Pressure induced enhancement of the exchange coupling in (III,Mn)V magnetic semiconductors

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Introduction

Carrier mediated magnetic coupling
- tuning of the J_{pd} coupling by application of pressure
- pressure induced ferromagnetism

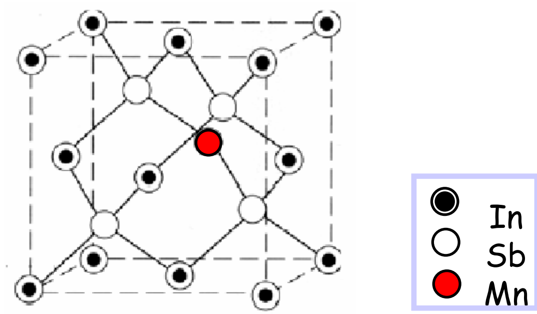
M. Csontos et al., Nature Materials **4**, 447 (2005)

Magnetic scattering of spin polarized carriers
- enhancement of magnetoresistance by application of pressure
- mechanism of magnetic scattering

M. Csontos et al., Phys. Rev. Lett. (submitted), cond-mat/0505582

Conclusion

Dilute magnetic semiconductors



Substitutional Mn
acceptor

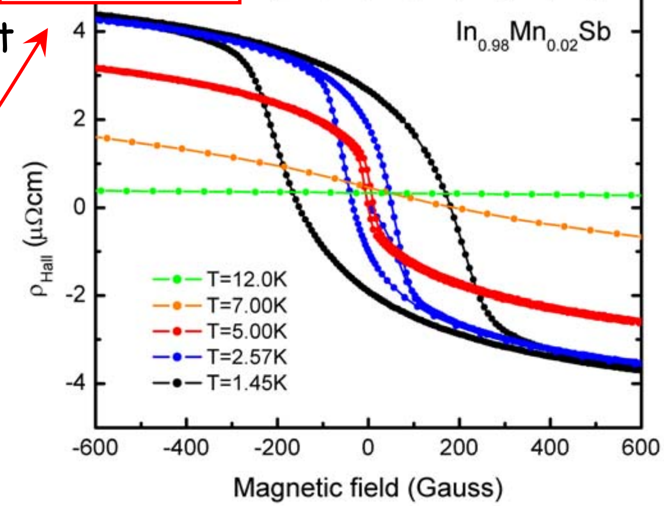
Mn provides
-- magnetic moments
-- holes

Mn-Mn coupling
FM, mediated by holes

Anomalous Hall effect

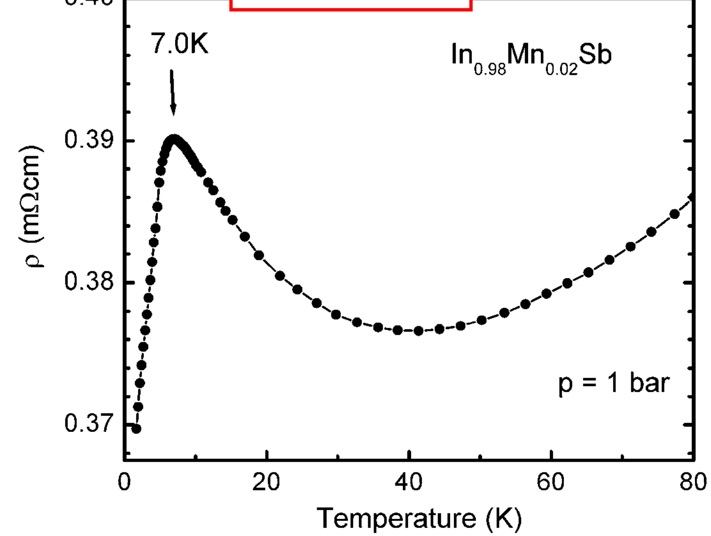
$$\rho_H = R_0 H + R_s M$$

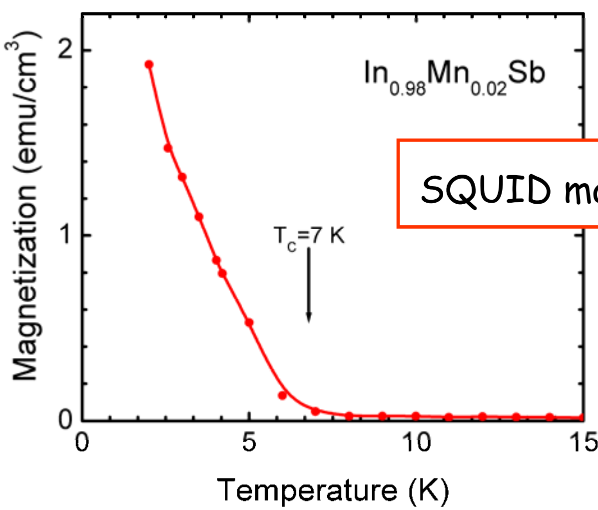
Hall effect



Experimental techniques

Resistivity





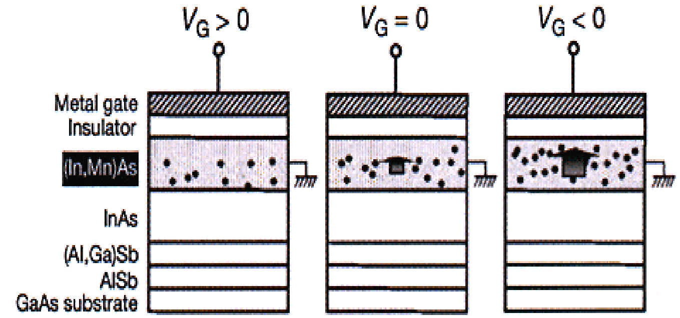
SQUID magnetization

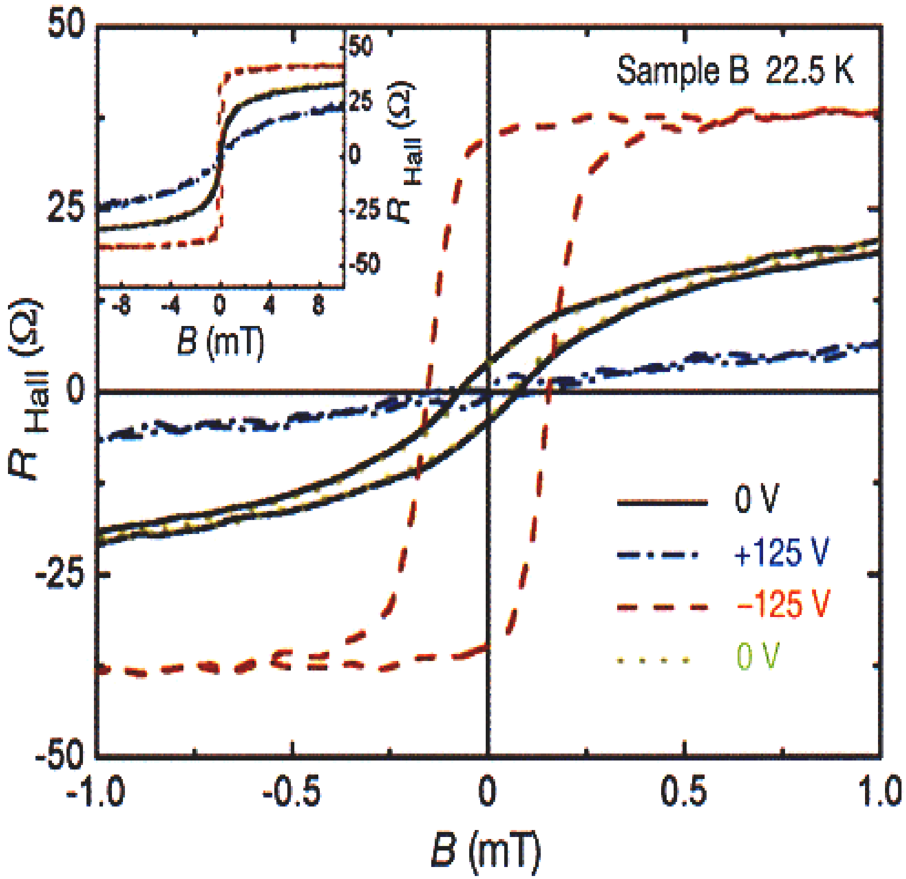
T. Wojtowicz et al., *APL* **82**, 4310 (2003)

Electric field control of magnetism

1. magnetic coupling is medited by holes

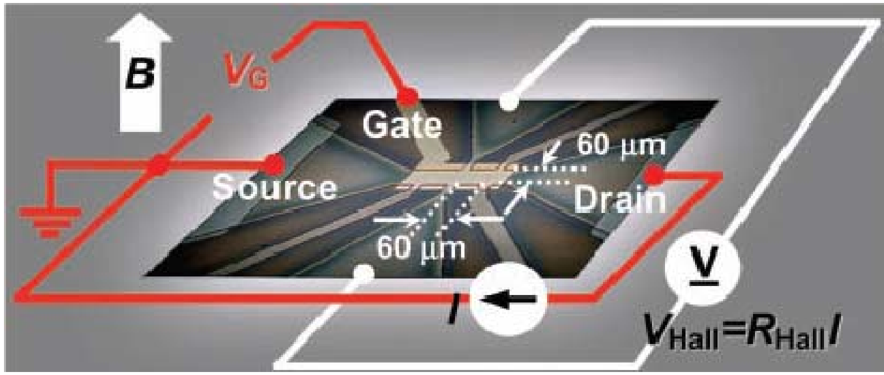
2. hole concentartion can be varied by field effect





Electrically manipulated magnetic memory unit

Controll -- gate voltage
Detection -- anomalous Hall signal



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

D. Chiba *et al.*, Science **301**, 943 (2003)

Carrier-mediated magnetic coupling

Motivation:

enhancement of magnetic coupling by application of pressure (a: 6.45 Å → 6.32 Å for p = 2.7 Gpa)

Advantage of $In_{1-x}Mn_xSb$:

- low value of the bulk modulus (48 Gpa)
- carrier density is pressure independent

Parameters of $In_{0.98}Mn_{0.02}Sb$:

$$n_{hole} \approx c_{Mn^{2+}} = 3\cdot 10^{20}\ \mathrm{cm}^{-3} \qquad (\approx 0.8x)$$

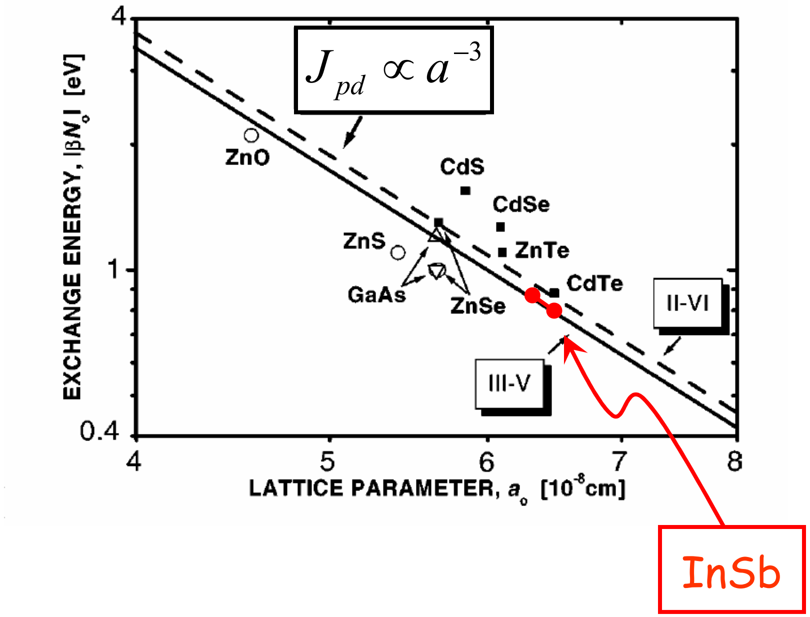
$$k_F l = \left(3\pi^2\right)^{\frac{3}{2}} \frac{\hbar}{e^2} \frac{1}{\rho\sqrt[3]{n}} \approx 30$$

$$\omega_C\ \tau = \frac{B}{ne\rho} = 0.104 \qquad \text{for } B = 10\ \mathrm{T}$$

RKKY interaction:

$$J = \frac{(3N)^2 \pi\, m_{eff}}{\hbar^2 (k_F r)^2} r^2 J_{pd}^2 F(k_F r)$$

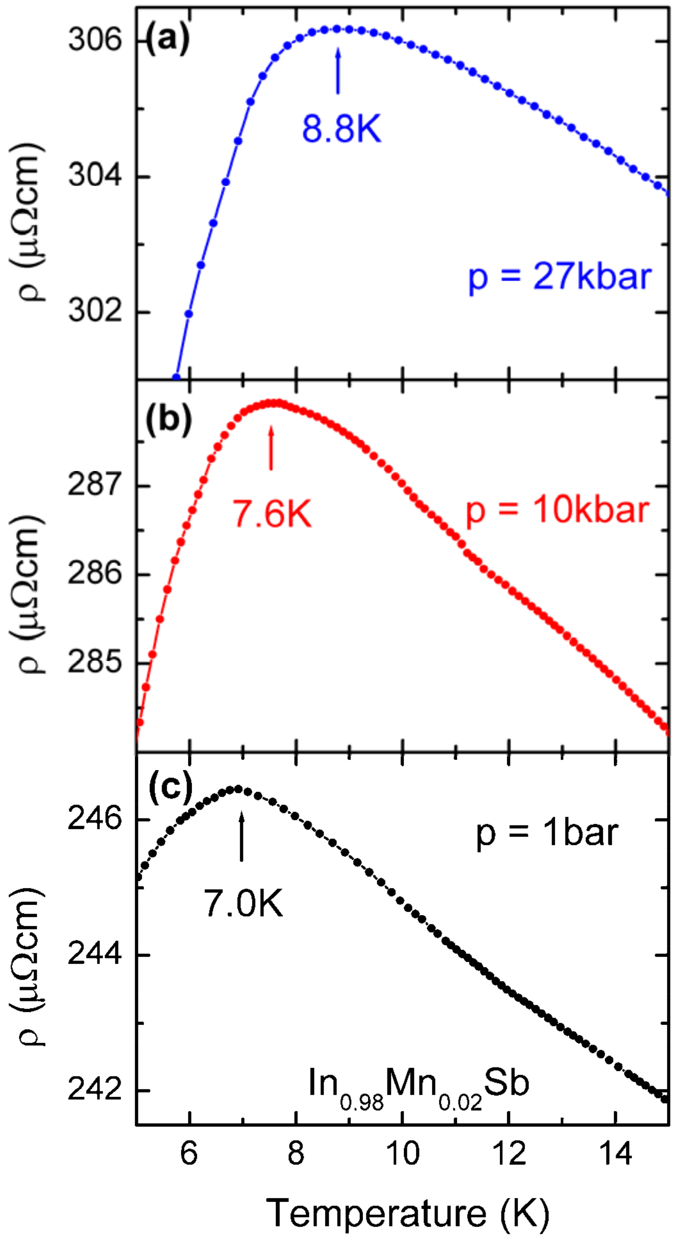
There is a random distribution of the magnetic Mn^{2+} ions (s=5/2), but the average nearest neighbor distance is below the firs node of the RKKY interaction.



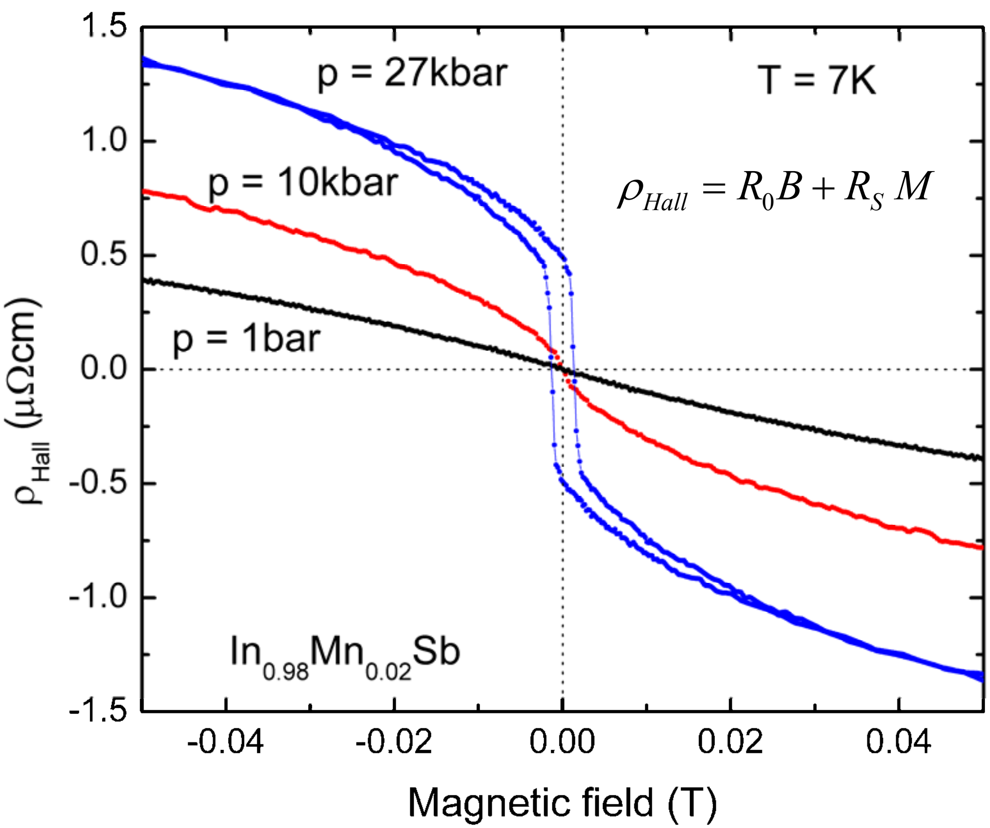
T. Dietl et al., Phys. Rev. B **63**, 195205 (2001)

Pressure effects

Pressure induced enhancement of T_C (9.3% / GPa)



Crossing of the paramagnetic-ferromagnetic phase boundary



The appearance of hysteresis in the AHE signifies the entering into the ferromagnetic phase

M. Csontos et al., Nature Materials **4**, 447 (2005)

Carrier-mediated magnetic coupling

RKKY interaction:

band parameters

$$k_B T_C = c\,\frac{S(S+1)\,m_{eff}\,k_F}{12 N_o \pi^2 \hbar^2}\,J_{pd}^2$$

Mn^{2+} concentration

local magnetic coupling between Mn^{2+} and the holes

$$\frac{1}{V}\frac{\partial V}{\partial p} = \frac{1}{\kappa}$$

$$\kappa = 48\,\text{GPa}$$

$$\frac{1}{V}\frac{\partial V}{\partial p} = -0.021\,\frac{1}{Gpa}$$

Pressure dependence of the exchange energy

Finding of a hole in the vicinity of Mn^{2+} increases inversely with the unit cell volume

$$\frac{1}{J_{pd}}\frac{\partial J_{pd}}{\partial p} \propto 0.02\,\frac{1}{\text{GPa}}$$

Pressure dependence of the Fermi wave number

Normal Hall effect:
no change in the carrier density

k_F is pressure independent $\left(\text{within } \frac{0.2\%}{\text{GPa}}\right)$

Pressure dependence of the band mass

Increase of the resistance

$$\frac{1}{m_{eff}}\frac{\partial m_{eff}(p)}{\partial p} = 0.07\,\frac{1}{\text{GPa}}$$

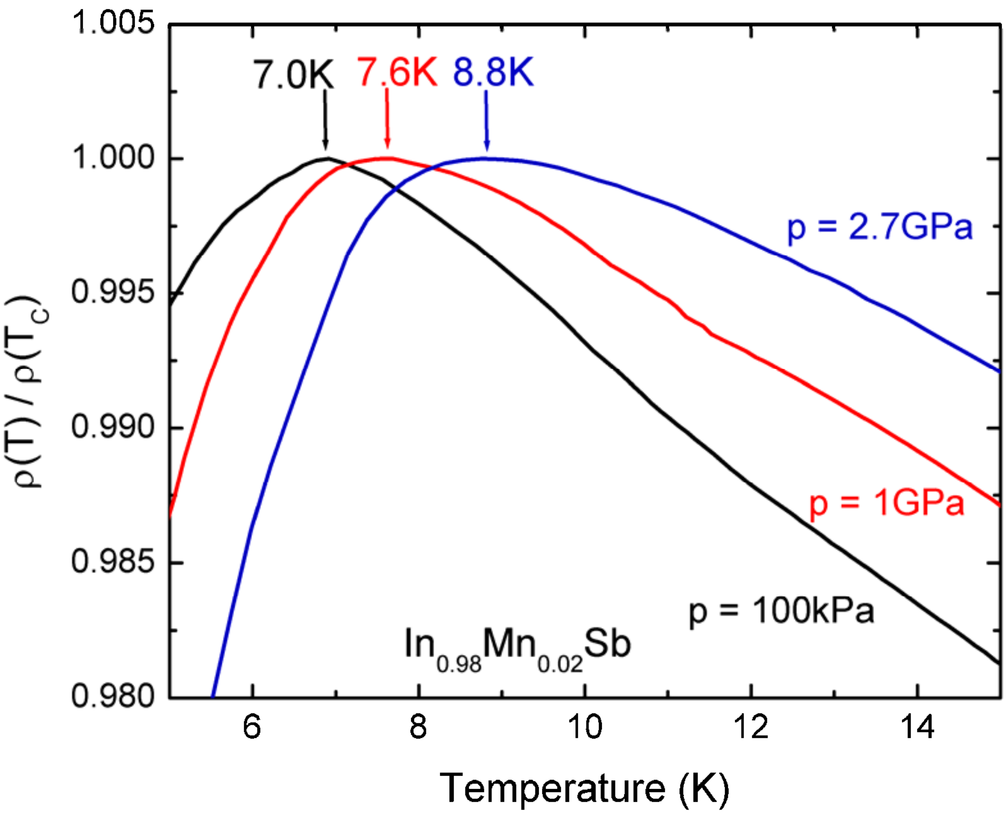
Carrier-mediated magnetic coupling

Theory

$$\frac{\Delta T_C}{T_C} \approx 9 \frac{\%}{\text{GPa}}$$

Experiment

T_C enhancement $\dfrac{25\%}{2.7\text{ GPa}} \approx 9.3\dfrac{\%}{\text{GPa}}$

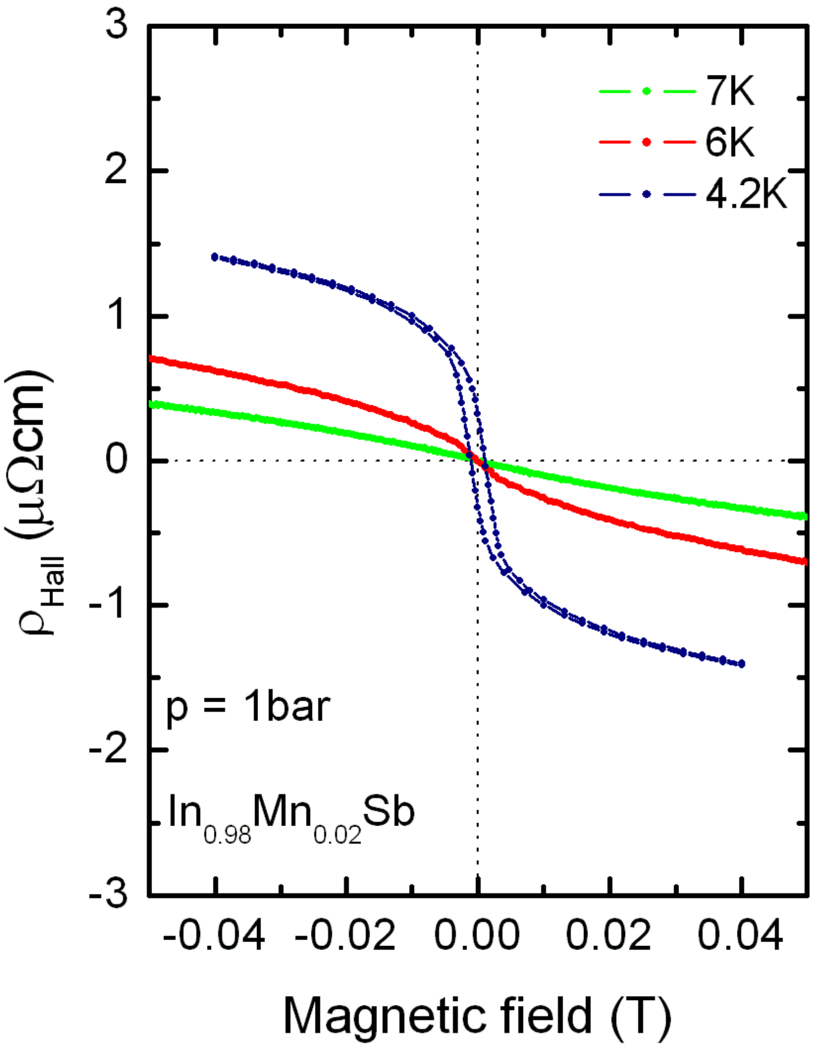


$$\frac{1}{J_{pd}}\frac{\partial J_{pd}}{\partial p} \propto 0.02\frac{1}{\text{GPa}}$$

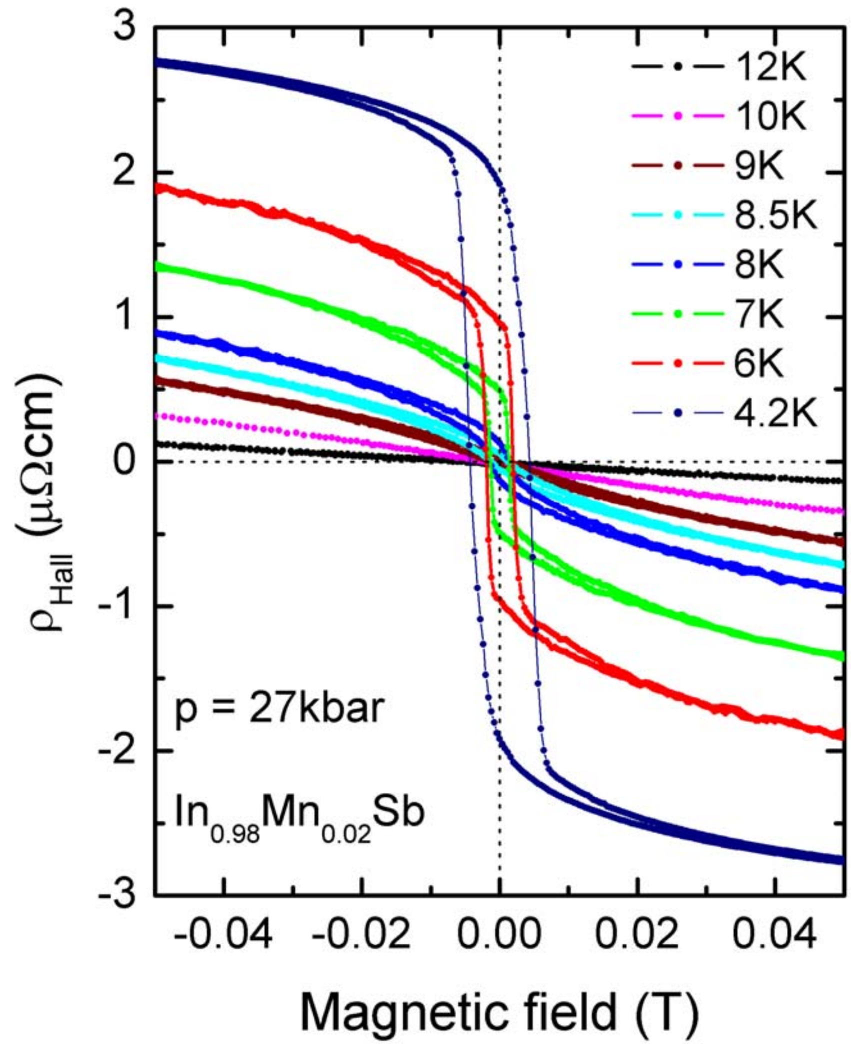
$$k_F \text{ is pressure independent } \left(\text{within } \frac{0.2\%}{\text{GPa}}\right)$$

$$\frac{1}{m_{eff}}\frac{\partial m_{eff}(p)}{\partial p} = 0.07\frac{1}{\text{GPa}}$$

Pressure induced enhancement of the anomalous Hall effect in $In_{0.98}Mn_{0.02}Sb$

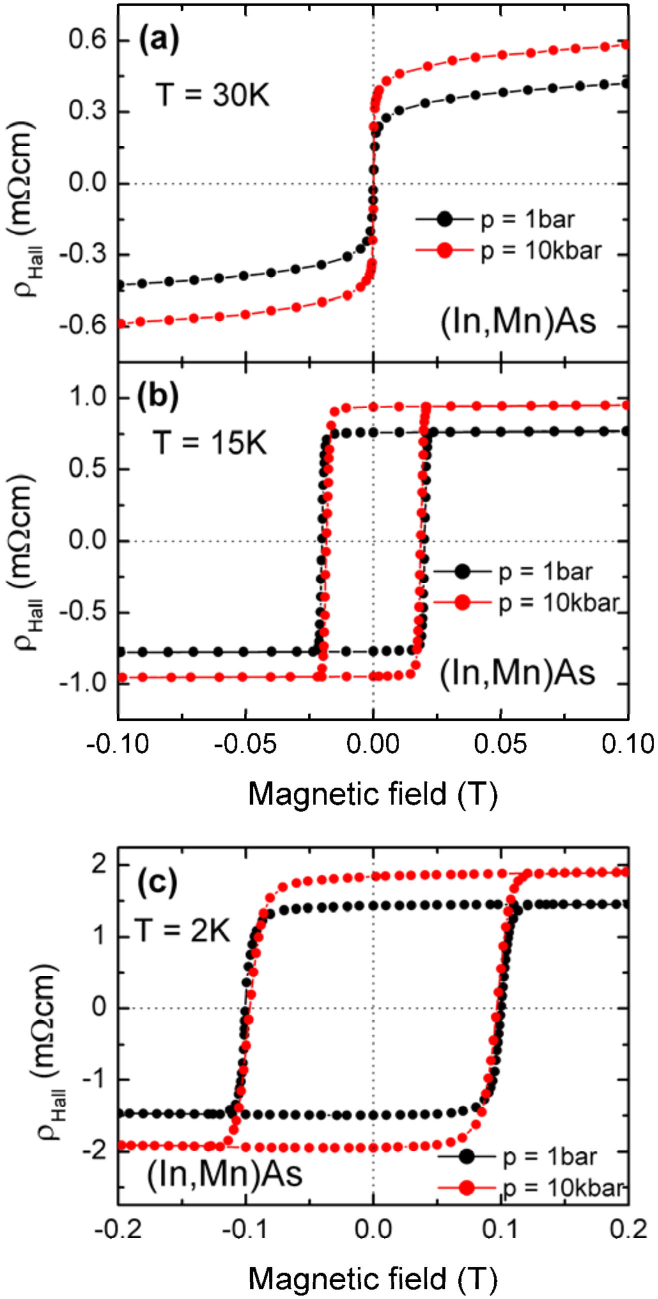


Shift of the transition temperature as measured by he Hall signal



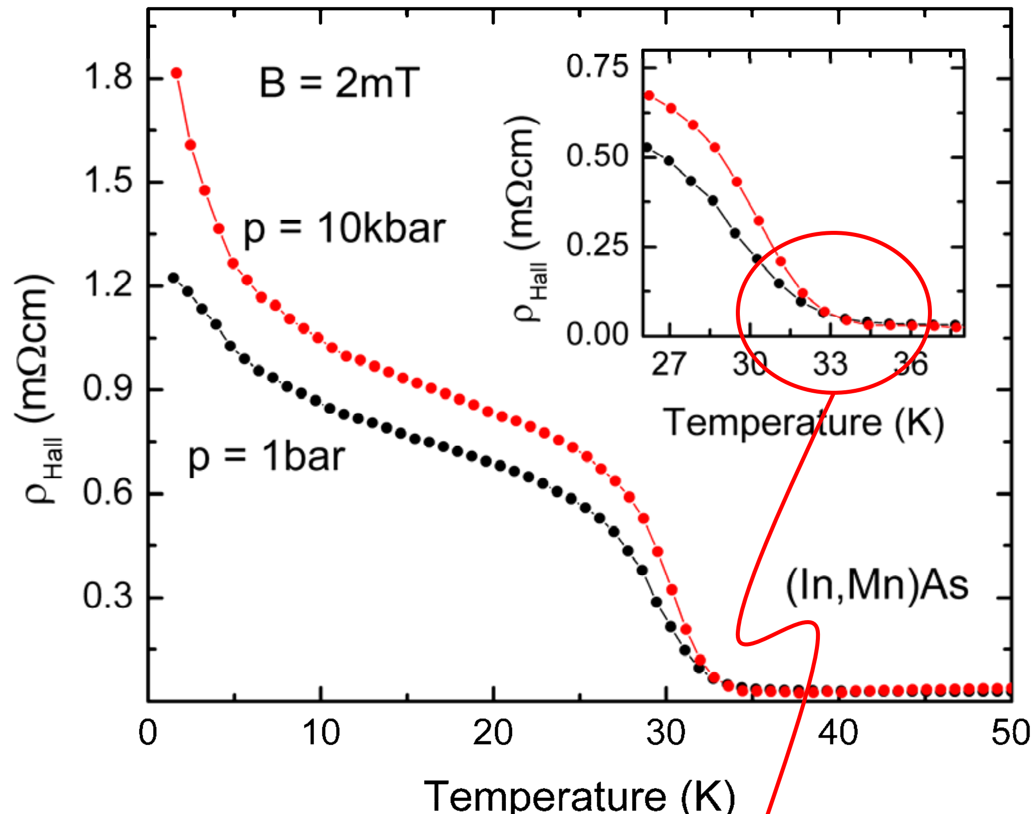
Pressure induced enhancement of the anomalous Hall effect in $In_{0.91}Mn_{0.09}As$

Increase of the magnitude of the hyteresesis loops



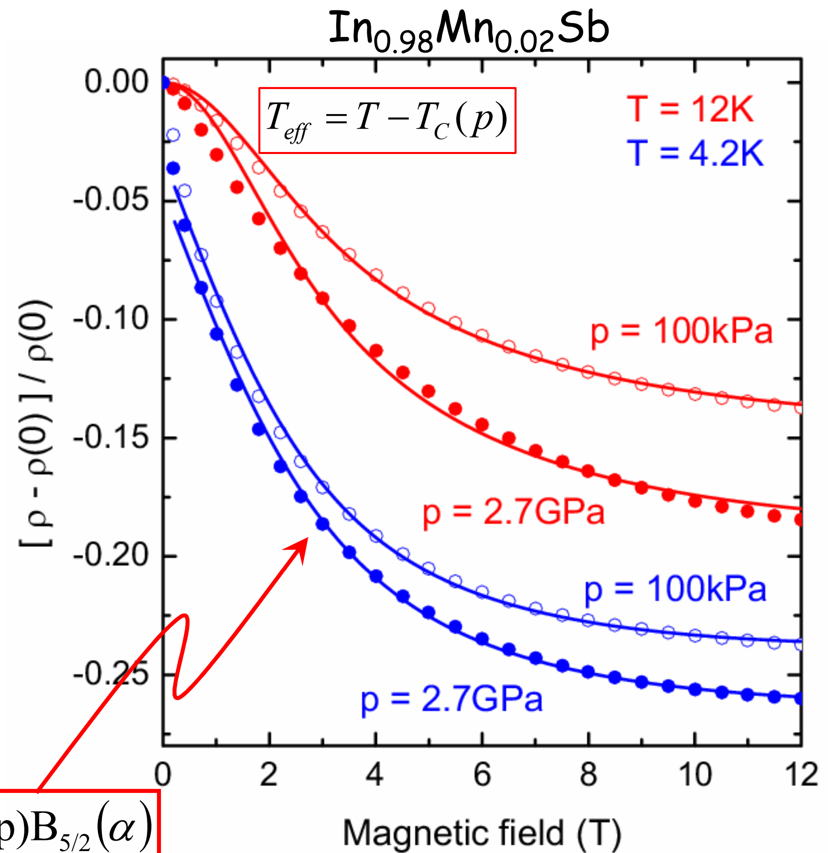
$$\rho_{Hall} = R_0 B + R_S(p) M$$

Temperature and pressure dependence of the remanent AHE signal



No change in T_C : J_{pd} increases, n decreases

Pressure induced enhancement of the magnetoresistance



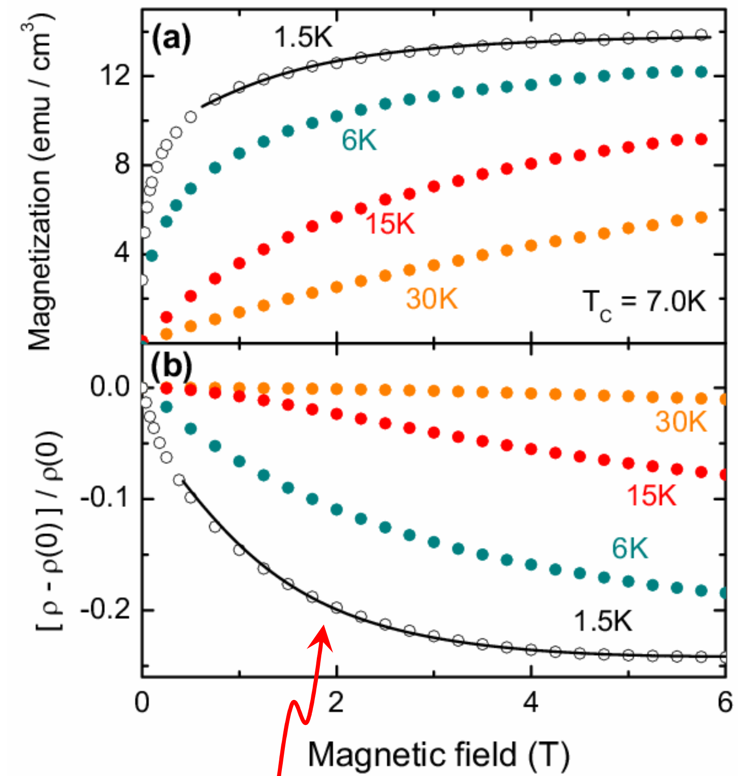
$J_{pd}^2(\mathrm{p})\mathrm{B}_{5/2}(\alpha)$

$\mathrm{B}_{5/2}(\alpha)$

Strength of the magnetic scattering

$$\frac{1}{\tau_\pm} = C\left[1 \mp \frac{2J_{pd}}{V}\langle S_Z\rangle + \left(\frac{2J_{pd}}{V}\right)^2 f(\langle S_Z\rangle)\right]$$

Béal-Monod et al.,Phys. Rev. **170**, 552 (1967)



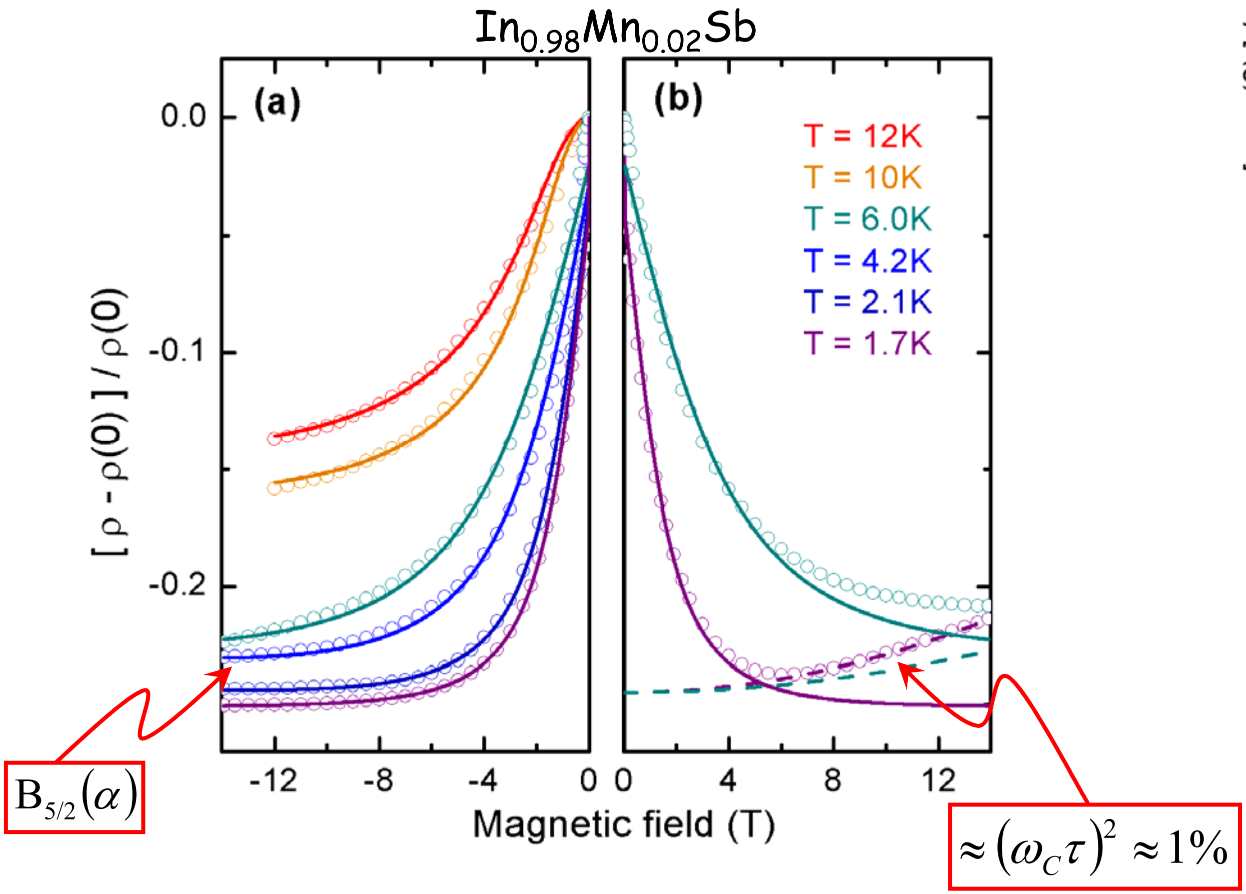
$\mathrm{B}_{5/2}(\alpha)$

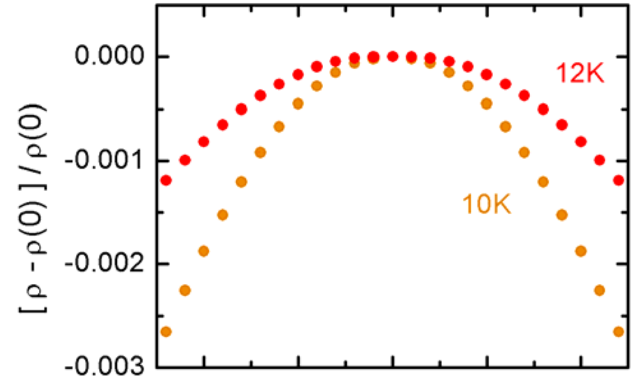
$\alpha = g\mu_B B / k_B T_{eff}$

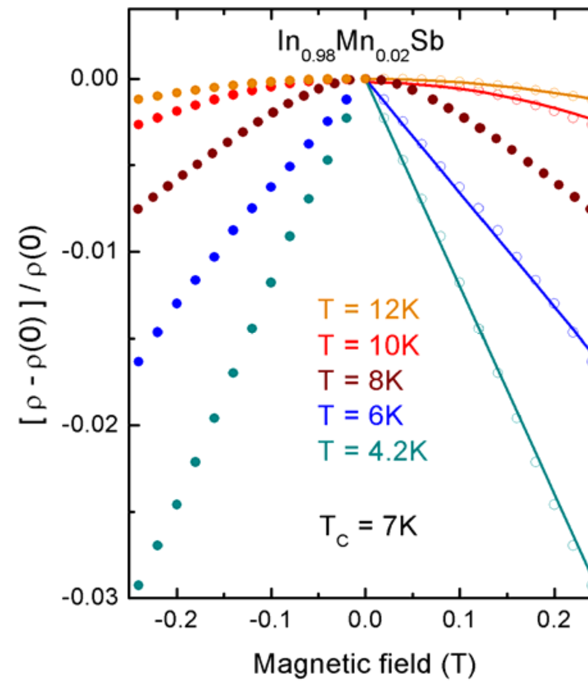
$$\frac{\rho(B)-\rho_0}{\rho_0} = \begin{cases} -4P\dfrac{J_{pd}}{V}\langle S_Z\rangle & \text{for } T < T_C \\ -\left(\dfrac{J_{pd}}{V}\right)^2\left\{4\langle S_Z\rangle^2 + \langle S_Z\rangle\left(\coth\dfrac{\alpha}{2} - \dfrac{\alpha}{2\sinh^2\alpha/2}\right)\right\} & \text{for } T > T_C \end{cases}$$

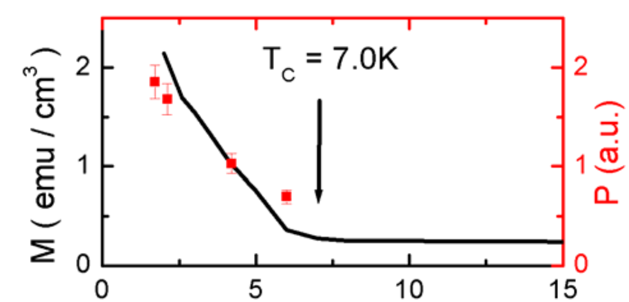
M. Csontos et al., Phys. Rev. Lett. , (submitted), cond-mat/0505582

Scattering on Mn^{2+} ions located outside the ferromagnetically-ordered regions









$$\frac{\rho(B)-\rho_0}{\rho_0} = \begin{cases} -4P\dfrac{J_{pd}}{V}\langle S_Z\rangle & \text{for } T<T_C \\ -\left(\dfrac{J_{pd}}{V}\right)^2\left\{4\langle S_Z\rangle^2+\langle S_Z\rangle\left(\coth\dfrac{\alpha}{2}-\dfrac{\alpha}{2\sinh^2\alpha/2}\right)\right\} & \text{for } T>T_C \end{cases}$$

$$\alpha = g\mu_B B/k_B T_{eff}$$

M. Csontos et al., Phys. Rev. Lett. , (submitted), cond-mat/0505582

Conclusions

The carrier mediated nature of the ferromagnetic coupling has been demonstrated by pressure experiments. Good agreement was found with numerical estimate based on RKKY interaction for the shift of T_C.

The magnetoresistance is due to scattering on those Mn^{2+} ions which are not included in the ferromagnetic clusters. Quantitative description can be given both below and above T_C.

Further studies:

- anomalous Hall-effect: open question $R_S(p)$
- pressure dependence of the magnetization (SQUID, magneto-optics)