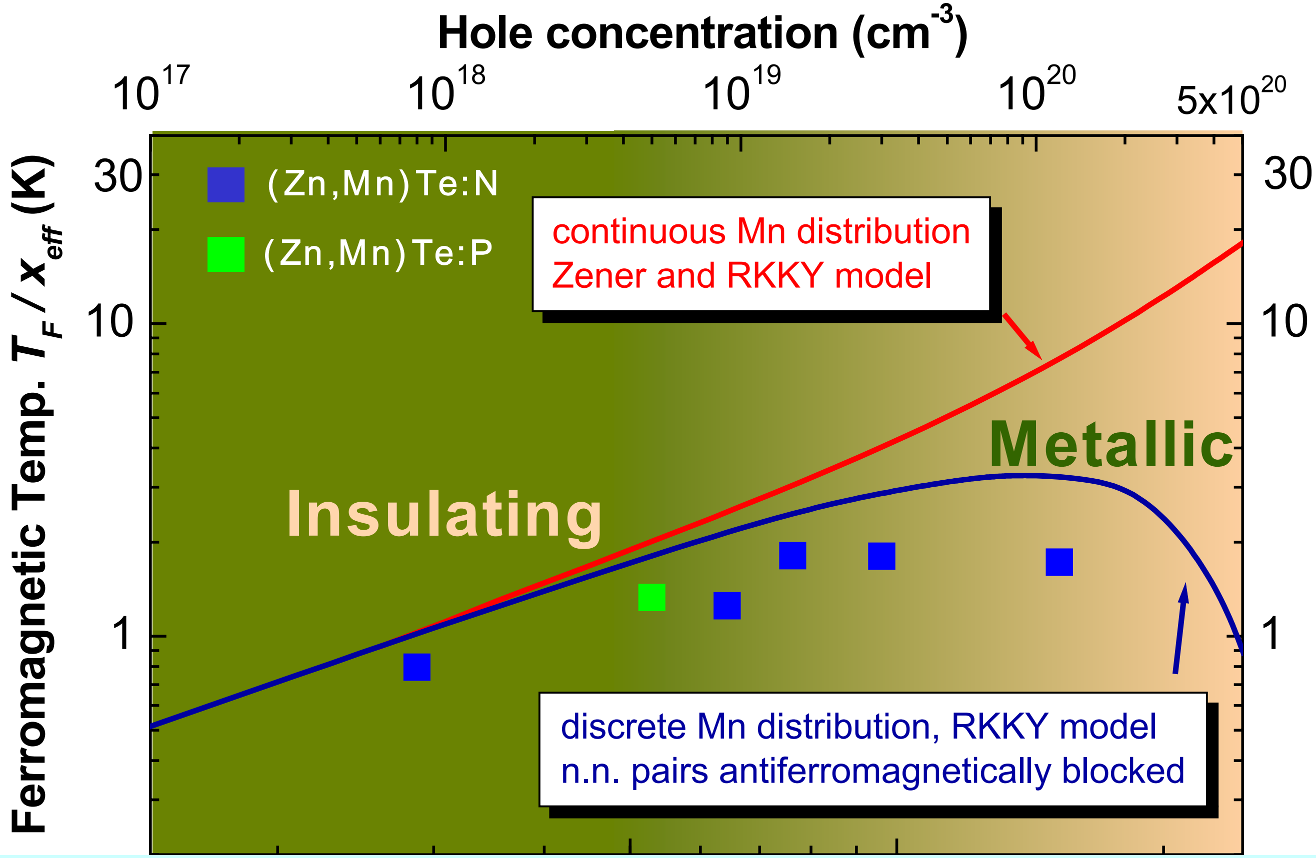
Properties of diluted ferromagnetic semiconductors

T. Dietl, Schladming'05 lecture VI

Hole controlled ferromagnetic semiconductors -- outline

- Theoretical challenges
- Magnetic anisotropy
- Magnetic stiffness and spin waves
- Transport and optical properties
- Manipulation with spin ordering
    - -- electric field
    - -- light
- High T_c ferromagnetic semiconductors
  -- where do we stand?

Ferromagnetic temperature theory vs. experiment in p–(Zn,Mn)Te



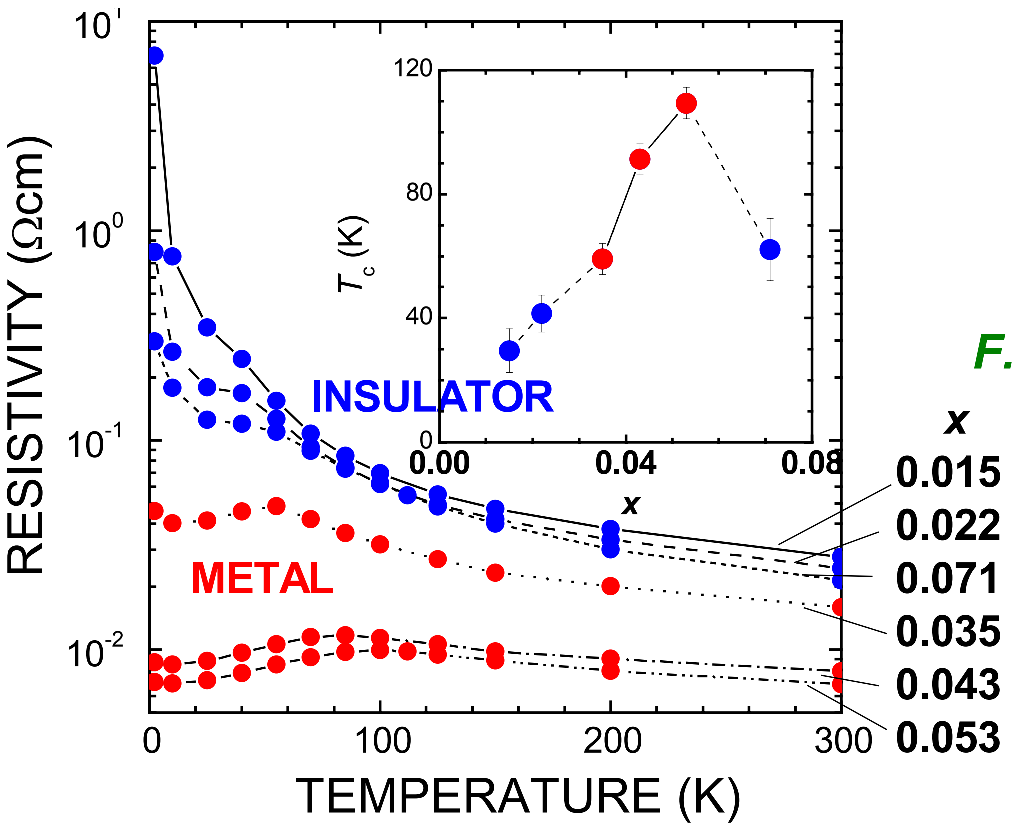
continuous Mn distribution
Zener and RKKY model

discrete Mn distribution, RKKY model
n.n. pairs antiferromagnetically blocked

- **ferromagnetism disappears in the absence of holes**
- **ferromagnetism on both sides of metal-insulator transitions**

D. Ferrand, ..., T.D., PRB'01

$Ga_{1-x}Mn_xAs$: resistance vs. temperature and Curie temperature vs. x



F. Matsukura et al.'98

- ferromagnetism disappears in the absence of holes
- ferromagnetism on both sides of metal-insulator transitions

Carrier-induced ferromagnetism in DMS

- **ferromagnetism on both sides of metal-insulator transitions**
- **coexistence of physics of:**

  -- strongly correlated metals

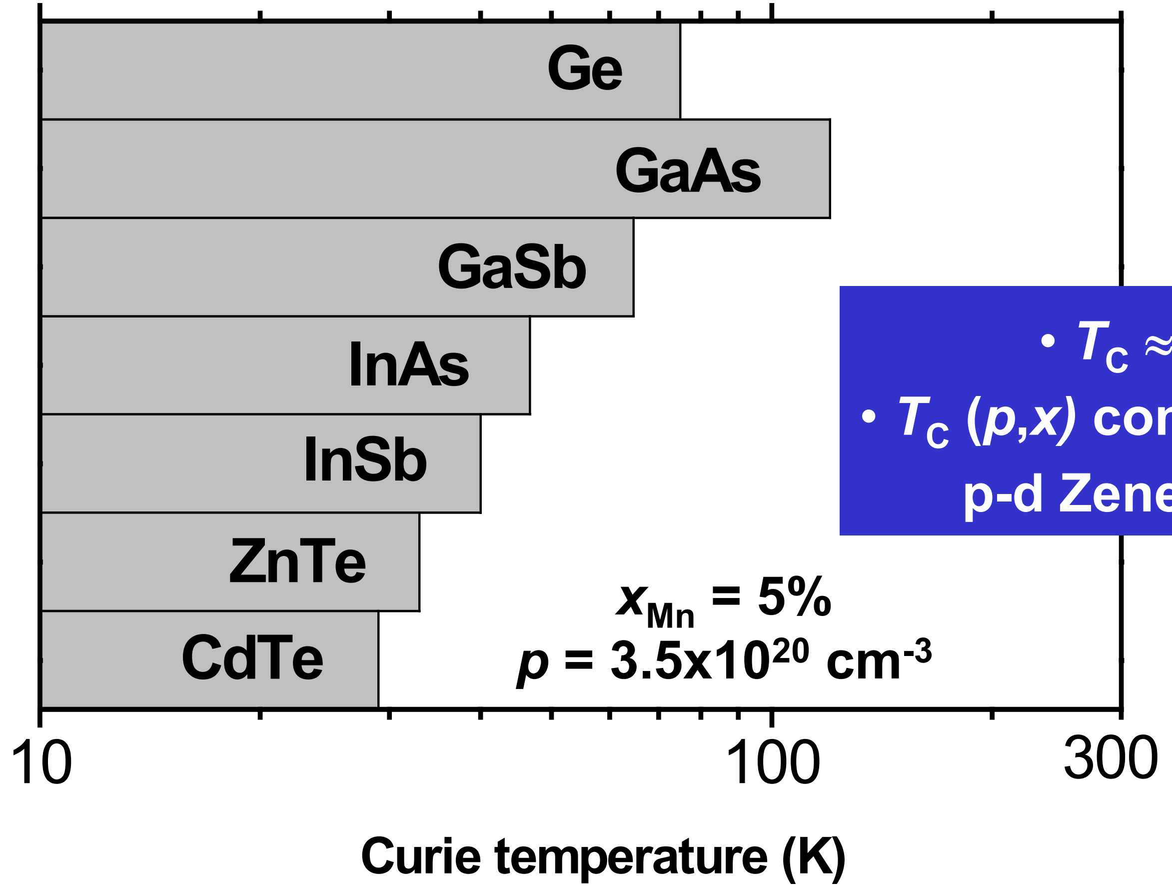
  -- disordered magnetic insulators

  -- highly doped semiconductors

  (Andersona-Mott localization, self-compensation)

Despite complexity (Ga,Mn)As
the best understood ferromagnet

Mn-based p-type DMS to which p-d Zener model has been found to apply

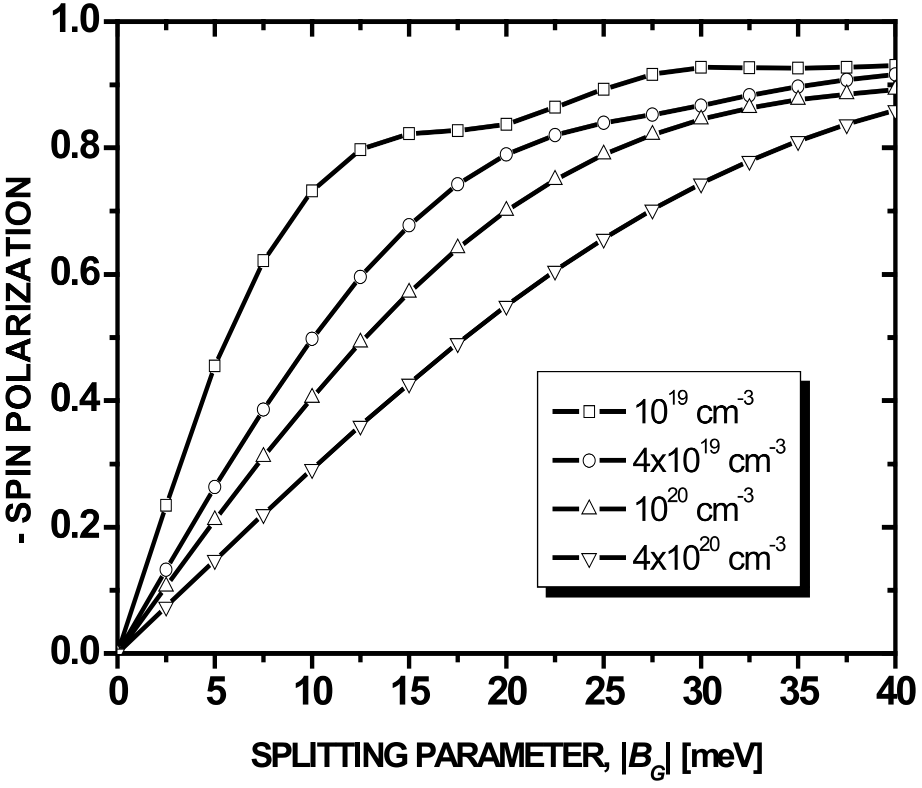


- $T_C \approx \Theta_{CW}$
- T_C (p,x) consistent with p-d Zener model

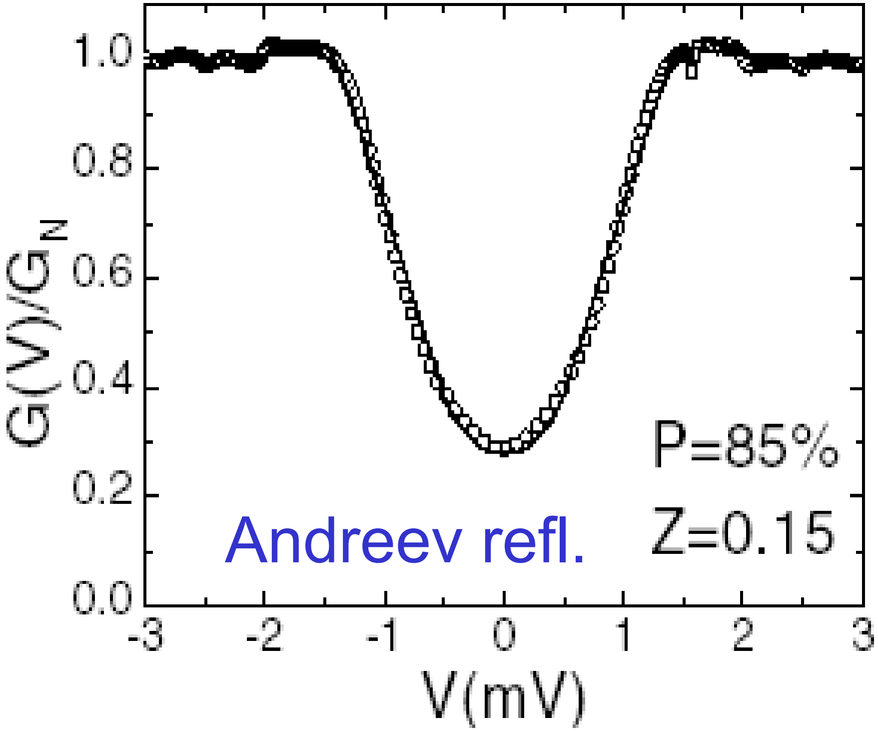
$x_{Mn} = 5\%$
$p = 3.5 \times 10^{20}$ cm^{-3}

Theory: *T. D et al., (Warsaw, Tohoku, Grenoble) Science'00, PRB'01*
Jungwirth et al. (Austin, Prague, PRB'02), also UCSD, NRL, …
Expl.: *Tohoku, Kanagawa, Tokyo, Grenoble, PSU, NRL, Notre Dame, UCSB, Nottingham, …*

Carrier spin polarization



T.D. et al., PRB'01



Braden et al., PRL'03

Properties of ferromagnetic phase

Ferromagnetic phase characterized by:

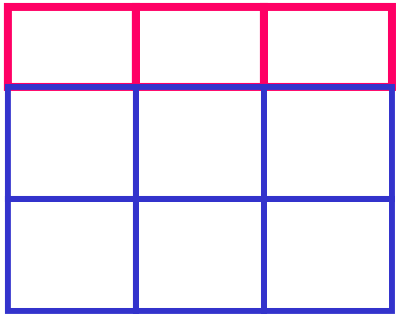
- magnetic anisotropy *K* (cubic or uniaxial)
- magnetic stiffness *A*

$$E[\,\hat{\vec{n}}(\vec{r})\,] = E_o + \int \mathrm{d}\,\vec{r}\,\left[K_u \sin^2\theta + A(\nabla\,\hat{\vec{n}}(\vec{r})\,)^2\right]$$

Magnetic anisotropy – exists due to spin-orbit interaction:

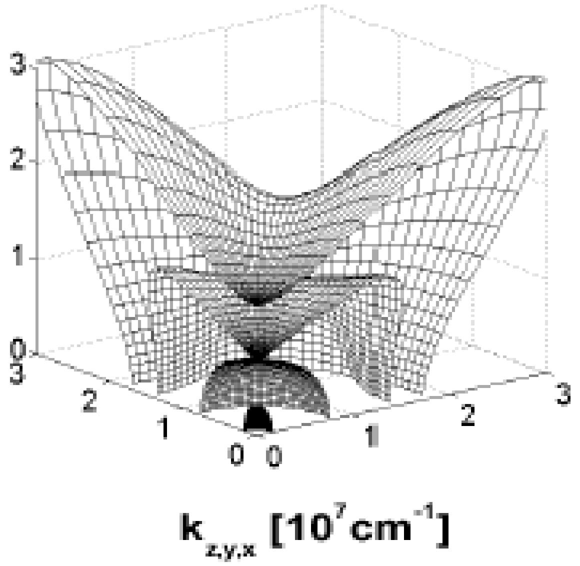
- within magnetic ion [vanishes for Mn in $^6A_1$ state (L = 0)]
- within bands mediating exchange coupling

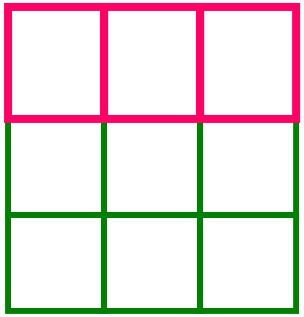
Magnetic anisotropy and epitaxial strain engineering



Tensile strain

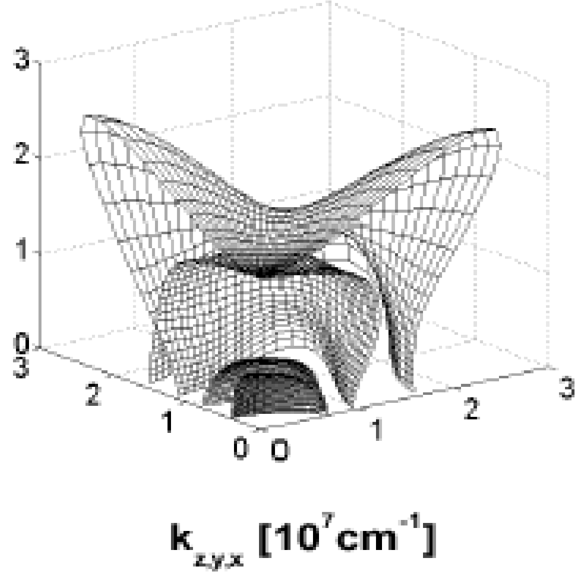
e.g (Ga,Mn)As/InAs





Compressive strain

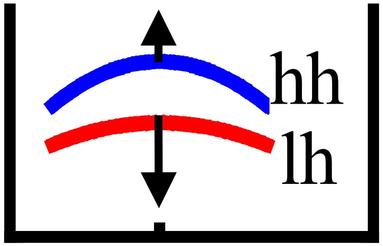
e.g (Ga,Mn)As/GaAs

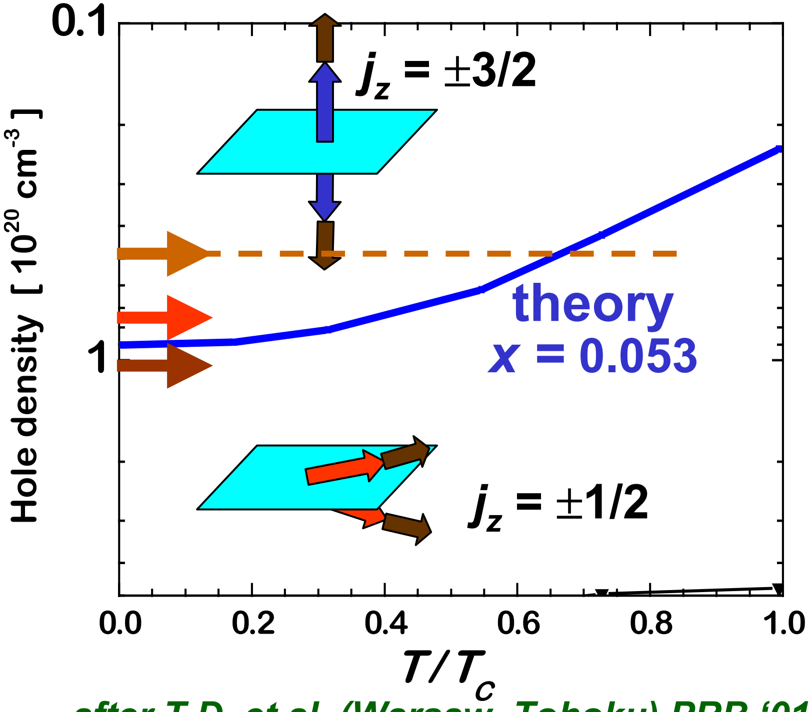


Reorientation transition –theory and expt.

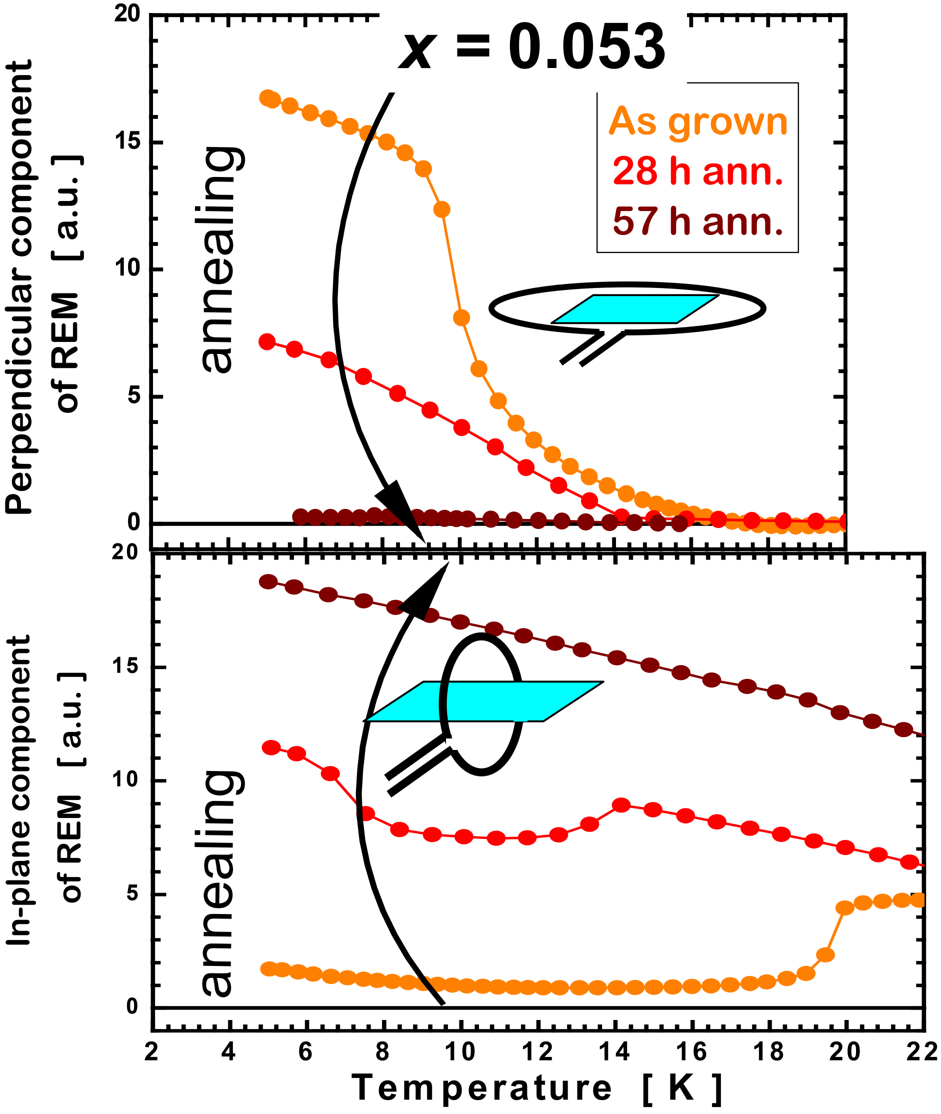
$Ga_{1-x}Mn_xAs/GaAs$

➔ compressive strain



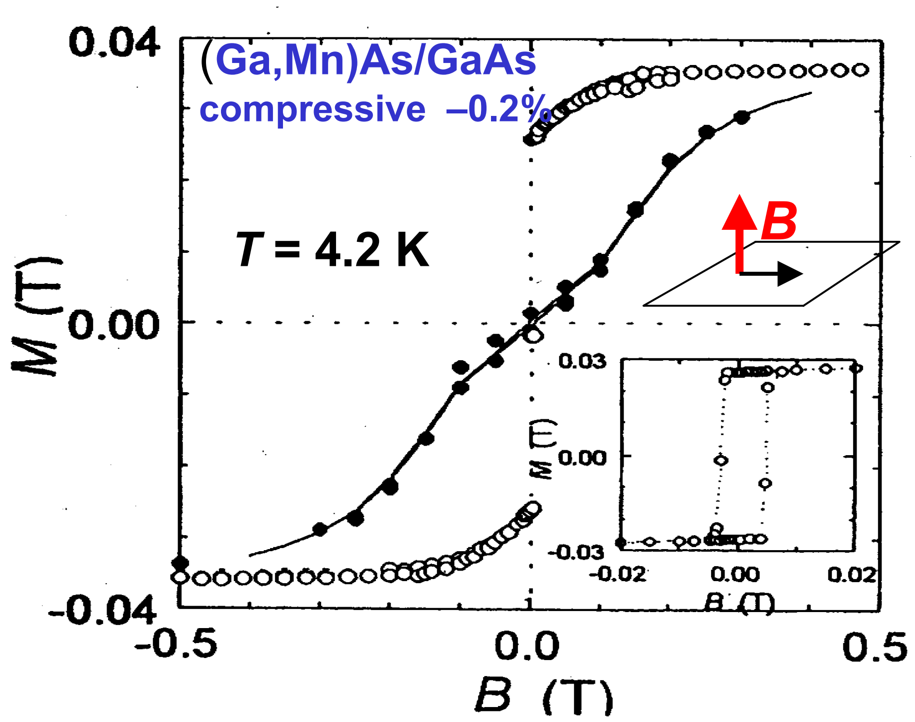


after T.D. et al. (Warsaw, Tohoku) PRB '01

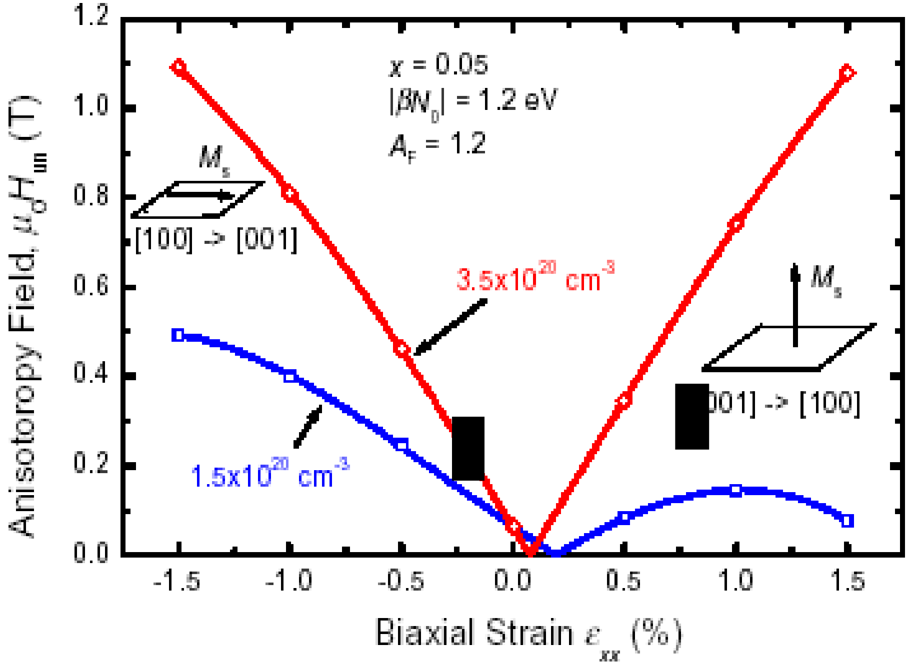


Sawicki et al.'(Warsaw, Wuerzburg)'04

Uniaxial anisotropy engineering by strain



F. Matsukura et al.



theory *T.D. et al., PRB '01*
exp. FMR *Liu et al.'03*
M(H) *Munekata et al.'93,*
Matsukura et al., Ferre et al.

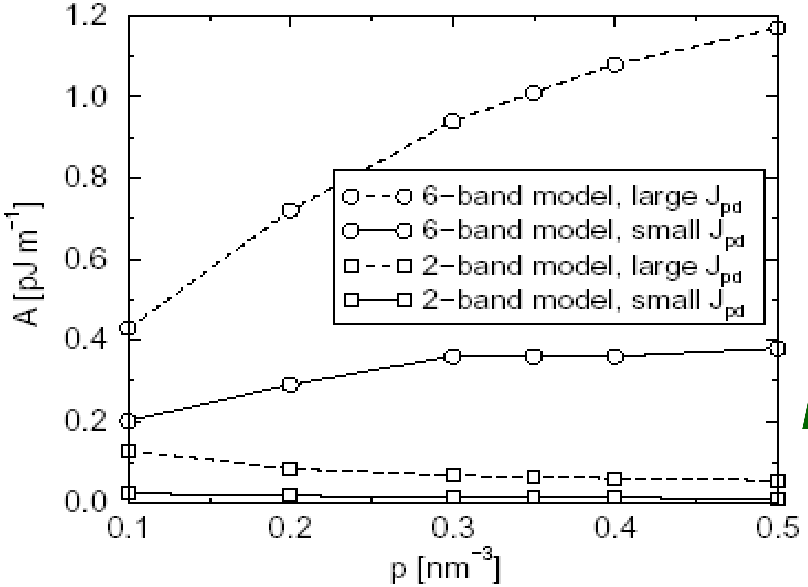
- (Ga,Mn)As/GaAs compressive strain => easy axis in plane
- (Ga,Mn)As/(Ga,In)As tensile strain => easy axis out of plane

Magnetic stiffness

$$\mathcal{F}[\mathbf{M}(\mathbf{r})] \rightarrow \mathcal{F}[\eta_q] = |\eta_q|^2(a + cq^2)$$

spin wave dispersion $\Omega(q) = 2g\mu_B(K_u + Aq^2)/M$

domain width $\lambda_c = 4(AK_u)^{1/2}/\mu_o M^2 d$

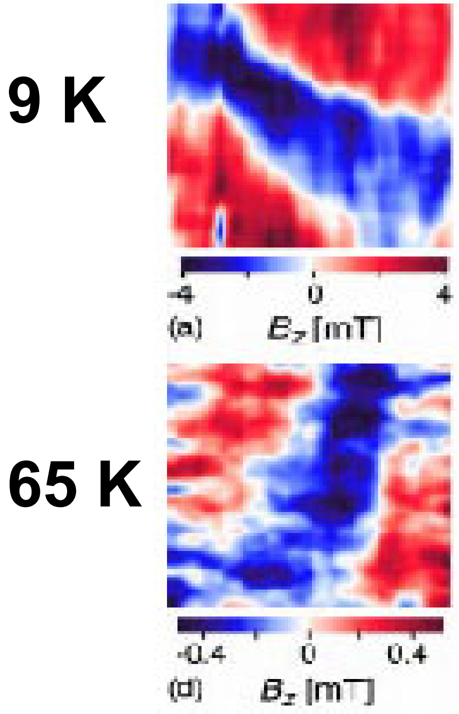


Koenig et al., PRB'01

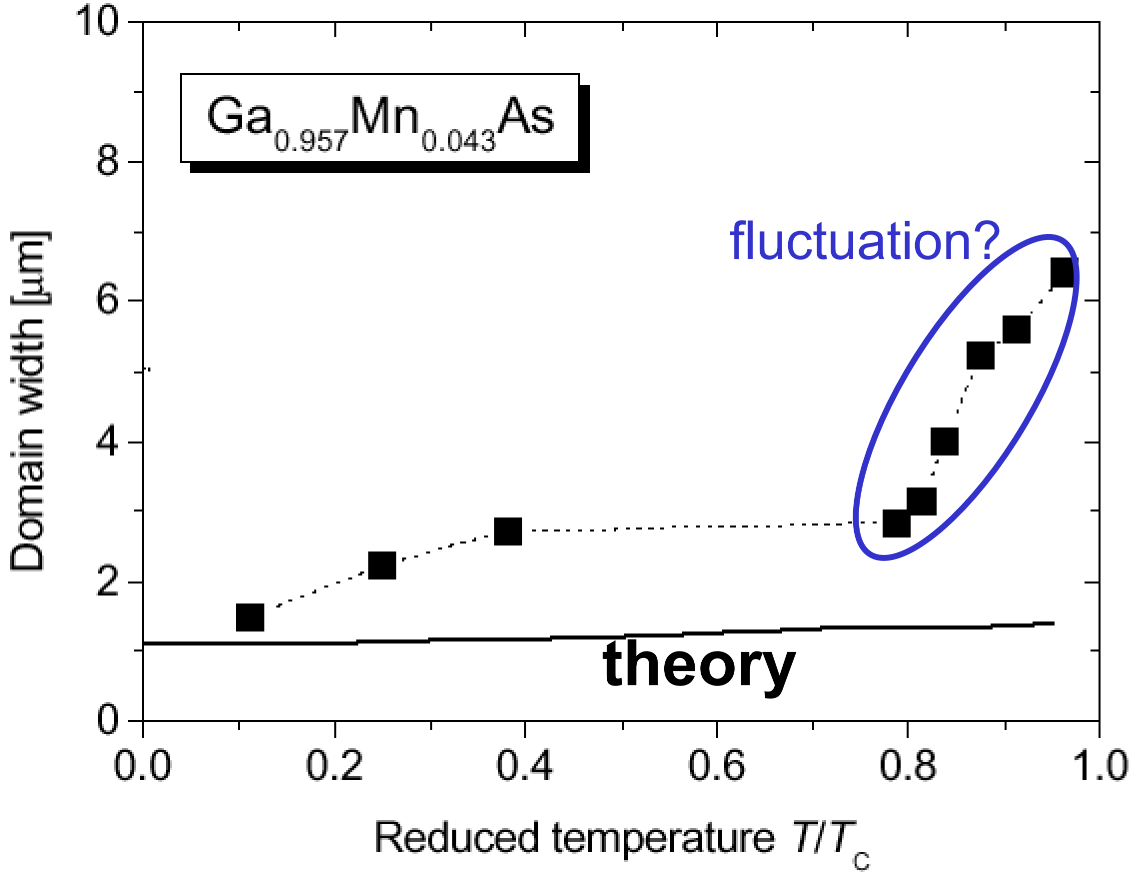
Tenfold enhancement of *A* by:
p-type symmetry of LK amplitudes
➔ accounts for excellent micromagnetic properties

Stripe domains in (Ga,Mn)As perpendicular films

domain walls
[110] → [100]

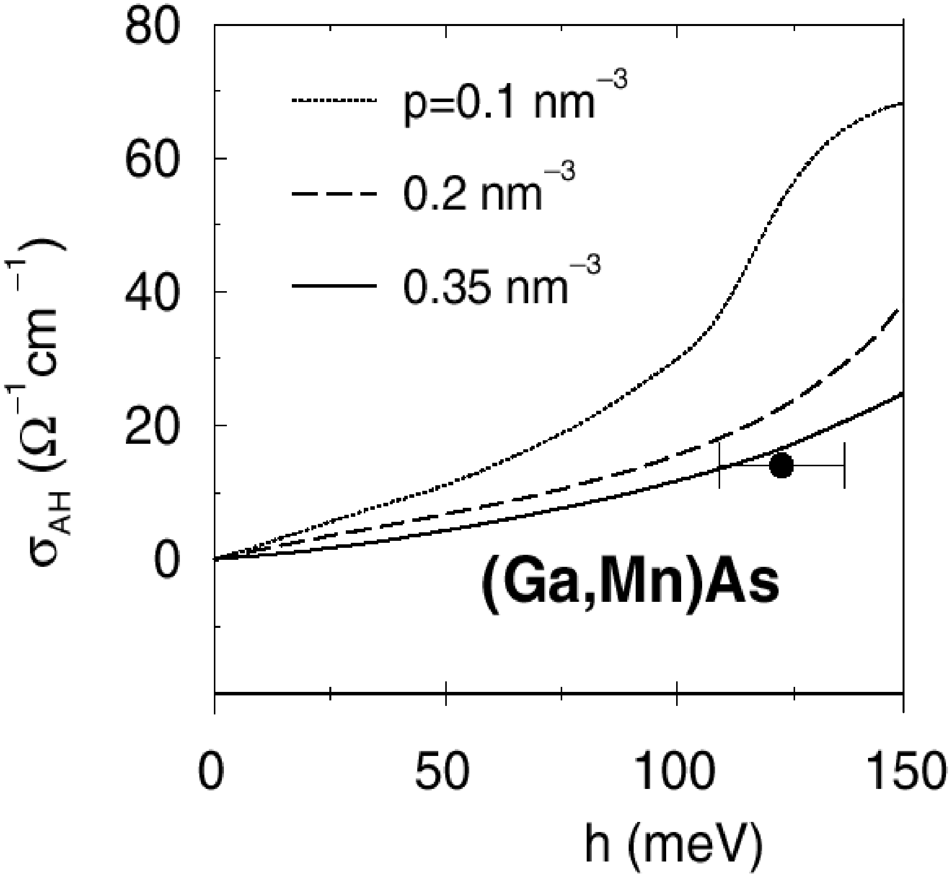


Shono et al.

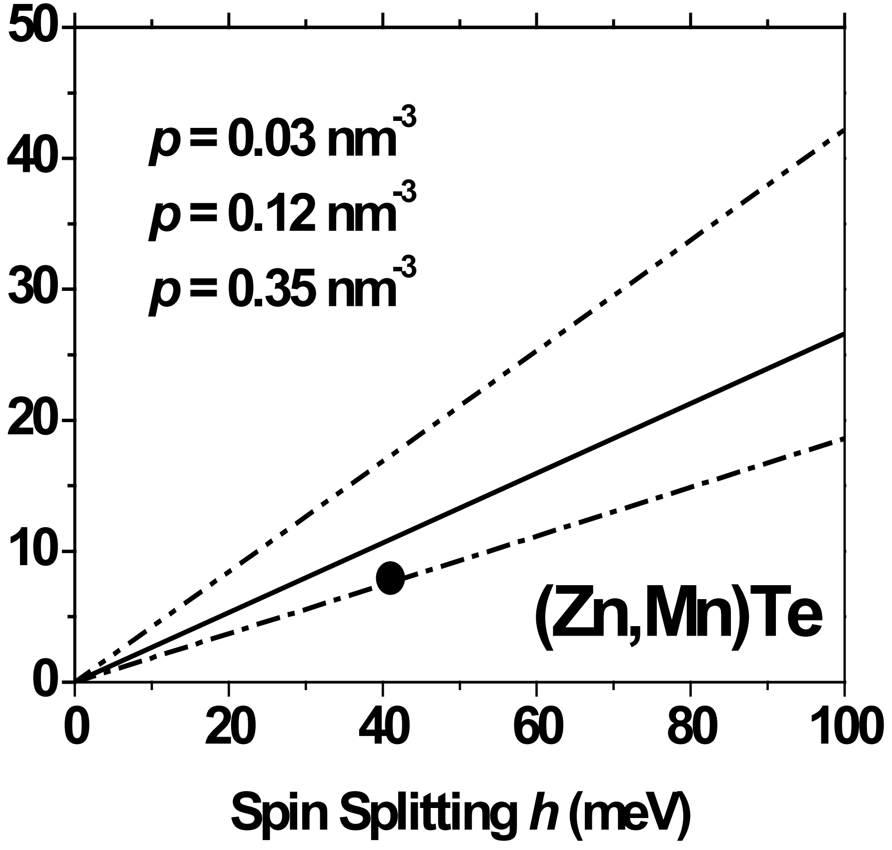


T.D. et al., PRB’01

Anomalous (spin) Hall effect
side jump mechanism – scattering independent



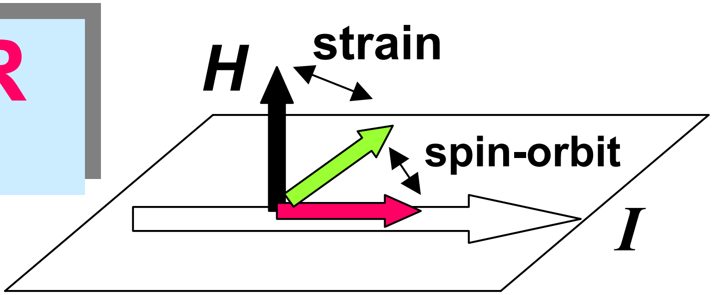
T. Jungwirth et al. PRL’02

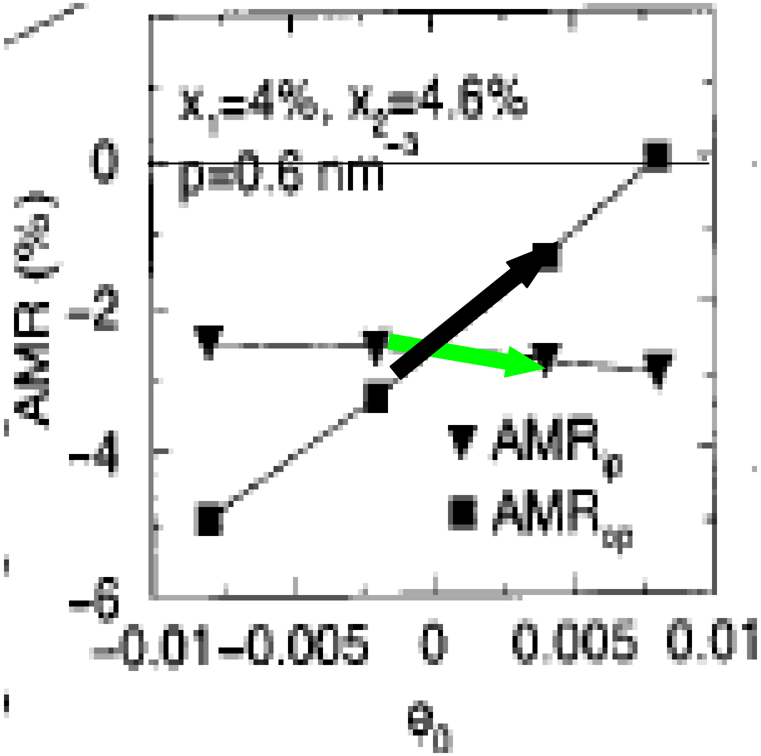


T.D. et al., Les Houches’02

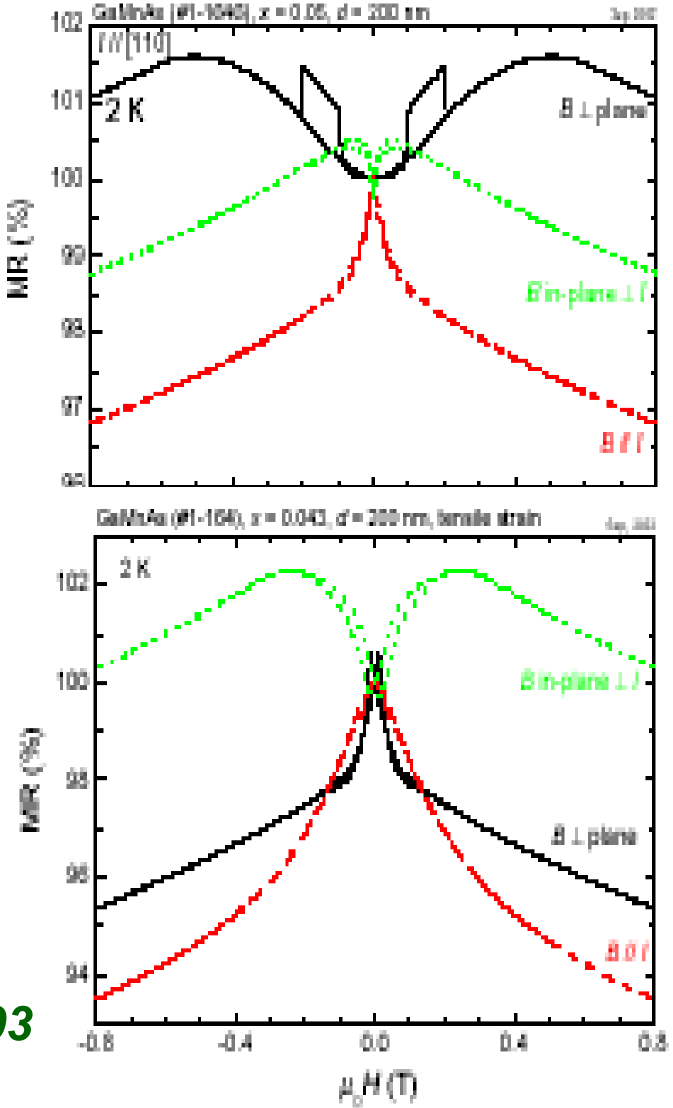
Transport properties: AMR

relaxation time approximation





T. Jungwirth et al., APL'02



$x = 0.05$
compressive
$\varepsilon \approx -0.002$

$x = 0.043$
tensile
$\varepsilon \approx 0.002$

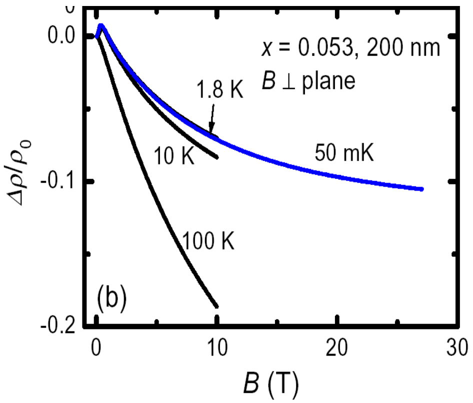
F.Matsukura, …, T.D.' 03

Transport: effects of Anderson-Mott (quantum) localization

not accounted for by Born approximation, CPA; important for $k_F l \approx 1$

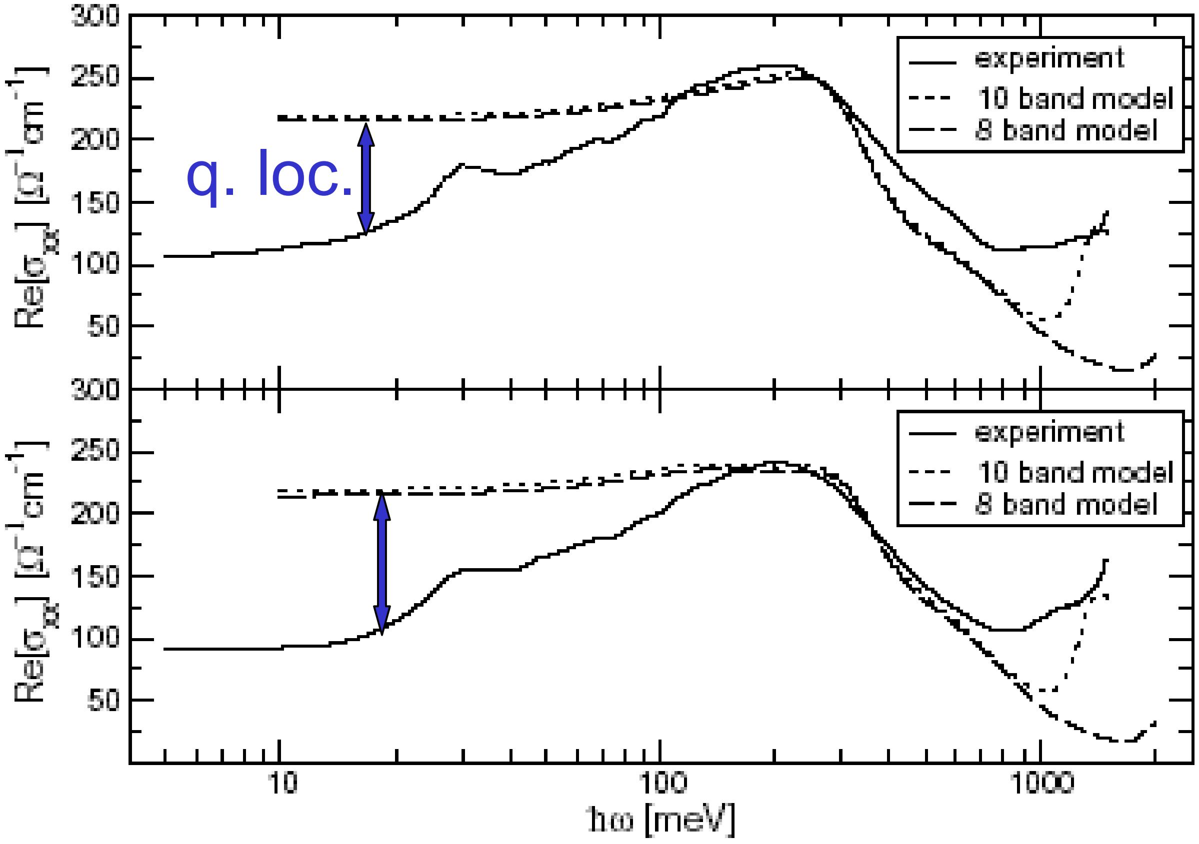
- **reduction of conductivity**
- **enhancement of localization by spin disorder scattering**
- **corrections to the Drude conductivity, $\sigma = \sigma_o + b\omega^{1/2}$**
- **upturn of resistance at $T \rightarrow 0$, $\rho = \rho_o - mT^{1/2}$**
- **negative magnetoresistance, $\rho = \rho_o - aB^{1/2}$**

Kawabata: $\Delta\rho/\rho = -n_v e^2 C_o \rho (eB/\hbar)^{1/2}/(2\pi^2\hbar)$; = 0.10



T.D. et al., Les Houches'02

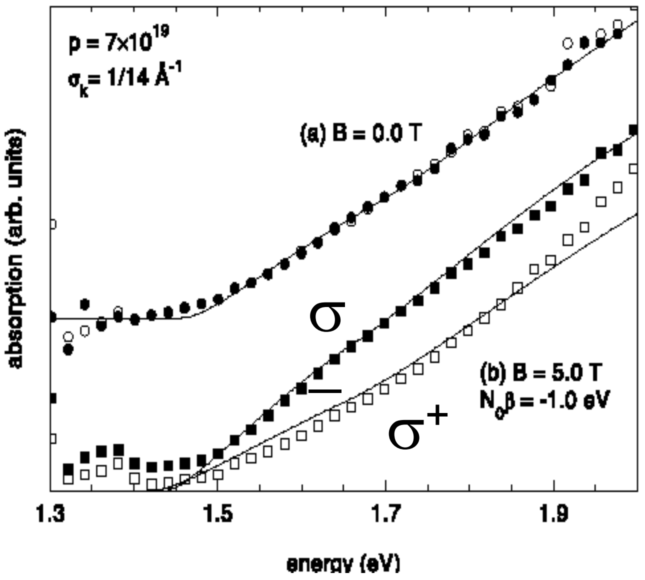
a.c. conductivity, 8x8 model



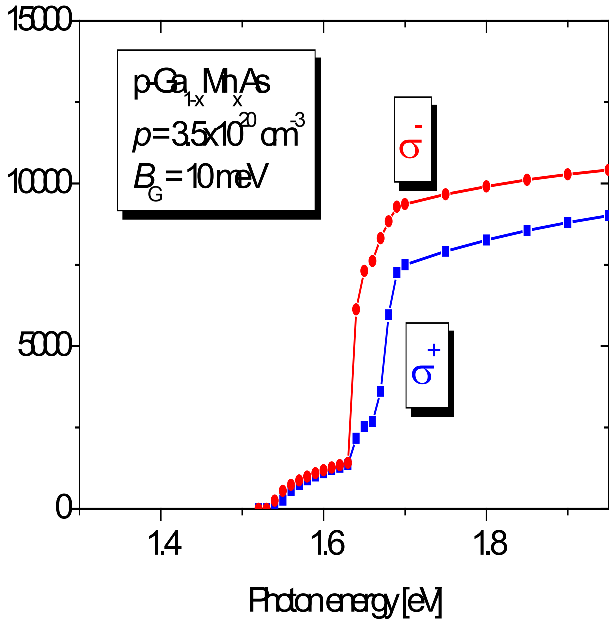
E. Hankiewicz, …T. D, …, PRB'04

Magnetoabsorption, sign of MCD

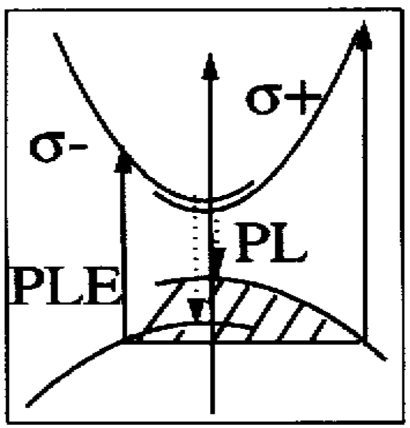
expl. **theory**



Szczytko et al. PRB'00



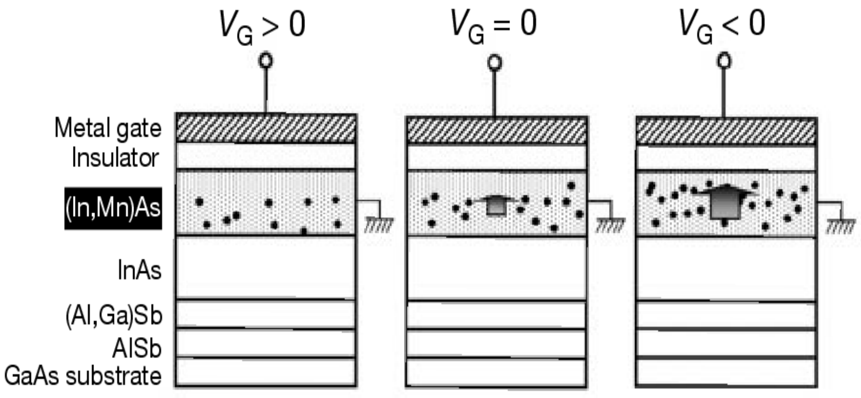
T.D. et al., PRB '01

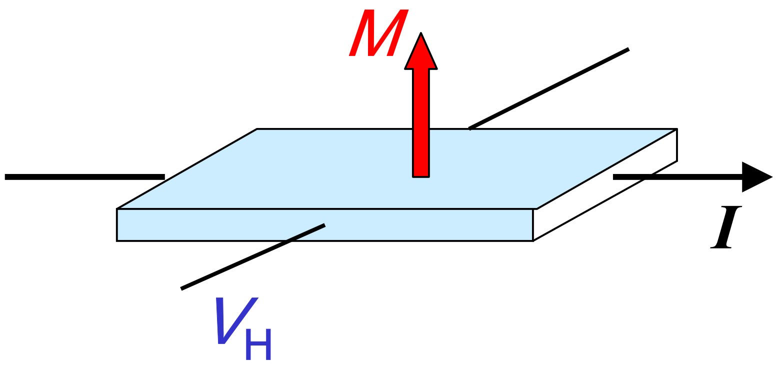


Moss-Burstein shift => positive sign of MCD

Spintronic functionalities

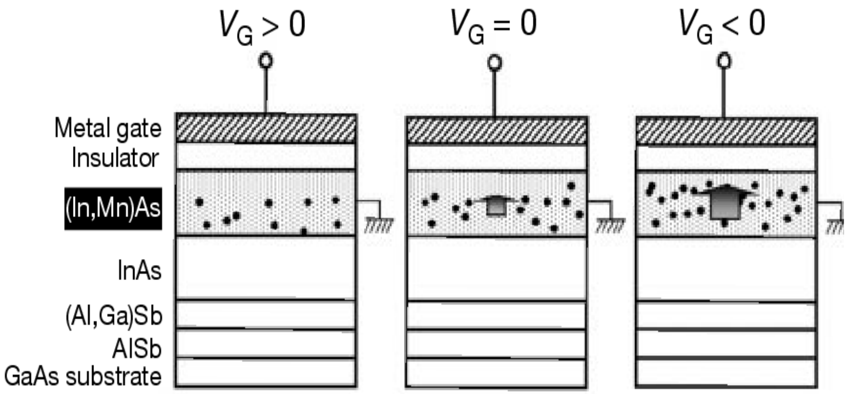
Tuning of magnetic ordering by electric field (ferro-FET) (In,Mn)As

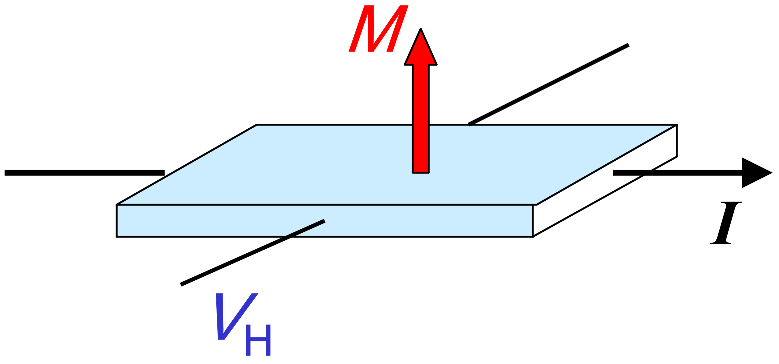


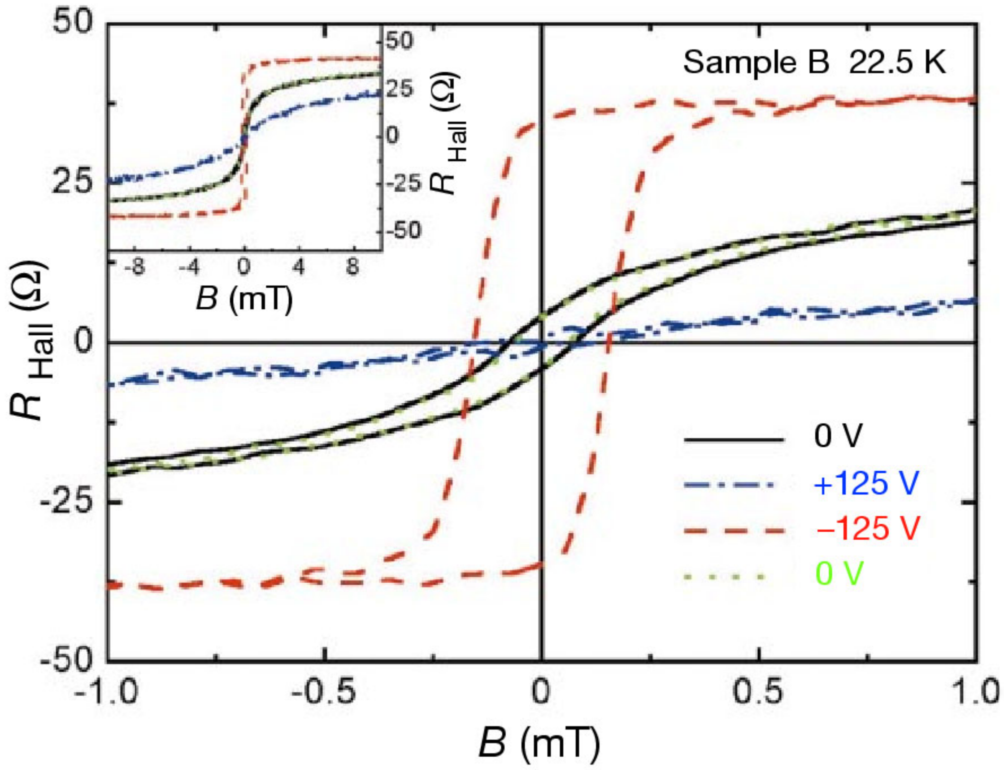


Ohno et al. (Tohoku, Warsaw) Nature ‘00

Tuning of magnetic ordering by electric field (ferro-FET) (In,Mn)As

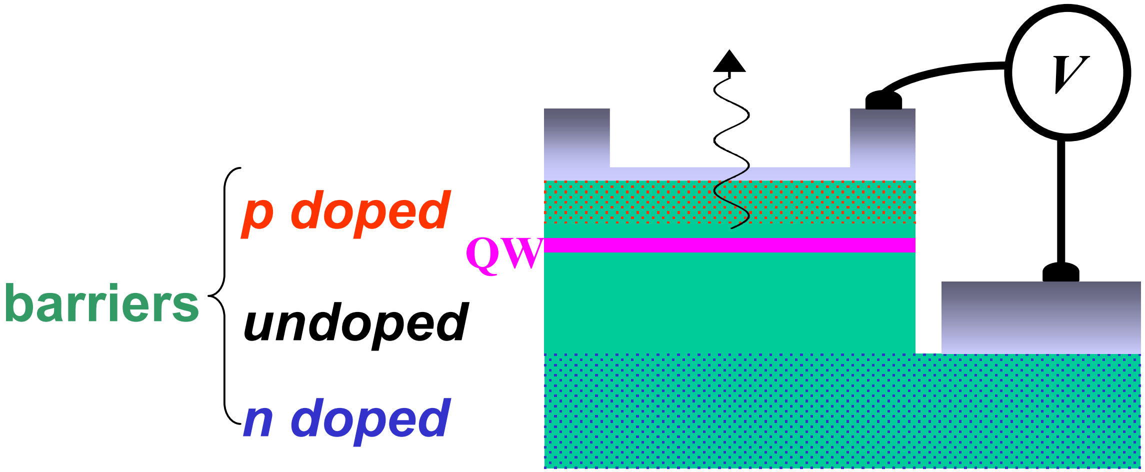




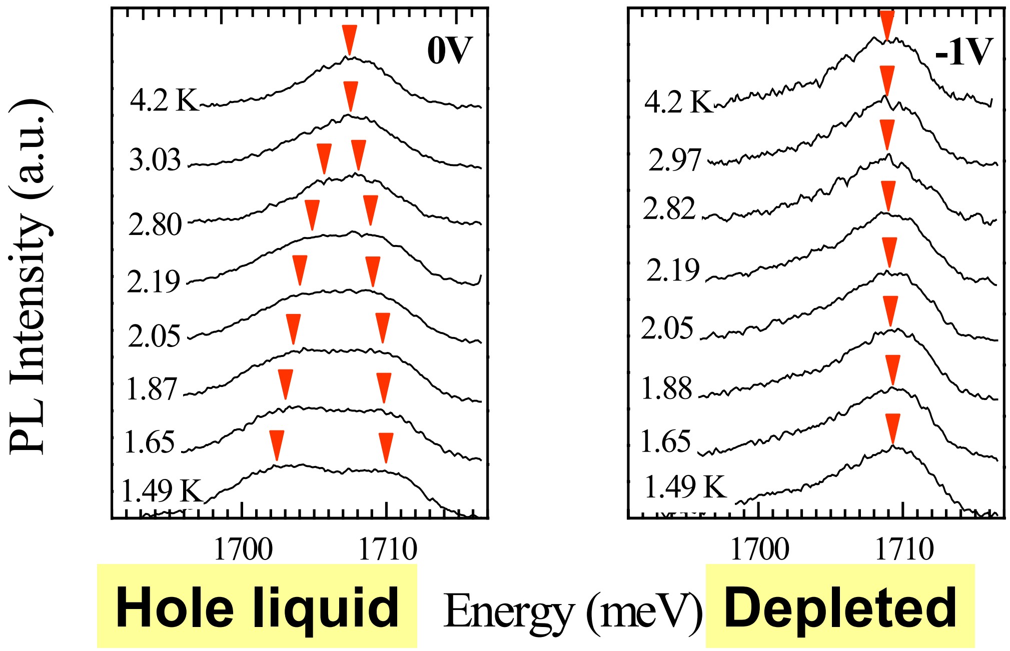


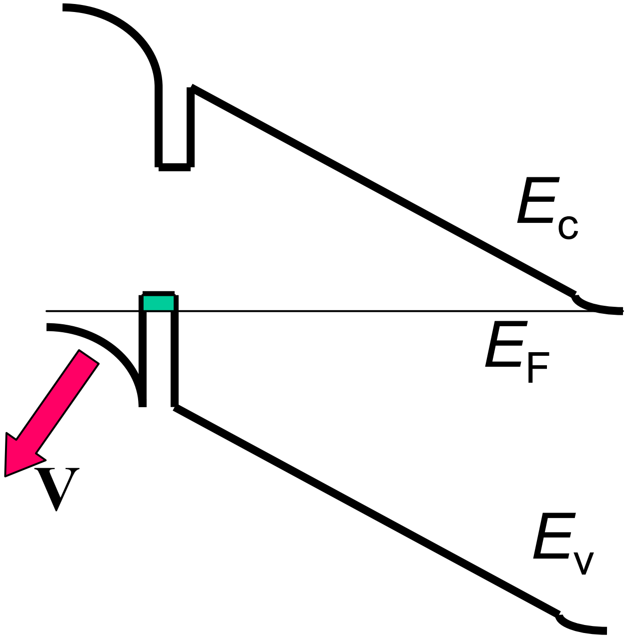
Ohno et al. (Tohoku, Warsaw) Nature ‘00

Hole-induced ferromagnetism in a *pin* diode – ferro-LED (Cd,Mn)Te



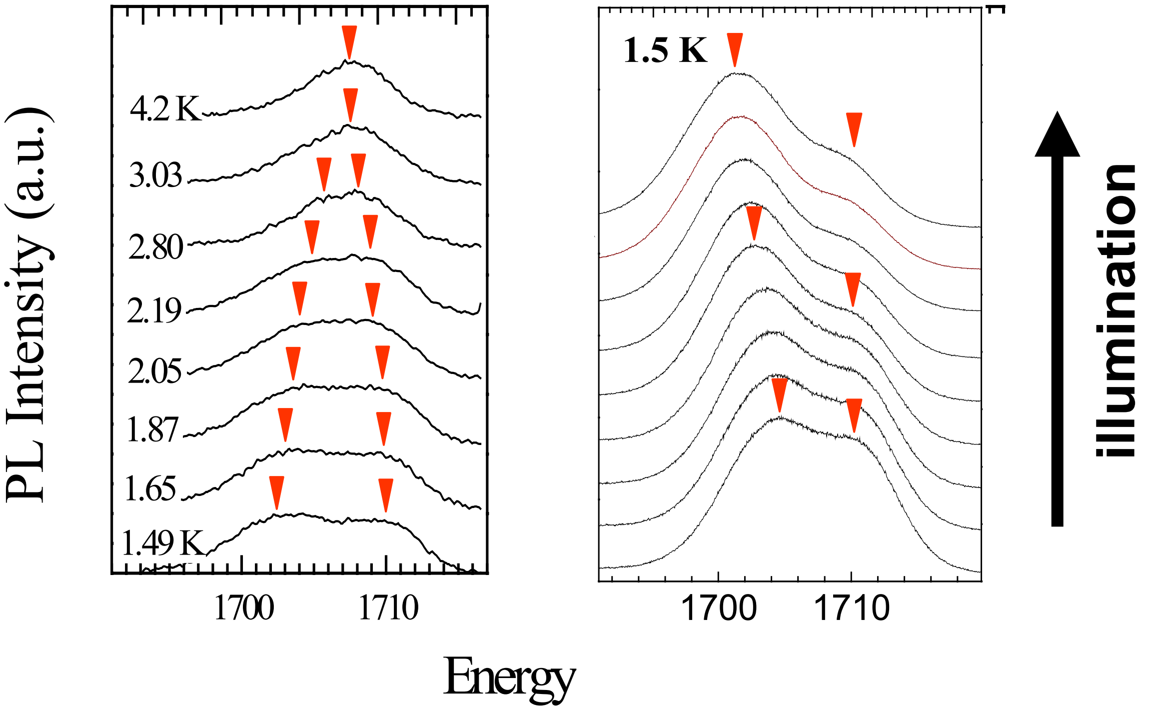
Photoluminescence

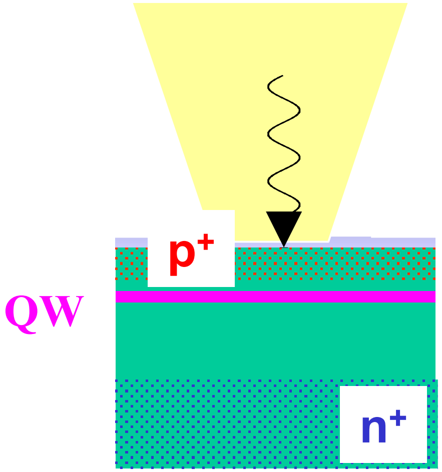


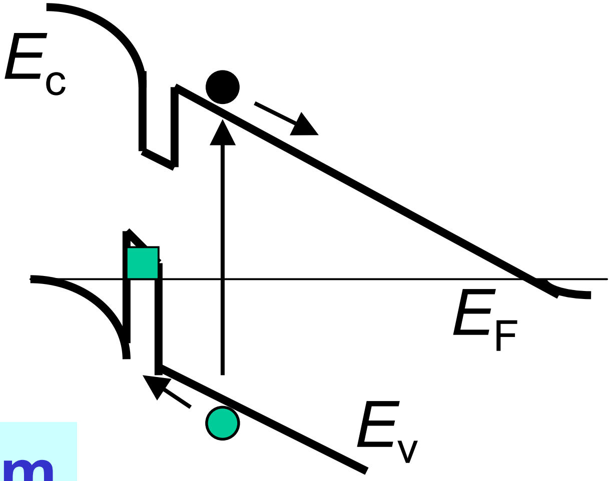


Boukari et al. (Grenoble, Warsaw) PRL'02

Effect of illumination in (Cd,Mn)Te p-i-n diode



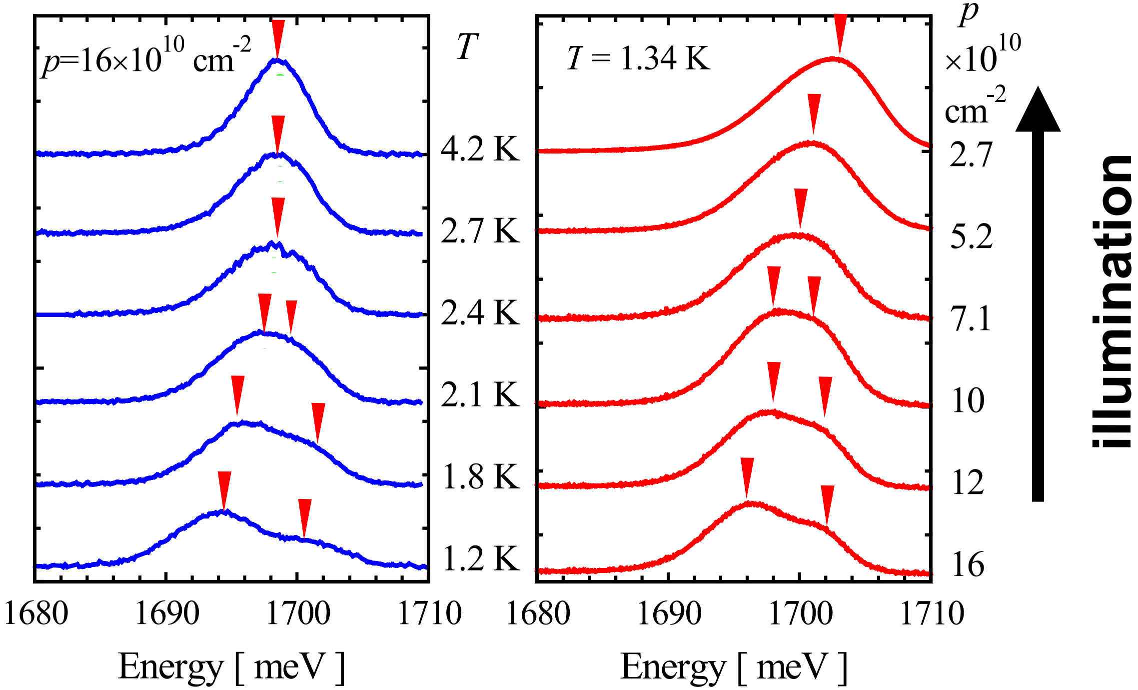




Boukari et al. (Grenoble, Warsaw) PRL'02

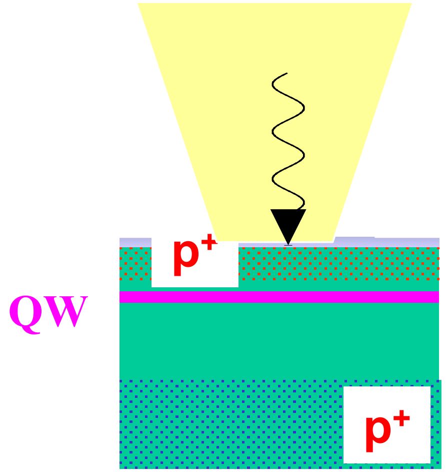
Enhancement of ferromagnetism

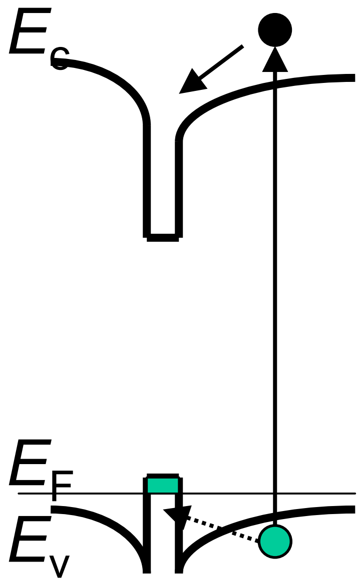
Effect of illumination in (Cd,Mn)Te p-i-n diode



p = const

***T* = const**

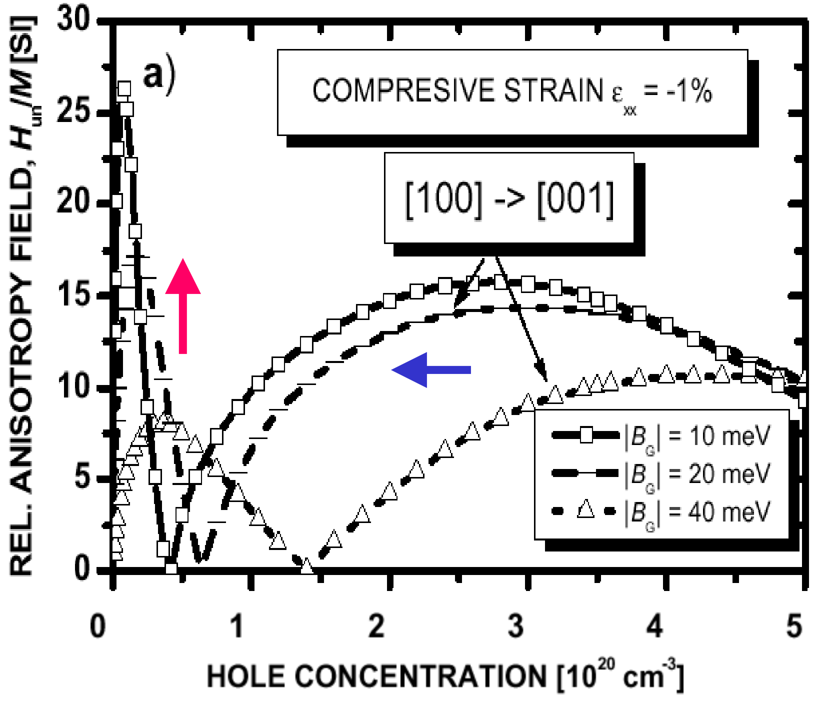




Boukari et al. (Grenoble, Warsaw) PRL'02

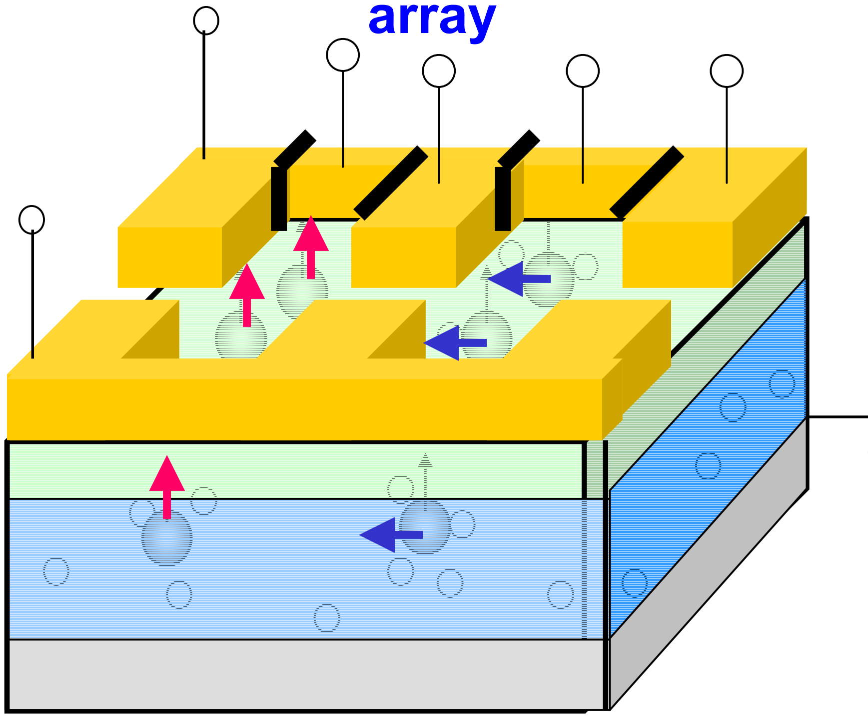
Destruction of ferromagnetism

Controlling quantum magnetic dots



GATE VOLTAGE

Ferromagnetic quantum dot array



to be demonstrated

Pushing T_c higher

Strategies

- **Two strategies for pushing T_C higher**

  -- increasing *p* and/or *x* in existing ferromagnetic DMS

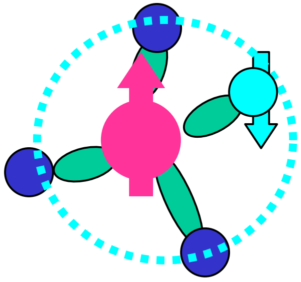
  -- searching for DMS with greater coupling constant $\beta^2\rho(E_F)$

- **Obstacles**

  -- self-compensation

  -- solubility limits

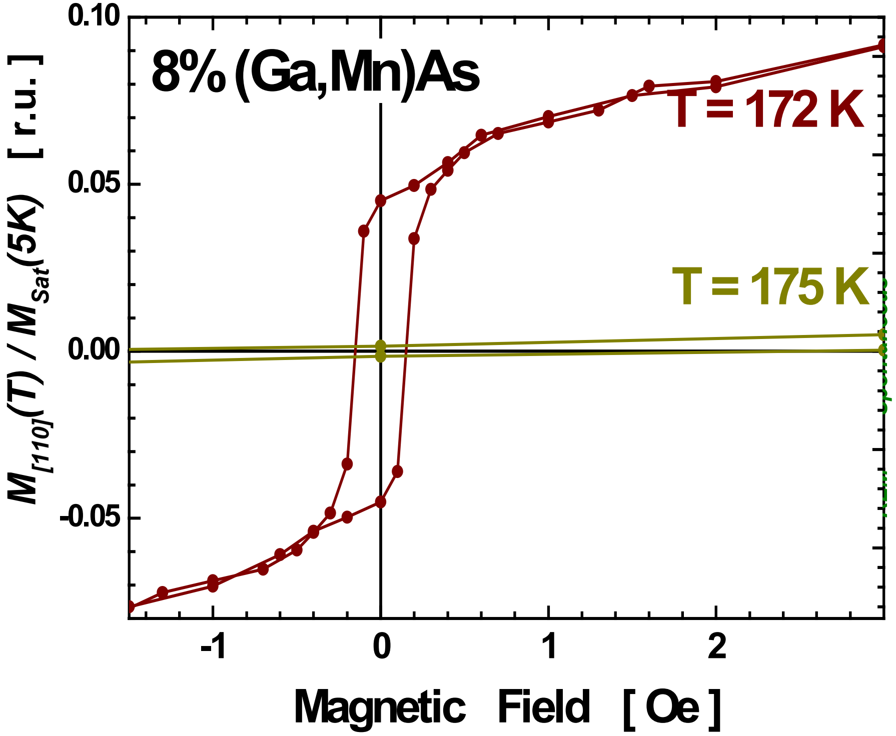
  -- tight binding of holes by TM ions
  (Zhang-Rice polaron)



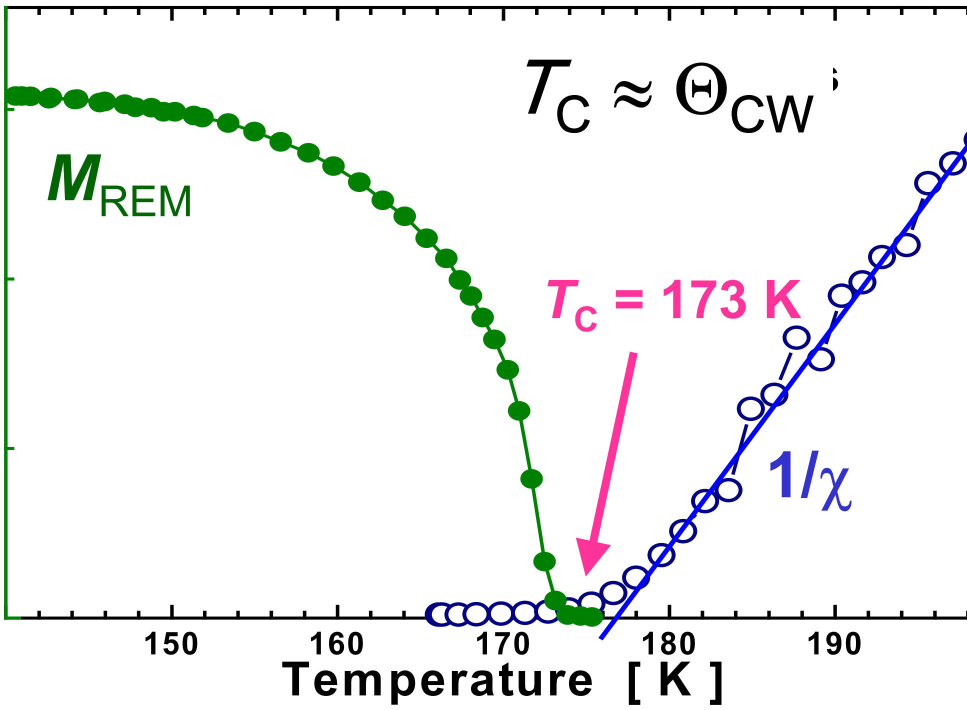
T.D. et al. (Warsaw, Tohoku, Grenoble) Science'00

Where are we?

hysteresis loops

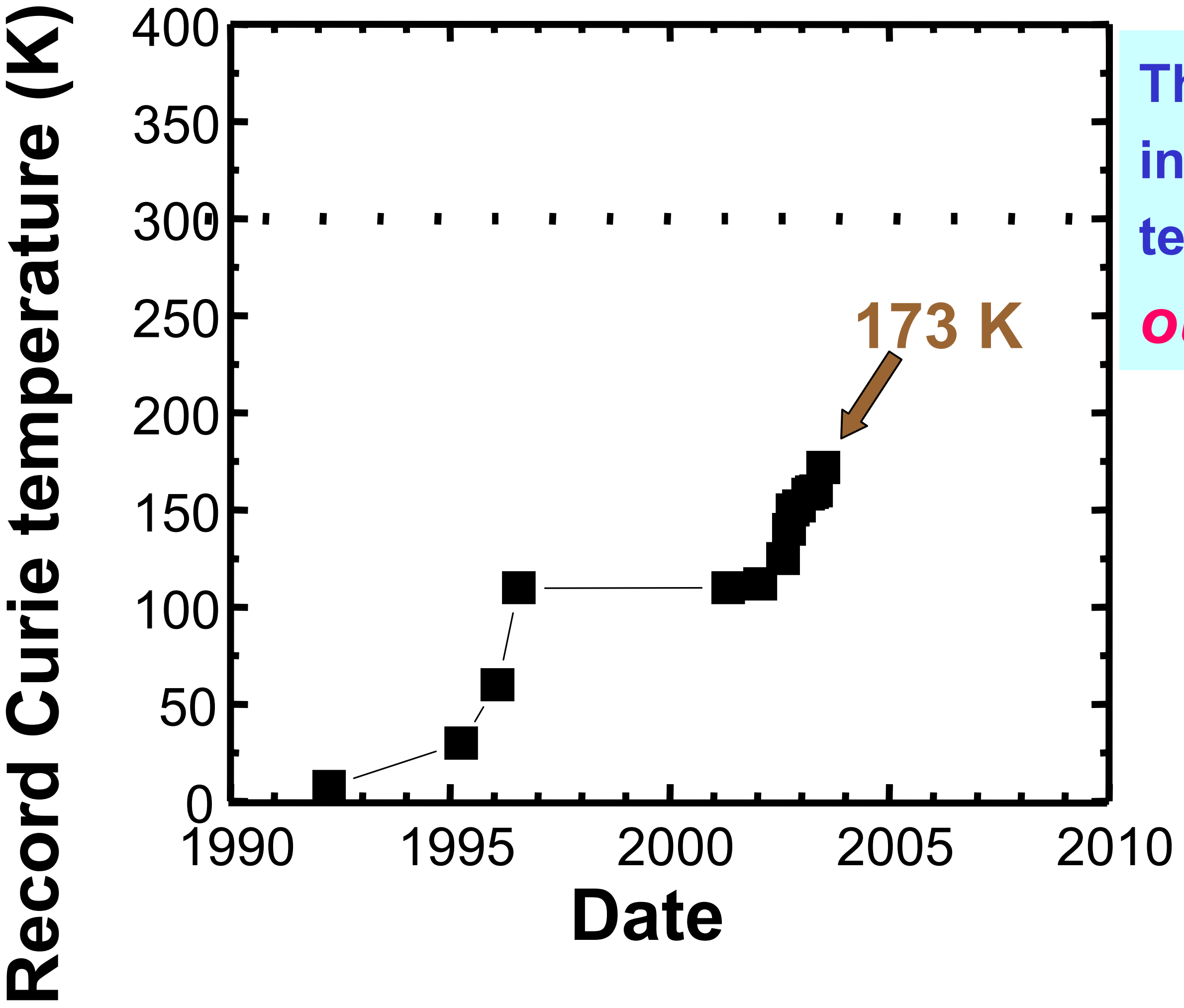


remanent magnetization and $1/\chi$ vs. T



Wang , T.D. et al. (Nottingham, Warsaw) ICPS'04

T_C in (III,Mn)As



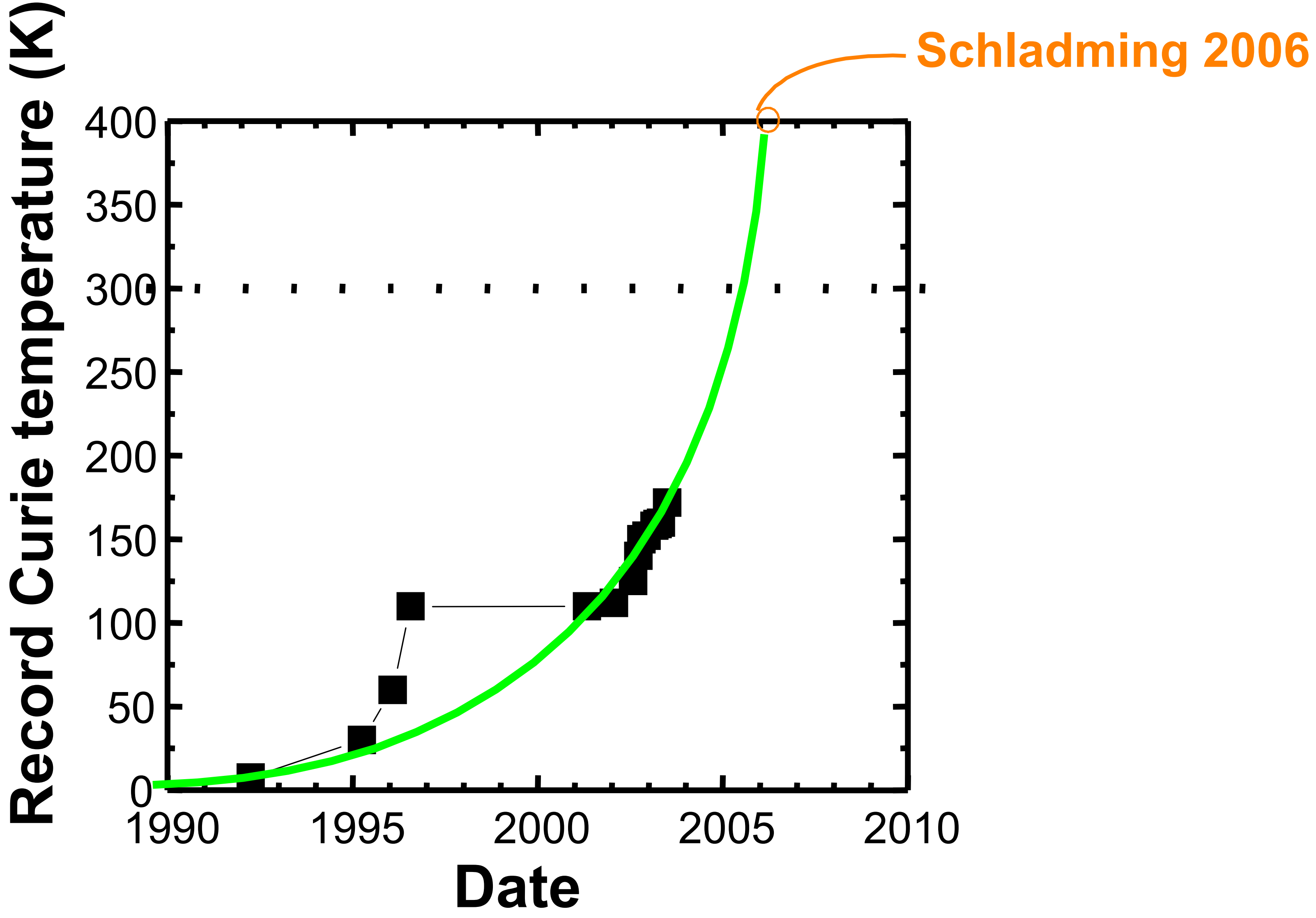
The progress due to increase of *p* by low temperature annealing→ ***out diffusion of Mn_I:***

Yu et al. (Berkeley, Notre Dame, Warsaw) ICPS'04

Edmonds T.D. et al. (Nottingham, Warsaw) PRL'04

data: IBM, Tohoku, Tokyo, Notre Dame, PSU, Tohoku, Nottingham

T_C in (III,Mn)As



OTHER SYSTEMS

Materials showing hysteresis and spontaneous magnetization at 300 K

wz-c-(Ga,Mn)N, (In,Mn)N, (Ga,Cr)N, (Al,Cr)N, (Ga,Gd)N,

(Ga,Mn)As, (In,Mn)As, (Ga,Mn)Sb, (Ga,Mn)P:C

(Zn,Mn)O, (Zn,Ni)O, (Zn,Co)O, (Zn,V)O, (Zn,Fe,Cu)O

(Zn,Cr)Te

(Ti,Co)O_2, (Sn,Co)O_2, (Sn,Fe)O_2, (Hf,Co)O_2

(Cd,Ge,Mn)P_2, (Zn,Ge,Mn)P_2, (Zn,Sn,Mn)As_2

(Ge,Mn)

(La,Ca)B_6, C_{60}, …

In many cases high T_C consistent with *ab initio* computations within DFT

- None proven to be 300 K ferromagnetic semiconductor
- Each brings new challenges