Materials physics in ferromagnetic semiconductors and AMR effects in GaMnAs nanostructures

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in collaboration with

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1. Introduction (Ga,Mn)As material

intrinsic and extrinsic properties

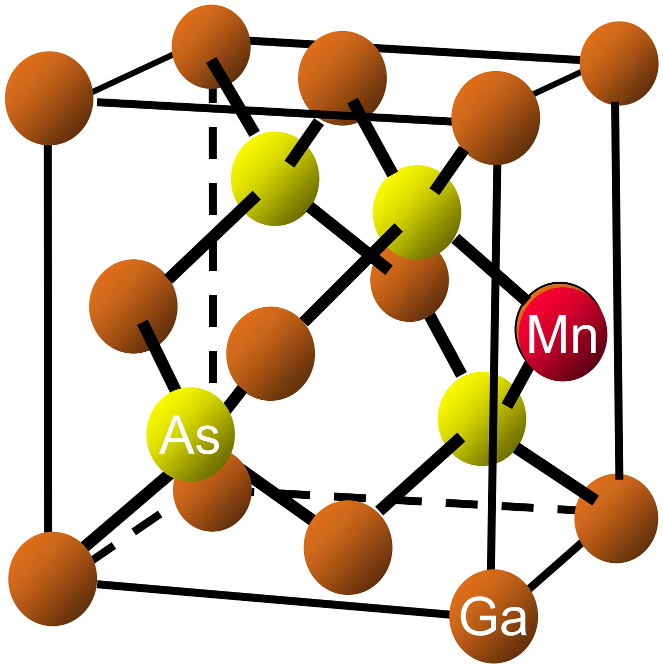
2. Other related diluted magnetic semiconductors

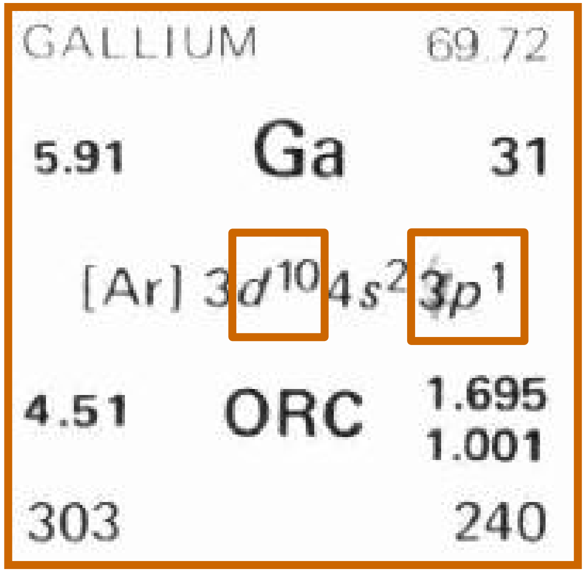
search for higher Curie temperature and p- and n-type FS

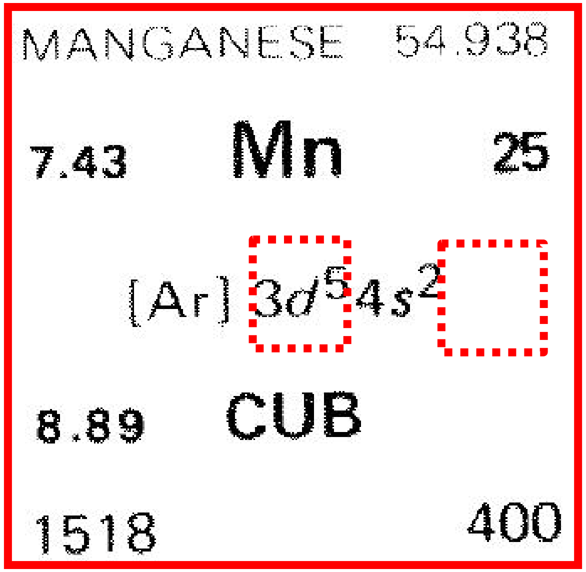
3. AMR effects in (Ga,Mn)As

spin-valves and SETs

1. Introduction - (Ga,Mn)As material



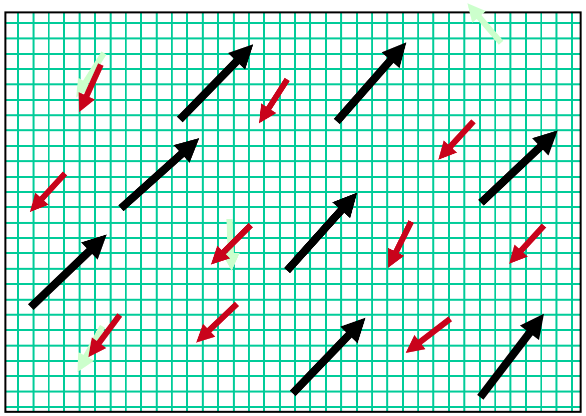




- **Mn local moments** too dilute (near-neghbors cople AF)

- Holes don't polarize in pure GaAs

- **Hole mediated Mn-Mn FM coupling**

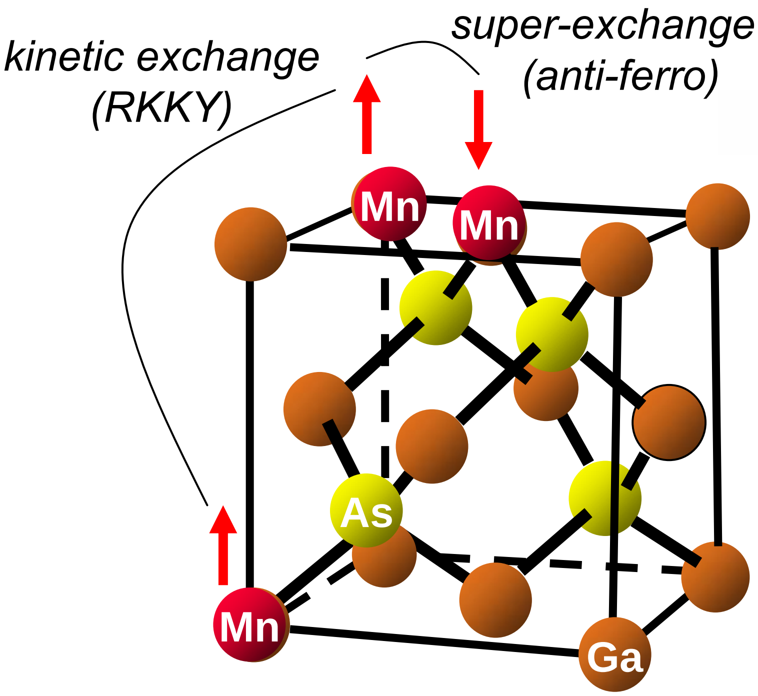


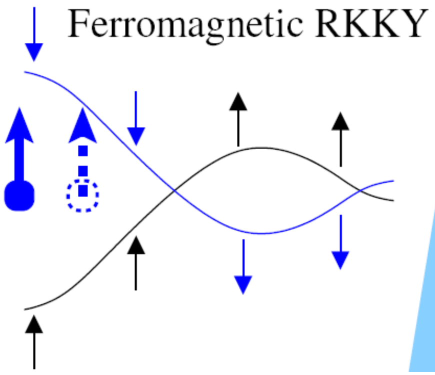
5 *d*-electrons with L=0
→ **S=5/2 local moment**

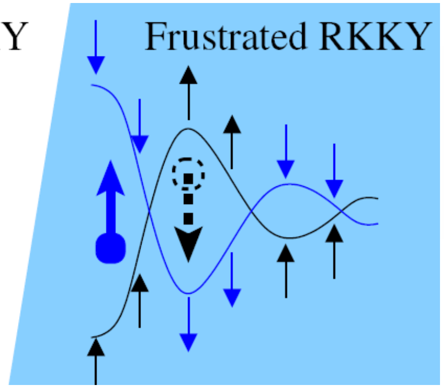
moderately shallow acceptor (110 meV)
→ **hole**

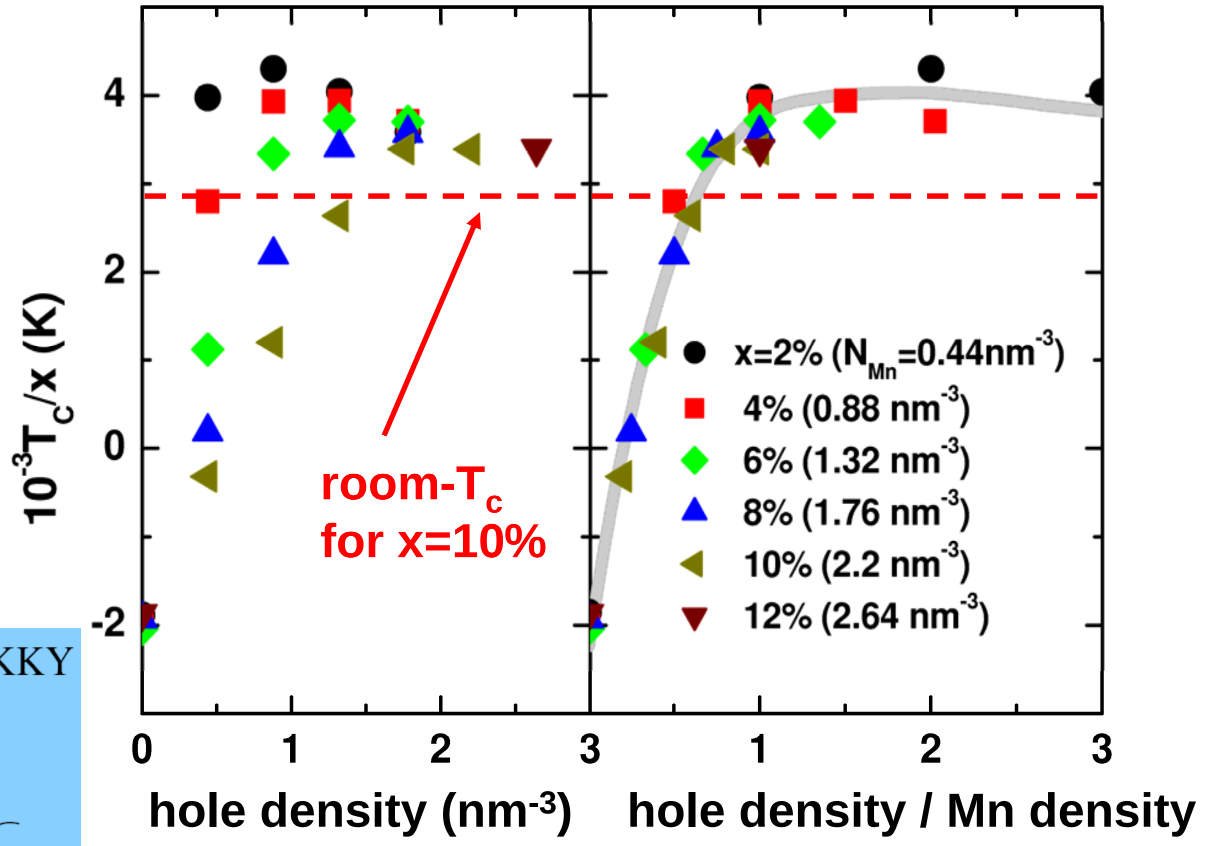
Jungwirth, Sinova, Mašek, Kučera, MacDonald, Rev. Mod. Phys. (2006),
http://unix12.fzu.cz/ms

Intrinsic properties of $Ga_{1-x}Mn_xAs$





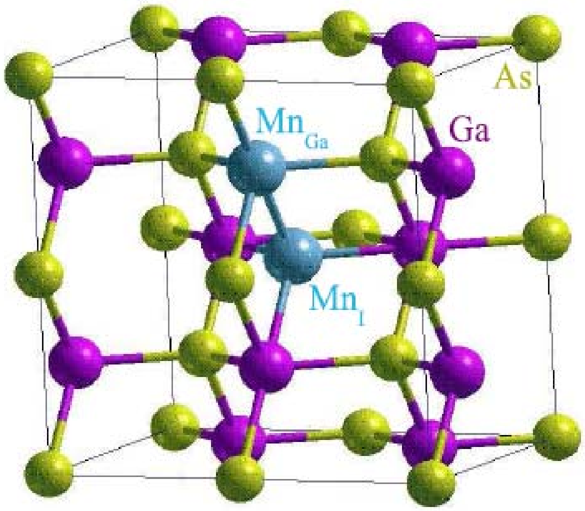




Effective kinetic-exchange Hamiltonian, microscopic TBA or LDA+U

- T_c linear in Mn_{Ga} local moment concentration
- Falls rapidly with decreasing hole density in more than 50% compensated samples
- Nearly independent of hole density for compensation < 50%.

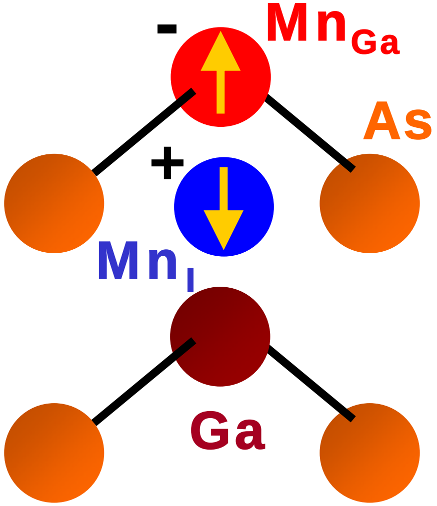
Extrinsic effects - covalent SC do not like doping
→ self-compensation by interstitial Mn



Interstitial Mn_I is detrimental to magnetic order:

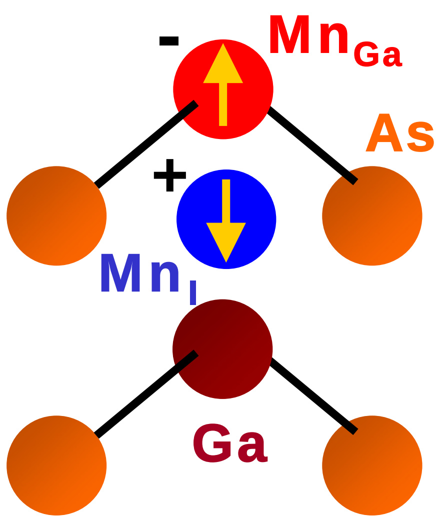
- compensating double-donor – reduces carrier density
- attracted to substitutional Mn_{Ga} acceptor and couples antiferromagnetically to Mn_{Ga} even at low compensation

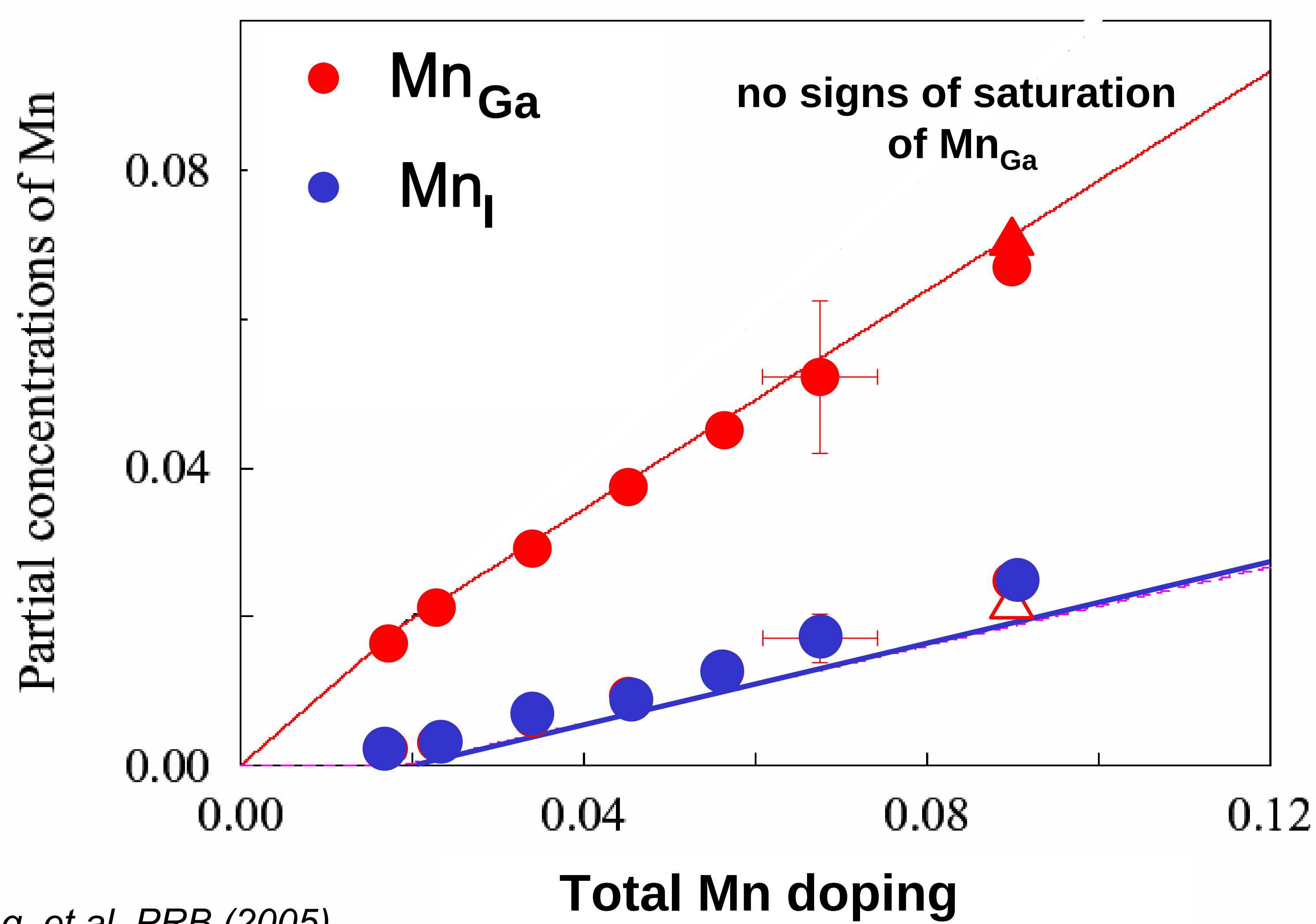
Yu et al., PRB ’02; Blinowski PRB ‘03; Mašek, Máca PRB '03



Generation of $\mathrm{Mn_I}$ during growth

Theoretical linear dependence of $\mathrm{Mn_{Ga}}$ on total Mn confirmed experimentally

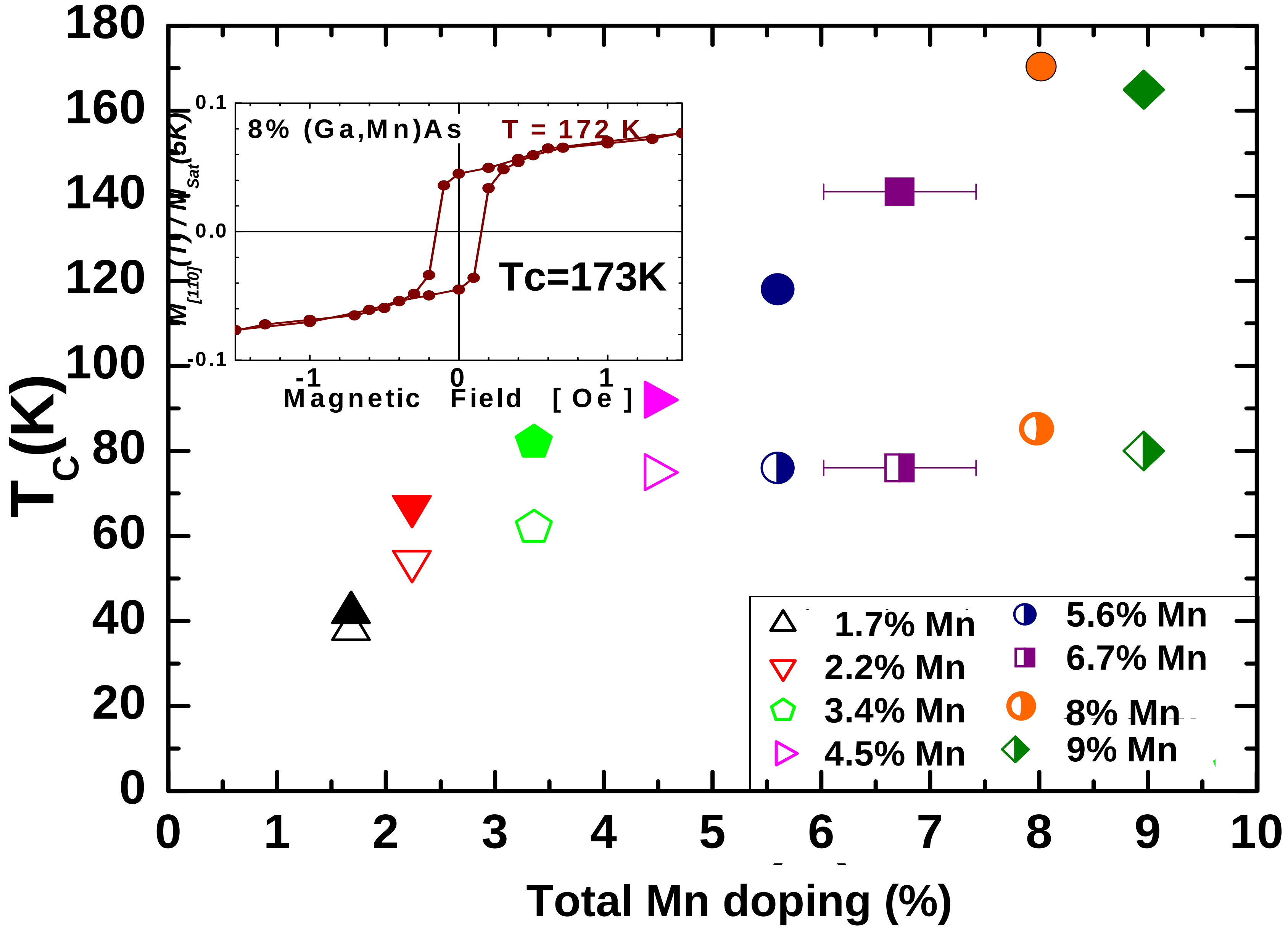




Jungwirth, Wang, et al. PRB (2005)

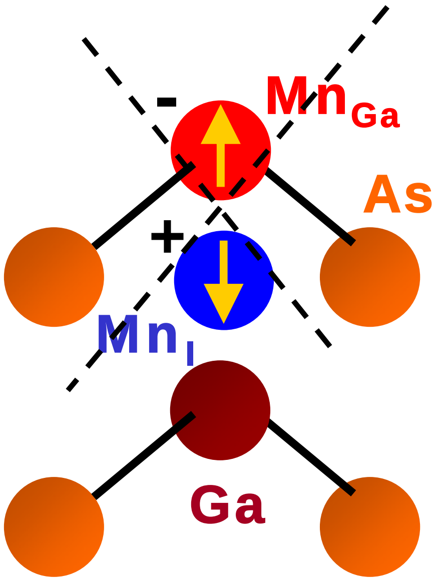
T_c in as-grown and annealed samples

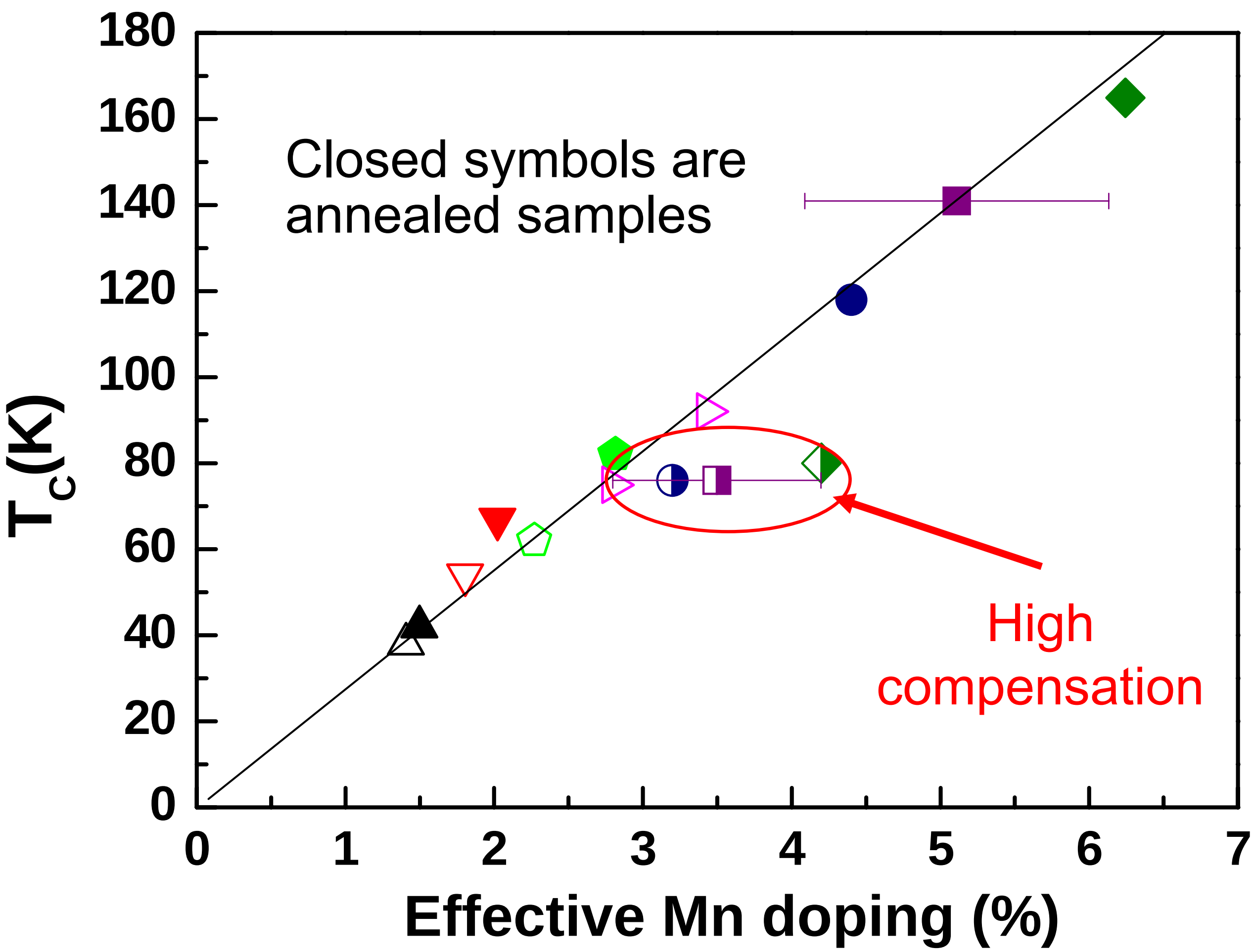
Open symbols as-grown. Closed symbols annealed



Linear increase of T_c with effective Mn moment doping

$Mn_{eff} = Mn_{Ga} - Mn_I$

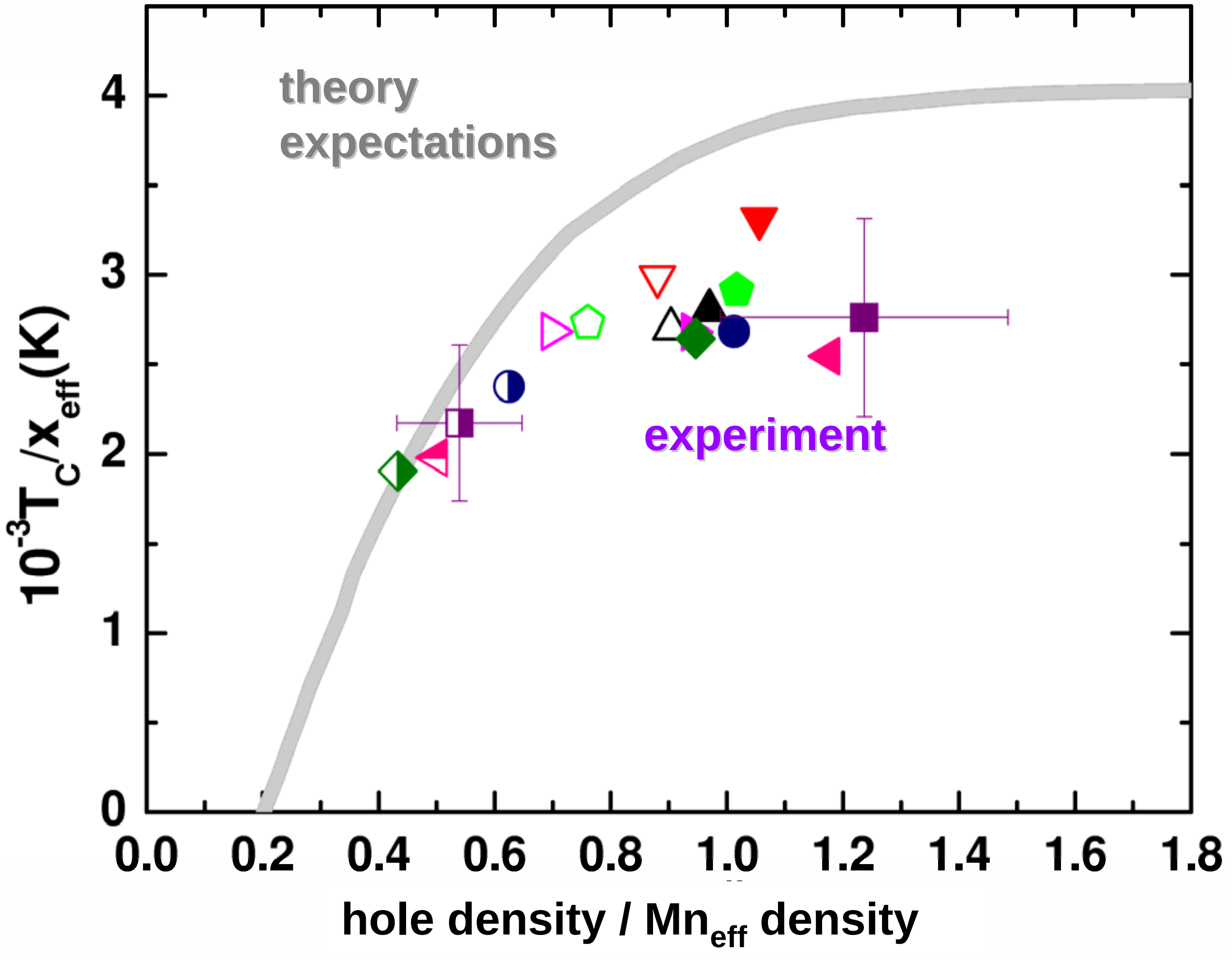




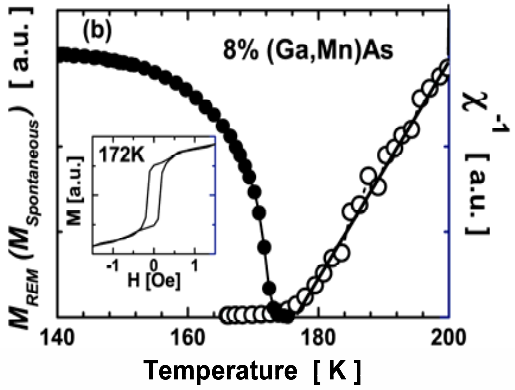
T_c increases with Mn_{eff} when compensation is less than ~40%.

No saturation of T_c at high Mn concentrations

Universal scaling of T_c per Mn_{eff} vs. hole per Mn_{eff}



Robust mean-field ferromagnet



No signs of approaching an intrinsic T_c limit in current (Ga,Mn)As materials yet

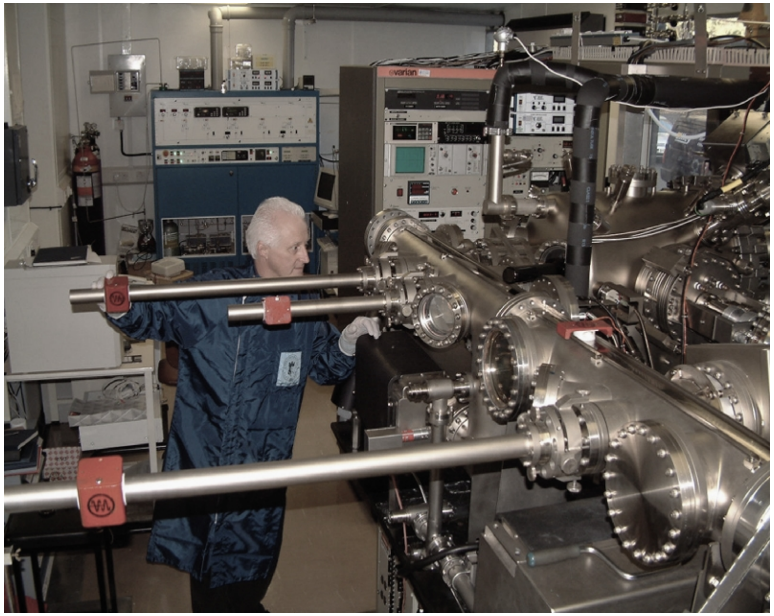
Prospects for higher T_c in (Ga,Mn)As

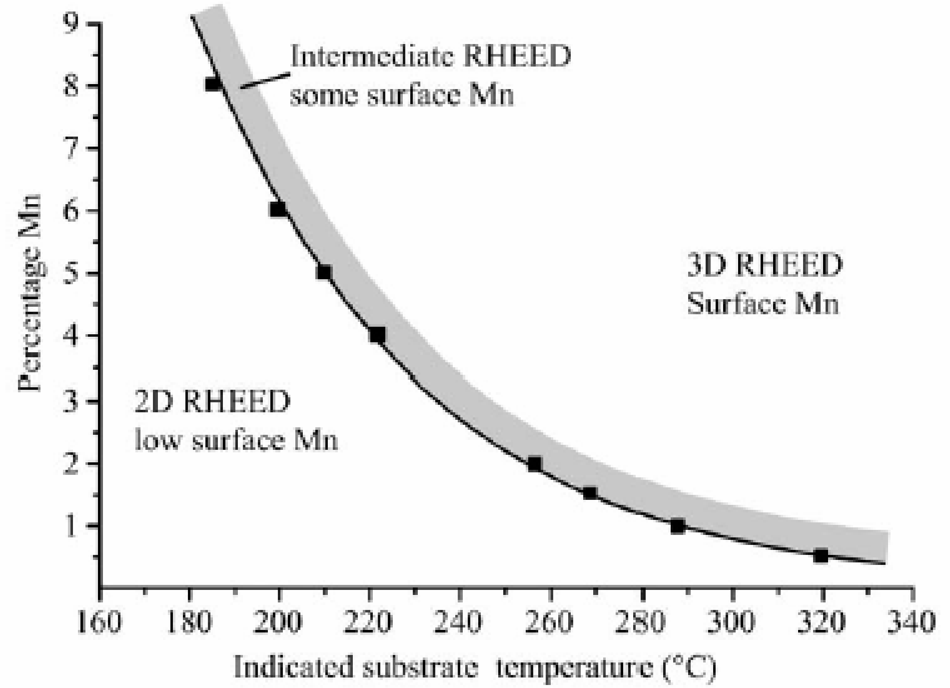
- Effective concentration of uncompensated Mn_{Ga} moments has to increase beyond 6.2% of the current record T_c=173K sample

- Charge compensation not so important unless > 40%

- Technology (precise control of growth-T, stoichiometry) is expected to move T_c above 200K

- T_c above 400 K needed for widespread applications





2. Other related diluted magnetic semiconductors

The central tension in dilute moment systems

- Keep the number of moments (local and band-electrons) large for large T_c

- Keep the number of moments low to retain semiconductor characteristics

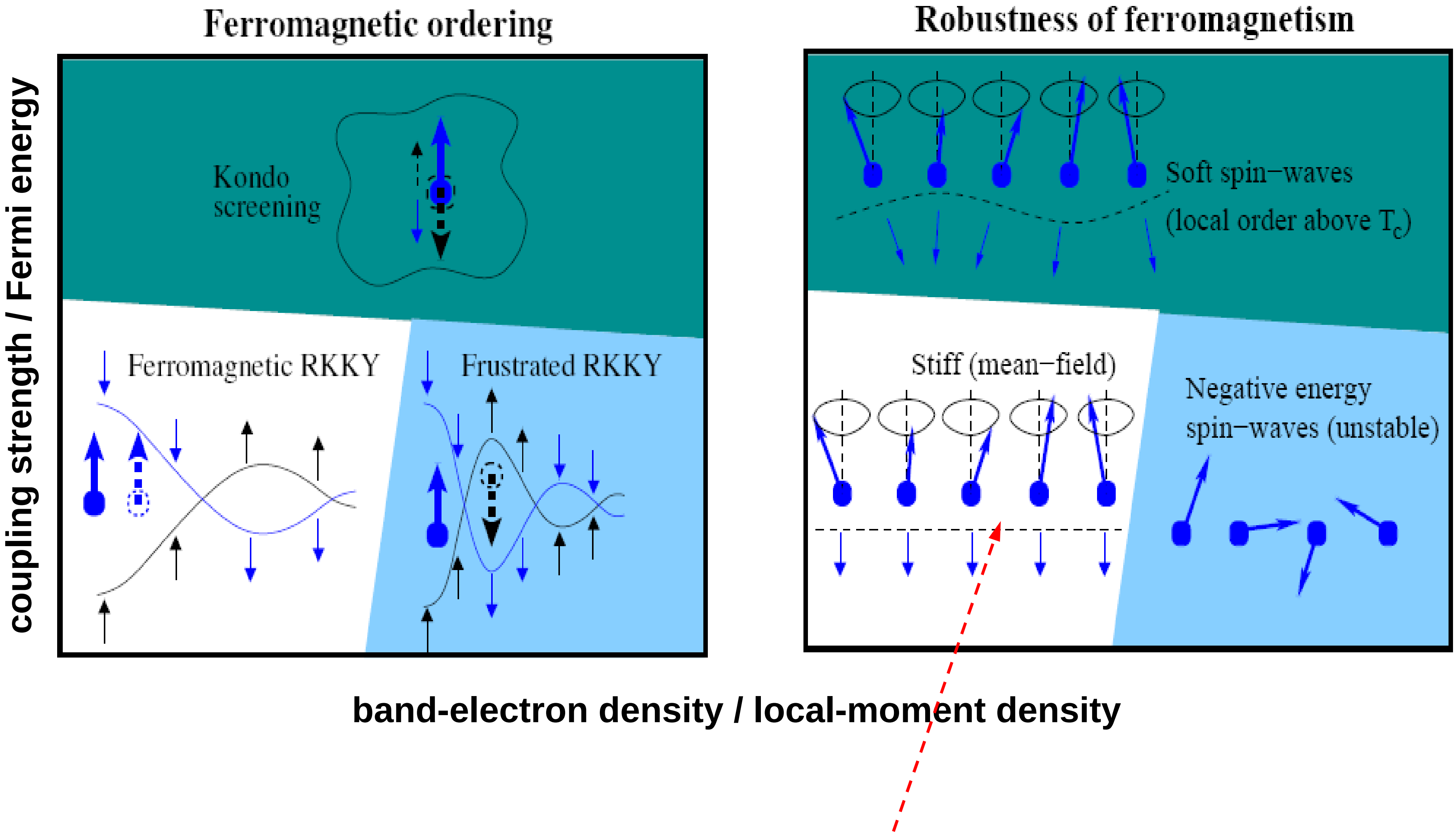
The central question in dilute magnetic semiconductors materials

- Where to find the factor of ~2 T_c enhancement?

How far can we go (physics and technology wise) with doping and local-carrier moment coupling strength while still increasing T_c?

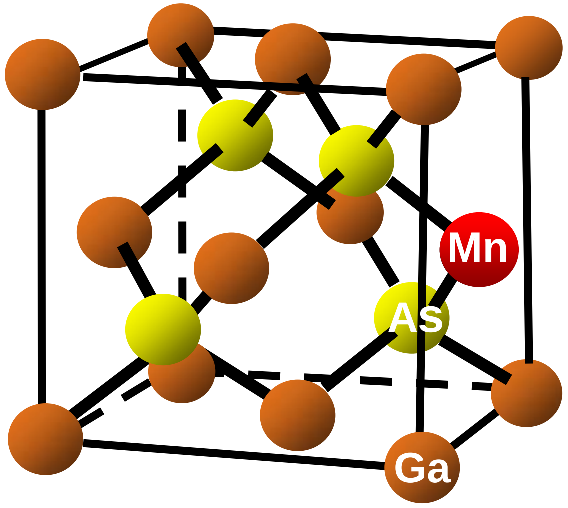
Which semiconductor host is optimal?

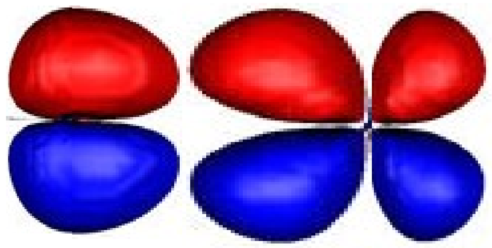
Magnetism in systems with coupled dilute moments and delocalized band electrons



(Ga,Mn)As

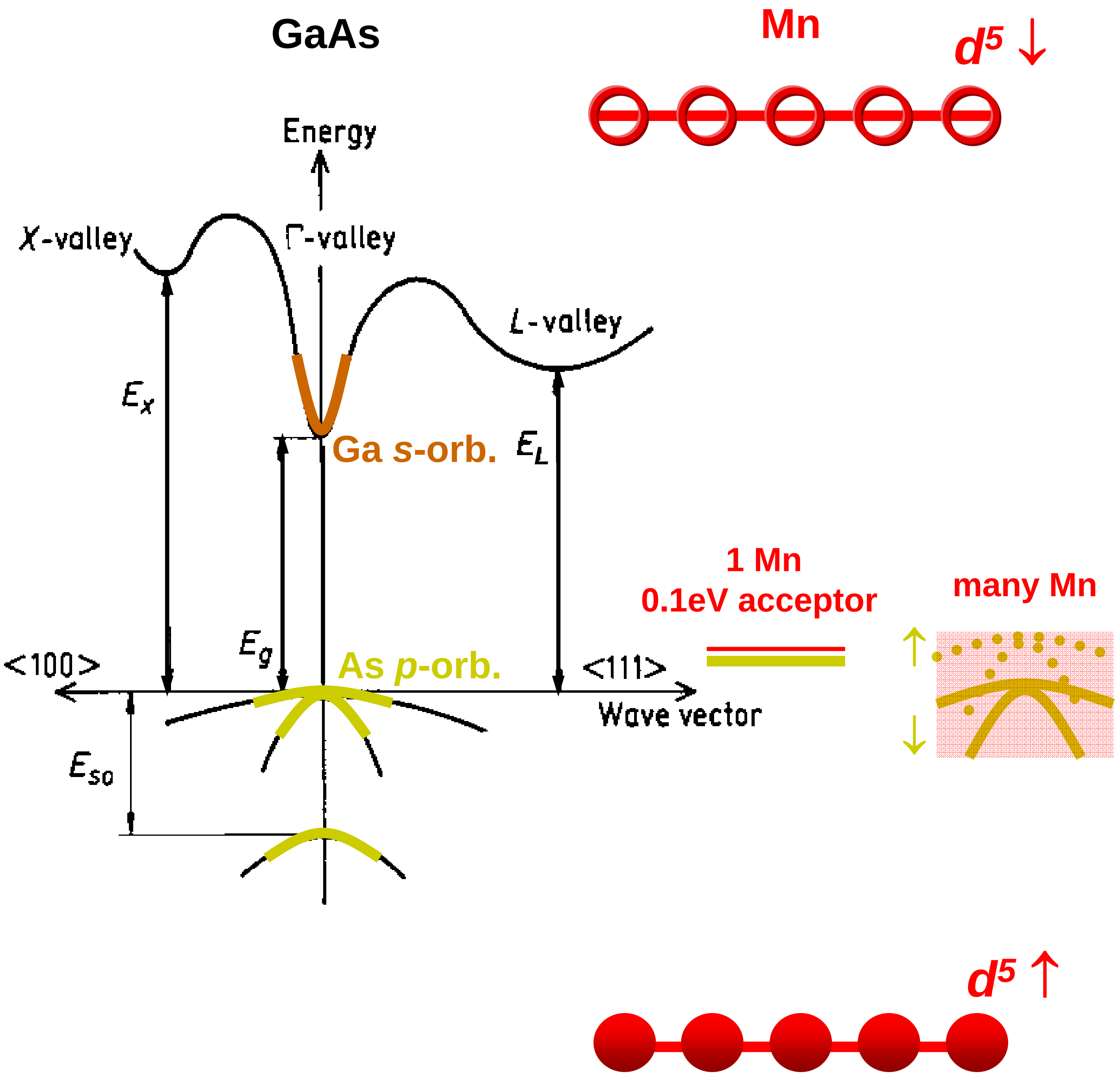
(III,Mn)V materials: Microscopic picture of Mn-hole coupling in (Ga,Mn)As



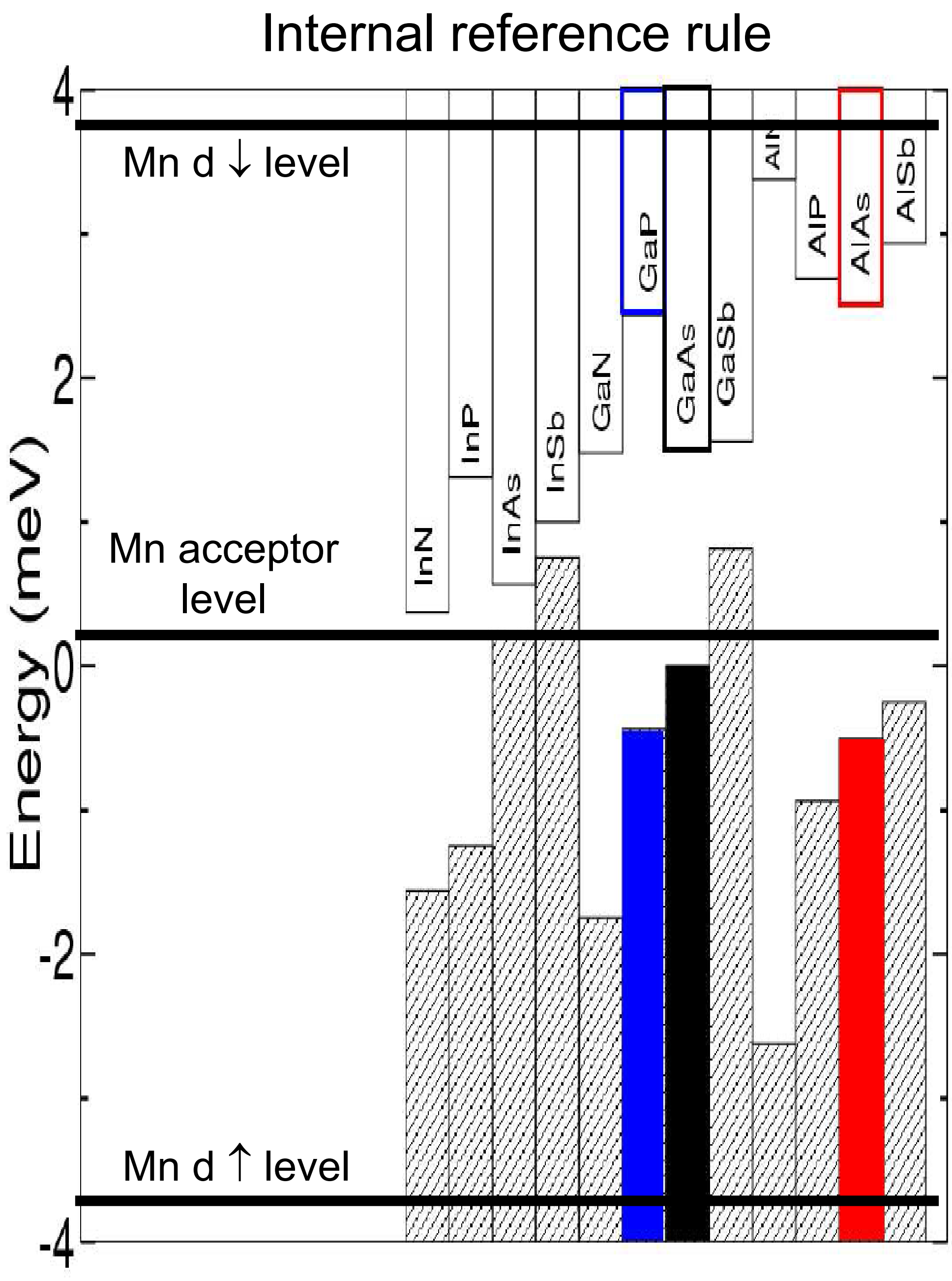


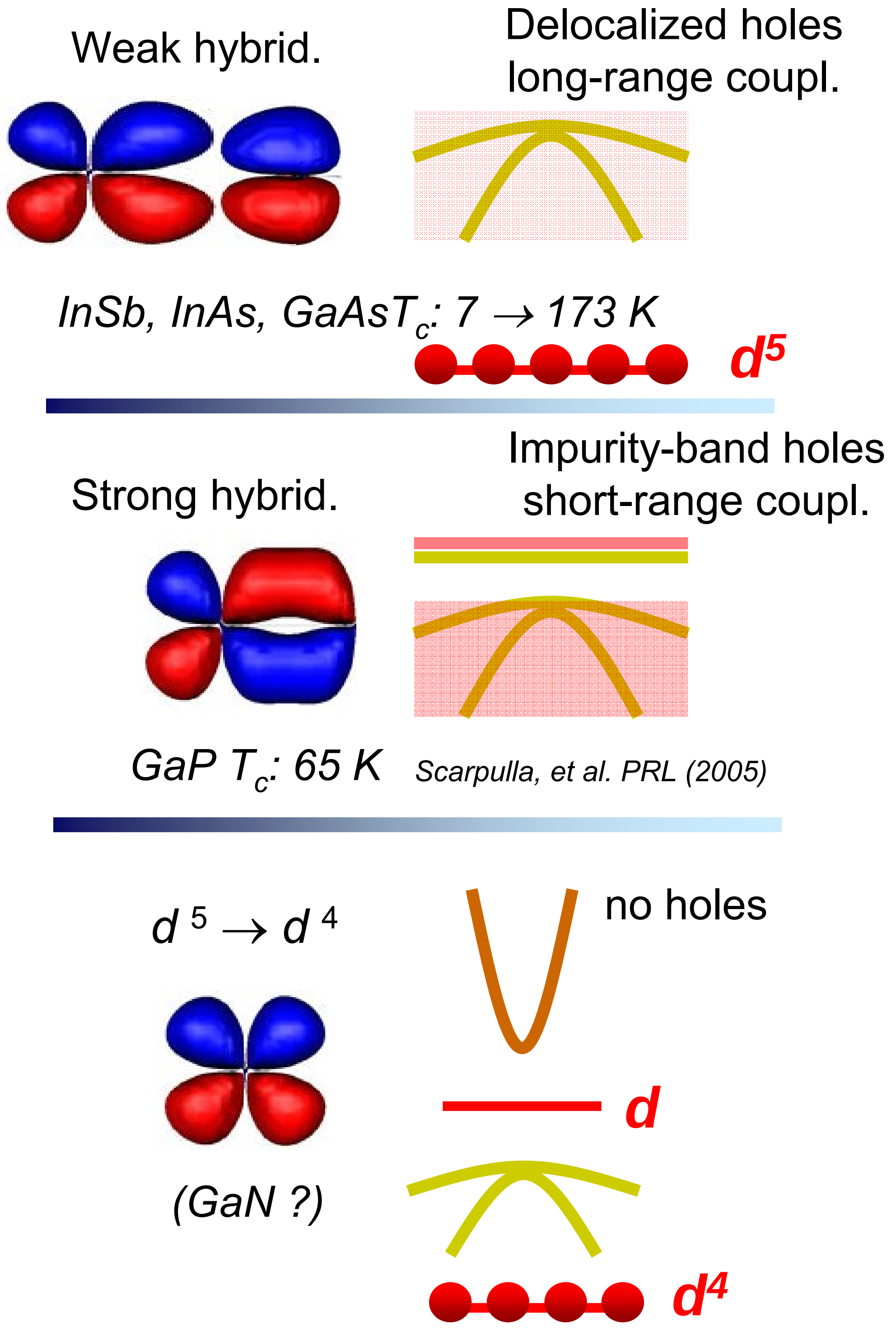
As 4*p* - Mn 3*d*

hybridization



Other III-V hosts


Internal reference rule


Weak hybrid.

Delocalized holes
long-range coupl.

InSb, InAs, GaAsT_c: 7 → 173 K

Strong hybrid.

Impurity-band holes
short-range coupl.

GaP T_c: 65 K

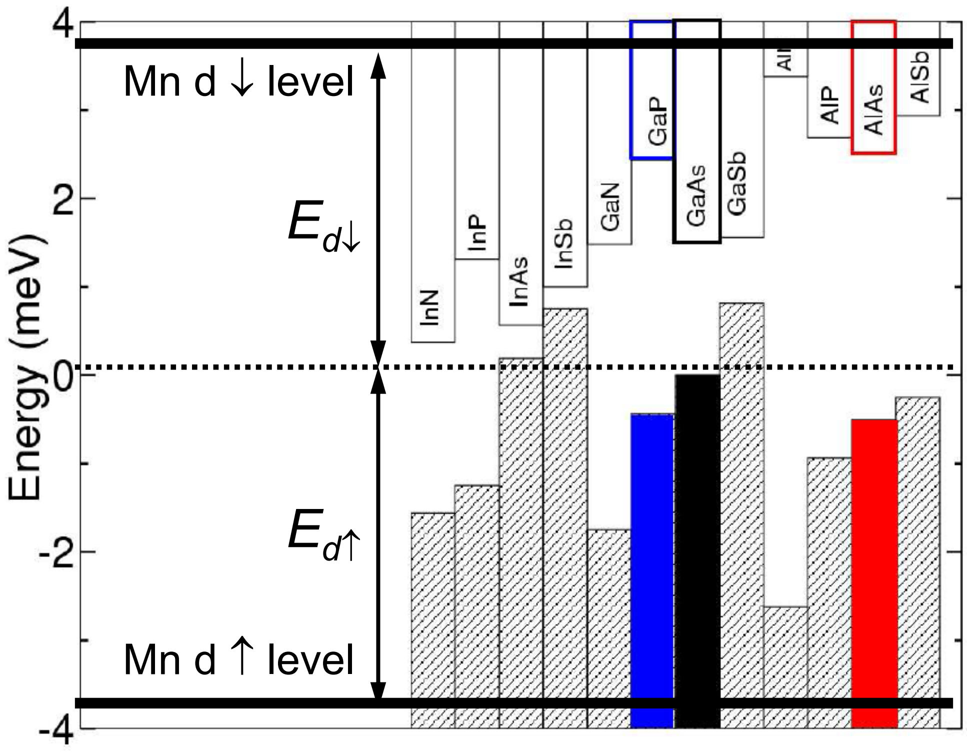
Scarpulla, et al. PRL (2005)

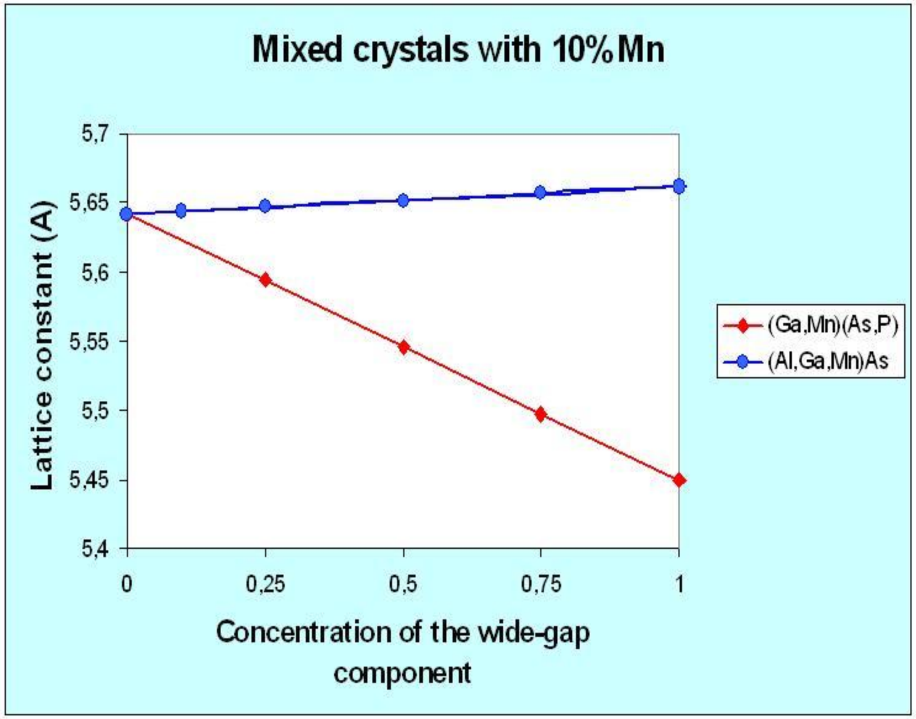
$d^5 \rightarrow d^4$

(GaN ?)

no holes

Mixed (Al,Ga)As and Ga(As,P) hosts





$$1/|E_{d\downarrow}| + 1/|E_{d\uparrow}| \sim \text{const.}$$

$$|V_{pd}|^2 \sim a_{lc}^{-7}$$

Hole - local moment Kondo coupling:

$$J_{pd} \propto \Omega_{u.c.}|V_{pd}|^2(1/|E_{d\uparrow}| + 1/|E_{d\downarrow}|)$$

$$\Omega_{u.c.} = a_{lc}^3/4$$

Mean-field Curie temperature:

$$T_c \propto J_{pd}^2 x/\Omega_{u.c.} = \boxed{a_{lc}^{-11}}\boxed{(1/|E_{d\uparrow}| + 1/|E_{d\downarrow}|)^2}$$

50% in GaP

4% in GaP and AlAs

p-d coupling and T_c in mixed (Al,Ga)As and Ga(As,P)

Smaller lattice const. more important
for enhancing *p-d* coupling than larger gap

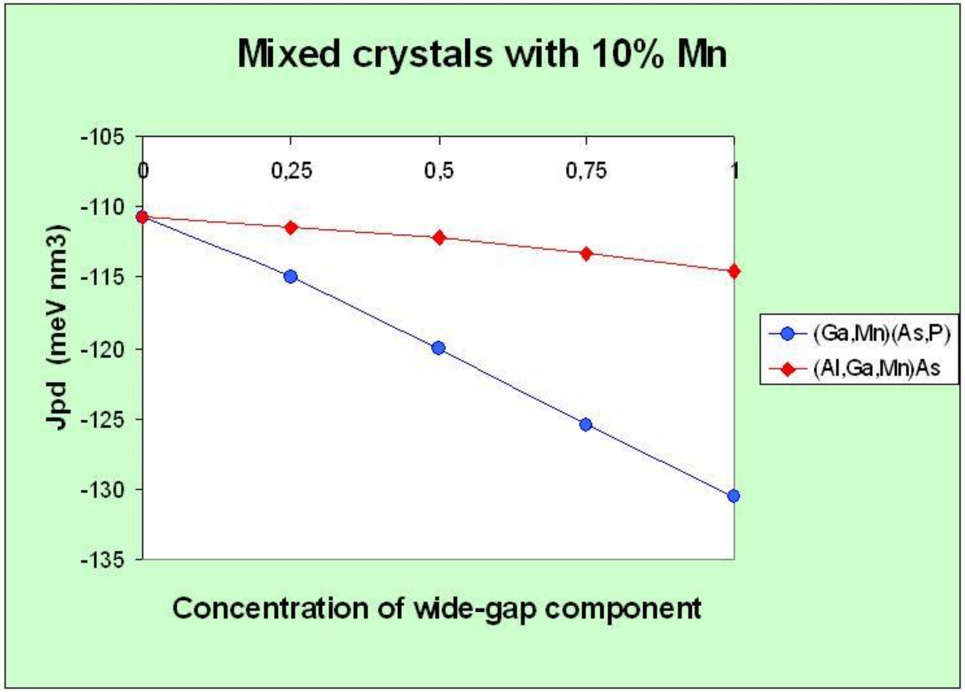
↓

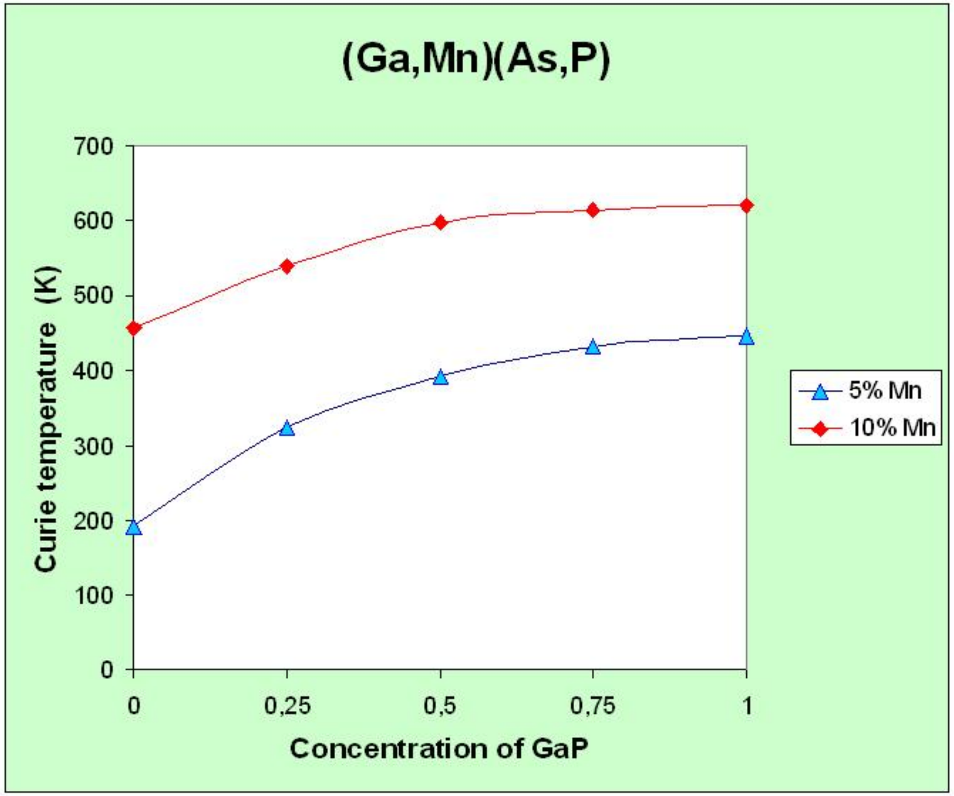
Mixing P in GaAs more favorable
for increasing mean-field T_c than Al

No dramatic decrease in the LDA+U
range of Mn-Mn interactions

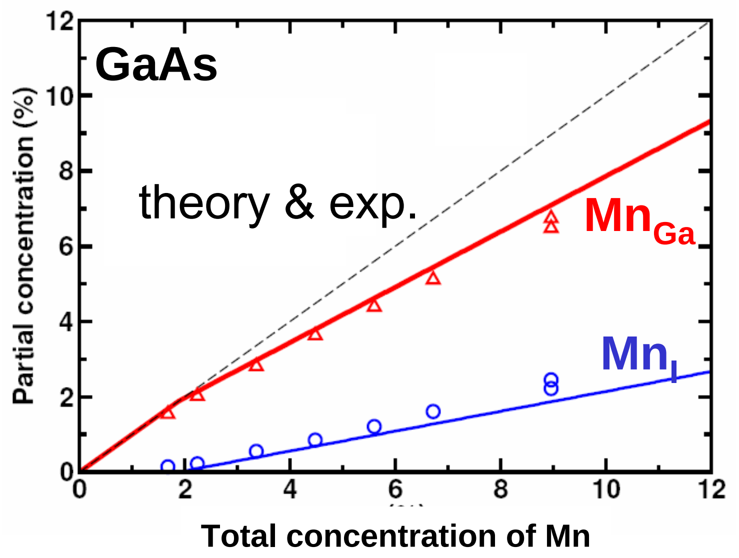
Mašek, et al. to be published

Microscopic TBA/CPA or LDA+U/CPA

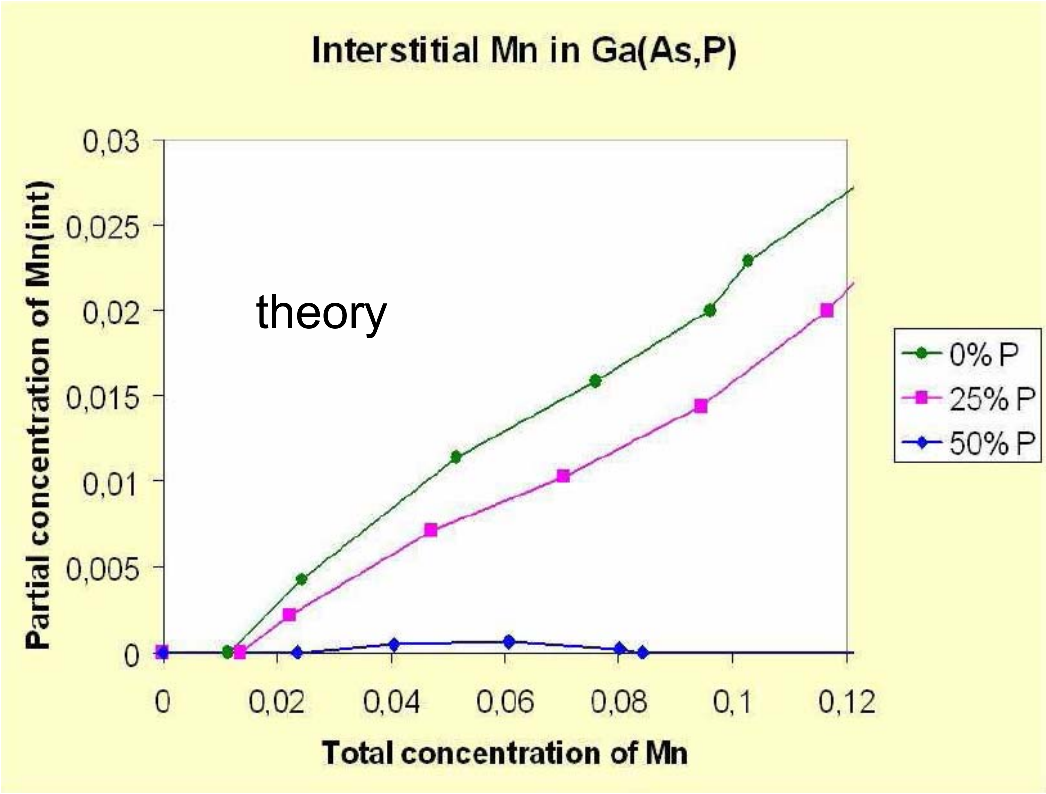




Mn formation energies in mixed Ga(As,P)



Additional motivation for MBE research:
Mixing P in GaAs might lead to
easier incorporation of Mn_{Ga}



III-V [(Ga,Al)(As,P)] based ferromagnetic semiconductors:

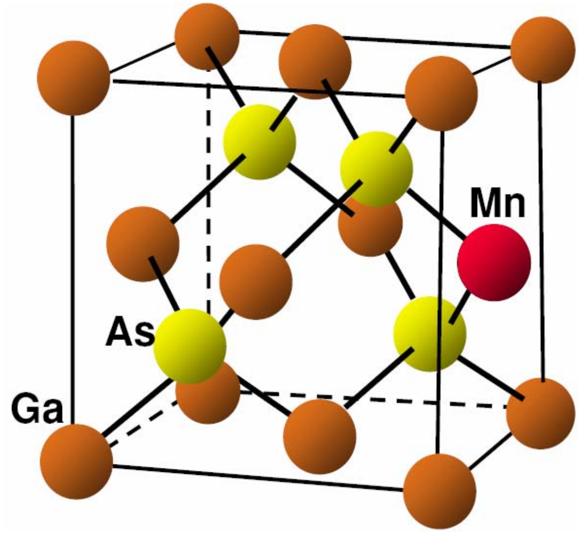
- adding few % of one type of dopand (Mn) in a common semiconductor

but the simplicity brings limitations

- Mn solubility limits; correlated local-moment and carrier densities;

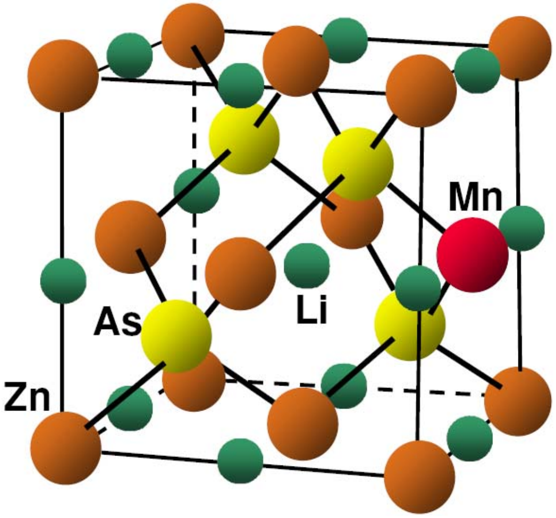
  p-type only

III = I + II → Ga = Li + Zn



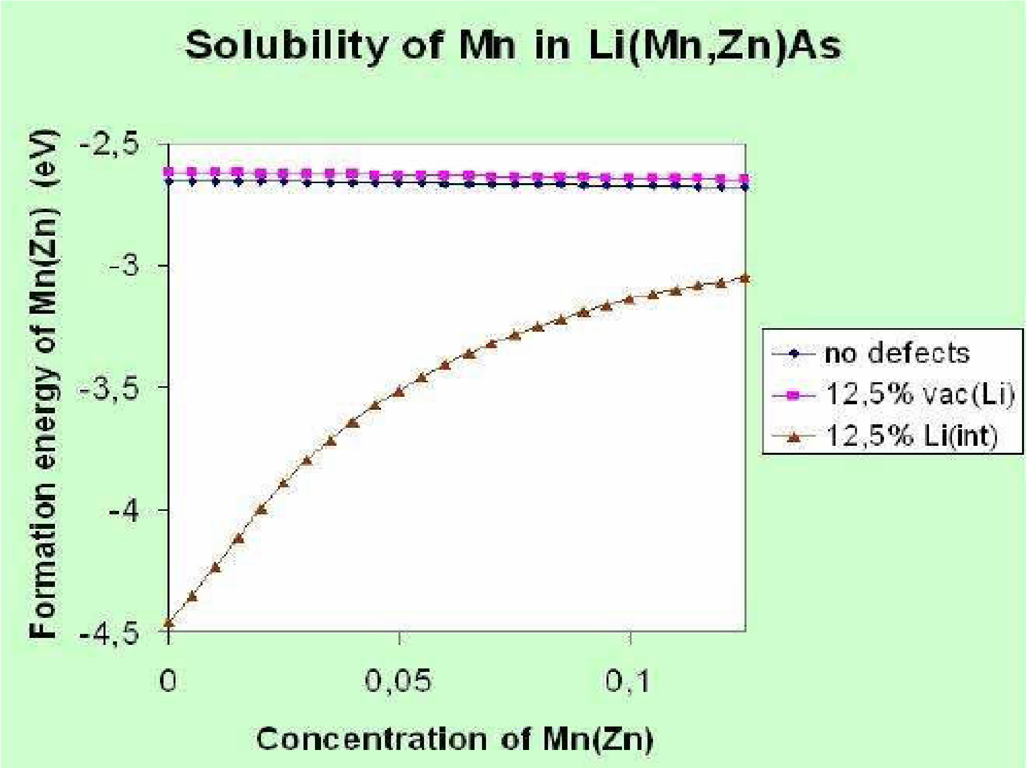
GaAs and LiZnAs are twin SC

- Band gaps 1.5 eV vs. 1.6 eV
- similar band dispersions
- similar GS charge densities
- similar phonon dispersions, ...



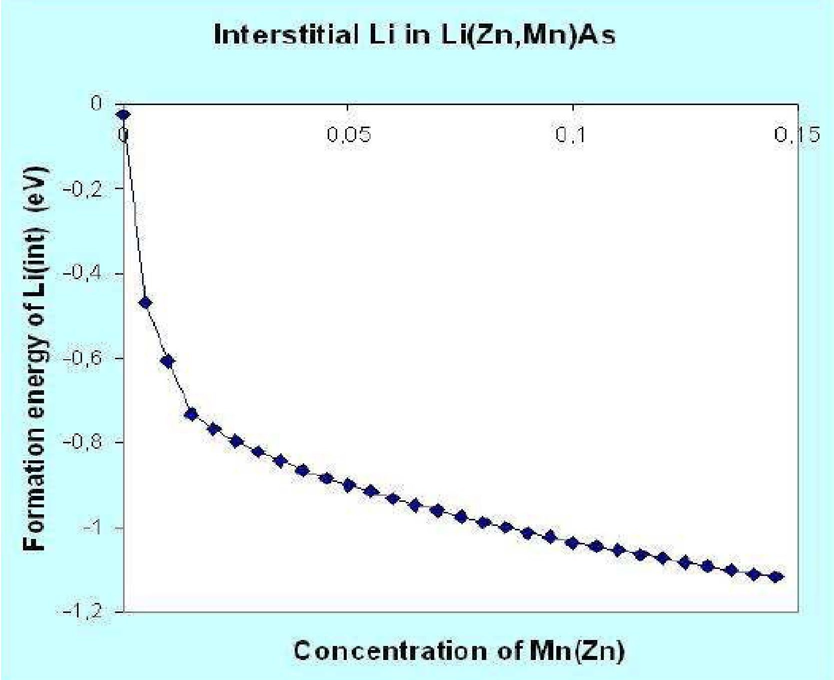
Wei, Zunger '86;
Bacewicz, Ciszek '88;
Kuriyama, et al. '87,'94;
Wood, Strohmayer '05

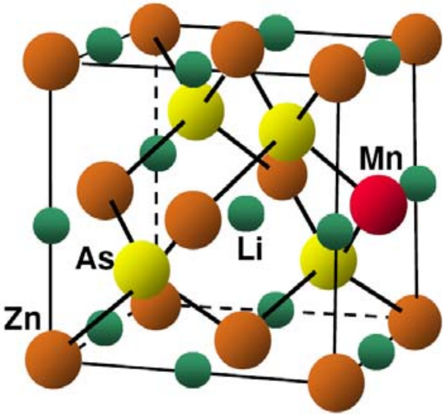
No solubility limit for Mn_{Zn}



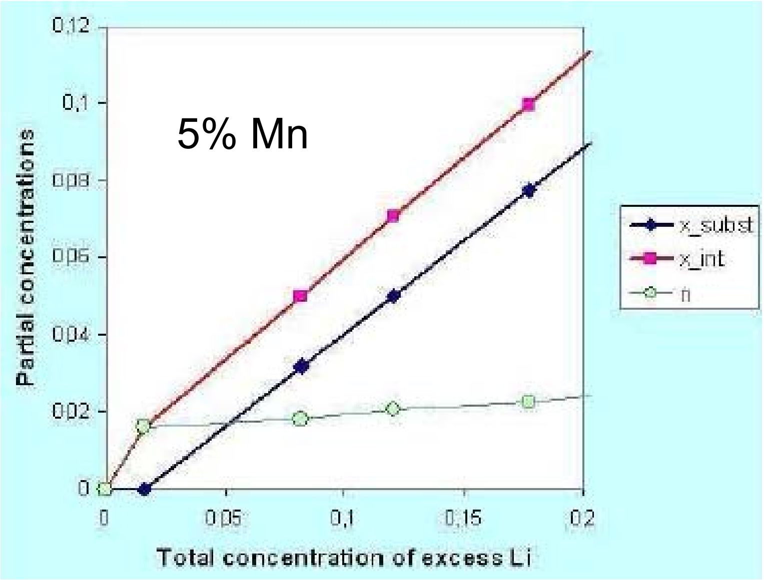
Kudrnovský, et al.
to be published

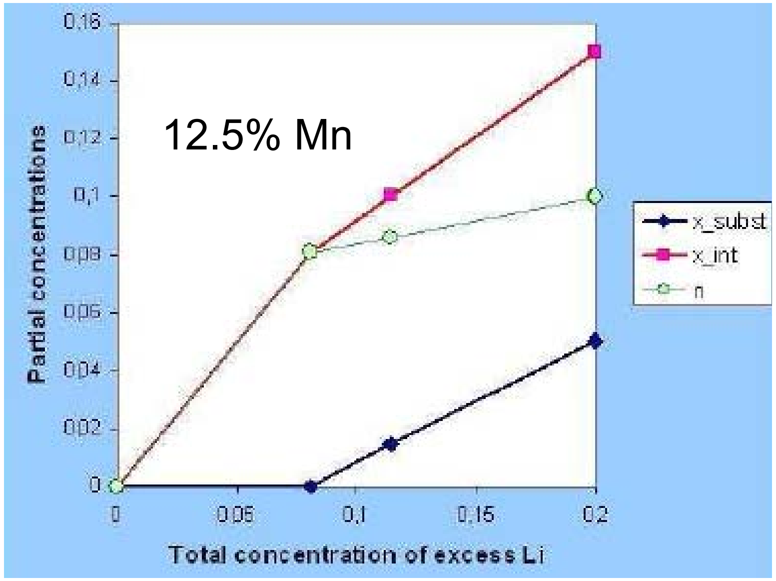
Large electron densities in non-stoichiometric n-type Li(Zn,Mn)As



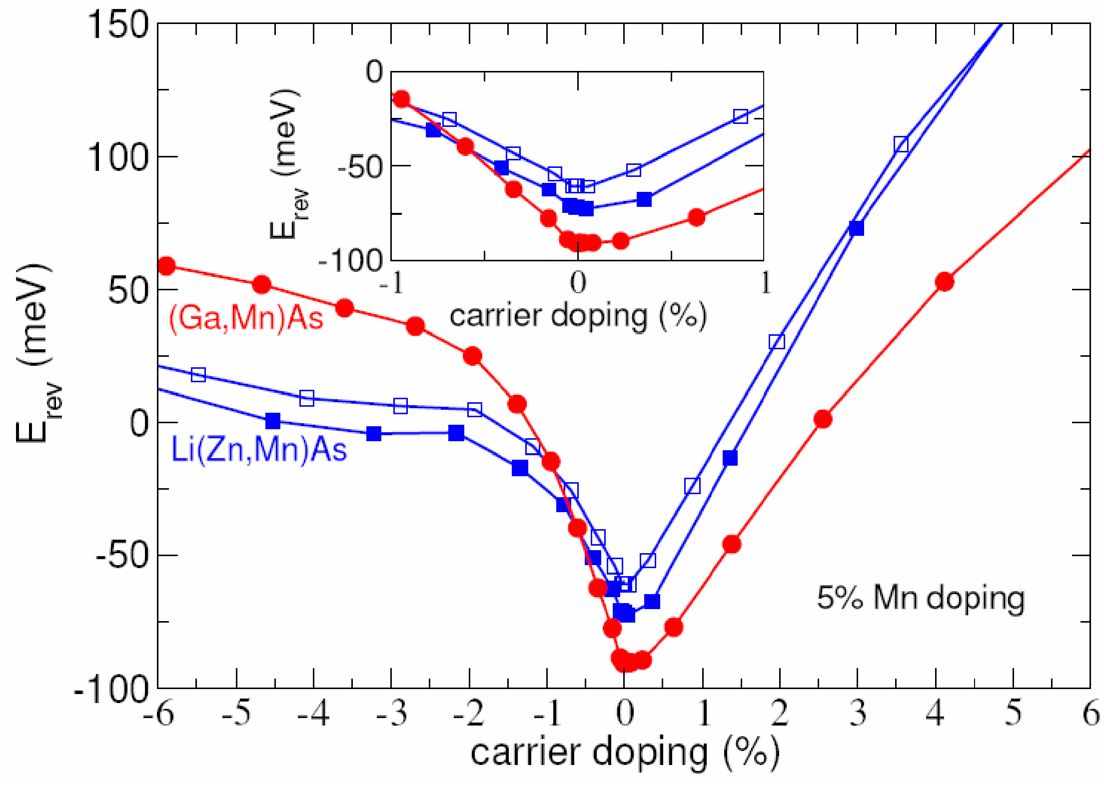


\+ interstitial Li in Ga tetrahedral position

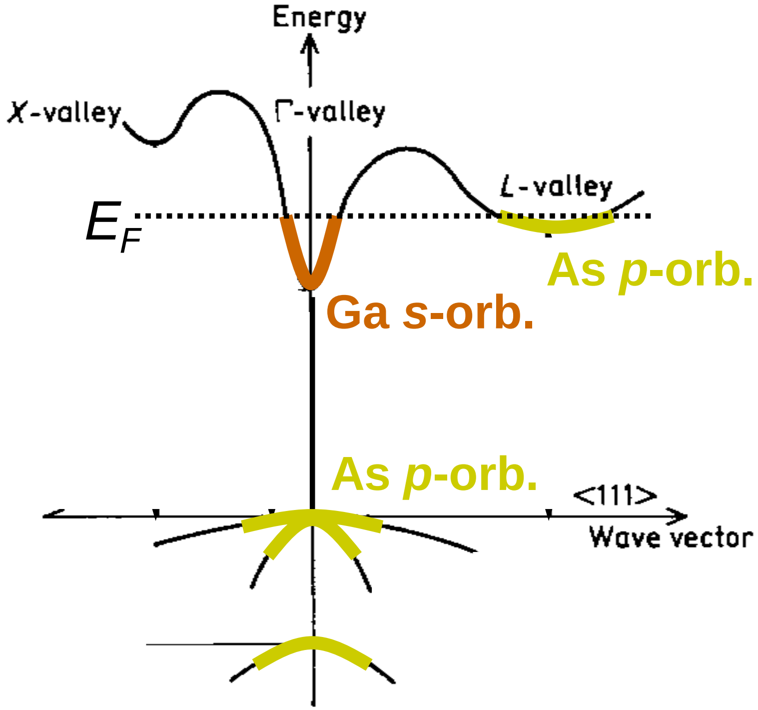




Mean-field T_c



Also, comparable LDA+U range of Mn-Mn interactions in n-type Li(Zn,Mn)As as in p-type (Ga,Mn)As



p-d hybridization quickly builds up when moving from CB Γ-point

↓

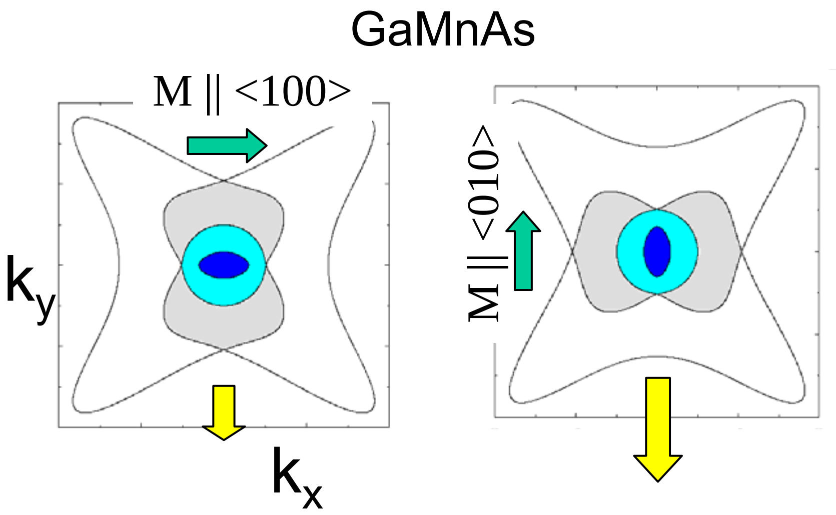
n-type DMS ferromagnetism

Li(Mn,Zn)As: similar to (Ga,Mn)As but lifts all the limitations of Mn solubility; correlated local-moment and carrier densities; p-type only

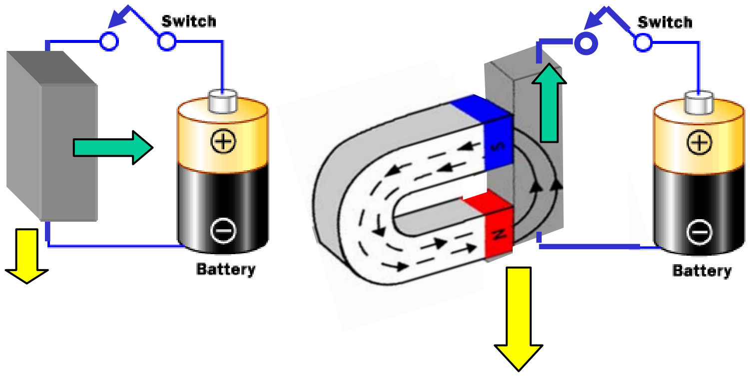
3. AMR (anisotropic magnetoresistance) effects in (Ga,Mn)As

Ferromagnetism: sensitivity to magnetic field

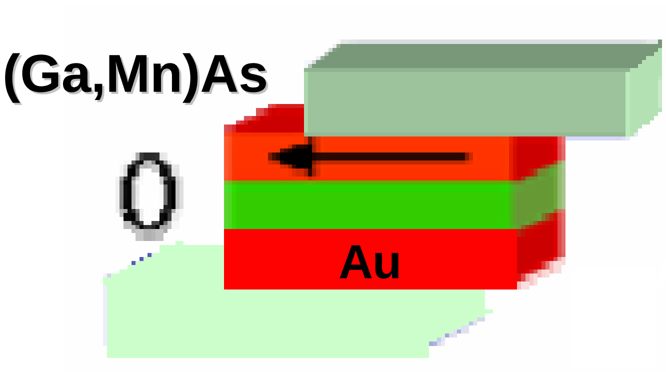
SO-coupling: transport coefficients depend on angle between magnetization and current (crystal axes)

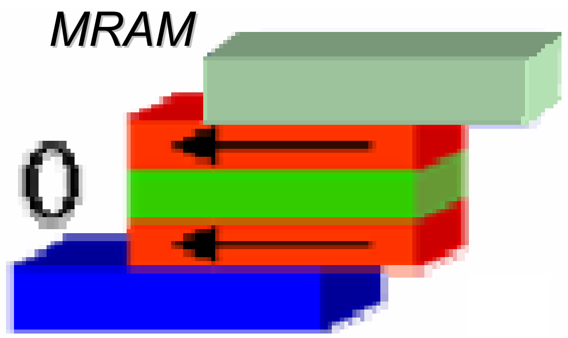


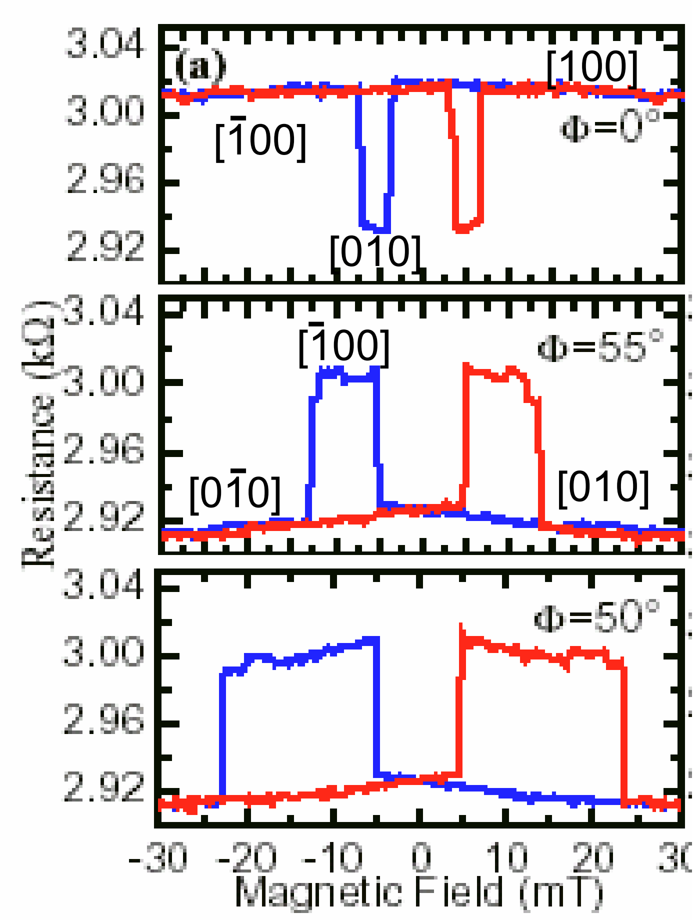
Band structure depends on *M*

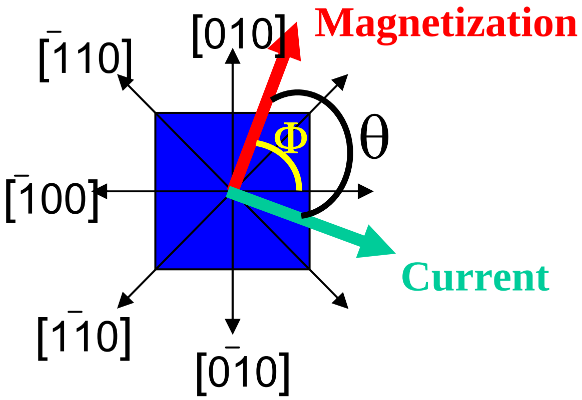


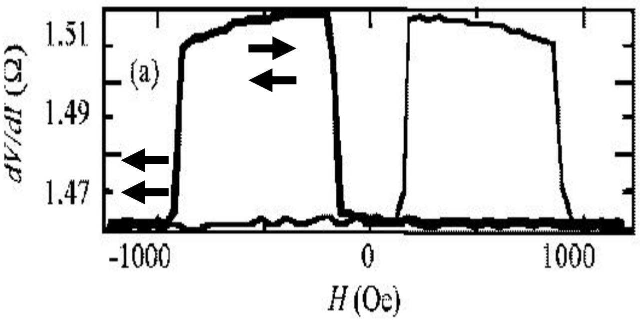
Tunneling AMR: anisotropic tunneling DOS due to SO-coupling









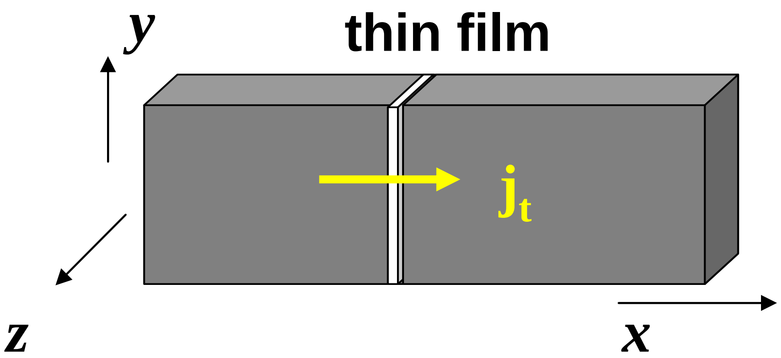


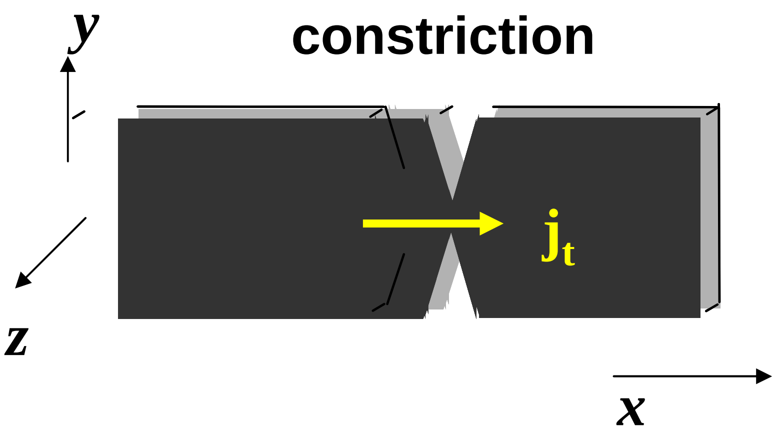
- no exchange-bias needed

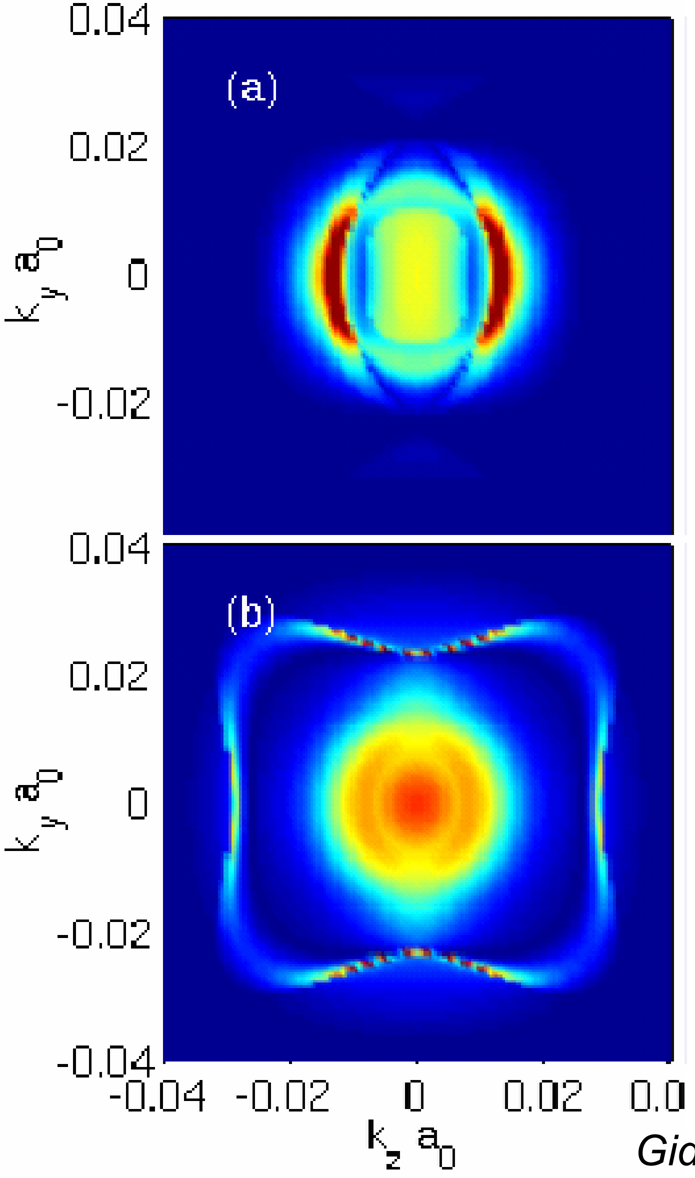
- spin-valve with ritcher phenomenology than TMR

Gould, Ruster, Jungwirth, et al., PRL '04, '05

Wavevector dependent tunnelling probability T (k_y, k_z) in GaMnAs
Red high T; blue low T.







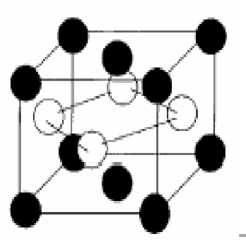
Magnetization perp. to plane

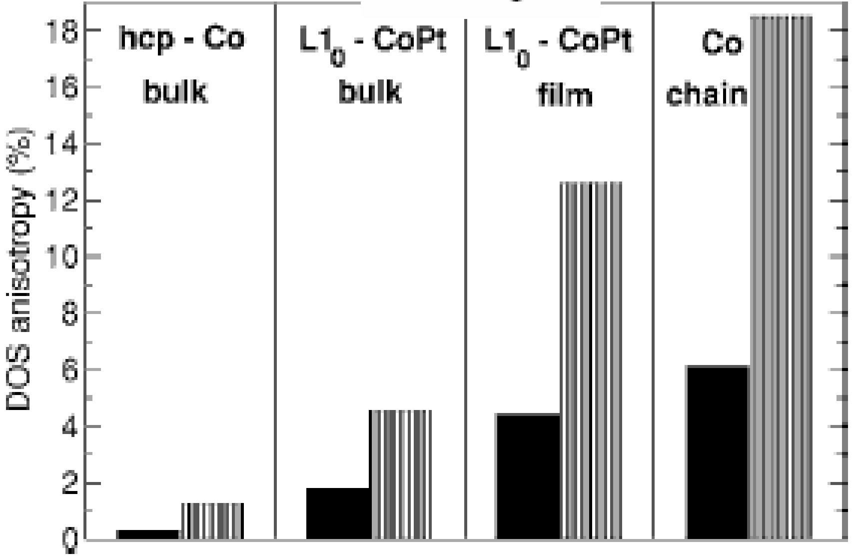
Magnetization in-plane

Giddings, Khalid, Jungwirth, Wunderlich et al., PRL '05

TAMR in metals

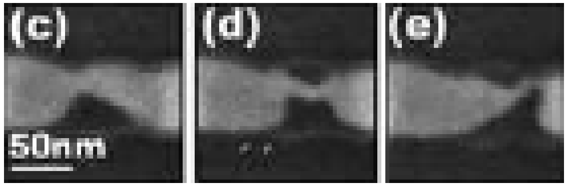
ab-initio calculations

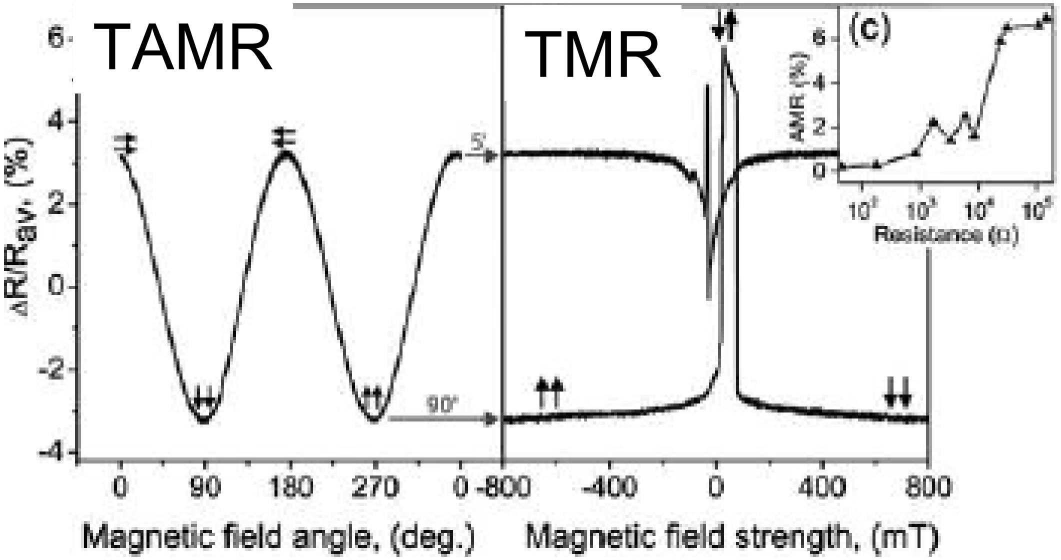




Shick, Maca, Masek, Jungwirth, PRB '06

NiFe





Bolotin,Kemmeth, Ralph, cond-mat/0602251

TMR ~TAMR >>AMR

Viret et al., cond-mat/0602298 Fe, Co break junctions TAMR >TMR

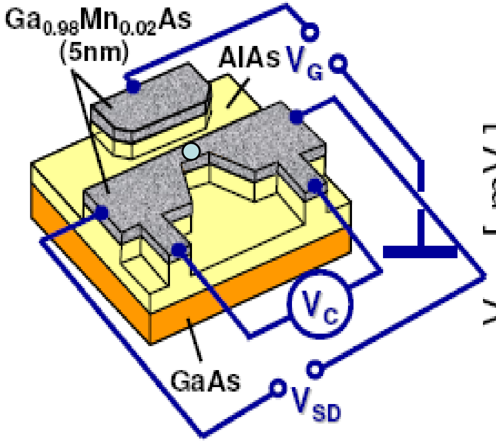
Coulomb blockade AMR

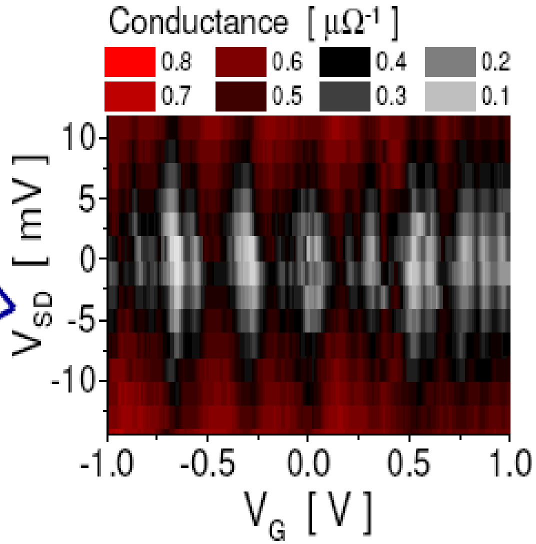
Spintronic transistor - magnetoresistance controlled by gate voltage

Single-electron FET

Narrow channel SET

dots due to disorder potential fluctuations





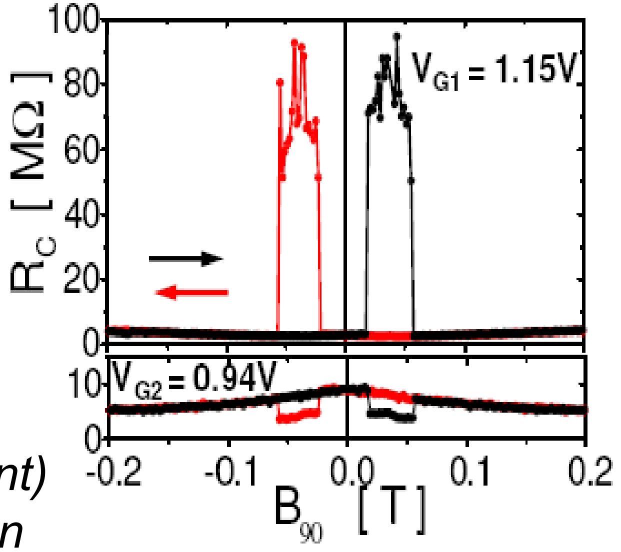
CB oscillations

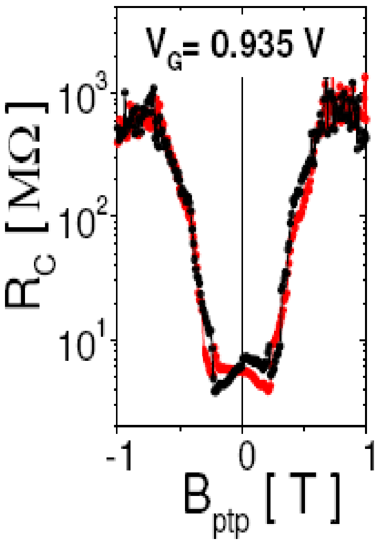
low V_{sd} → blocked due to SE charging

Huge hysteretic low-field MR

Sign & magnitude tunable by small gate valtages

spin-coherent (resonant) tunneling unlikely origin





Strong dependence on field angle

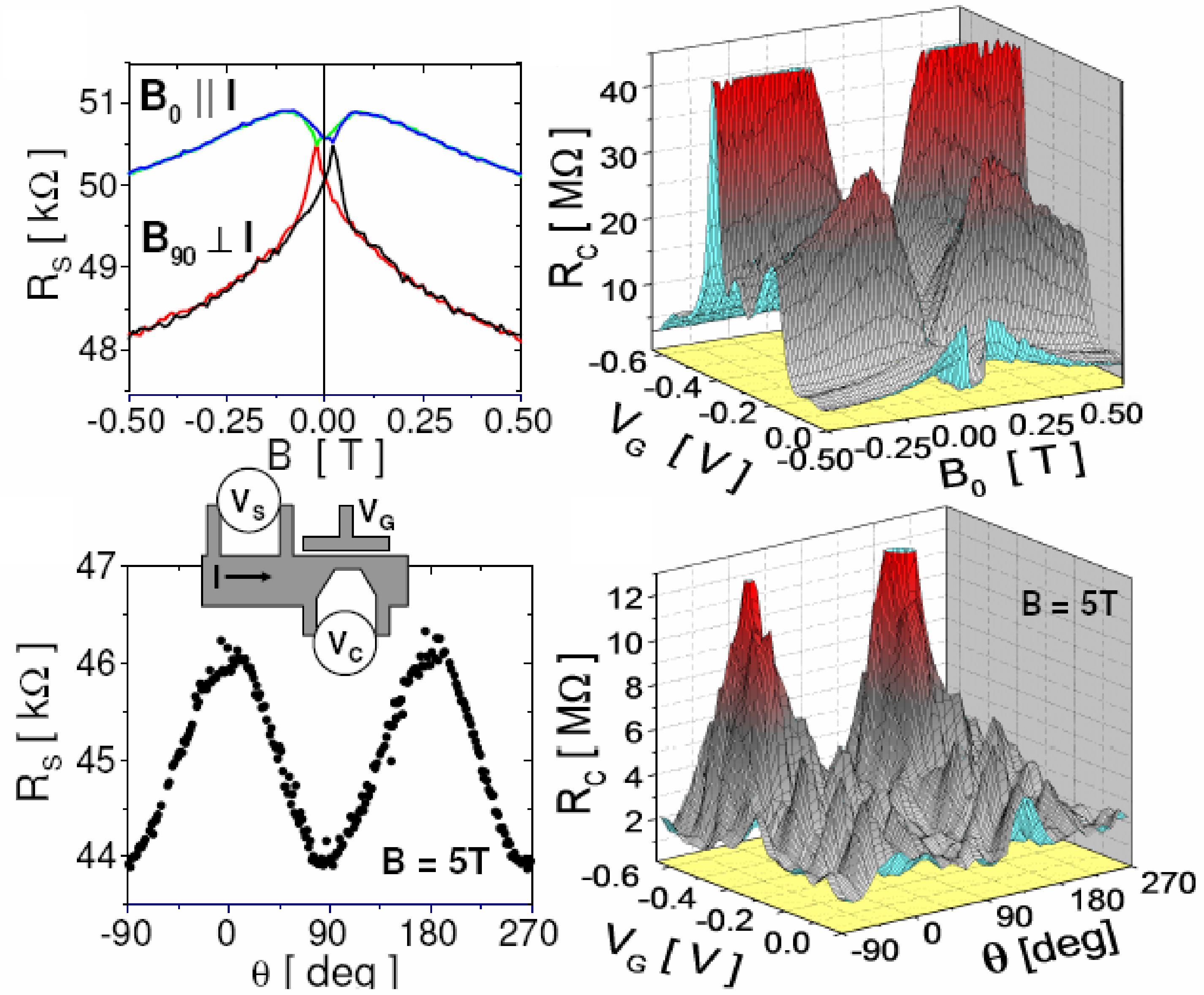
→hints to AMR origin

Wunderlich, Jungwirth, Kaestner et al., cond-mat/0602608

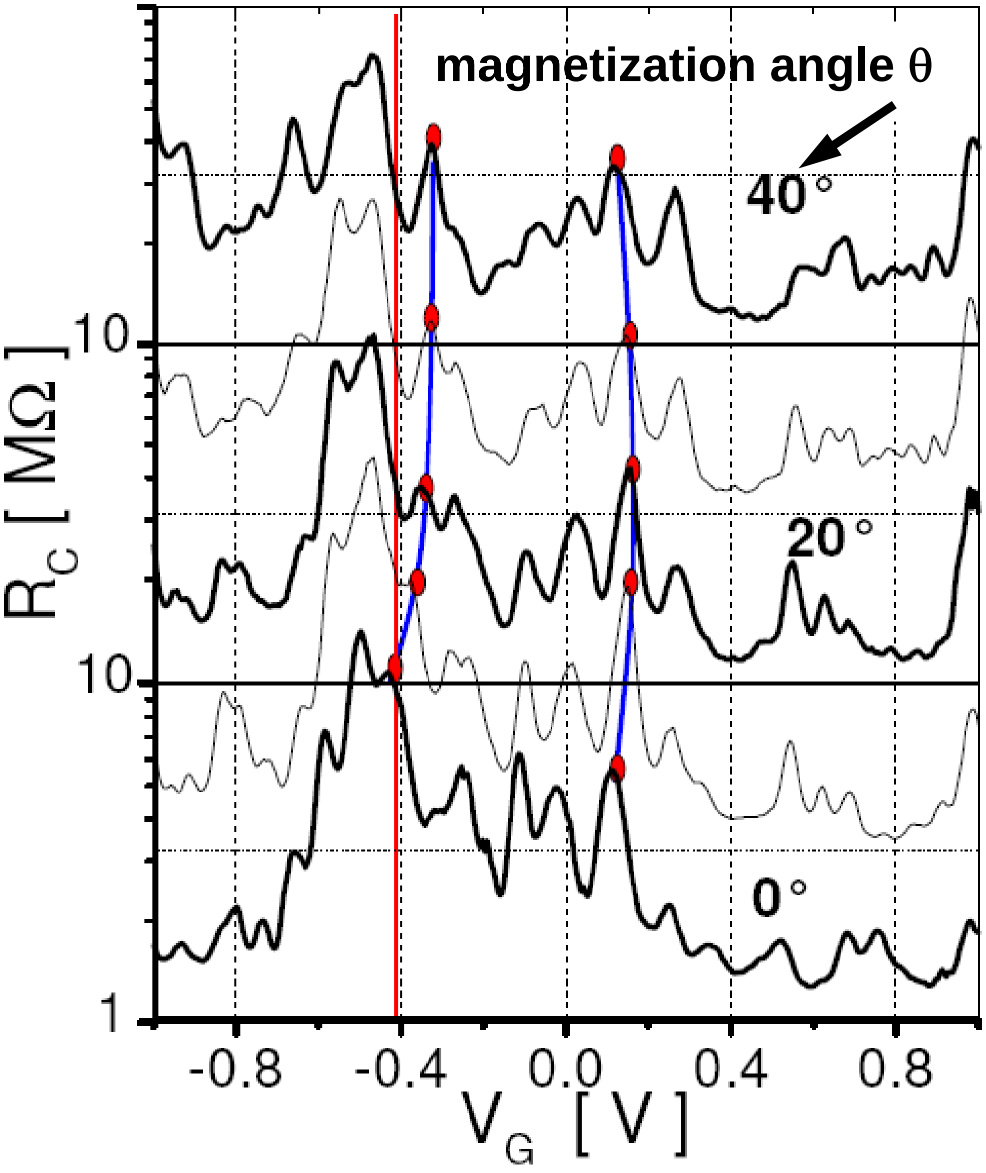
AMR nature of the effect

normal AMR

Coulomb blockade AMR



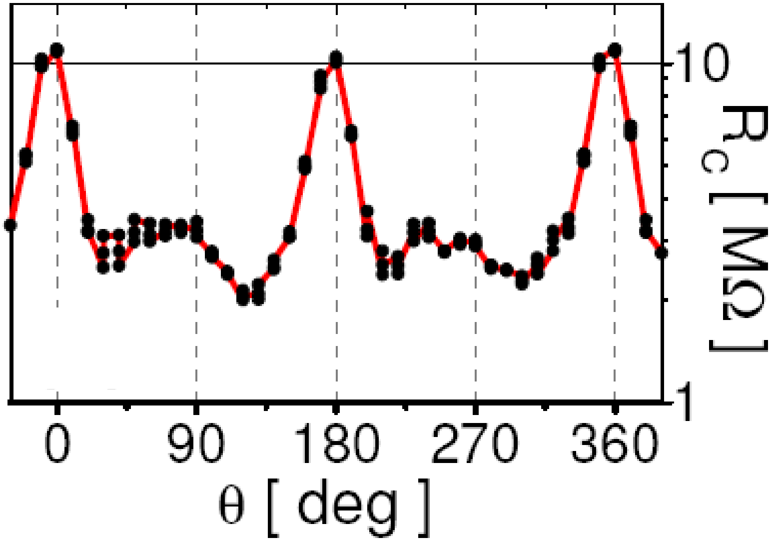
CB oscillation shifts by magnetication rotations



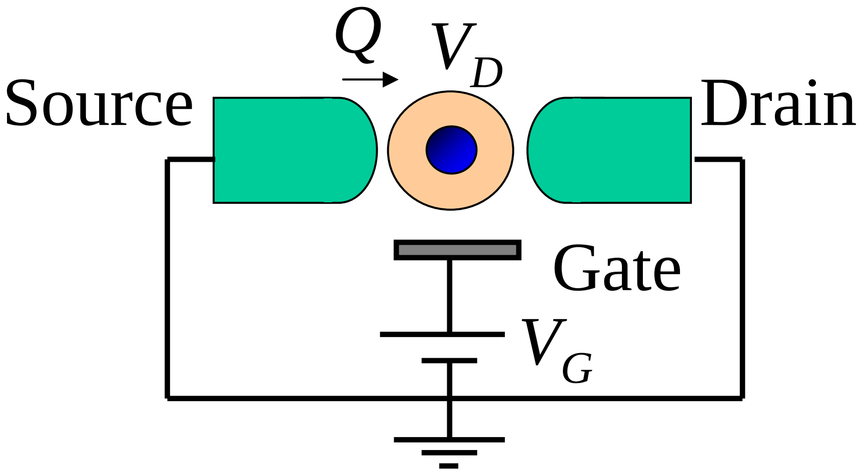
At fixed Vg peak → valley
or valley → peak

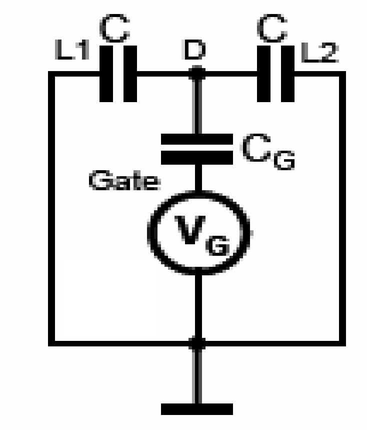
↓

MR comparable to CB
negative or positive MR(V_g)



Microscopic origin





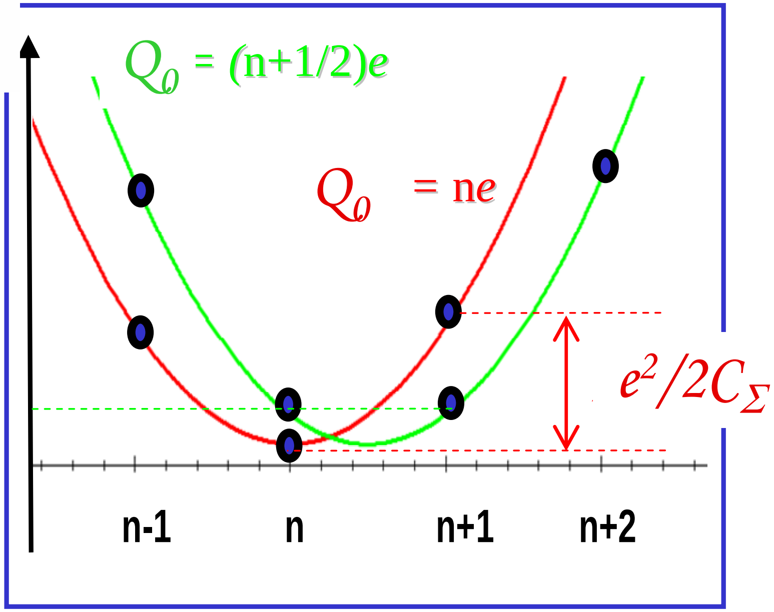
- $V_g = 0$

$$U = \int_0^Q dQ' V_D(Q')\ \&\ V_D = Q/C_\Sigma \rightarrow U = \frac{Q^2}{2C_\Sigma}$$

$\frac{e^2}{2C_\Sigma} > k_B T$ → Coulomb blockade

- $V_g \neq 0$

$$U = \frac{(Q+Q_0)^2}{2C_\Sigma}\ \&\ Q_0 = C_G V_G$$



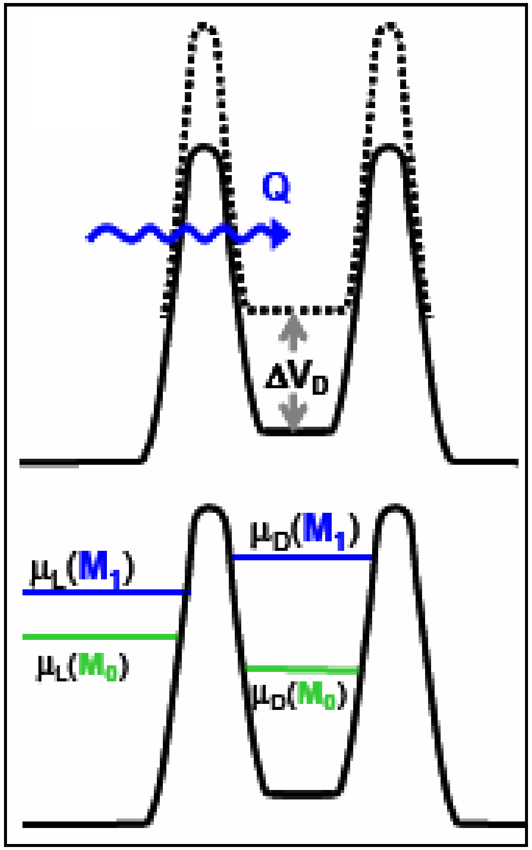
$Q=ne$ - discrete
$Q_0=C_gV_g$ - *continuous*

$Q_0=-ne$ → blocked

$Q_0=-(n+1/2)e$ → open

Spin-orbit coupling →

chemical potential depends on $\vec{M}$



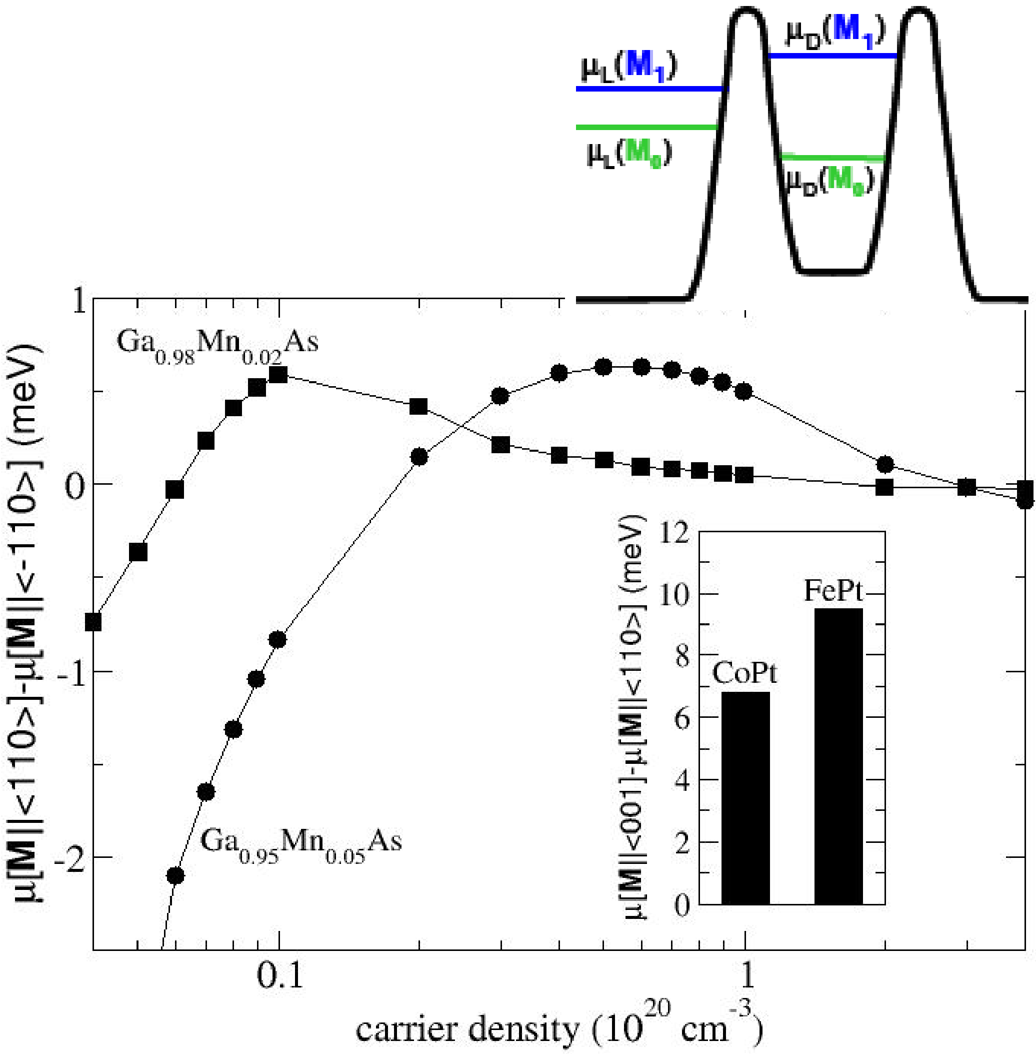
If lead and dot different
(different carrier concentrations in our (Ga,Mn)As SET)

$$U = \int_0^Q dQ' V_D(Q') + \frac{Q\Delta\mu(\vec{M})}{e} \ \& \ \Delta\mu(\vec{M}) = \mu_L(\vec{M}) - \mu_D(\vec{M})$$

$$U = \frac{(Q+Q_0)^2}{2C_\Sigma} \ \& \ Q_0 = C_G[V_G + V_M(\vec{M})] \ \& \ V_M = \frac{\Delta\mu(\vec{M})}{e}\frac{C_\Sigma}{C_G}$$

electric & magnetic

control of Coulomb blockade oscillations

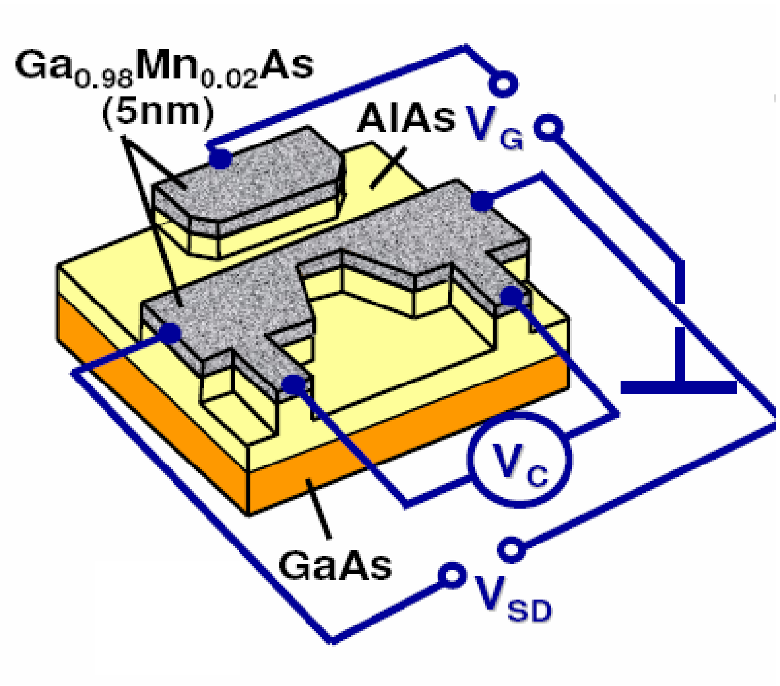


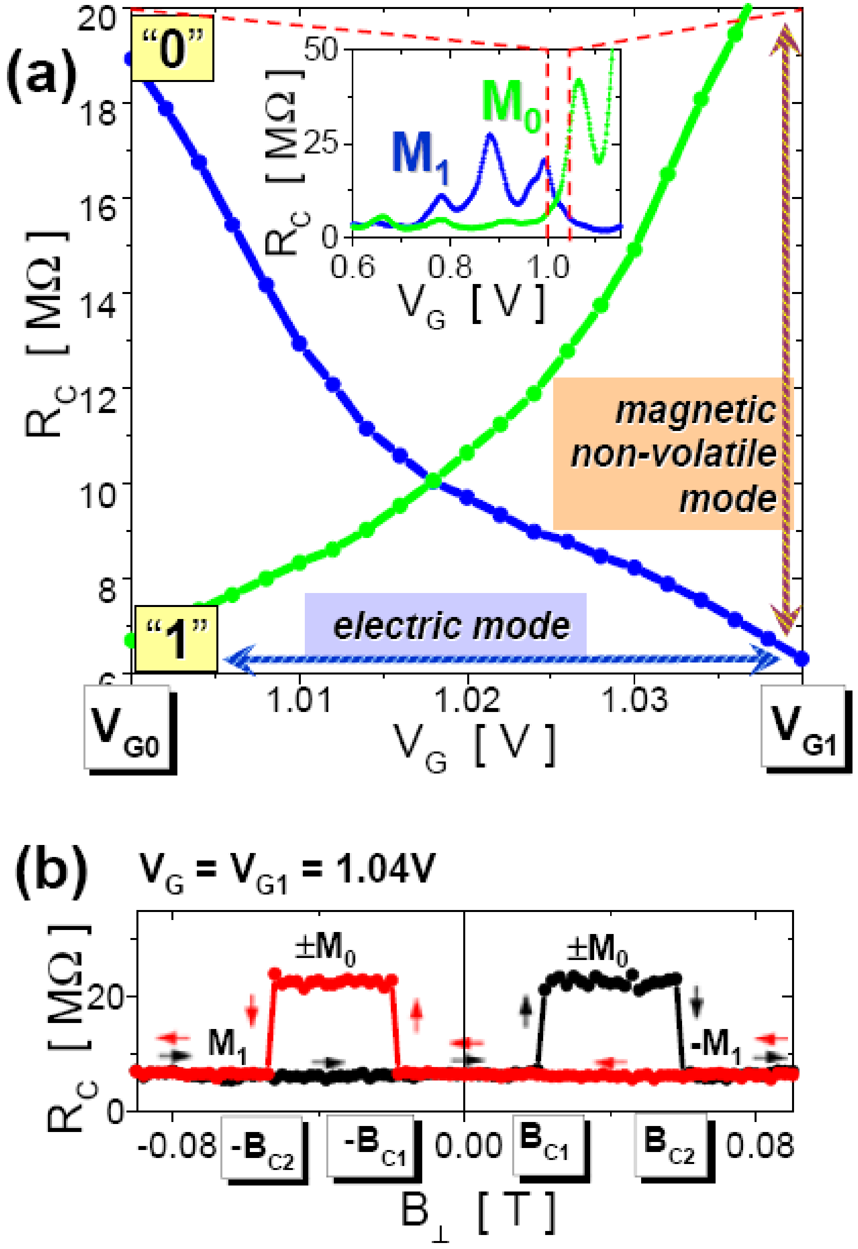
- CBAMR if change of $|\Delta\mu(\mathbf{M})| \sim e^2/2C_\Sigma$

occurs when anisotropy of band-structure derived parameter comparable to independent energy scale (single-electron charging) → distinct from all other AMRs

- In (Ga,Mn)As ~ meV (~ 10 Kelvin)

- In room-T ferromagnet change of $|\Delta\mu(\mathbf{M})|$~100K





- Combines electrical transitor action with permanent storage
- n-type or p-type FET characteristic switched by magnetization rotation