

Diluted Magnetic Semiconductors

- An Introduction -

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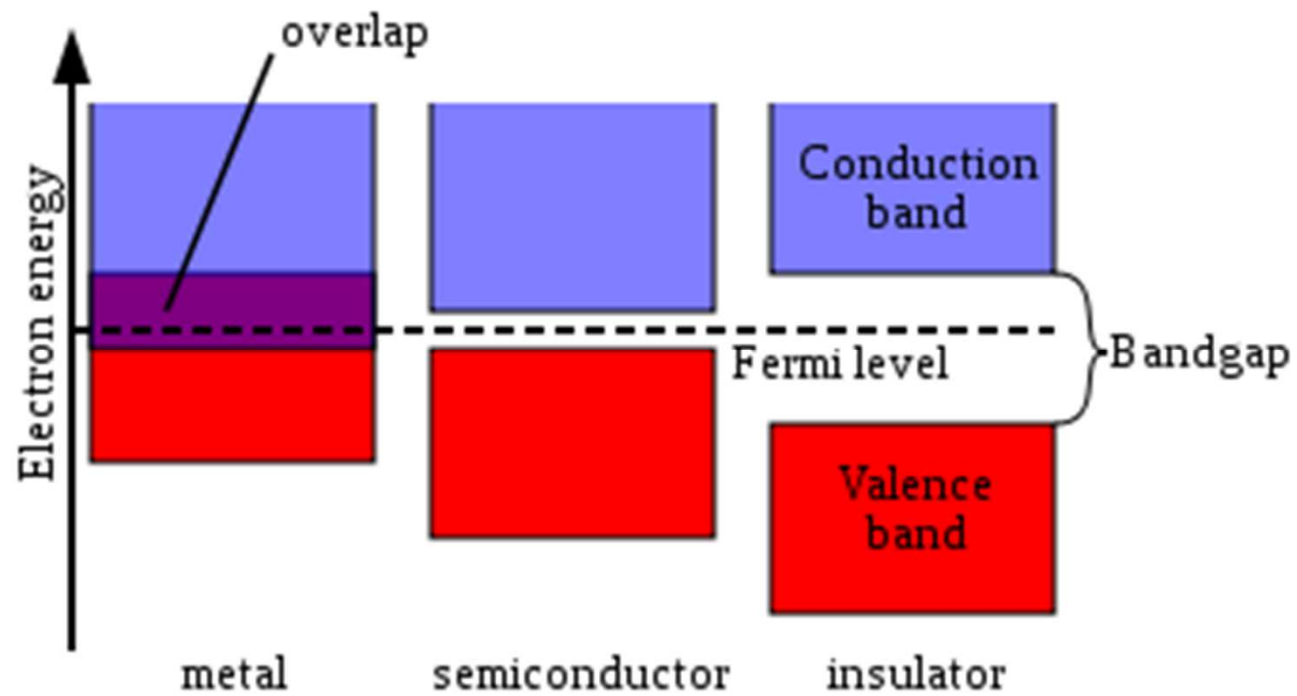
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1. What you need to know about nonmagnetic semiconductors
 - Band structure
2. How you make a semiconductor magnetic
 - Doping and *sp-d* exchange
3. The consequences of exchange interaction
 - Spin-split bands and ferromagnetism
4. Making “use” of 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.

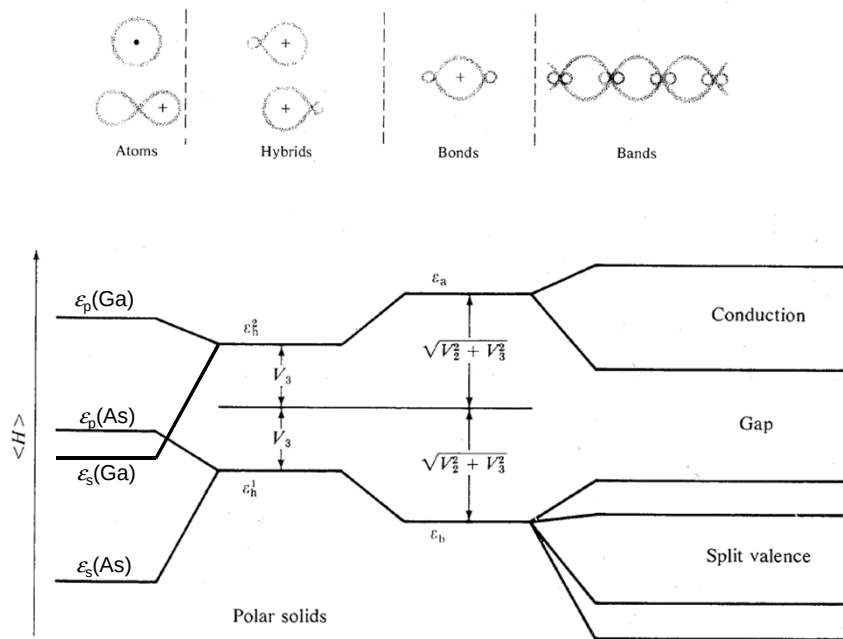
1. What you need to know about nonmagnetic semiconductors

- **Band structure**

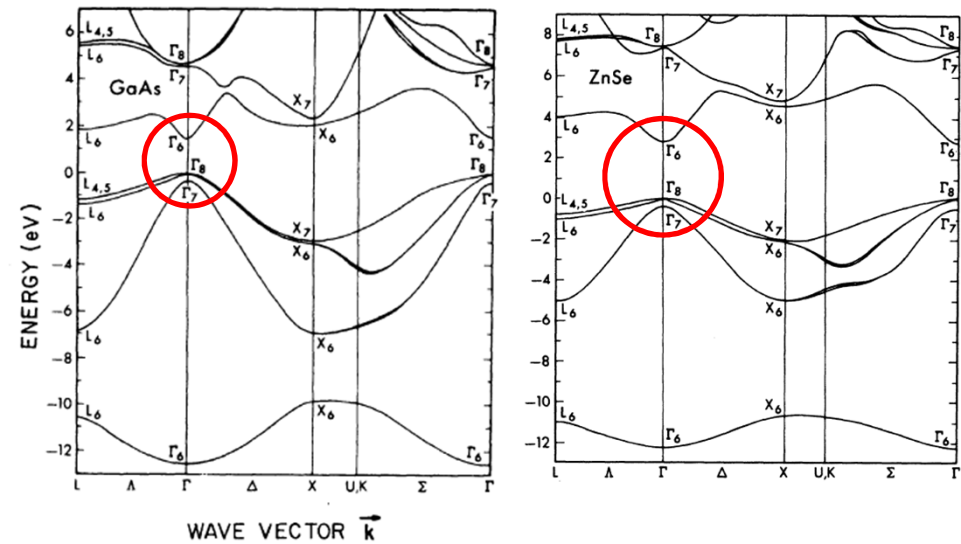


Electronic band structure

From Wikipedia, the free encyclopedia

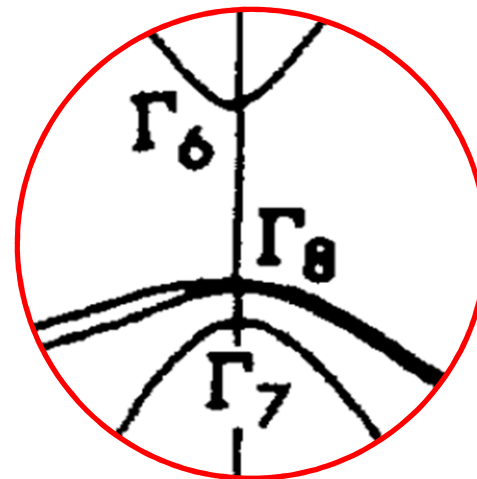


taken from Walter A. Harrison "Electronic Structure and the Properties of Solids
-The Physics of Chemical Bond -, 1980

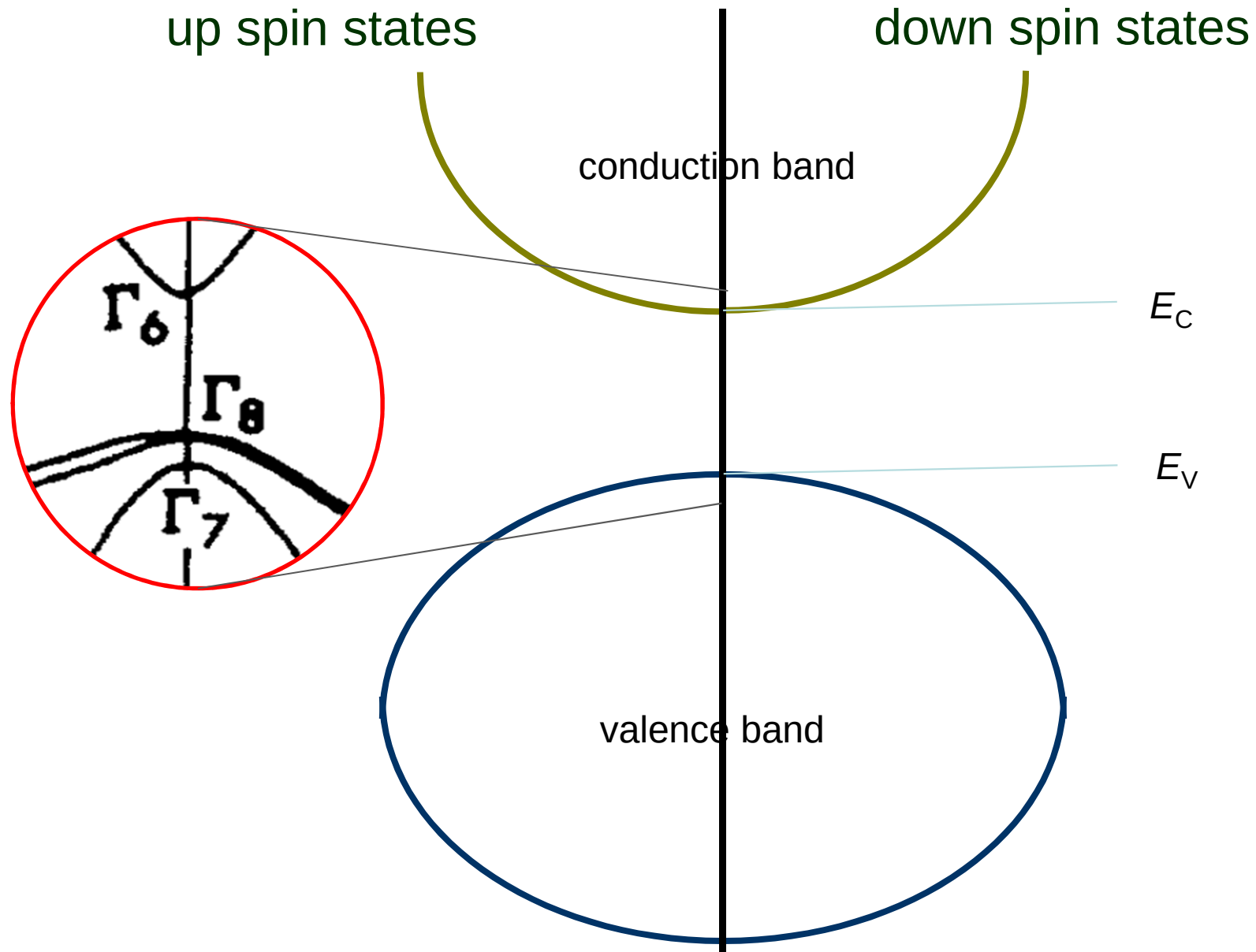


J. R. Chelikowsky and M. L. Cohen, *Phys. Rev.* **B14**, 556 (1976)

Bottom of the conduction band: **Ga 4s**
Top of the valence band: **As 4p**



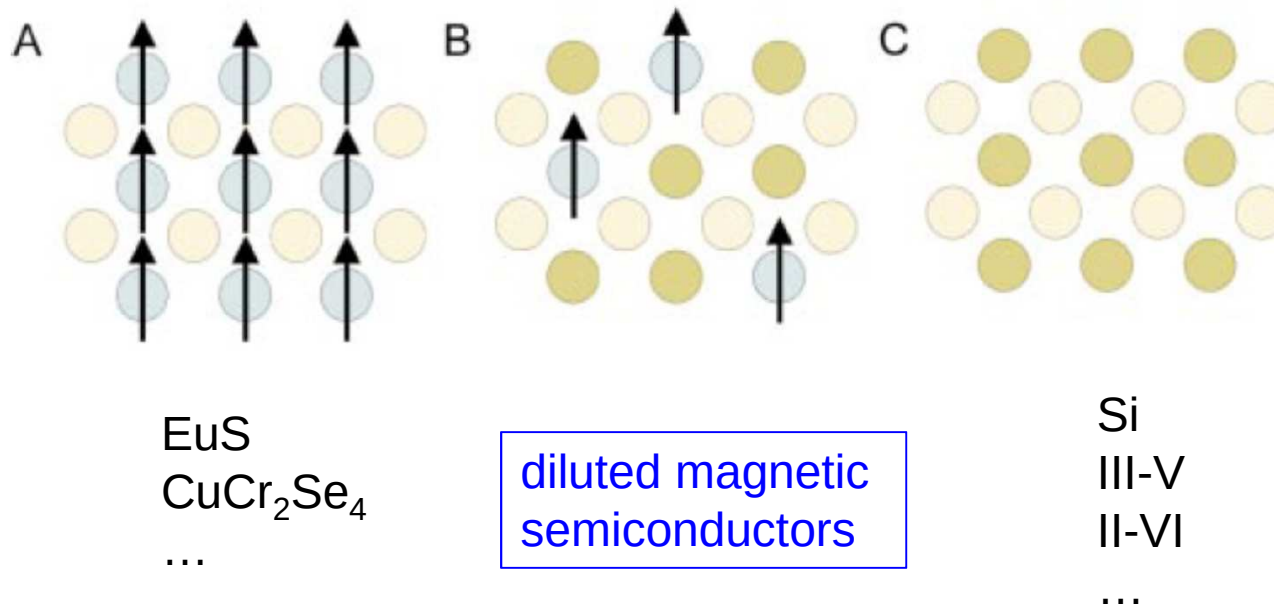
Density of states



2. How you make a semiconductor magnetic

- Doping and *sp-d* exchange

Making semiconductor magnetic



Magnetic ion: Mn

PERIODIC TABLE
Atomic Properties of the Elements

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum c 299 792 458 m s⁻¹ (exact)
Planck constant h 6.626 068 96 × 10⁻³⁴ J s ($\hbar = h/2\pi$)
elementary charge e 1.602 176 634 × 10⁻¹⁹ C
electron mass m_e 9.109 383 56 × 10⁻³¹ kg
proton mass m_p 1.672 621 63 × 10⁻²⁷ kg
fine-structure constant α 1/137.035 999 084
Rydberg constant R_∞ 1.097 373 156 850 9 × 10¹⁰ m⁻¹
 $R_\infty hc$ 13.605 698 065 8 eV
Boltzmann constant k 1.380 658 × 10⁻²³ J K⁻¹

☐ Solids
☐ Liquids
☐ Gases
☐ Artificially Prepared

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Physics Laboratory physics.nist.gov
Standard Reference Data Group www.nist.gov/srd

Group 1 IA	2 IIA											13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA																																																																																																													
1 H 1.00794 1s	4 Be 9.012182 1s ² 2s ²											5 B 10.811 1s ² 2s ² 2p ¹	6 C 12.0107 1s ² 2s ² 2p ²	7 N 14.0064 1s ² 2s ² 2p ³	8 O 15.9994 1s ² 2s ² 2p ⁴	9 F 18.9984032 1s ² 2s ² 2p ⁵	10 Ne 20.1797 1s ² 2s ² 2p ⁶																																																																																																													
3 Li 6.941 1s ² 2s ¹	11 Na 22.989770 [Ne]3s ¹	12 Mg 24.3050 [Ne]3s ²	19 K 39.0983 [Ar]4s ¹	20 Ca 40.078 [Ar]4s ²	21 Sc 44.955910 [Ar]3d ¹ 4s ²	22 Ti 47.867 [Ar]3d ² 4s ²	23 V 50.9415 [Ar]3d ³ 4s ²	24 Cr 51.9961 [Ar]3d ⁵ 4s ¹	25 Mn 54.938049 [Ar]3d ⁵ 4s ²	26 Fe 55.845 [Ar]3d ⁶ 4s ²	27 Co 58.933200 [Ar]3d ⁷ 4s ²	28 Ni 58.6934 [Ar]3d ⁸ 4s ²	29 Cu 63.546 [Ar]3d ¹⁰ 4s ¹	30 Zn 65.409 [Ar]3d ¹⁰ 4s ²	31 Ga 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹	32 Ge 72.64 [Ar]3d ¹⁰ 4s ² 4p ²	33 As 74.92160 [Ar]3d ¹⁰ 4s ² 4p ³	34 Se 78.96 [Ar]3d ¹⁰ 4s ² 4p ⁴	35 Br 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵	36 Kr 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶																																																																																																										
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¹⁴ 6s ²	71 Lu 174.967 [Xe]4f ¹⁴ 5d ¹ 6s ²	72 Hf 178.49 [Xe]4f ¹⁴ 5d ² 6s ²	73 Ta 180.94788 [Xe]4f ¹⁴ 5d ³ 6s ²	74 W 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ²	75 Re 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ²	76 Os 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ²	77 Ir 192.222 [Xe]4f ¹⁴ 5d ⁷ 6s ²	78 Pt 195.084 [Xe]4f ¹⁴ 5d ⁹ 6s ¹	79 Au 196.96657 [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹	80 Hg 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ²	81 Tl 204.38 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	82 Pb 207.2 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	83 Bi 208.9804 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	84 Po 209 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	85 At 210 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	86 Rn 222 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶	87 Fr 223 [Rn]7s ¹	88 Ra 226 [Rn]7s ²	89 Ac 227 [Rn]6d ¹ 7s ²	90 Th 232.0377 [Rn]6d ² 7s ²	91 Pa 231.03688 [Rn]5f ² 6d ¹ 7s ²	92 U 238.02891 [Rn]5f ³ 6d ¹ 7s ²	93 Np 237.04817 [Rn]5f ⁴ 6s ²	94 Pu 239.05216 [Rn]5f ⁶ 7s ²	95 Am 243.06138 [Rn]5f ⁷ 7s ²	96 Cm 247.07715 [Rn]5f ⁷ 6d ¹ 7s ²	97 Bk 247.07031 [Rn]5f ⁷ 6d ¹ 7s ²	98 Cf 251.0833 [Rn]5f ¹⁰ 7s ²	99 Es 252.083 [Rn]5f ¹¹ 7s ²	100 Fm 257.10 [Rn]5f ¹² 7s ²	101 Md 258.10 [Rn]5f ¹³ 7s ²	102 No 259.10 [Rn]5f ¹⁴ 7s ²	103 Lr 262.10 [Rn]5f ¹⁴ 6d ¹ 7s ²	104 Rf 261.10 [Rn]5f ¹⁴ 6d ² 7s ²	105 Db 262.10 [Rn]5f ¹⁴ 6d ³ 7s ²	106 Sg 266.10 [Rn]5f ¹⁴ 6d ⁴ 7s ²	107 Bh 264.10 [Rn]5f ¹⁴ 6d ⁵ 7s ²	108 Hs 277.10 [Rn]5f ¹⁴ 6d ⁶ 7s ²	109 Mt 268.10 [Rn]5f ¹⁴ 6d ⁷ 7s ²	110 Ds 271.10 [Rn]5f ¹⁴ 6d ⁸ 7s ²	111 Rg 272.10 [Rn]5f ¹⁴ 6d ⁹ 7s ²	112 Uub 285.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ²	113 Uut 288.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ¹	114 Uuq 289.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	115 Uup 290.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ³	116 Uuh 291.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁴	117 Uus 292.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁵	118 Uuo 293.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶	119 Uue 294.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ¹	120 Uub 295.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ²	121 Uut 296.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ¹	122 Uuq 297.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ²	123 Uup 298.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ³	124 Uuh 299.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁴	125 Uus 300.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁵	126 Uuo 301.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶	127 Uue 302.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹	128 Uub 303.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ²	129 Uut 304.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ³	130 Uuq 305.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ⁴	131 Uup 306.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ⁵	132 Uuh 307.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ⁶	133 Uus 308.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ⁷	134 Uuo 309.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ⁸	135 Uue 310.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ⁹	136 Uub 311.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰	137 Uut 312.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ¹	138 Uuq 313.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ²	139 Uup 314.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ¹	140 Uuh 315.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ²	141 Uus 316.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ³	142 Uuo 317.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁴	143 Uue 318.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁵	144 Uub 319.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶	145 Uut 320.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ¹	146 Uuq 321.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ²	147 Uup 322.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ¹	148 Uuh 323.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ²	149 Uus 324.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ³	150 Uuo 325.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁴	151 Uue 326.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁵	152 Uub 327.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶	153 Uut 328.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶ 11s ¹	154 Uuq 329.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶ 11s ²	155 Uup 330.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶ 11s ² 11p ¹	156 Uuh 331.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶ 11s ² 11p ²	157 Uus 332.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶ 11s ² 11p ³	158 Uuo 333.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶ 11s ² 11p ⁴	159 Uue 334.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶ 11s ² 11p ⁵	160 Uub 335.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶ 11s ² 11p ⁶	161 Uut 336.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 8s ² 8p ⁶ 8d ¹⁰ 9s ² 9p ⁶ 10s ² 10p ⁶ 11s ² 11p ⁶ 12s ¹	162 Uuq 337.10 [Rn]5f ¹⁴ 6d ¹⁰ 7s ²

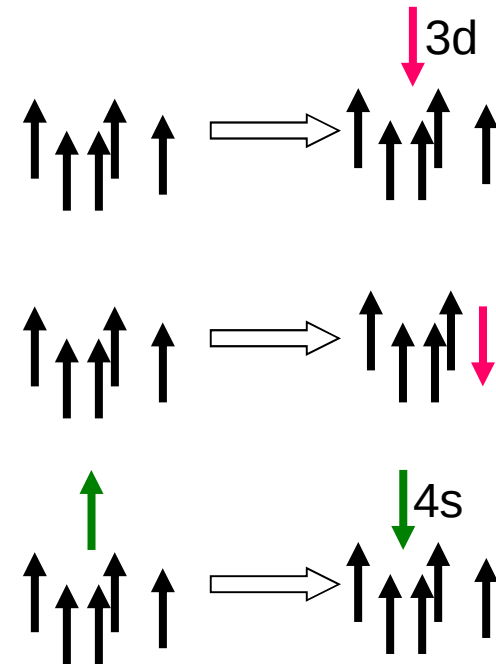
Magnetic ion: Mn

- intra site correlation energy $U = E_{n+1} - E_n$
for $n = 5$, $U \approx 15$ eV

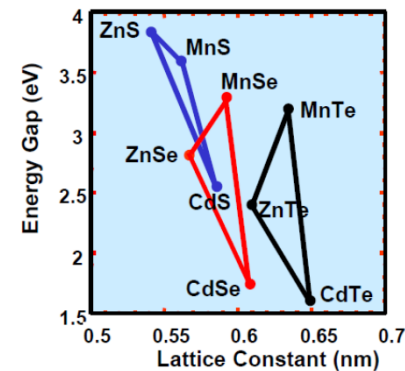
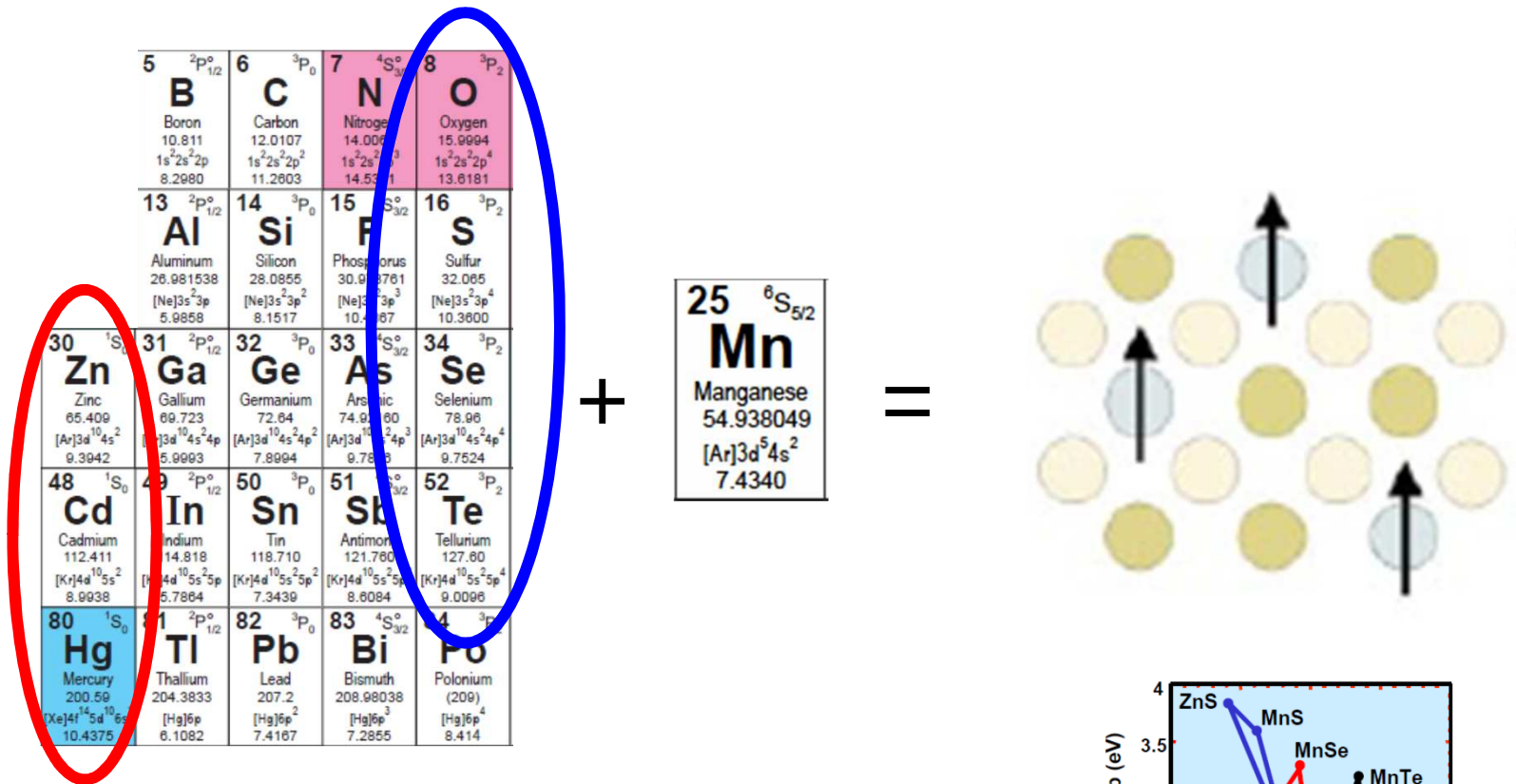
- intra-site exchange interaction: *ferromagnetic*
Hund's rule: S the highest possible
for $n = 5$, $E_{S=3/2} - E_{S=5/2} \approx 2$ eV

- transition metal atoms, $3d^n 4s^1$, e.g., Mn: *ferromagnetic*

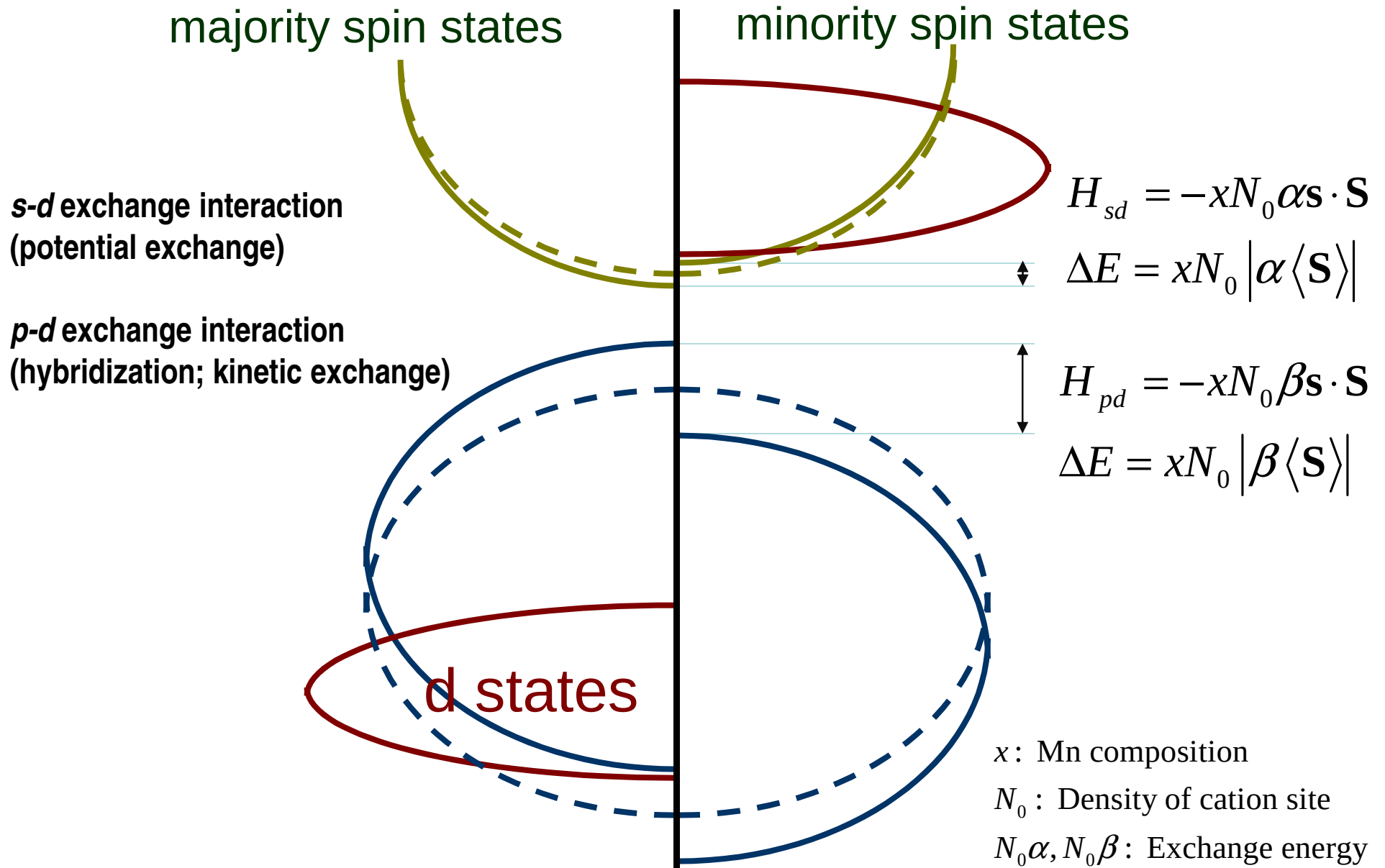
$$E_{S=2} - E_{S=3} \approx 1.2 \text{ eV} \rightarrow J_{s-d} \approx 0.4 \text{ eV}$$

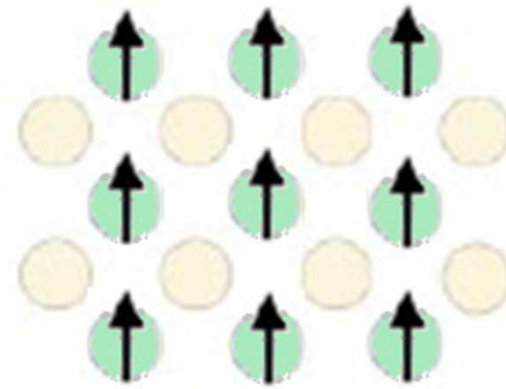
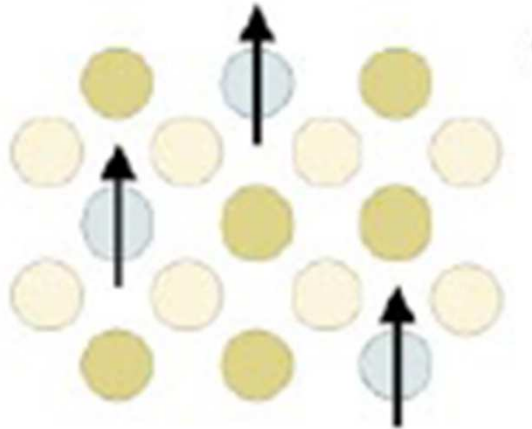


II-VI Diluted Magnetic Semiconductors



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

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

mean-field approximation $\rightarrow -\frac{\mathbf{M}}{g\mu_B}; \quad \mathbf{M} = \langle \mathbf{M}(\mathbf{r}) \rangle$

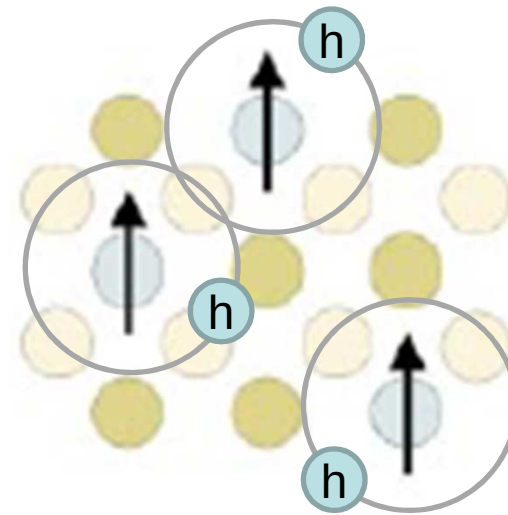
III-V Diluted Magnetic Semiconductors

5 B Boron 10.811 $1s^2 2s^2 2p^1$	6 C Carbon 12.0107 $1s^2 2s^2 2p^2$	7 N Nitrogen 14.0067 $1s^2 2s^2 2p^3$	8 O Oxygen 15.9994 $1s^2 2s^2 2p^4$
13 Al Aluminum 26.981538 $[Ne] 3s^2 3p^1$	14 Si Silicon 28.0855 $[Ne] 3s^2 3p^2$	15 P Phosphorus 30.973761 $[Ne] 3s^2 3p^3$	16 S Sulfur 32.065 $[Ne] 3s^2 3p^4$
30 Zn Zinc 65.409 $[Ar] 3d^{10} 4s^2$	31 Ga Gallium 69.723 $[Ar] 3d^{10} 4s^2 4p^1$	32 Ge Germanium 72.64 $[Ar] 3d^{10} 4s^2 4p^2$	33 As Arsenic 74.92160 $[Ar] 3d^{10} 4s^2 4p^3$
48 Cd Cadmium 112.411 $[Kr] 4d^{10} 5s^2$	49 In Indium 114.818 $[Kr] 4d^{10} 5s^2 5p^1$	50 Sn Tin 118.710 $[Kr] 4d^{10} 5s^2 5p^2$	51 Sb Antimony 121.760 $[Kr] 4d^{10} 5s^2 5p^3$
80 Hg Mercury 200.59 $[Xe] 4f^{14} 5d^{10} 6s^2$	81 Tl Thallium 204.3833 $[Hg] 6p^1$	82 Pb Lead 207.2 $[Hg] 6p^2$	83 Bi Bismuth 208.98038 $[Hg] 6p^3$

+

25 Mn Manganese 54.938049 $[Ar] 3d^5 4s^2$

=



not to scale

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

Mn in GaAs

Mn on Ga site: 113 meV acceptor

- **d⁵+hole (weak coupling)** ←
- d⁴
- d⁵+hole (strong coupling)

from spectroscopy

$$H = T - \frac{e^2}{\epsilon r} - V_0 \exp\left(-\left(\frac{r}{r_0}\right)^2\right) - xN_0\beta \mathbf{s} \cdot \mathbf{S} \quad N_0\beta = -0.9 \text{ eV}$$

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

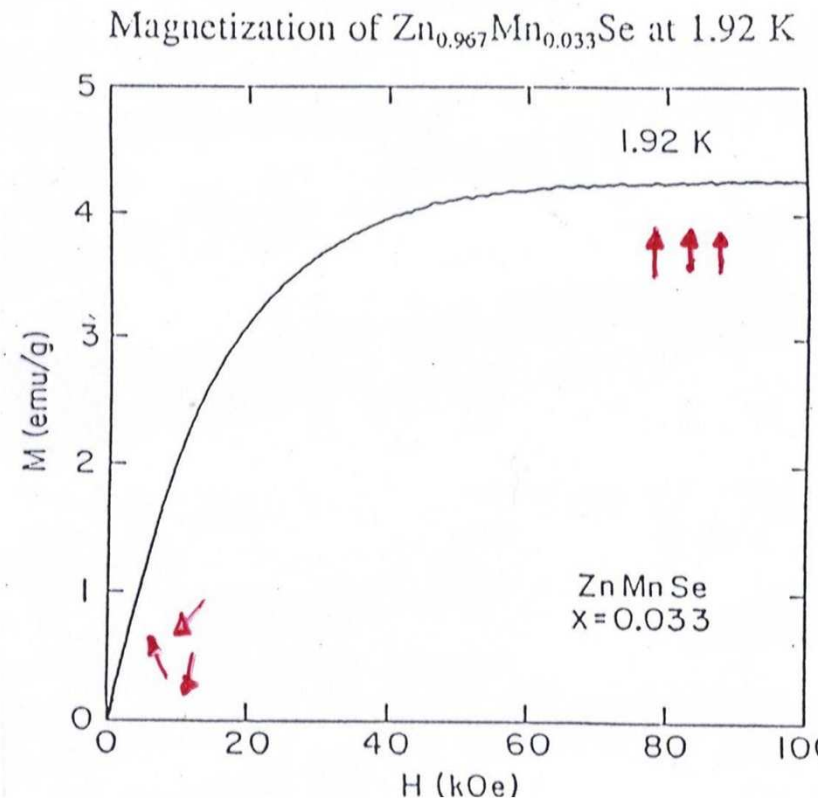
$$M(T,H) = g\mu_B S x_{\text{eff}} N_0 B_S[g\mu_B H/k_B(T + T_{AF})]$$

antiferromagnetic interactions

$$x_{\text{eff}} < x$$

$$T_{AF} > 0$$

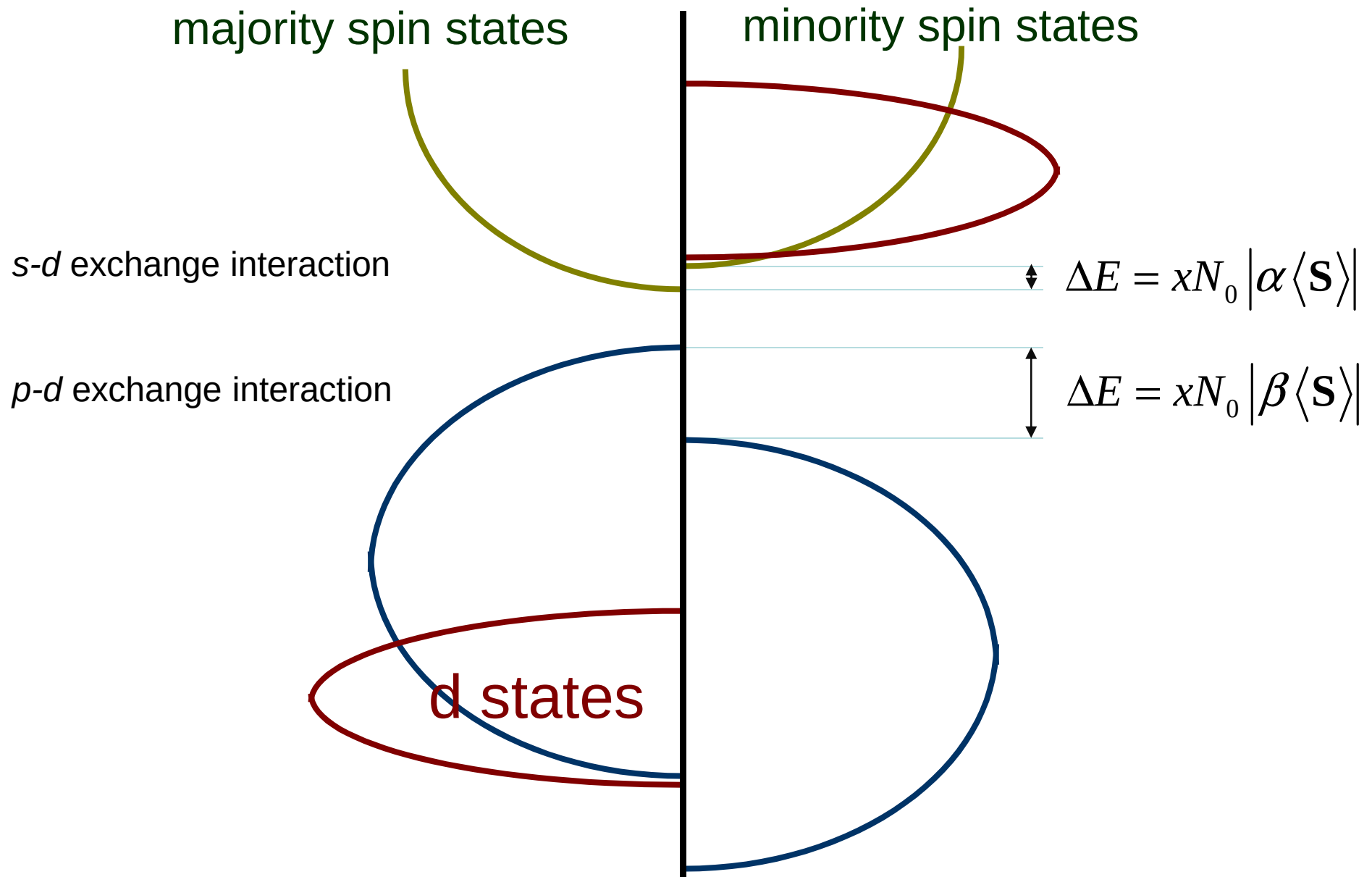
Modified Brillouin function



Y. Shapira et al.

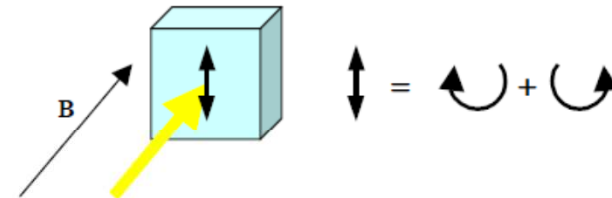
no spontaneous magnetization

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

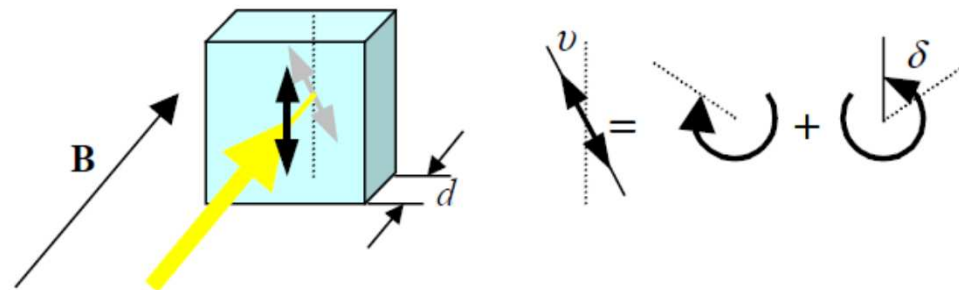


- After travelling in the medium over a distance d the two components develop a phase shift

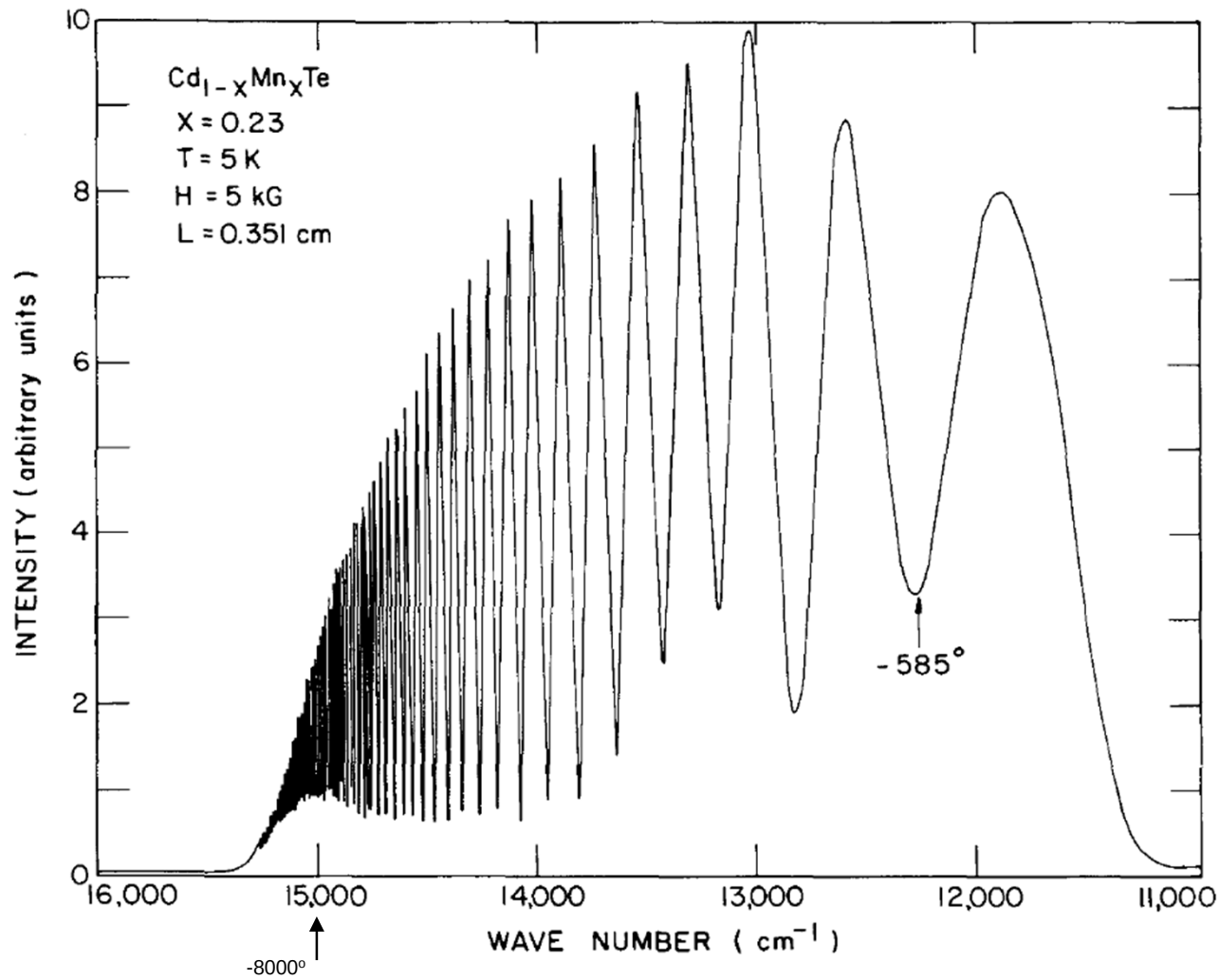
$$\delta = \frac{\omega}{c}(n_+ - n_-)d$$

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

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

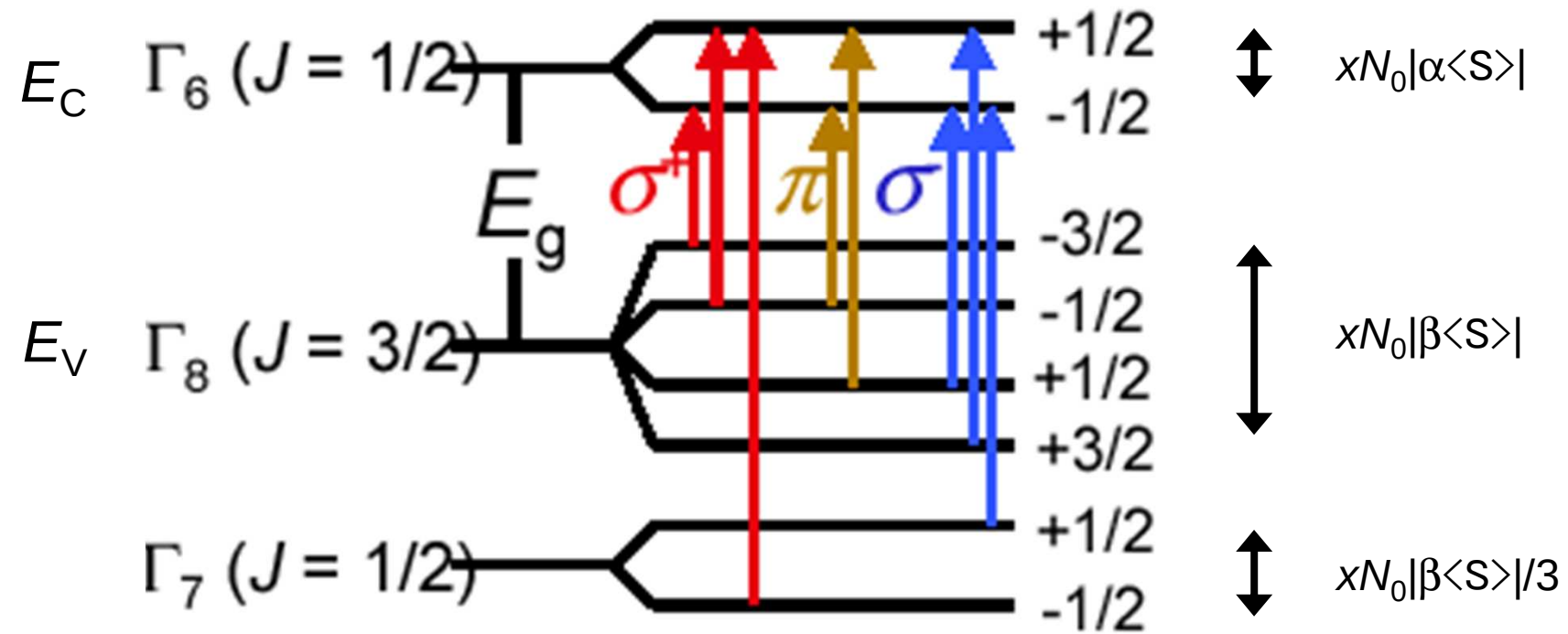


Faraday effect

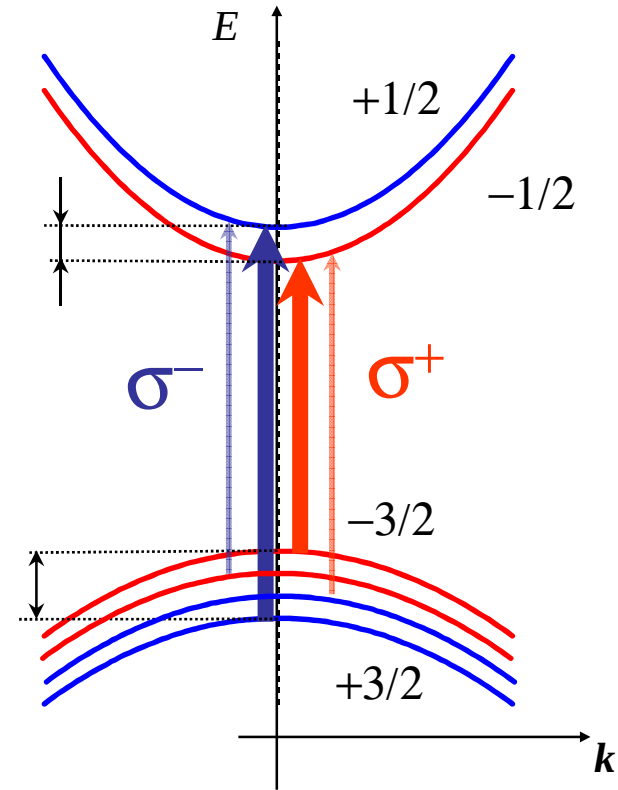
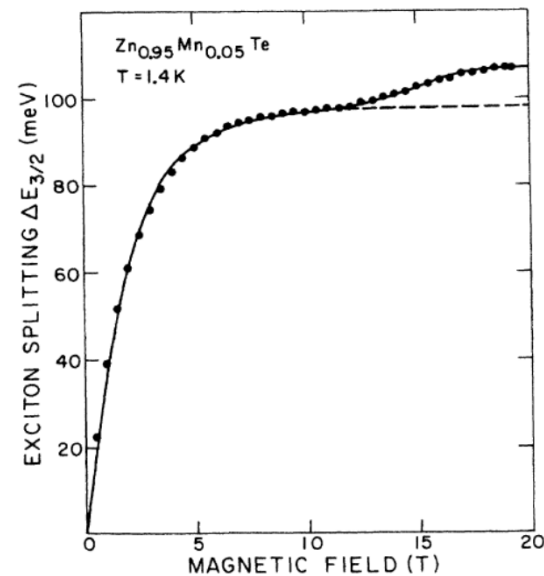
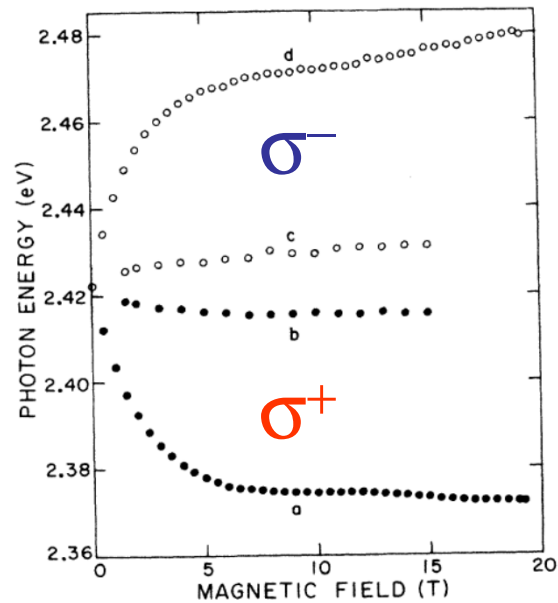


J. A. Gaj, R. R. Galazka, and M. Nawrocki, *Solid State Commun.*, vol. 25, p. 193 (1978).

Splitting of the bands



Measurements of the band splitting



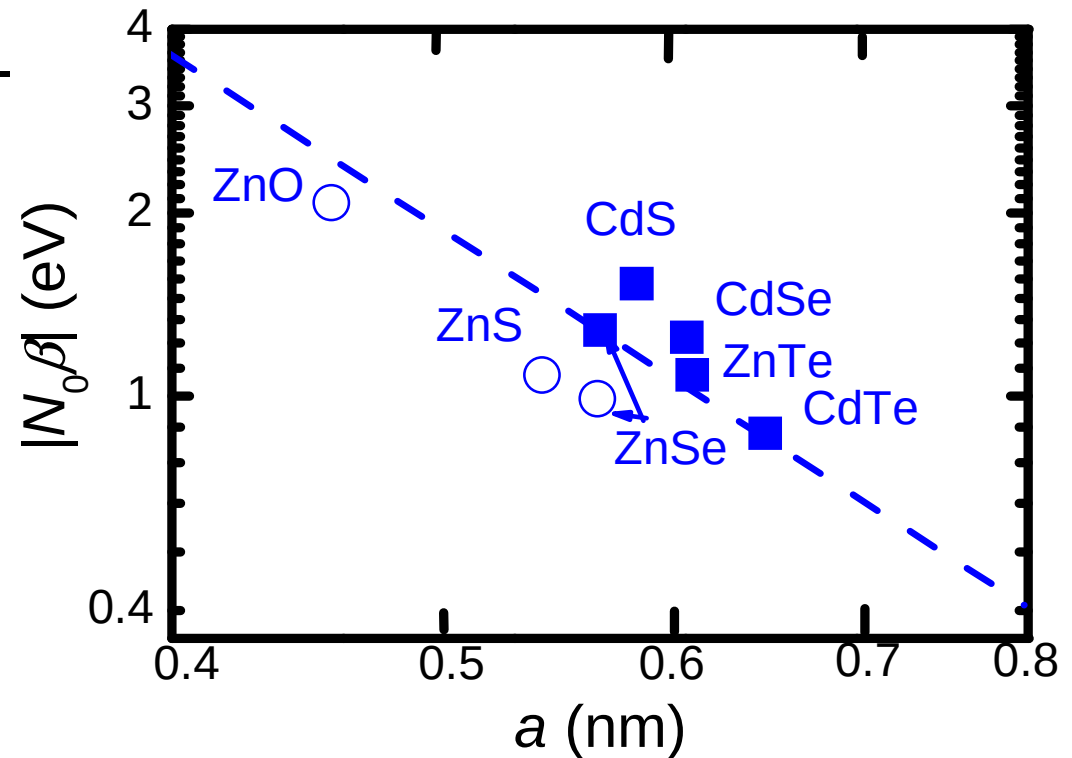
$$\Delta E = 2g_{\text{eff}}\mu_B H S, S = 1/2$$

- $g_{\text{eff}} \sim 400 > 0$

- Follows M not H

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

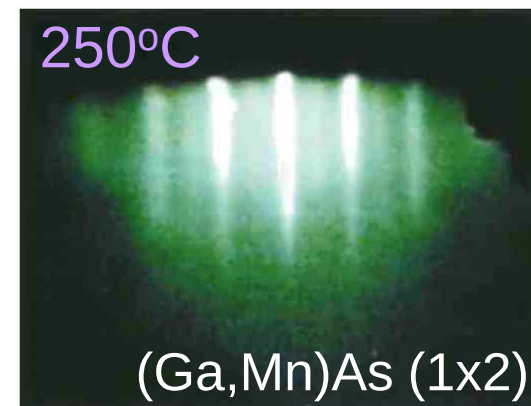
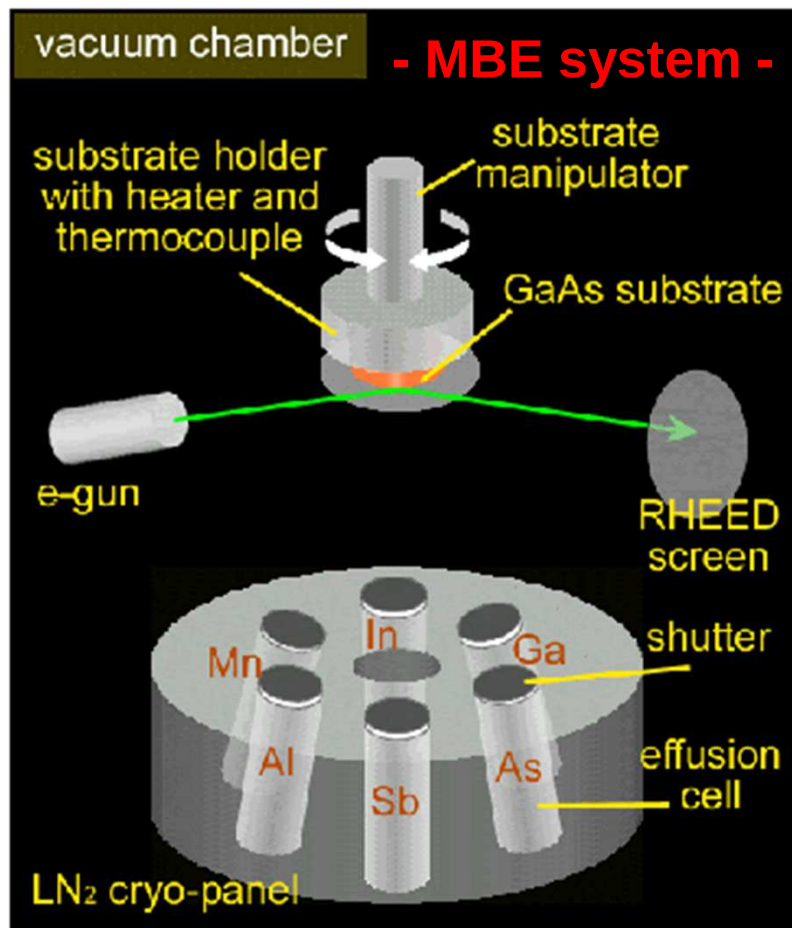
3. The consequences of exchange interaction

- Spin-split bands and **ferromagnetism**

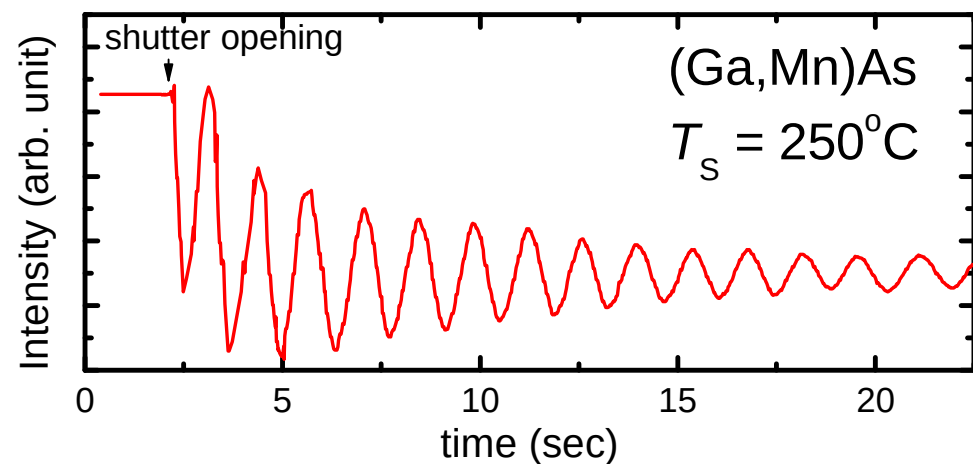
GaAs (or InAs) + Mn

Material Science

Molecular beam epitaxy of (Ga,Mn)As



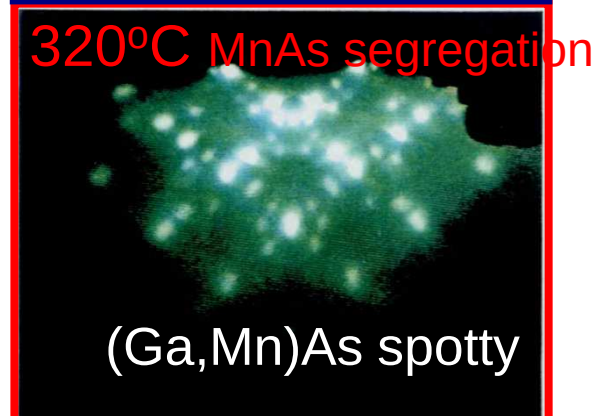
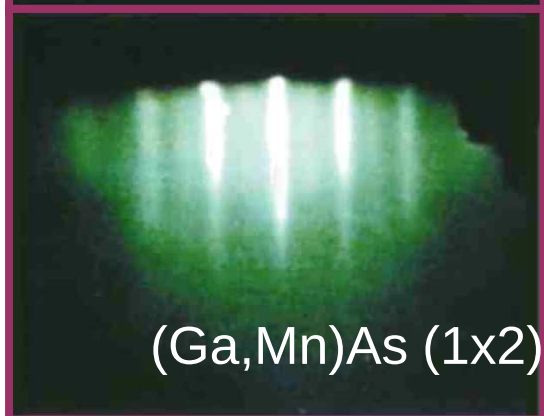
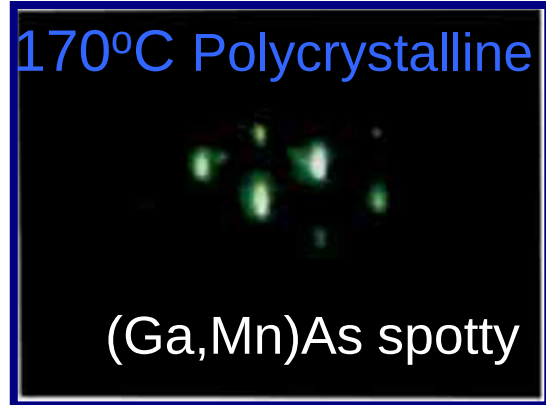
Single crystal (Ga,Mn)As



Molecular beam epitaxy of (Ga,Mn)As



[-110] azimuth

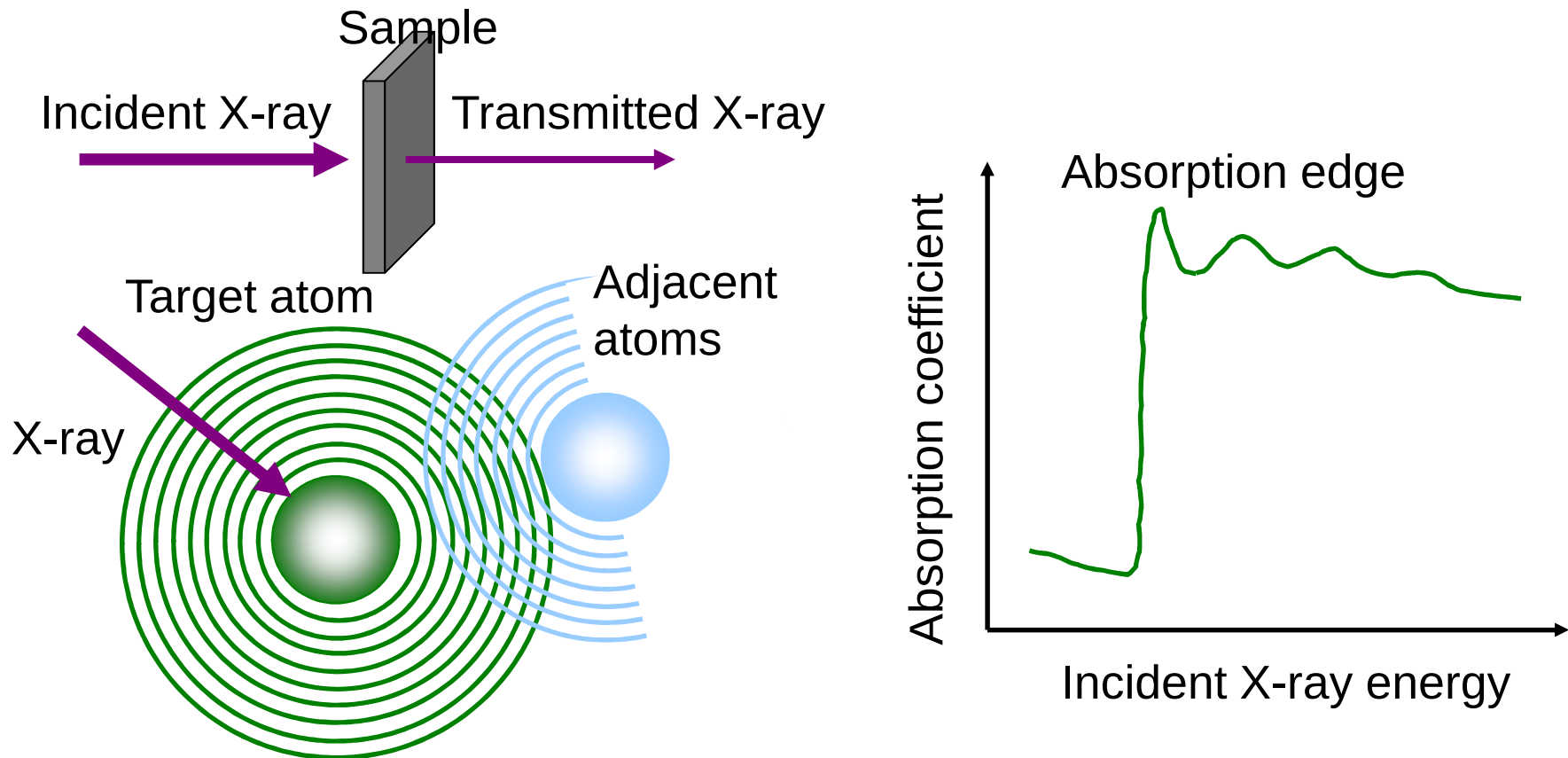


ZB-(Ga,Mn)As can be grown by selecting appropriate growth temperature

Highest Mn composition without segregation is about 10%.

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

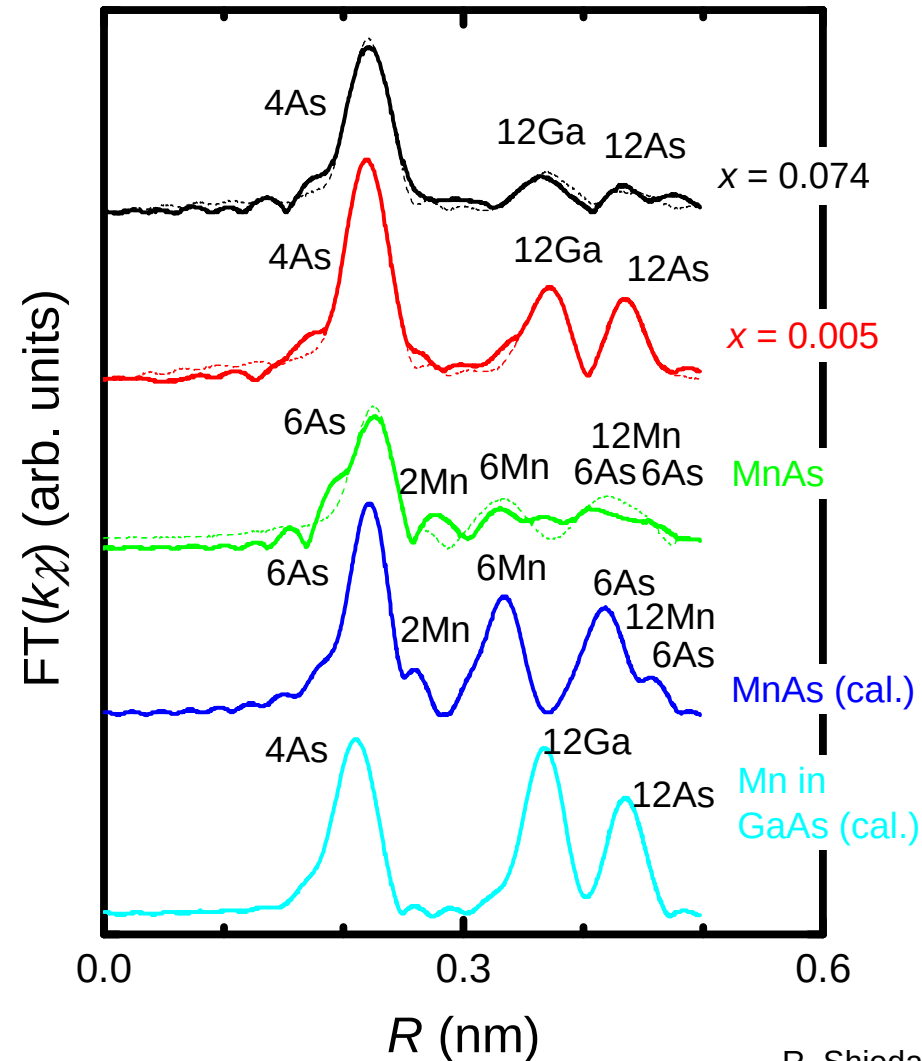
Extended X-ray-Absorption Fine Structure (EXAFS)



- 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)

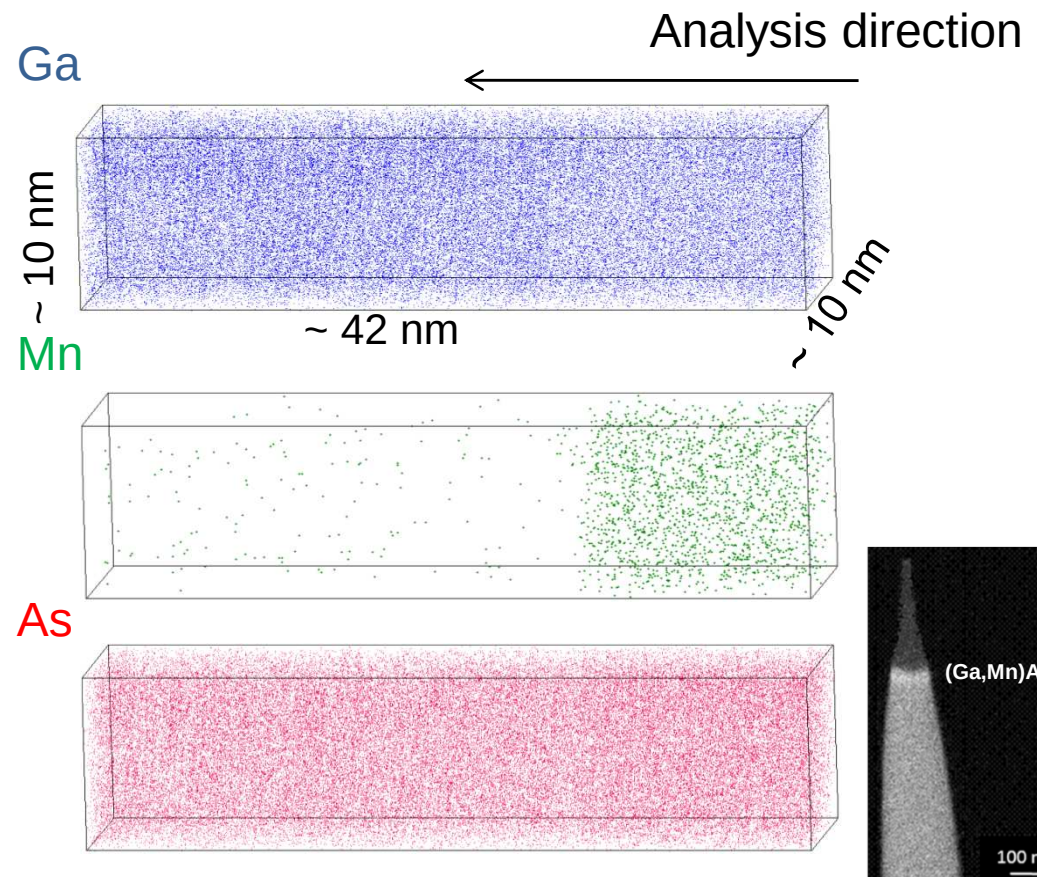
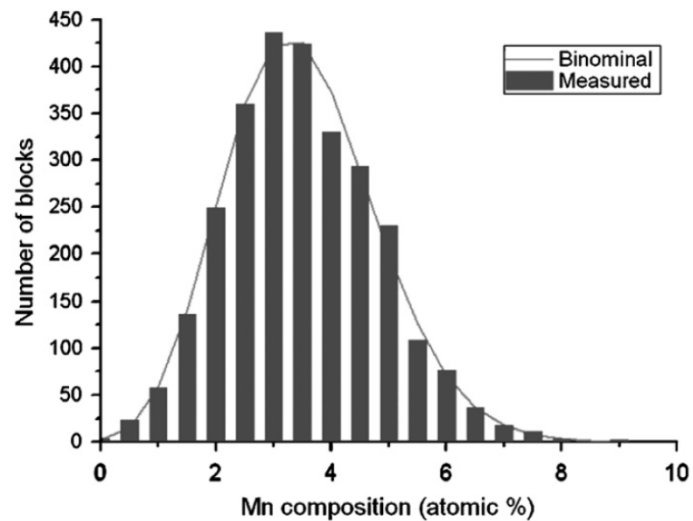
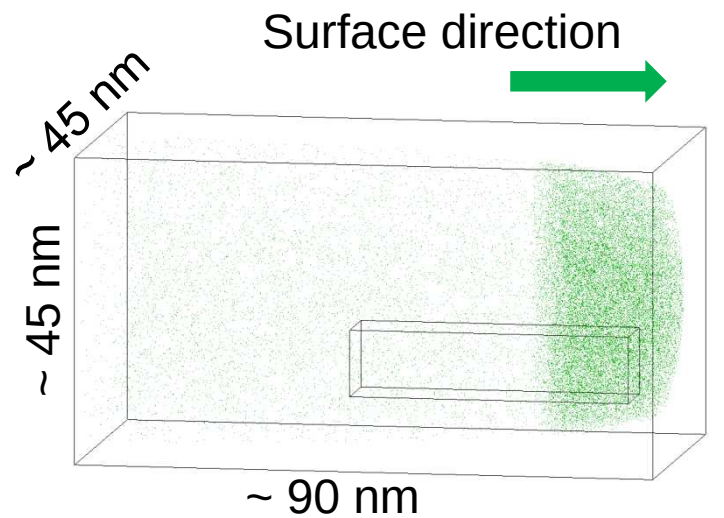
(Ga,Mn)As



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

Most of Mn substitute III-cation site ($\text{Mn}^{2+} \rightarrow \text{acceptor}$)

Atom Probe Microscopy of (Ga,Mn)As

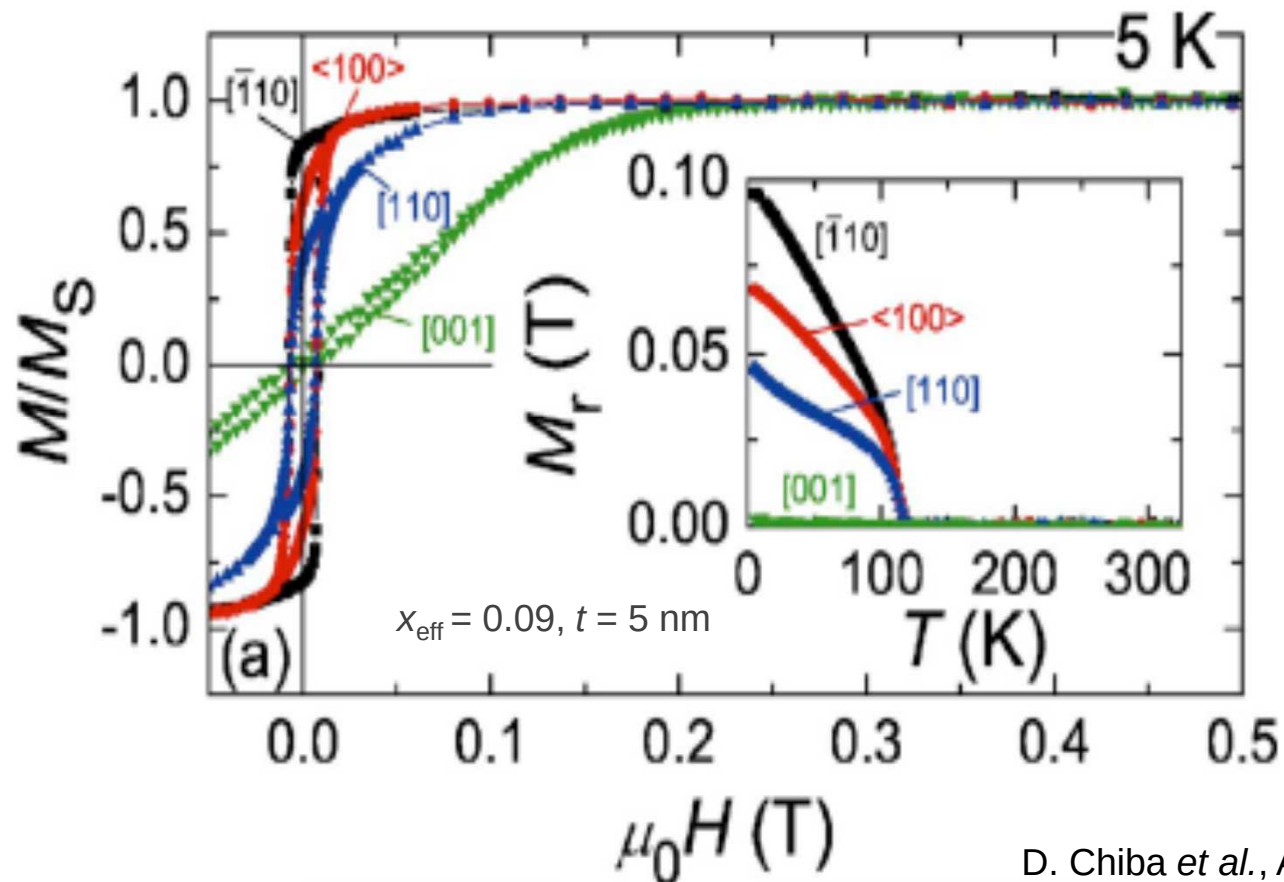


**Magnetism, transport,
and more materials science**

Magnetization of (Ga,Mn)As

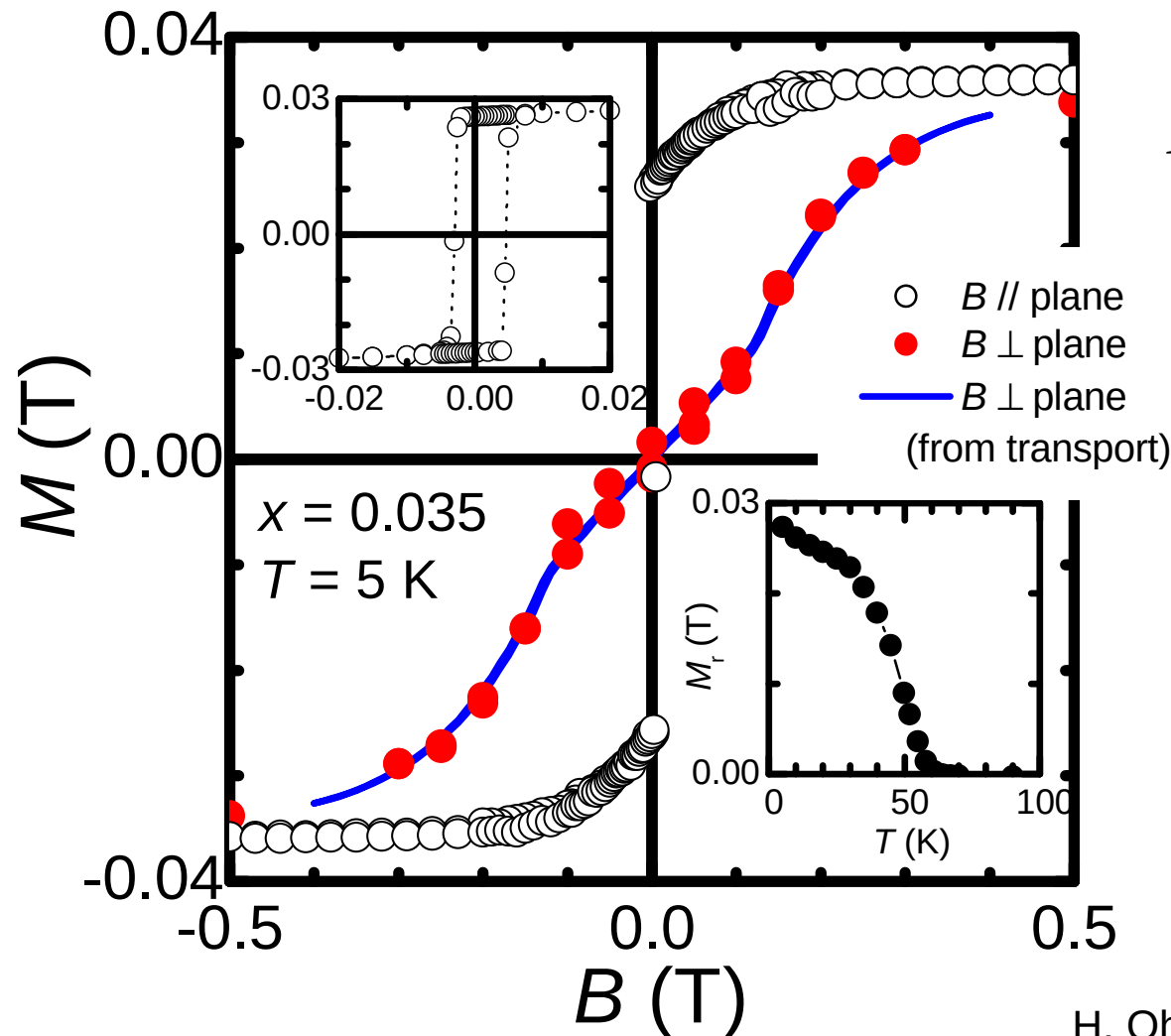
(Ga,Mn)As & (In,Mn)As: Mn acts as a source of spin and hole

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

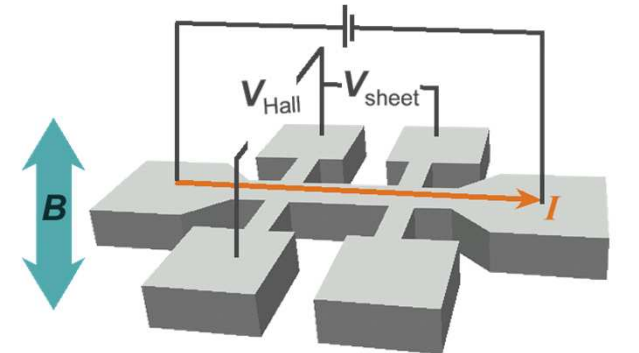


D. Chiba *et al.*, APL **90**, 122503 (2007)

Magnetization and transport of (Ga,Mn)As



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



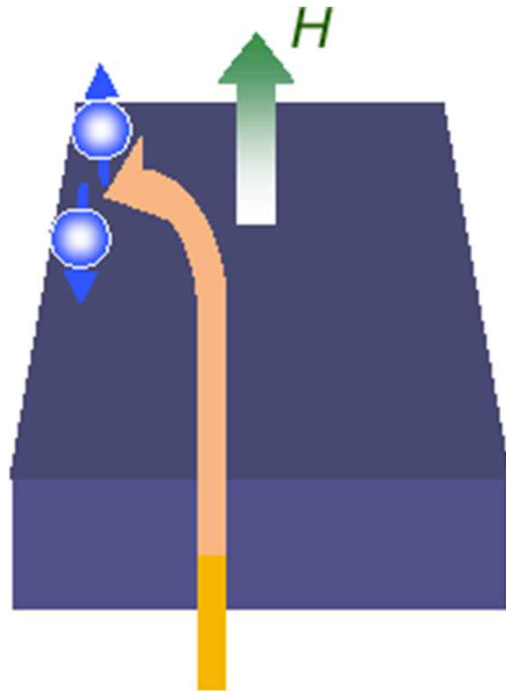
$$R_{\text{Hall}} = V_{\text{Hall}}/I$$

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

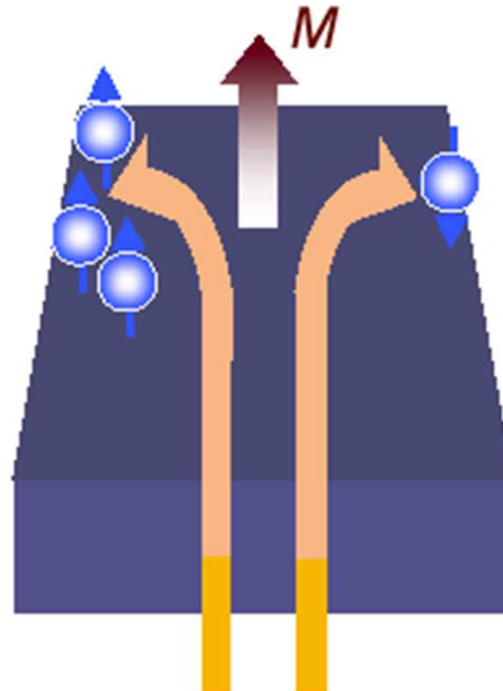
H. Ohno *et al. Appl. Phys. Lett.* 1996
 H. Ohno *Science* 1998

Hall Effects

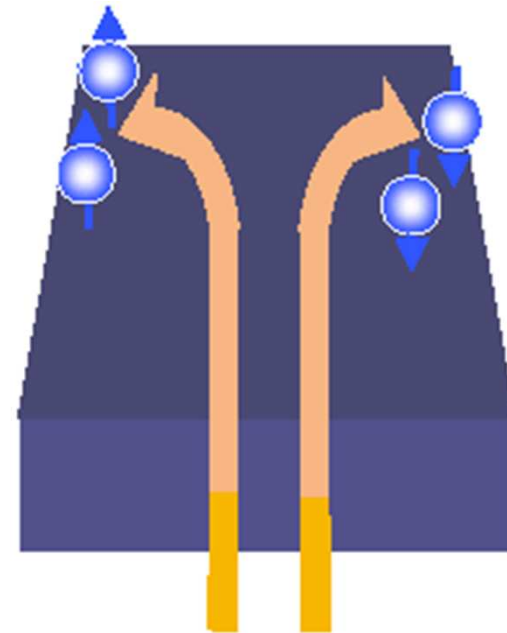
Ordinary Hall effect



Anomalous Hall effect



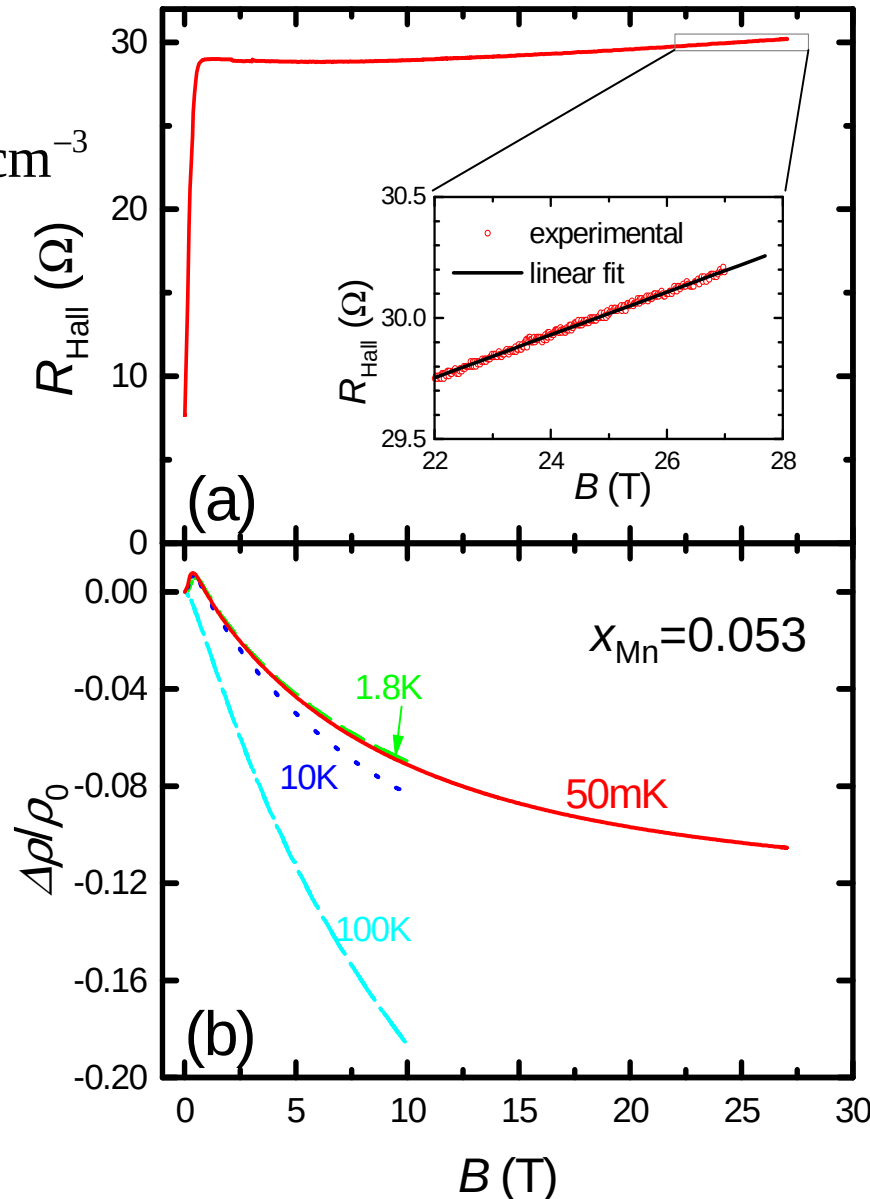
Spin Hall effect



Low-temperature & high-field measurements

$\text{Ga}_{0.947}\text{Mn}_{0.053}\text{As}$

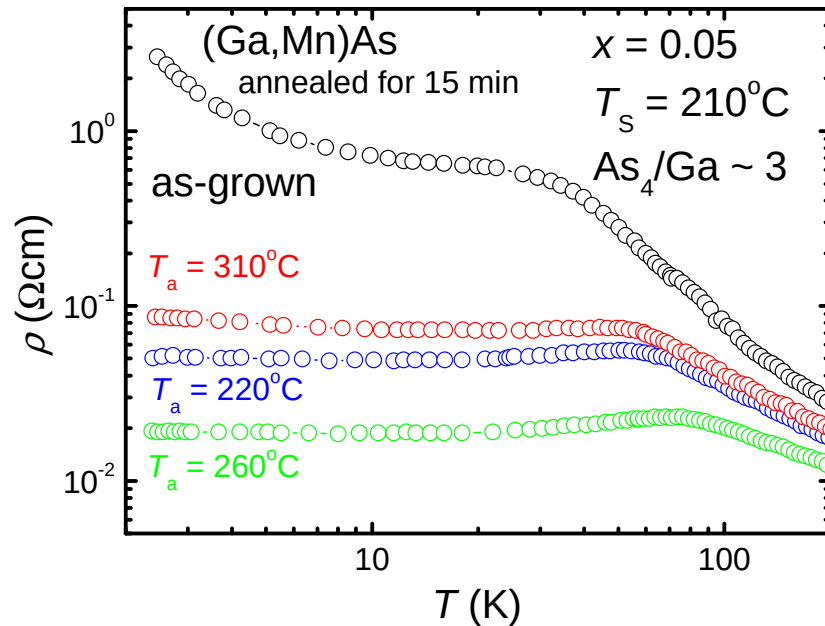
$[\text{Mn}] = 1.2 \times 10^{21} \text{ cm}^{-3}$



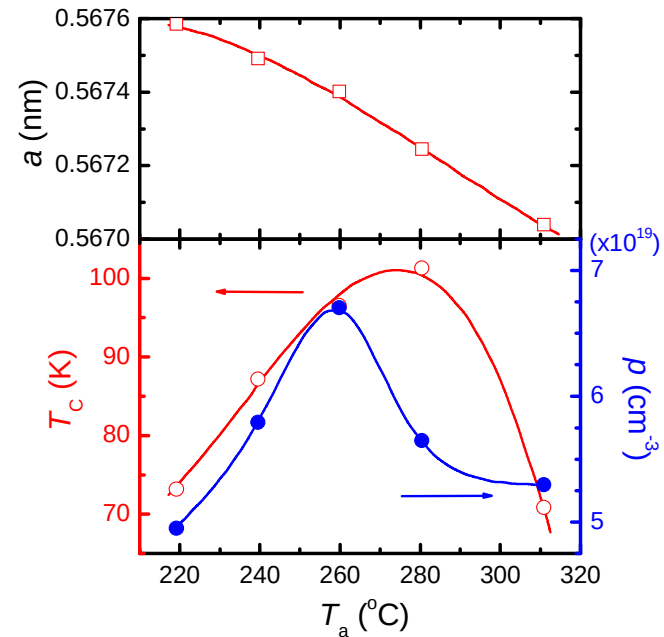
$p = 3.5 \times 10^{20} \text{ cm}^{-3}$
(30% of Mn)

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

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

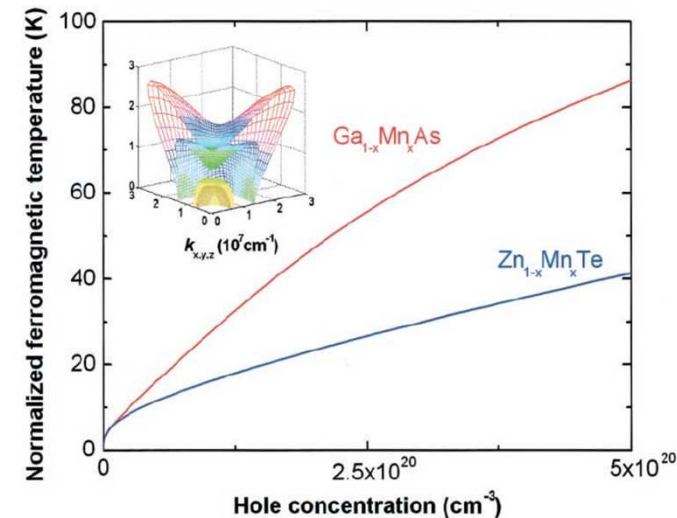
Zener Model Description of Ferromagnetism in Zinc-Blende Magnetic Semiconductors

T. Dietl,^{1,2*} H. Ohno,^{1*} F. Matsukura,¹ J. Cibert,³ D. Ferrand³

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 $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ and that of its II-VI counterpart $\text{Zn}_{1-x}\text{Mn}_x\text{Te}$ and is used to predict materials with T_C exceeding room temperature, an important step toward semiconductor electronics that use both charge and spin.

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Like other thermodynamic quantities, $F_c[M]$ 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 $\text{Ga}_{1-x}\text{Mn}_x\text{As}$

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

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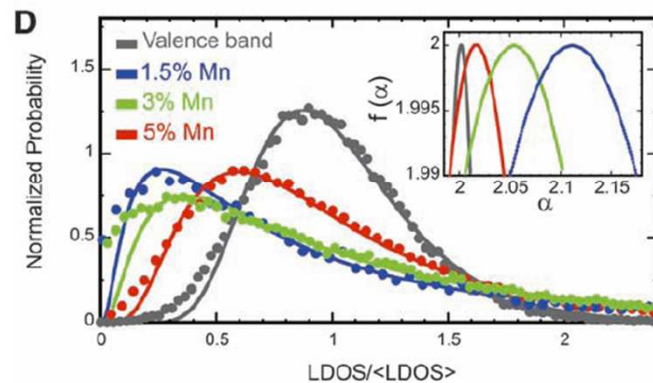
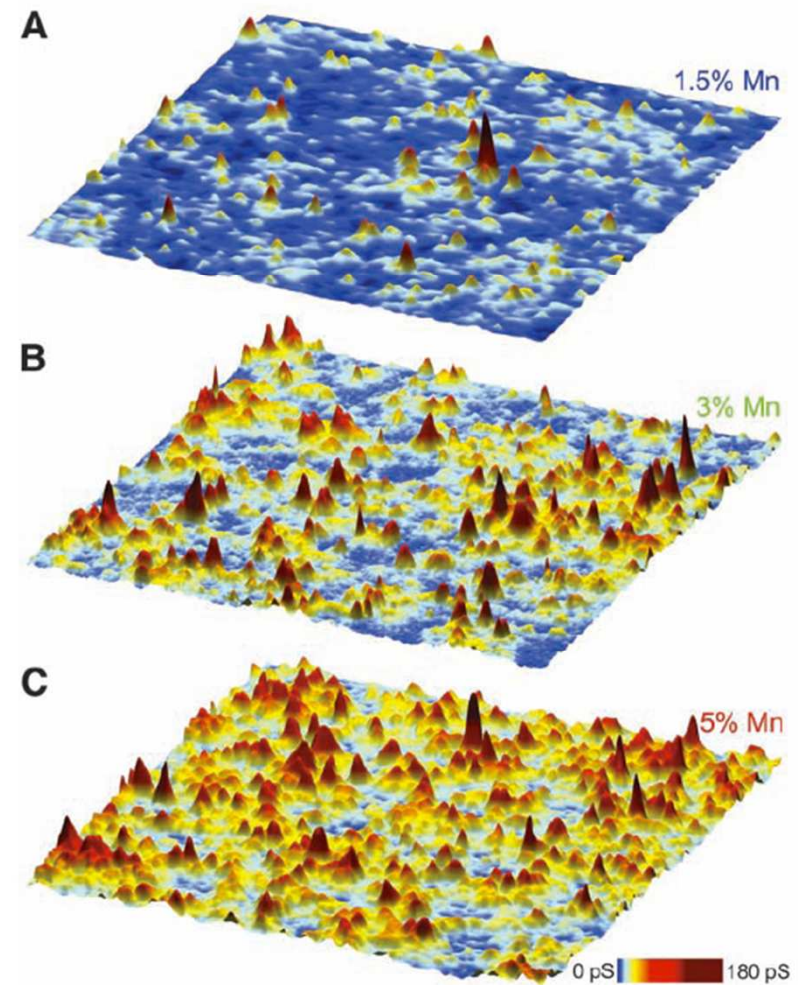


Fig. 5. The spatial variations of the LDOS at the Fermi level, with their histogram and multifractal spectrum. The LDOS mapping of a 700 Å by 700 Å area of (A) $\text{Ga}_{0.985}\text{Mn}_{0.015}\text{As}$, (B) $\text{Ga}_{0.97}\text{Mn}_{0.03}\text{As}$, and (C) $\text{Ga}_{0.95}\text{Mn}_{0.05}\text{As}$. (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.



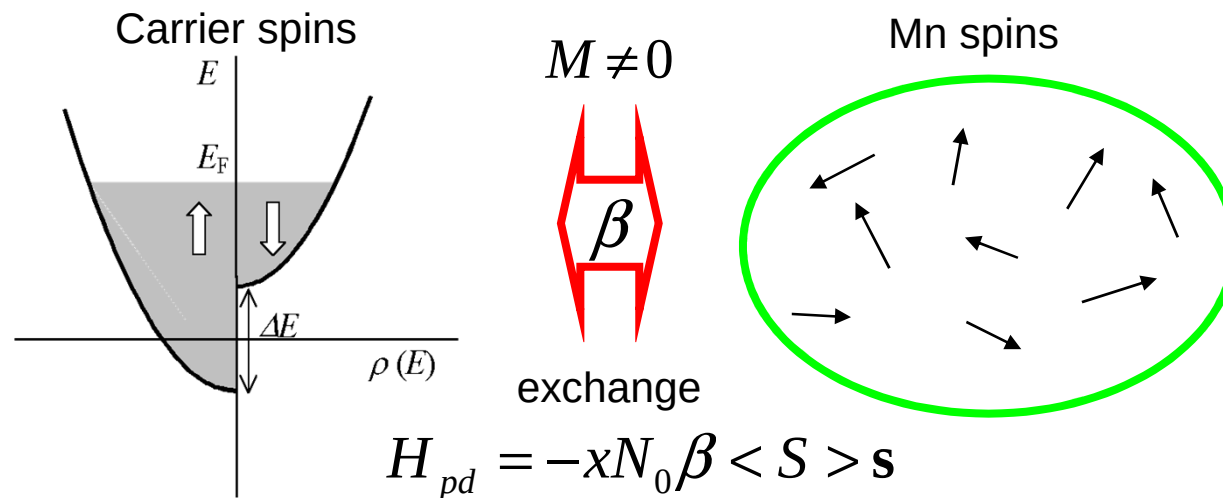
p-d Zener model of ferromagnetism

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

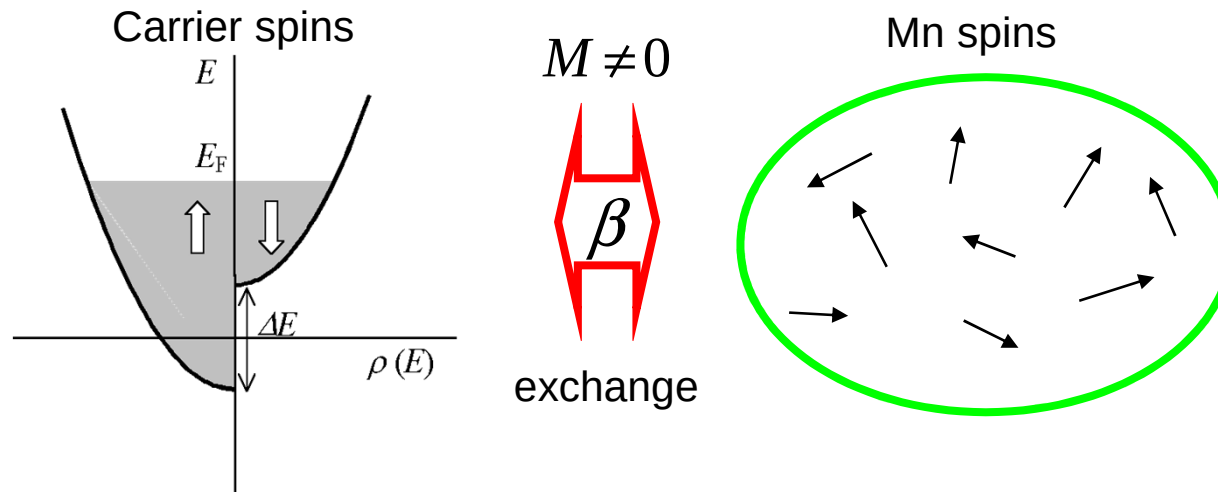


$$T_c = \frac{xN_0 S(S+1)A_F \rho(E_F) \beta^2}{12k_B}$$

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

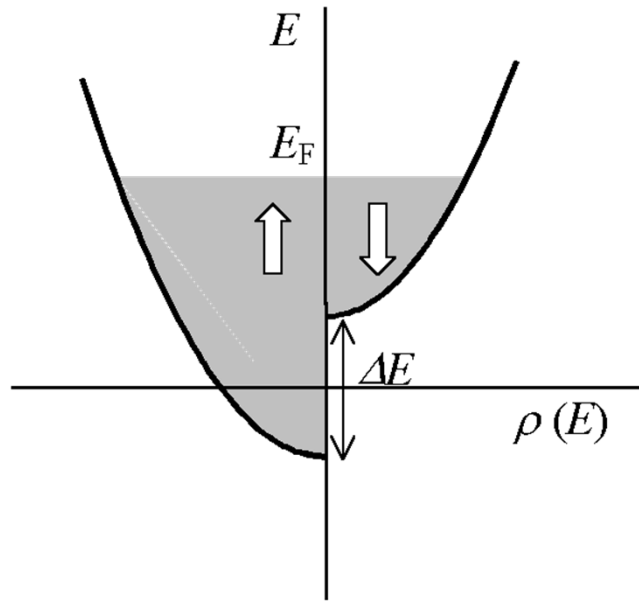


$$\begin{aligned}\Delta F_{total} &= \Delta F_{Mn} + \Delta F_c \\ &= \frac{M^2}{2\chi_{Mn}} - \frac{\chi_c}{2} H^2\end{aligned}$$

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

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

T_c by the p - d Zener model



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

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

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

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

$$\left. \begin{aligned} \Delta E &= 2\mu_B H \\ \Delta E &= xN_0 |\beta \langle S \rangle| \\ M &= xN_0 g \mu_B |\langle S \rangle| \end{aligned} \right\} \begin{aligned} H &= \frac{\Delta E}{2\mu_B} \\ &= \frac{|\beta| M}{2g \mu_B^2} \end{aligned}$$

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

$$= \left(\frac{1}{2 \left(\frac{g^2 \mu_B^2 x N_0 S(S+1)}{3k_B T} \right)} - \frac{\rho(E_F) \beta^2}{8g^2 \mu_B^2} \right) M^2$$

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

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

Valence band structure (Γ_7, Γ_8)

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

Basis functions

$$\begin{aligned} u_1 &= \frac{1}{\sqrt{2}}(X+iY)\uparrow, & u_2 &= i\frac{1}{\sqrt{6}}[(X+iY)\downarrow - 2Z\uparrow], & u_3 &= \frac{1}{\sqrt{6}}[(X-iY)\uparrow + 2Z\downarrow], \\ u_4 &= i\frac{1}{\sqrt{2}}(X-iY)\downarrow, & u_5 &= \frac{1}{\sqrt{3}}[(X+iY)\downarrow + Z\uparrow], & u_6 &= i\frac{1}{\sqrt{3}}[-(X-iY)\uparrow + Z\downarrow] \end{aligned}$$

$k\cdot p$ matrix

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

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

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

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

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

p - d exchange interaction matrix

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

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

$$w_z = \langle S_z \rangle / \langle S \rangle, \quad w_{\pm} = (\langle S_x \rangle \pm i \langle S_y \rangle) / \langle S \rangle$$

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

Exchange energy: $N_0\beta$

Core level photoemission and modeling:

$$N_0\beta = -1.2 \pm 0.2 \text{ eV}$$

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

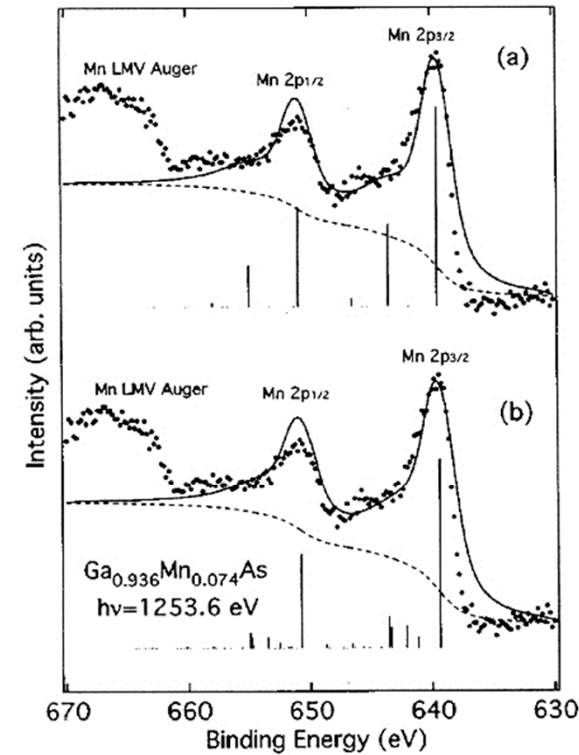
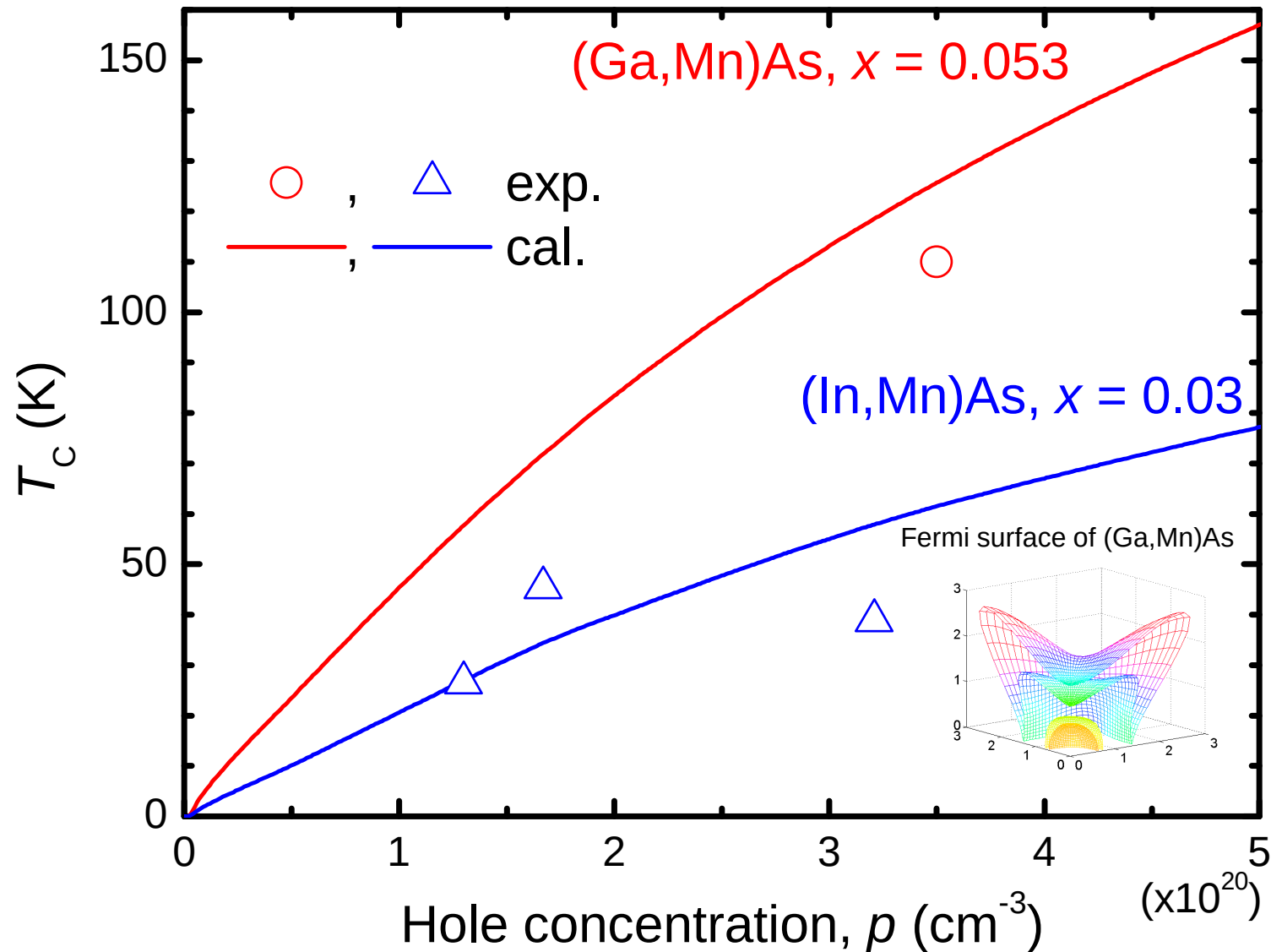
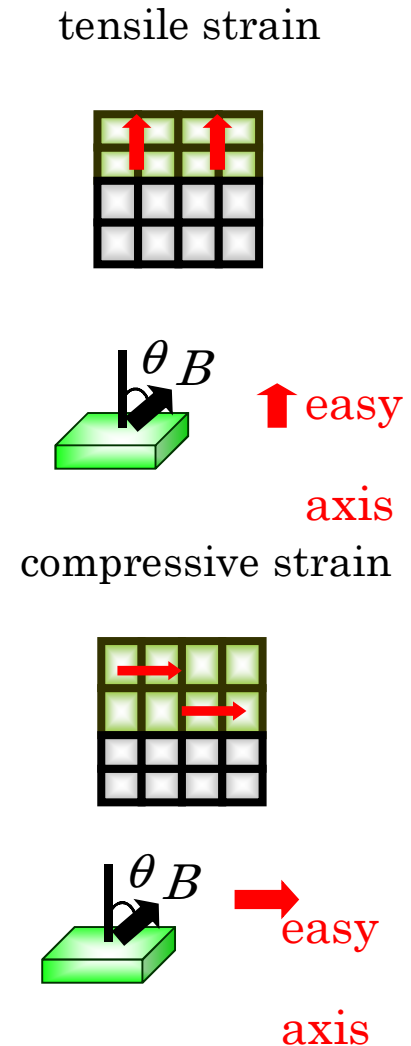
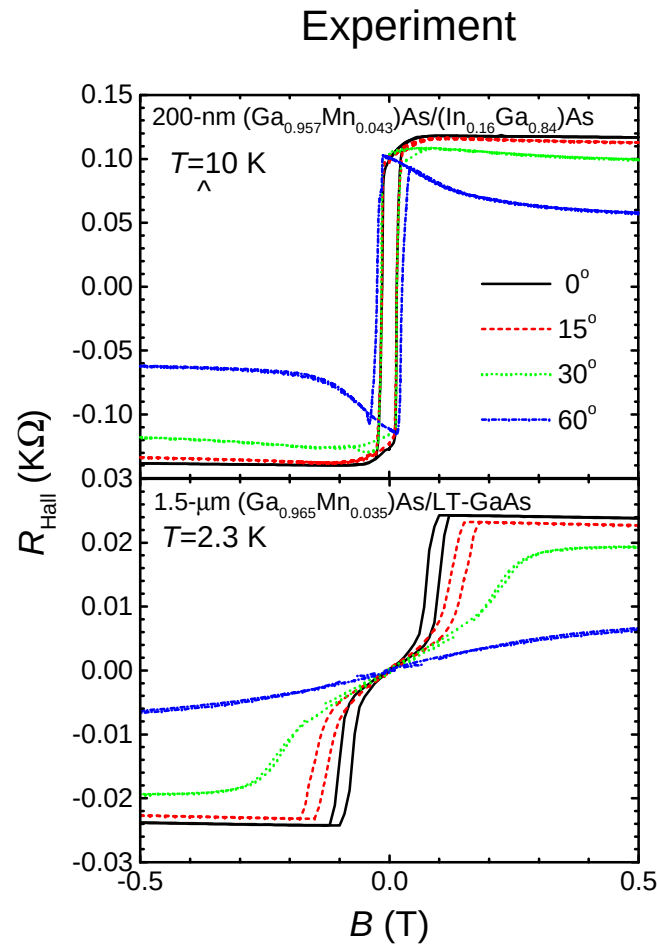
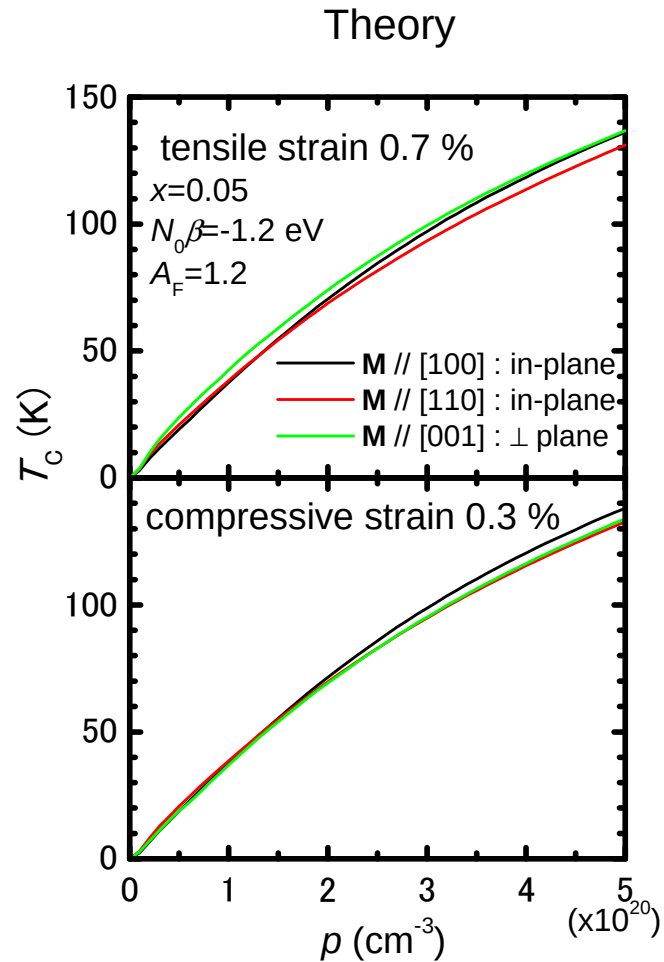


FIG. 1. Photoemission spectrum of the Mn 2p core level (dots) and its cluster-model analysis (solid curves) assuming the negatively ionized Mn²⁺ (a) and neutral Mn³⁺ (b) ground states. The vertical bars are unbroadened spectra. The calculated background is shown by dashed curves.

Comparison of exp. and calculated T_c

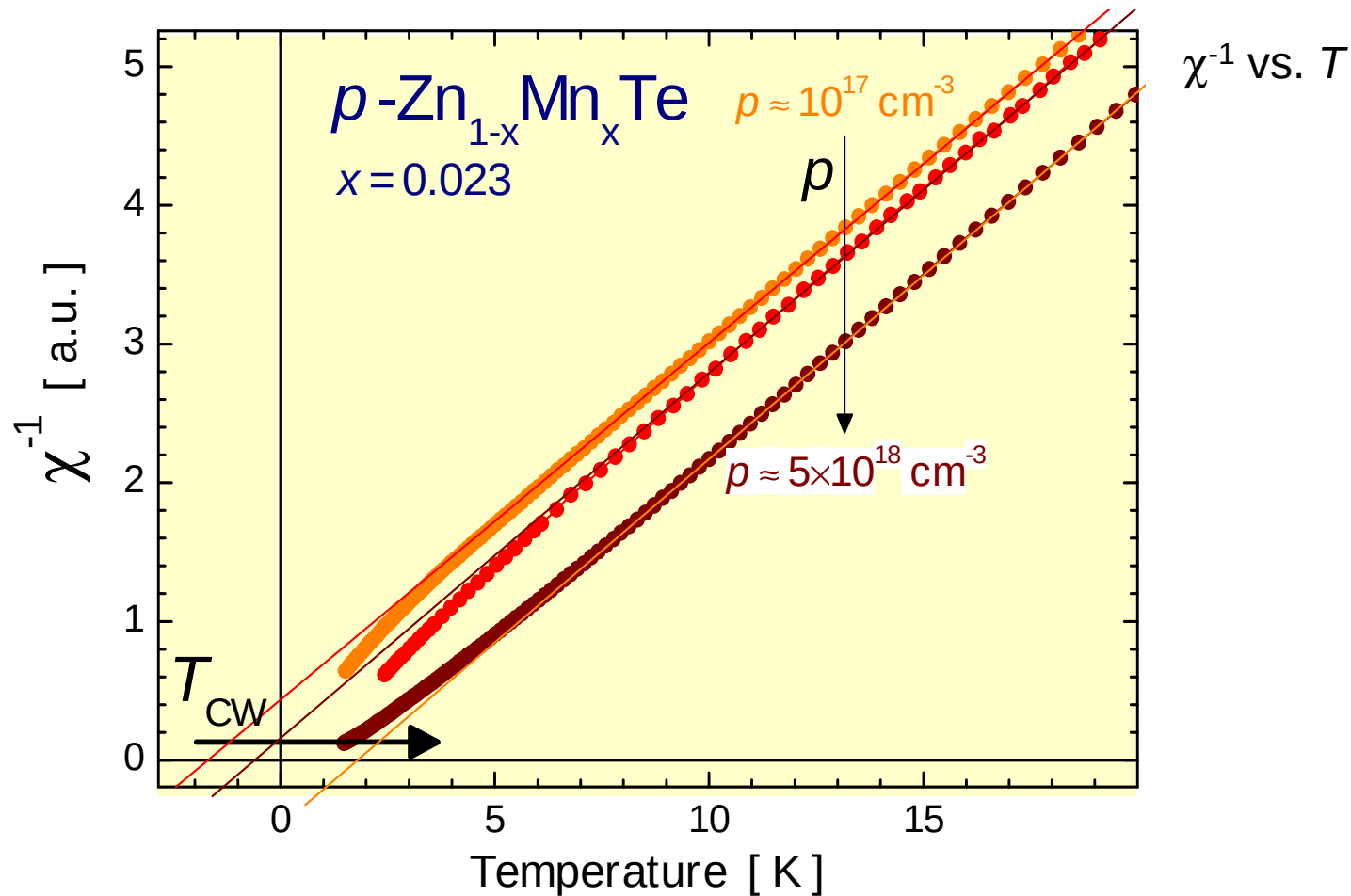


Strain induced-anisotropy: Theory vs. Experiment



Hole bands are responsible for the anisotropy

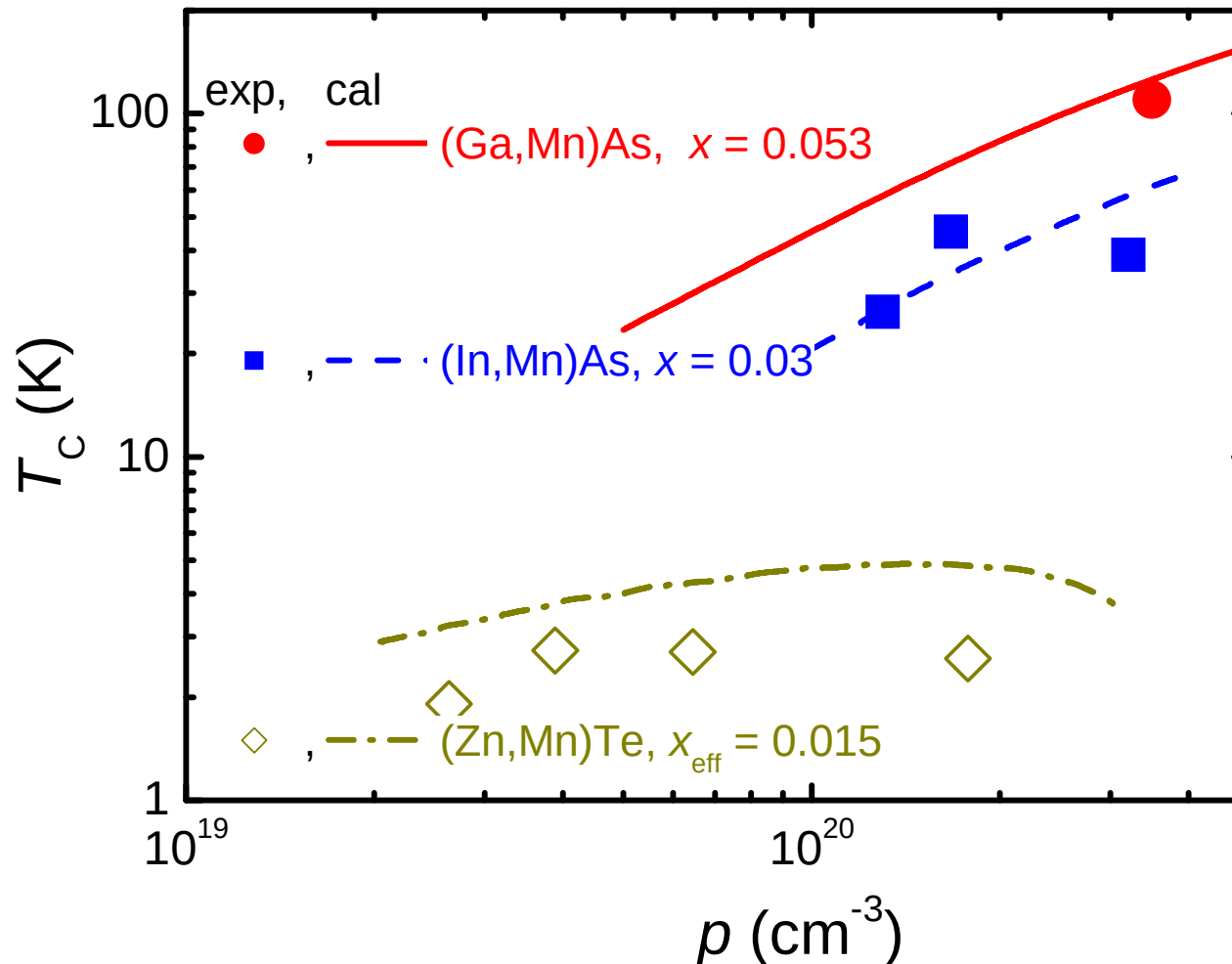
Acceptor doping and susceptibility of $\text{Zn}_{1-x}\text{Mn}_x\text{Te:P}$



Sawicki et al. (Warsaw) pss'02

Kępa et al. (Warsaw, Oregon) PRL'03

Comparison of Experimental and Calculated T_C

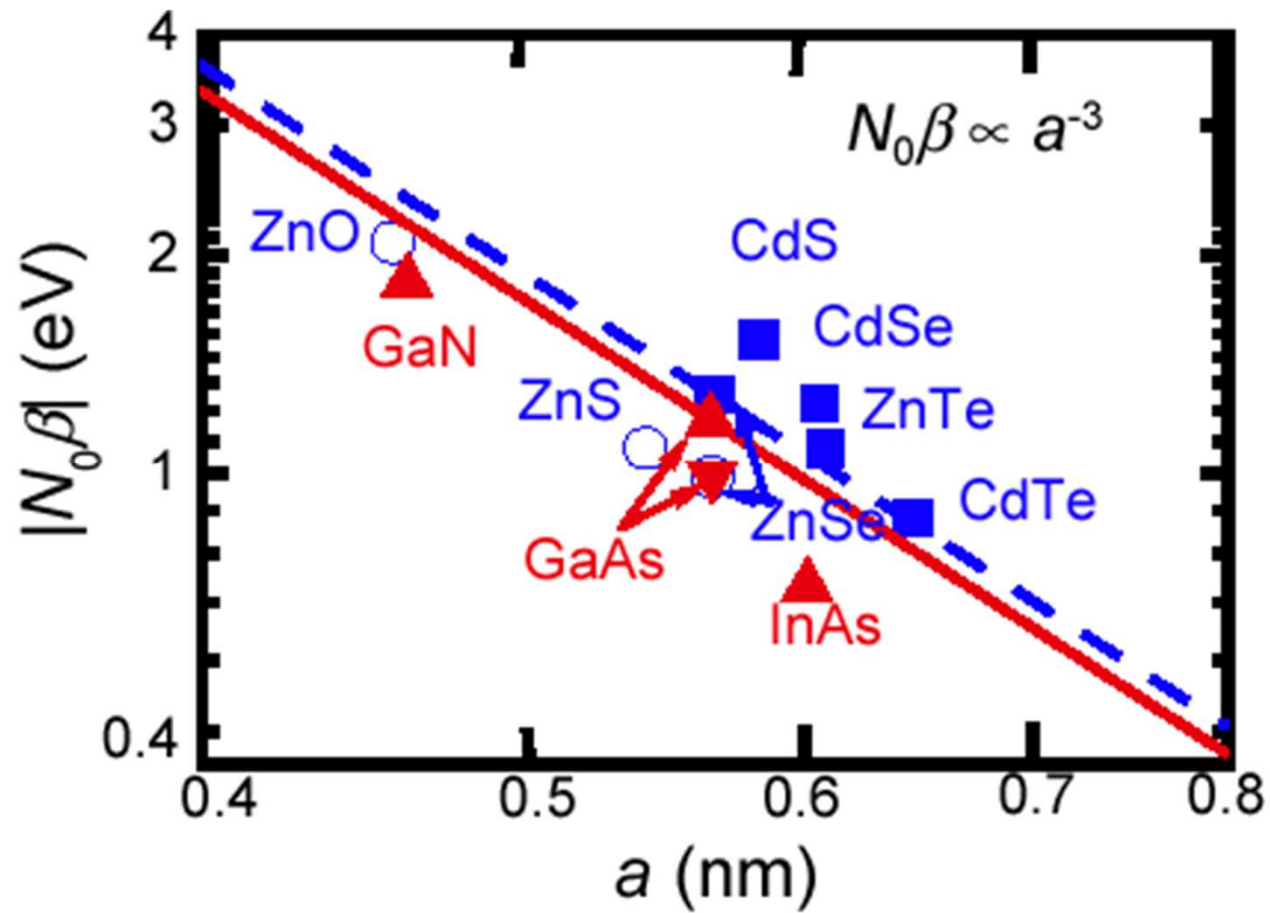


exp.:(Ga,Mn)As:T. Omiya *et al.*, Physica E **7**, 976 (2000).

(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

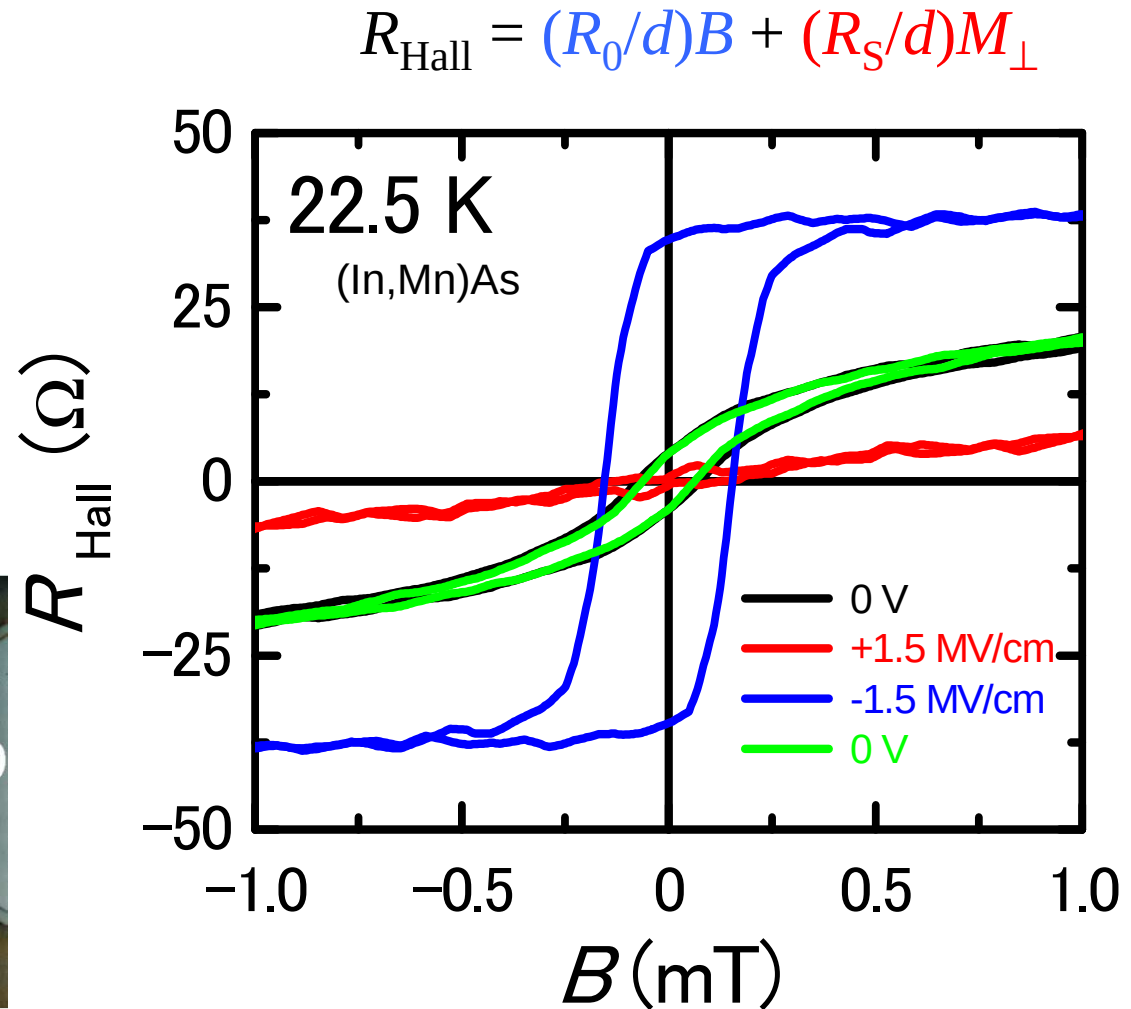
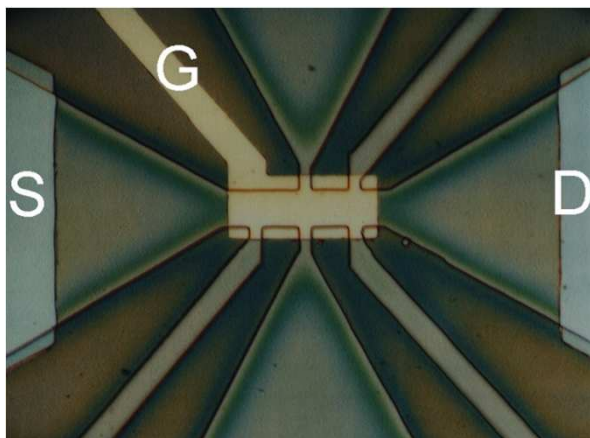
4. Making “use” of ferromagnetism in semiconductors

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

Electric-field control of ferromagnetism

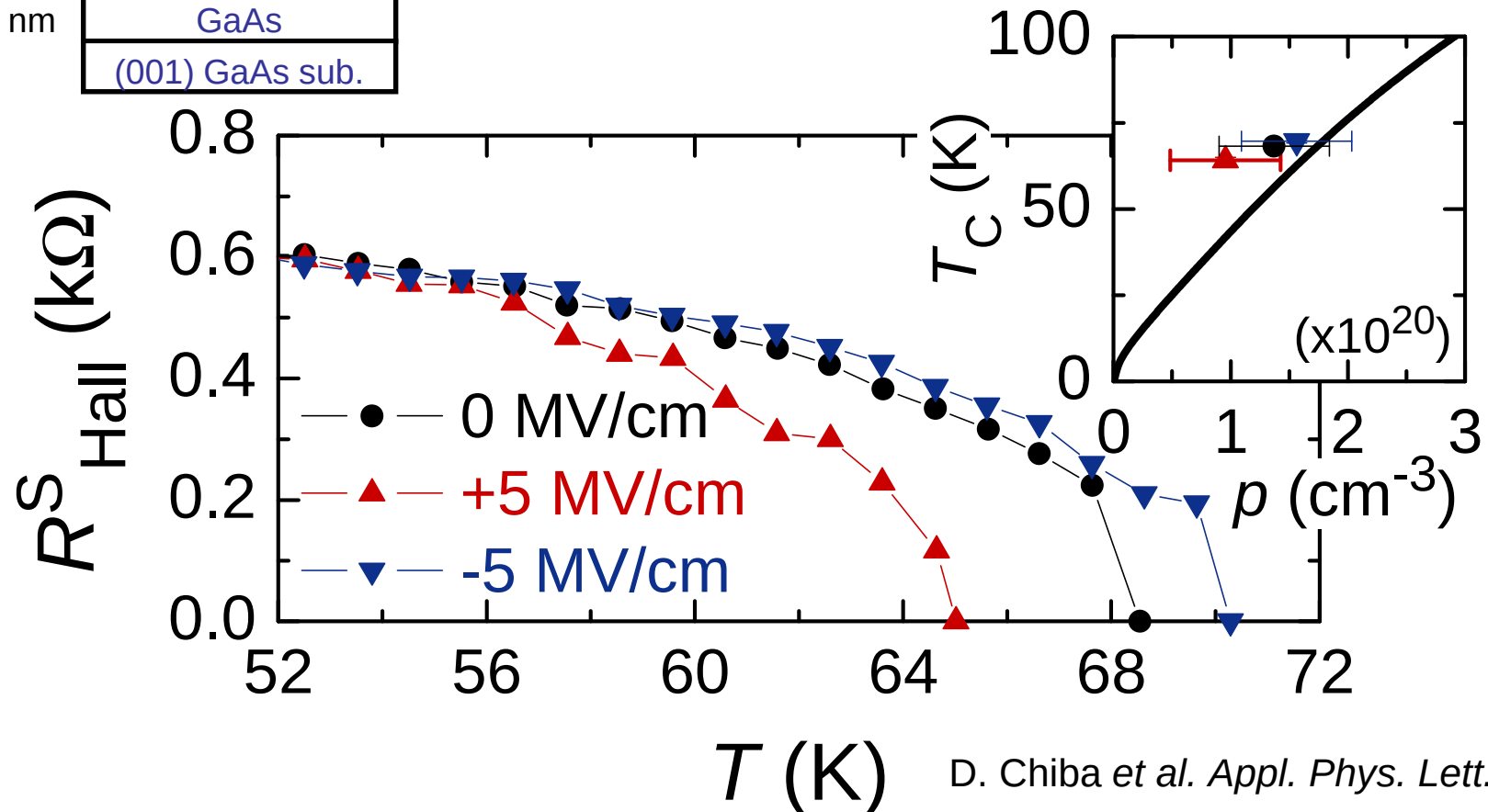
(In,Mn)As

95/5 nm	Au/Cr
800 nm	polyimide
5 nm	(In _{0.97} Mn _{0.03})As
10 nm	InAs
400 nm	(Al _{0.6} Ga _{0.4})Sb
100 nm	AlSb
	GaAs sub.



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

100/5 nm	Au/Cr
50 nm	Al ₂ O ₃
7 nm	(Ga _{0.953} Mn _{0.047})As
30 nm	(Al _{0.80} Ga _{0.20})As
500 nm	(In _{0.13} Ga _{0.87})As
100 nm	GaAs
	(001) GaAs sub.

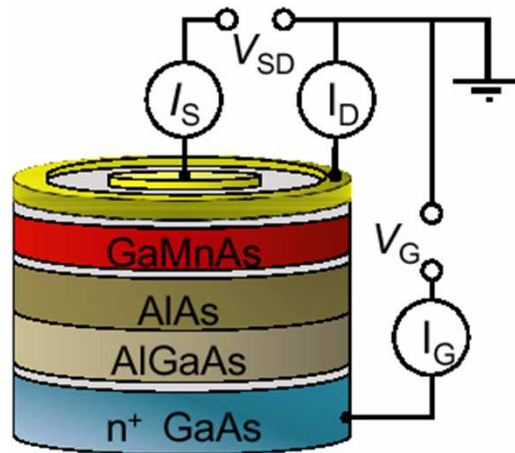
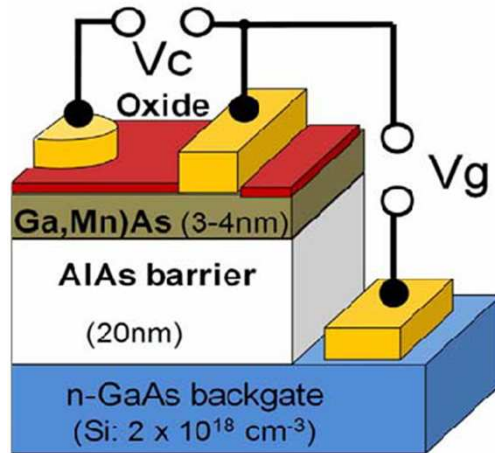


D. Chiba et al. *Appl. Phys. Lett.* 2006

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

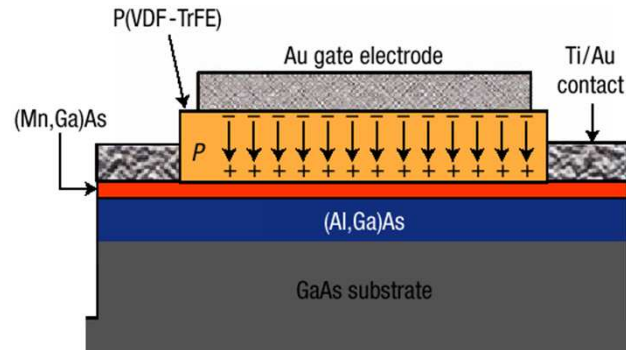
Field-effect structures of (Ga,Mn)As

backgate structure



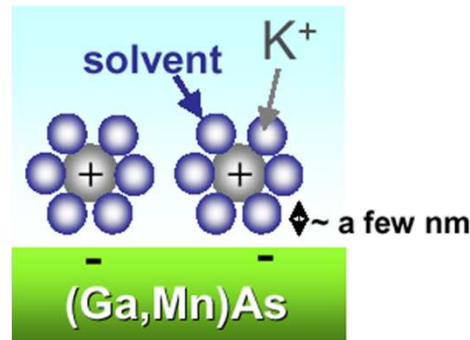
K. Olejník *et al.*,
Phys. Rev. B **78**, 054403 (2008);
M. S. H. Owen *et al.*, New J. Phys. **11**, 023008 (2009).

ferroelectric-gate structure



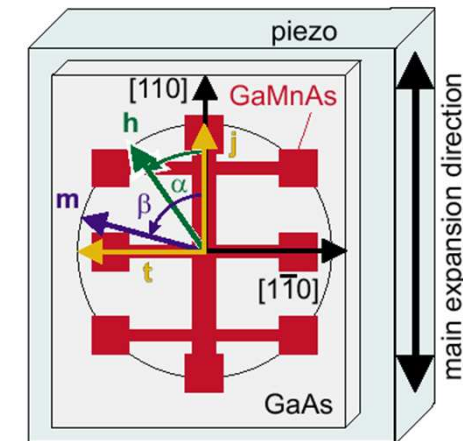
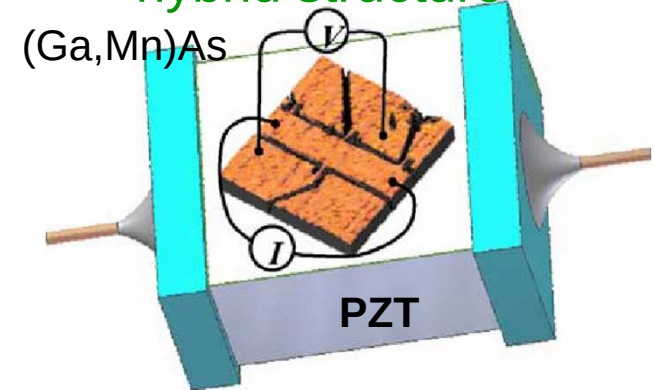
I. Stokichnov *et al.*, Nature Mater.
7, 464 (2008).

electric double layer



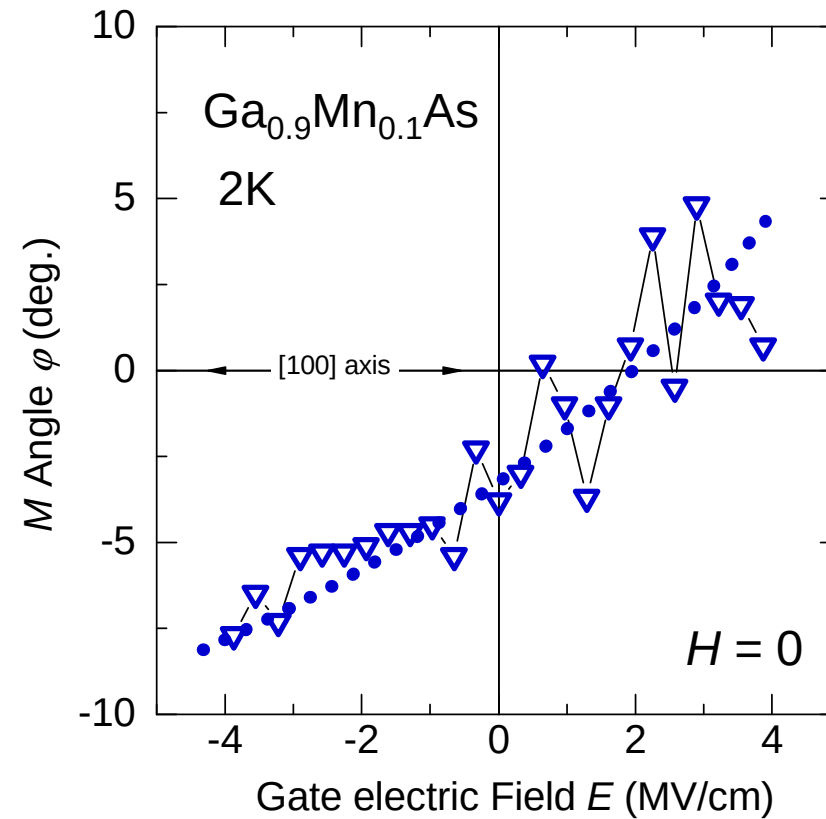
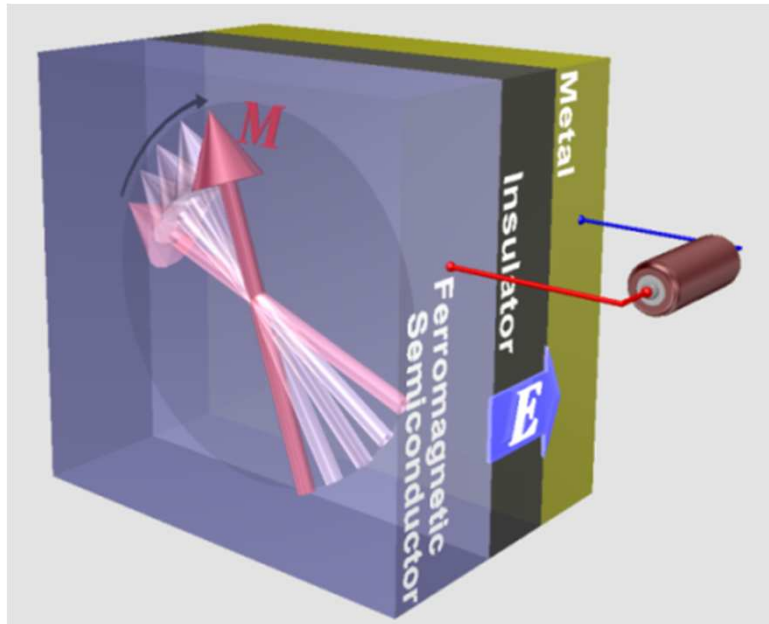
M. Endo *et al.*, Appl. Phys. Lett.
96, 022515 (2010).

piezoelectric hybrid structure

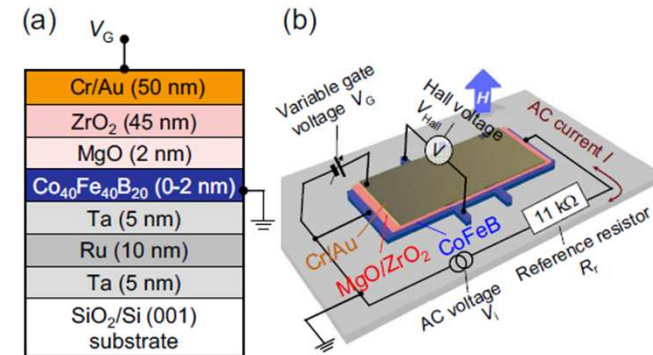
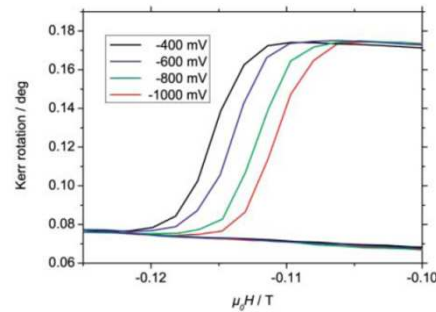
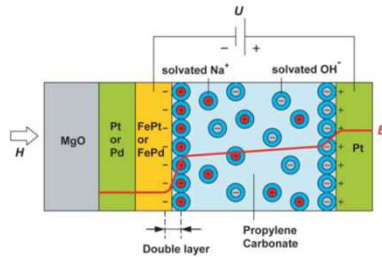


M. Overby *et al.*, Appl. Phys. Lett **92**,
192501 (2008); A. W. Rushforth *et al.*,
Phys. Rev. B **78**, 085314 (2008); S. T. B.
Goennenwein *et al.*, phys. stat. sol. (RRL)
2, 96 (2008); C. Bihler *et al.*, Phys. Rev. B
78, 045203 (2008).

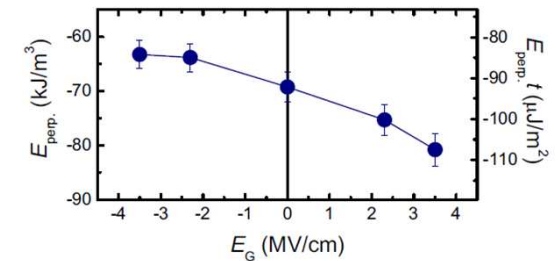
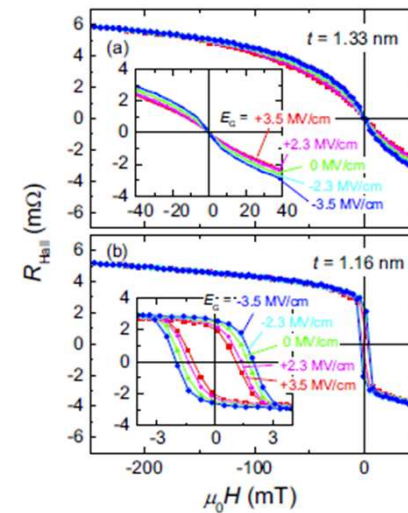
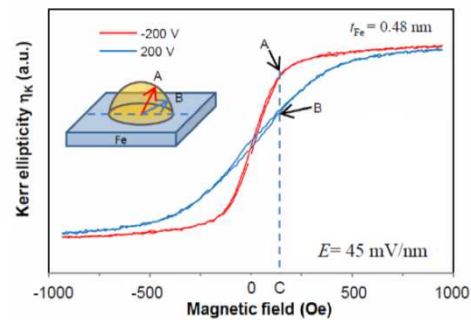
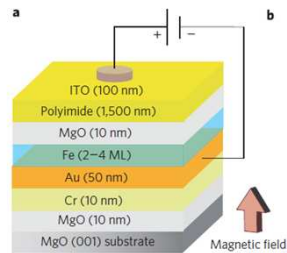
Electric-field control of magnetization direction



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

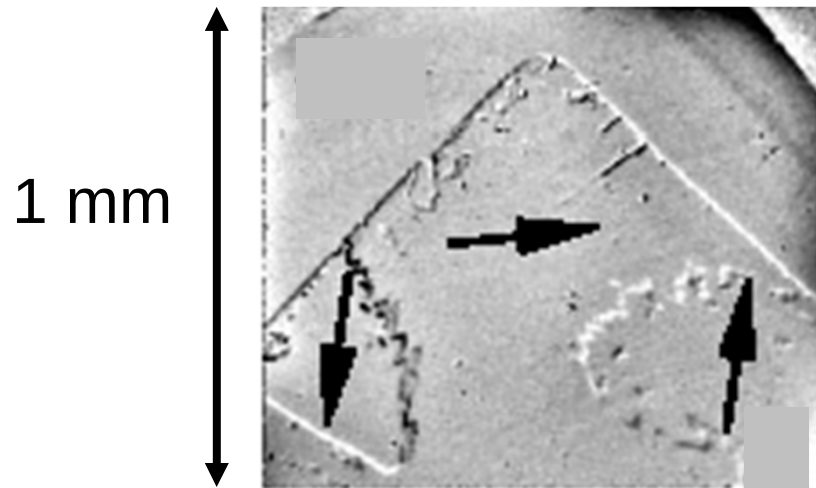
All at room temperature

O-23 Kanai et al.

4. Making “use” of ferromagnetism in semiconductors

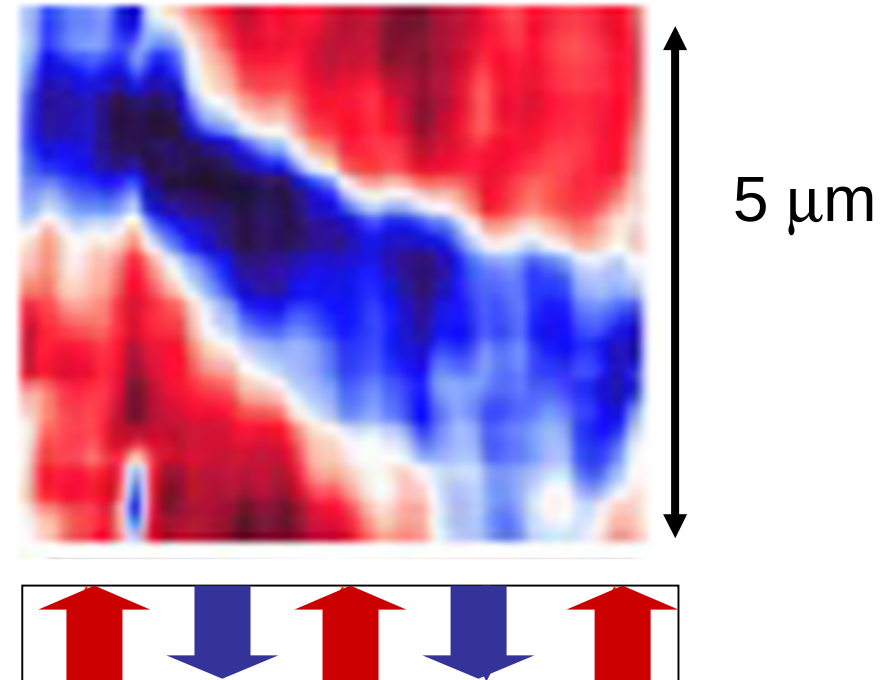
- Electrical control of ferromagnetism
- **Current induced domain wall motion**
- Tunneling with magnetism

Well defined domains: (Ga,Mn)As



Welp et al., PRL 2003

compressive strain
in-plane easy axis
90° domains

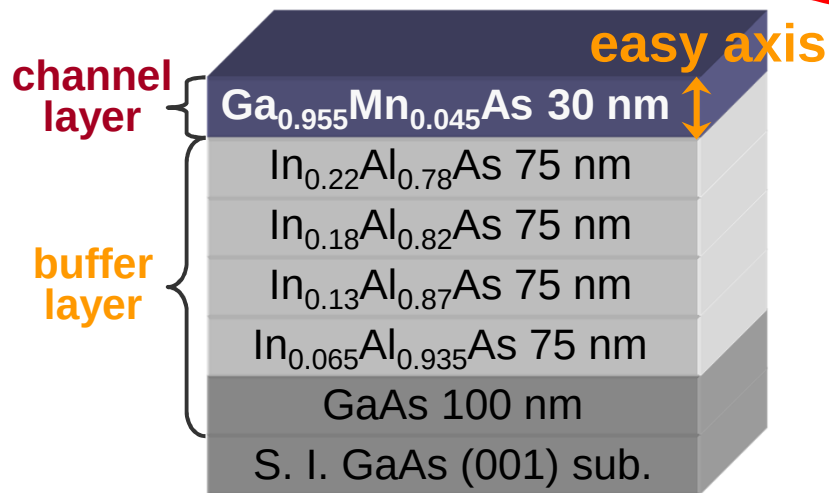


Shono et al., APL 2000

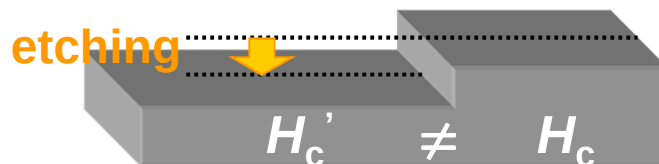
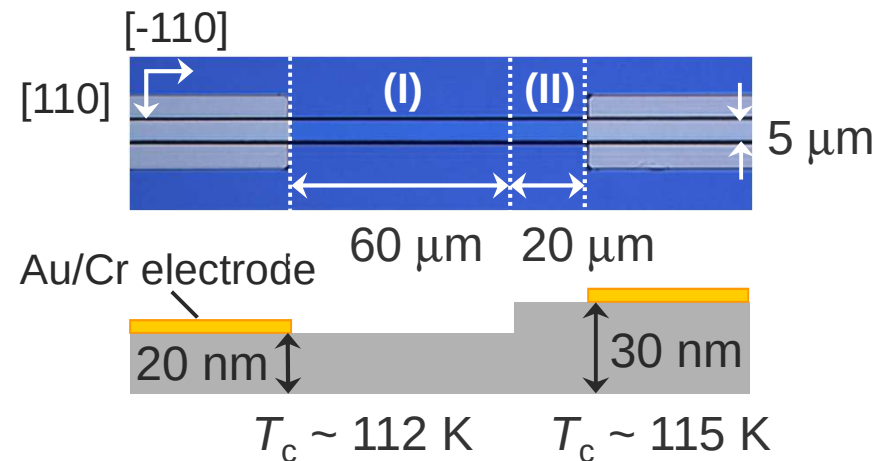
tensile strain
perpendicular easy axis
stripe domains

Current induced domain wall motion

Sample structure



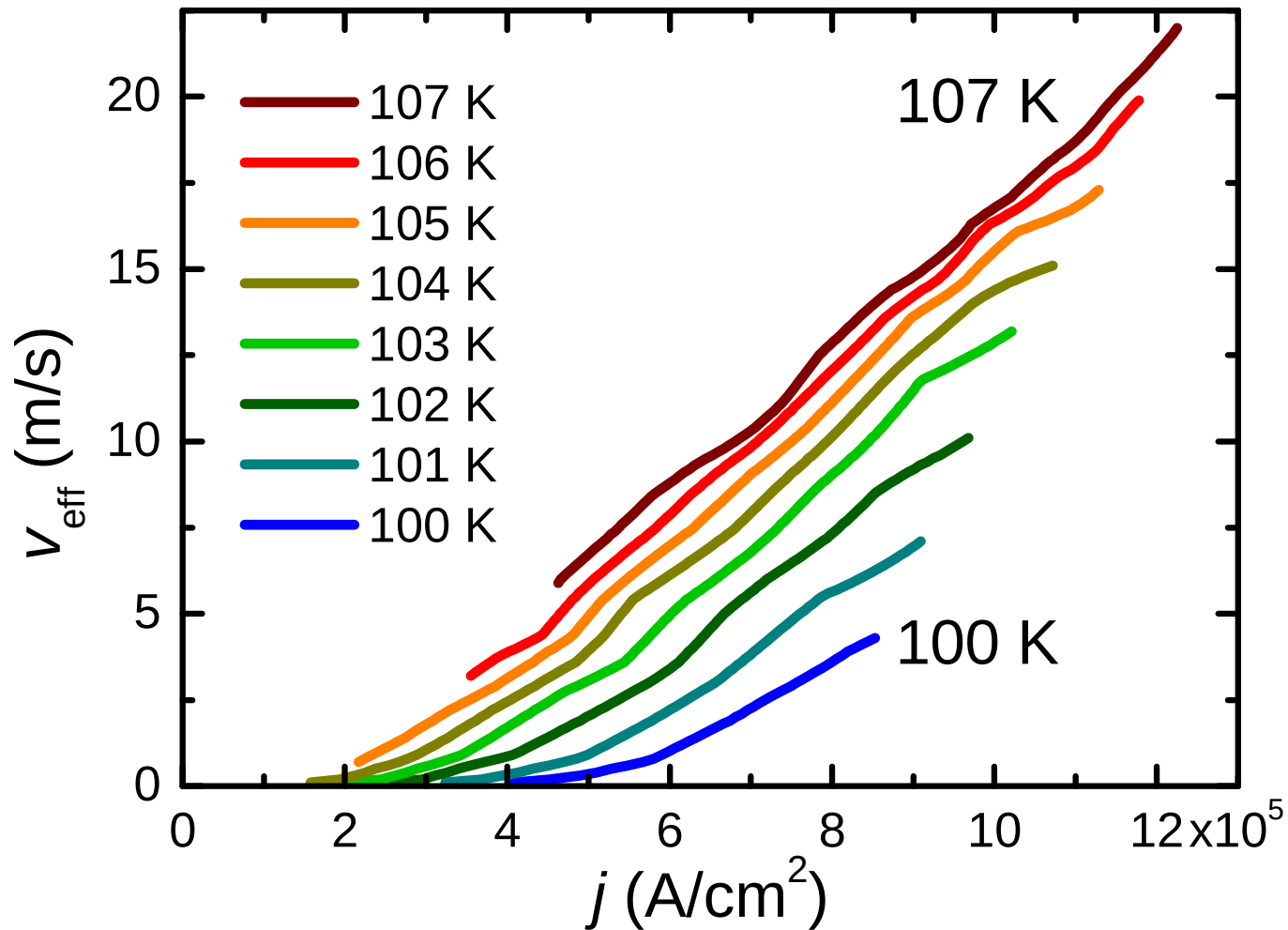
perpendicular
easy axis



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

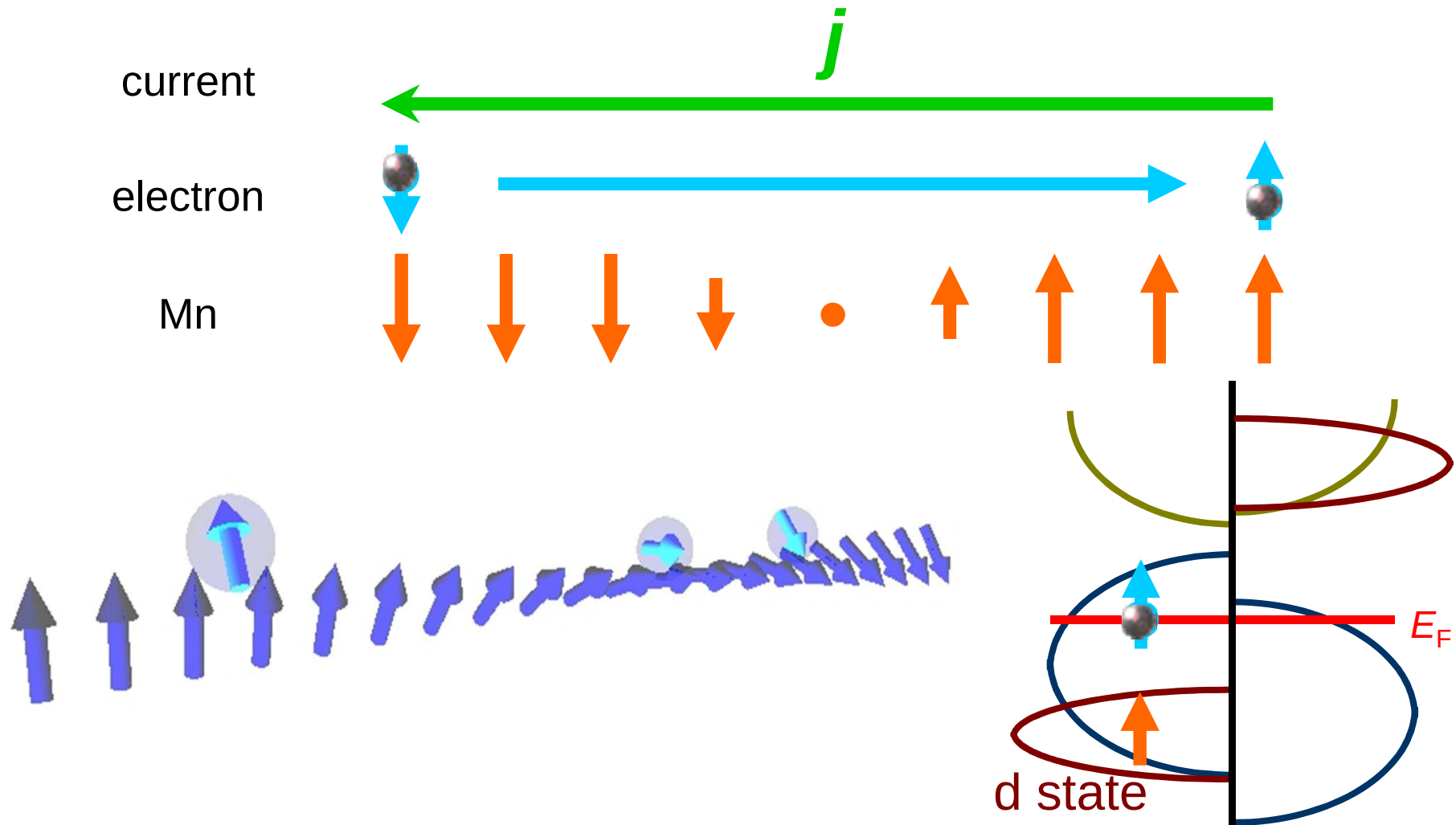
Preparation of domain wall

Current induced domain wall motion



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

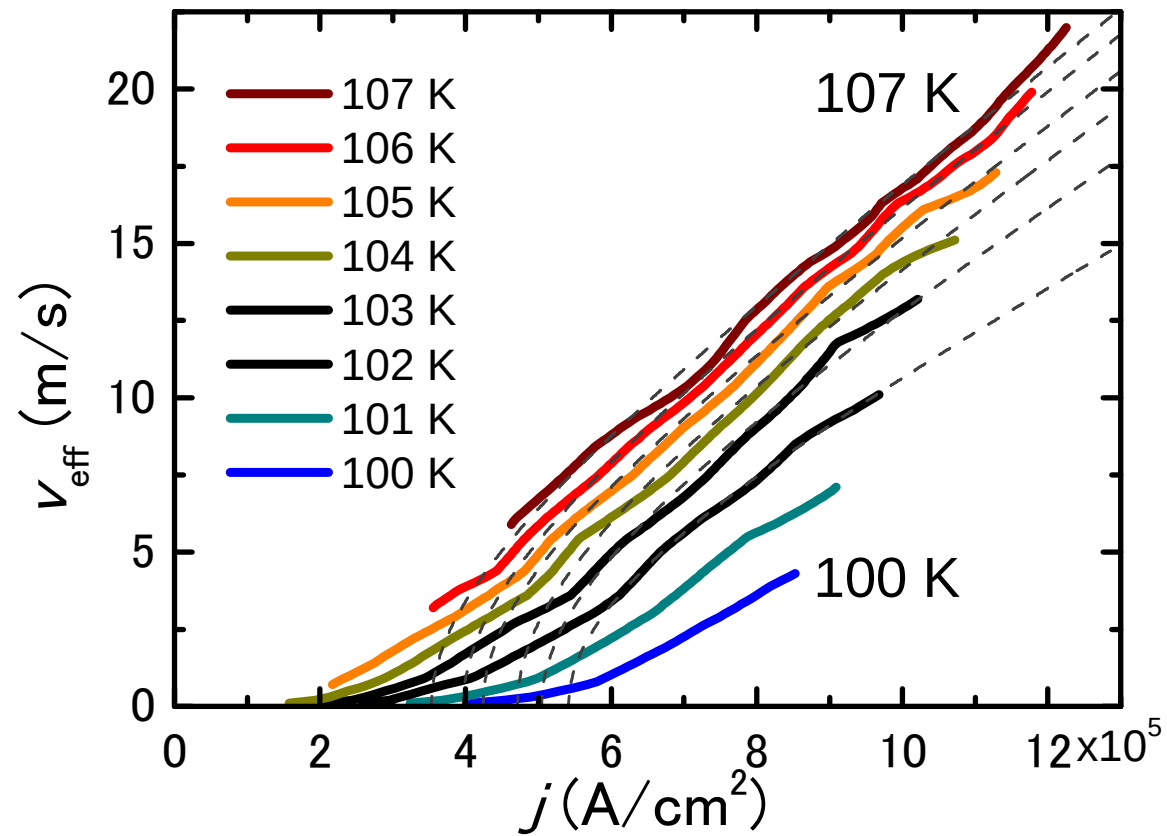
e : charge of electron

M : magnetization

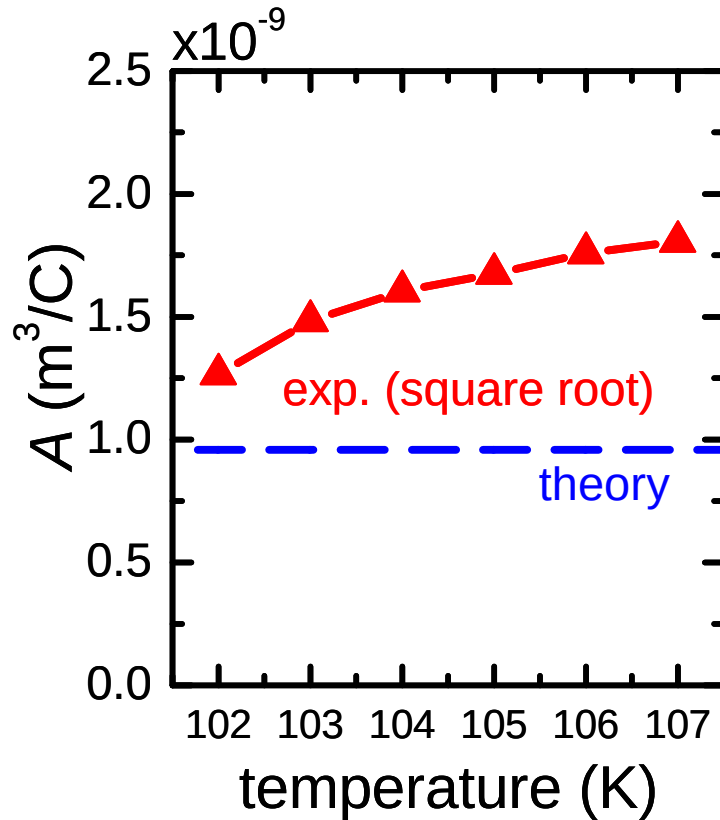
K : transverse anisotropy

δ_w : DW width

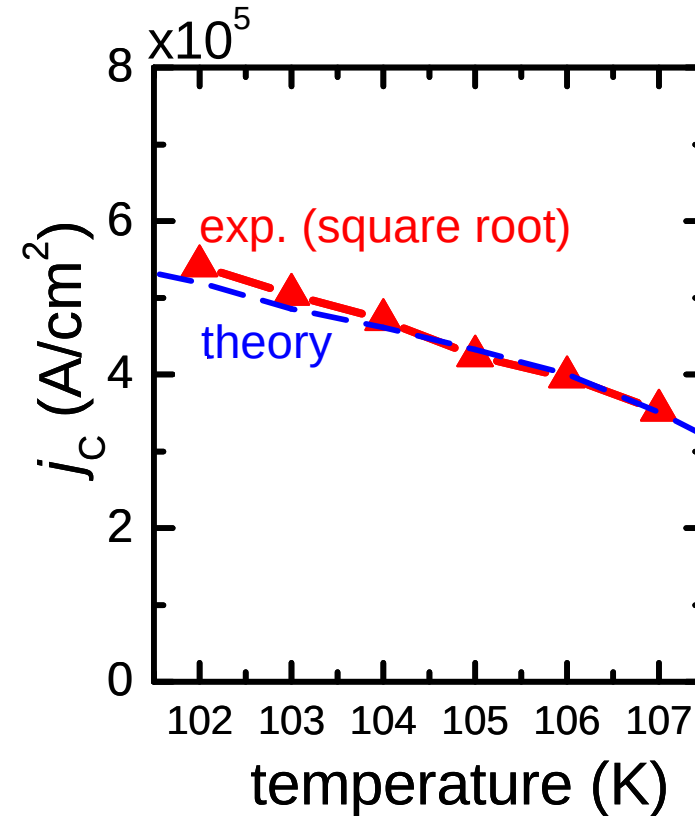
Current induced domain wall motion



Transfer factor and threshold current density



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



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

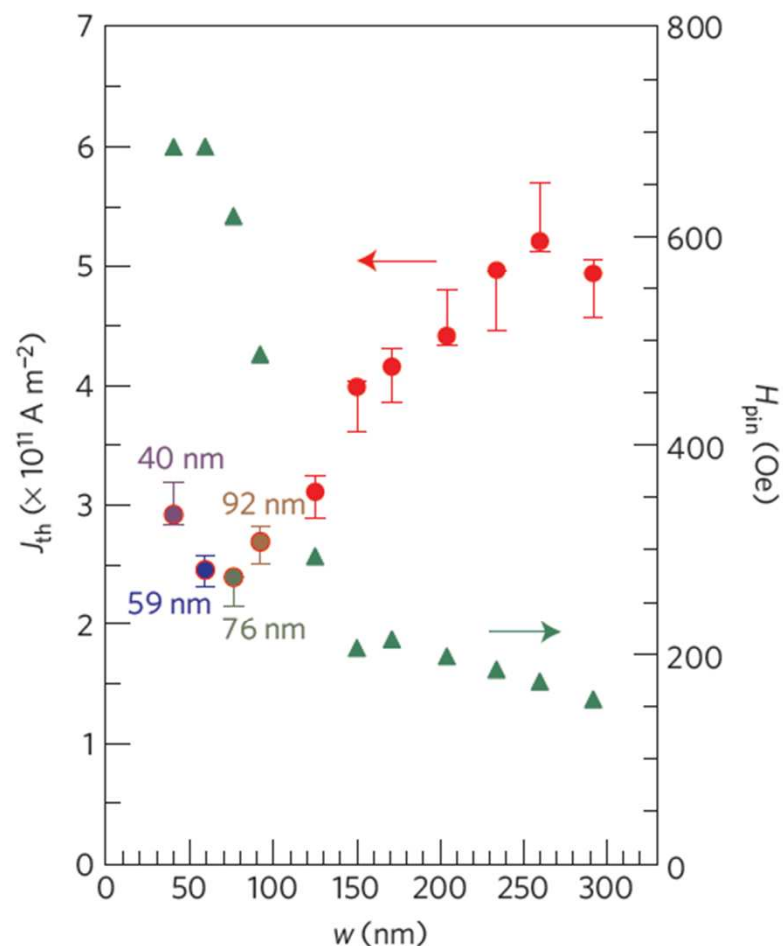
$$j_C = \frac{2eK\delta_w}{\pi\hbar P}$$

	(Ga,Mn)As ($T/T_c \sim 0.9$)	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}

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

T. Koyama¹, D. Chiba^{1,2}, K. Ueda¹, K. Kondou¹, H. Tanigawa³, S. Fukami³, T. Suzuki³, N. Ohshima³, N. Ishiwata³, Y. Nakatani⁴, K. Kobayashi¹ and T. Ono^{1*}

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 pinning³. 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

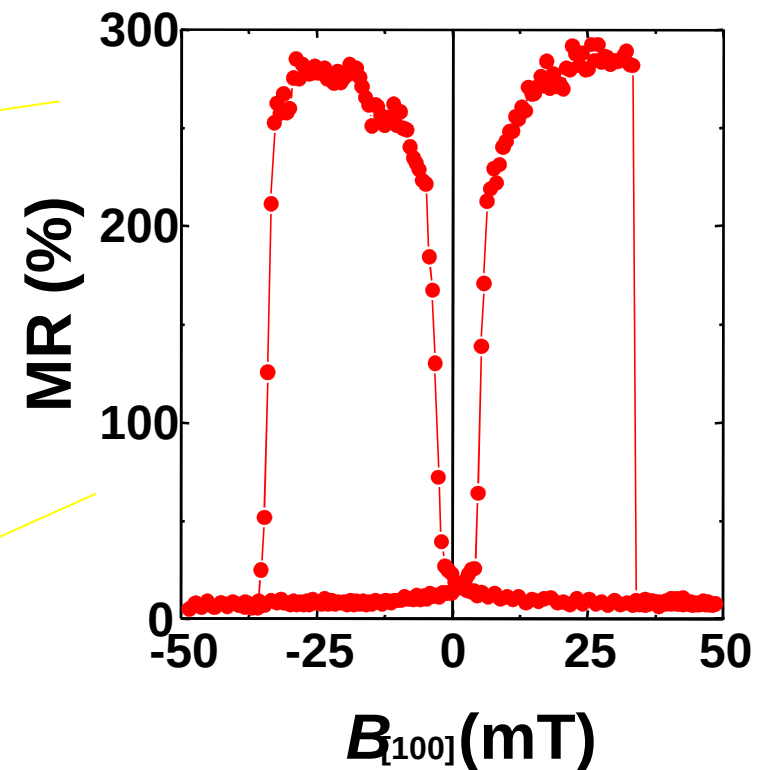
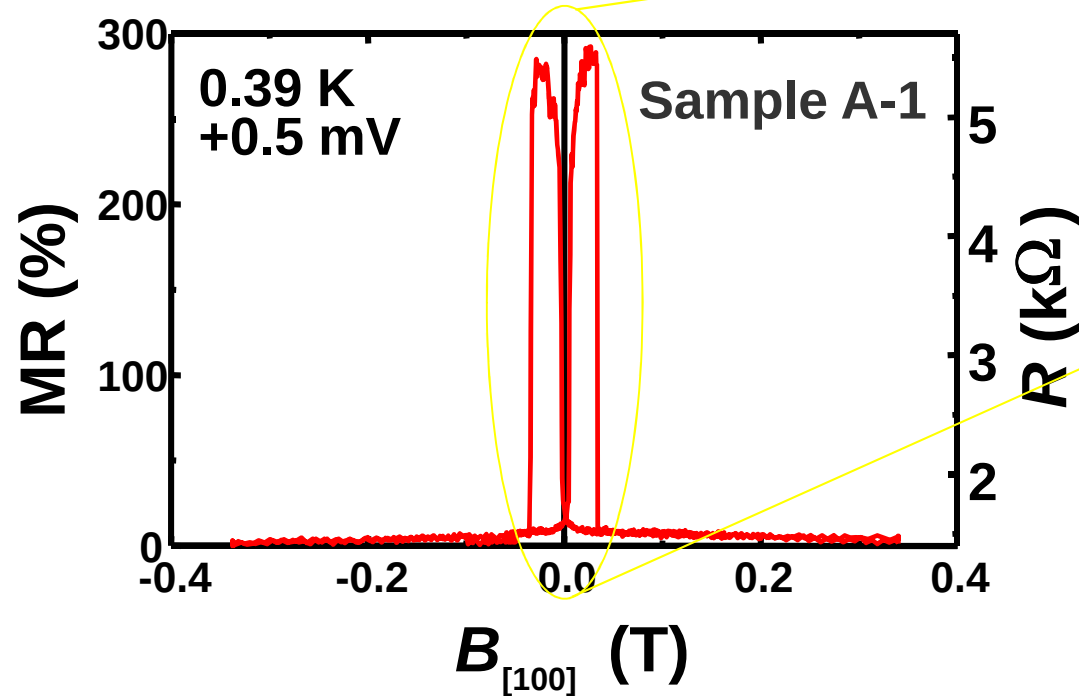
- Electrical control of ferromagnetism
- Current induced domain wall motion
- **Tunneling with magnetism**

Tunnel Magnetoresistance (TMR)

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

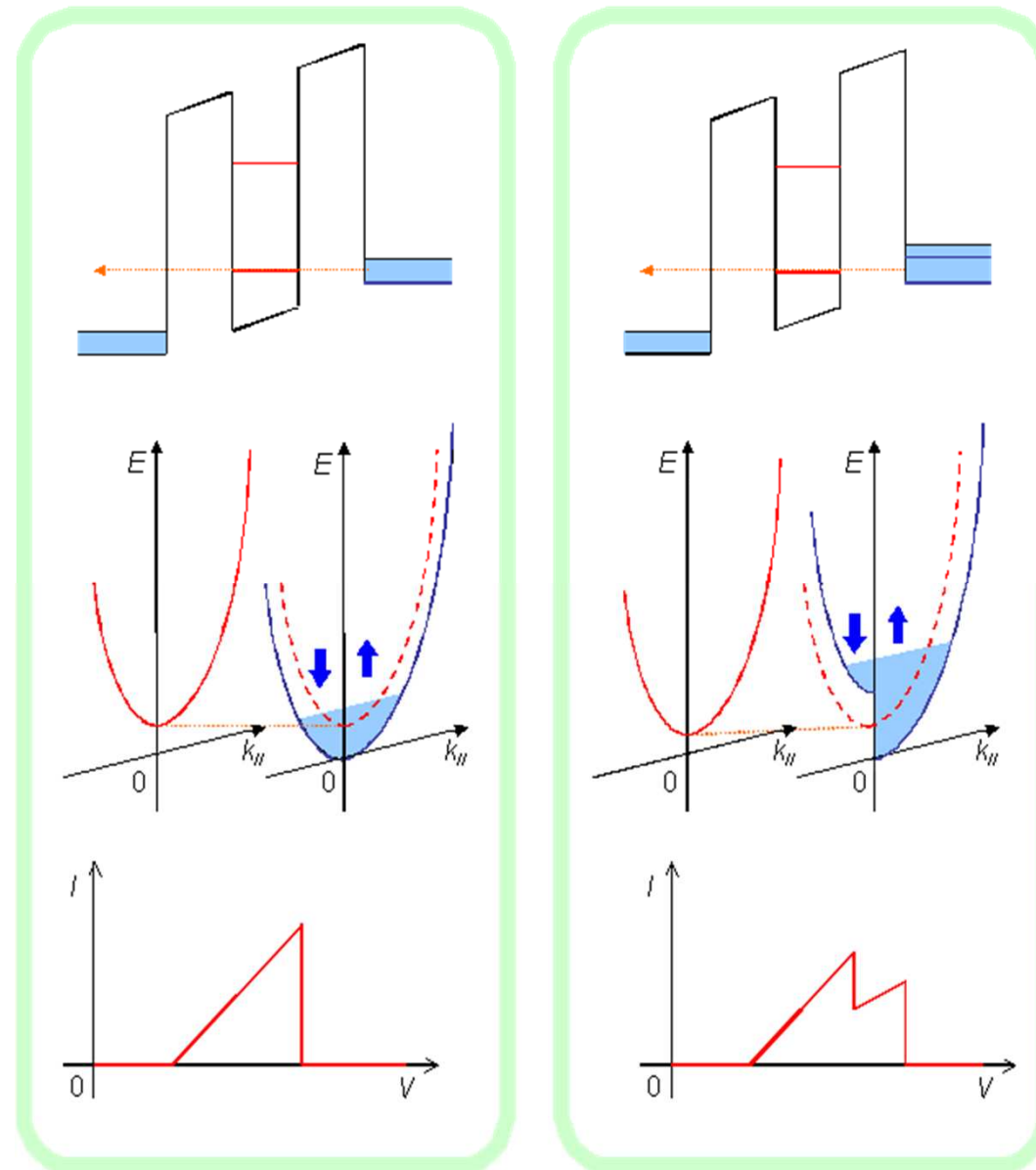
20 nm	(Ga _{0.926} Mn _{0.074})As	230-240 °C
6 nm	GaAs	250 °C
20 nm	(Ga _{0.956} Mn _{0.044})As	250 °C
50 nm	GaAs:Be	560 °C
<i>p</i> ⁺ - GaAs (001) sub		

290 %, $P = 77$ %



D. Chiba et al. *Physica E* 2004

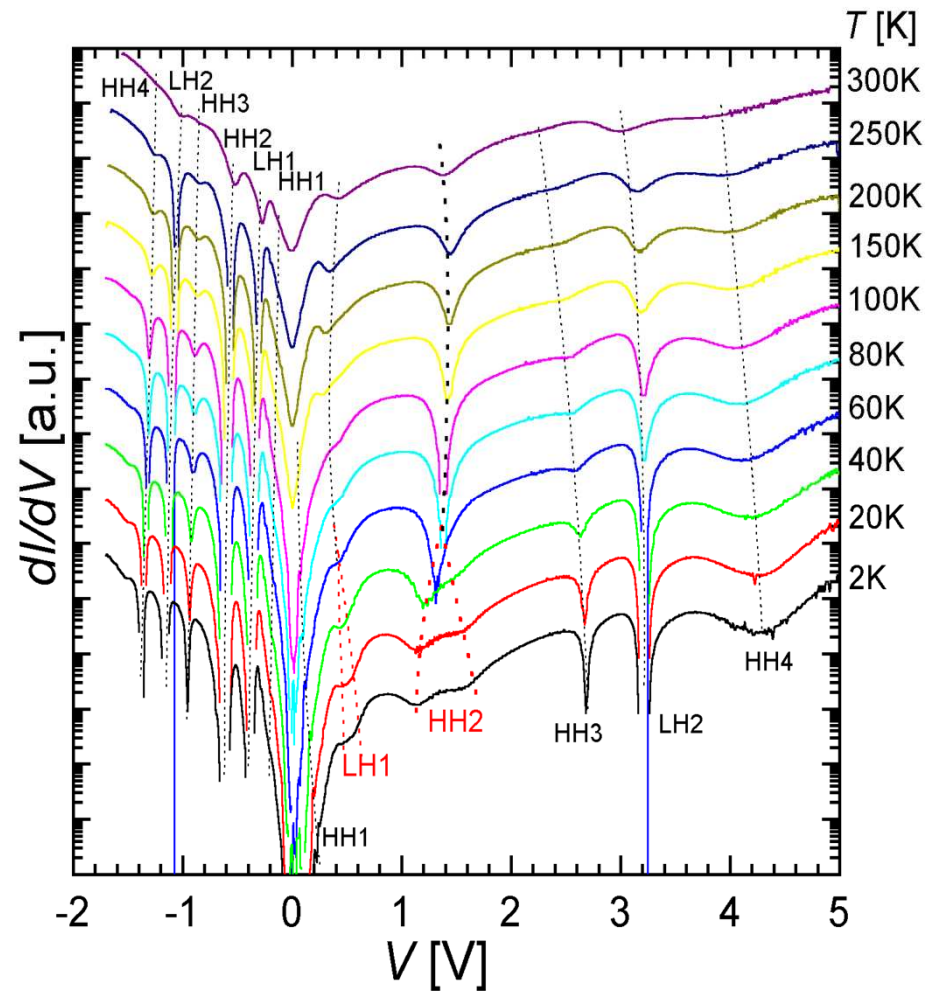
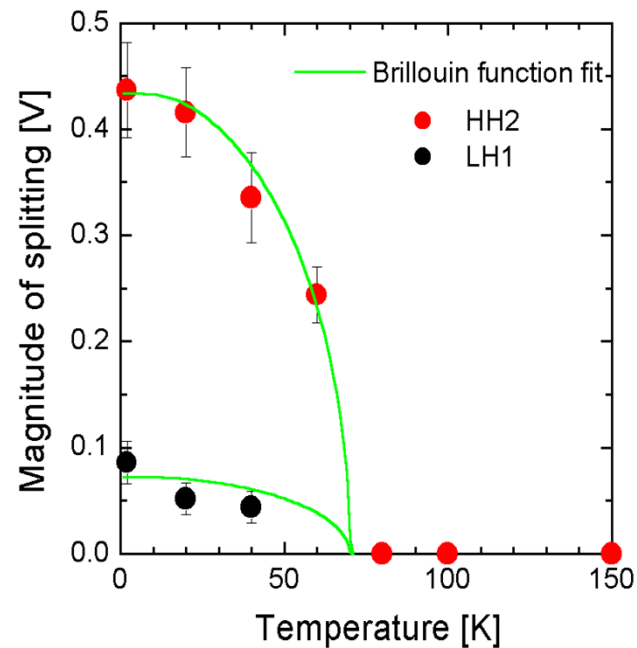
Resonant Tunneling Diode with a Ferromagnetic Emitter



Resonant Tunnel Diode with a Ferromagnetic Emitter

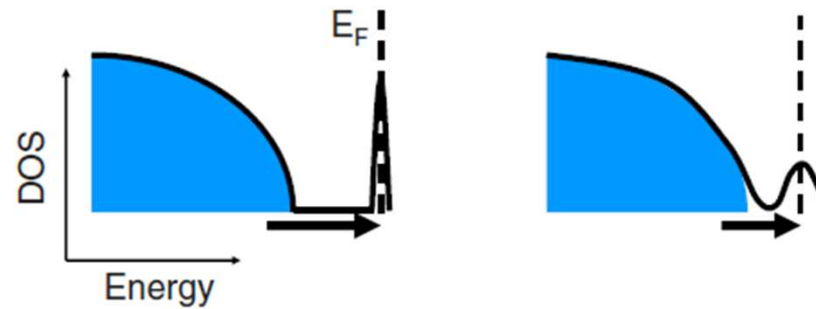
Sample structures

$(\text{Ga}_{0.965}\text{Mn}_{0.035})\text{As}$	200 nm
GaAs	15 nm
AlAs	5 nm
GaAs	d_w nm
AlAs	5 nm
GaAs	5 nm
GaAs:Be ($5 \times 10^{17} \text{ cm}^{-3}$)	150 nm
GaAs:Be ($5 \times 10^{18} \text{ cm}^{-3}$)	150 nm
p^+ GaAs sub.	

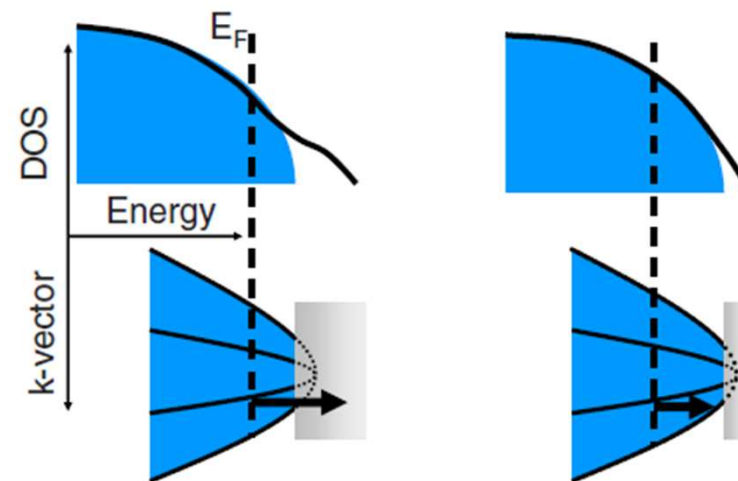


Ultra-high doping of Mn in III-V compounds

Insulating – impurity band detached from valence band



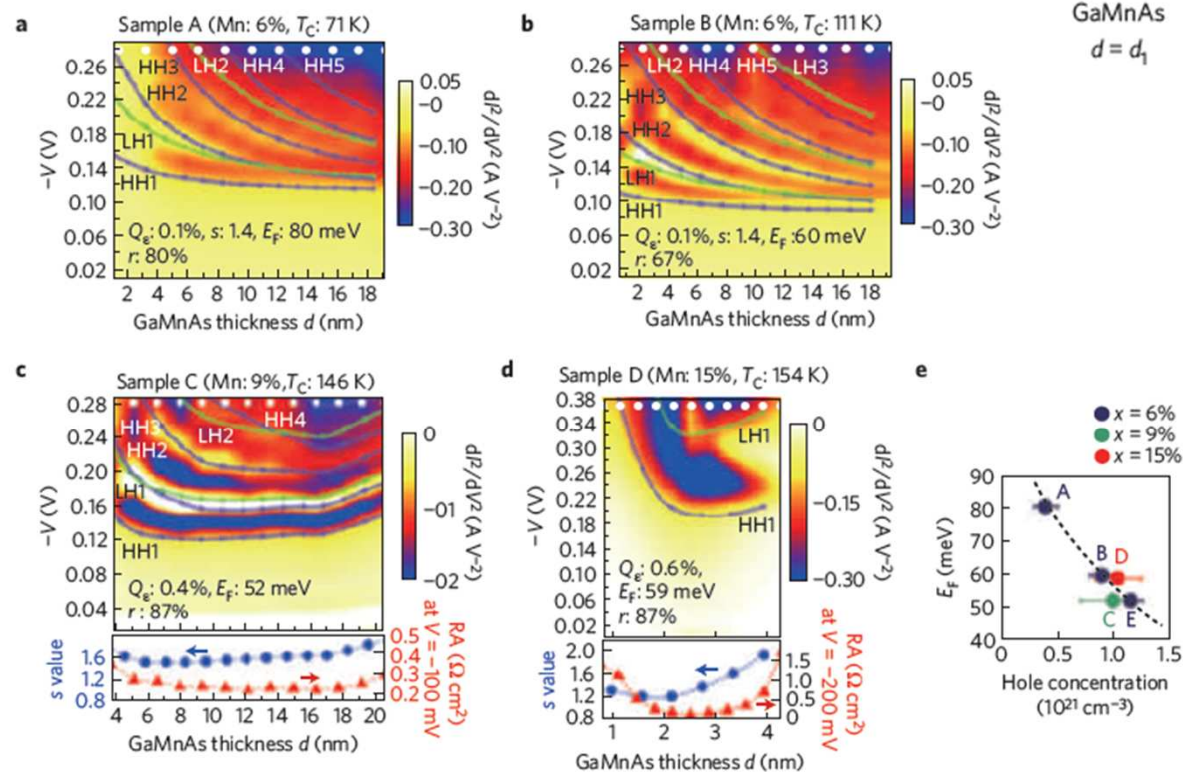
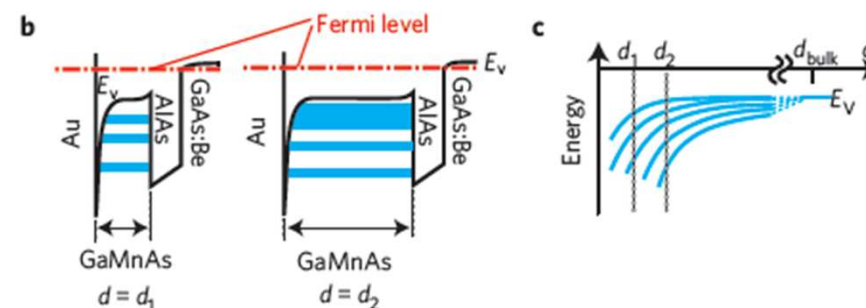
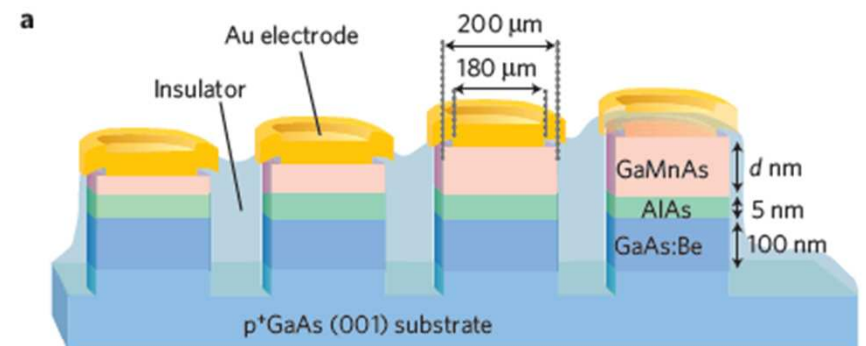
Metallic - merged impurity and valence bands



Nearly non-magnetic valence band of the ferromagnetic semiconductor GaMnAs

Shinobu Ohya*, Kenta Takata and Masaaki Tanaka*

Spintech VI, O-10

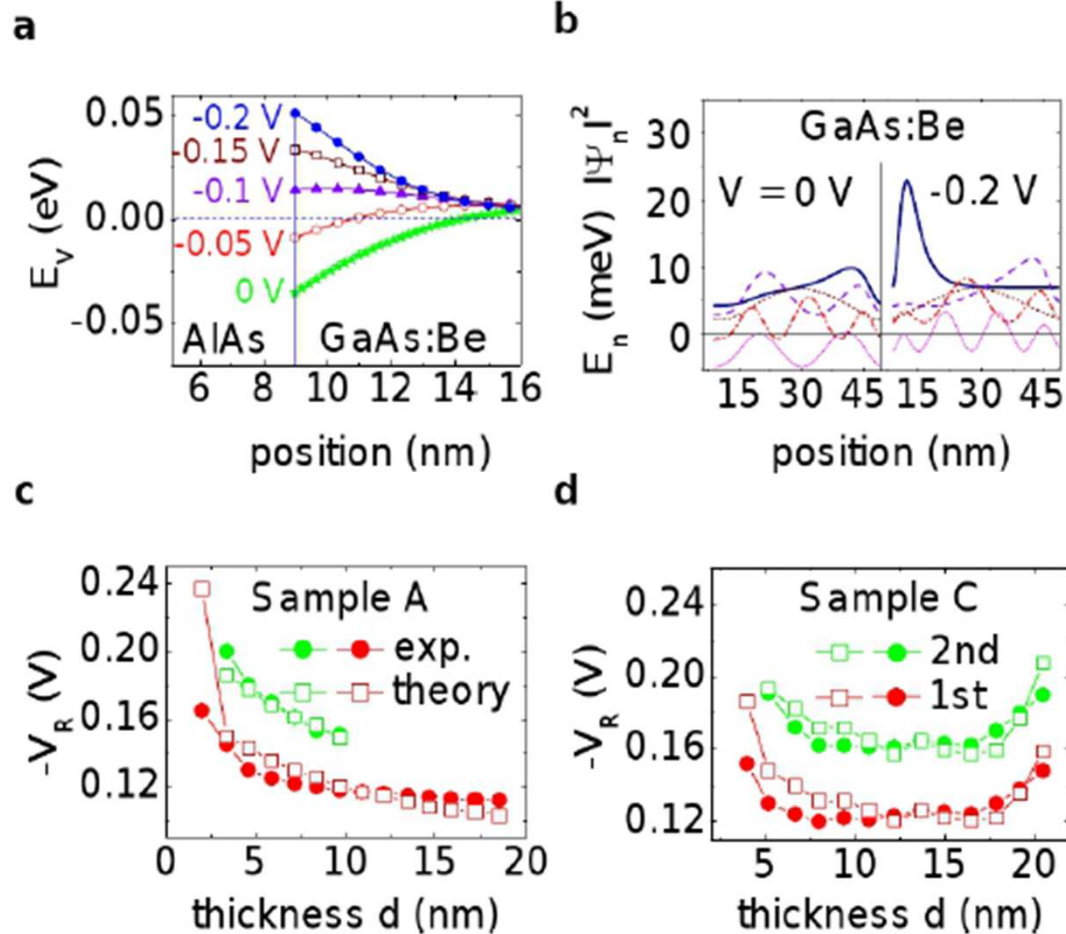


Reconciling results of tunnelling experiments on (Ga,Mn)As

T. Dietl^{1,2} and D. Sztenkiel¹

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