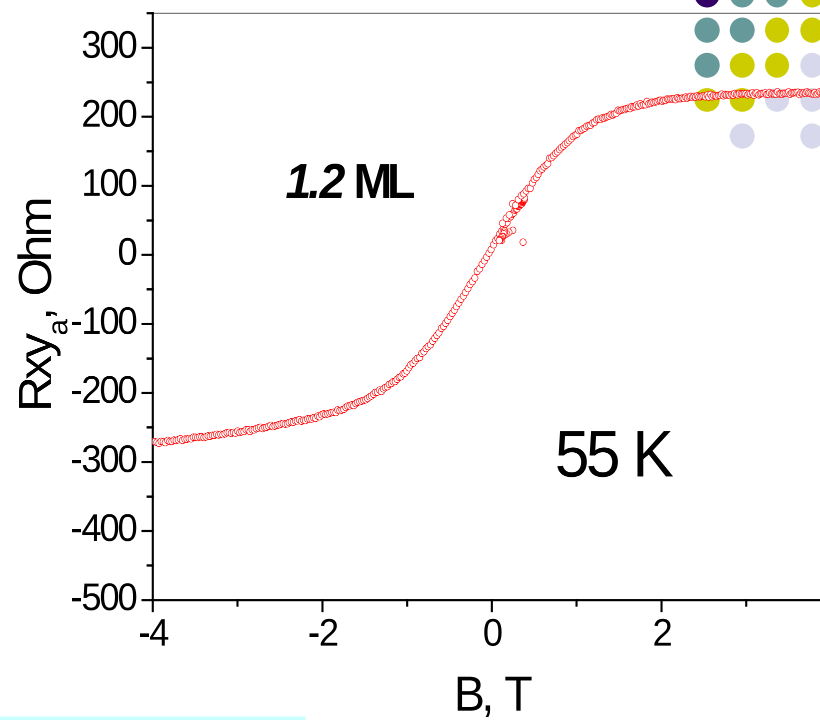
Anomalous Hall Effect





$\sigma_{xy}^{a} \cong 0.07 e^2 / h$

2D calculated $\Rightarrow$ $0.1 e^2 / h$

$\sigma_{xy}^{a} \cong 0.17 e^2 / h$

S.Y. Liu, X.L. Lei, Phys. Rev. B **72**, 195329 (2005).
V.K. Dugaev, P. Bruno, M. Taillefumier, B. Canals, C. Lacroix, Phys. Rev. **71**, 224423 (2005).

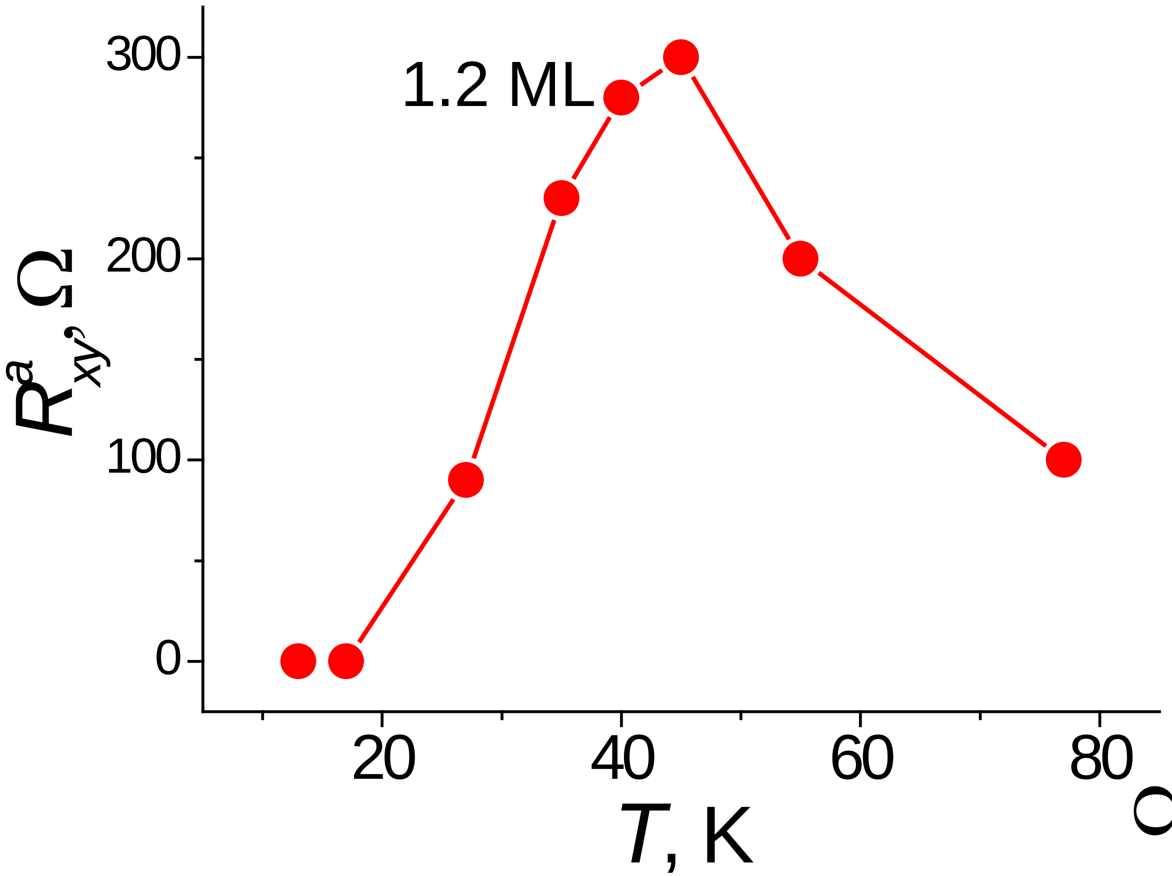
$$\sigma_{xy}^{n} = \rho_{xy}^{n} / \rho_{xx}^{2}$$
$$\sigma_{xy}^{a} = \rho_{xy}^{a} / \rho_{xx}^{2}$$

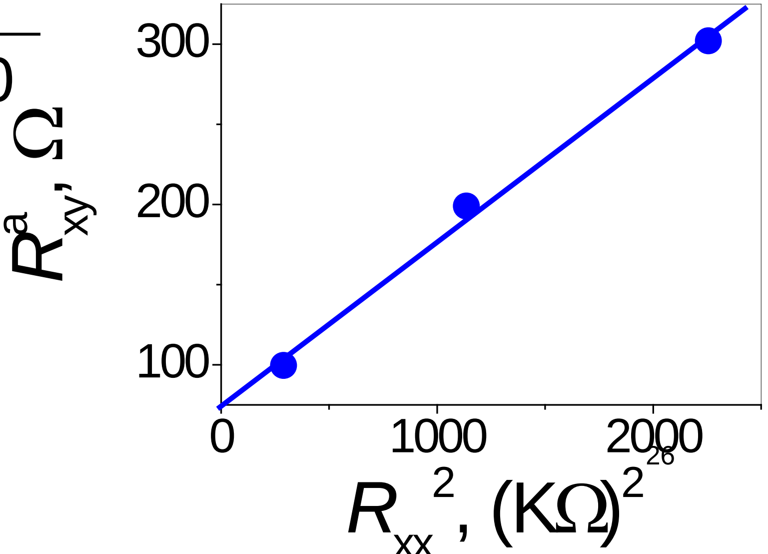
$$\sigma_{xy}^{n} = \frac{pe^2}{m}\omega_c \left(\frac{\tau^2}{1+\omega_c^2\tau^2} \right) \propto \tau^2 \Rightarrow \rho_{xy}^{a} / \rho_{xy}^{n} = \sigma_{xy}^{a} / \sigma_{xy}^{n} \propto \tau^{-2}$$

J. Phys. Cond. Matt. 2008

TR

Anomalous Hall Effect

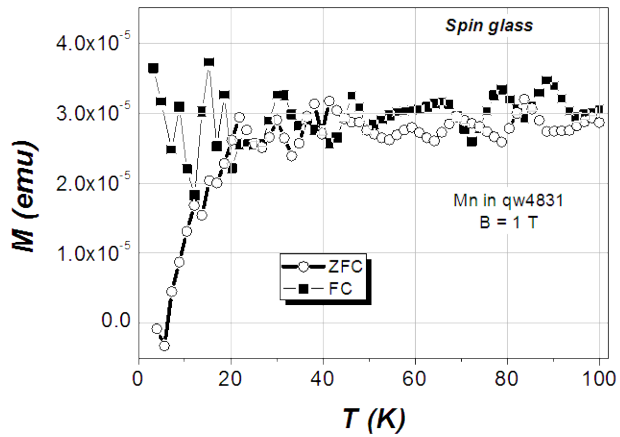


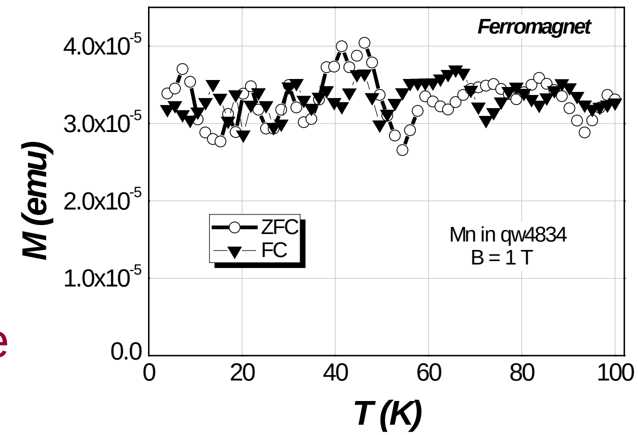


Magnetization

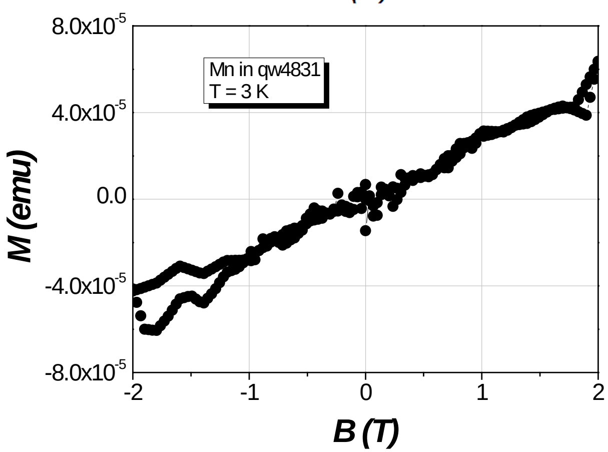
Metallic sample
Low Mn content

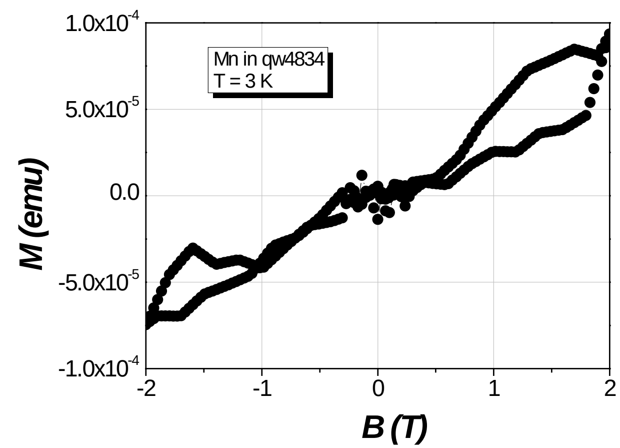
Insulator sample
High Mn content





What is the reason for unusual hysteresis loop?



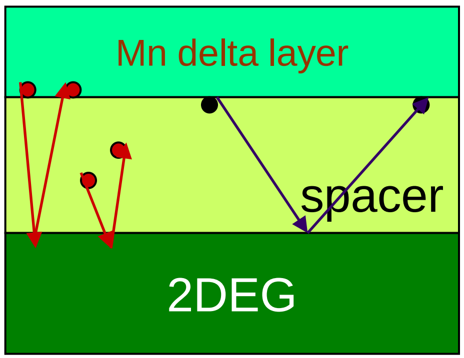


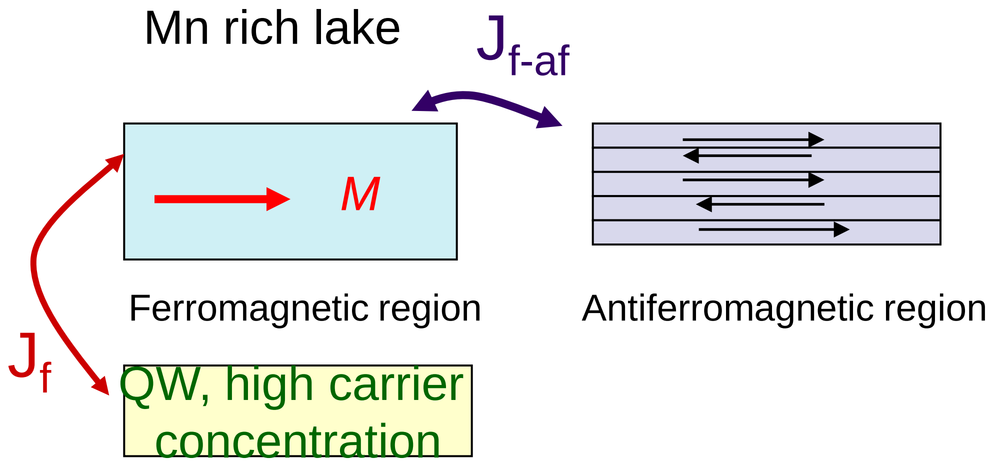
Exchange bias of hysteresis loop

Known for two phase systems with ferro - and anti-ferro inclusions, for example, phase separation in manganites

JETP Letters, 2008

Model





Magnetic moment of the lake is pinned by $J_{f\text{-}af}$

The percolation transition in magnetic system affect scattering and results in decrease of resistance – reason of the noise.

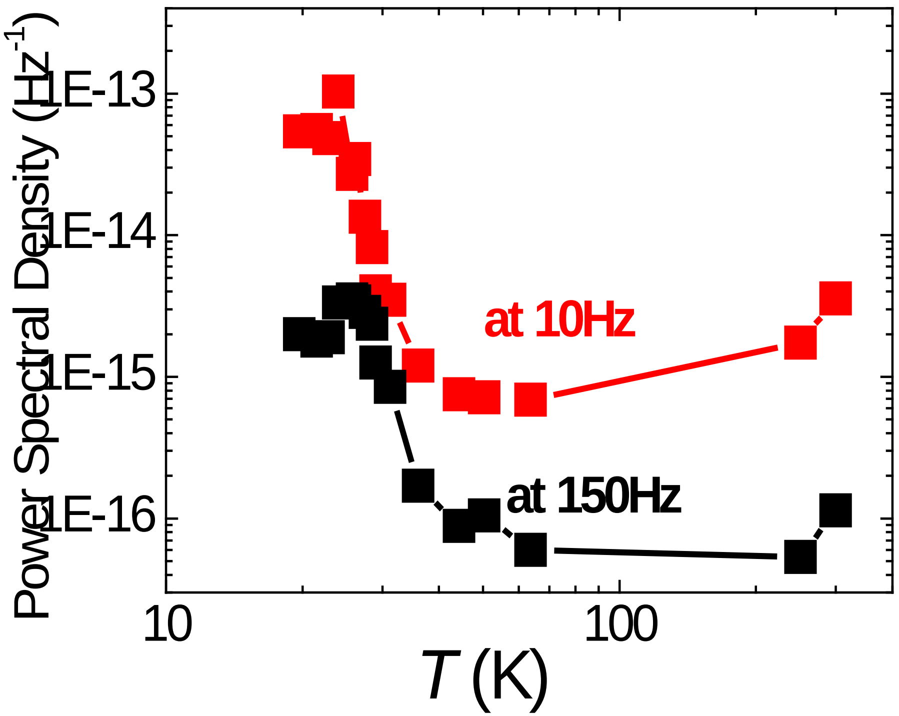
Due to shape anisotropy magnetic moment of Mn layer aligns along →

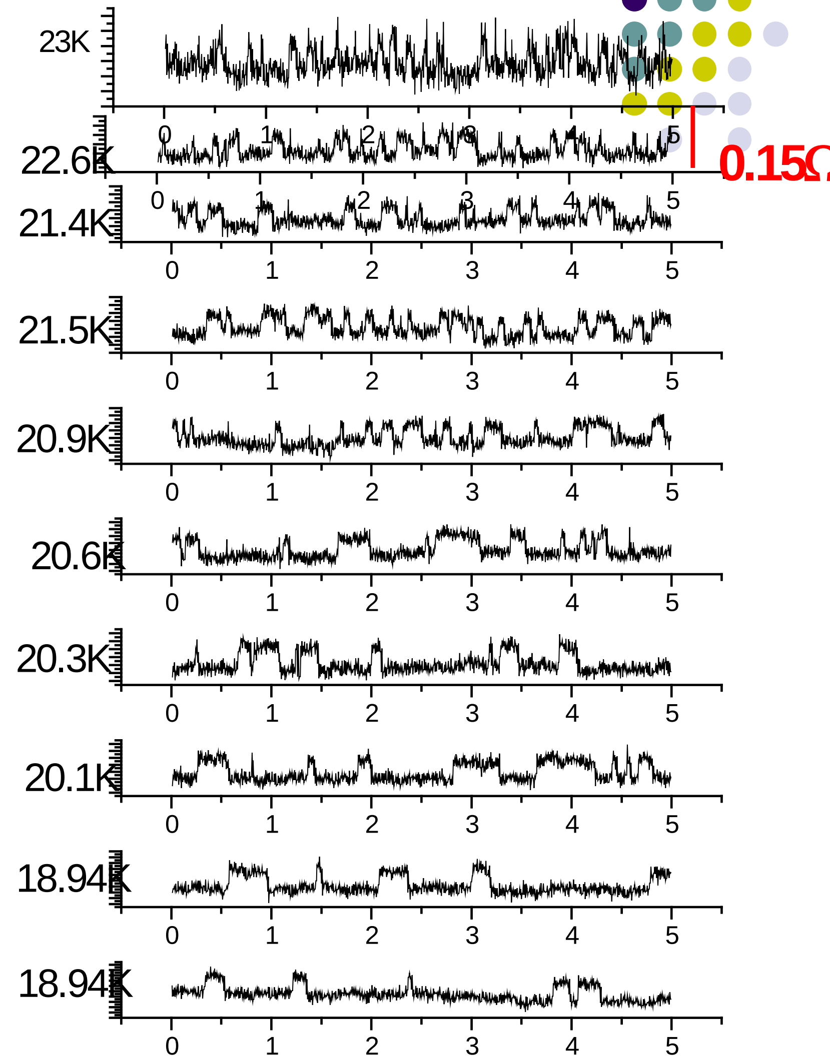
Due to quantization spin of heavy holes aligns perpendicularly ↓

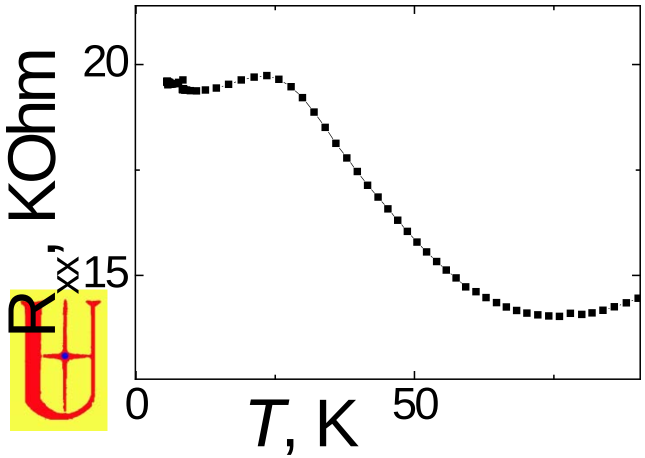
Is the exchange possible?
Yes, due to high Fermi energy and disorder.
d_{qw}=10 nm, r_{loc}= 20-30 nm, K in plane is about K_z

JETP Letters, 2008

Power spectral density of electrical noise







Percolation transition in magnetic system?

There are no transitions in transport

Conclusion

Maximum in the temperature dependence of resistance and anomalous Hall effect are the sign for magnetic ordering in 2D structures with Mn layer separated from the quantum well

Anomalous Hall effect was observed in 2D structures with Mn layer separated from the quantum well

The unusual shifted hysteresis loop was observed

Disorder and interactions affect strongly both transport and magnetic properties of the structures

Spin-polarization of carriers were observed

THANKS FOR YOUR ATTENTION