International Conference and School on Spintronics and Quantum Information Technology (Spintech VI)
School Lecture 2 "Diluted Magnetic Semiconductors"
Matsue, Japan, August 1, 2011

Diluted Magnetic Semiconductors

- An Introduction -

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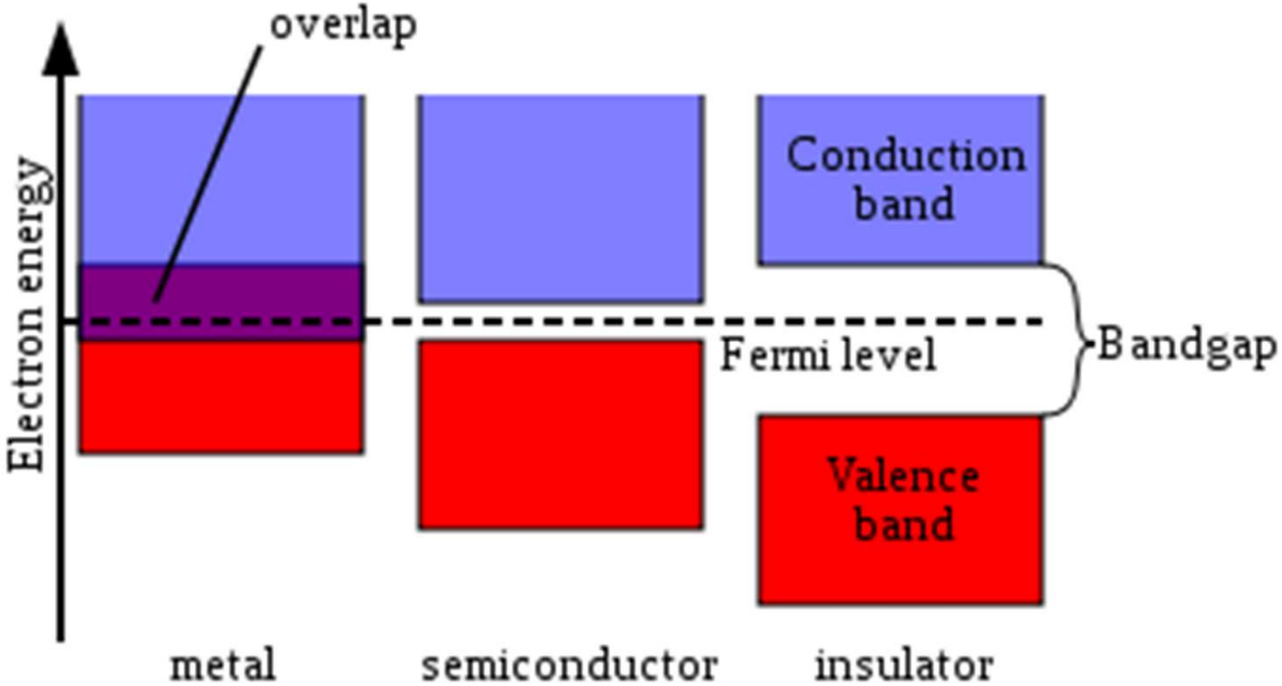
1. What you need to know about nonmagnetic semiconductors
   - Band structure
2. How you make a semiconductor magnetic
   - Doping and *sp-d* exchange
3. The consequences of exchange interaction
   - Spin-split bands and ferromagnetism
4. Making "use" of ferromagnetism in semiconductors
   - Electrical control of ferromagnetism
   - Current induced domain wall motion
   - Tunneling with magnetism

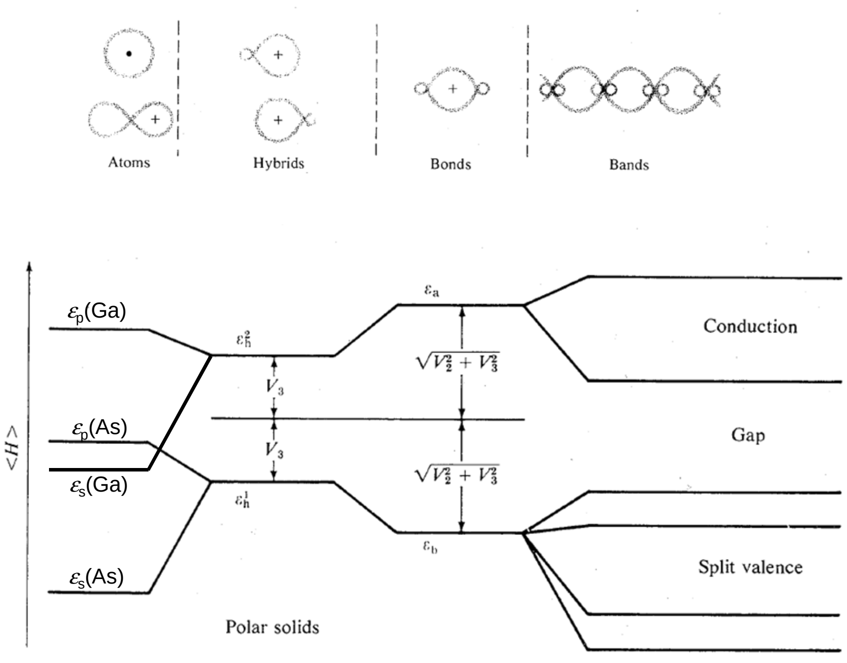
I am indebted to lecturers of earlier Spintechs, many collaborators, particularly Tomasz Dietl and Fumihiro Matsukura, for a number of materials used here.

1. What you need to know about nonmagnetic semiconductors

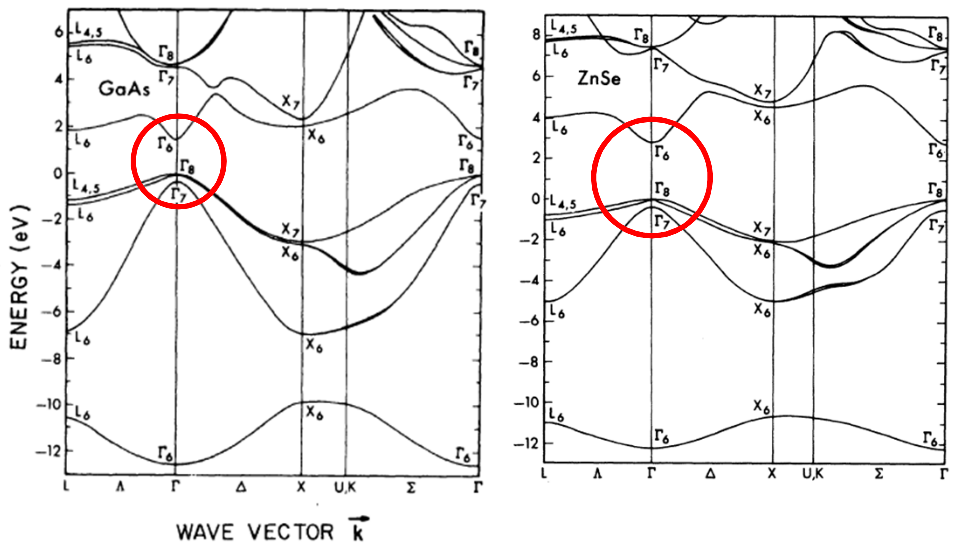
- **Band structure**



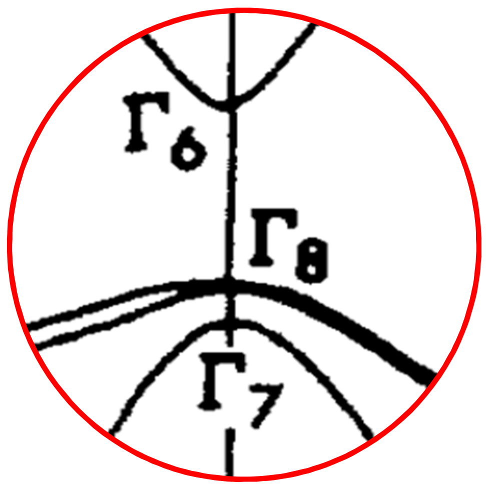
Electronic band structure
From Wikipedia, the free encyclopedia



taken from Walter A. Harrison "Electronic Structure and the Properties of Solids –The Physics of Chemical Bond –, 1980



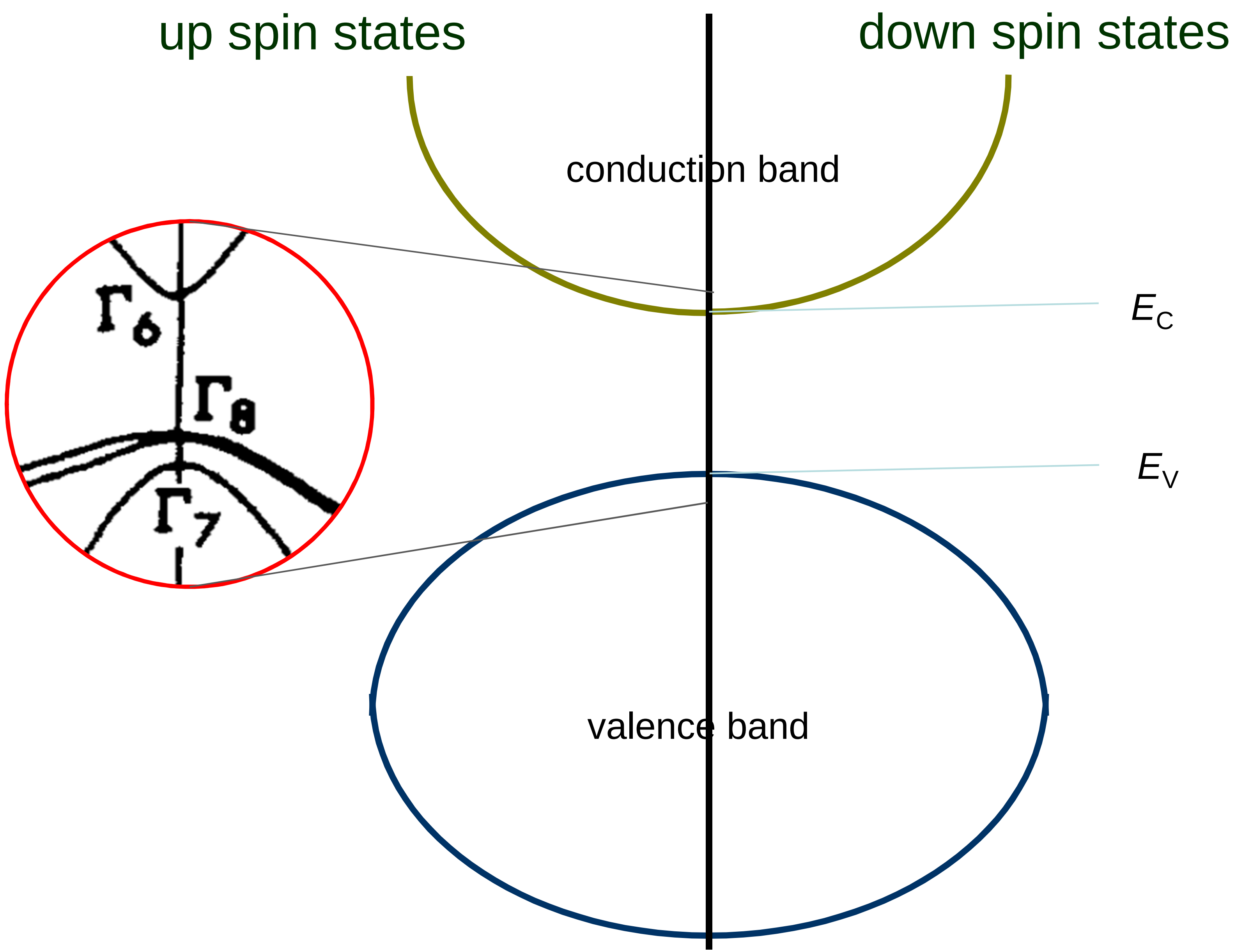
J. R. Chelikowsky and M. L. Cohen, *Phys. Rev.* **B14**, 556 (1976)



Bottom of the conduction band: **Ga 4s**

Top of the valence band: **As 4p**

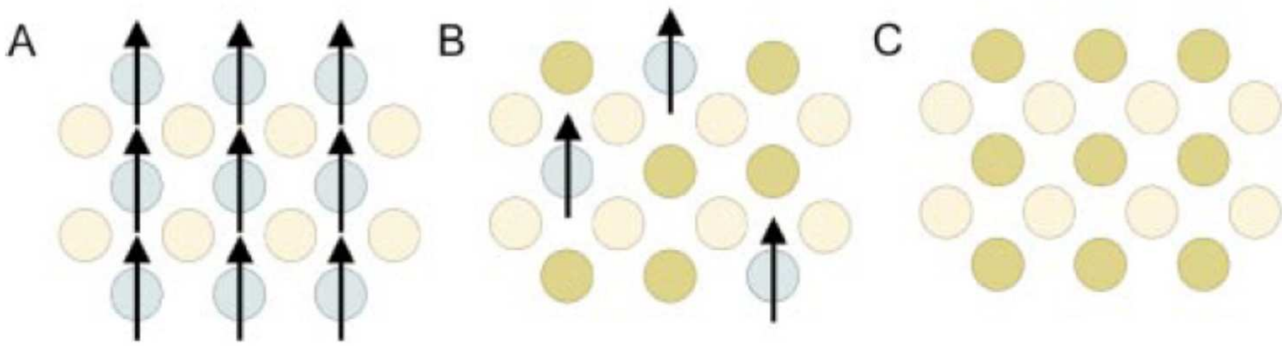
Density of states



2. How you make a semiconductor magnetic

- **Doping and *sp-d* exchange**

Making semiconductor magnetic

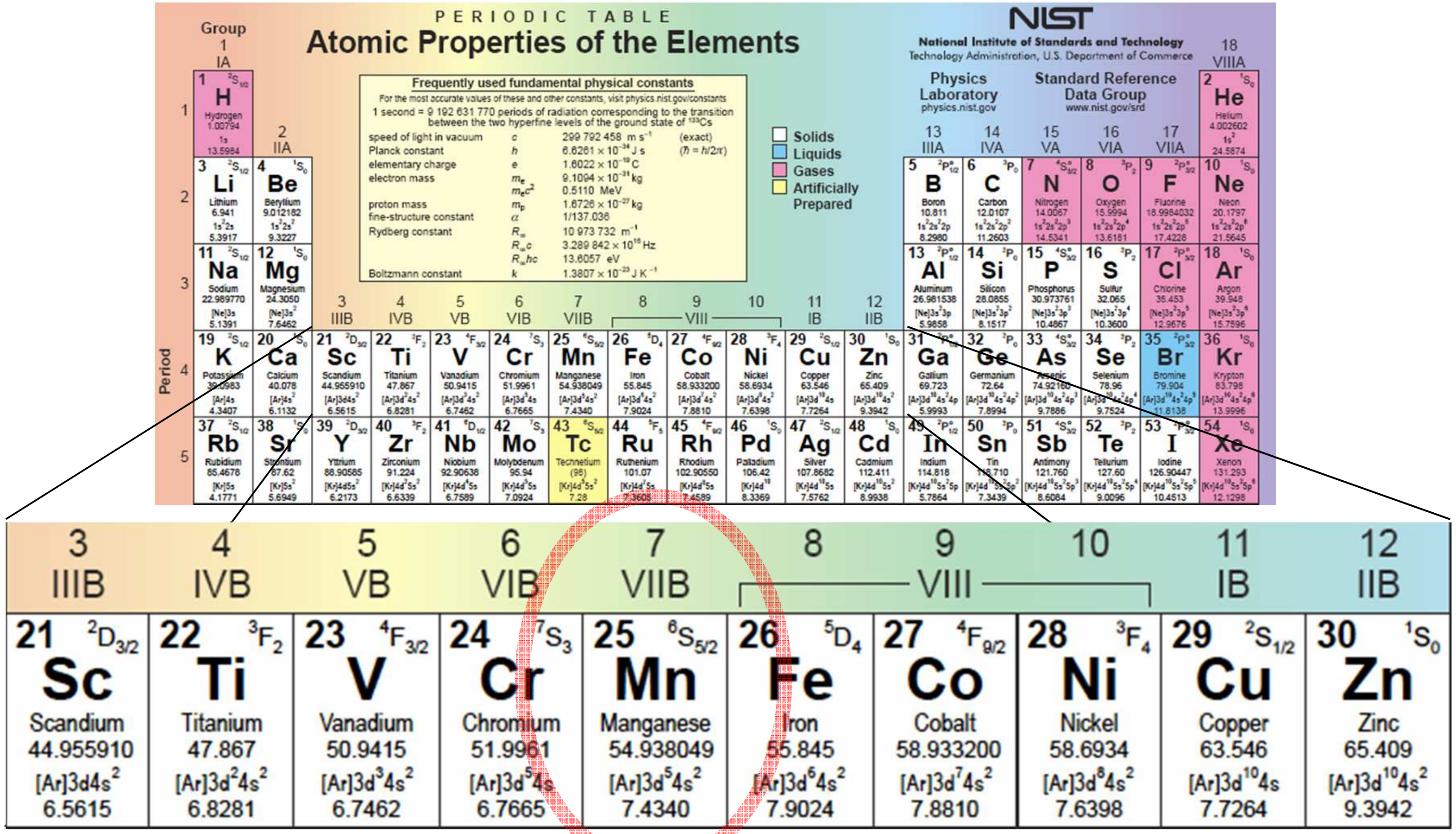


EuS
$CuCr_2Se_4$
…

diluted magnetic semiconductors

Si
III-V
II-VI
…

Magnetic ion: Mn



http://physics.nist.gov

Hund rule: Distributing *n* electrons over 2(2*l*+1) degenerate atomic orbitals, the lowest energy state is the state that maximize the total spin angular momentum *S*

Mn: l=2, n=5 -> S=5/2

Magnetic ion: Mn

- intra site correlation energy $U = E_{n+1} - E_n$

  for n = 5, $U \approx$ 15 eV

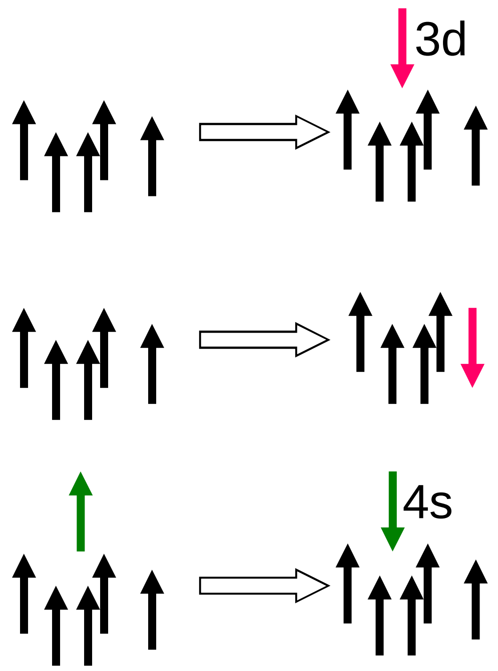
- intra-site exchange interaction: *ferromagnetic*

  Hund's rule: S the highest possible

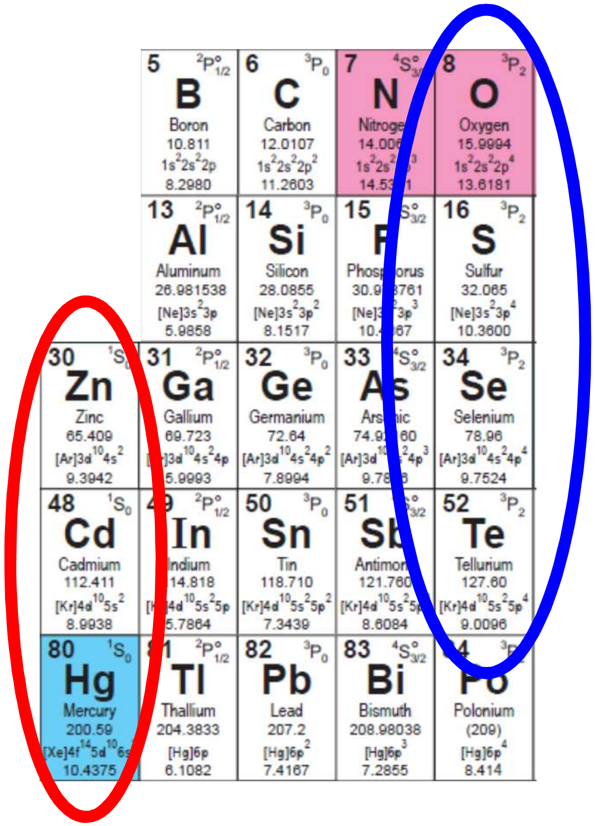
  for $n = 5$, $E_{S=3/2} - E_{S=5/2} \approx$ 2 eV

- transition metal atoms, $3d^n4s^1$, e.g., Mn: *ferromagnetic*

  $E_{S=2} - E_{S=3} \approx$ 1.2 eV ➔ $J_{s\text{-}d} \approx$ 0.4 eV



II-VI Diluted Magnetic Semiconducotors



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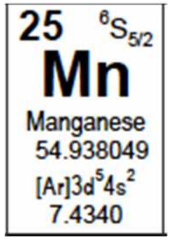

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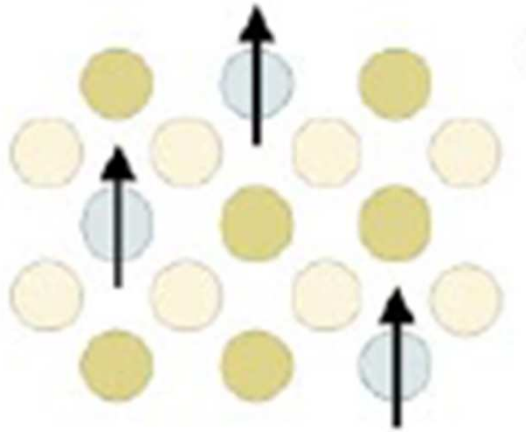
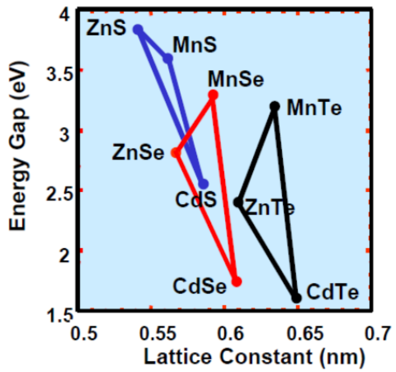
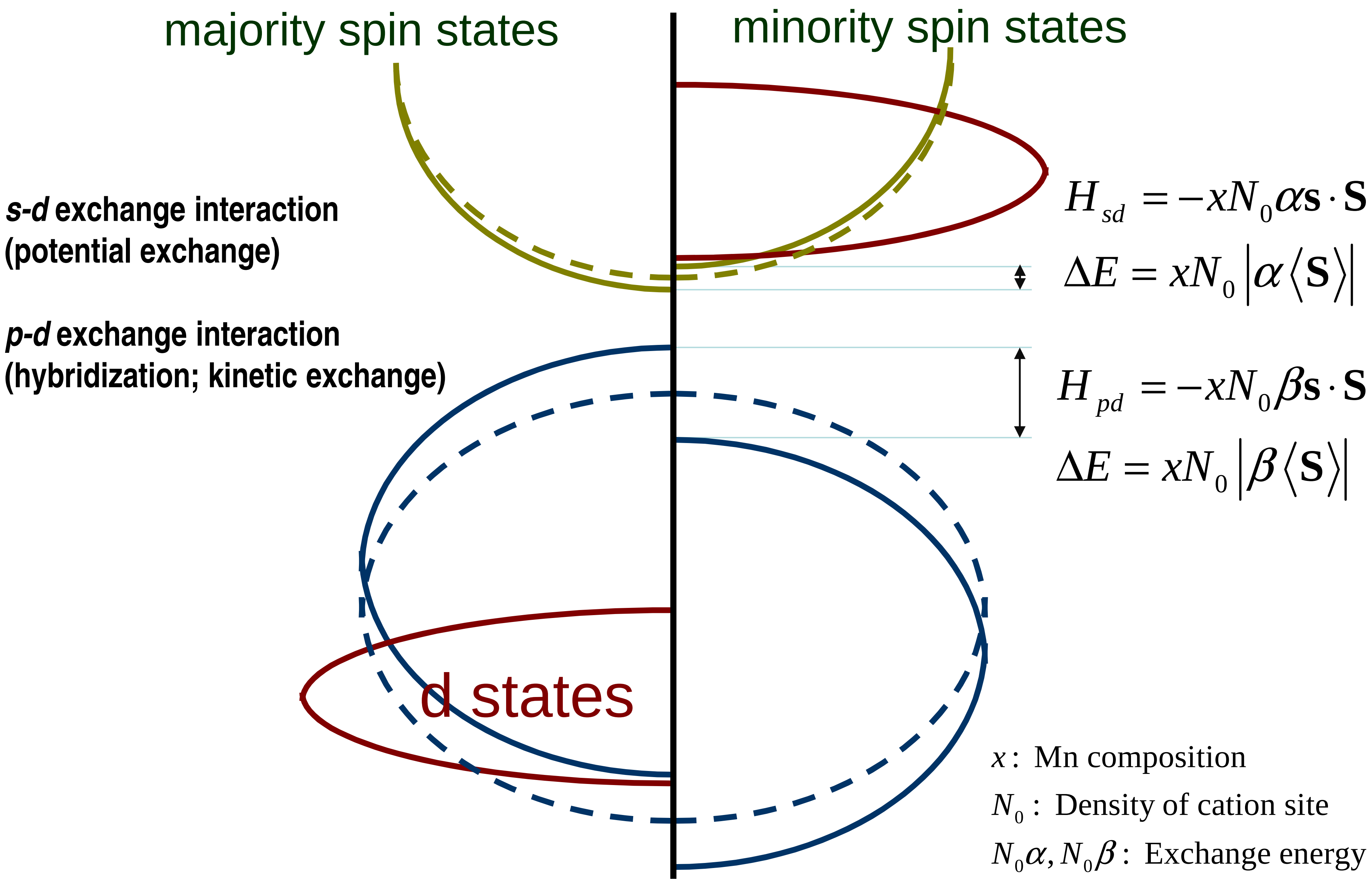
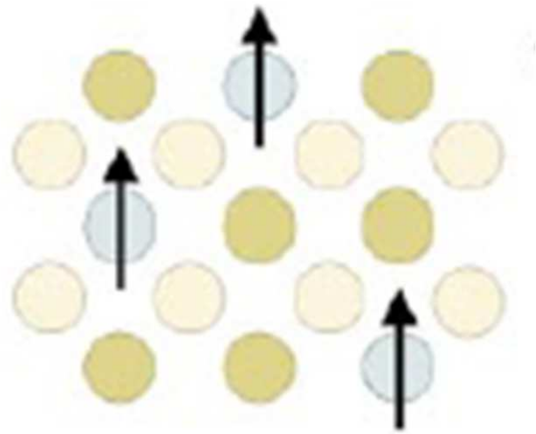
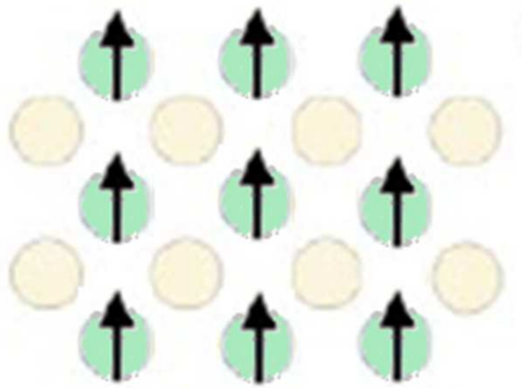




Density of states with transition metal impurity







Virtual crystal approximation $H_n = (1-x)U_0(\mathbf{r}-\mathbf{R}_n) + xU(\mathbf{r}-\mathbf{R}_n) - xJ(\mathbf{r}-\mathbf{R}_n)\mathbf{s}\cdot\mathbf{S}_n$

molecular-field approximation

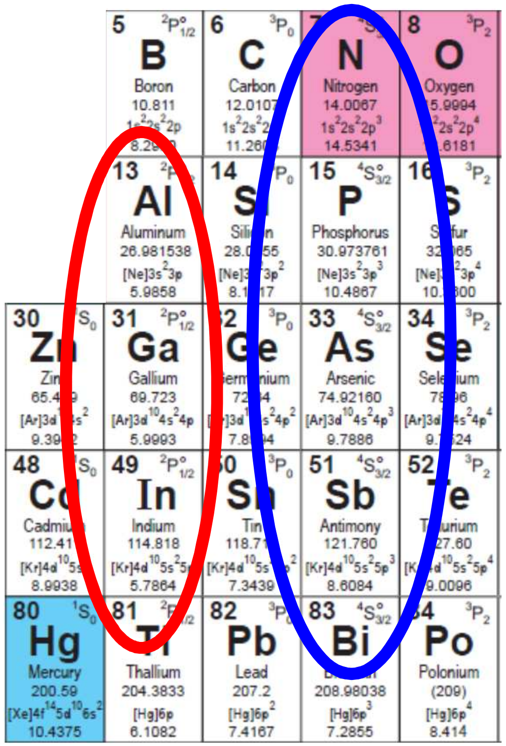
$$\frac{x}{V}\sum_n \mathbf{S}_n \to xN_0\langle\mathbf{S}(\mathbf{r})\rangle$$

$$\to -\frac{\mathbf{M}(\mathbf{r})}{g\mu_B};\quad \mathbf{M}(\mathbf{r}) = -xN_0 g\mu_B\langle\mathbf{S}(\mathbf{r})\rangle$$

mean-field approximation

$$\to -\frac{\mathbf{M}}{g\mu_B};\quad \mathbf{M} = \langle\mathbf{M}(\mathbf{r})\rangle$$

III-V Diluted Magnetic Semiconductors



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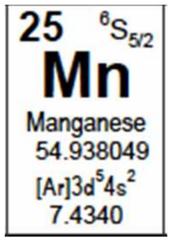

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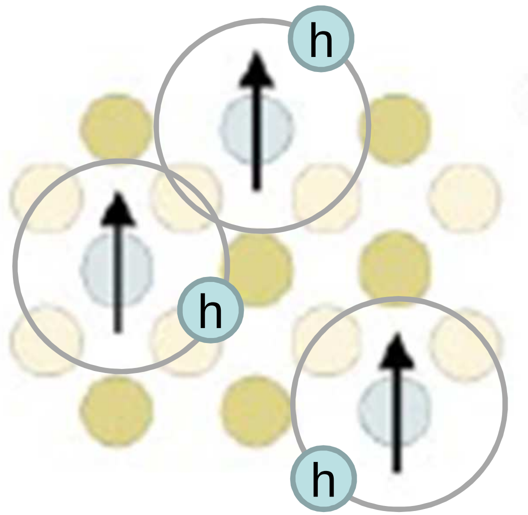


not to scale

(Ga,Mn)As, (In,Mn)As, (Ga,Mn)Sb

Mn in GaAs

Mn on Ga site: 113 meV acceptor

- **d^5+hole (weak coupling) ←**
- d^4
- d^5+hole (strong coupling)

from spectroscopy

$$H = T - \frac{e^2}{\varepsilon r} - V_0 \exp\left(-\left(\frac{r}{r_0} \right)^2 \right) - x N_0 \beta \mathbf{s} \cdot \mathbf{S}$$

$N_0\beta$ = -0.9 eV

kinetic, Coulomb, central cell correction, *p-d* exchange interaction

theory: Bhattacharjee & C. Benoit a la Guillaume, Solid State Commun. **113**, 17 (2000)
exp: M. Linnarsson et al. Phys. Rev. **B 55**, 6938 (1997)

3. The consequences of exchange interaction

- **Spin-split bands** and ferromagnetism

Magnetization of localized spins – no holes

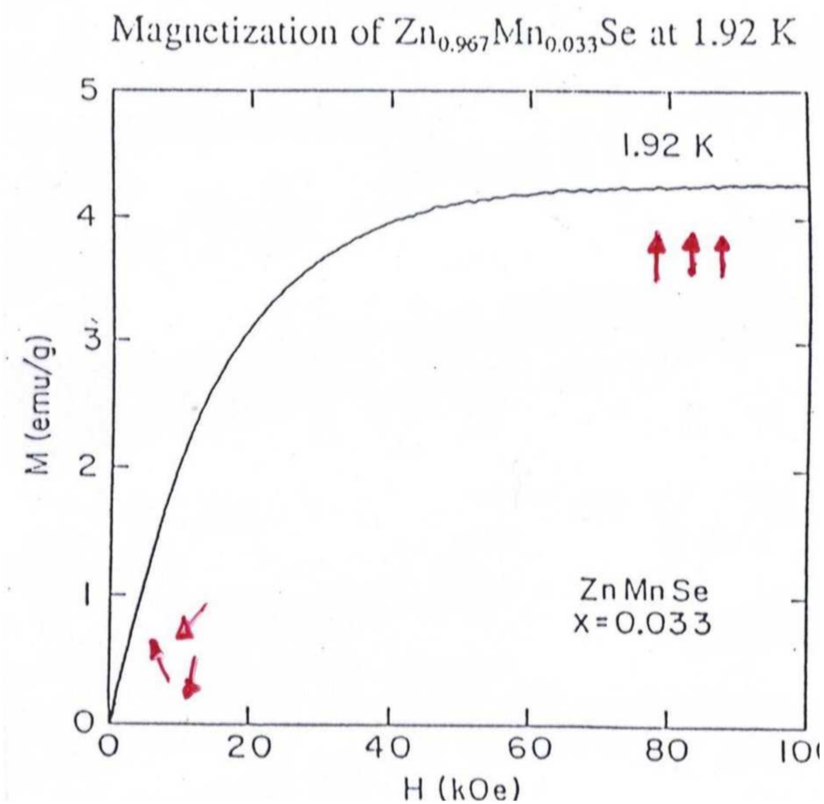
$M(T,H) = g\mu_B S x_{eff} N_o B_S[g\mu_B H/k_B(T + T_{AF})]$

antiferromagnetic interactions

$x_{eff} < x$

$T_{AF} > 0$

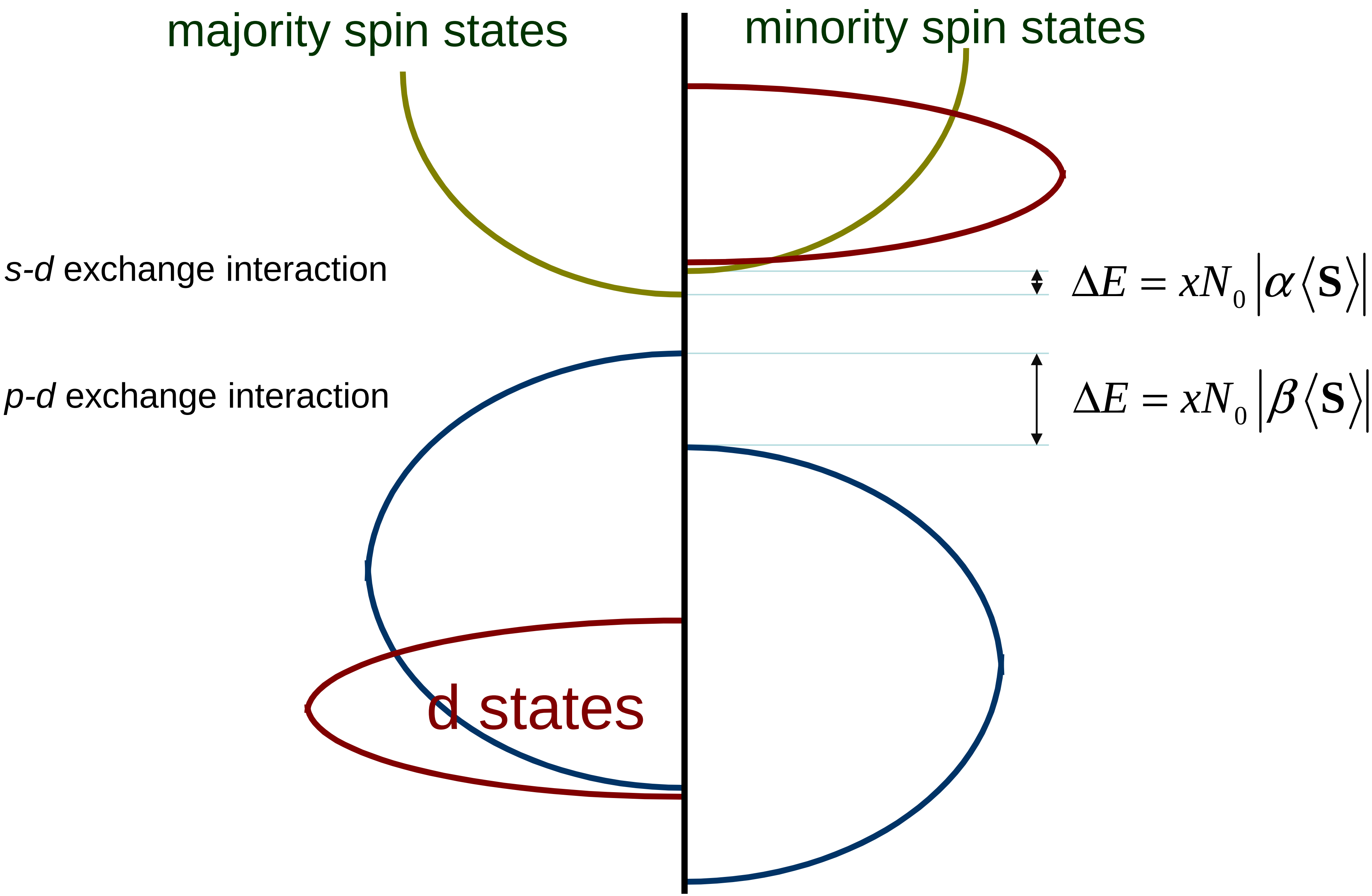
Modified Brillouin function



Y. Shapira et al.

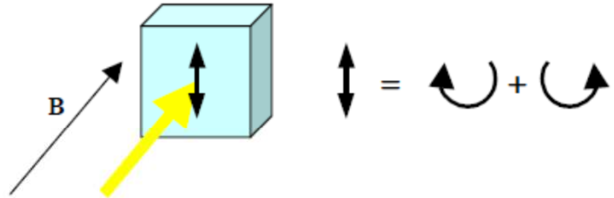
no spontaneous magnetization

Density of states with transition metal impurity



Faraday rotation

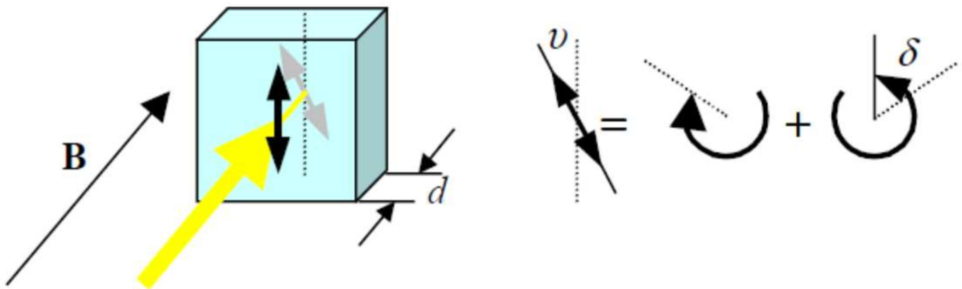
- A linearly polarized light arriving in the medium can be decomposed in two circularly polarized waves



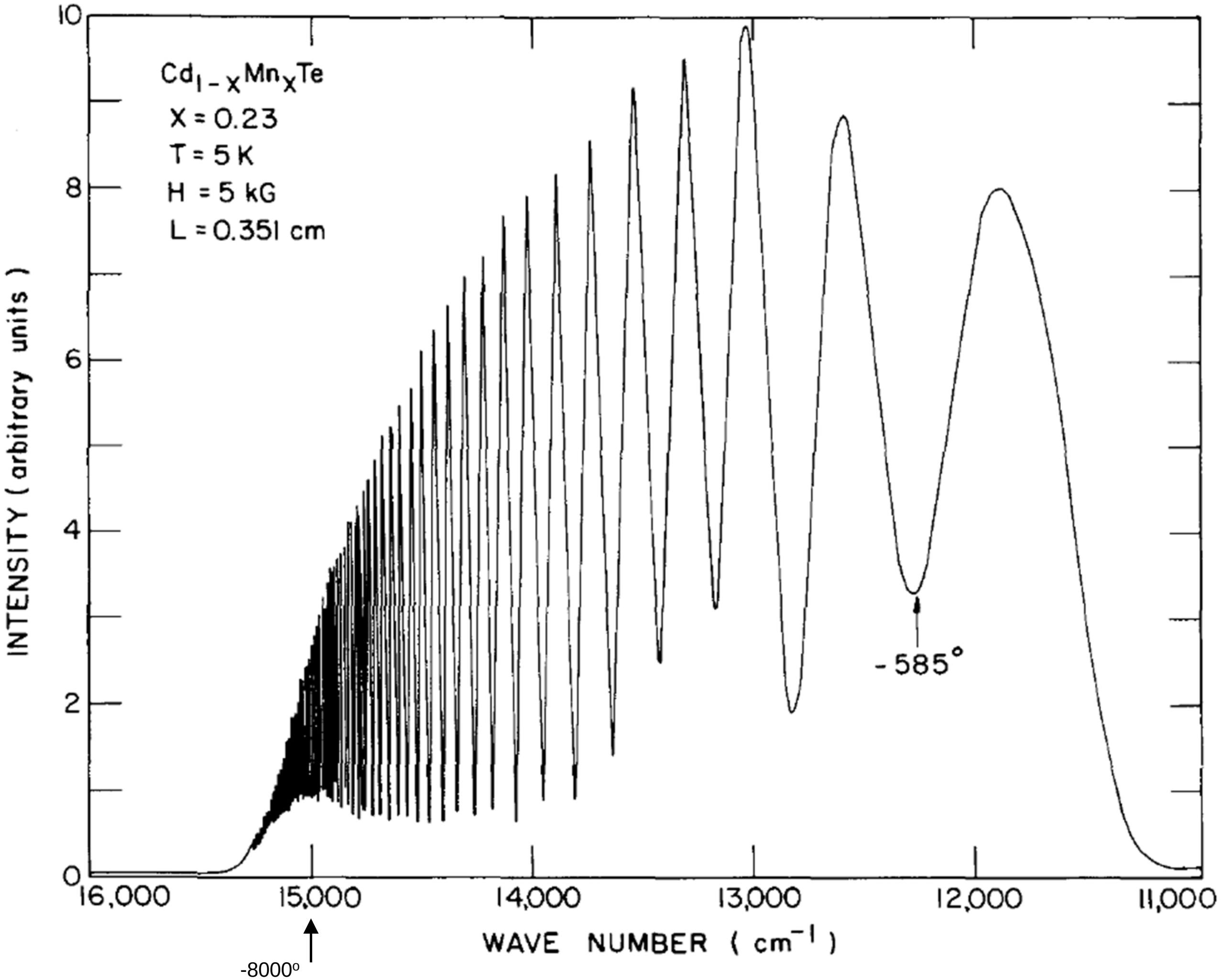
- After travelling in the medium over a distance *d* the two components develop a phase shift $$\delta = \frac{\omega}{c}(n_+ - n_-)d$$

- equivalent to a rotation of the polarization plane by the Faraday rotation angle

$$\vartheta = \tfrac{1}{2}\delta = \frac{\omega}{2c}(n_+ - n_-)d$$

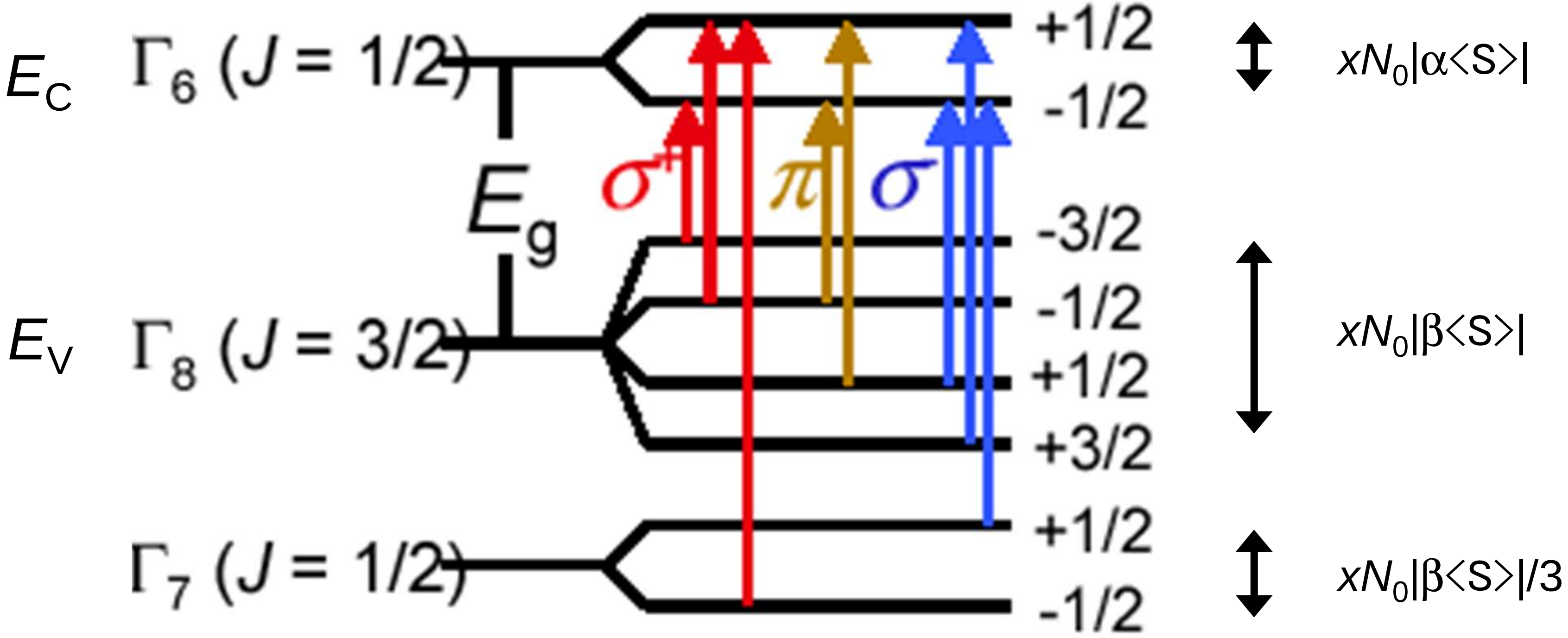


Faraday effect

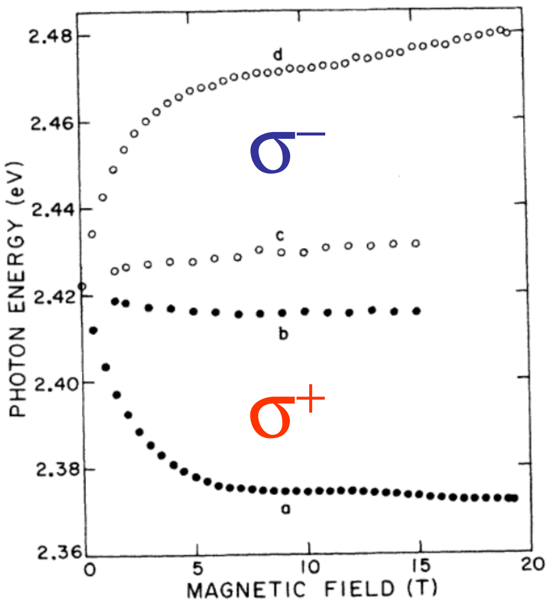


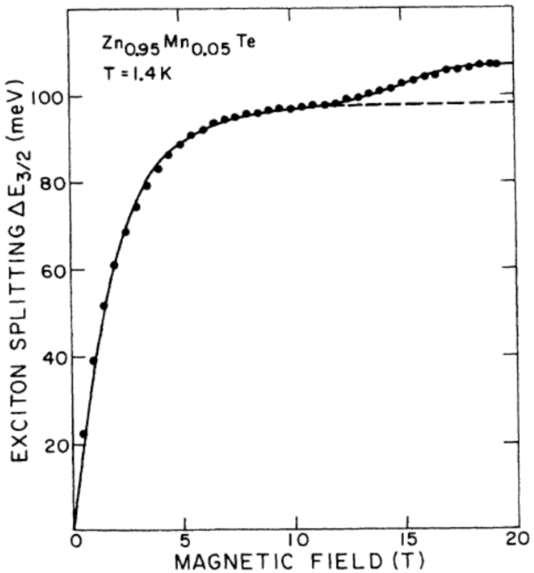
J. A. Gaj, R. R. Galazka, and M. Nawrocki, *Solid State Commun.*, vol. 25, p. 193 (1978).

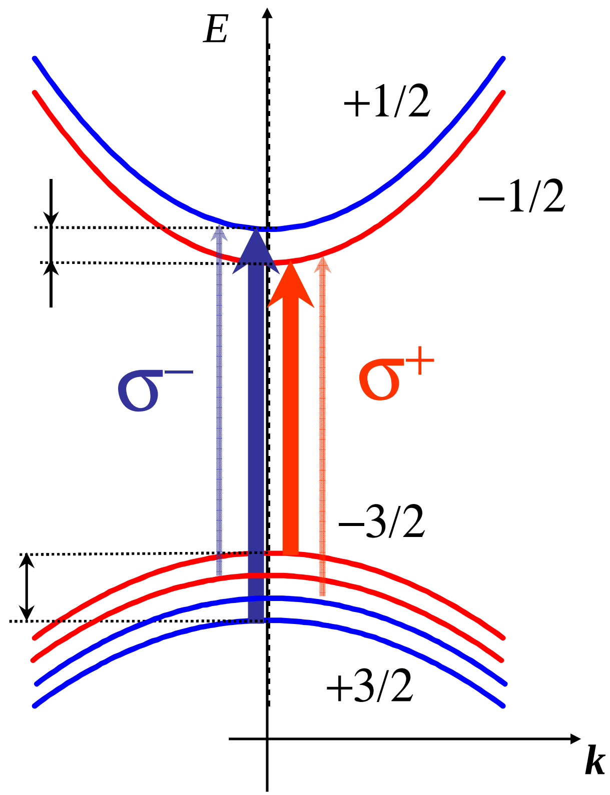
Splitting of the bands



Measurements of the band splitting







$\Delta E = 2 g_{eff} \mu_B H S$, $S = 1/2$

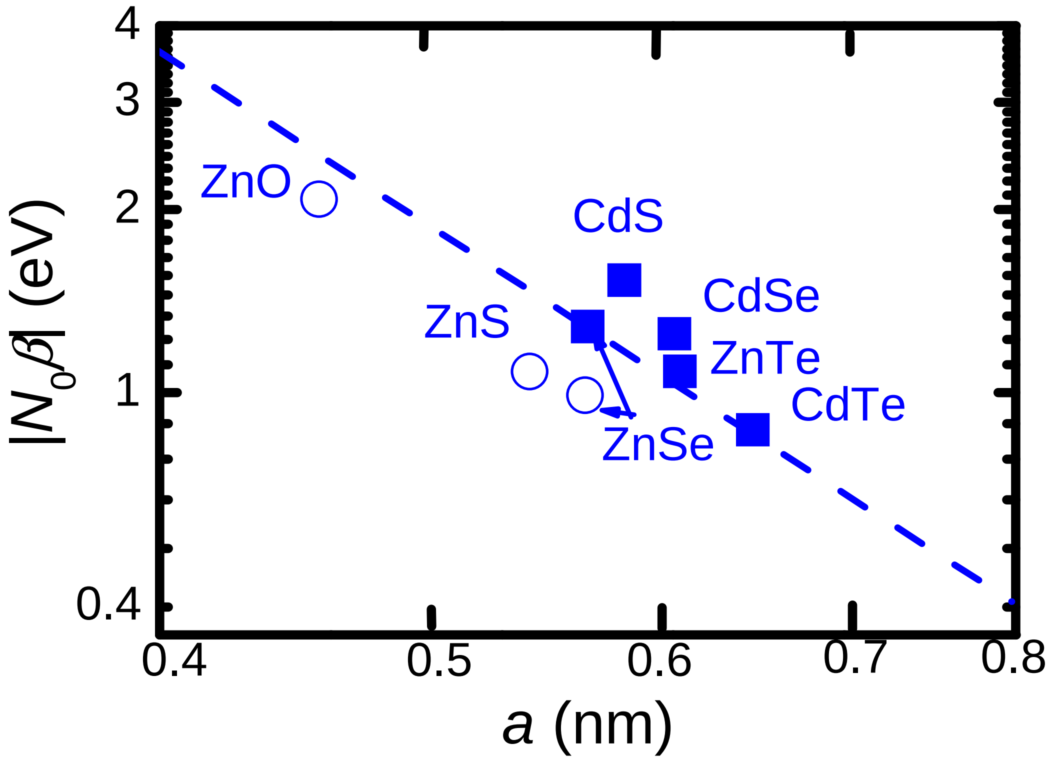
- $g_{eff} \sim 400 > 0$
- Follows *M* not *H*

SPINTECH II Joel Cibert

magnetoreflectance: Aggarwal et al. Phys. Rev**. B34**, 5894 (1986)

sp-d exchange

material	$N_0\alpha$ (eV)	$N_0\beta$ (eV)
(Cd,Mn)Te	0.22	-0.88
(Cd,Mn)Se	0.26	-1.24
(Cd,Mn)S	0.22	-1.8
(Zn,Mn)Te	0.19	-1.09
(Zn,Mn)Se	0.26	-1.32
(Cd,Fe)Se	0.25	-1.45
(Zn,Fe)Se	0.22	-1.74
(Cd,Co)Se	0.28	-1.87



circles: photoemission
squares: optical spectroscopy

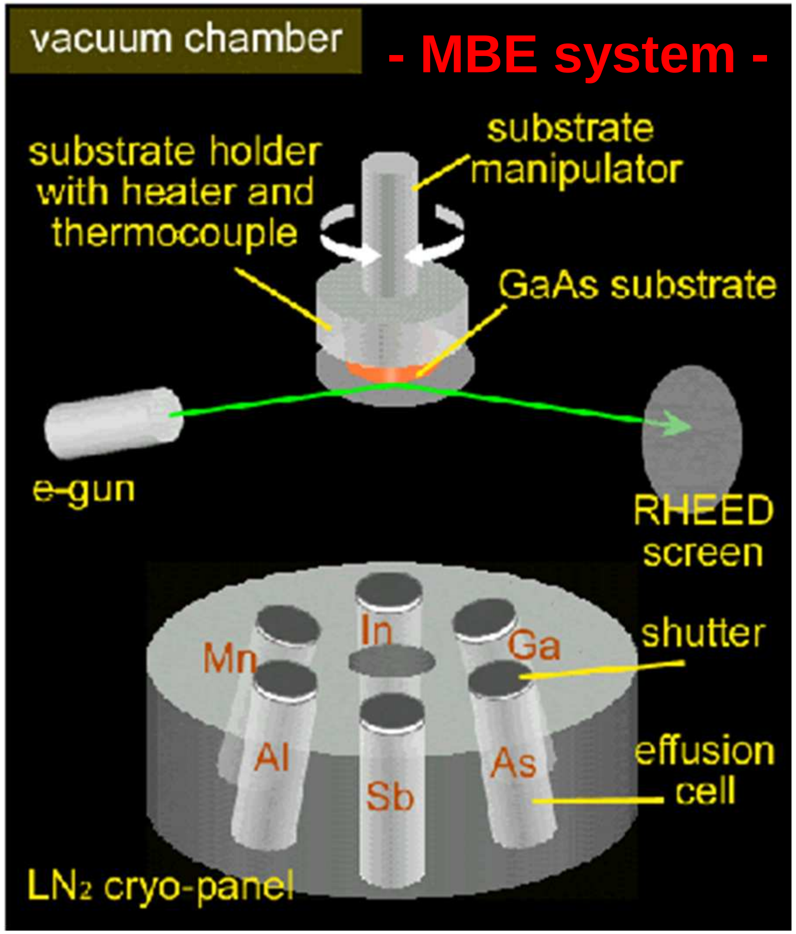
3. The consequences of exchange interaction

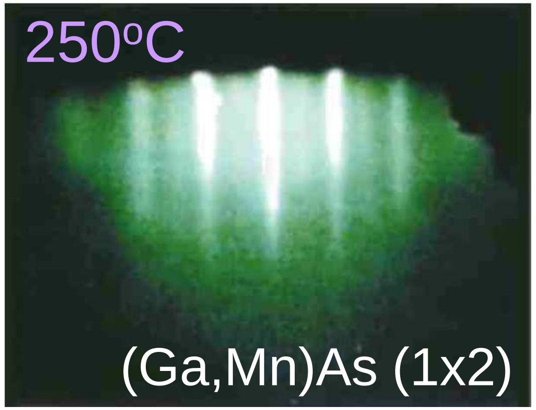
- Spin-split bands and **ferromagnetism**

GaAs (or InAs) + Mn

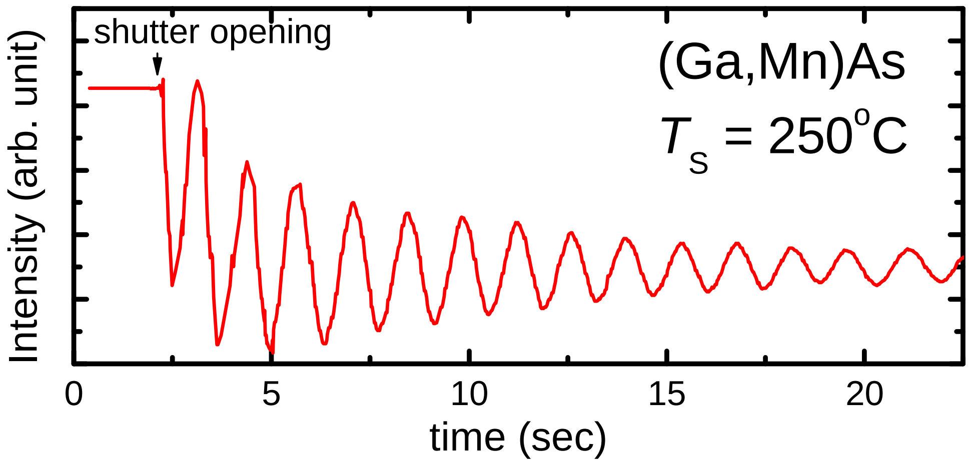
Material Science

Molecular beam epitaxy of (Ga,Mn)As

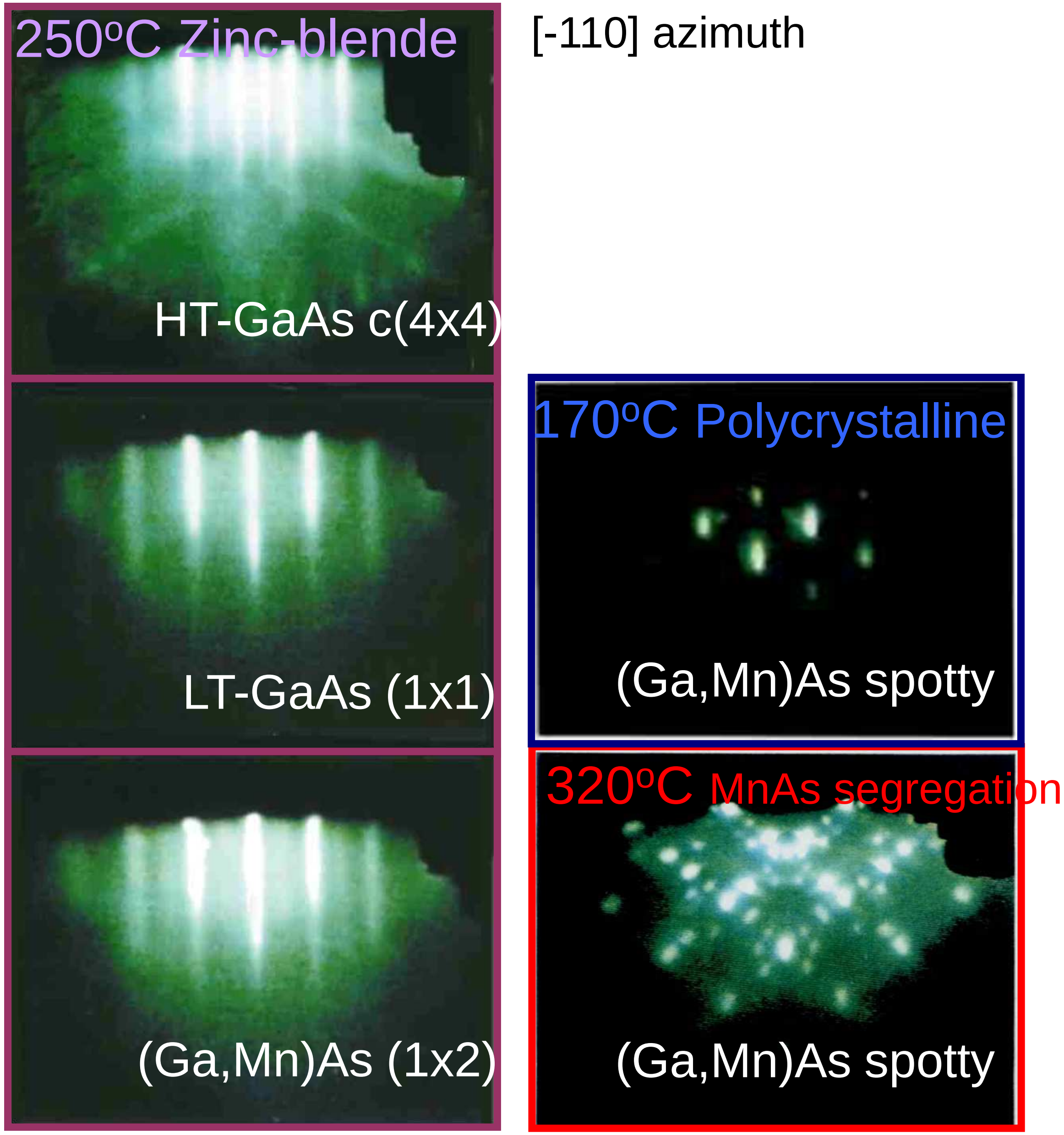




Single crystal (Ga,Mn)As



Molecular beam epitaxy of (Ga,Mn)As

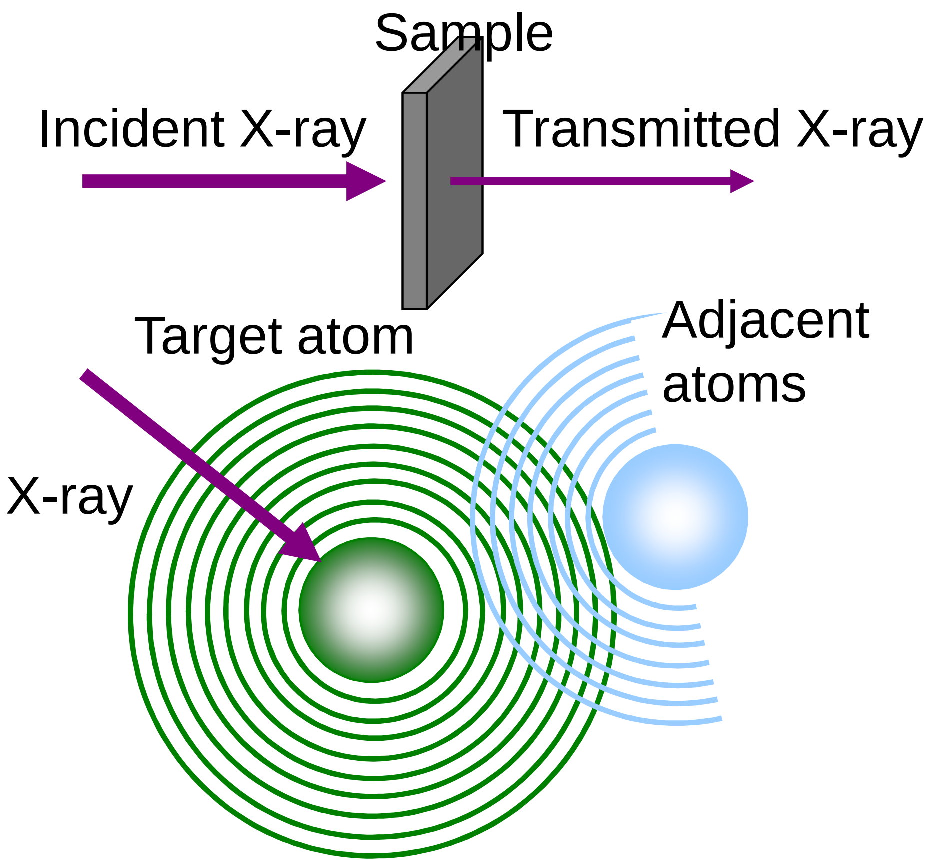


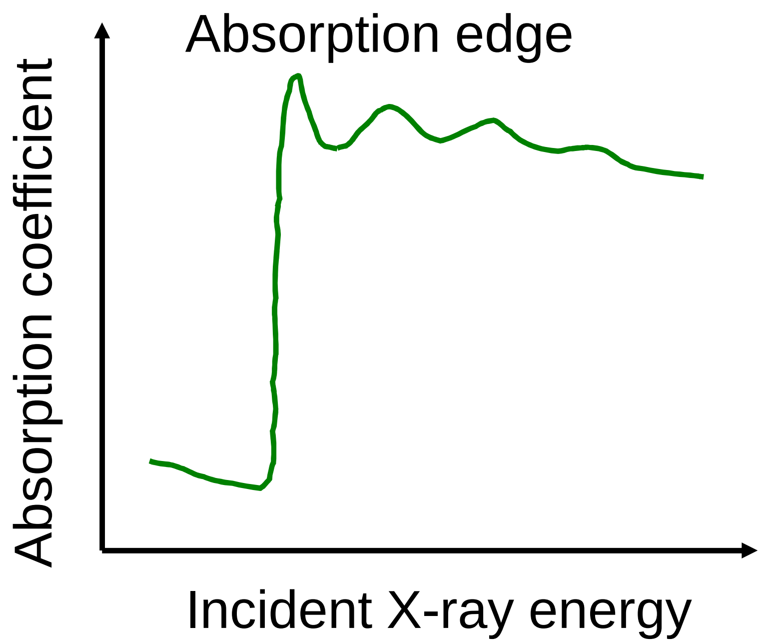
ZB-(Ga,Mn)As can be grown by selecting appropriate growth temperature

Highest Mn composition without segregation is about 10%.

A. Shen *et al*., J. Cryst. Growth **175/176**, 1069 (1997).

Extended X-ray-Absorption Fine Structure (EXAFS)

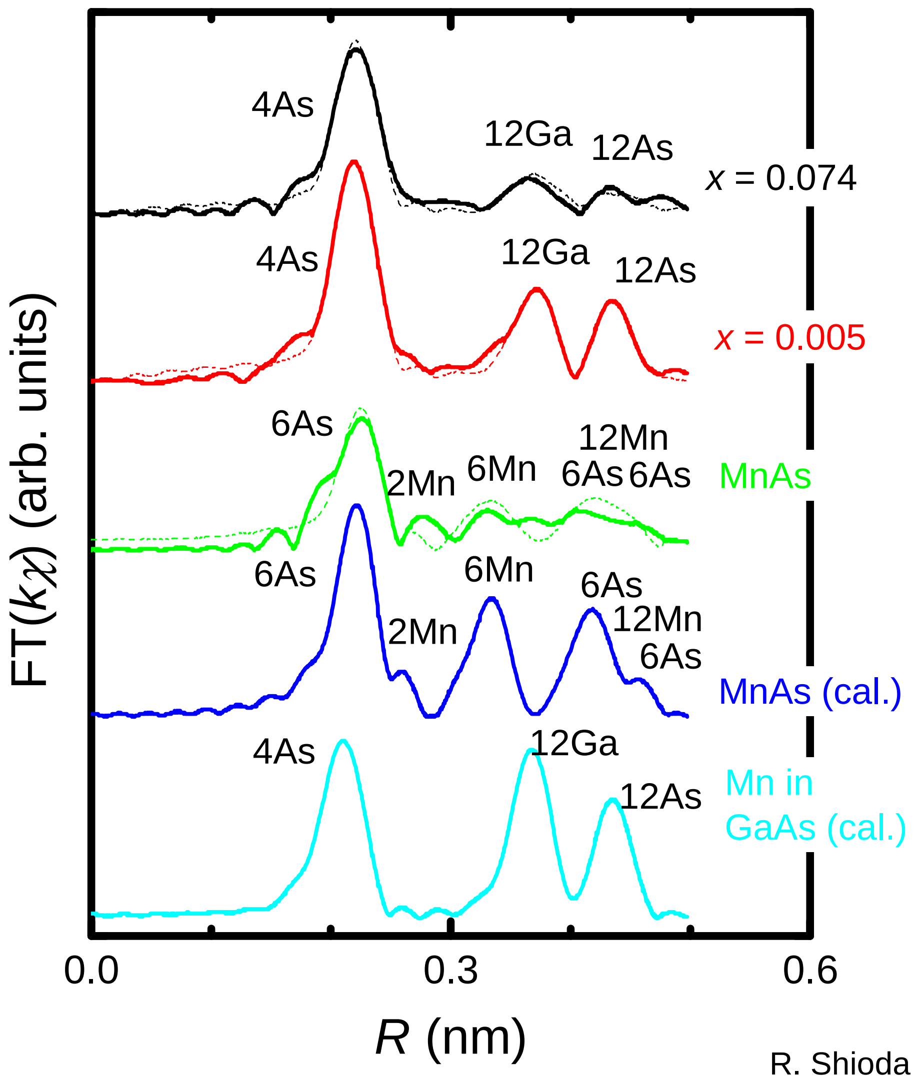




- X-ray is absorbed by target atom → creation of photoelectron
- Photoelectron is scattered by adjacent atoms
- Interference of photoelectron and reflected photoelectron
- Oscillating structure in absorption spectra includes the information of local structure around target atom

Local Structures - Extended X-ray-Absorption Fine Structure (EXAFS)

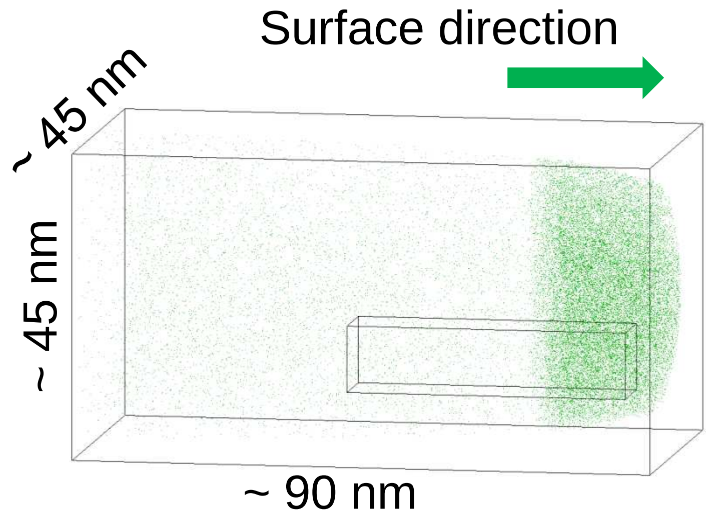
(Ga,Mn)As

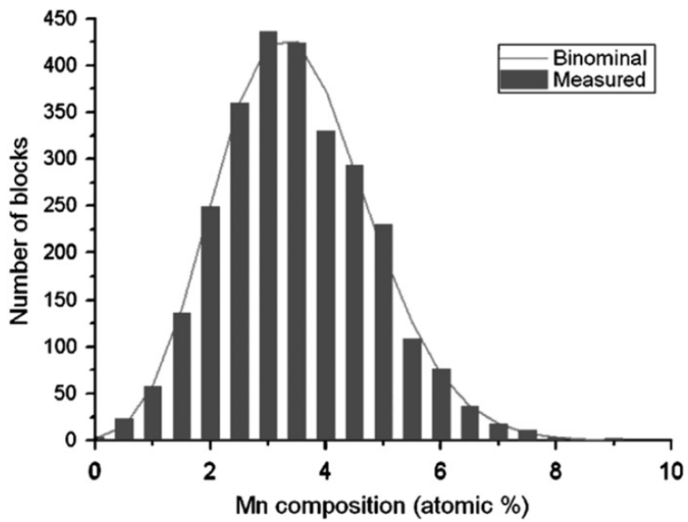


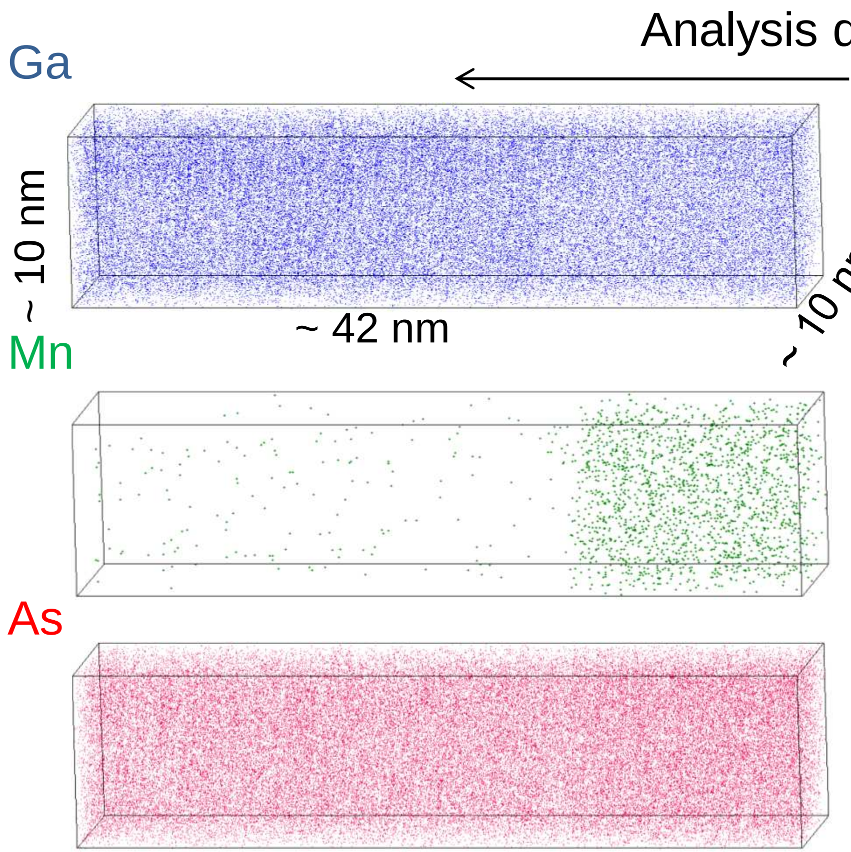
R. Shioda *et al*., Phys. Rev. B **58**, 1100 (1998).

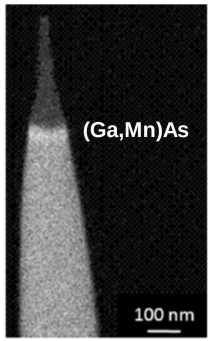
Most of Mn substitute III-cation site (Mn^{2+} → acceptor)

Atom Probe Microscopy of (Ga,Mn)As









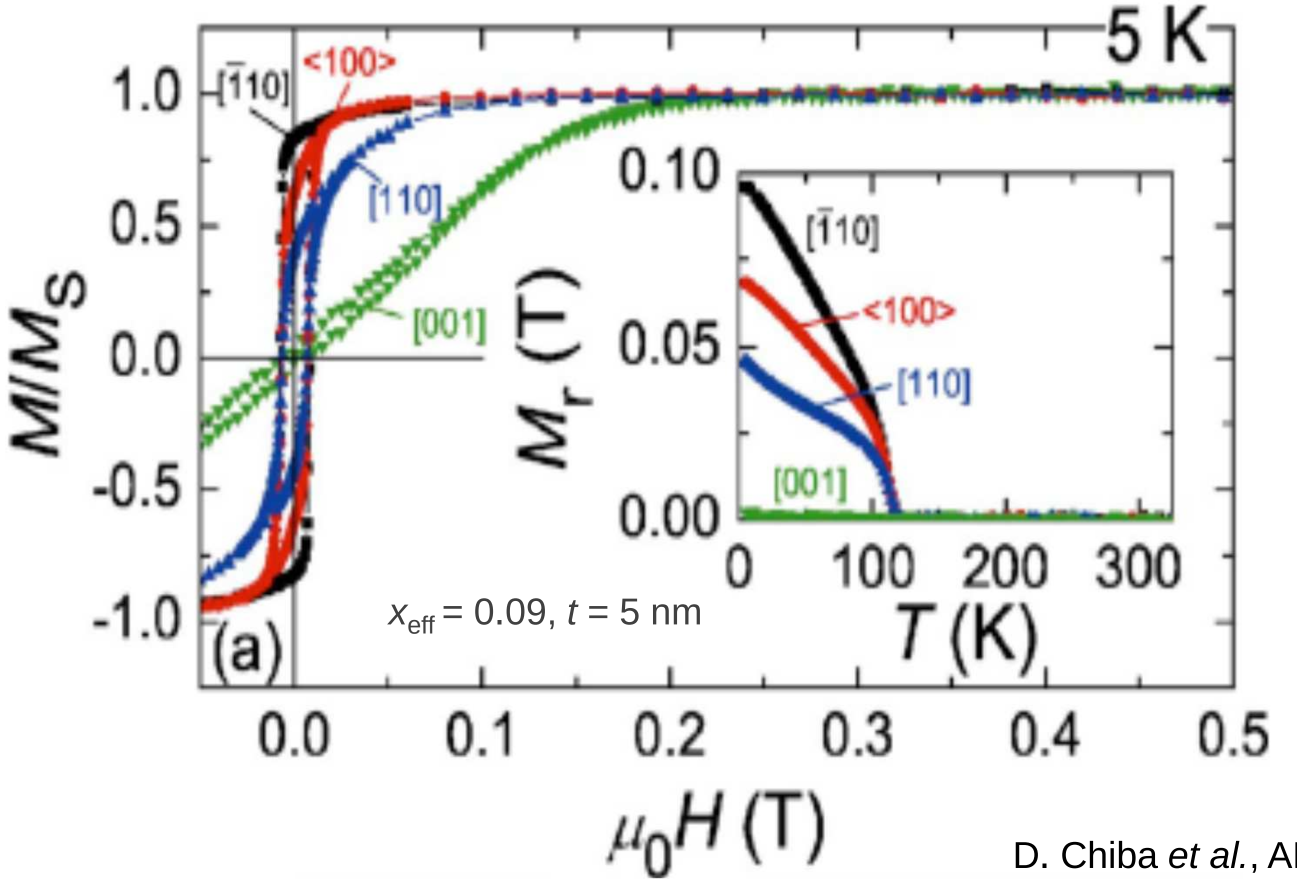
M. Kodzuka, T. Ohkubo, K. Hono (NIMS) F. Matsukura, and H. Ohno (Tohoku), Ultramicroscopy 2009

Magnetism, transport, and more materials science

Magnetization of (Ga,Mn)As

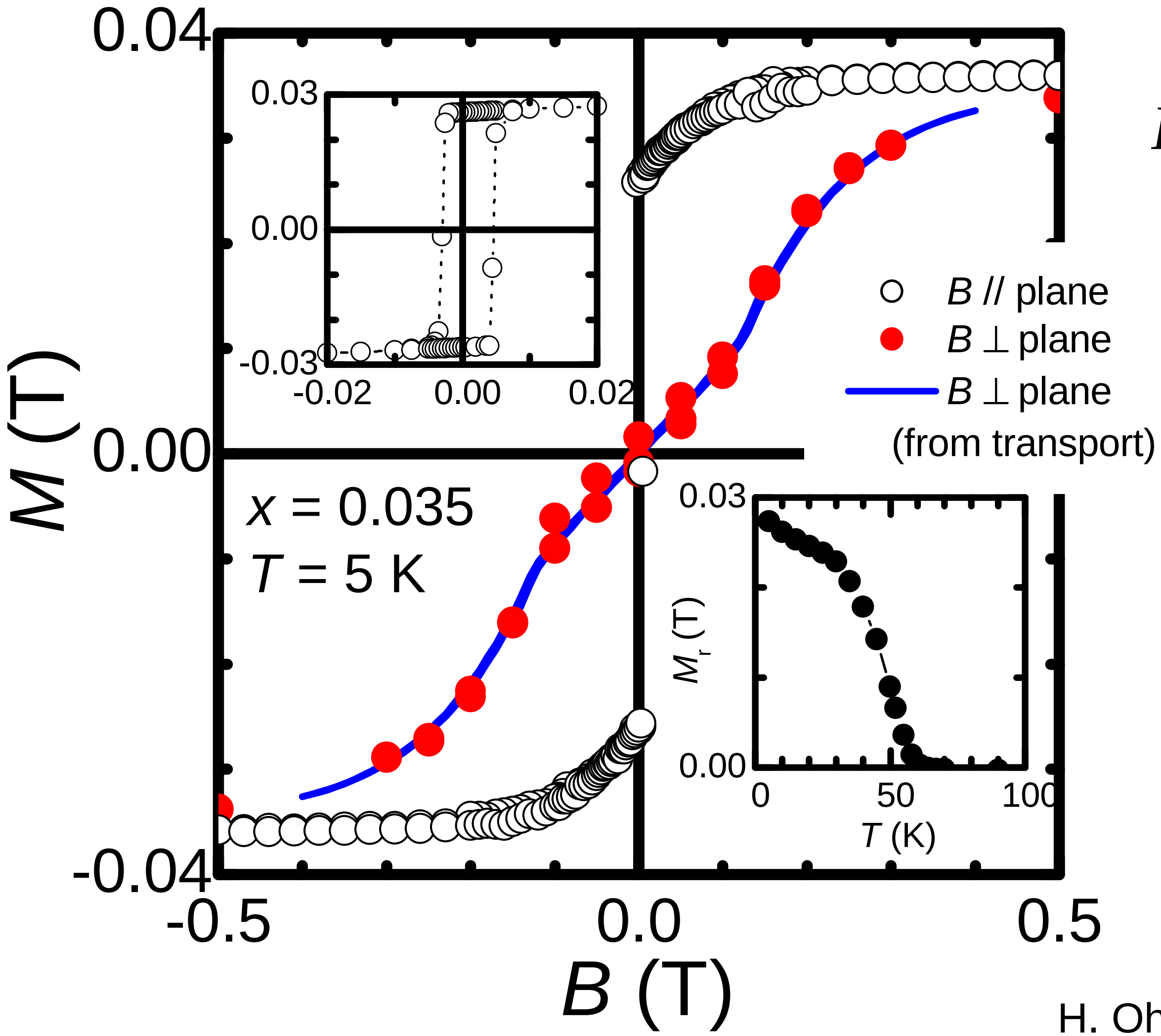
(Ga,Mn)As & (In,Mn)As: Mn acts as a source of spin and hole

Ferromagnetism in (In,Mn)As: H. Ohno *et al.*, *Phys Rev. Lett.* 1992
and in (Ga,Mn)As: H. Ohno *et al.*, *Appl. Phys. Lett.* 1996

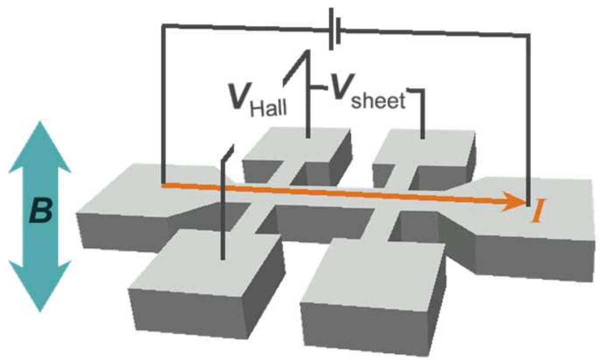


D. Chiba *et al.*, APL **90**, 122503 (2007)

Magnetization and transport of (Ga,Mn)As



$$R_{\mathrm{Hall}} = (R_0/d)B + (R_S/d)M_\perp$$



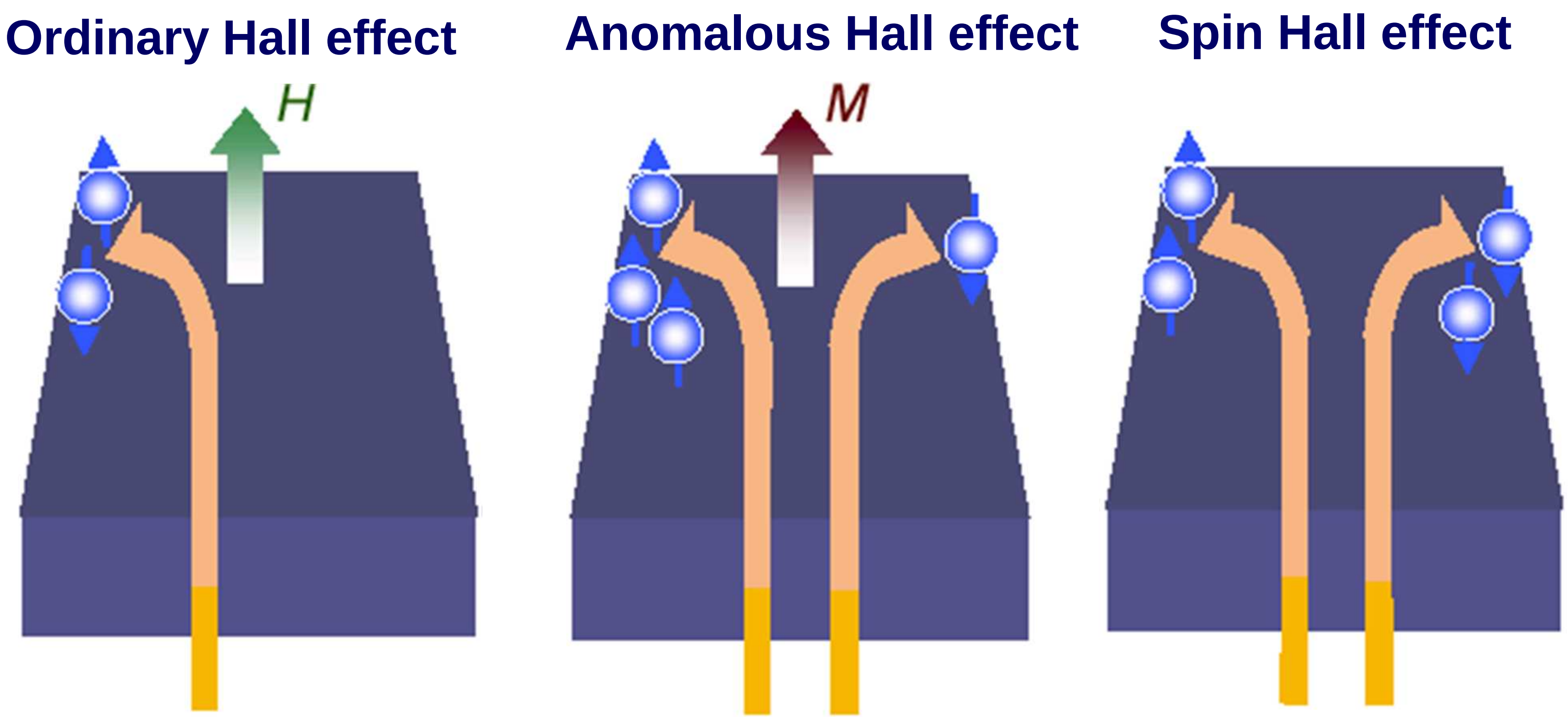
$R_{\mathrm{Hall}} = V_{\mathrm{Hall}}/I$

$R_{\mathrm{sheet}} \propto V_{\mathrm{sheet}}/I$

H. Ohno *et al. Appl. Phys. Lett.* 1996

H. Ohno *Science* 1998

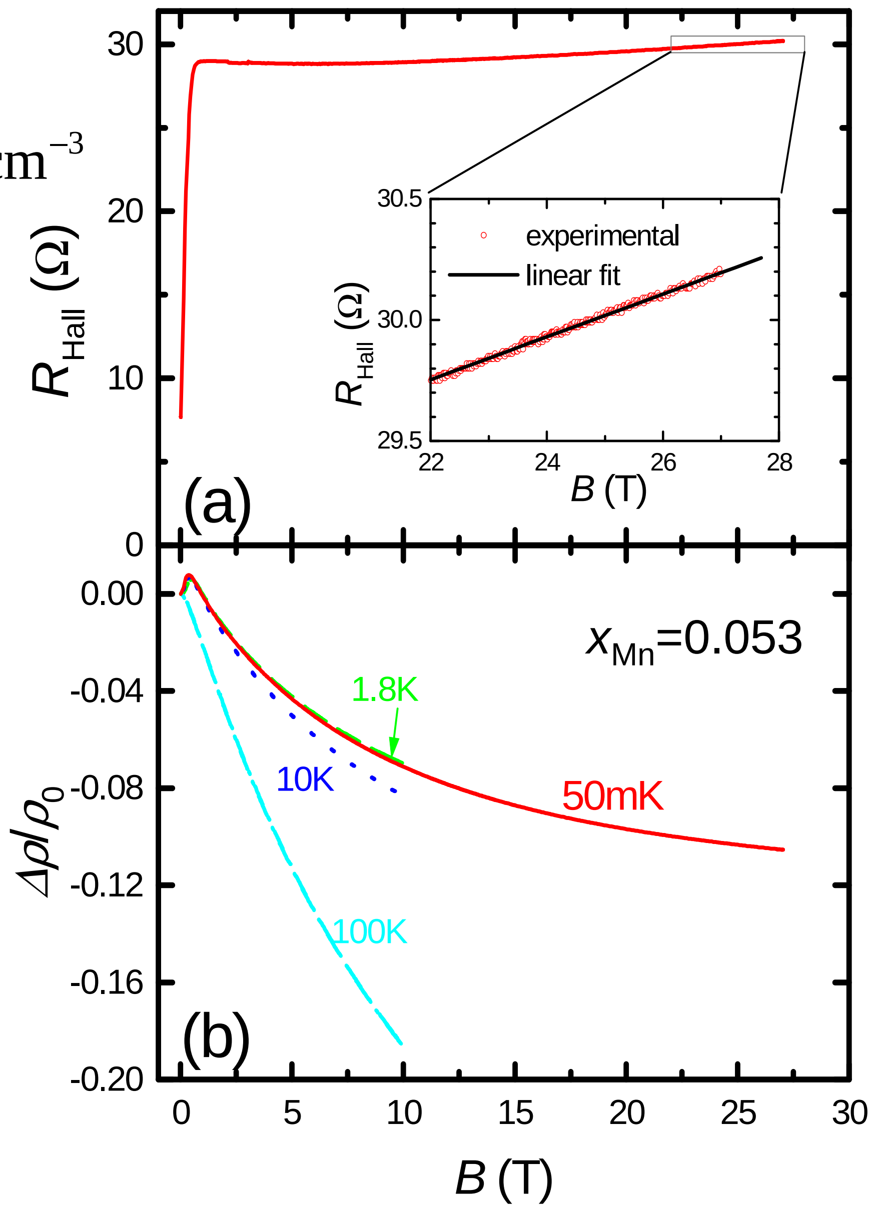
Hall Effects



Low-temperature & high-field measurements

$Ga_{0.947}Mn_{0.053}As$

$$[Mn] = 1.2\times10^{21}\ \text{cm}^{-3}$$

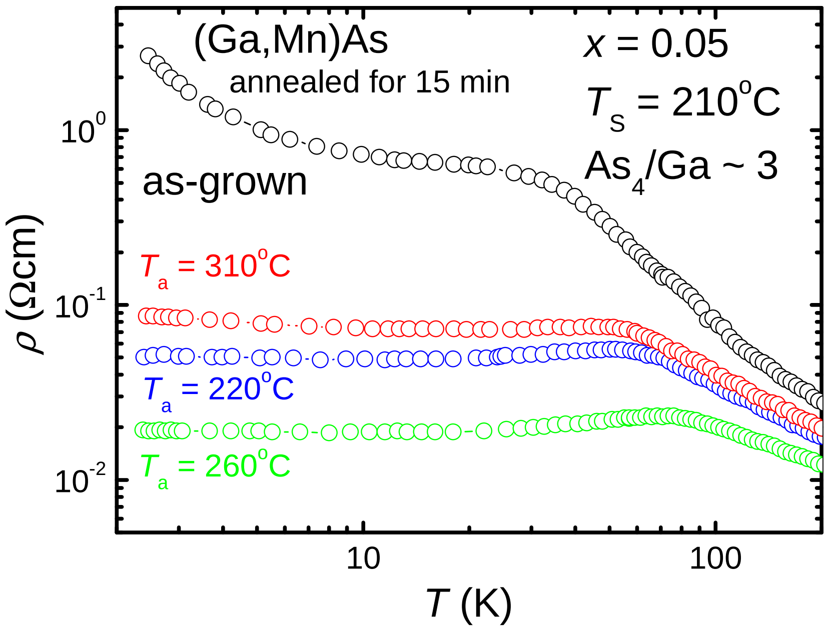


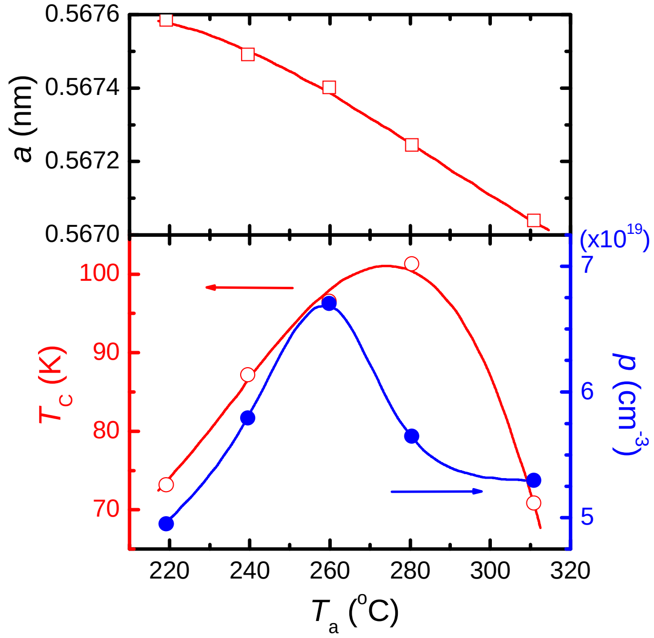
p = 3.5 x 10^{20} cm^{-3}
(30% of Mn)

$$\Delta\rho_{\text{Hall}} = \Delta(R_0 B + R_S M_\perp) \approx R_0 \Delta B = \frac{1}{qpd}\Delta B$$

T. Omiya et al. *Physica E*, 2000

Low-temperature annealing





T. Hayashi *et al*., Appl. Phys. Lett. **78**, 1691 (2001).

Low-temperature annealing 220-250°C

- Decreases lattice constant
- Increases electrical conductivity
- Increases hole concentration
- Increases ferromagnetic transition temperature

Mn_i

Correlation between T_C and p

See also K. W. Edmonds *et al*., Appl. Phys. Lett. **81**, 4991 (2002).

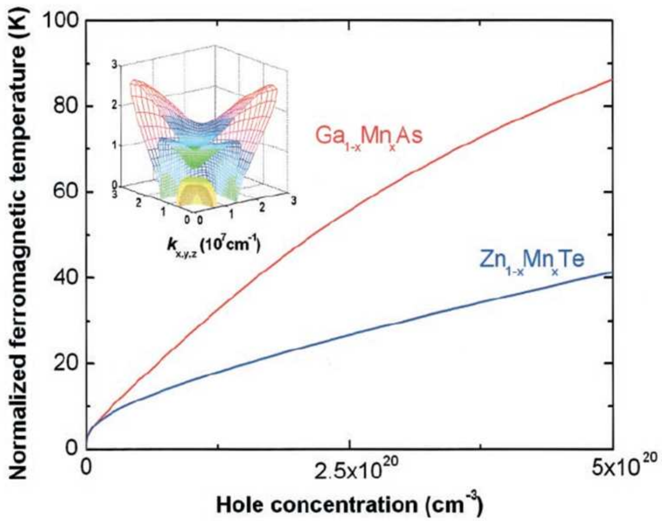
Ferromagnetism

Zener Model Description of Ferromagnetism in Zinc-Blende Magnetic Semiconductors

T. Dietl,[1,2*] H. Ohno,[1*] F. Matsukura,[1] J. Cibert,[3] D. Ferrand[3]

Ferromagnetism in manganese compound semiconductors not only opens prospects for tailoring magnetic and spin-related phenomena in semiconductors with a precision specific to III-V compounds but also addresses a question about the origin of the magnetic interactions that lead to a Curie temperature (T_C) as high as 110 K for a manganese concentration of just 5%. Zener's model of ferromagnetism, originally proposed for transition metals in 1950, can explain T_C of $Ga_{1-x}Mn_xAs$ and that of its II-VI counterpart $Zn_{1-x}Mn_xTe$ and is used to predict materials with T_C exceeding room temperature, an important step toward semiconductor electronics that use both charge and spin.

SCIENCE VOL 287 11 FEBRUARY 2000 1019



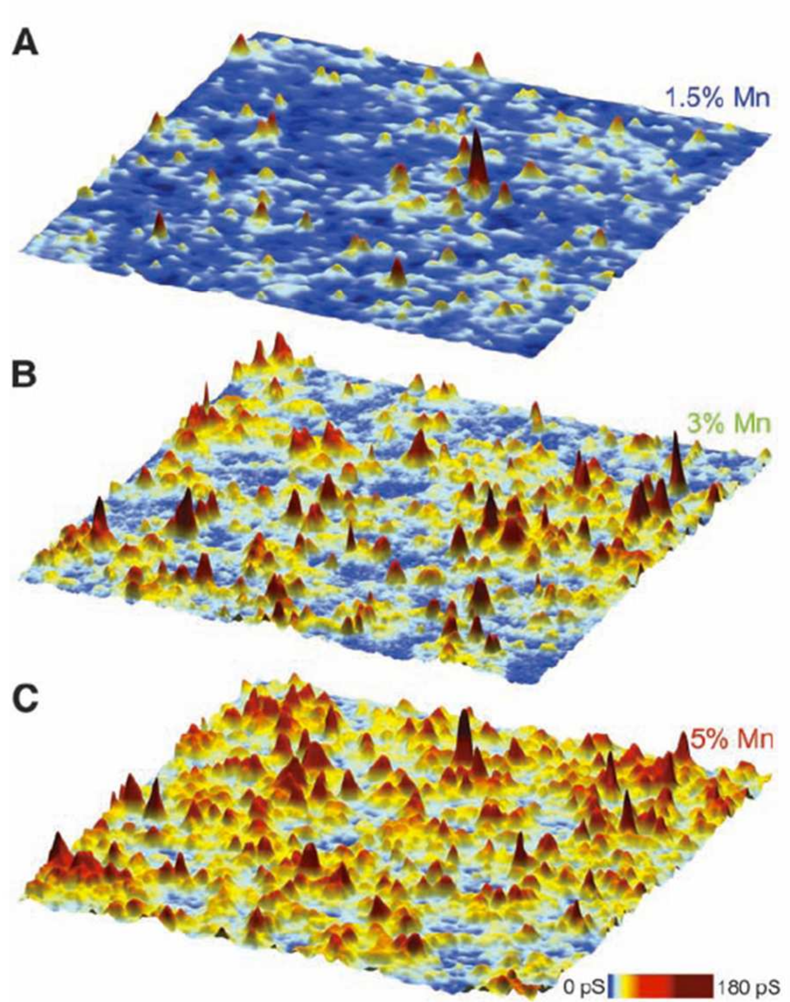
Like other thermodynamic quantities, Fc[M] is expected to be weakly perturbed by static disorder

We suggest that the holes in the extended or weakly localized states mediate the long-range interactions between the localized spins on both sides of the MIT in the III-V and II-VI magnetic semiconductors.

Visualizing Critical Correlations Near the Metal-Insulator Transition in $Ga_{1-x}Mn_xAs$

Anthony Richardella,[1,2*] Pedram Roushan,[1*] Shawn Mack,[3] Brian Zhou,[1] David A. Huse,[1] David D. Awschalom,[3] Ali Yazdani[1]†

www.sciencemag.org SCIENCE VOL 327 5 FEBRUARY 2010 665



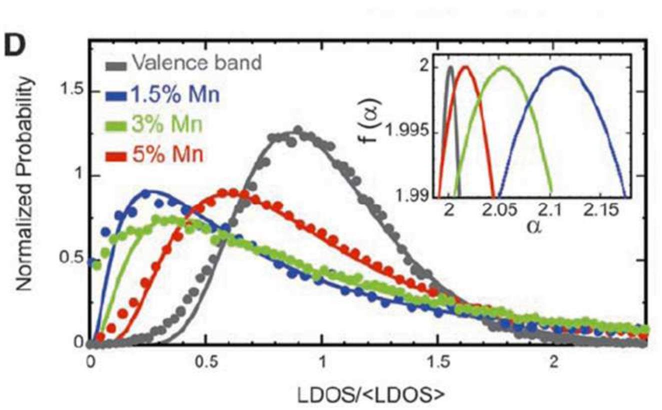


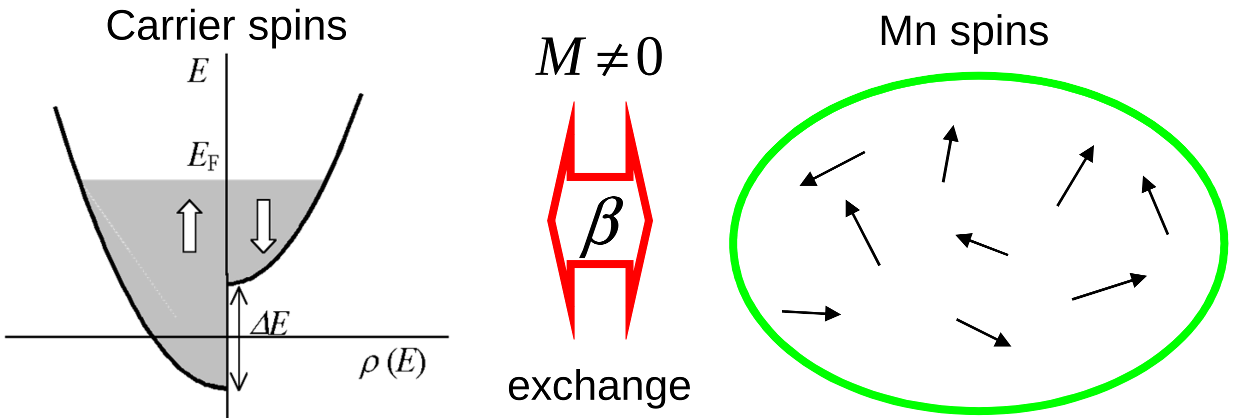
Fig. 5. The spatial variations of the LDOS at the Fermi level, with their histogram and multifractal spectrum. The LDOS mapping of a 700 Å by 700 Å area of **(A)** $Ga_{0.985}Mn_{0.015}As$, **(B)** $Ga_{0.97}Mn_{0.03}As$, and **(C)** $Ga_{0.95}Mn_{0.05}As$. **(D)** The normalized histogram of the maps presented in (A) to (C). The local values of the *dI/dV* are normalized by the average value of each map. The inset shows the multifractal spectrum, $f(\alpha)$, near the value α_0 where the maximum value occurs. For comparison, the results of a similar analysis over a LDOS map at −100 mV (valence band states) for the 1.5% doped sample are also shown.

p-d Zener model of ferromagnetism

Ferromagnetic (Ga,Mn)As

Mn acts as a source of spin and hole

H. Ohno *et al. Appl. Phys. Lett.* 1996
H. Ohno *Science* 1998

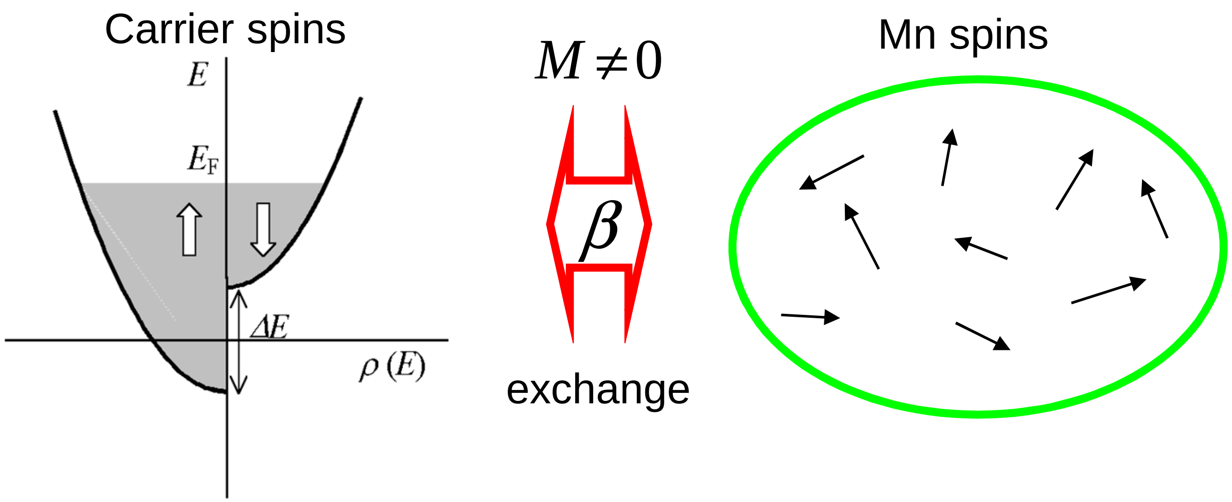


$$H_{pd} = -xN_0\beta < S > \mathbf{s}$$

$$T_c = \frac{xN_0 S(S+1)A_F\,\rho(E_F)\beta^2}{12k_B}$$

T. Dietl, *et al. Science* **287**, 1019 (2000) and *PRB* **63**, 195205 (2001)
also Koenig et al. *Phys. Rev. Lett.* 2000

T_C by the *p-d* Zener model



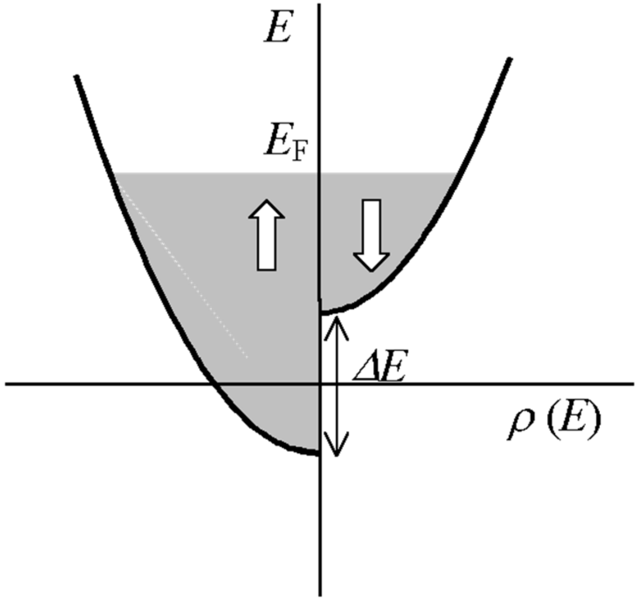
$$\Delta F_{total} = \Delta F_{Mn} + \Delta F_c$$

$$= \frac{M^2}{2\chi_{Mn}} - \frac{\chi_c}{2} H^2$$

$$\chi_{Mn} = \frac{g^2 \mu_B^2 x N_0 S(S+1)}{3 k_B T}$$

$$\chi_c = \mu_B^2 \rho(E_F)$$

T_C by the *p-d* Zener model



$$\Delta E = 2\mu_B H$$

$$\Delta E = xN_0 \left|\beta \langle S \rangle\right|$$

$$M = xN_0 g\mu_B \left|\langle S \rangle\right|$$

$$\Delta E = \frac{|\beta| M}{g\mu_B}$$

$$H = \frac{\Delta E}{2\mu_B} = \frac{|\beta| M}{2g\mu_B^2}$$

$$\Delta F_{total} == \frac{M^2}{2\chi_{Mn}} - \frac{\chi_c}{2} H^2$$

$$= \left(\frac{1}{2\left(\frac{g^2\mu_B^2 xN_0 S(S+1)}{3k_B T} \right)} - \frac{\rho(E_F)\beta^2}{8g^2\mu_B^2} \right) M^2$$

$$T_c = \frac{xN_0 S(S+1)\rho(E_F)\beta^2}{12k_B}$$

$$\Delta F_c(M) \approx -\frac{A_F \rho(E_F)\beta^2}{8g^2\mu_B^2} M^2$$

Valence band structure (Γ_7, Γ_8)

$$H_{kp}\Psi = E\Psi$$

Basis functions

$$u_1 = \frac{1}{\sqrt{2}}(X+iY)\uparrow,\quad u_2 = i\frac{1}{\sqrt{6}}[(X+iY)\downarrow - 2Z\uparrow],\quad u_3 = \frac{1}{\sqrt{6}}[(X-iY)\uparrow + 2Z\downarrow],$$

$$u_4 = i\frac{1}{\sqrt{2}}(X-iY)\downarrow,\quad u_5 = \frac{1}{\sqrt{3}}[(X+iY)\downarrow + Z\uparrow],\quad u_6 = i\frac{1}{\sqrt{3}}[-(X-iY)\uparrow + Z\downarrow]$$

k·p **matrix**

$$H_{kp} = -\frac{\hbar^2}{2m_0}\begin{pmatrix} P+Q & L & M & 0 & iL/\sqrt{2} & -i\sqrt{2}M \\ L^\dagger & P-Q & 0 & M & -i\sqrt{2}Q & i\sqrt{3/2}L \\ M^\dagger & 0 & P-Q & -L & -i\sqrt{3/2}L^\dagger & -i\sqrt{2}Q \\ 0 & M^\dagger & -L^\dagger & P+Q & -i\sqrt{2}M^\dagger & -iL^\dagger/\sqrt{2} \\ -iL^\dagger/\sqrt{2} & i\sqrt{2}Q & i\sqrt{3/2}L & i\sqrt{2}M & P+\Delta & 0 \\ i\sqrt{2}M^\dagger & -i\sqrt{3/2}L^\dagger & i\sqrt{2}Q & iL/\sqrt{2} & 0 & P+\Delta \end{pmatrix}$$

$$P = \gamma_1 k^2,\; Q = \gamma_2\left(k_x^2 + k_y^2 - 2k_z^2\right),\; L = -2\sqrt{3}\gamma_3\left(k_x - ik_y\right)k_z,\; M = -\sqrt{3}\left[\gamma_2\left(k_x^2 - k_y^2\right) - 2i\gamma_3 k_x k_y\right]$$

$\gamma_1 = 6.85$, $\gamma_2 = 2.1$, $\gamma_3 = 2.58$, $\Delta = 0.34$ eV for GaAs

T. Dietl, H. Ohno and F. Matsukura, Phys. Rev. B63, 195205 (2001)

Valence band structure with *p-d* exchange (Γ_7, Γ_8)

$$(H_{kp} + H_{pd})\Psi = E\Psi$$

p-d **exchange interaction matrix**

$$H_{pd} = B \cdot \begin{pmatrix} 3b_x w_z & i\sqrt{3}b_x w_- & 0 & 0 & \sqrt{6}b_x w_- & 0 \\ -i\sqrt{3}b_x w_+ & (2b_z - b_x)w_z & 2ib_z w_- & 0 & i\sqrt{2}(b_x + b_z)w_z & \sqrt{2}b_z w_- \\ 0 & -2ib_z w_+ & -(2b_z - b_x)w_z & i\sqrt{3}b_x w_- & \sqrt{2}b_z w_+ & -i\sqrt{2}(b_x + b_z)w_z \\ 0 & 0 & -i\sqrt{3}b_x w_+ & -3b_x w_z & 0 & -\sqrt{6}b_x w_+ \\ \sqrt{6}b_x w_+ & -i\sqrt{2}(b_x + b_z)w_z & \sqrt{2}b_z w_- & 0 & -(2b_x - b_z)w_z & ib_z w_- \\ 0 & 0 & i\sqrt{2}(b_x + b_z)w_z & -\sqrt{6}b_x w_- & -ib_z w_+ & (2b_x - b_z)w_z \end{pmatrix}$$

$$B = -\frac{1}{6} x N_0 \beta \langle S_z \rangle, \qquad \beta_x = b_x \beta, \qquad \beta_z = b_z \beta$$

$$w_z = \langle S_z \rangle / |\langle S \rangle|, \qquad w_\pm = \left(\langle S_x \rangle \pm i \langle S_y \rangle \right) / |\langle S \rangle|$$

$$|\langle S \rangle| = \left| \langle S_x \rangle^2 + \langle S_y \rangle^2 + \langle S_z \rangle^2 \right|^{1/2}$$

T. Dietl, H. Ohno and F. Matsukura, Phys. Rev. B63, 195205 (2001)

Exchange energy: $N_0\beta$

Core level photoemission and modeling:
$N_0\beta$ = -1.2 ± 0.2 eV

Okabayashi et al., Phys. Rev. B58, 1998.

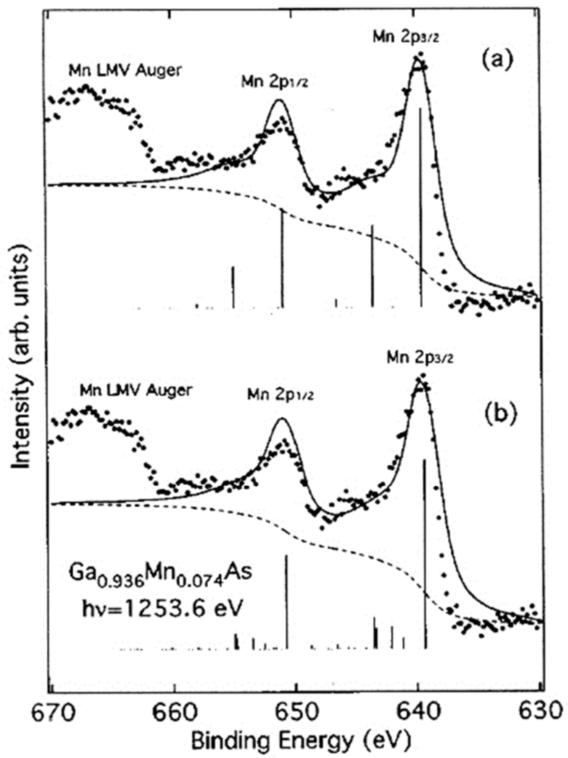
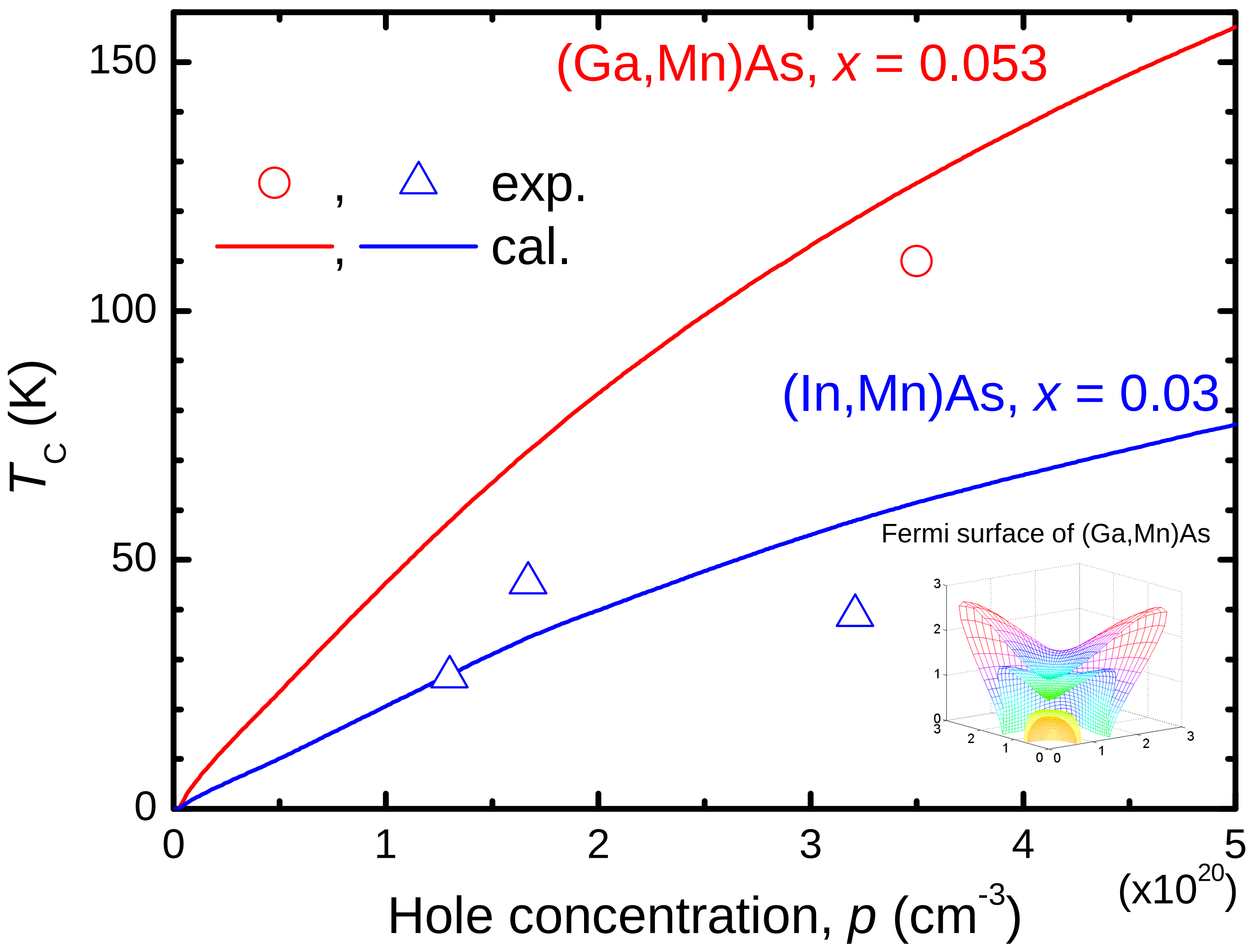


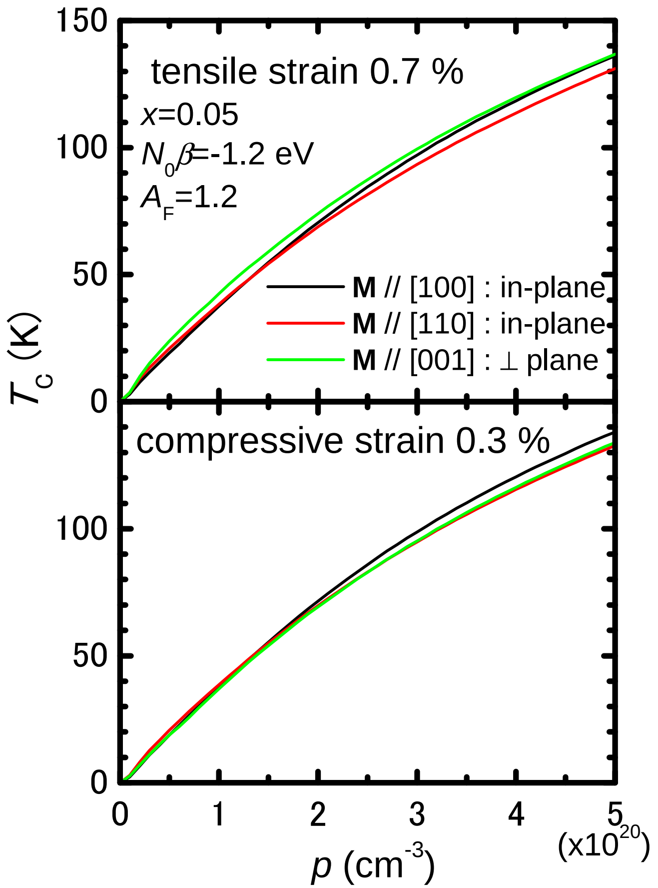
FIG. 1. Photoemission spectrum of the Mn 2p core level (dots) and its cluster-model analysis (solid curves) assuming the negatively ionized Mn^{2+} (a) and neutral Mn^{3+} (b) ground states. The vertical bars are unbroadened spectra. The calculated background is shown by dashed curves.

Comparison of exp. and calculated T_C

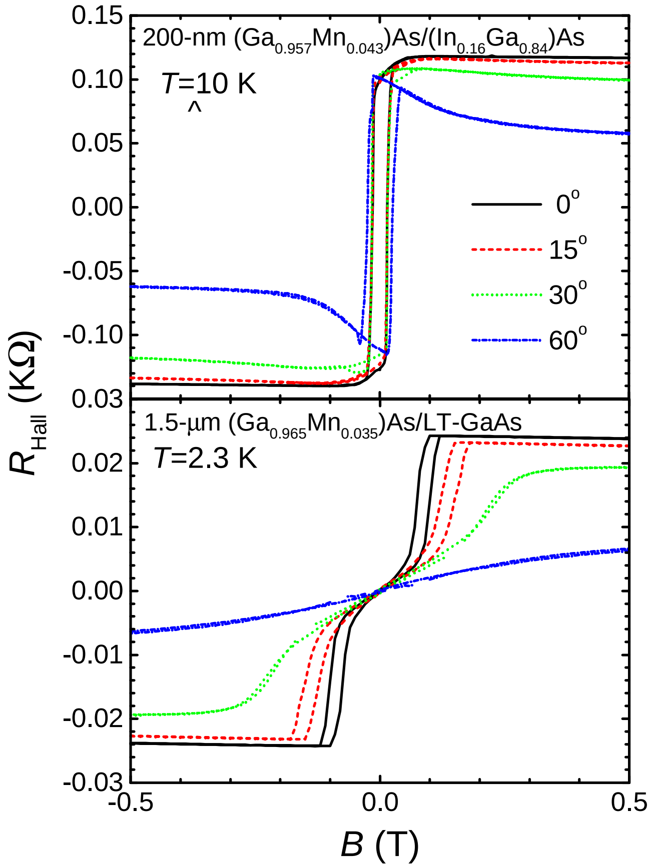


Strain induced-anisotropy: Theory vs. Experiment

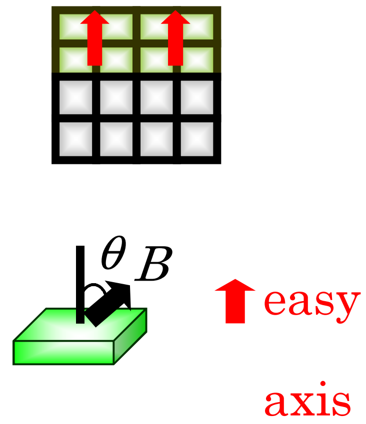
Theory



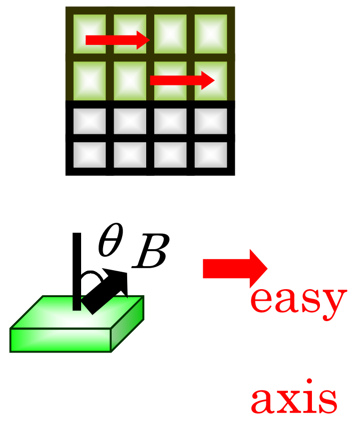
Experiment



tensile strain

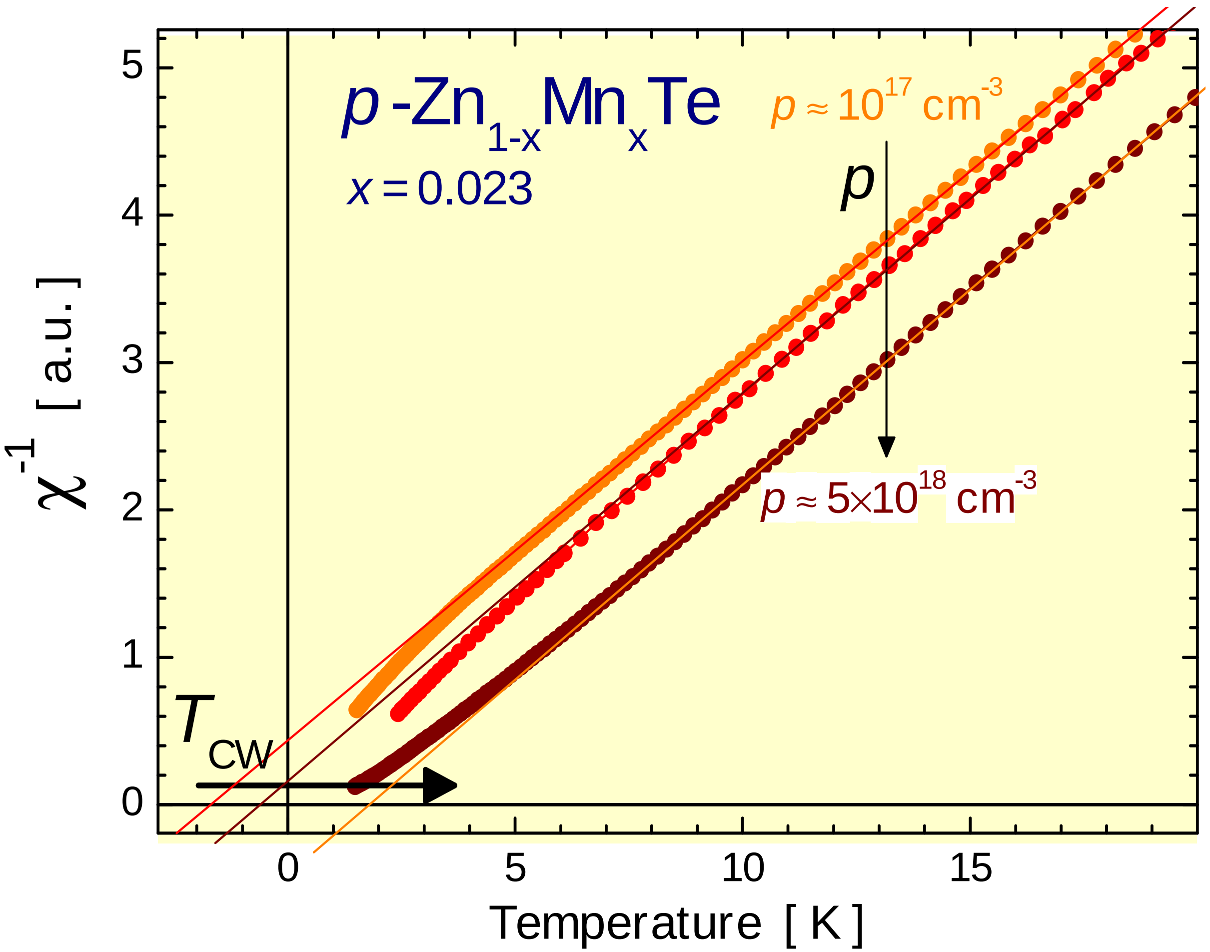


compressive strain



Hole bands are responsible for the anisotropy

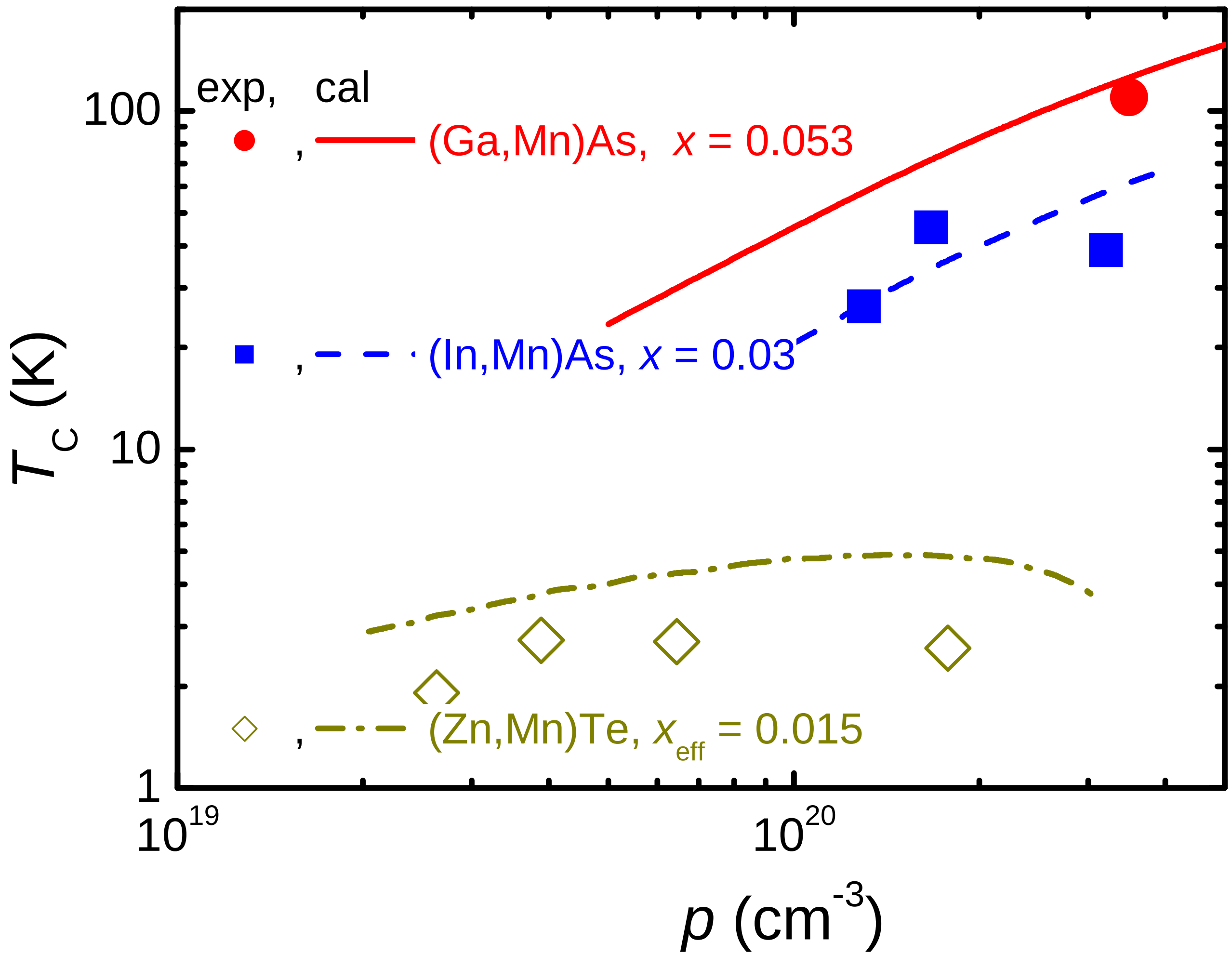
Acceptor doping and susceptibility of $Zn_{1-x}Mn_xTe$:P



χ^{-1} vs. T

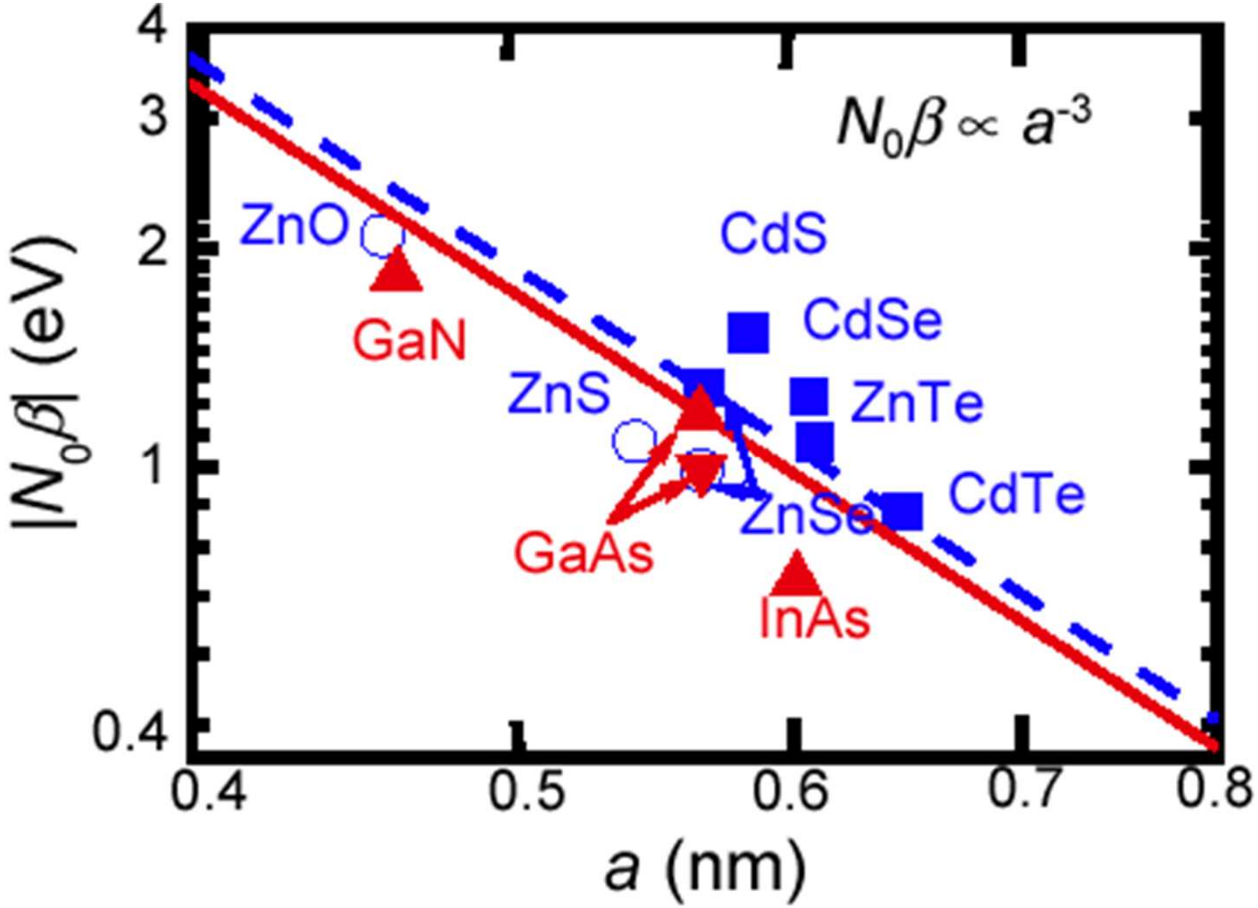
Sawicki et al. (Warsaw) pss'02
Kępa et al. (Warsaw, Oregon) PRL'03

Comparison of Experimental and Calculated T_C



exp.:(Ga,Mn)As:T. Omiya *et al*., Physica E **7**, 976 (2000).
(In,Mn)As: D. Chiba *et al*., J. Supercond. and Novel Mag.16, 179 (2003).
(Zn,Mn)Te: D. Ferrand *et al*., Phys. Rev. B **63**, 085201 (2001).

p-d exchange energy



4. Making “use” of ferromagnetism in semiconductors

- **Electrical control of ferromagnetism**
- **Current induced domain wall motion**
- **Tunneling with magnetism**

commentary

A window on the future of spintronics

Hideo Ohno

NATURE MATERIALS | VOL 9 | DECEMBER 2010 | 952

4. Making “use” of ferromagnetism in semiconductors

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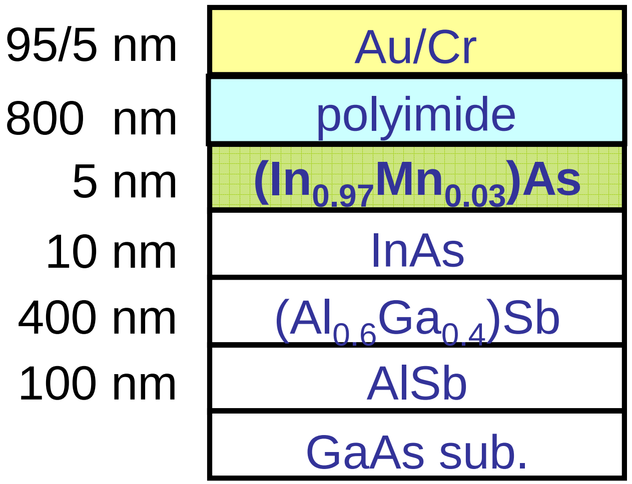
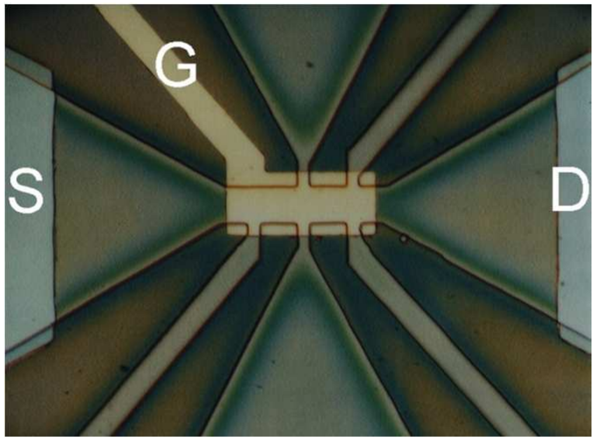
- Tunneling with magnetism

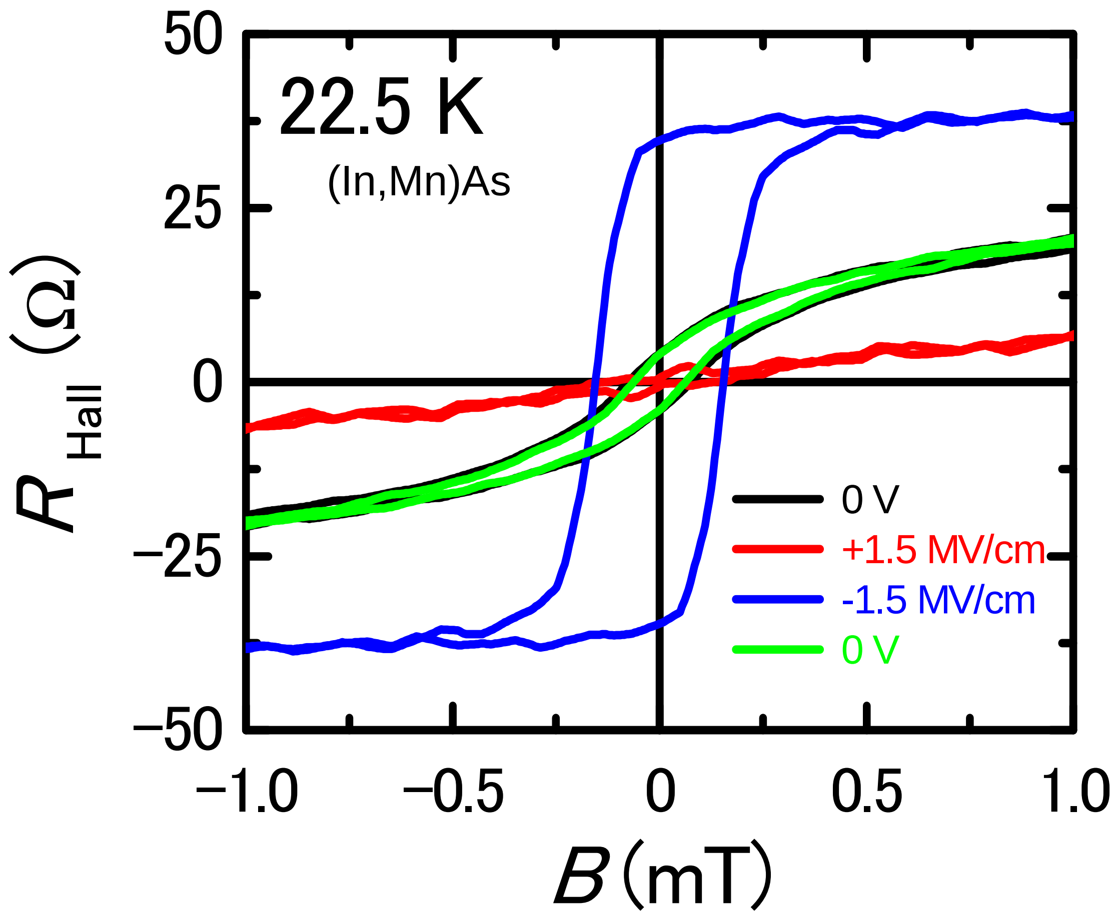
Electric-field control of ferromagnetism

(In,Mn)As



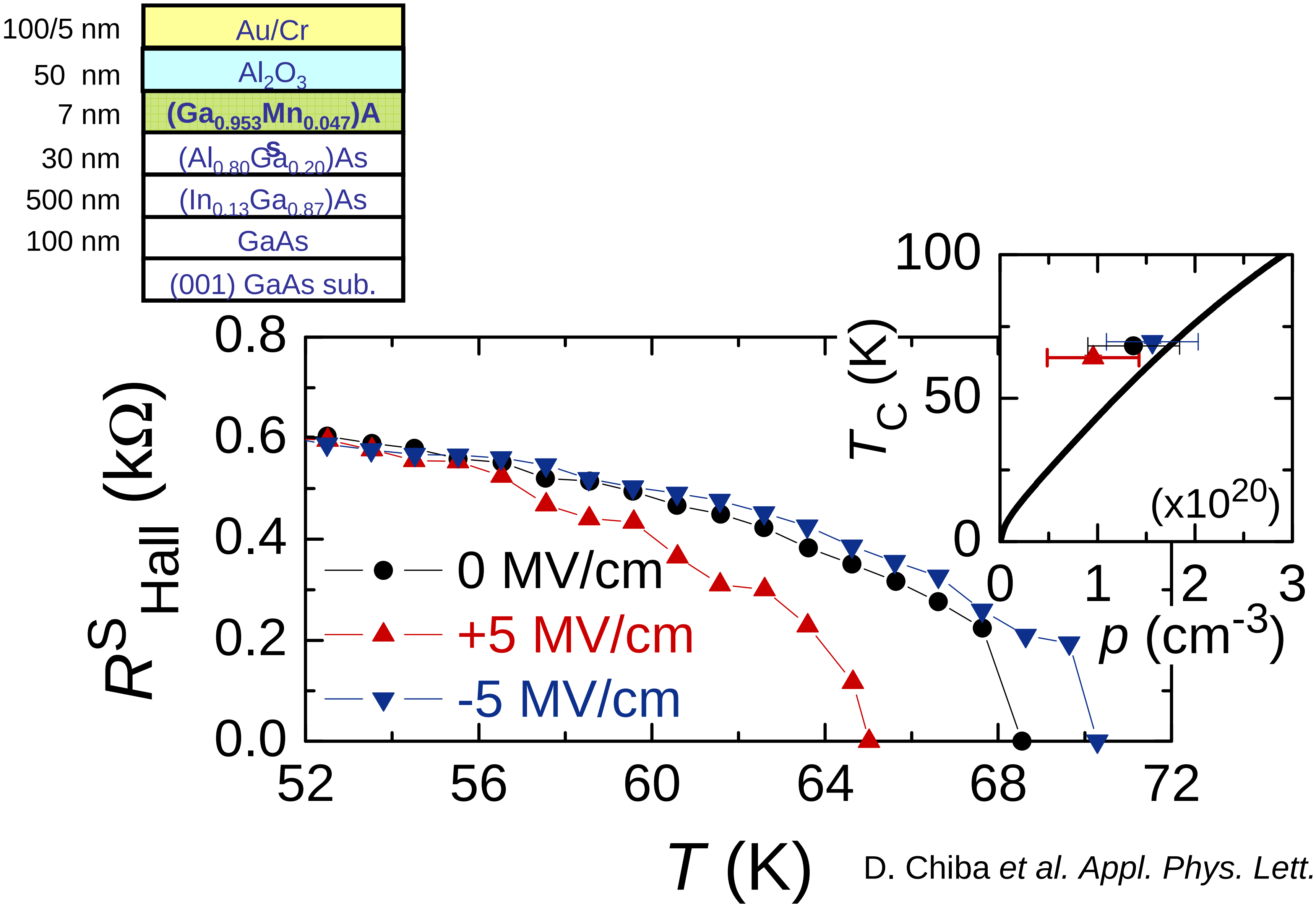


$$R_{Hall} = (R_0/d)B + (R_S/d)M_\perp$$



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

Electric-field control: the case of (Ga,Mn)As

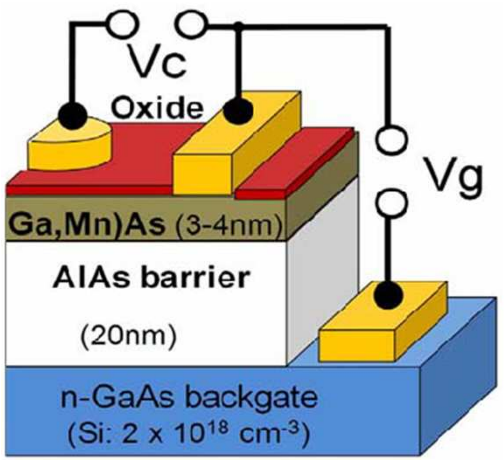


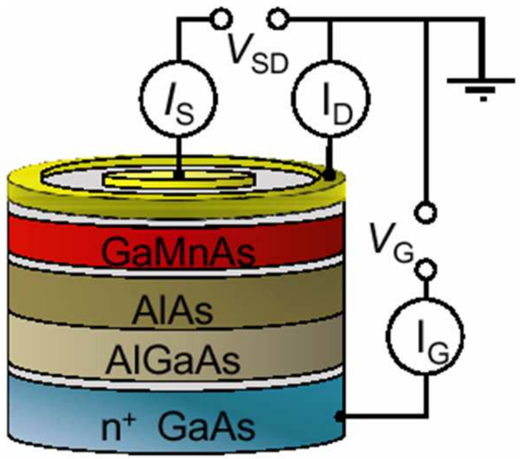
D. Chiba *et al. Appl. Phys. Lett.* 2006

See also Y. Nishitani *et al.*, Phys. Rev. B **81**, 045208 (2010) and M. Sawicki, et al., *Nature Physics*, **6**, 22 (2010)

Field-effect structures of (Ga,Mn)As

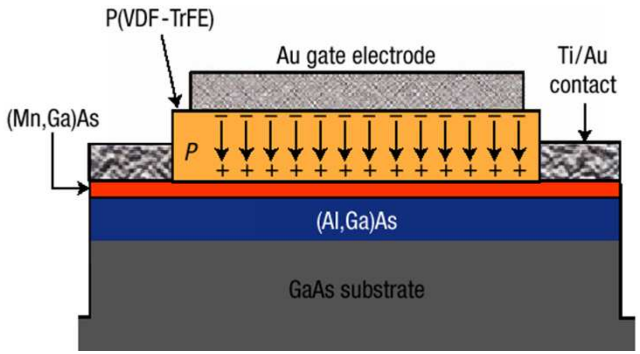
backgate structure





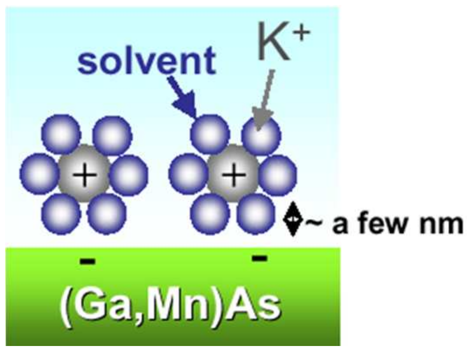
K. Olejník *et al*.,
Phys. Rev. B **78**, 054403 (2008);
M. S. H. Owen *et al*., New J. Phys. **11**, 023008 (2009).

ferroelectric-gate structure



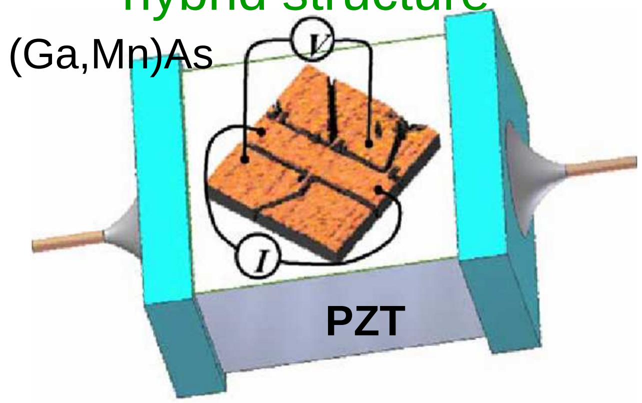
I. Stokichnov *et al*., Nature Mater. **7**, 464 (2008).

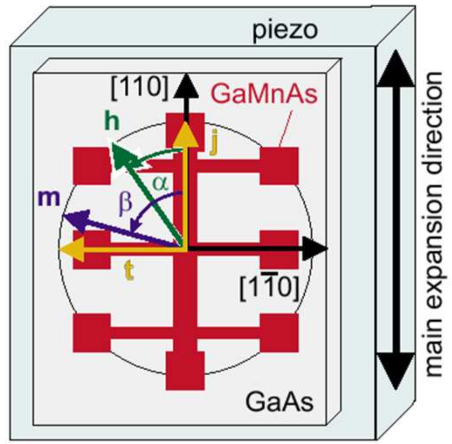
electric double layer



M. Endo *et al*., Appl. Phys. Lett. **96**, 022515 (2010).

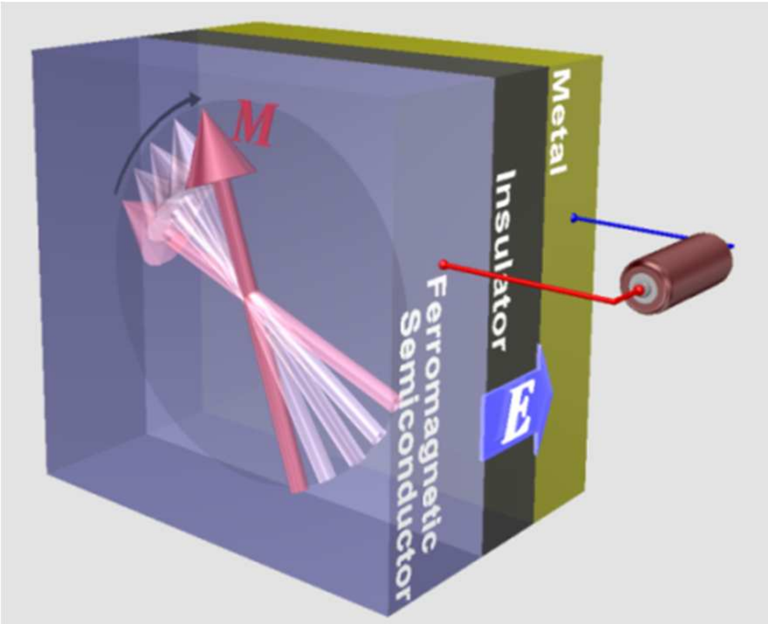
piezoelectric hybrid structure

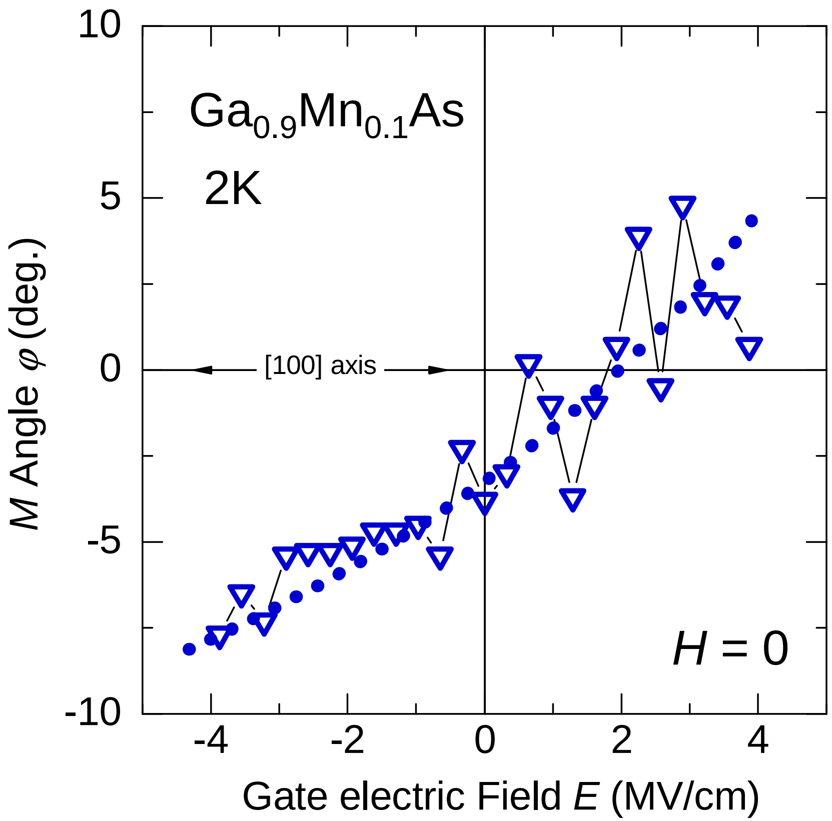




M. Overby *et al*., Appl. Phys. Lett **92**, 192501 (2008); A. W. Rushforth *et al*., Phys. Rev. B **78**, 085314 (2008); S. T. B. Goennenwein et al., phys. stat. sol. (RRL) **2**, 96 (2008); C. Bihler *et al*., Phys. Rev. B **78**, 045203 (2008).

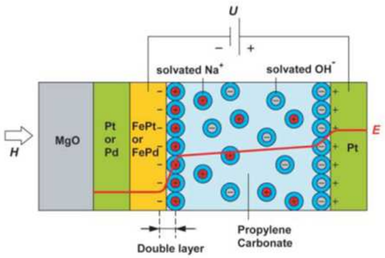
Electric-field control of magnetization direction

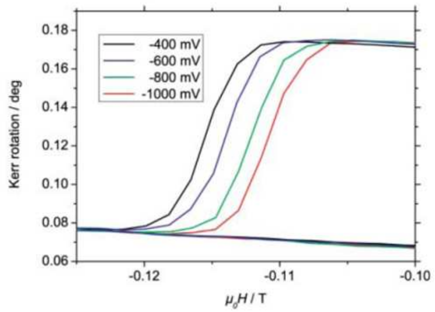


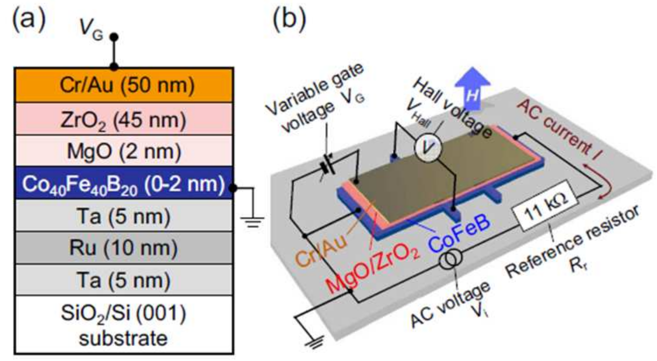


D. Chiba *et al.* Nature (2008).

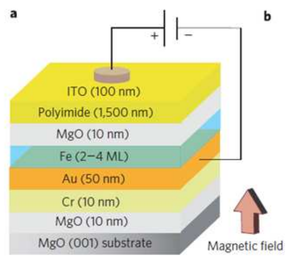
Electric-field effects on metals

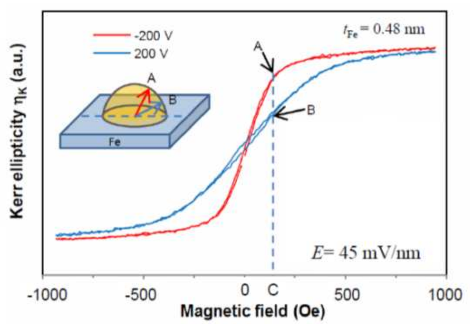


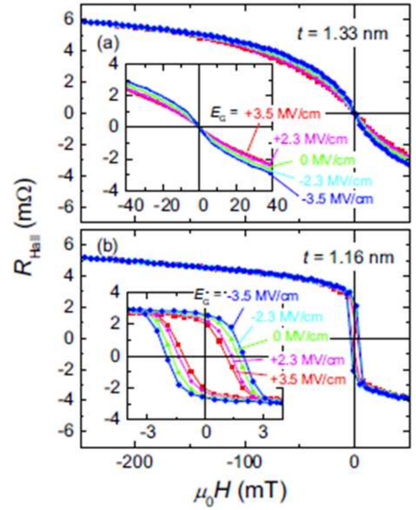


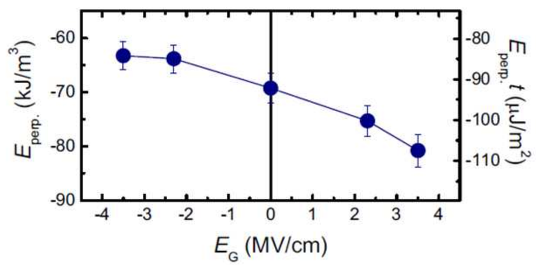


FePt, FePd: M. Weisheit *et al.*, Science (2007).









Au/ ultrathin Fe: T. Maruyama *et al.*, Nature Nanotechnology (2009).

CoFeB: M. Endo, S. Kanai, S. Ikeda, F. Matsukura, and H, Ohno, *Appl. Phys. Lett.* 2010

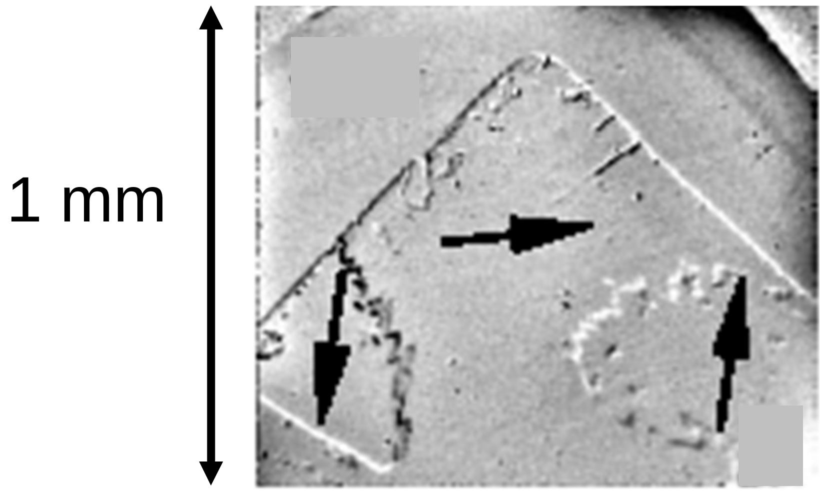
All at room temperature

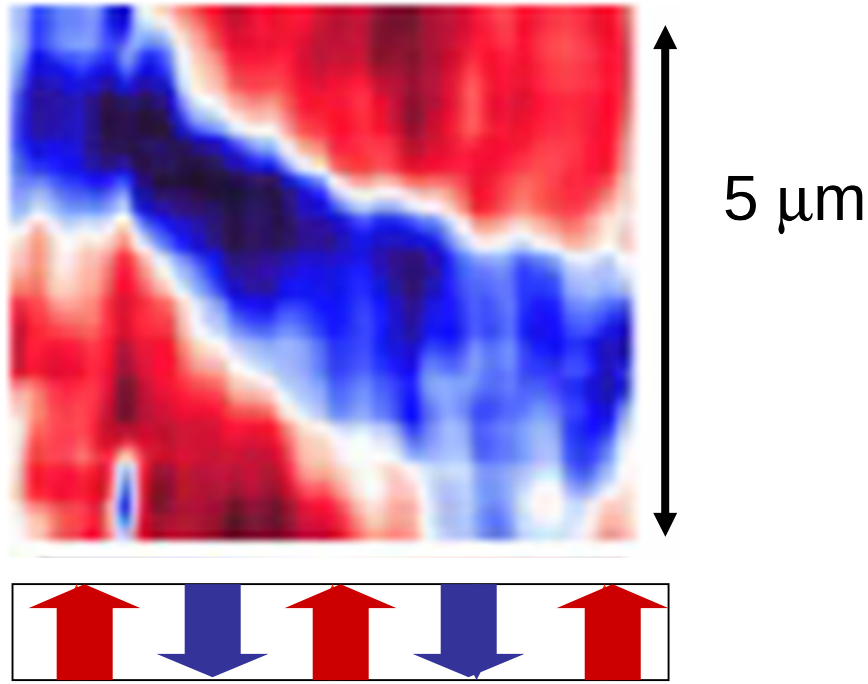
O-23 Kanai et al.

4. Making “use” of ferromagnetism in semiconductors

- Electrical control of ferromagnetism
- **Current induced domain wall motion**
- Tunneling with magnetism

Well defined domains: (Ga,Mn)As





Welp *et al.*, *PRL* 2003

Shono *et al.*, *APL* 2000

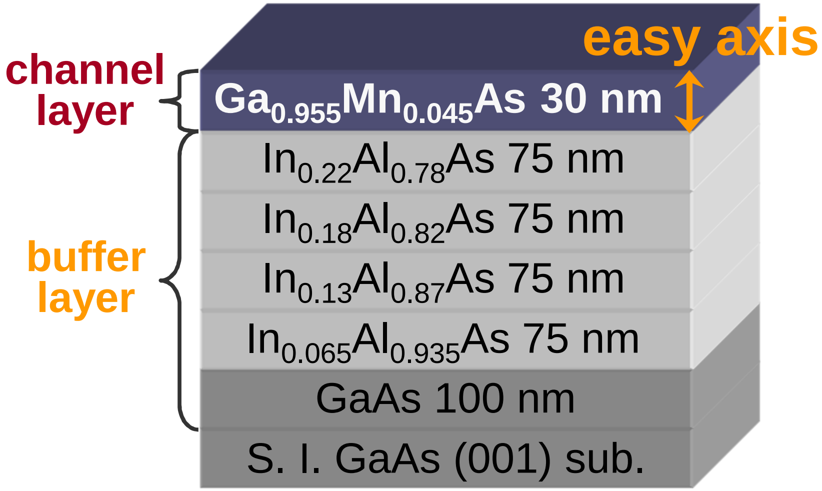
compressive strain
in-plane easy axis
90º domains

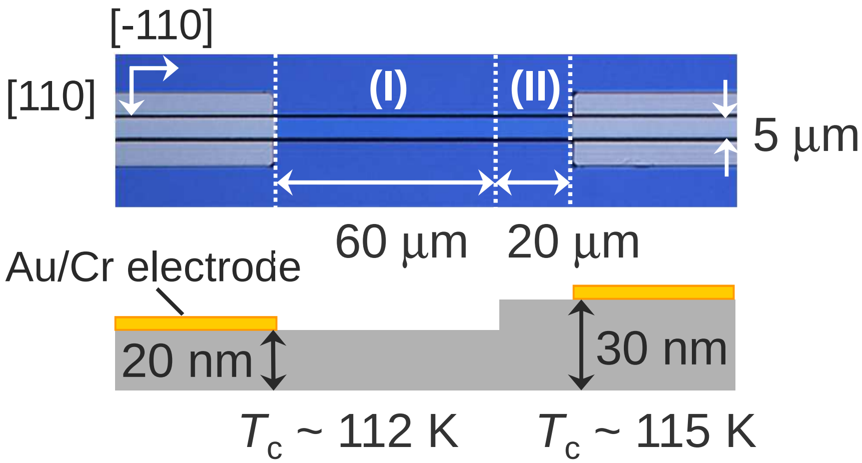
tensile strain
perpendicular easy axis
stripe domains

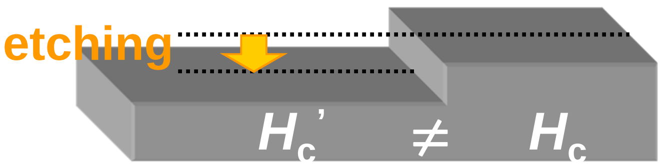
Current induced domain wall motion

Sample structure

perpendicular easy axis



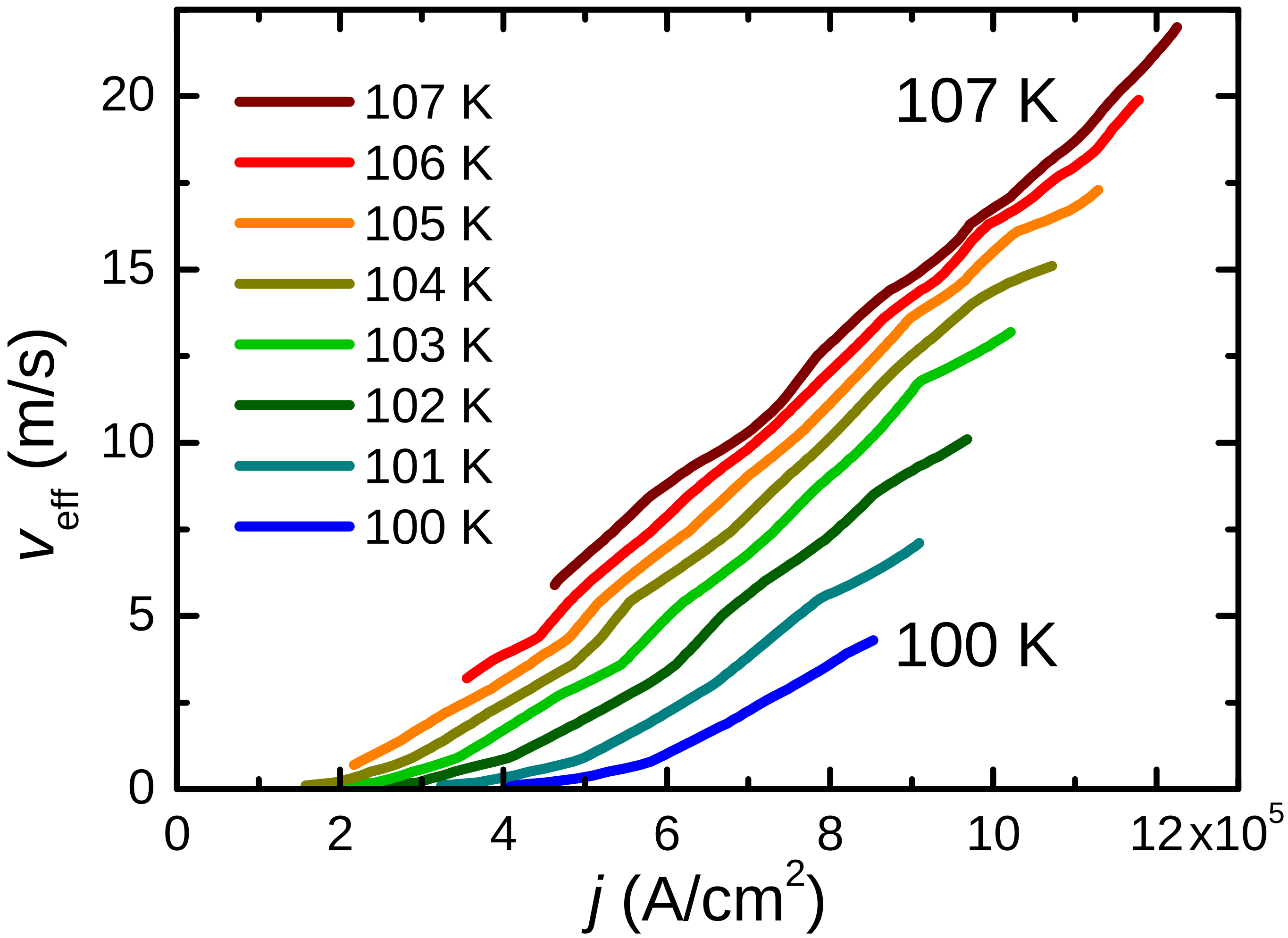




Patterning of coercive force H_c by etching of (Ga,Mn)As

Preparation of domain wall

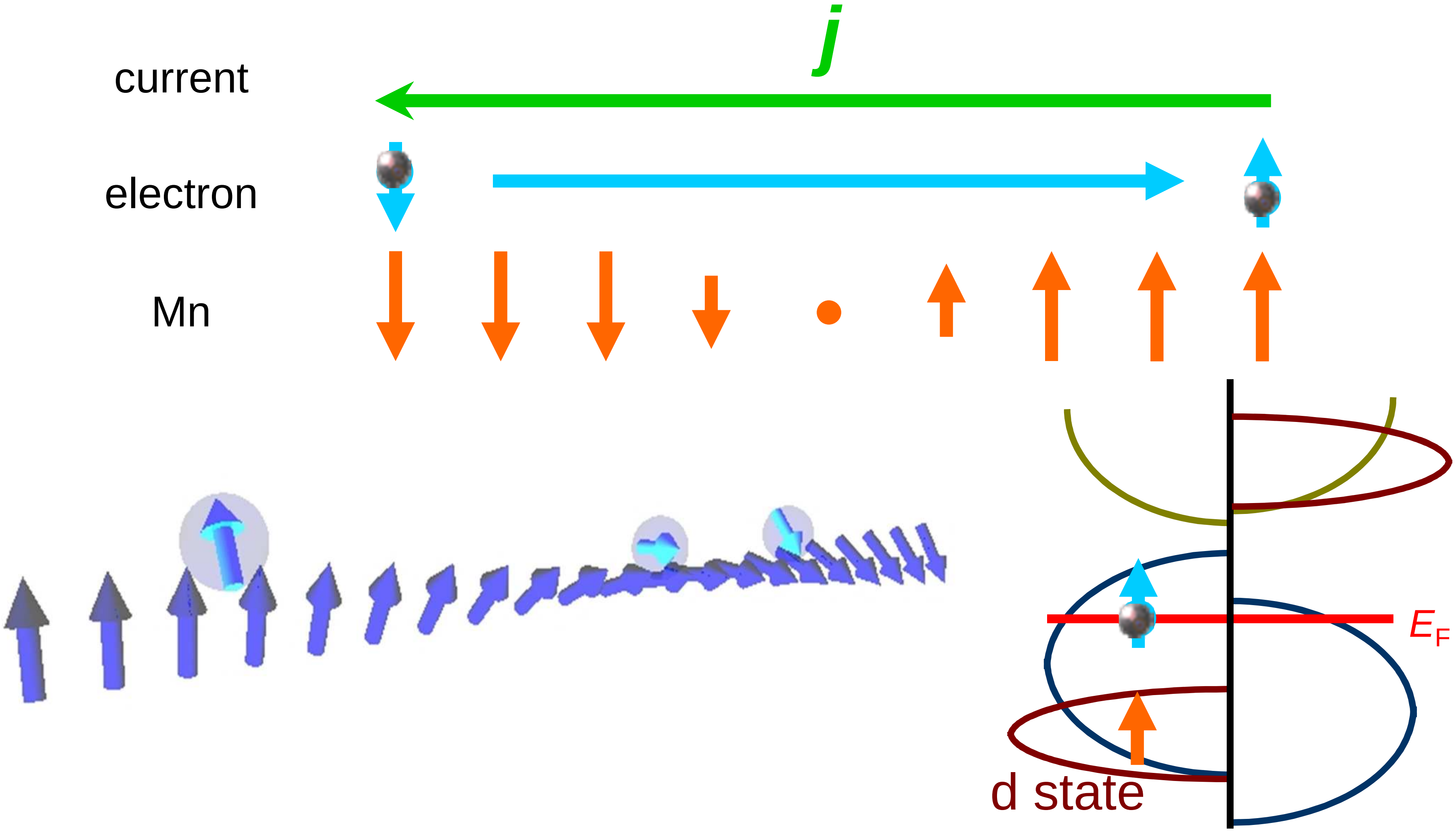
Current induced domain wall motion



M. Yamanouchi *et al.*, *Phys. Rev. Lett.* **96**, 096601 (2006)

Mechanism

- ◆ **Adiabatic spin transfer (conservation of angular momentum)**



Domain wall motion: Theory

- **Square root dependence** (Spin transfer)

G. Tatara and H. Kohno, Phys. Rev. Lett. 92, 086601 (2004).

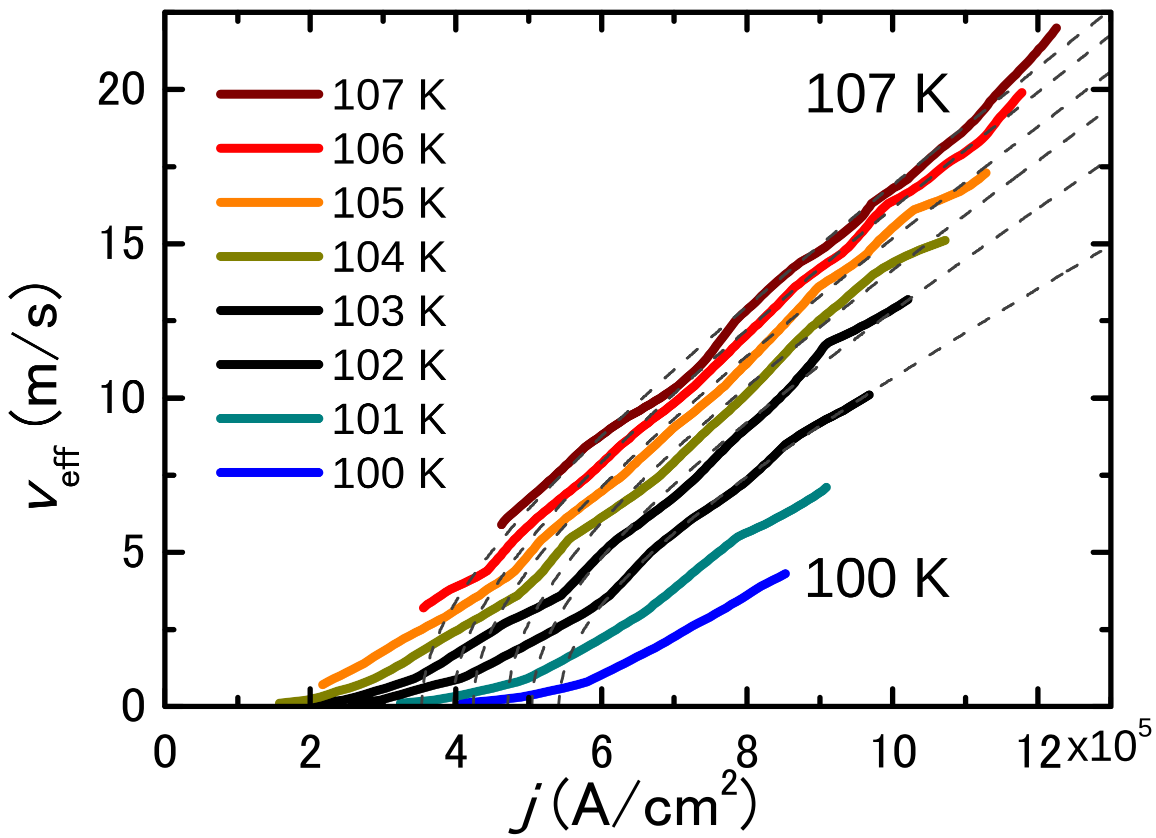
$$v = A(j^2 - j_C^2)^{1/2}$$

$$A = \frac{P g \mu_B}{2 e M}$$

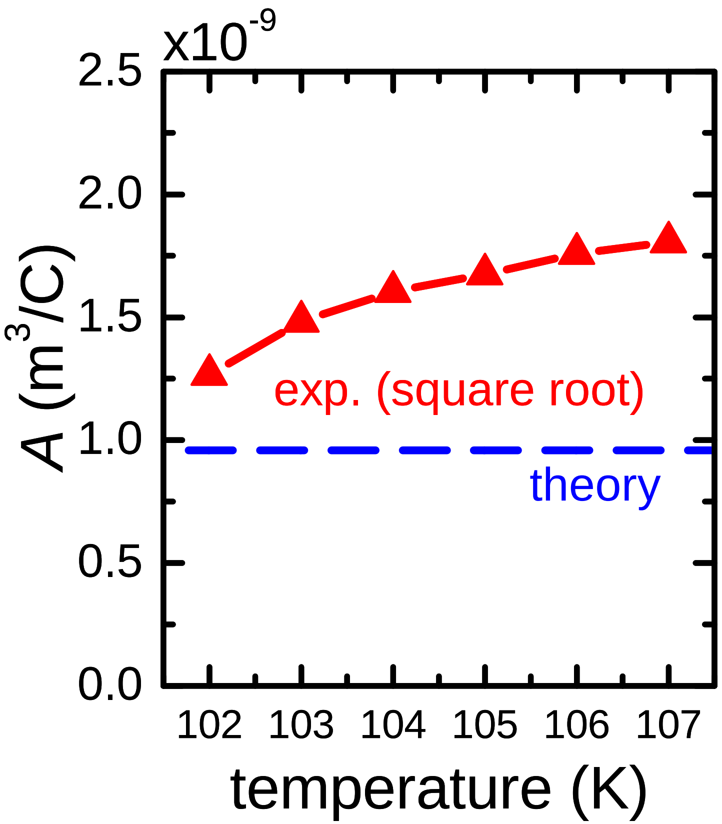
$$j_C = \frac{2 e K \delta_w}{\pi \hbar P}$$

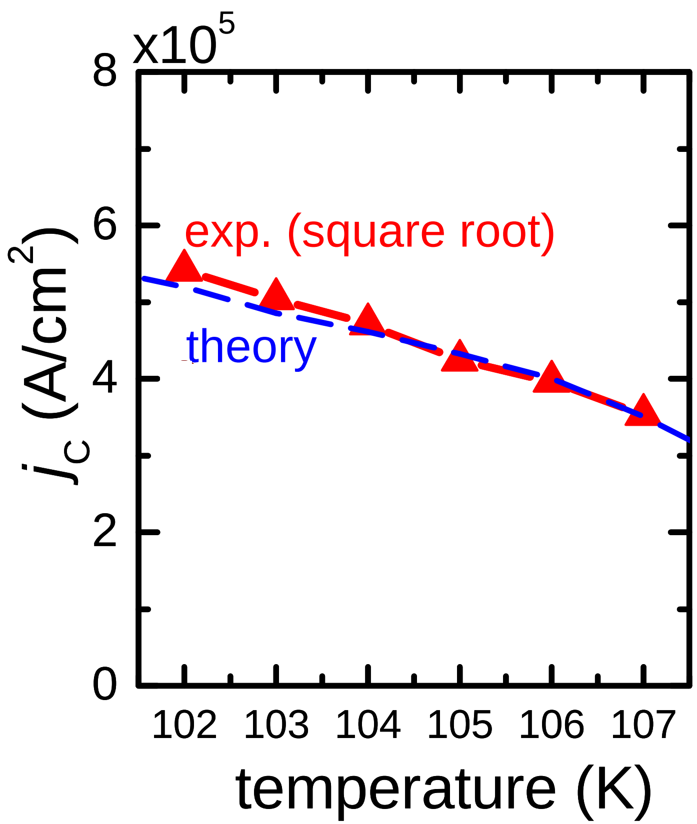
P : spin polarization
g : g factor of Mn spin
μ_B : Bohr magneton
e : charge of electron
M : magnetization
K : transverse anisotropy
δ_w : DW width

Current induced domain wall motion



Transfer factor and threshold current density





$$A = \frac{P\, g\, \mu_B}{2\, e\, M}$$

$$j_C = \frac{2\, e\, K\, \delta_w}{\pi\, \hbar\, P}$$

M. Yamanouchi *et al.*, *Phys. Rev. Lett.* **96**, 096601 (2006)

$$j_C = \frac{2eK\delta_w}{\pi\hbar P}$$

	(Ga,Mn)As (T/T_c ~ 0.9)	**Metal (in plane)**	**Metal (perpendicular)**
K (hard axis anisotropy, J/m^3)	60	4×10^5	10^5
δ_w (domain wall width, nm)	20	100	10
P (spin polarization, %)	20	60	60
j_C (A/m^2)	6×10^9	7×10^{13}	2×10^{12}

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Observation of the intrinsic pinning of a magnetic domain wall in a ferromagnetic nanowire

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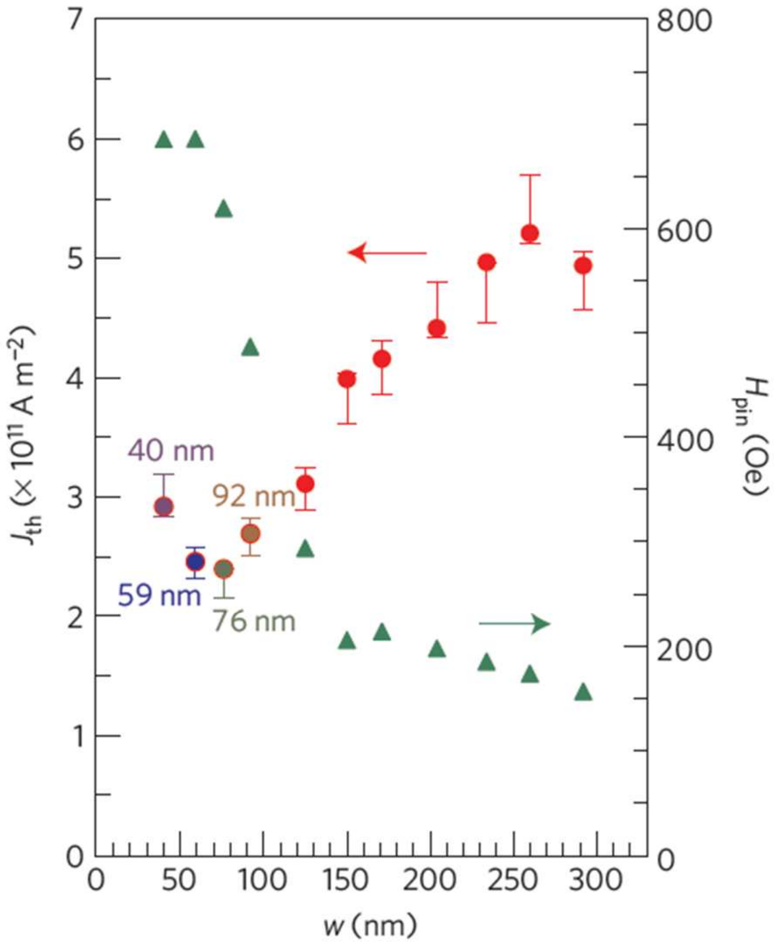
The spin transfer torque is essential for electrical magnetization switching[1,2]. When a magnetic domain wall is driven by an electric current through an adiabatic spin torque, the theory predicts a threshold current even for a perfect wire without any extrinsic pinning[3]. The experimental confirmation of this 'intrinsic pinning', however, has long been missing. Here, we give evidence that this intrinsic pinning determines the threshold, and thus that the adiabatic spin torque dominates the domain wall motion in a perpendicularly magnetized Co/Ni nanowire. The intrinsic nature manifests itself both in the field-independent threshold current and in the presence of its minimum on tuning the wire width. The demonstrated domain wall motion purely due to the adiabatic spin torque will serve to achieve robust operation and low energy consumption in spintronic devices[5-8].



4. Making “use” of ferromagnetism in semiconductors

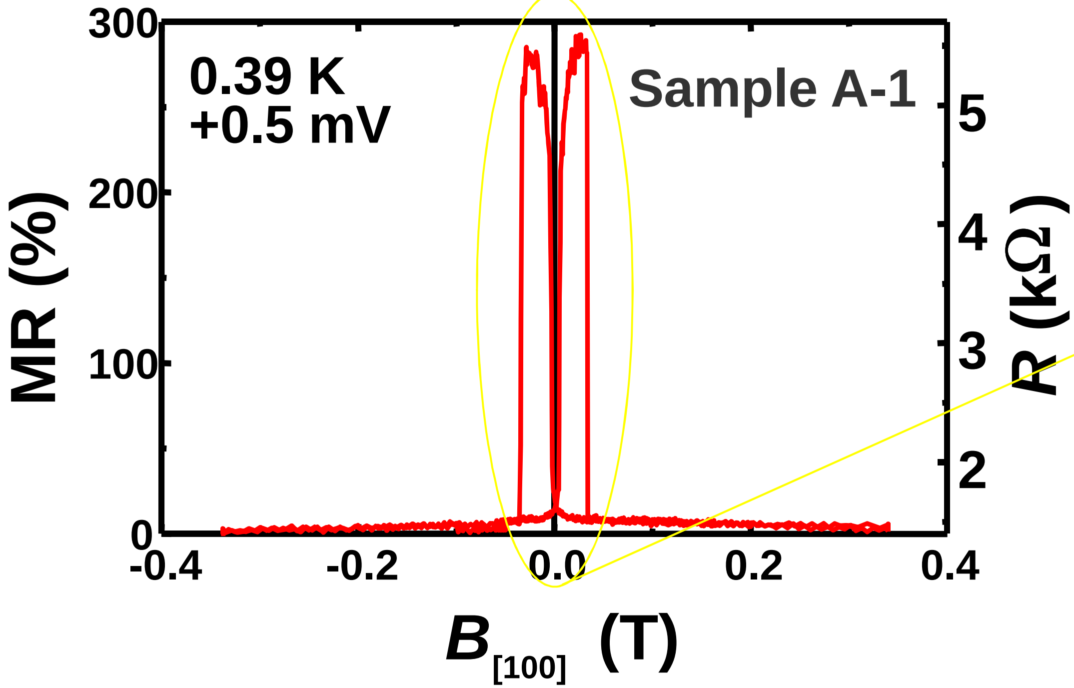
- Electrical control of ferromagnetism
- Current induced domain wall motion
- **Tunneling with magnetism**

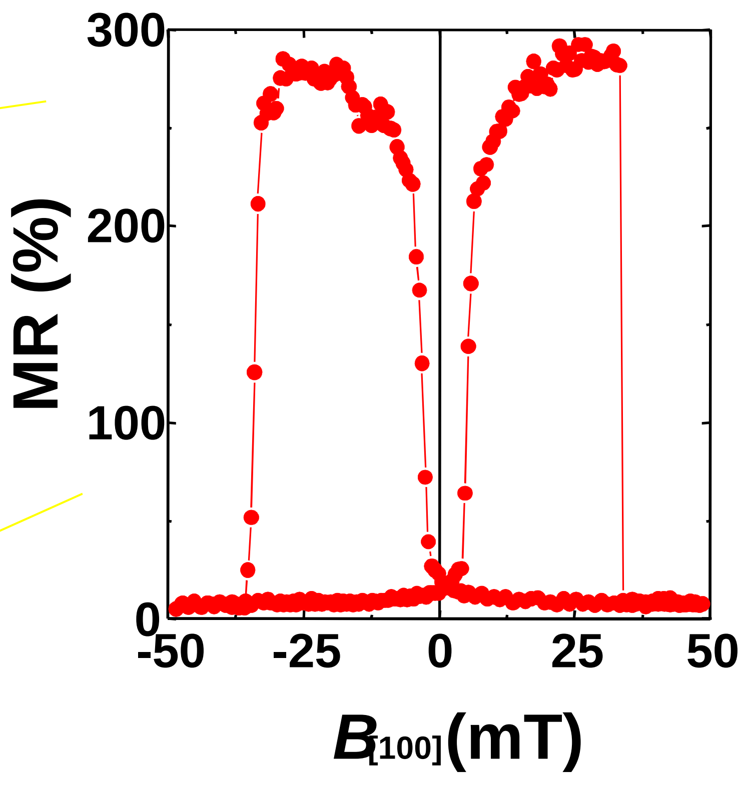
Tunnel Magnetoresistance (TMR)

$$TMR = \frac{2P^2}{1-P^2}$$

20 nm	$(Ga_{0.926}Mn_{0.074})As$	230-240 ℃
6 nm	GaAs	250 ℃
20 nm	$(Ga_{0.956}Mn_{0.044})As$	250 ℃
50 nm	GaAs:Be	560 ℃
p^+- GaAs (001) sub		

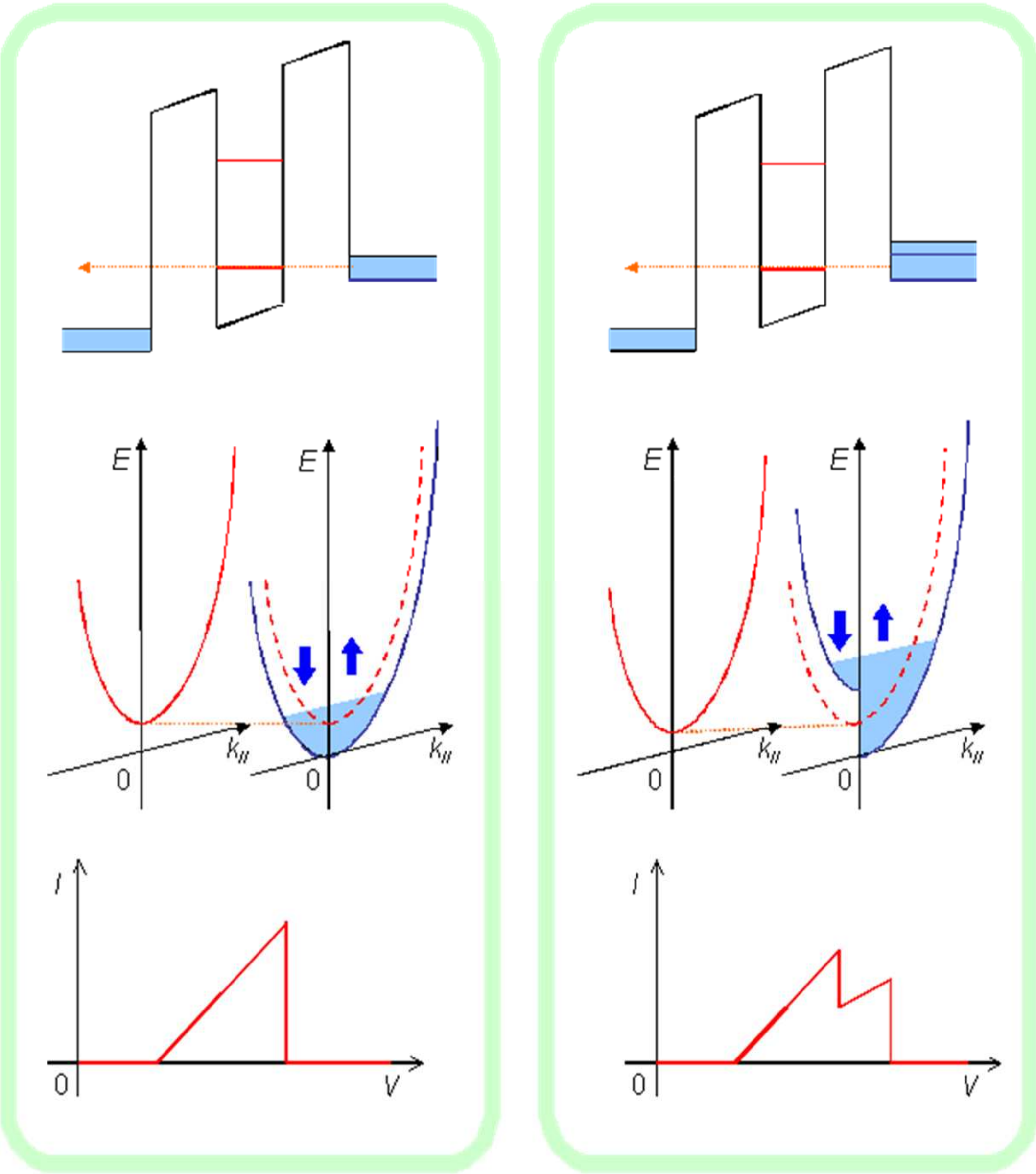
290 %, *P* = 77 %





D. Chiba *et al. Physica E* 2004

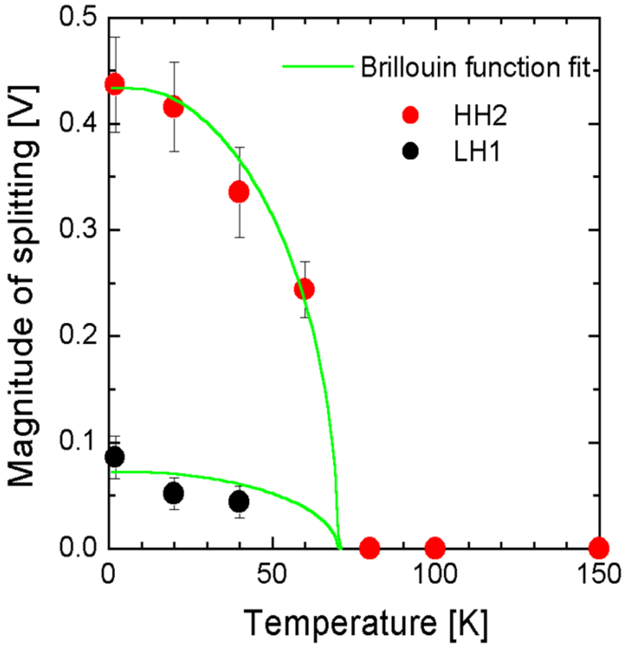
Resonant Tunneling Diode with a Ferromagnetic Emitter

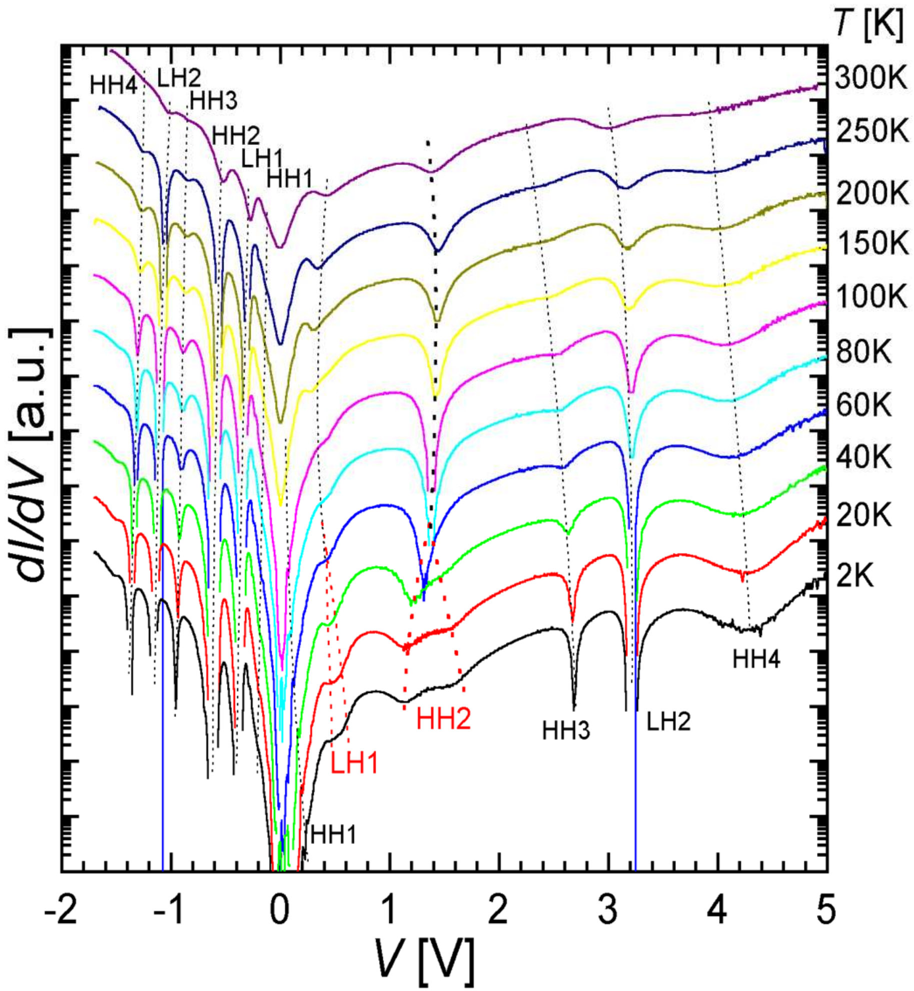


Resonant Tunnel Diode with a Ferromagnetic Emitter

Sample structures

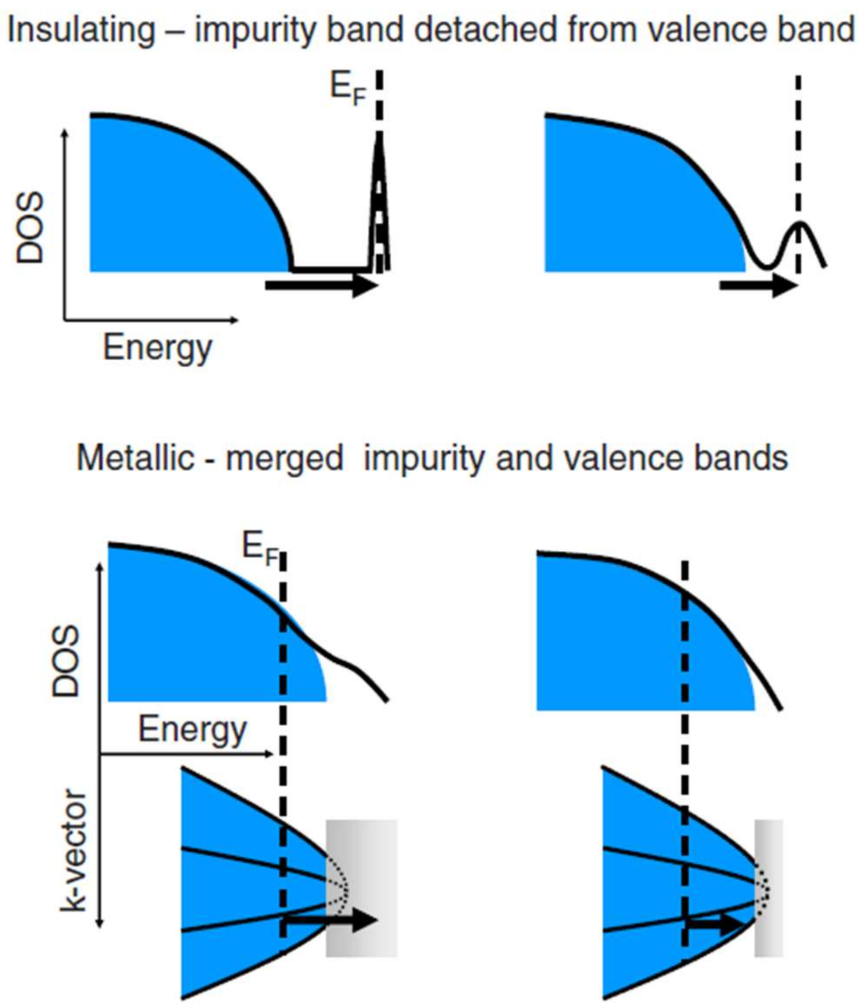
$(Ga_{0.965}Mn_{0.035})As$	200 nm
GaAs	15 nm
AlAs	5 nm
GaAs	d_W nm
AlAs	5 nm
GaAs	5 nm
GaAs:Be ($5x10^{17}cm^{-3}$)	150 nm
GaAs:Be ($5x10^{18}cm^{-3}$)	150 nm
p^+ GaAs sub.	





H. Ohno *et al. Appl. Phys. Lett.*, 1998

Ultra-high doping of Mn in III-V compounds



T. Jungwirth et al., *Phys. Rev.* **B76**, 125206 (2007)

ARTICLES
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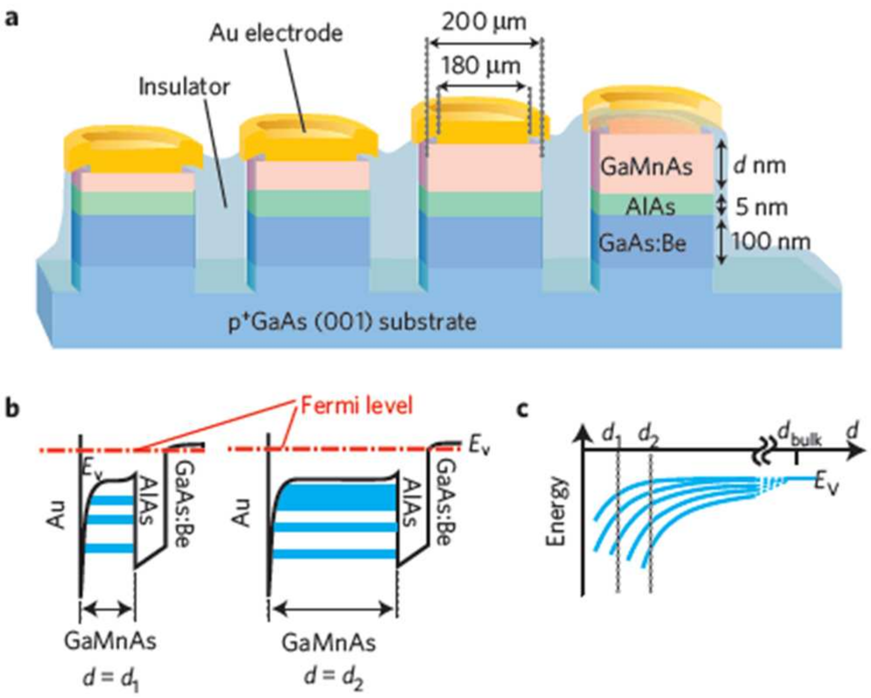
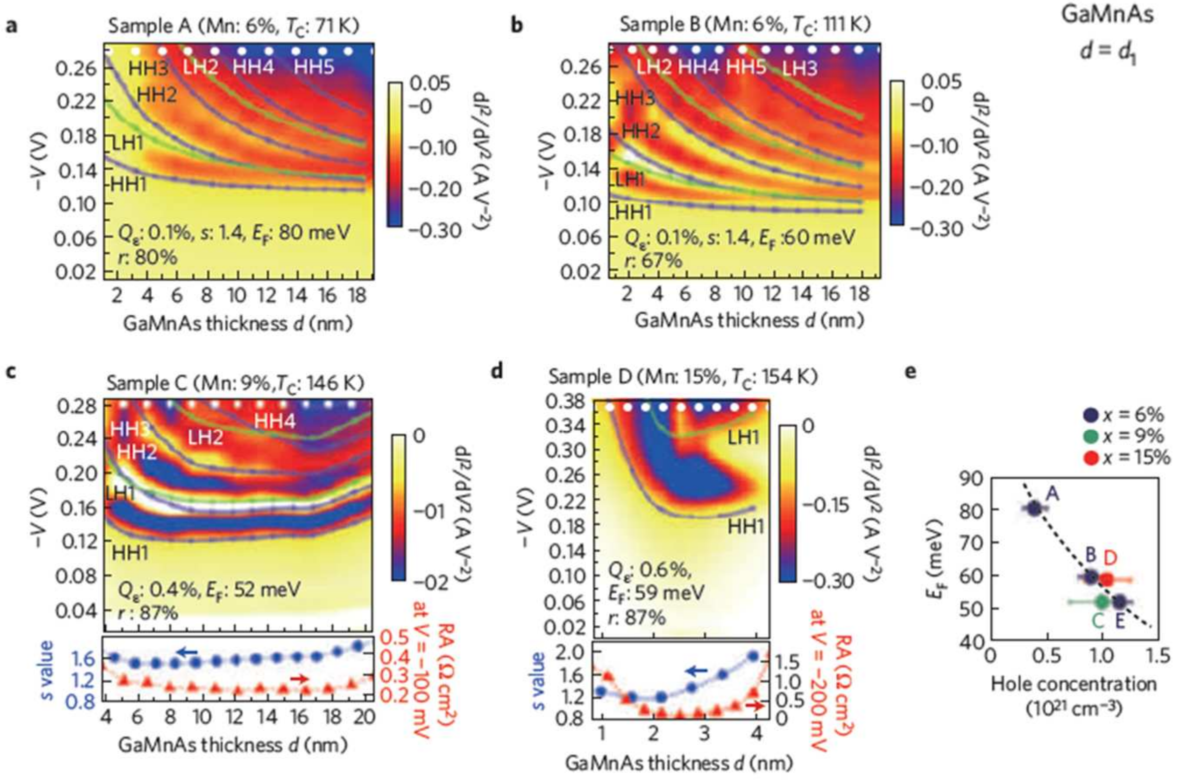
nature physics

Nearly non-magnetic valence band of the ferromagnetic semiconductor GaMnAs

Shinobu Ohya*, Kenta Takata and Masaaki Tanaka*



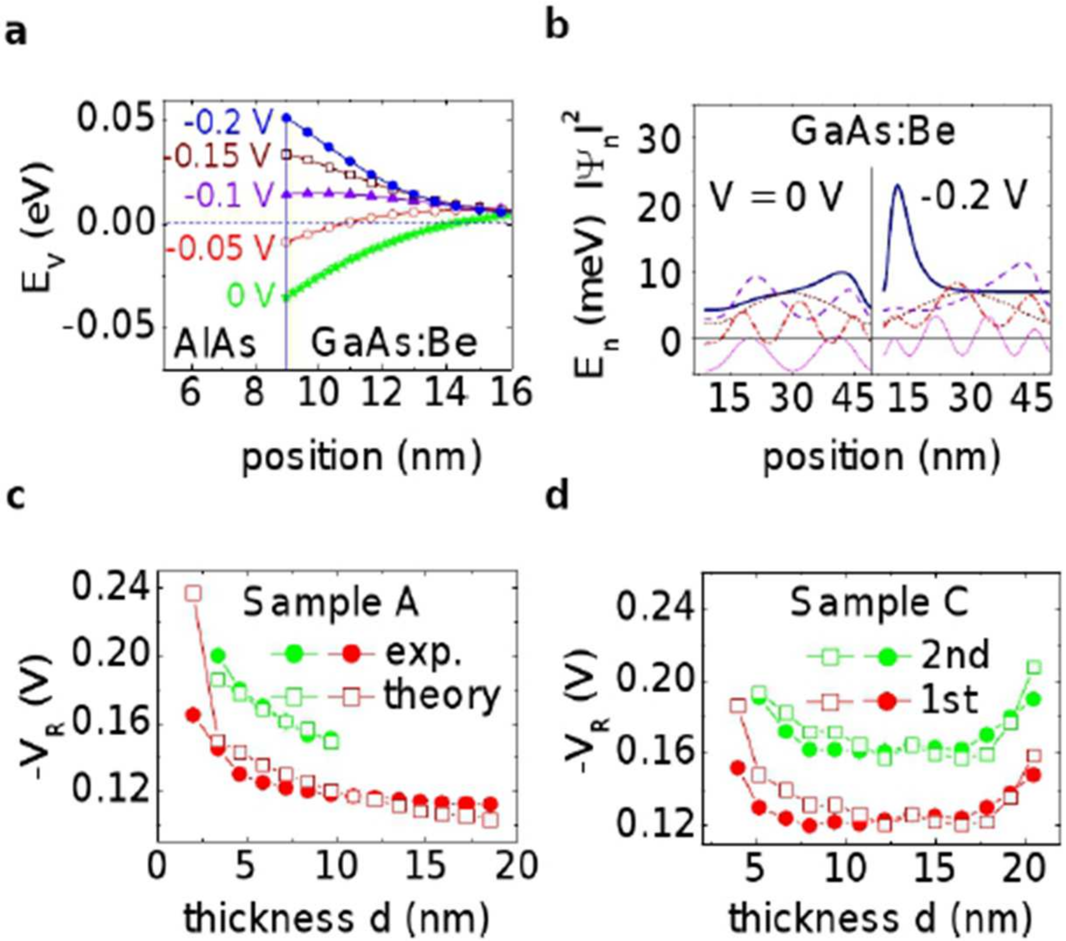
Spintech VI, O-10



Reconciling results of tunnelling experiments on (Ga,Mn)As

T. Dietl[1,2] and D. Sztenkiel[1] arXiv 1102.3267v2 (Spintech VI poster FP-42)

(Formation of 2D holes in GaAs:Be explains the resonant tunnel-like feature and the thickness dependence)



Diluted Magnetic Semiconductors

1. What you need to know about nonmagnetic semiconductors
   - Band structure
2. How you make a semiconductor magnetic
   - Doping and *sp-d* exchange
3. The consequences of exchange interaction
   - Spin-split bands and ferromagnetism
4. Making “use” of ferromagnetism in semiconductors
   - Electrical control of ferromagnetism
   - Current induced domain wall motion
   - Tunneling with magnetism