Magnetyzm w półprzewodnikach

Tomasz DIETL

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Institute of Theoretical Physics, Warsaw University

współpracownicy:

M. Sawicki et al.* – *Warszawa

J. Cibert et al.* – *Grenoble

H. Ohno et al.* – *Sendai

S. Kuroda et al.* – *Tsukuba

A. Bonanni et al.* – *Linz

B. Gallagher et al.* – *Nottingham

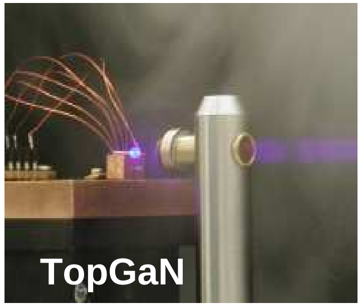
L. Molenkamp et al.* – *Wuerzburg

finansowanie: *ERATO – JST; NANOSPIN -- EC project; SPINTRA – ESF; Humboldt Foundation, AdG ERC „FunDMS”*

artykuły przeglądowe, patrz arXiv; : J. Phys. C’07; JAP’08, JPSJ’08

Spintronics -- materials aspect

Why to do not combine complementary resources of ferromagnets and semiconductors?



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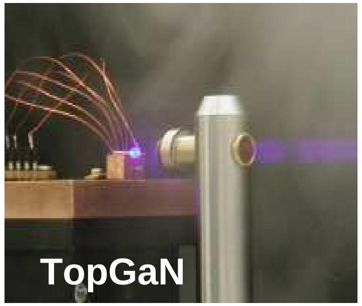


- **hybrid ferromagnetic-metal/semiconductor structures**

  - **spin injection** *A. Hanbicki et al. (NRL) APL'03, Nature Phys. '07*
  - **optical isolators** *H. Shimizu et al. (Tokyo) JJAP'04*
  - **Stern-Gerlach aparatus** *J. Wróbel et al. (Warsaw) PRL'04*
  - **.....**

Spintronics -- materials aspect

Why to do not combine complementary resources of ferromagnets and semiconductors?

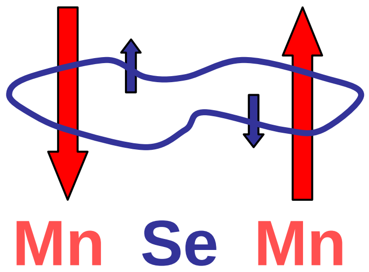
- **ferromagnetic semiconductors** ***– multifunctional materials***

Making *semiconductors* ferromagnetic

- ***Antiferromagnetic* superexchange dominates in magnetic insulators and semiconductors**

  ➔ no spontaneous magnetization

  NiO, MnSe, EuTe, …



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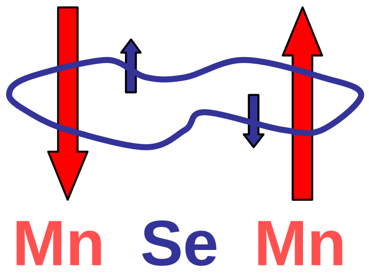
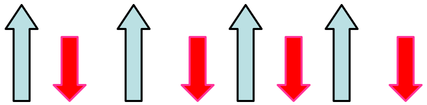


- **Exceptions**

  -- ferrimagnets (two ions or two spin states co-exist)

  NiO(Fe_2O_3), Mn_4N, …



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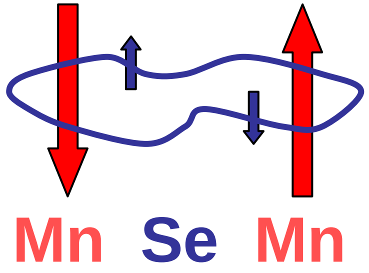

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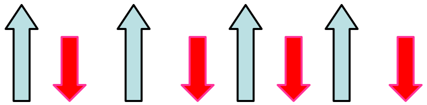
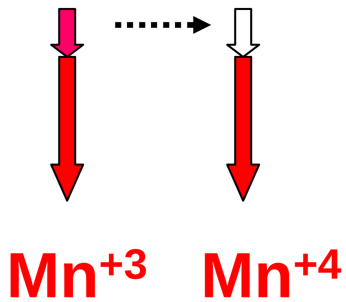


  -- double exchange (two charge states co-exist)
  $LaMnO_3$ → $La_{1-x}Sr_xMnO_3$ (holes in d band)

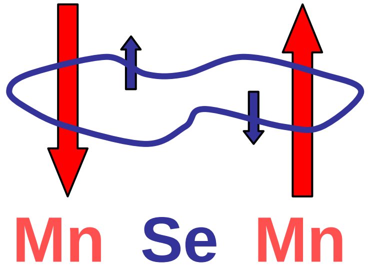


Search for ferromagnetic semiconductors

- ***Antiferromagnetic*** **superexchange dominates in magnetic insulators and semiconductors**

  → **no spontaneous magnetization**

  NiO, MnSe, EuTe, …



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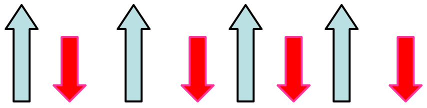

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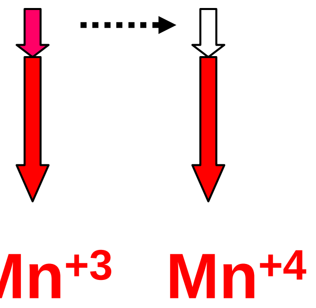
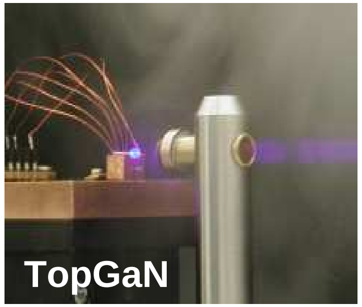


  -- ferromagnetic superexchange dominates

  EuO, $ZnCr_2Se_4$, … $T_C \approx 100$ K ***IBM, MIT, Tohoku, … '60-'70***

Spintronics -- materials aspect

Why to do not combine complementary resources of ferromagnets and semiconductors?



- **ferromagnetic semiconductors** – ***multifunctional materials***

  - **making good semiconductors of magnetic oxides**

cf. J. Fontcuberta, R. Gross, N. Keller, ...

Spintronics -- materials aspect

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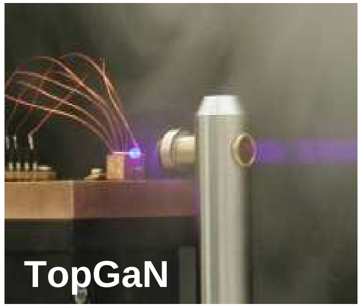


- **ferromagnetic semiconductors** *– multifunctional materials*

  - **making good semiconductors of magnetic oxides**

  - **making good semiconductors magnetic**

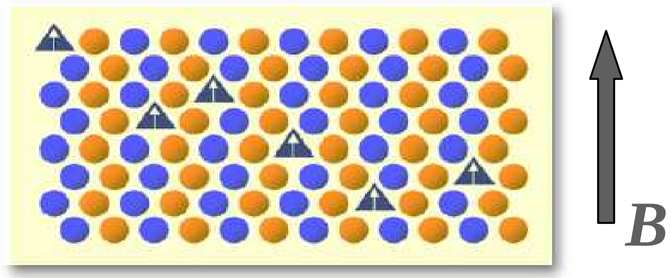
    R.R. Gałązka et al. (Warsaw)'77- ; H. Ohno et al. (IBM, Tohoku) '89 – see, Spin Physics, Nature Milestones (2008)

Making DMS ferromagnetic

- **Intrinsic DMS – random *antiferromagnets***

$Cd_{1-x}Mn_xTe$

$Zn_{1-x}Co_xO$



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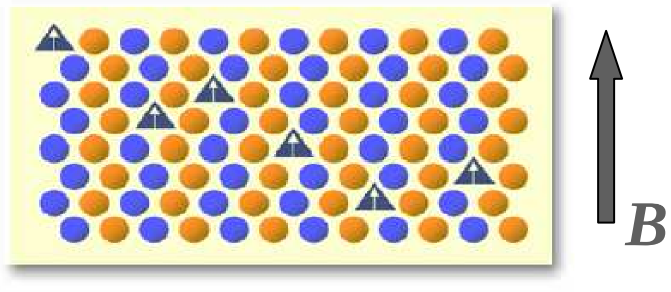


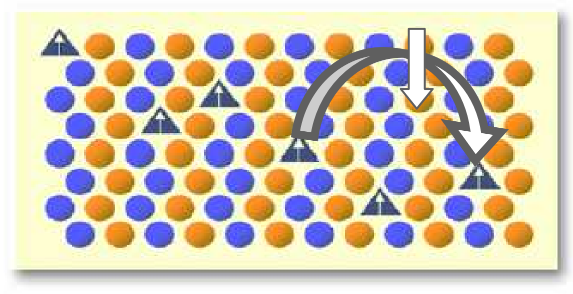
- **p^+-type DMS – Zener/RKKY *ferromagnets***

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

Story et al. (Warsaw, MIT) PRL'86

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

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

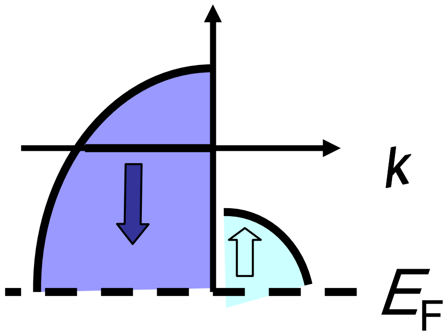


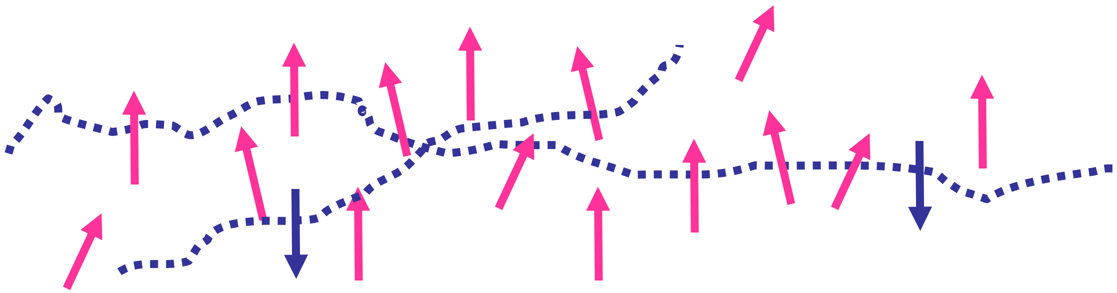
$T_C \approx 100$ K for $x = 0.05$

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

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

p-d Zener/RKKY model of hole-controlled ferromagnetism in DMS





Driving force:

lowering of the hole energy due to redistribution between hole spin subbands split by p-d exchange interaction

T.D. , Y. Merle d'Aubigné PRB'97-
T. D, H. Ohno – Science'00 -
Jungwirth et al. (Austin/Prague) '99-

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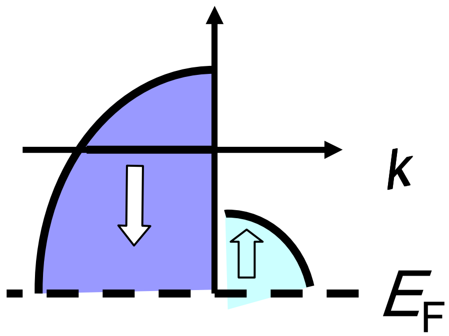
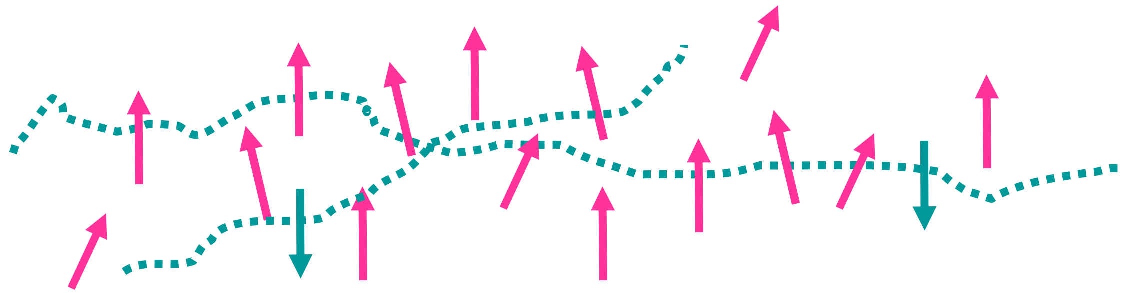


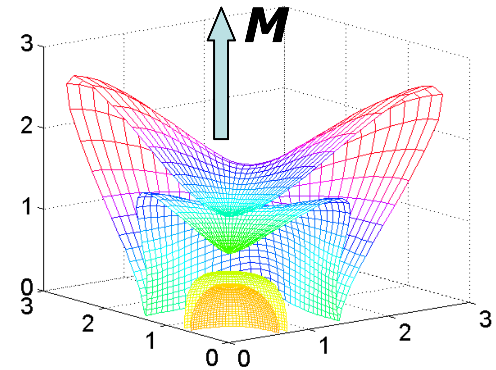


Driving force:

lowering of the hole energy due to redistribution between hole spin subbands split by *p-d* exchange interaction. $\Delta \sim \beta M$

Essential ingredient:

Complexity of the valence band structure has to be taken into account

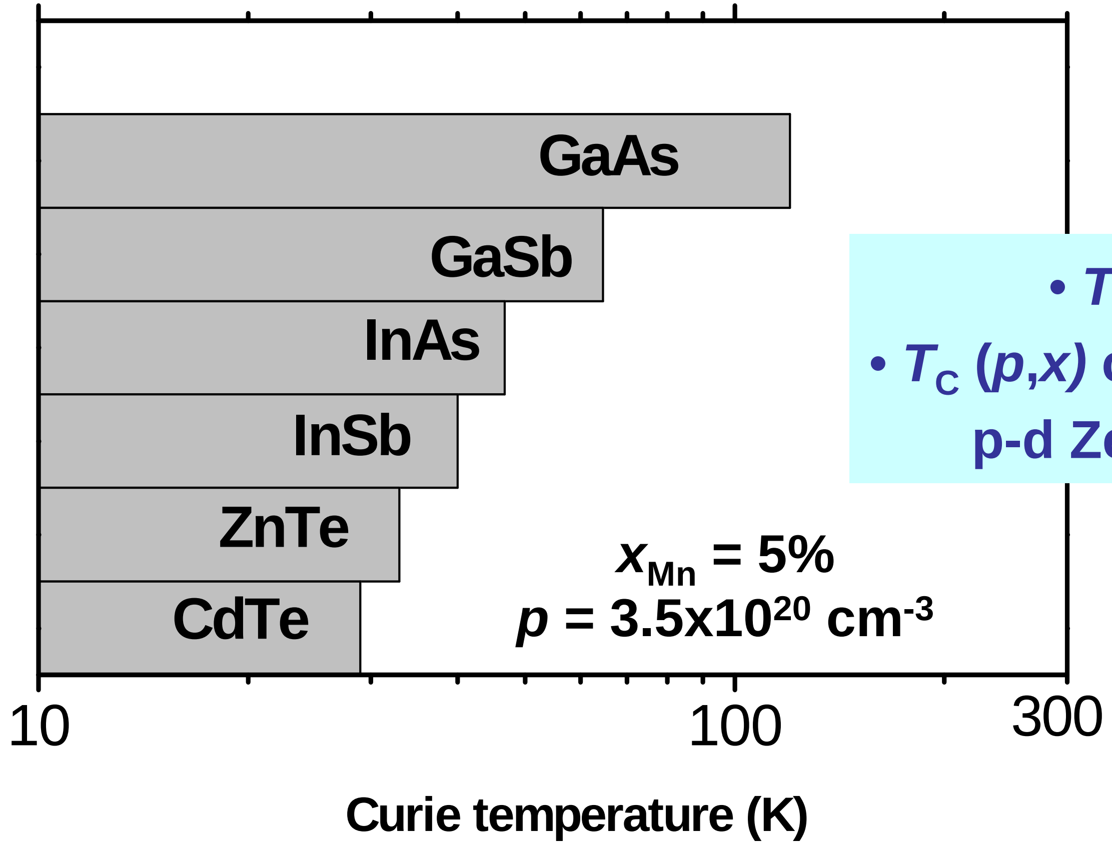


No adjustable parameters

$T_C \sim x\beta^2\rho^{(s)}_{DOS}$

T.D. , Y. Merle d'Aubigne PRB'97-
T. D, H. Ohno – Science'00 -
T. Jungwirth et al. (Austin/Prague) '99-

Mn-based p-type DMS with valence-band hole mediated ferromagnetism



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

Expl.:

Tohoku, Tokyo, Grenoble, Wuerzburg, PSU, Notre Dame,Lund, UCSB,Nottingham, Prague…

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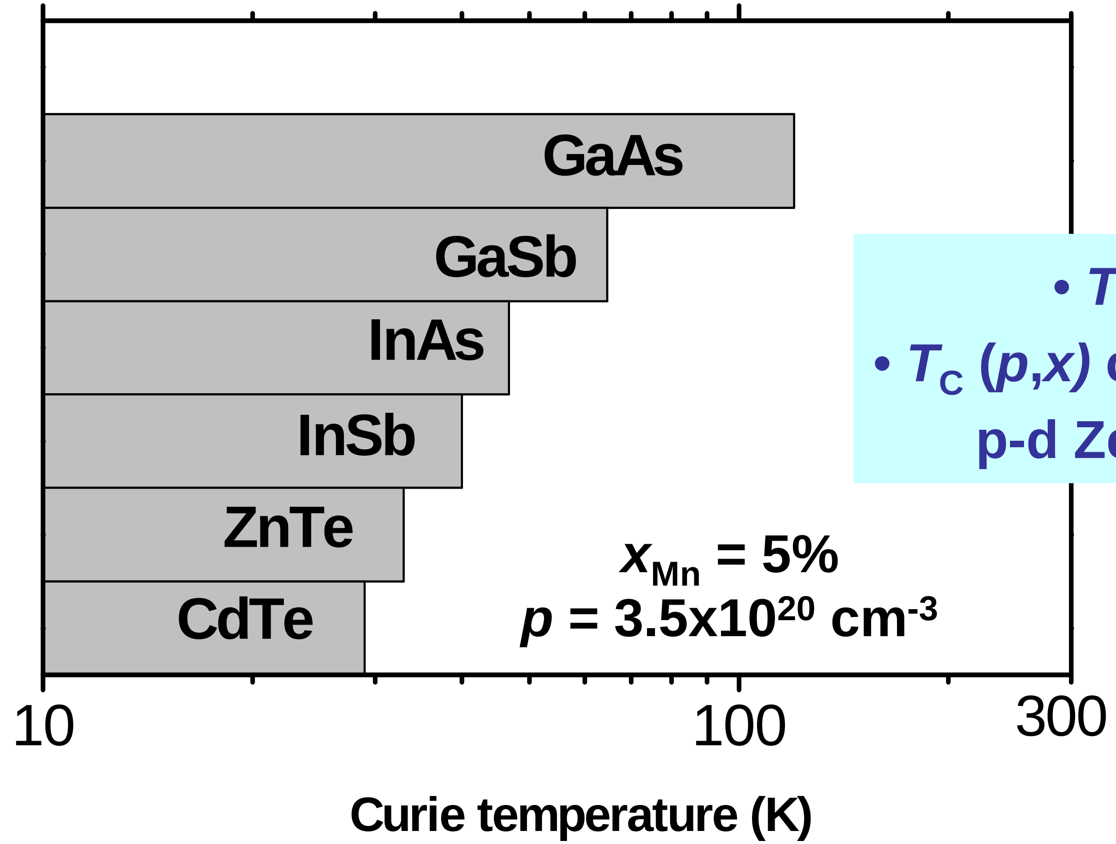

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Tohoku, Tokyo, Grenoble, Wuerzburg, PSU, Notre Dame, Lund, UCSB, Nottingham, Prague…

- **not double exchange**
- **not impurity band models**

see, T. Jungwirth, … T.D., PRB'07

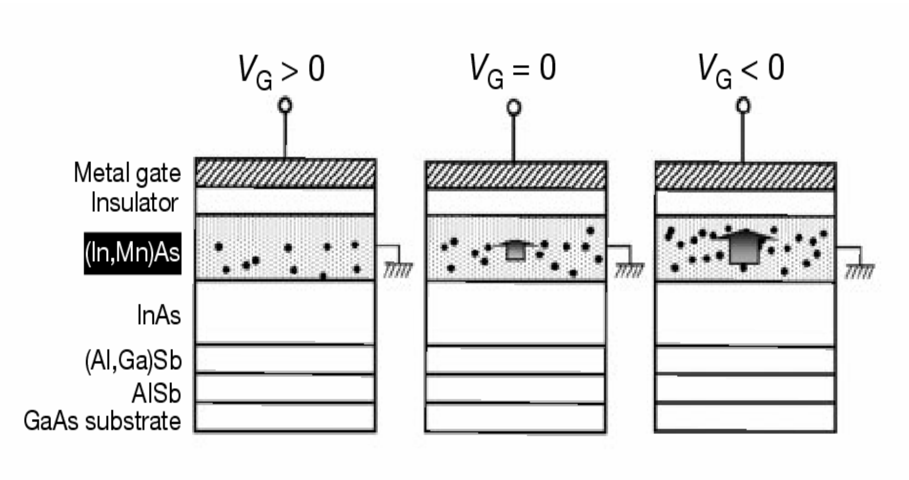
Spintronic functionalities of ferro DMS

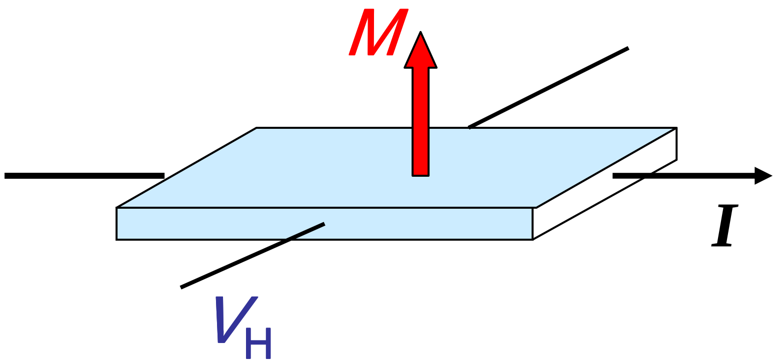
- **spin injection** ***(Tohoku/St. Barbara Nature'99, JJAP'01, PRB'02 APL'03,'06; IMEC/Warsaw APL'04, PRB'05)***
- **GMR, TMR, TAMR** ***(Tohoku Physica'00,'04; Thaless PRL'03, Wuerzburg PRL'04,'05, Nottingham PRL'05)***
- **RTD** ***(Tohoku APL'98, Tokyo APL'06; Thaless PRL'07)***
- **,,,,,,,,**

Magnetisation manipulation by:

- **light** ***(Tokyo PRL'97, Grenoble/Warsaw PRL'97,'02)***
- **electric field** ***(Tohoku/Warsaw Nature'00,'08 Grenoble/Warsaw PRL'02)***
- **electric current in trilayer structures** ***(Tohoku PRL'04, Orsay PRB'06)***
- **domain-wall displacement induced by electric current** ***(Tohoku, Nature '04, Science'07, Tohoku/Warsaw PRL'06)***

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





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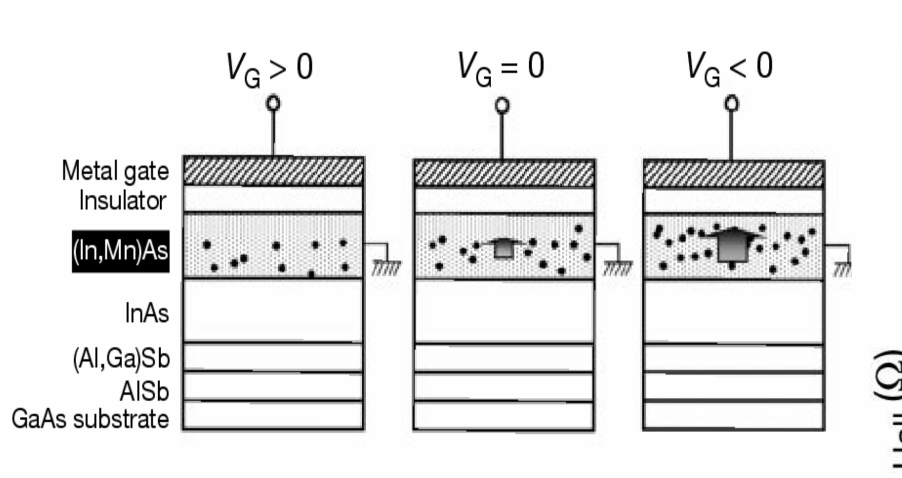
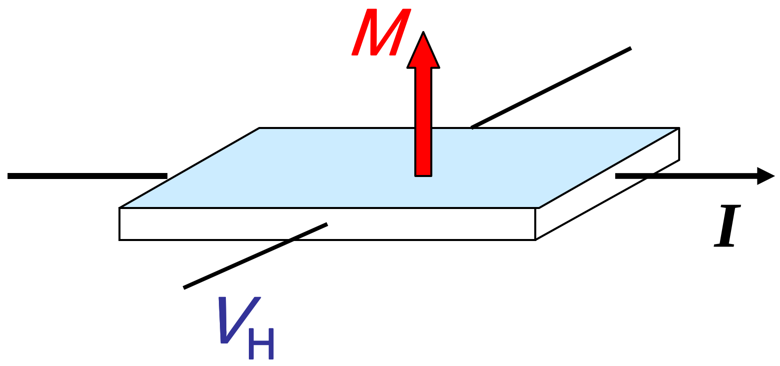
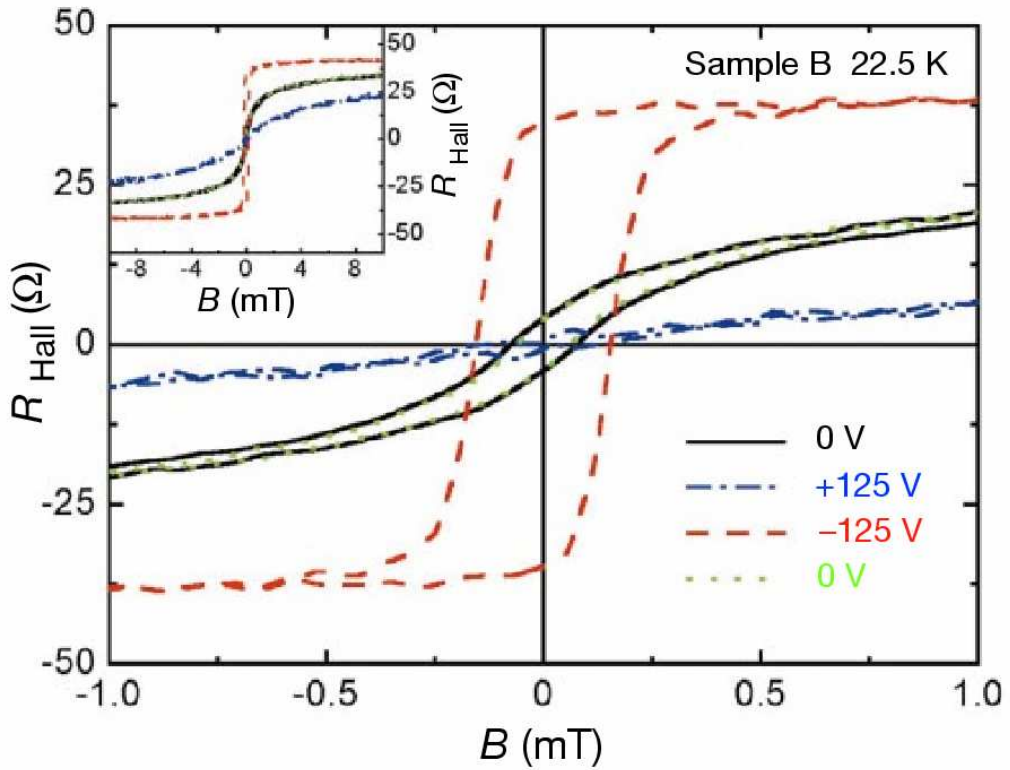


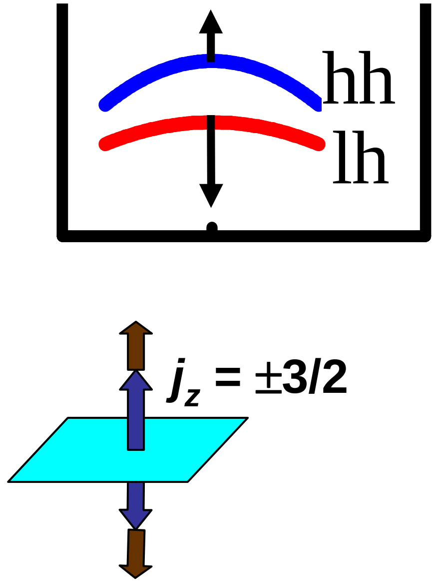


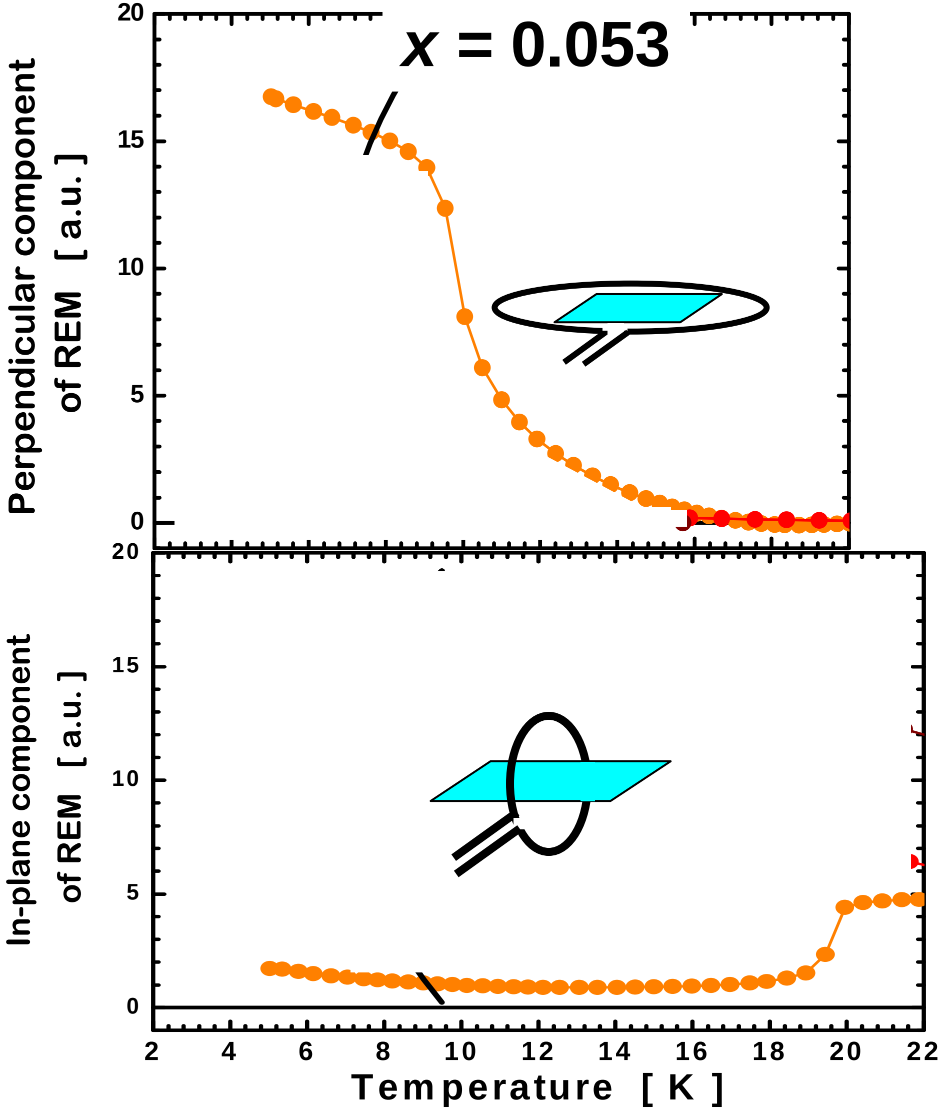


H. Ohno … TD., Nature 2000

Epitaxial-strain-induced magnetic anisotropy

$Ga_{1-x}Mn_xAs/GaAs$
➔ compressive strain





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

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

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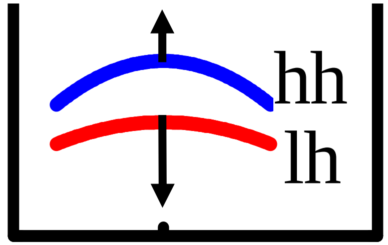
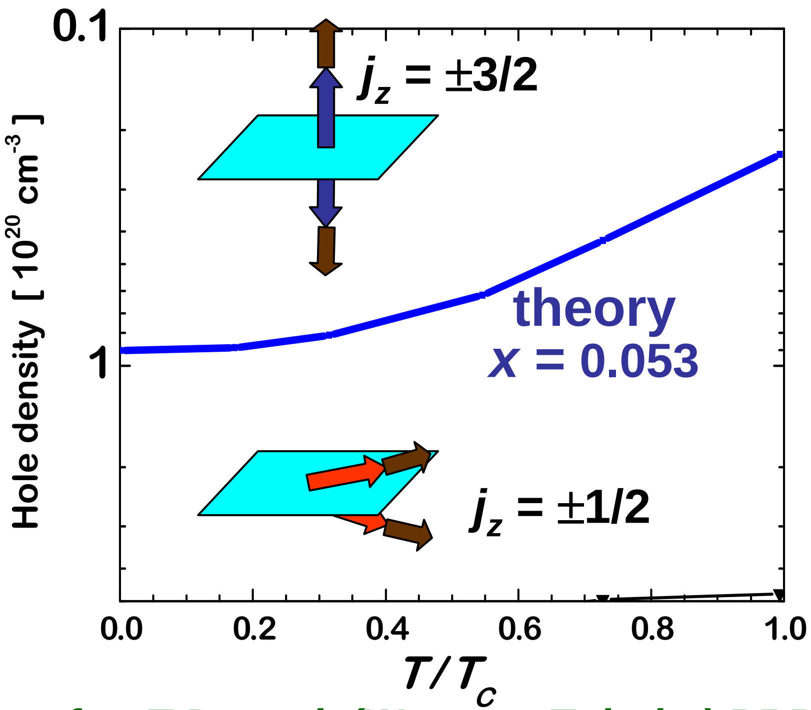
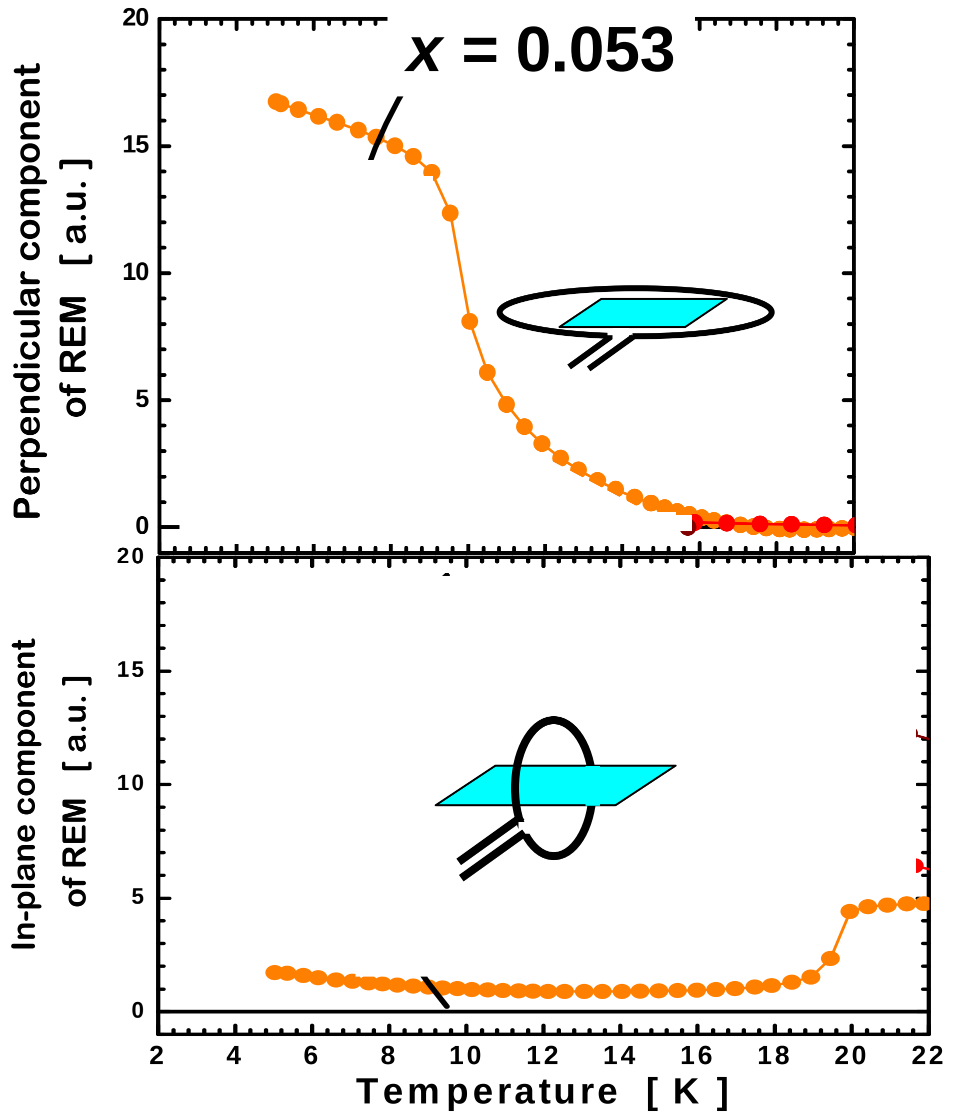


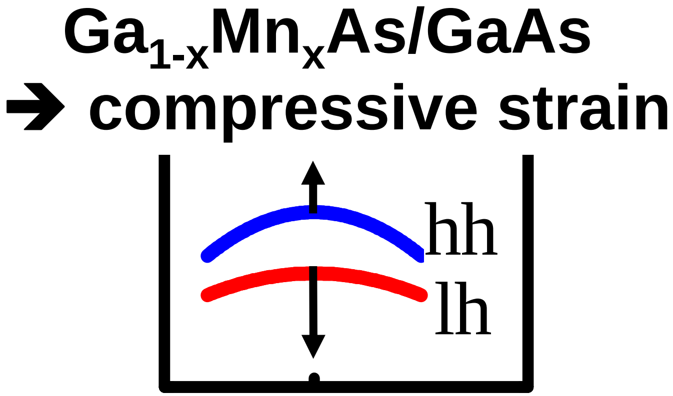


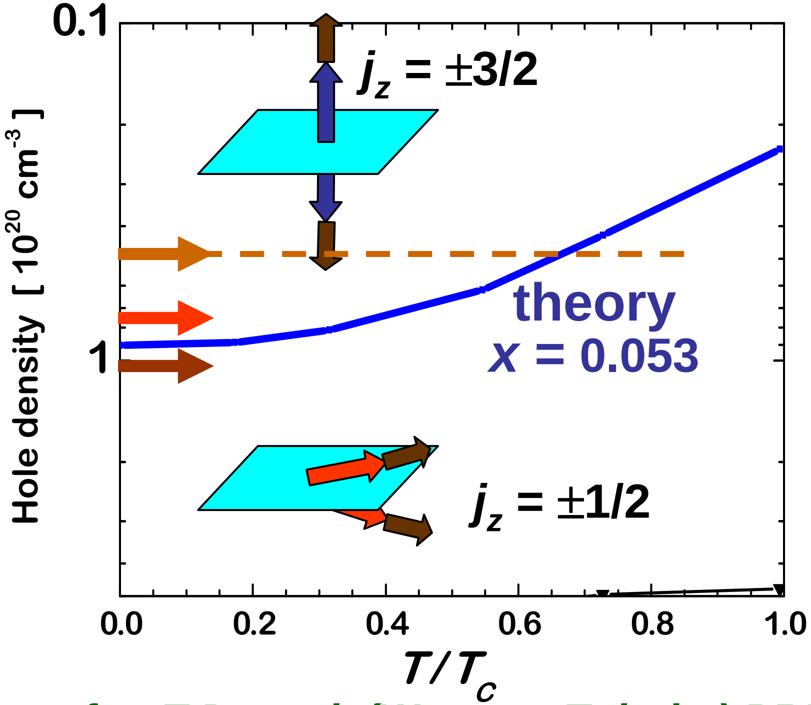
after T.D. et al. (Warsaw, Tohoku) PRB '01



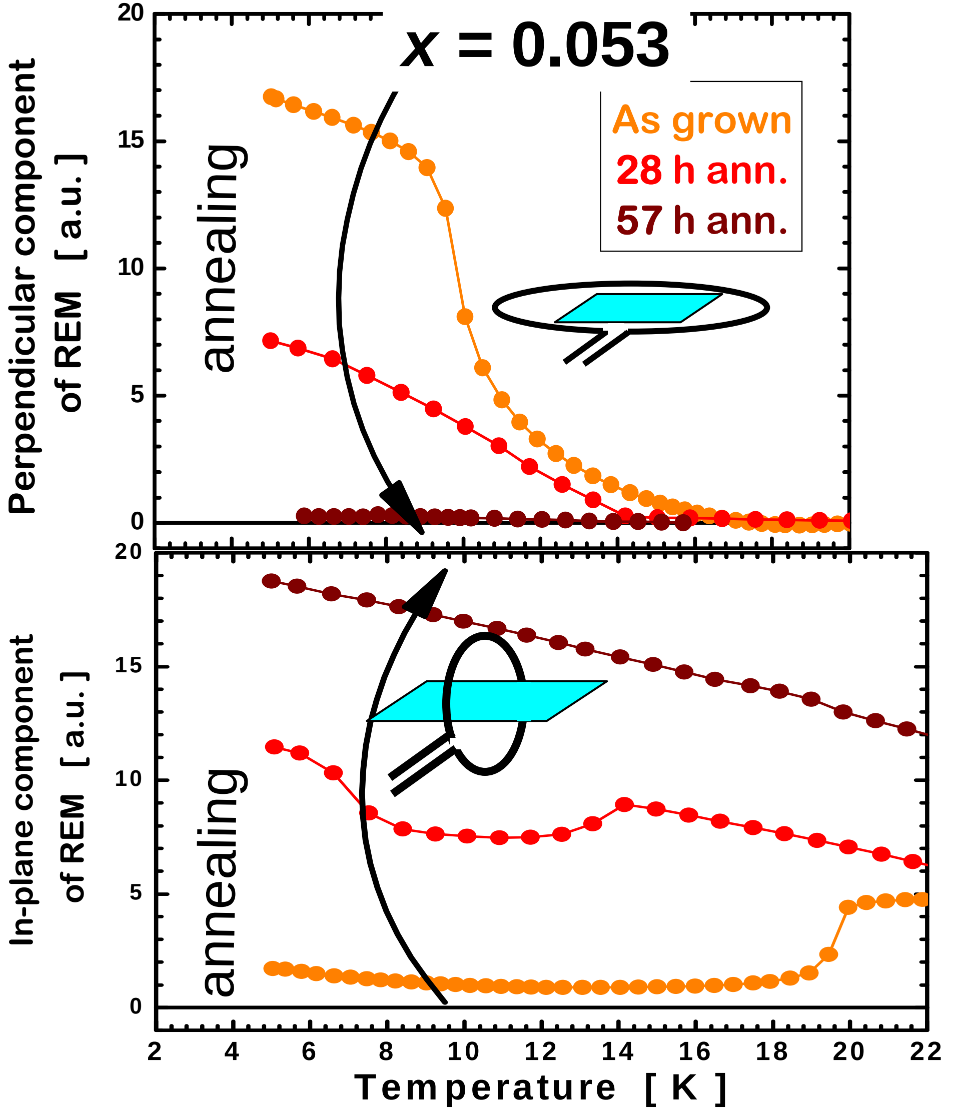
Sawicki et al. (Warsaw, Wuerzburg) PRB'04

Reorientation transition –theory and expt.





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



Sawicki et al. (Warsaw, Wuerzburg) PRB'04
(Warsaw, Nottingham) RB'05, PRL'05

Combining FET and anisotropy

Vol 455|25 September 2008|**doi:10.1038/nature07318** nature

Magnetization vector manipulation by electric fields

D. Chiba[1,2], M. Sawicki[2,3], Y. Nishitani[2], Y. Nakatani[4], F. Matsukura[2,1] & H. Ohno[2,1]

[1]Semiconductor Spintronics Project, Exploratory Research for Advanced Technology, Japan Science and Technology Agency, Sanban-cho 5, Chiyoda-ku, Tokyo 102-0075, Japan. [2]Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan. [3]Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, PL-02668, Warszawa, Poland. [4]University of Electro-communications, Chofugaoka 1-5-1, Chofu, Tokyo 182-8585, Japan.

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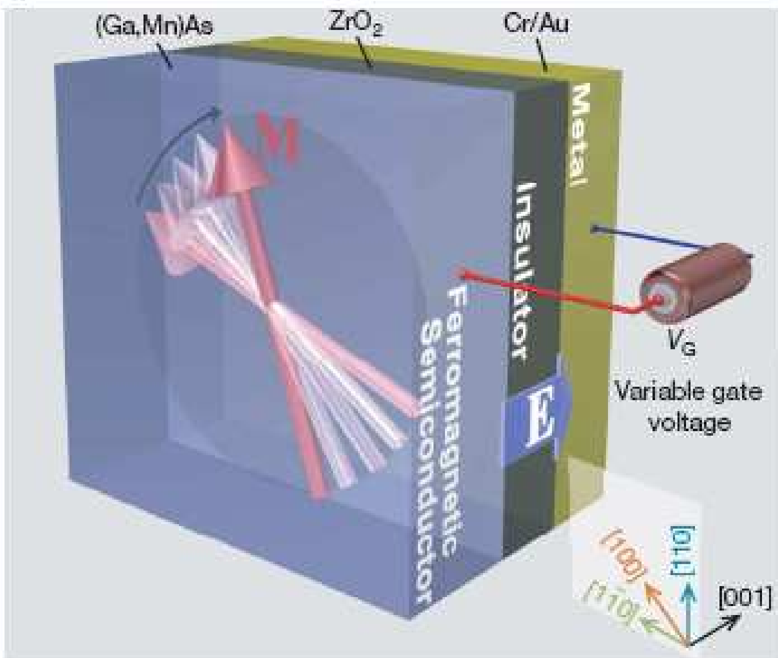

Strategies for high T_C in hole-controlled DMS

- **Strategies:**

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

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

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  nitrides, oxides

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

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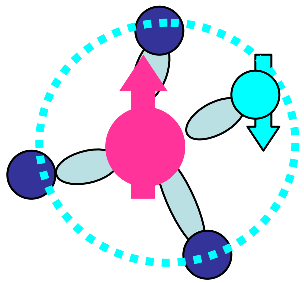
  nitrides, oxides

- **Obstacles:**

  -- self-compensation

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

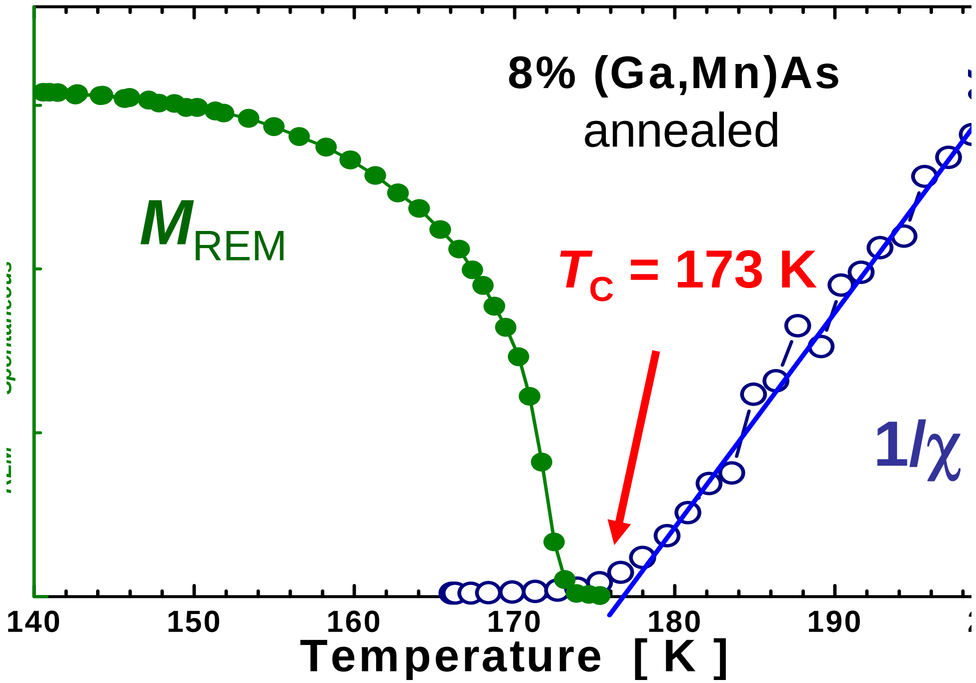
  -- solubility limits



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

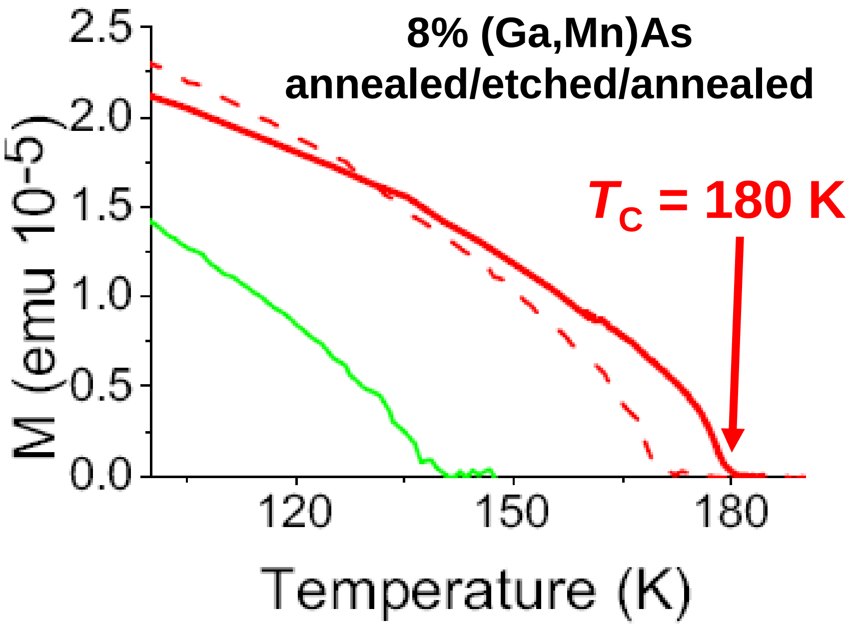
Where are we? (Ga,Mn)As

remanent magnetization and 1/χ vs. *T*



Wang/ Sawicki (Nottingham, Warsaw) ICPS'04

remanent magnetization



Olejnik et al. (Prague) cond-mat/08

Sendai, Tokyo, Notre Dame, PSU, Lund, Wuerzburg, IMEC, UCSB,…

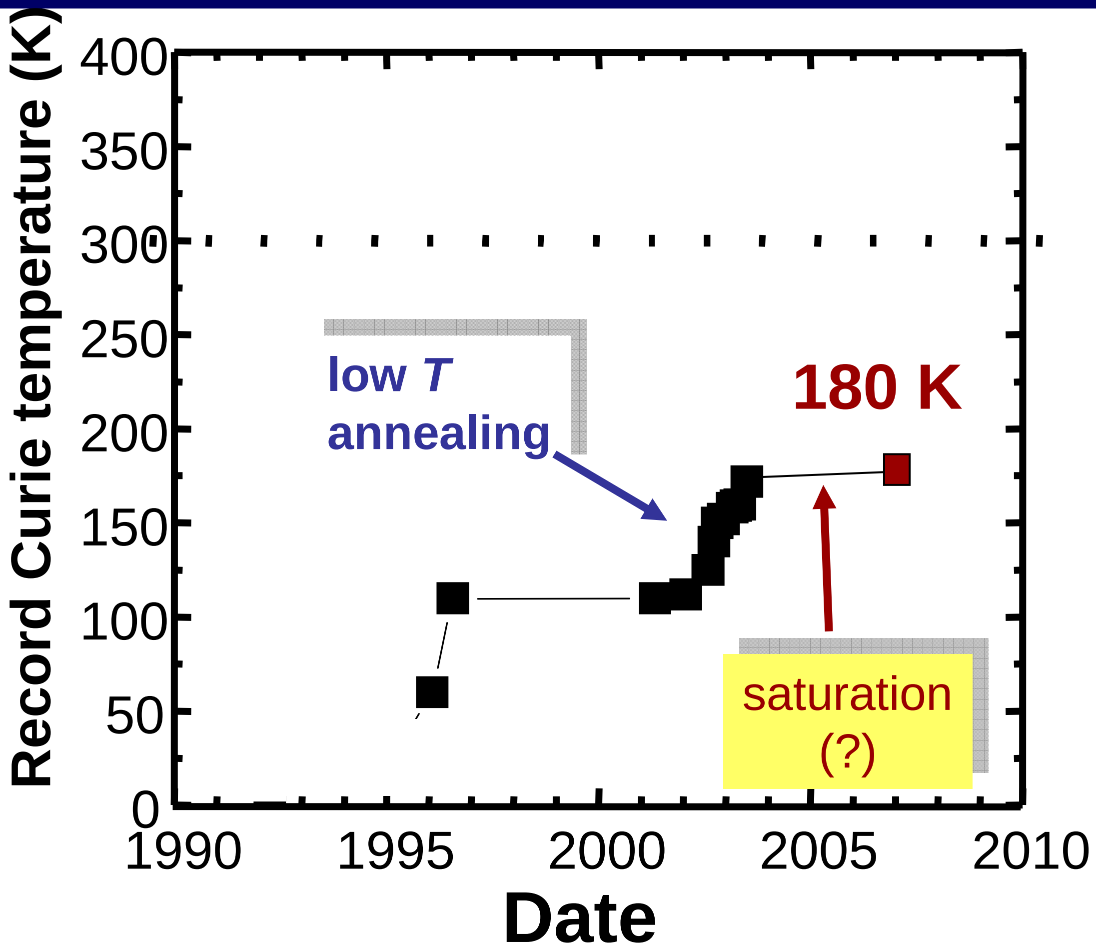
Self-compensation

T_C in (Ga,Mn)As

The progress due to increase of p by low temperature annealing ➔

out diffusion of Mn_I:

Máca and Mašek (Prague) PRB'02, Yu et al. (Berkeley, Notre Dame) PRB'02; APL'04 Edmonds et al. (Nottingham, Warsaw) PRL'04



Nottingham, Sendai, Tokyo, Notre Dame, PSU, Lund, Wuerzburg, IMEC, St. Barbara, Prague…

Beyond (Ga,Mn)As

Strong coupling

Chemical trends in exchange energy βN_0

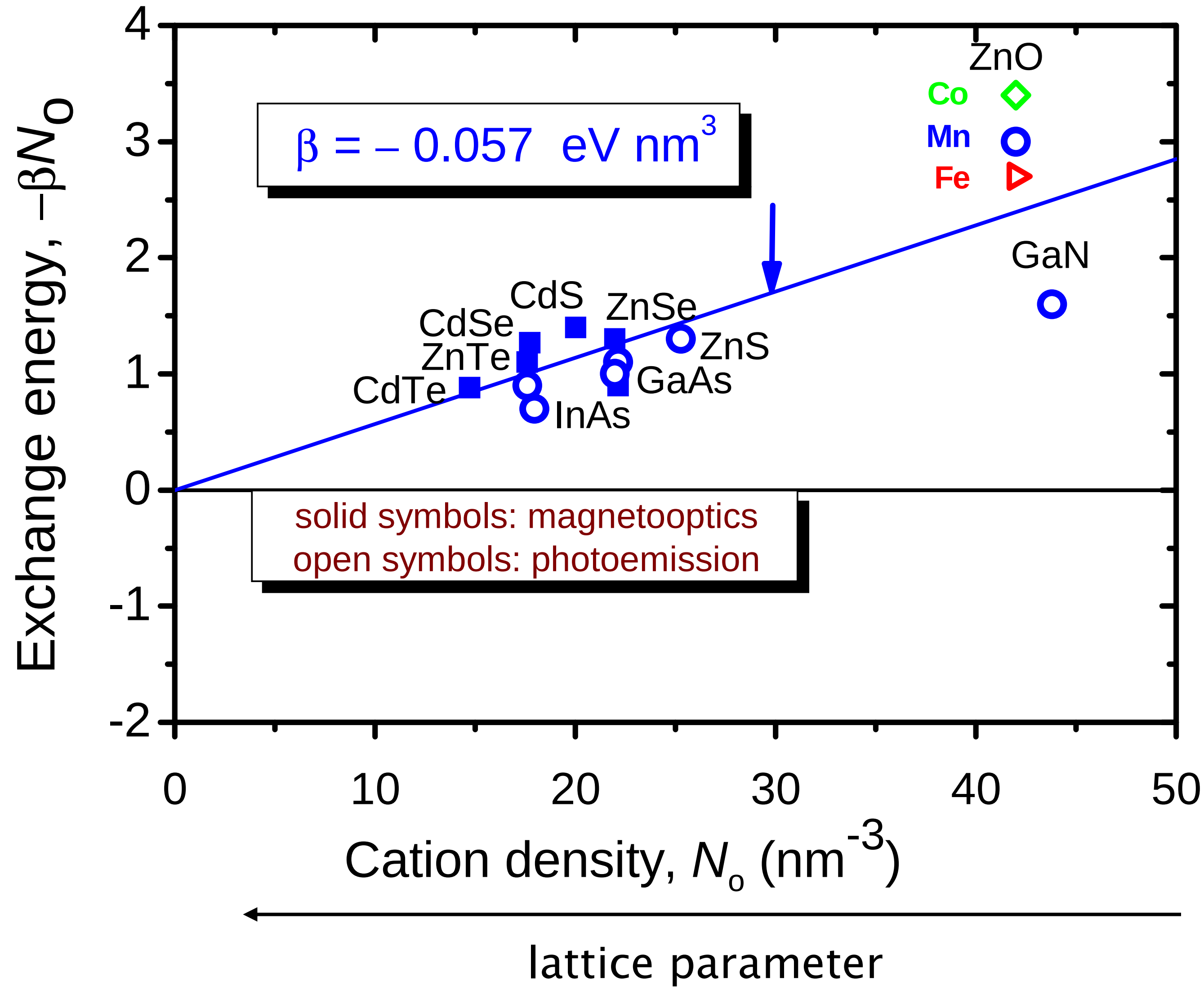
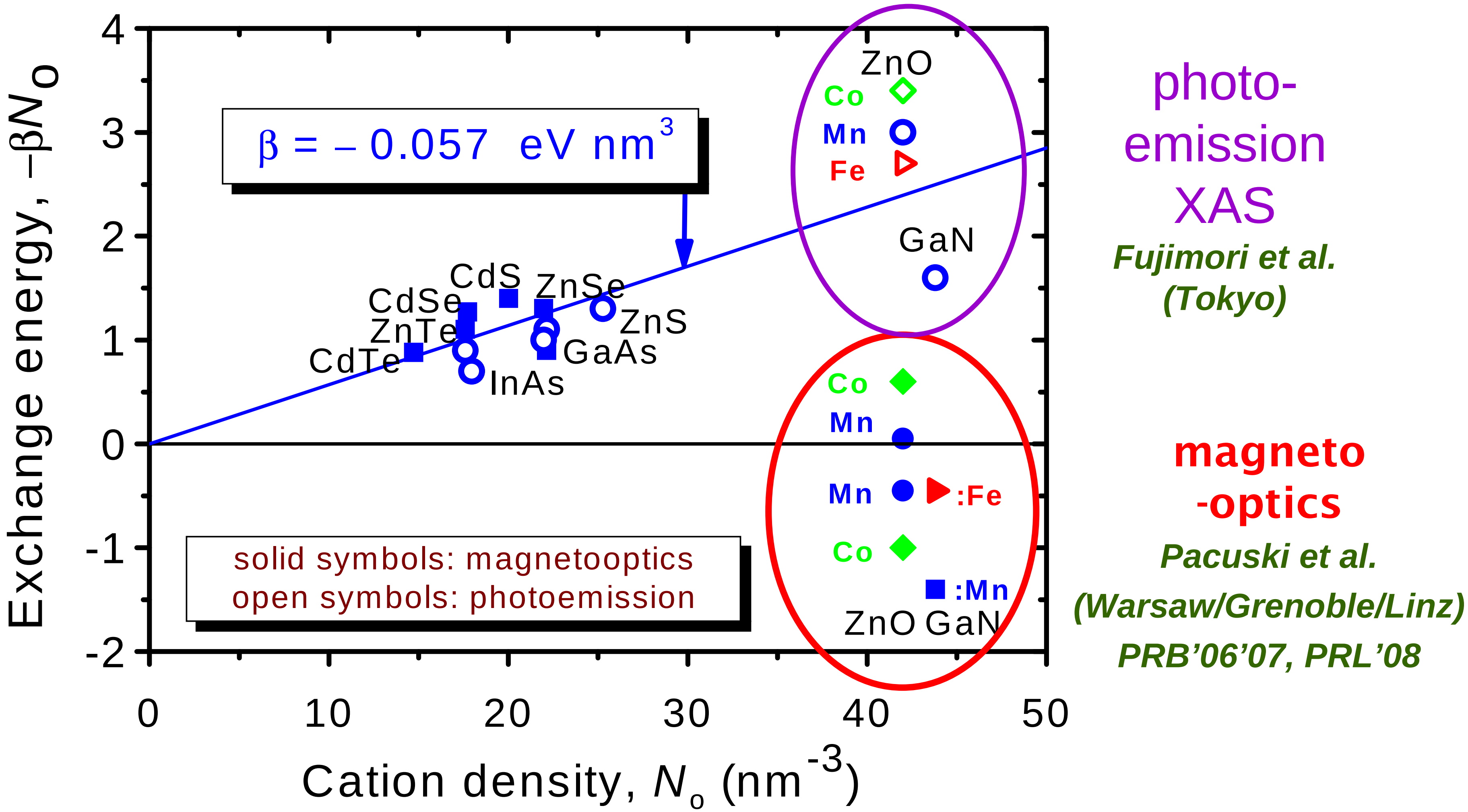


photo-
emission
XAS

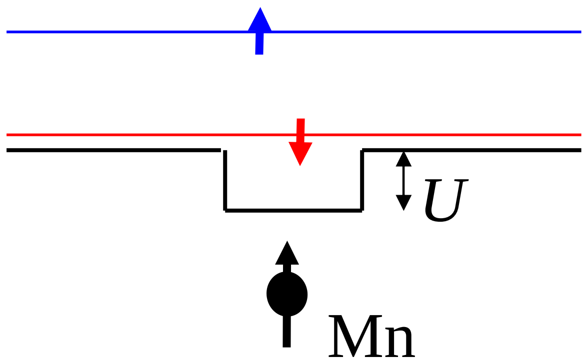
Fujimori et al.
(Tokyo)

Exchange energy βN_0
Photoemission vs. magnetooptics



Spin splitting

weak coupling



VCA, MFA
splitting ~ *M*

Spin splitting

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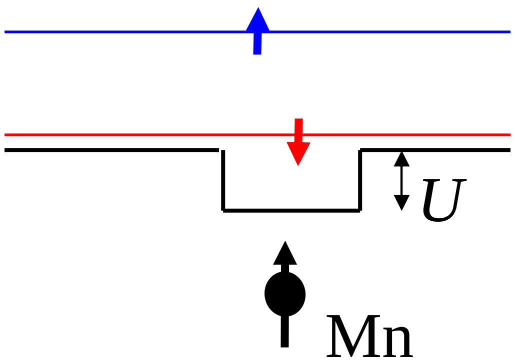
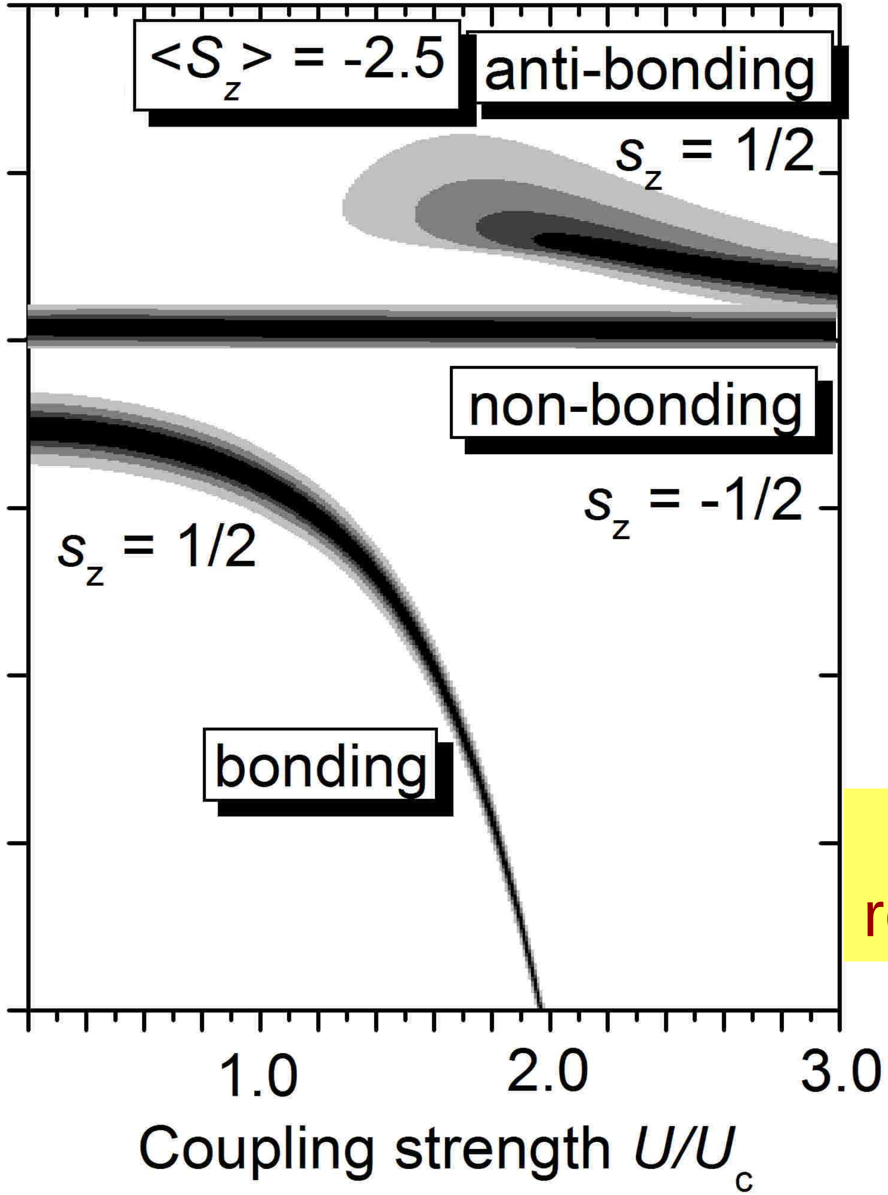
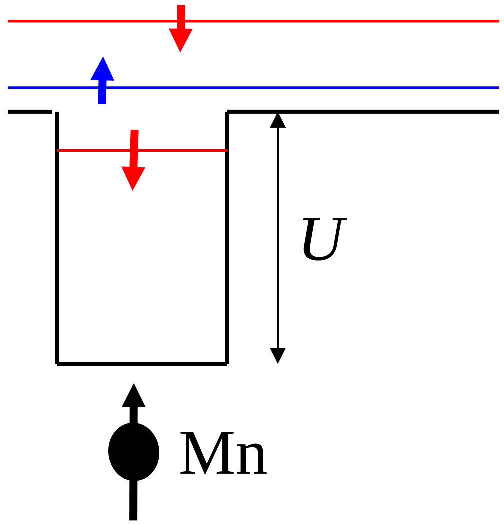


VCA, MFA
splitting ~ M



strong coupling



reversed sign
reduce magnitude

T.D. PRB'08

Effect of strong coupling on ferromagnetism

deep hole trap formed

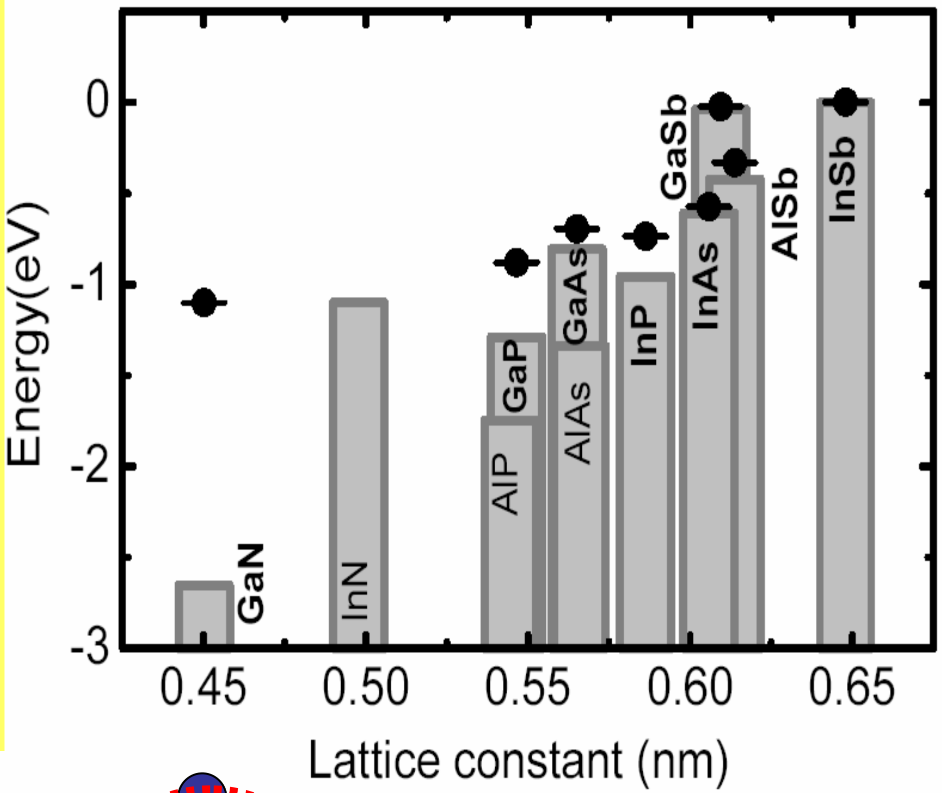
➔

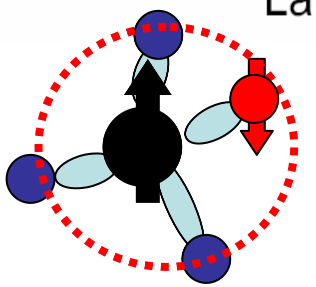
no holes

➔

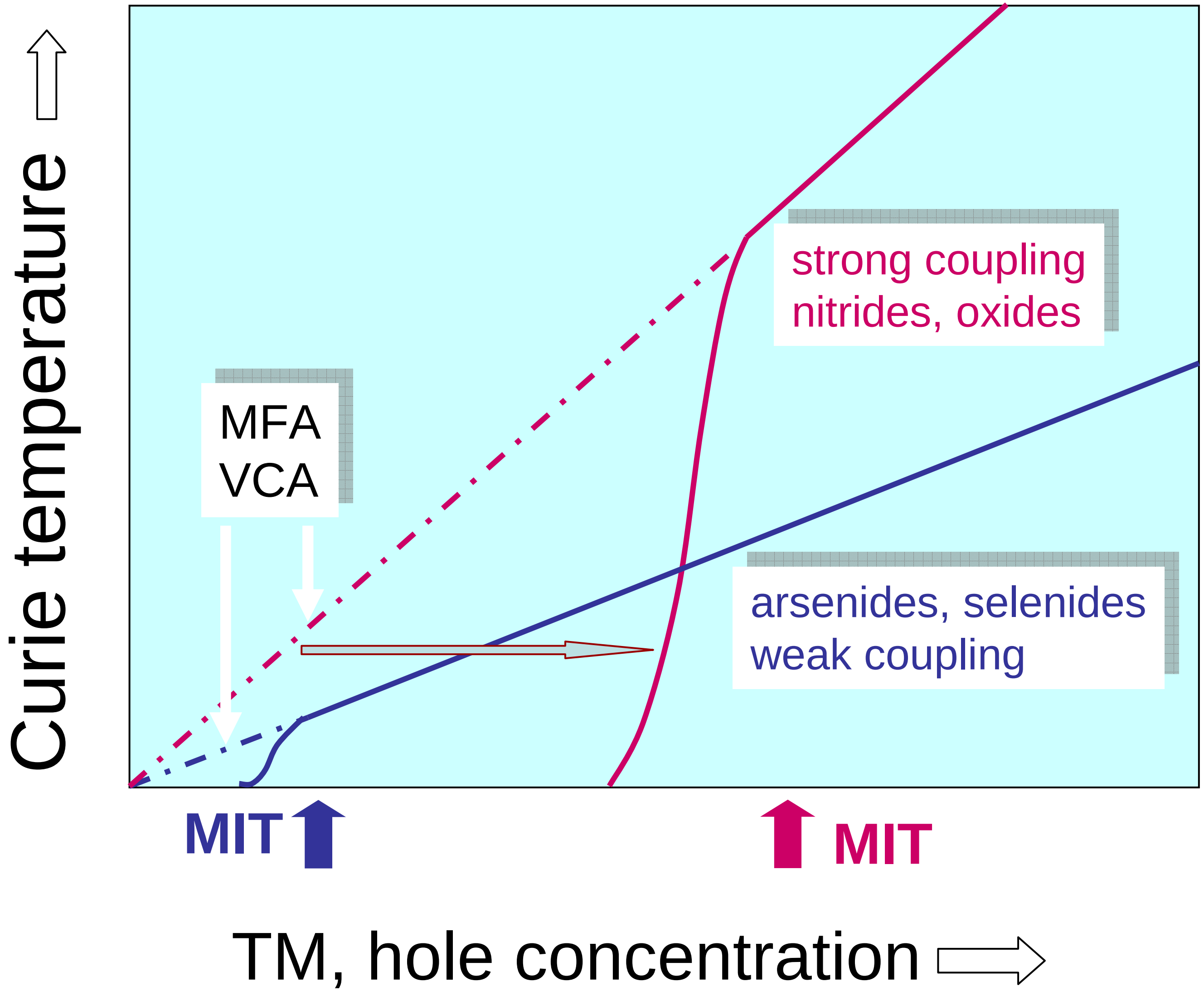
no efficient ferro-magnetism according to *p-d* Zener model

Mn acceptor energy



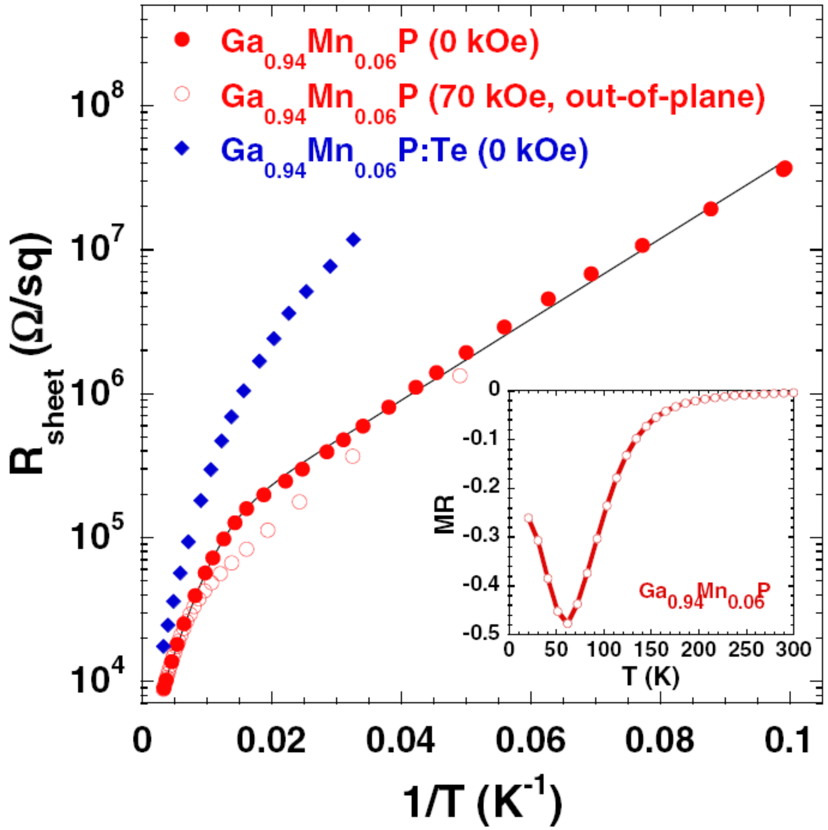


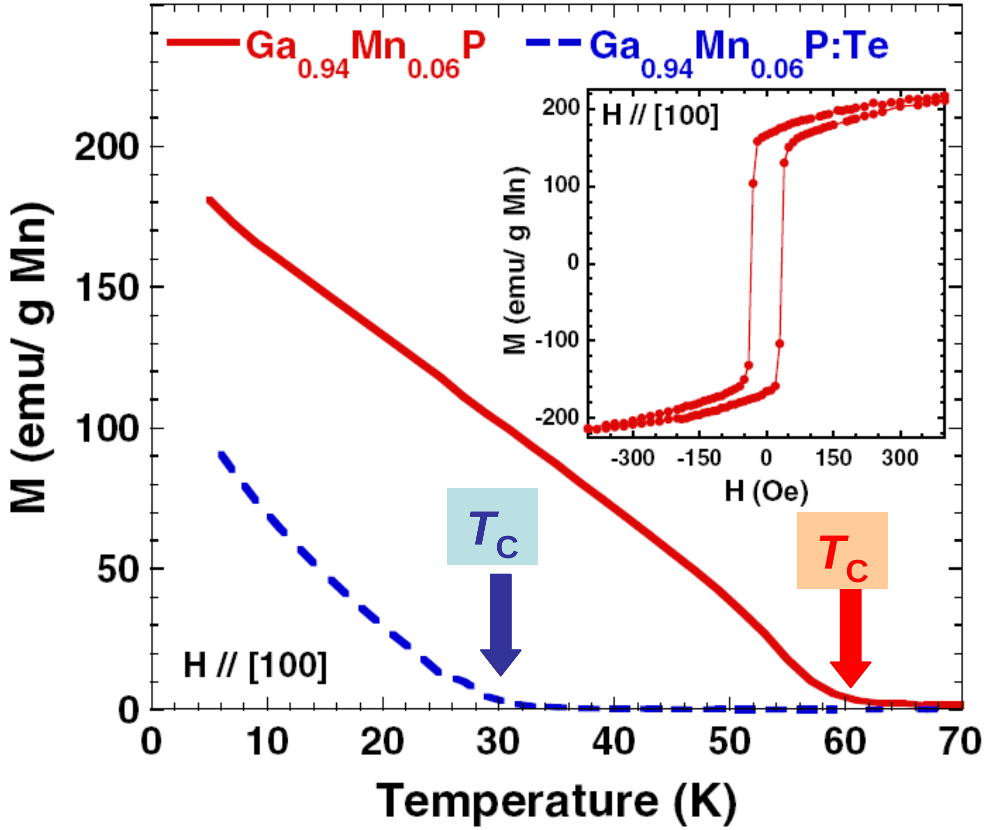
Effect of strong *p-d* coupling on T_C in p-type DMS



Properties of implanted $Ga_{1-x}Mn_xP$

x = 6%, $T_C \cong 55$ K



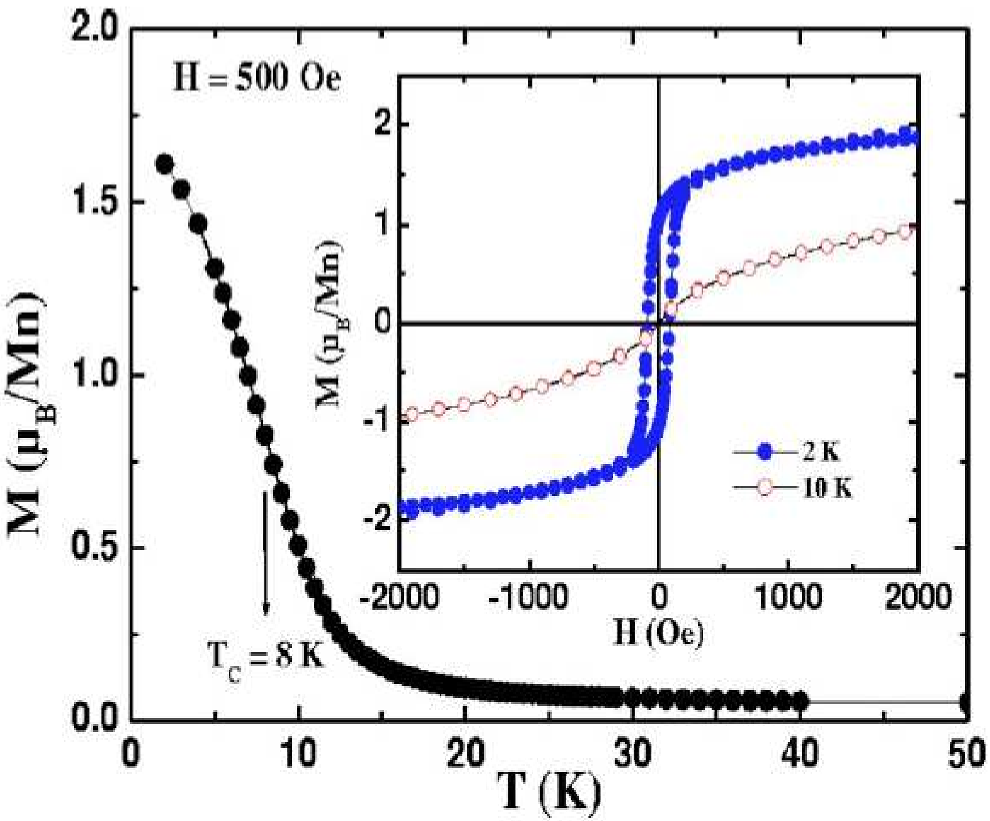


localisation

Scarpulla et al. (Berkeley) PRL'05

Magnetic properties of uniform $Ga_{1-x}Mn_xN$

x = 6%, $T_C \cong 8$ K



Sarigiannidou et al. (Grenoble) PRB'06

weak FM

DMS, DMO, and *non*-magnetic materials showing spontaneous magnetization at 300 K

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

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

(Zn,Cr)Te

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

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

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

(Ge,Mn), (Ge,Cr), (Ge,Mn,Fe), (Si,Fe), (Si,Mn), (SiC,Fe)

no valence band holes

DMS, DMO, and *non*-magnetic materials showing spontaneous magnetization at 300 K

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

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(Zn,Cr)Te

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

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

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

(Ge,Mn), (Ge,Cr), (Ge,Mn,Fe), (Si,Fe), (Si,Mn), (SiC,Fe)

(La,Ca)B_6, CaB_2C_2, C, C_{60}, HfO_2, ZnO, (Ga,Gd)N, (Ga,Eu)N ...

no valence band holes, no TM ions

DMS, DMO, and *non*-magnetic materials showing spontaneous magnetization at 300 K

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(Zn,Cr)Te

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

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(Ge,Mn), (Ge,Cr), (Ge,Mn,Fe), (Si,Fe), (Si,Mn), (SiC,Fe)

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no valence band holes, no TM ions
often supported by DFT computations

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

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(Ge,Mn), (Ge,Cr), (Ge,Mn,Fe), (Si,Fe), (Si,Mn), (SiC,Fe)

(La,Ca)B_6, CaB_2C_2, C, C_{60}, HfO_2, ZnO, (Ga,Gd)N, (Ga,Eu)N ...

no valence band holes, no TM ions
often supported by DFT computations

... *no devices* ...

DMS, DMO, and *non*-magnetic materials showing spontaneous magnetization at 300 K

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

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

(Zn,Cr)Te

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

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

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

(Ge,Mn), (Ge,Cr), (Ge,Mn,Fe), (Si,Fe), (Si,Mn), (SiC,Fe)

(La,Ca)B_6, CaB_2C_2, C, C_{60}, HfO_2, ZnO, (Ga,Gd)N, (Ga,Eu)N ...

origin of UFO ?

SQUID studies of DMS and DMO in Warsaw

M. Sawicki et al. (Warsaw):

wz-c-(Ga,Mn)N, (Ga,Fe)N

(Ga,Mn)As

(Zn,Mn)Te:N, P

(Cd,Mn)Te, (Cd,Mn)Se

(Cd,Cr)Te, (Zn,Cr)Se

(Zn,Mn)O, (Zn,Co)O, (Zn,Cr)O

Experimental challenges

-- precipitates of magnetic metals (Co, Fe)

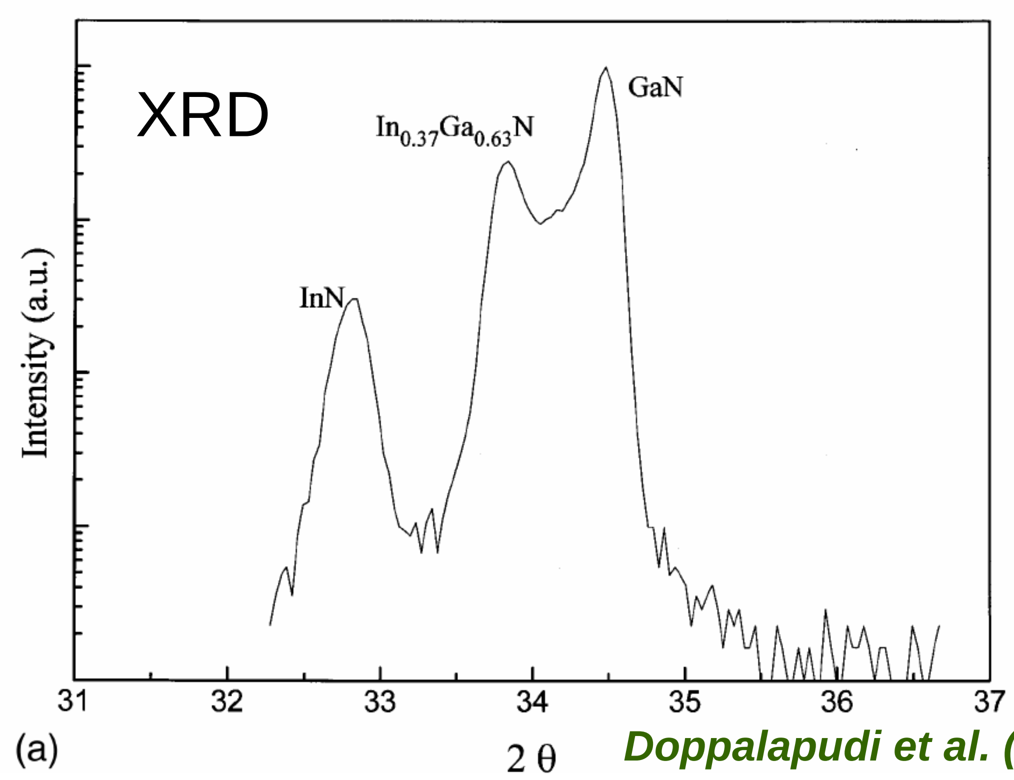
-- contamination by magnetic nanoparticles
(growth, processing)

-- sample but also substrate, interface, holder,…

-- SQUID: residual fields, software, ….

Beyond solubility limit

Spinodal decomposition in MBE-grown (Ga,In)N



Doppalapudi et al. (Boston) JAP'98
Liliental-Weber et al. (Berkeley), JEM'05

controlled by:
- -- solubility limit?
- -- surface phase separation and kinetic barrier?
- -- ??

Model for high T_C DMS

Model for DMS and DMO beyond solubility limit

- phase separation or spinodal decomposition into regions with low and high concentration of magnetic constituents

- FM or AFM regions with high concentration determine magnetic properties (through high blocking temperature)

T. D. ICPS'04, MRS'04, Nature Mat. Sept.'06 -
K. Sato, H. Katayama-Yoshida, P. Dederichs, JAAP'05-
S. Kuroda et al. (Tsukuba/Warsaw) Nature Mat.'07

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K. Sato, H. Katayama-Yoshida, P. Dederichs, JAAP'05-
S. Kuroda et al. (Tsukuba/Warsaw) Nature Mat.'07

spinodal decomposition hard to detect:

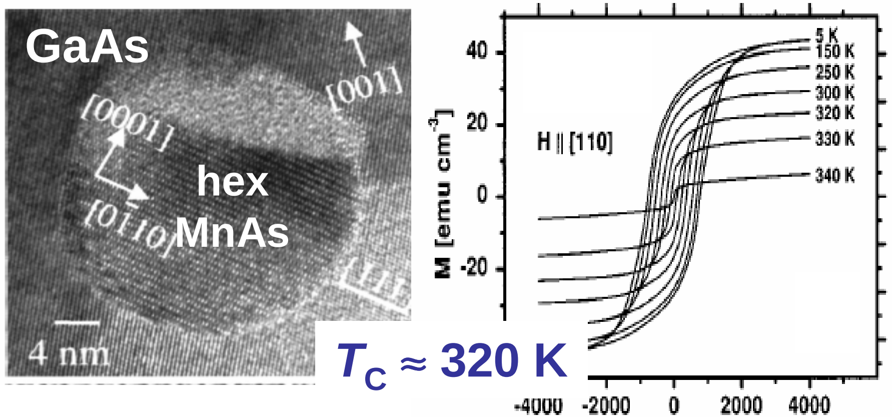
-- crystallographic structure remains uniform

-- magnetic regions may gather at surface or interface

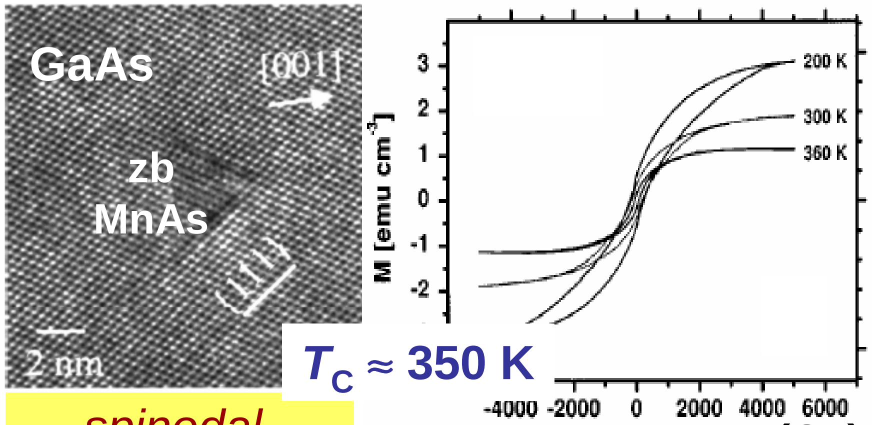
-- element specific 3D nanoanalyzer required

Phase separations in (Ga,Mn)As

- **depending on growth conditions precipitates or spinodal decomposition**



Moreno et al. (Berlin) JAP'02



spinodal decomposition

Mn-rich regions:

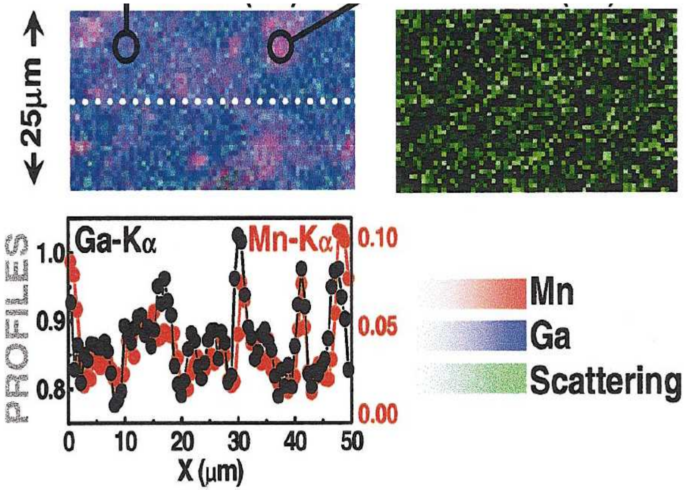
- control magnetic properties ***De Boeck et al. (IMEC) APL'96***
- enhance magnetooptical effects (MCD) ***Akinaga et al. (Tsukuba) APL'00; Shimizu et al. (Tokyo) APL'01; Yokoyama et al. (Tokyo) JAP'05***
- affect conductance and Hall effect ***Heimbrodt et al. (Marburg) PRB'04***

DMS with spinodal decomposition
➔ functional high T_C composite systems

Spinodal decomposition in DMS from TEM + EDS

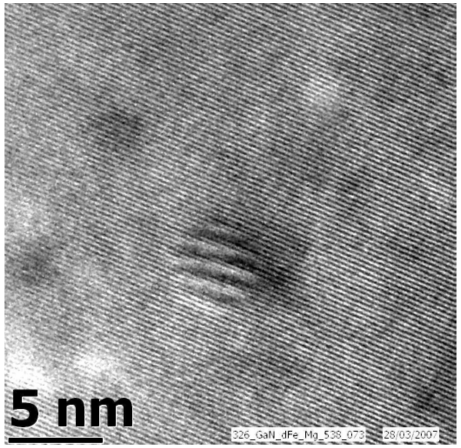
Dots

(Ga,Mn)N



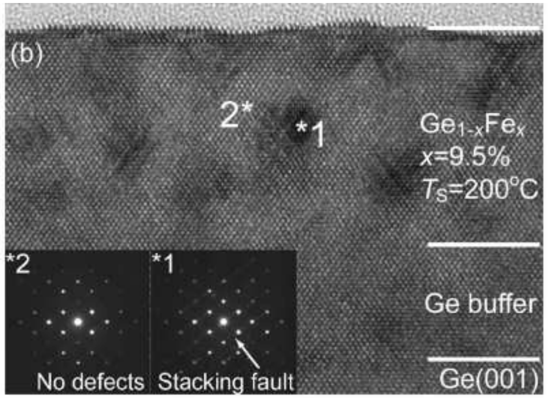
Martínez-Criado,et al. (Grenoble) APL'05

(Ga,Fe)N



Bonanni (Linz/Warsaw) PRB'07

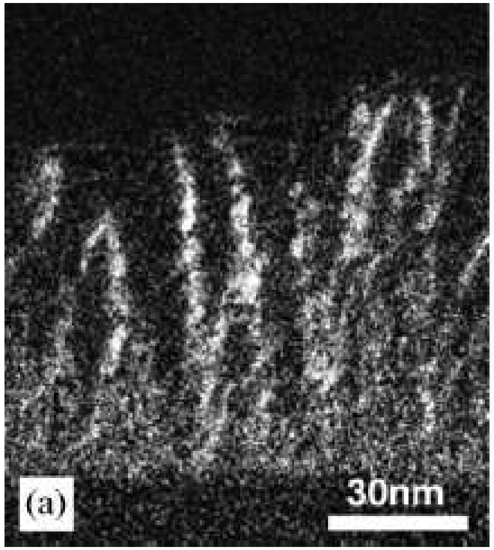
(Ge,Fe)



Shuto et al. (Tokyo) APL'07

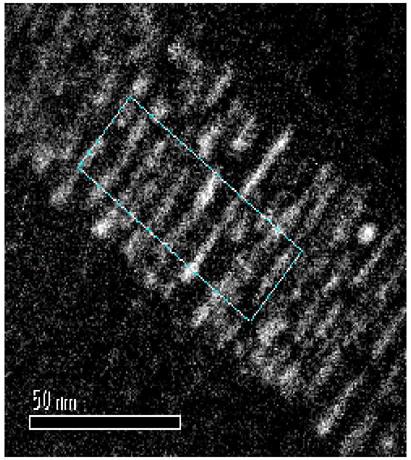
Nanocolumns

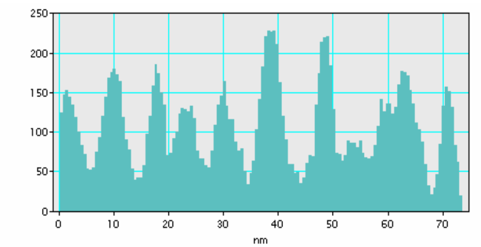
(Al,Cr)N

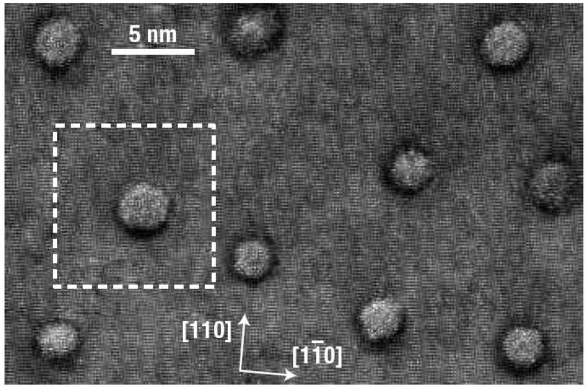


Guo et al. (Arizona)
JMMM'06

(Ge,Mn)



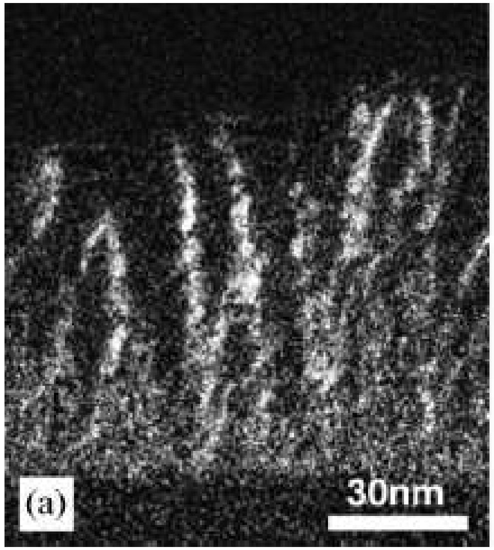




Jamet et al. (Grenoble)
Nature Mat. '06

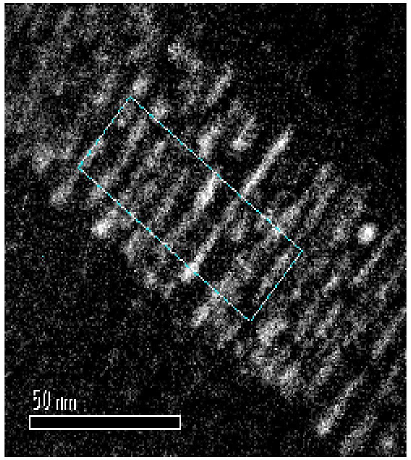
Nanocolumns

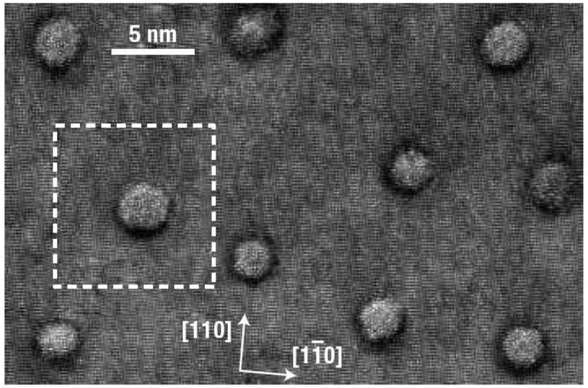
(Al,Cr)N

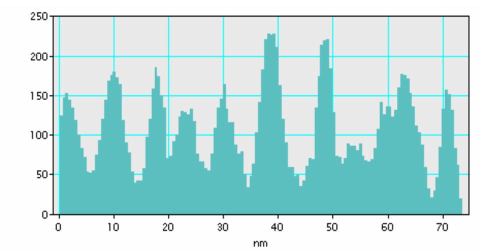


Guo et al. (Arizona)
JMMM'06

(Ge,Mn)



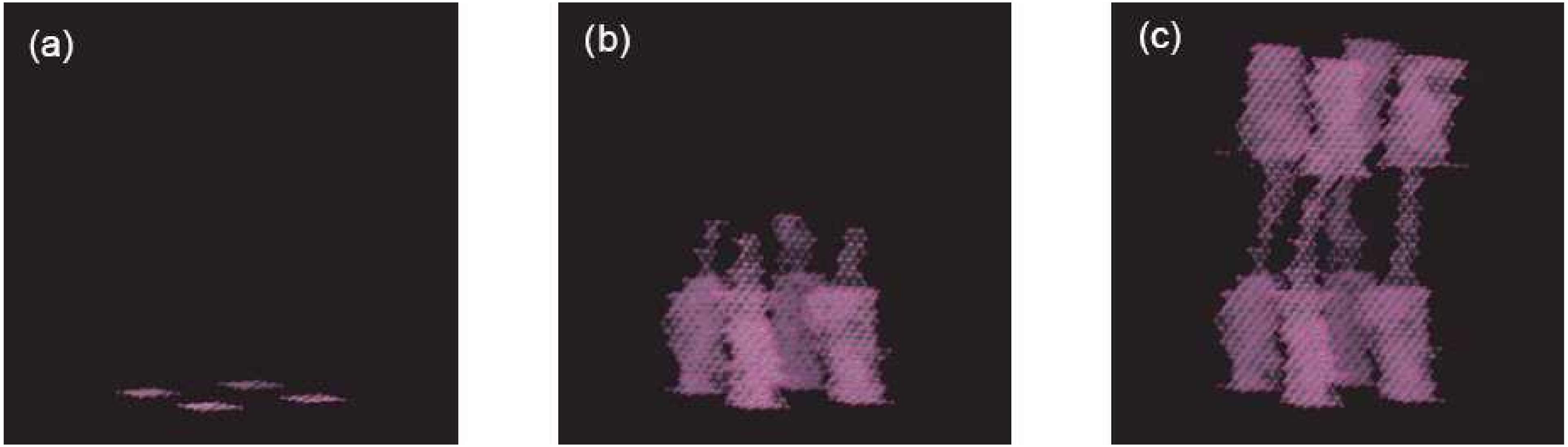




Jamet et al. (Grenoble)
Nature Mat. '06

Nanomagnets in form of dots or nanocolumns

Formation of tunnel/Coulomb blockade junctions

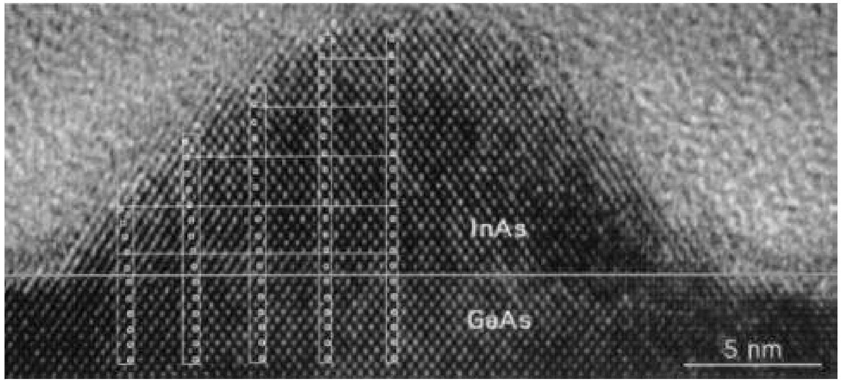


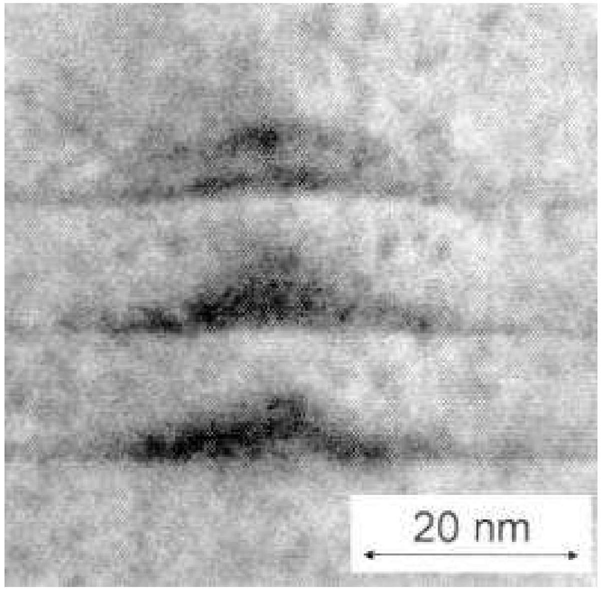
Fukushima et al. (Osaka) phys.stat.sol. (c)'06

How to control spinodal decomposition?

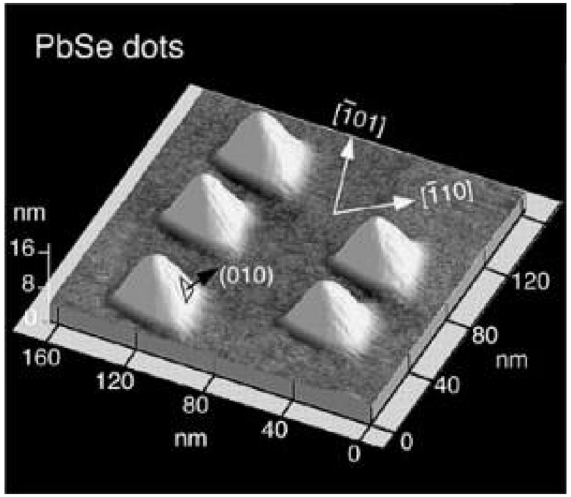
Self-organized quantum dots in semiconductors

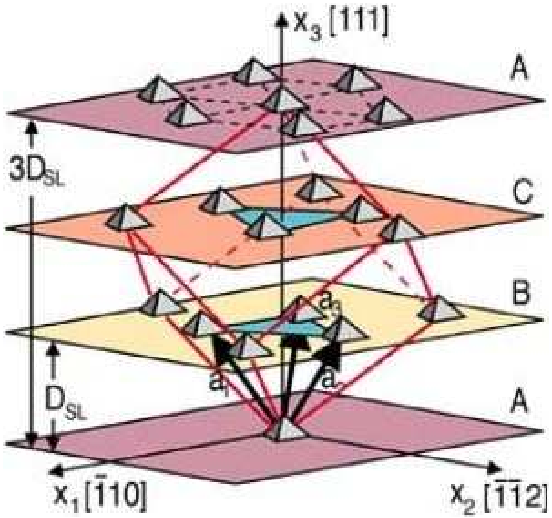
InAs in GaAs





PbSe in (Pb,Eu)Te



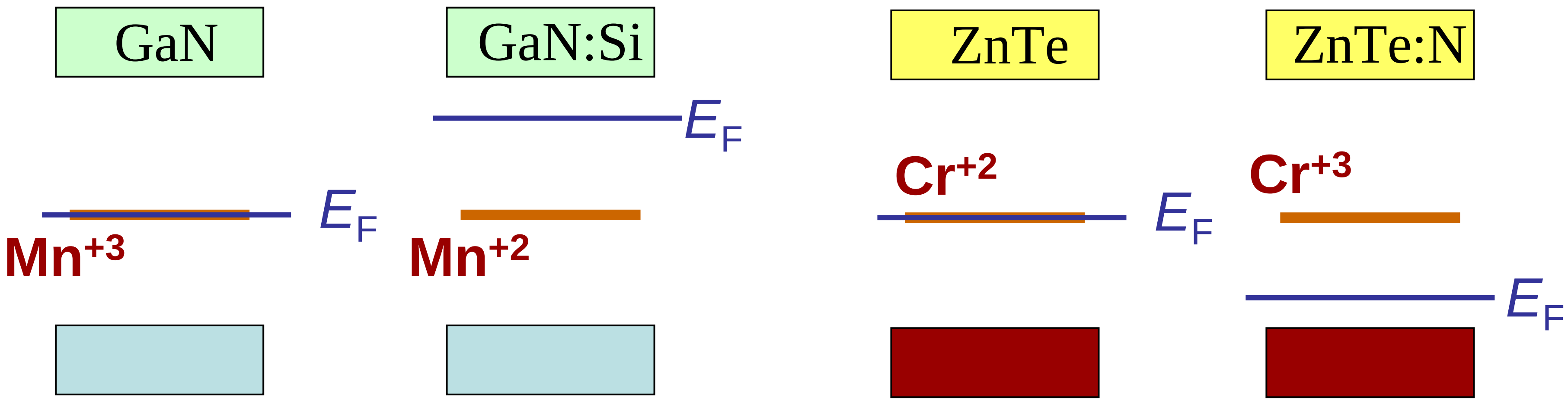


Springholz et al.
(Linz) Science'98

spinodal decomposition controlled by epitaxial strain

Effect of doping on spinodal decomposition

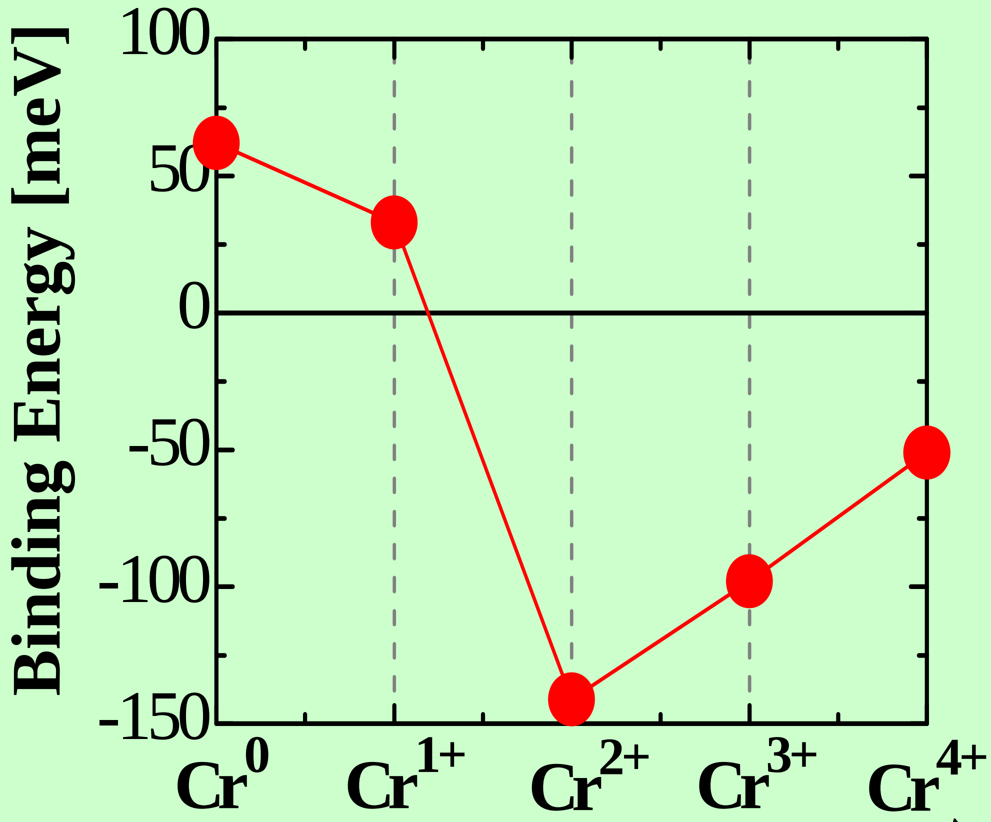
TM charge state is controlled by co-doping with shallow impurities. Because of Coulomb repulsion spinodal decomposition is blocked if TM is charged



T.D., Nature Mat.'06
L.-H. Ye et al. (NWU) PRB'06

Effect of charge state on binding energy of Cr pair

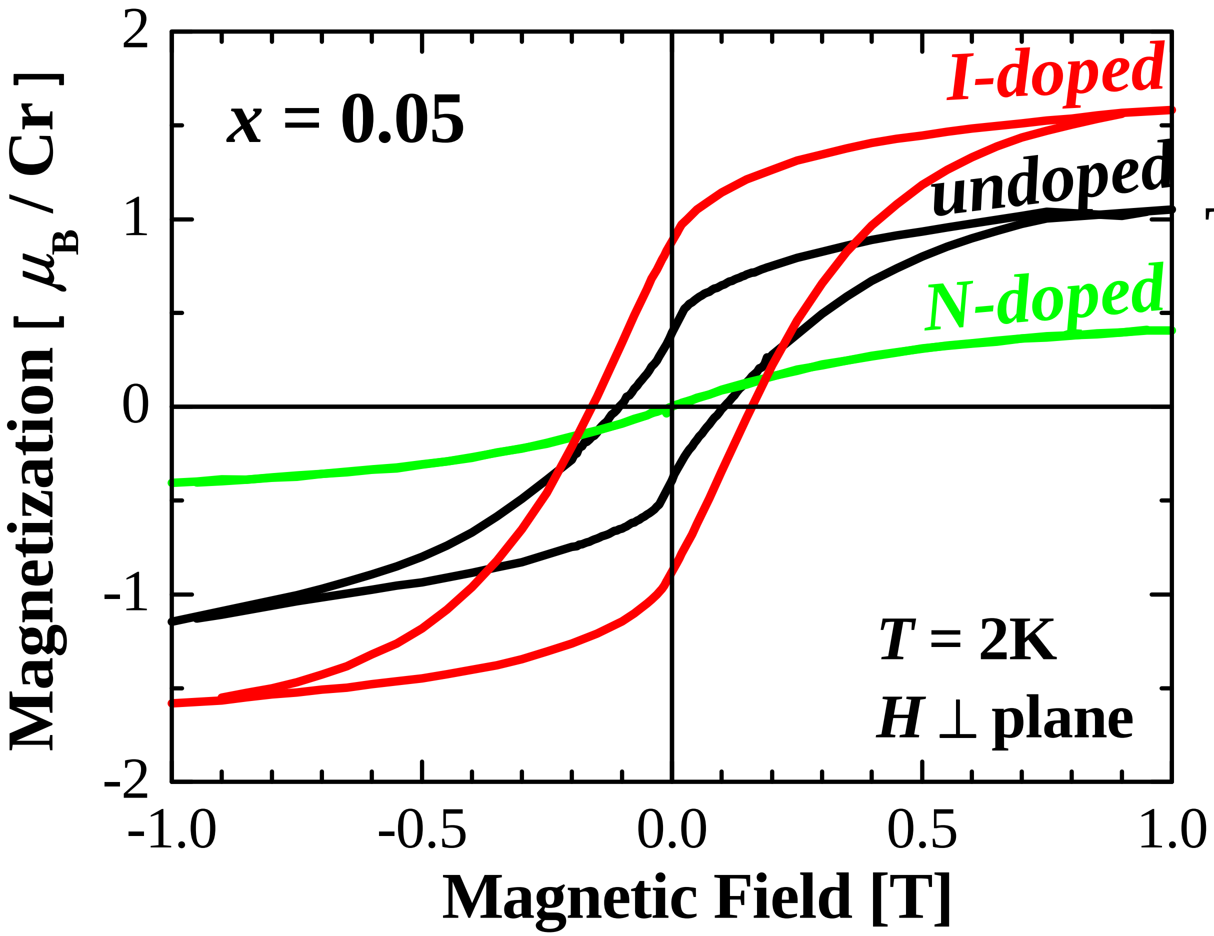
Formation energy of Cr-Cr pair in ZnTe



lower limit because
p-d hybridization
overestimated by LSDA

S. Kuroda … T.D.
(Tsukuba, Warsaw)
Nature Mat., '07

Effect of co-doping on magnetism



[I] ~ 2 x 10^{18} cm^{-3} Cr^{2+}

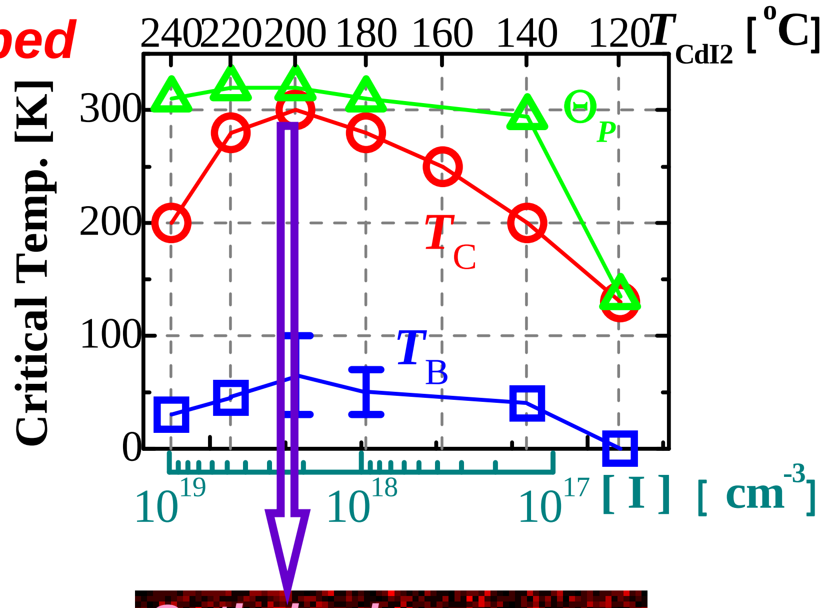
Te-rich growth Cr^{2+}/Cr^{3+}

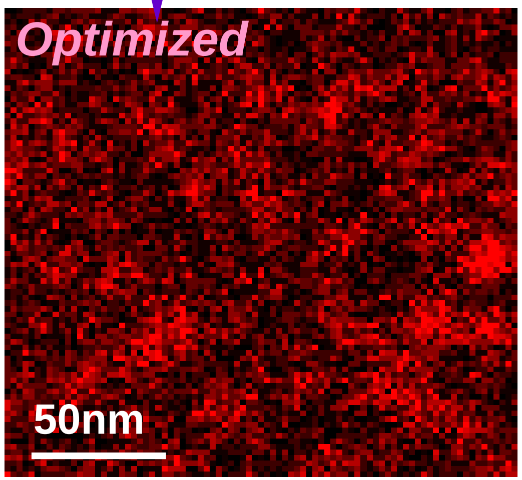
[N] ~ 3 x10^{20} cm^{-3} Cr^{3+}

S. Kuroda … T.D. (Tsukuba, Warsaw) Nature Mat., '07

Effect of co-doping on Cr distribution

I-doped

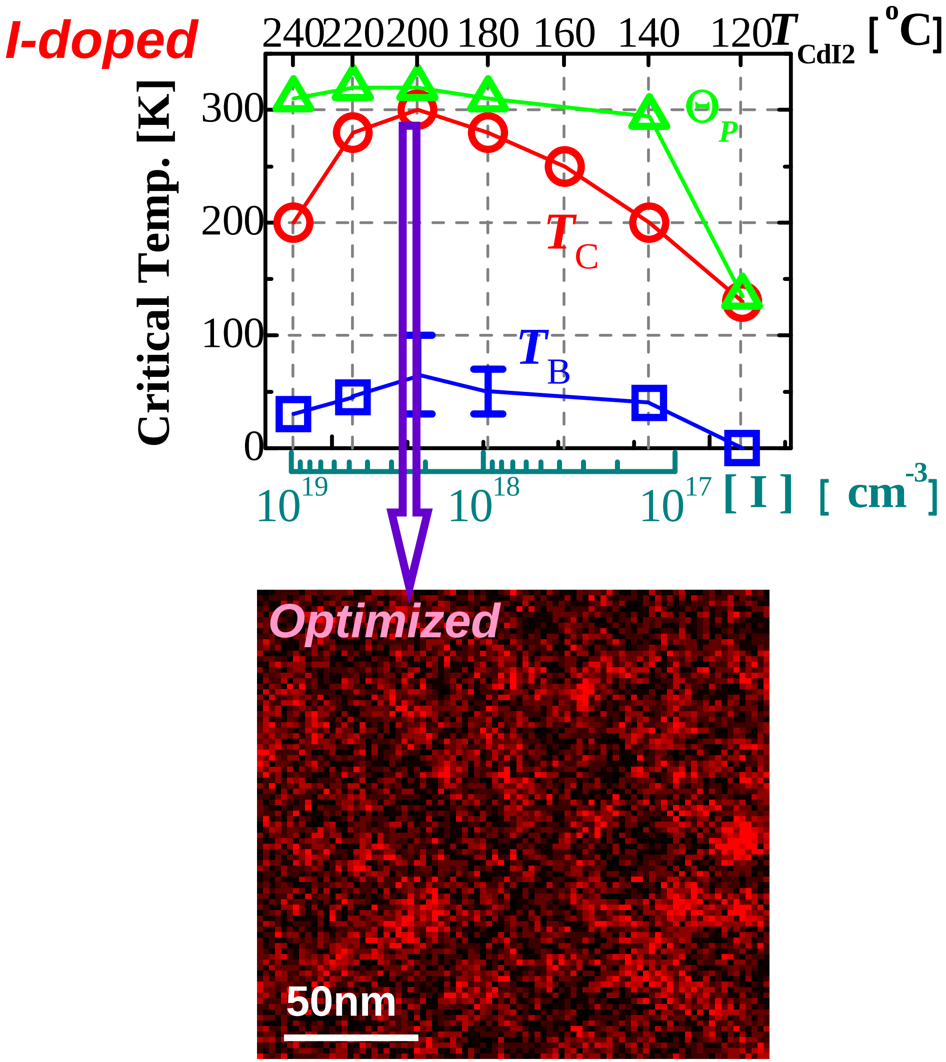




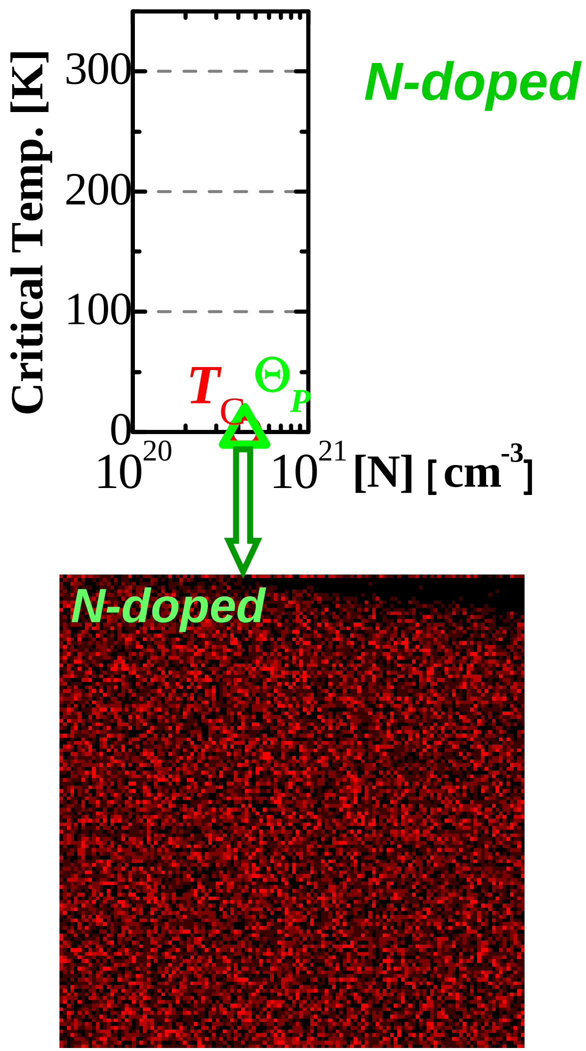
Inhomogeneous

S. Kuroda ... T.D. (Tsukuba, Warsaw) Nature Mat., '07

Effect of co-doping on Cr distribution



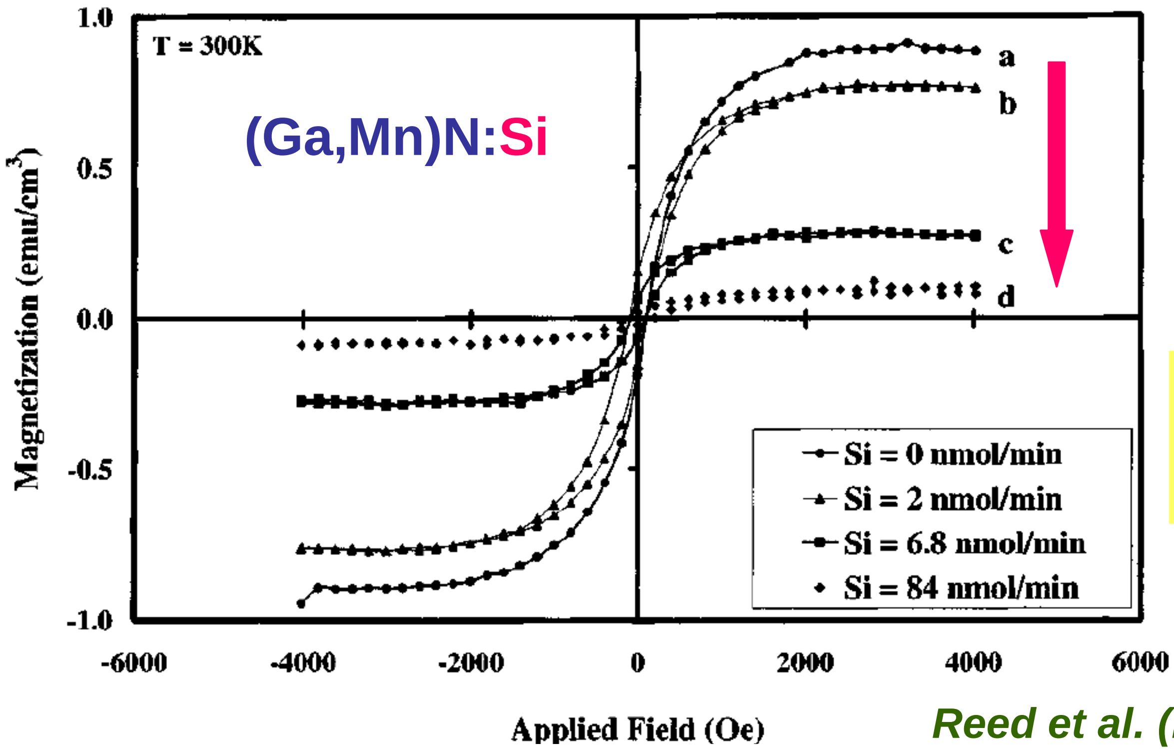
Inhomogeneous



Homogeneous

S. Kuroda … T.D. (Tsukuba, Warsaw) Nature Mat., '07

Ferromagnetism of (Ga,Mn)N – effect of co-doping



(Ga,Mn)N
***x* = 0.2%**
T_C >> 300 K

(Ga,Mn)N, *x* = 0.2%
T_C ➔ 0 for Si doping

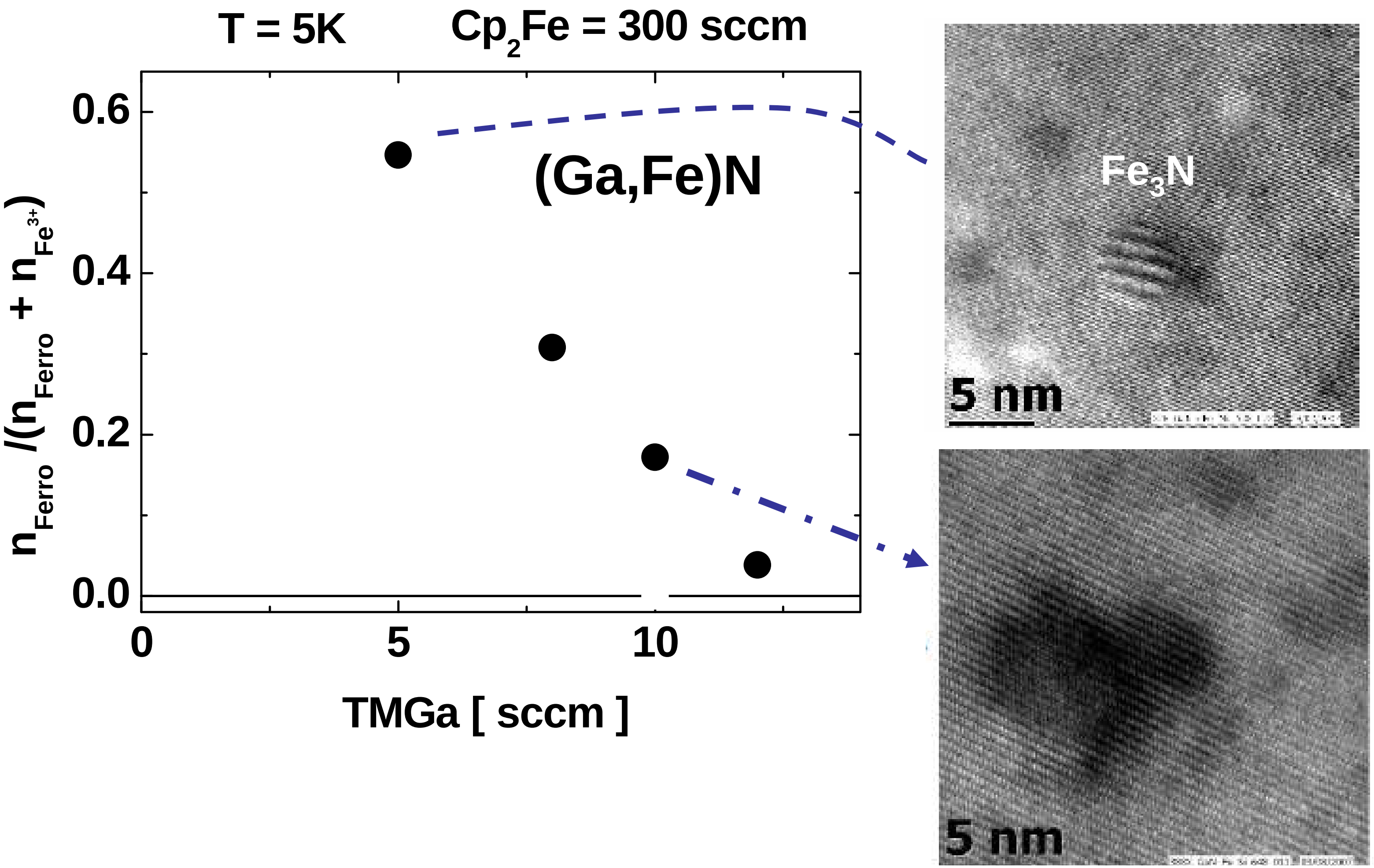
Reed et al. (NCSU) APL'05

cf. Kane et al. (Georgia) JCG'06

Effect of co-doping and stoichiometry on T_C also in (Zn,Mn)O and (Zn,Co)O

cf. Kittilstved et al. (Washington) PRL'05

(Ga,Fe)N -- ferromagnetic response *vs.* growth rate

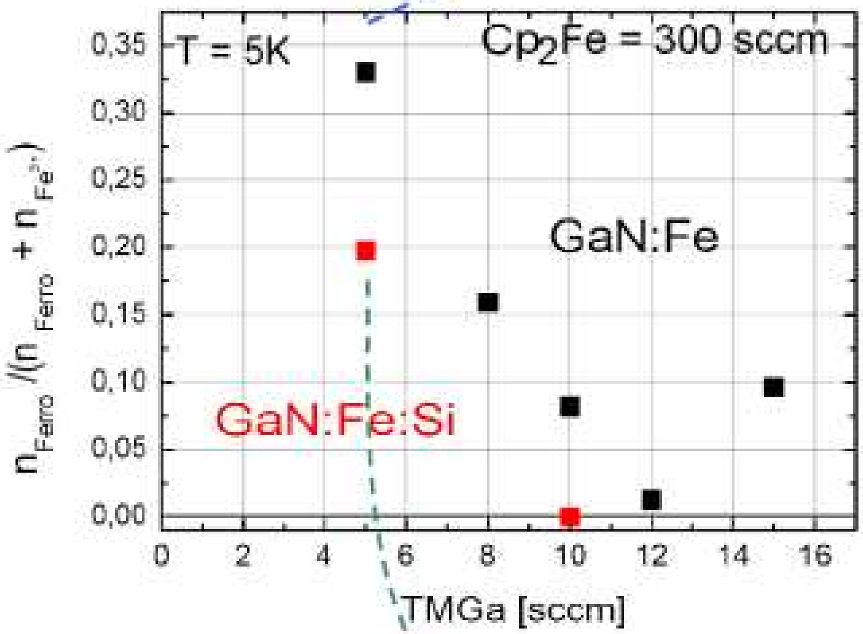


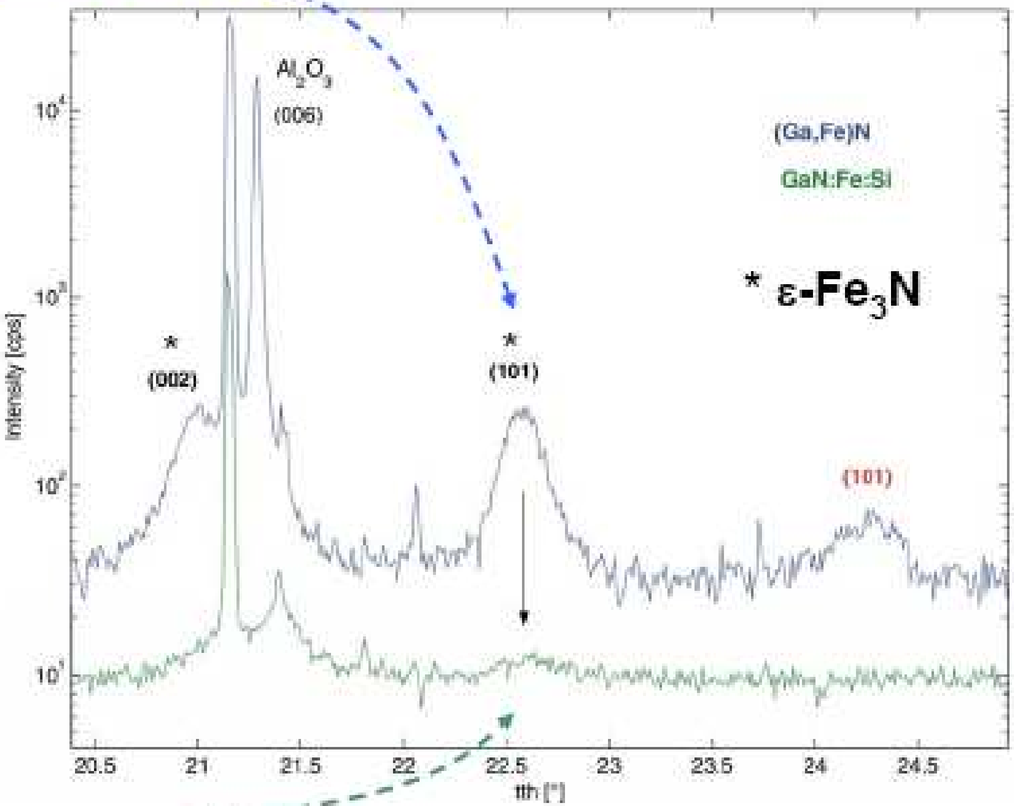
A. Bonanni …. T.D. (Linz/Warsaw/Grenoble/Prague) PRL'08

Ferromagnetism of (Ga,Fe)N – effect of co-doping

ferromagnetic response
vs. growth rate

synchrotron XDR

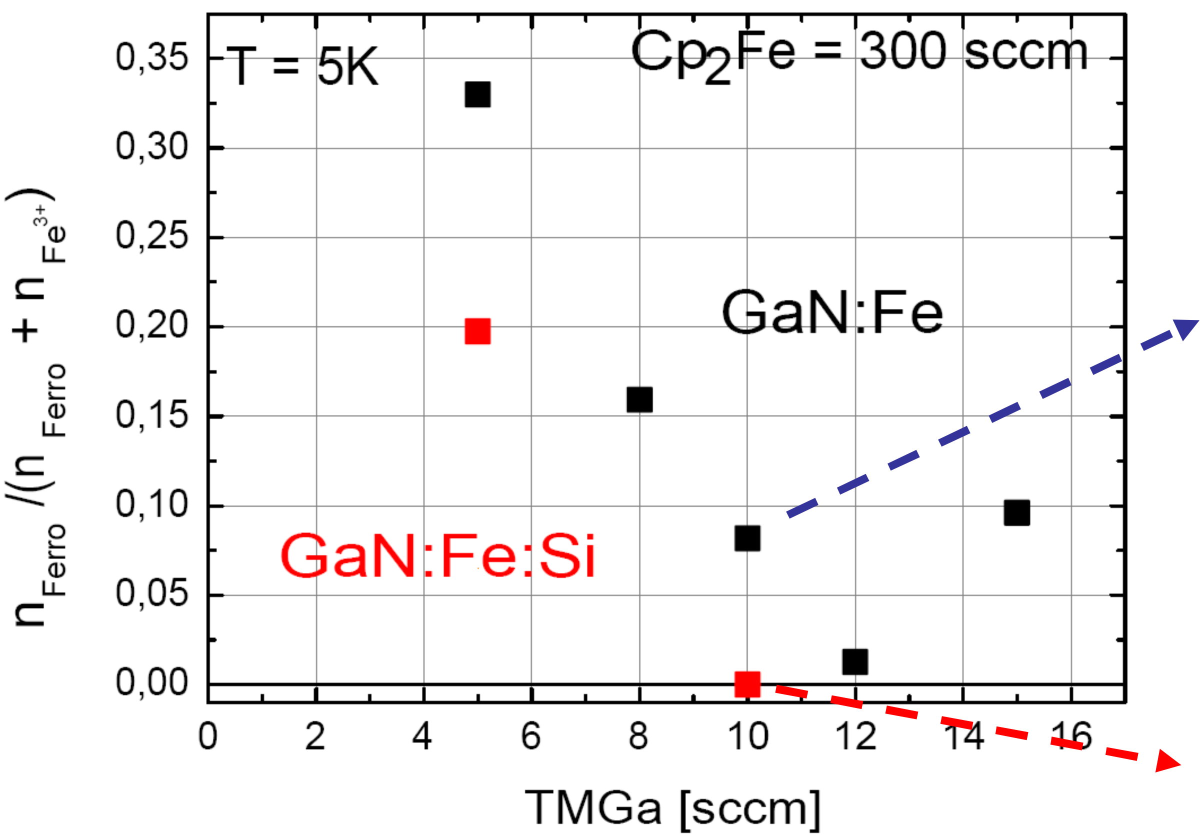


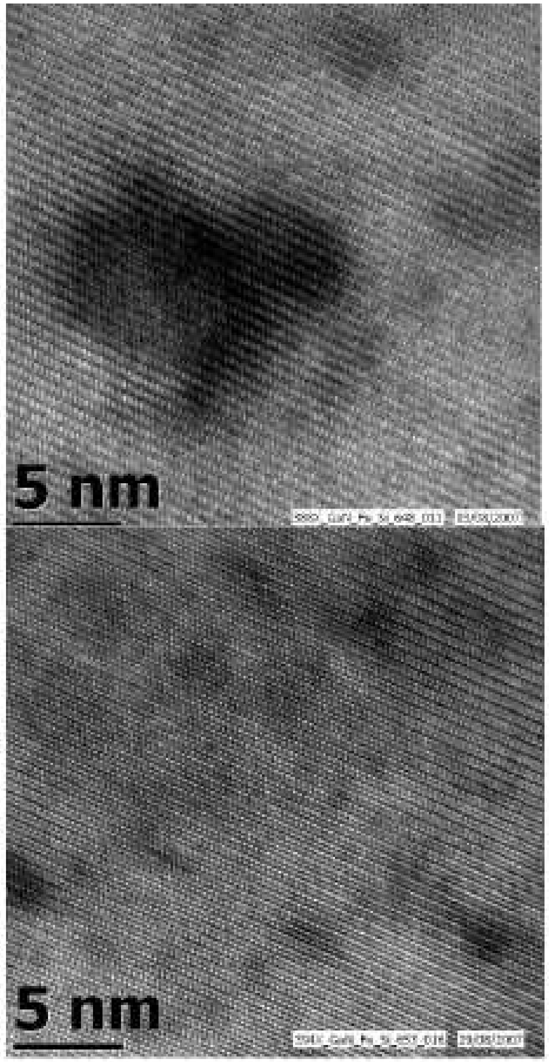


Reduction/dissolution of second phases

A. Bonanni …. T.D. (Linz/Warsaw/Grenoble/Prague) PRL'08

Ferromagnetism of (Ga,Fe)N – effect of co-doping





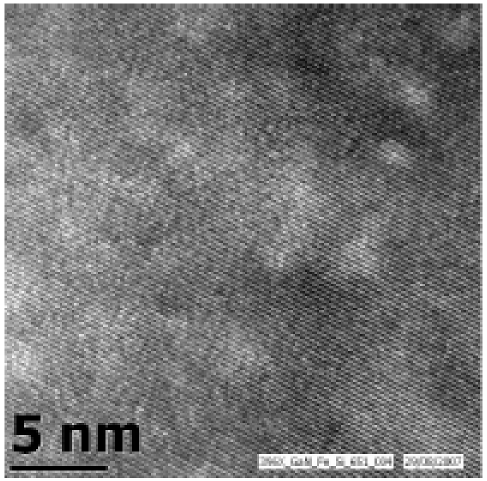
disolution of spinodal decomposition

A. Bonanni …. T.D. (Linz/Warsaw/Grenoble/Prague) PRL'08

Summary: distribution of TM in DMS

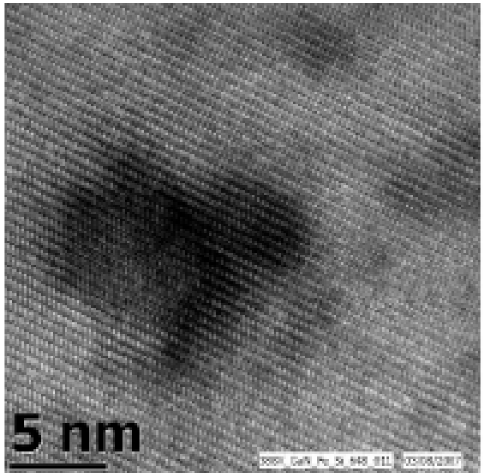
diluted material

paramagnetic behavior of Fe^{3+} ions



spinodal decomposition

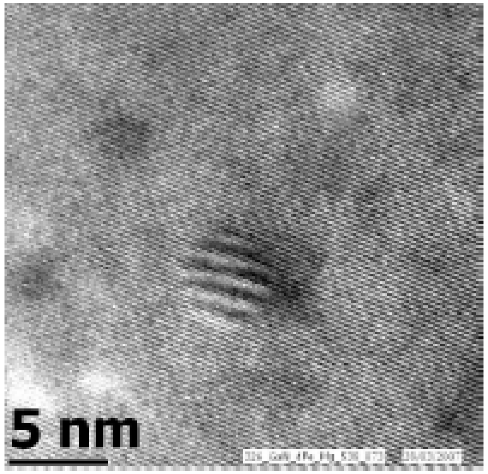
nano-scale chemical phase separation / regions with high magnetic ions concentration / novel magnetic phases stabilized



precipitation

of known ferromagnetic, ferrimagnetic, antiferromagnetic compounds in semiconductor matrix

Fe_3N



A. Bonanni …. T.D. (Linz/Warsaw/Grenoble/Prague) PRL'08

SUMMARY cont.

1. New coherent magnetic compounds formed

2. High T_C, T_N; high blocking temperature

   ➔ spontaneous magnetization at high temperatures

3. Nanoassembling (shape, size) can be controlled *in situ* by growth conditions/co-doping

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4th generation epitaxy

SUMMARY cont.

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4. Functionalities:

➔ nanometalization ➔ nanoelectronics, optoelectronics, plasmonics

_➔ large magnetotransport effects ➔ field sensors

➔ large magnetooptical effects ➔ optical isolators, tunable photonic crystals

➔ spintronic structure ➔high density MRAMs/race track memories/logic

➔ large spin entropy ➔ thermoelectricity

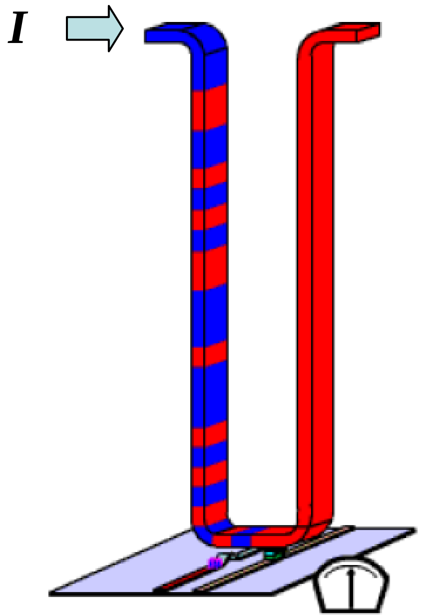
➔ ….

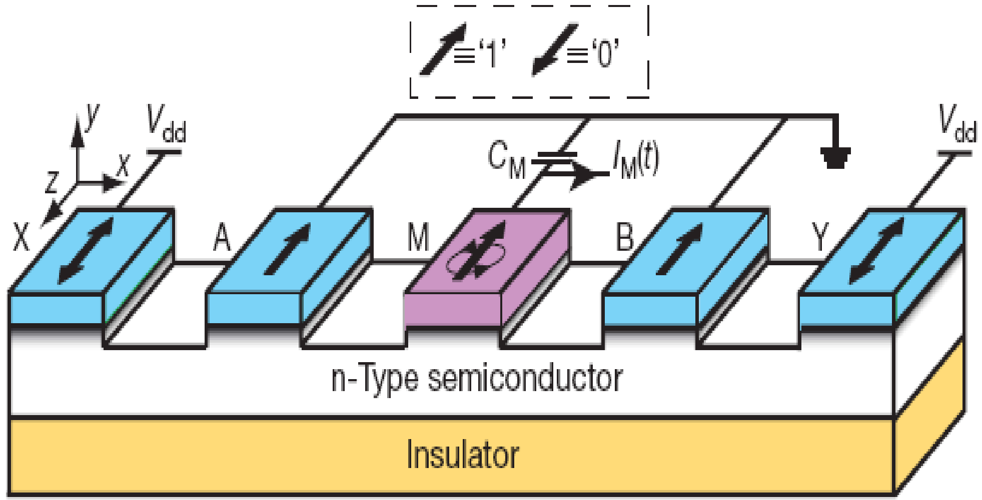
OUTLOOK

Self-organised nanomagnets in semiconductors -- media for:

race track memory

logic gates





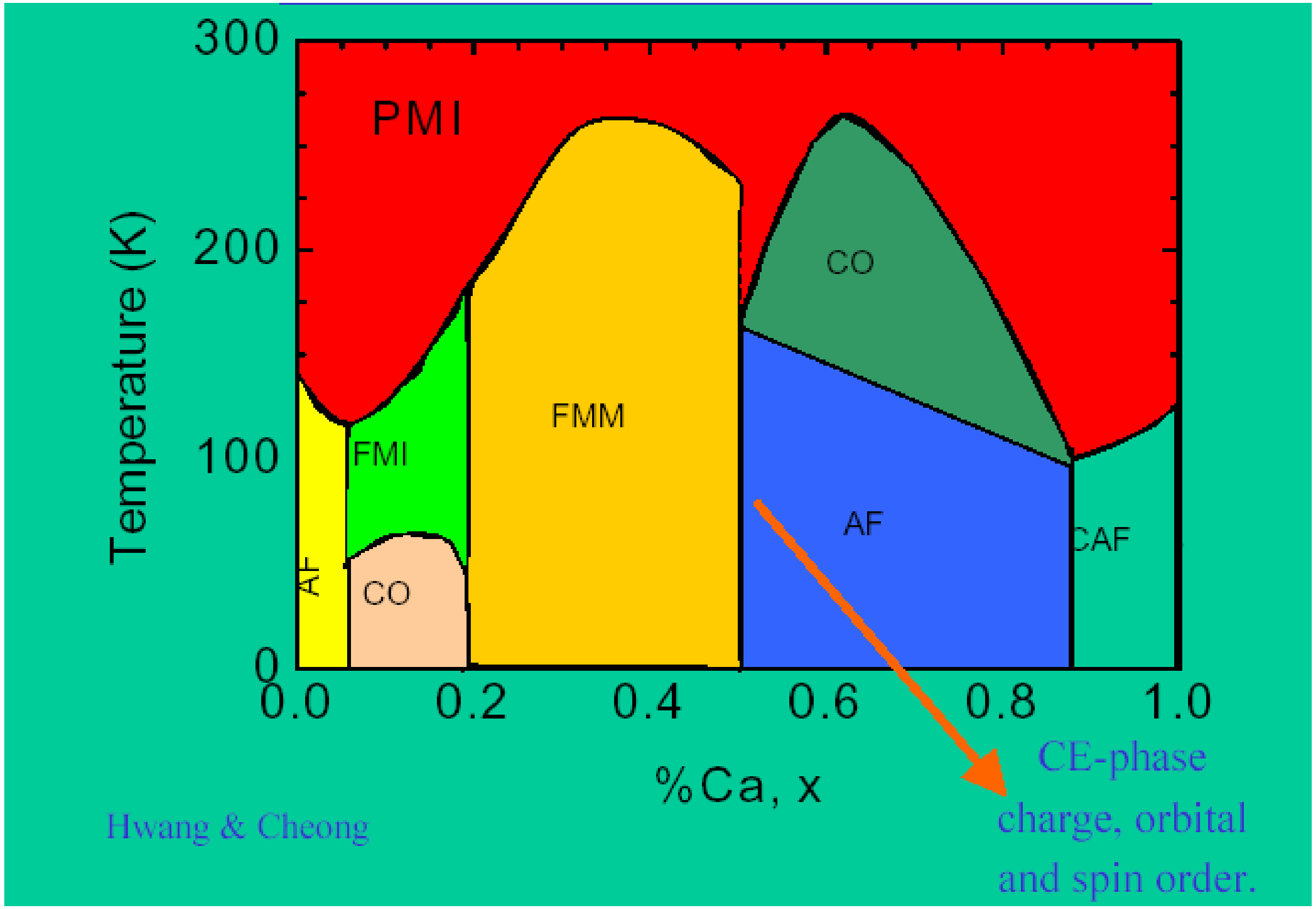
Dery et al. (UCSD) Nature'07

Parkin et al. (IBM) SPINTECH'05, Science'06

magnetooptical devices

metallization

Phase diagram of $La_{1-x}Ca_xMnO_3$



DMS and DMO: interactions determine spatial distribution of both carriers *and* localised spins