Diluted (ferro-) magnetic semiconductors: An overview

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- Why diluted magnetic semiconductors?
- Materials classes
- Experimental results
- Important aspects for theory
- Modelling of DMS
- Exotic quantum order

Why diluted magnetic semiconductors?

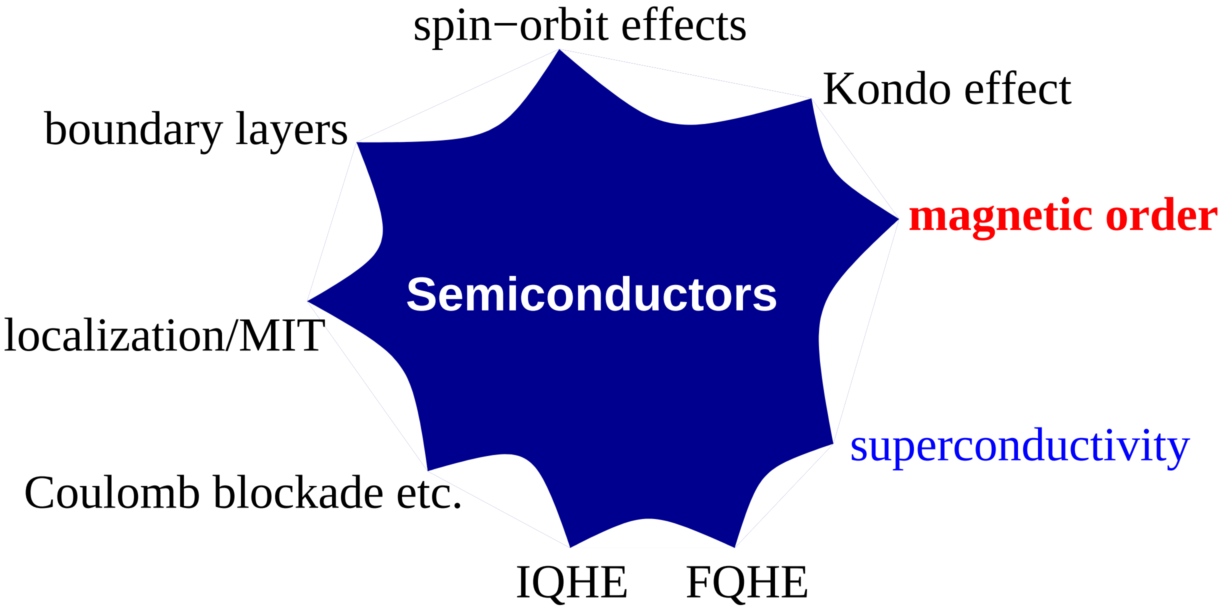
- applications in spintronics [Žutić *et al*., RMP **76**, 323 (2004)]:
  integration of data storage and processing
- fundamental physics:

Control of magnetism

- doping
- gate voltage (FET)

Vision:
control of positions and interactions of moments

Universal "physics construction set"



spin−orbit effects

Kondo effect

magnetic order

superconductivity

FQHE

IQHE

Coulomb blockade etc.

localization/MIT

boundary layers

Semiconductors

Vision:
new effects due to competition of old effects

Materials classes: Ferromagnetic semiconductors

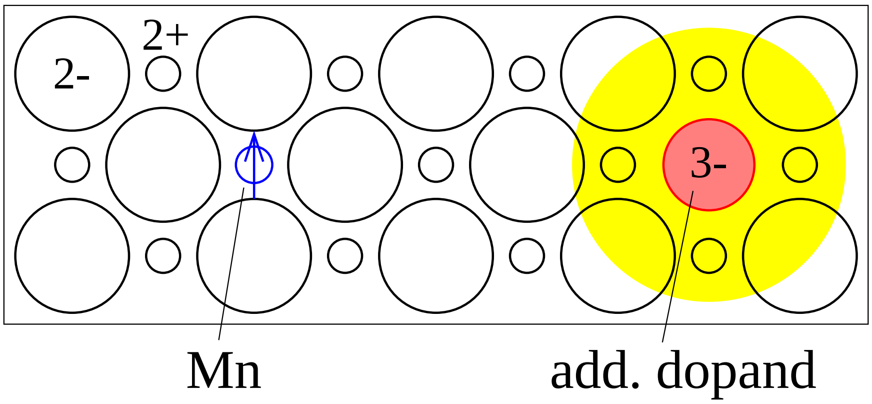
Non−diluted	**Diluted magnetic semiconductors**			
Eu−chalcogenides	II−VI	III−V	group IV	oxides
e.g. $Eu_{1-x}Gd_xS$	$Be_{1-x}Mn_xTe$	$Ga_{1-x}Mn_xAs$ $In_{1-x}Mn_xAs$ $Ga_{1-x}Mn_xN$	$Ge_{1-x}Mn_x$	$Zn_{1-x}Co_xO$
n−type	isovalent	p−type	p−type	isovalent/n−type
T_c ~ 80K	(2.5 K)	160K 333K ? > 750K ?	116K	> 300K ?
not carrier−mediated	modulation doping	compensation	strongly insulating	
regular spin array	disordered spin positions			

“independent” control of carrier/spin density and potential/spin scattering

Diluted magnetic semiconductors with Mn (Fe, Co)

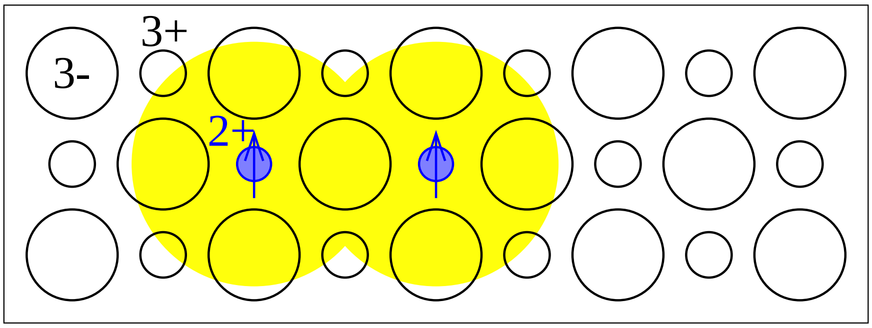
- valence Mn^{2+}
- half-filled d shell → spin $5/2$
- carriers mediate magnetic interaction

II-VI semiconductors with Mn: isovalent



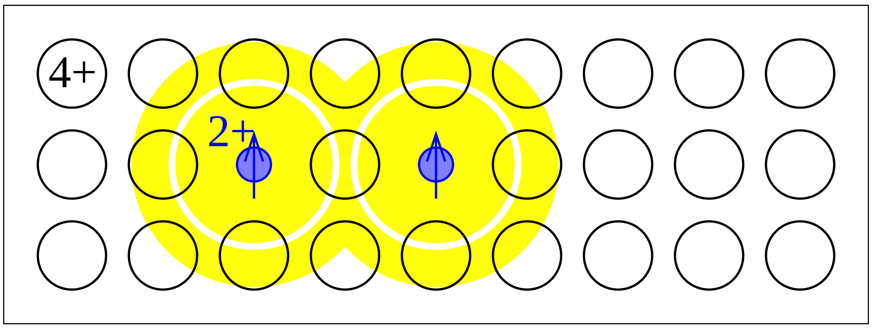
$T_c \approx 0$

III-V semiconductors with Mn: acceptor



$T_c > 160\,\mathrm{K}$

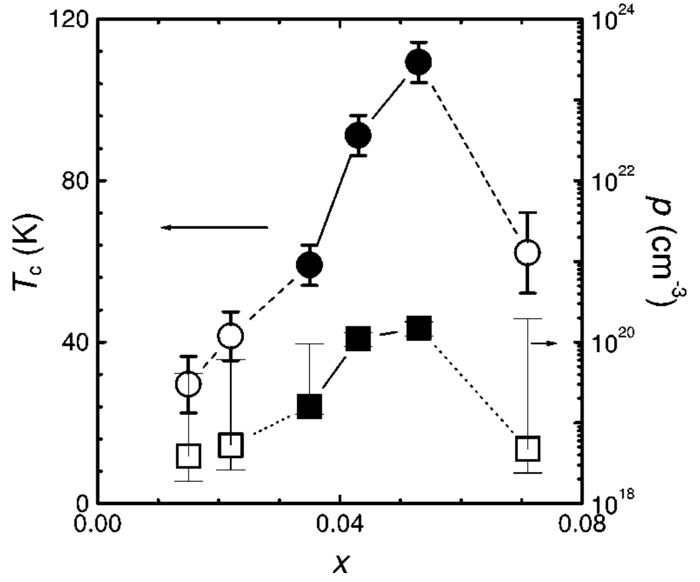
group IV semiconductor Ge with Mn: double acceptor



$T_c \approx 116\,\mathrm{K}$

Experimental results on DMS: $(\mathrm{Ga}, \mathrm{In}, \mathrm{Mn})\mathrm{As}$

- $\mathrm{Ga}_{1-x}\mathrm{Mn}_x\mathrm{As}$: $T_c > 100\ \mathrm{K}$ and MIT



Matsukura *et al.*, PRB **57**, R2037 (1998)

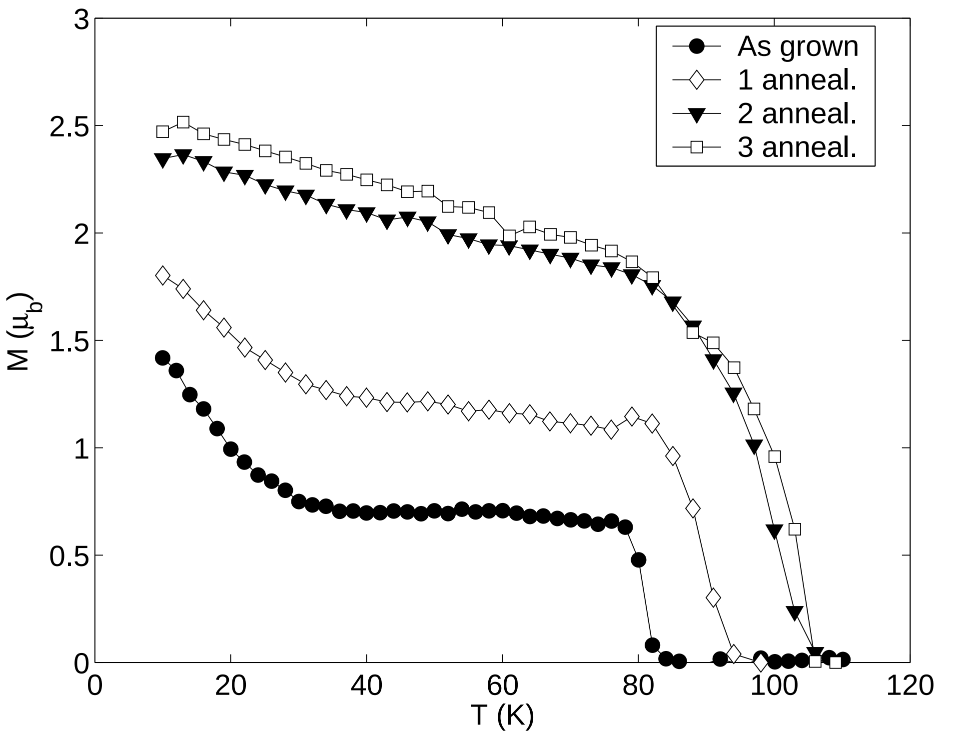
- $T_c \gtrsim 160\ \mathrm{K}$ due to reduced concentration of compensating As antisites

Ku *et al.*, APL **82**, 2302 (2003);

Edmonds *et al.*, PRL **92**, 037201 (2004)

- then always metallic

- concave–convex crossover of $M(T)$



Mathieu *et al.*, PRB **68**, 184421 (2003)

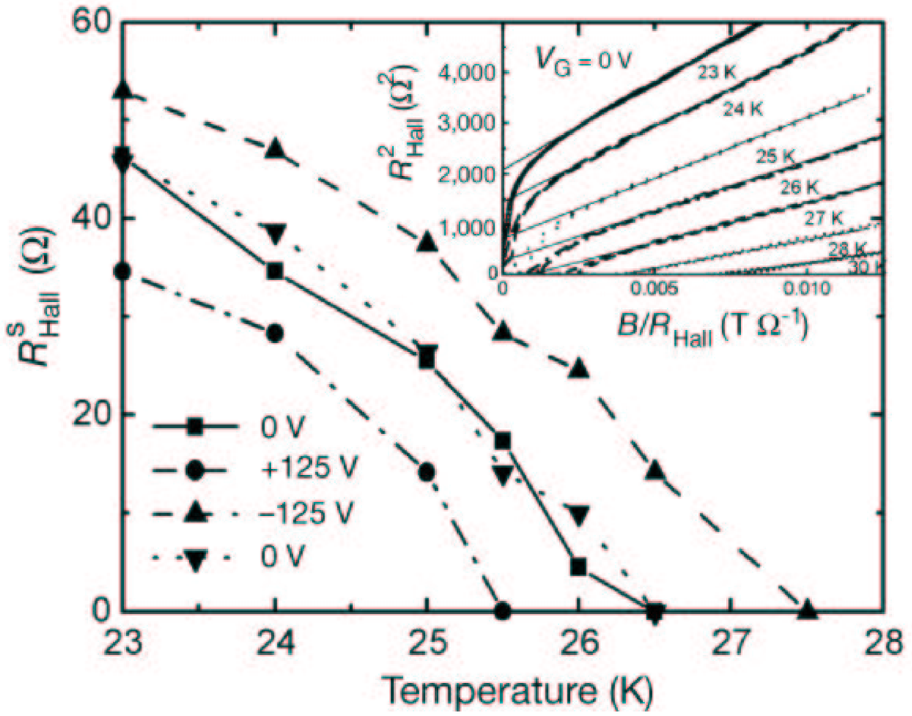
- T_c highest for thin films (Ku *et al.*)

- T_c decreases for capped films

Stone *et al.*, APL **83**, 4568 (2003)

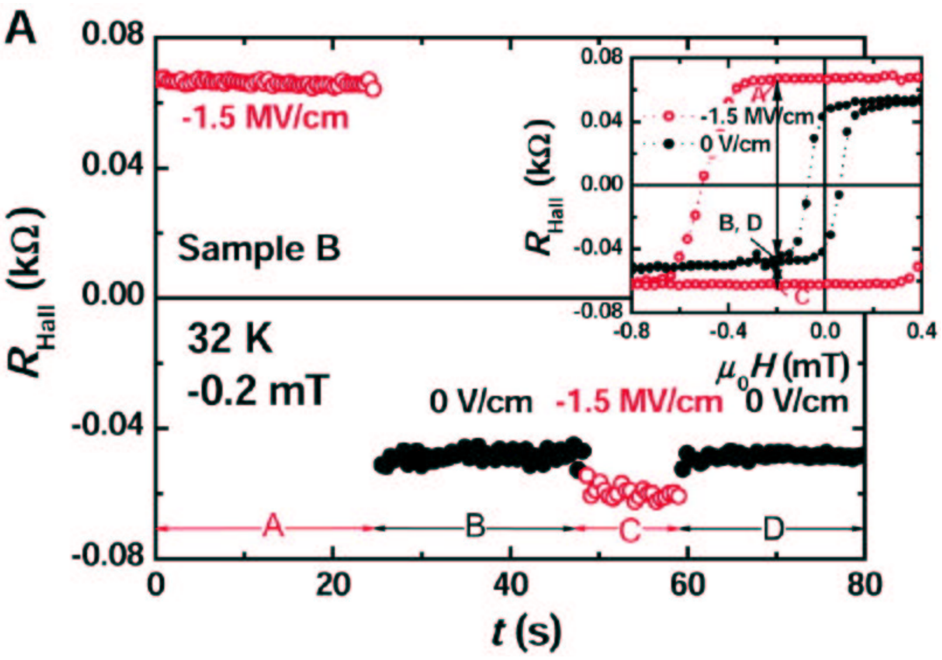
Control of ferromagnetism: gate doping of $\mathrm{In}_{1-x}\mathrm{Mn}_{1-x}\mathrm{As}$

control of T_c:



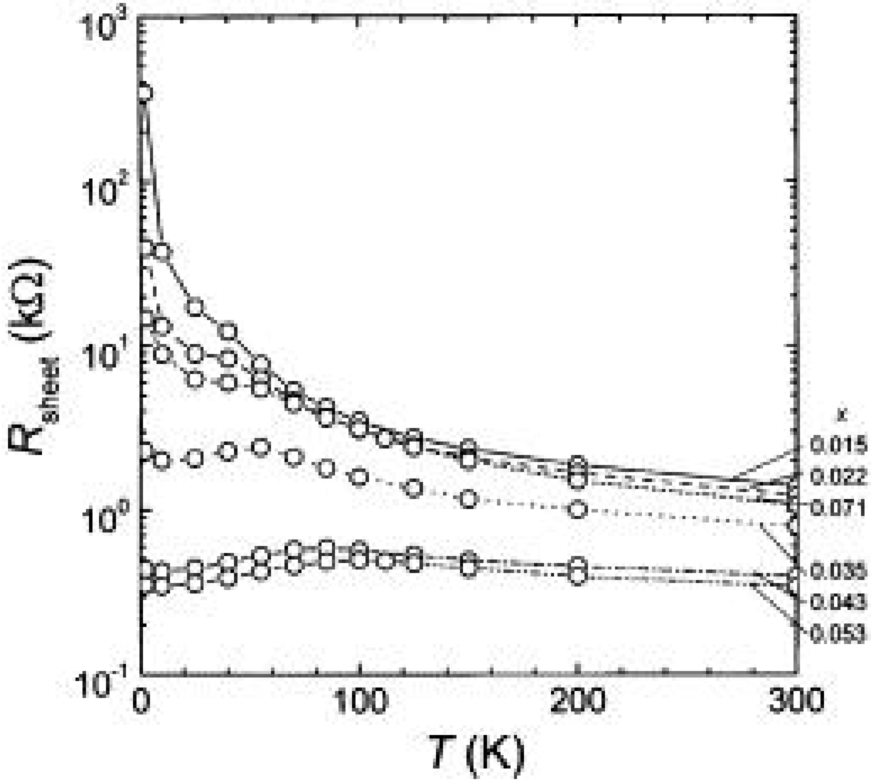
Ohno *et al.*, Nature **408**, 944 (2000)

voltage-induced magnetization reversal:



Chiba *et al.*, Science **301**, 943 (2003)

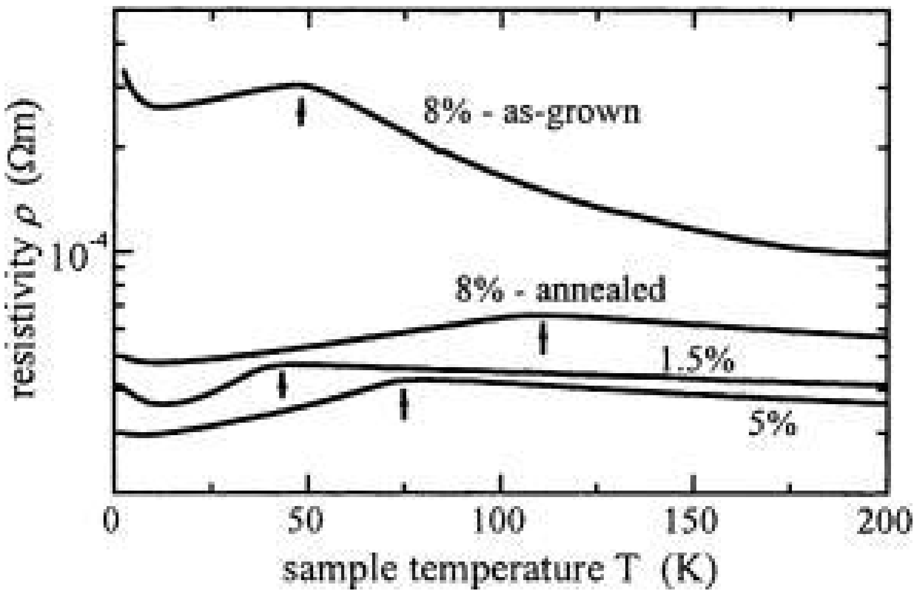
- metal-insulator transition for $T \to 0$



x: Mn concentration in $\mathrm{Ga}_{1-x}\mathrm{Mn}_x\mathrm{As}$

H. Ohno, JMMM **200**, 110 (1999)

- robust resistivity maximum at T_c



Edmonds *et al.*, APL **81**, 3010 (2002)

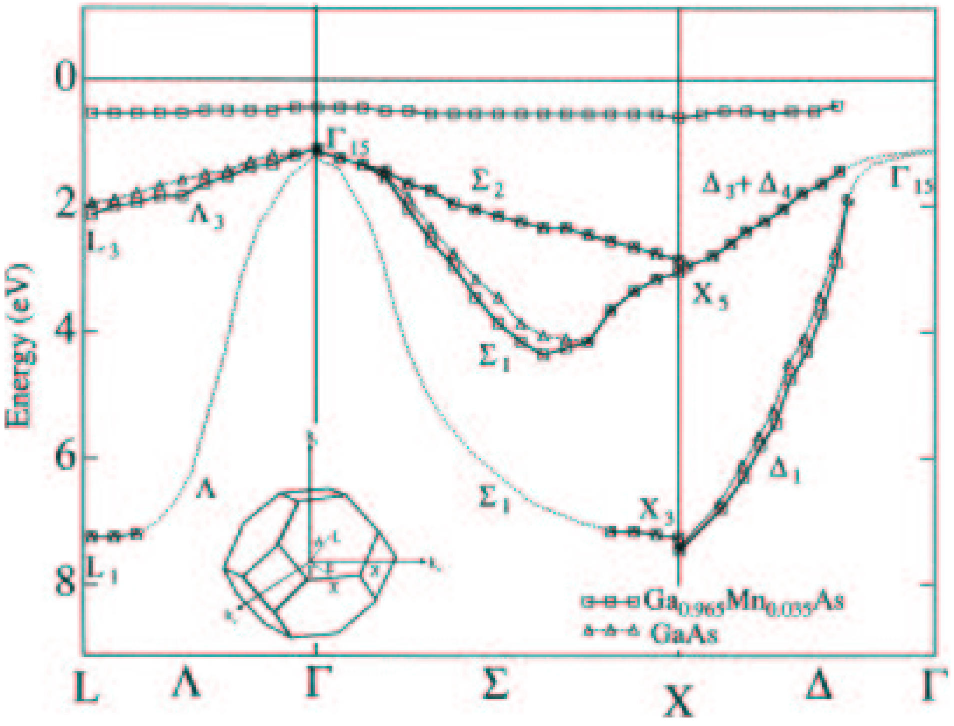
- no colossal magnetoresistance:
  no double exchange

- cyclotron resonance:
  many effective-mass-type holes
  Matsuda *et al.*, cond-mat/0404635

Defects: substitutional Mn, interstitial Mn, As antisites

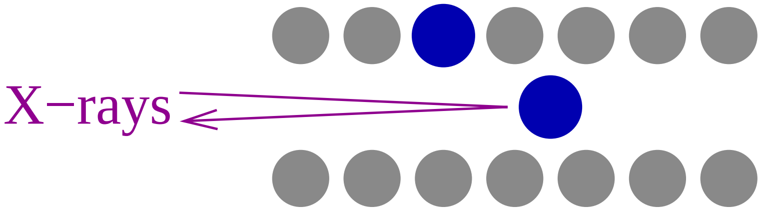
- isolated $\mathrm{Mn_{Ga}}$: $d^5 +$ shallow acceptor

  $\mathrm{Ga}_{1-x}\mathrm{Mn}_x\mathrm{N}$: deep d-rich acceptor
- antiferromagnetic hole-Mn exchange
- what happens for heavy doping?



PE: Okabayashi *et al.*, Physica E **10**, 192 (2001)

- low-T MBE creates As antisites
- antisites are double donors
  $\rightarrow$ compensation
- antisites reduced by $\mathrm{As_4}$ cracking
- Rutherford backscattering:
  $\sim 17\%$ of Mn in interstitial positions
  Yu *et al.*, PRB **65**, 201303(R) (2002)

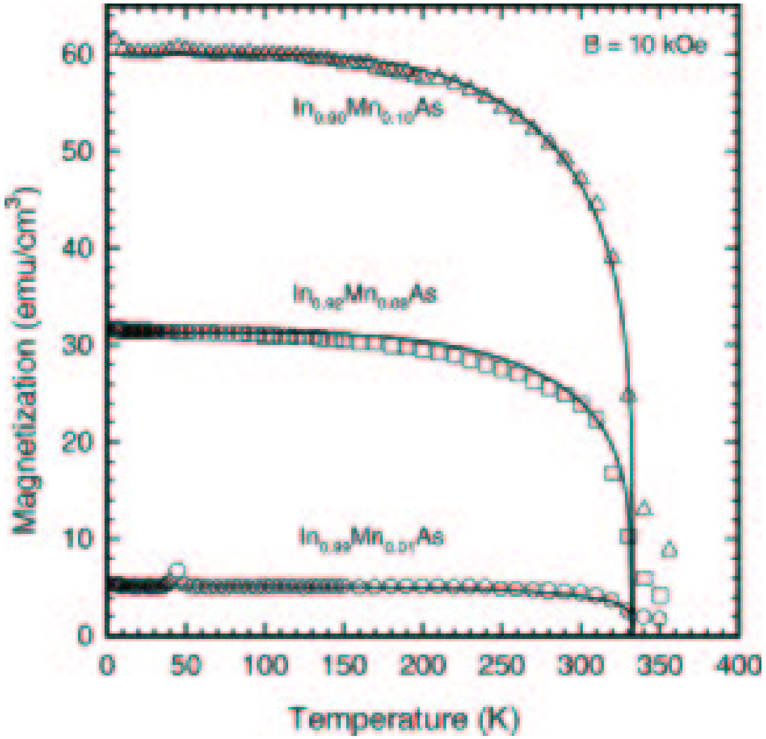


- X-ray absorption: interstitials move to surface upon annealing, reduce ferromagnetism there (Dürr *et al.*)

Experimental results on other DMS

The hunt for higher T_c:

$\mathrm{In}_{1-x}\mathrm{Mn}_x\mathrm{As}$ grown by MetalOrganic Vapor Phase Epitaxy



Blattner & Wessels, Appl. Surf. Sci. **221**, 155 (2004)

- no observable MnAs precipitates
- strange: T_c independent of x
- attributed to Mn dimers...

Important aspects for theory

- strong potential scattering
  → importance of compensation
  and defect distribution

- (weaker) exchange scattering

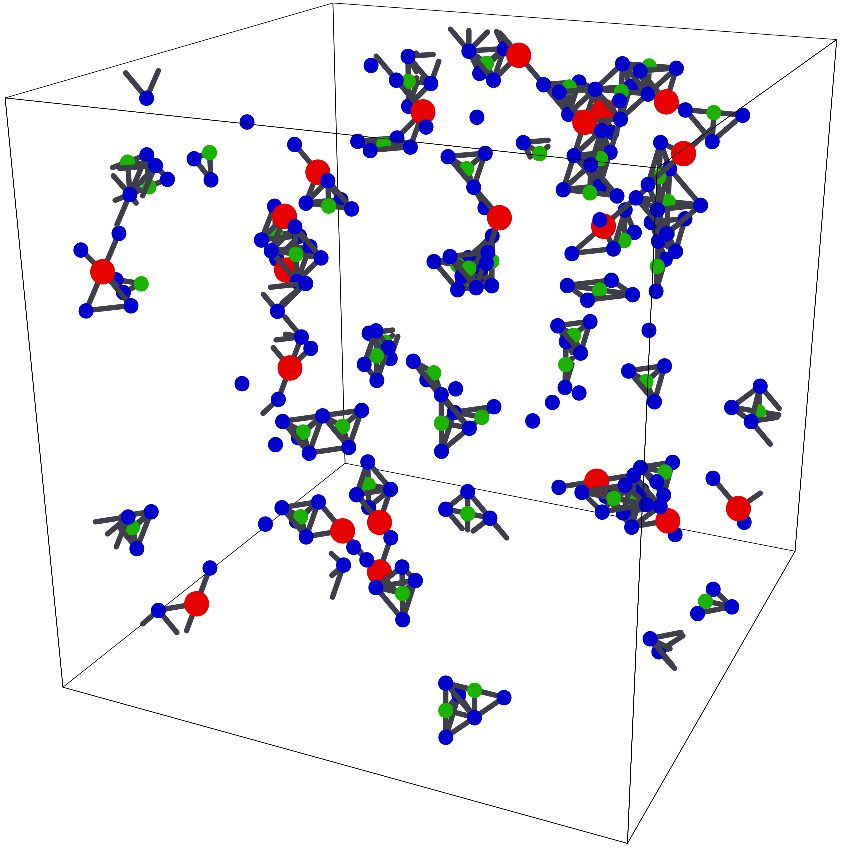
- spin-orbit coupling (p-type)
  - band structure
  - intrinsic anomalous Hall effect
    Jungwirth *et al.*, PRL **88**, 207208 (2002)
  - non-magnetic semiconductors:
    dissipationless spin-Hall current
    Sinova *et al.*, PRL **92**, 126603 (2004);
    Murakami *et al.*, Science **301**, 1348 ('03)

- nature of impurity states
  (low → high doping)

- carrier $\lesssim$ impurity concentration
  → not Kondo

MC simulation
of defect configurations

Timm *et al.*, PRL **89**, 137201 (2002)
Timm, J. Phys.: CM. **15**, R1865 (2003)



cluster formation, ionic screening

Modelling of DMS

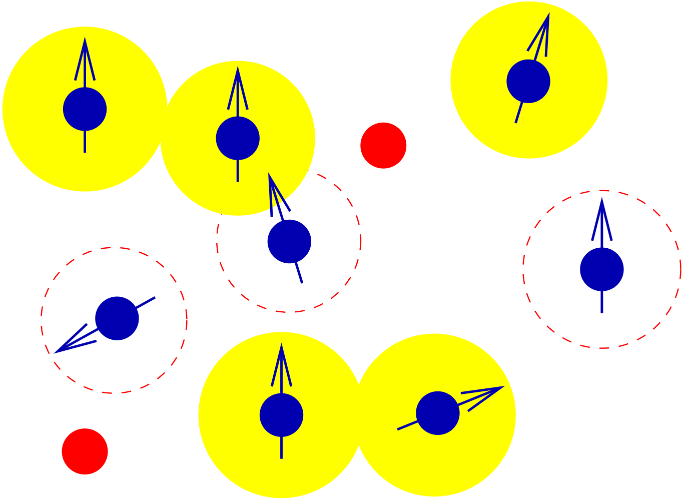
(1) Low doping

- hopping between impurity states

  Berciu & Bhatt, PRL **87**, 107203 (2001)
- percolation

  e.g. Kaminski & Das Sarma, PRL **88**, 247202 (2002); PRB **68**, 235210 (2003)
- only for very small doping

  Timm *et al.*, PRL **90**, 029701 (2003)
- ferromagnetic order?



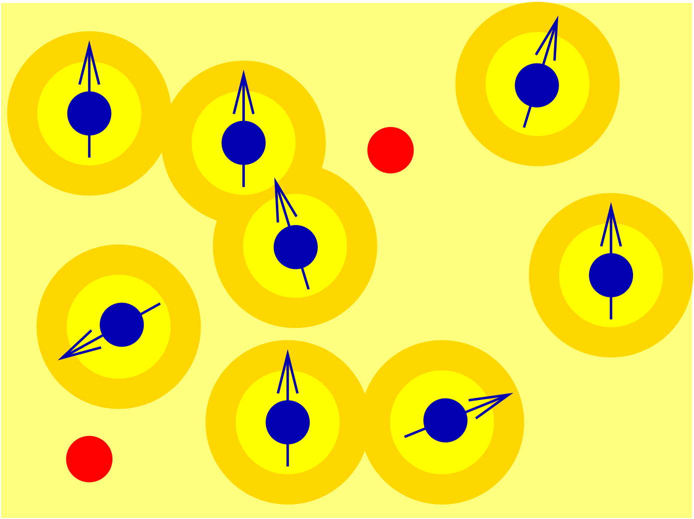
(2) High doping

- Zener model:
  – (impurity or valence) bands
  – hole-impurity exchange J_{pd}

  Dietl *et al.*, PRB **55**, R3347 (1997)

$$k_B T_c \propto J_{pd}^2 \, N(E_F) \, n_{\text{impurities}}$$

- potential scattering
- RKKY-type effective interaction



Modelling of DMS—high doping

Description of band structure

- effective mass
- Kohn-Luttinger $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian

$$\left[\frac{p^2}{2m} + V(\mathbf{r}) + \frac{\mathbf{k}\cdot\mathbf{p}}{m}\right] u_{\mathbf{k}n}(\mathbf{r}) = \left(\epsilon_{\mathbf{k}n} - \frac{k^2}{2m}\right) u_{\mathbf{k}n}(\mathbf{r})$$

expand in $\mathbf{k}\cdot\mathbf{p}$ to order k^2

- Slater-Koster TB Hamiltonian

Tang & Flatté, PRL **92**, 047201 (2004);
Timm & MacDonald, cond-mat/0405484

$$H = \sum_{\mathbf{k}\alpha\alpha'\sigma\sigma'} \epsilon_{\alpha\sigma;\alpha'\sigma'}(\mathbf{k})\, c^\dagger_{\mathbf{k}\alpha\sigma} c_{\mathbf{k}\alpha'\sigma'}$$

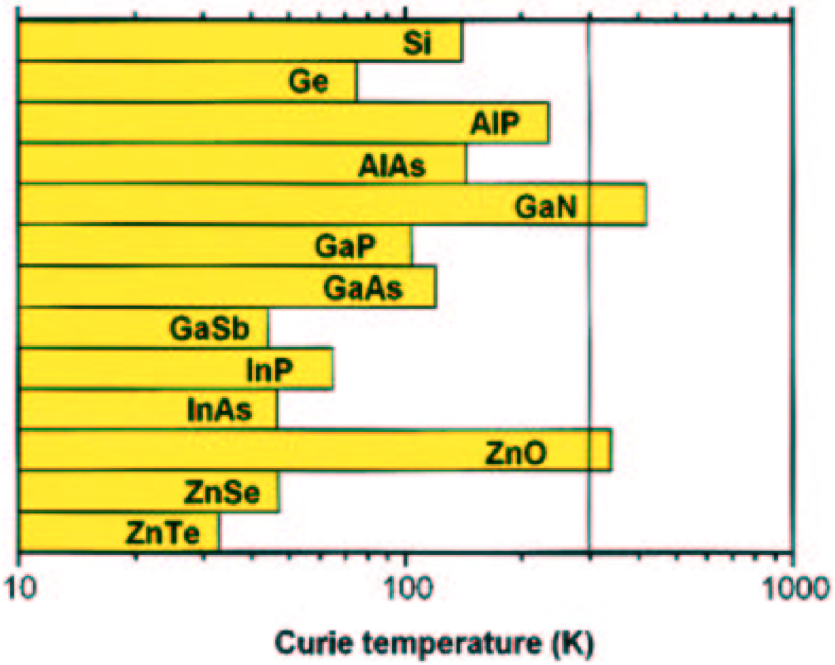
fit $\epsilon_{\alpha\sigma;\alpha'\sigma'}(\mathbf{k}) \longrightarrow$ valid for all $\mathbf{k}$

Zener model

$$H = H_{\text{bands}} - J_{pd} \sum_{\text{impurities}\, i} \mathbf{s}_i \cdot \mathbf{S}_i$$

+ mean-field approximation

T_c from 6-band KL model:

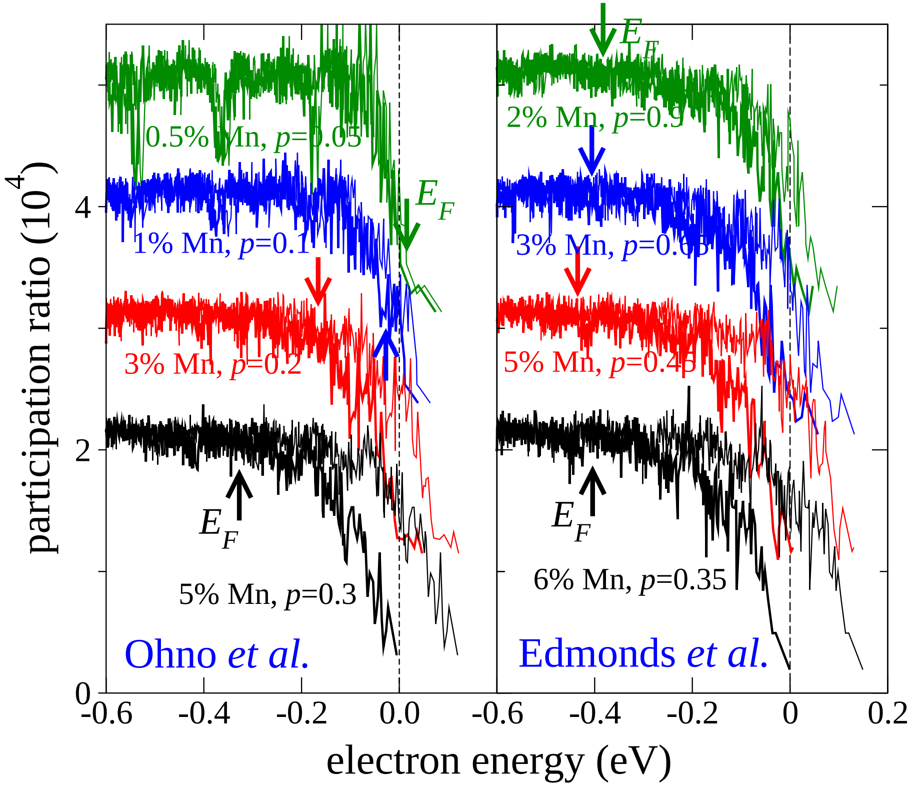


Dietl *et al.*, Science **287**, 1019 (2000)

Importance of potential scattering

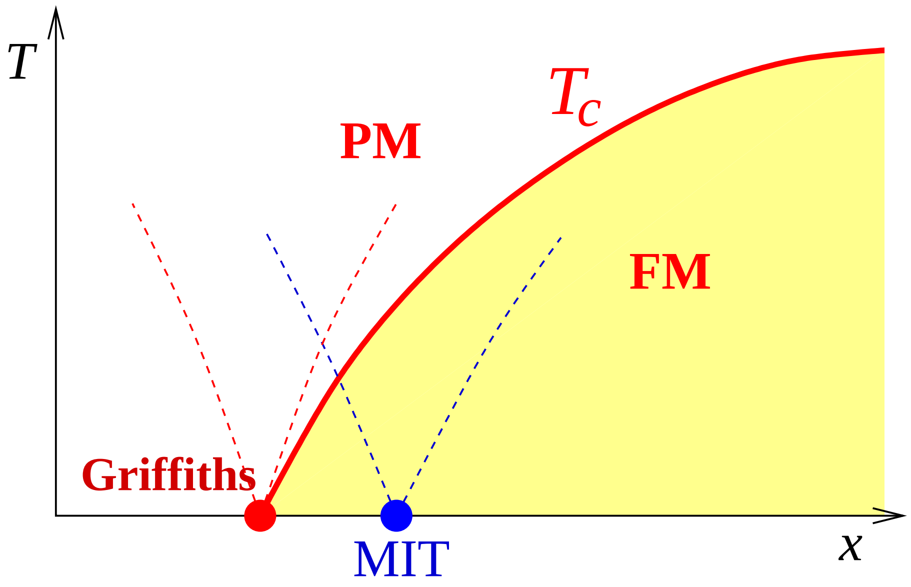
Charged defects + weak screening
→ strong potential scattering
→ localization, MIT

localization for annealed defects:



Timm, J. Phys.: CM. **15**, R1865 (2003)

Quantum critical points



- $T_c(x)$ is continuous in x due to long localization length
- rare ordered regions: Griffiths-McCoy singularities
  Galitski *et al.*, PRL **92**, 177203 (2004)
- interplay of QCP's
- MIT in impurity or merged bands?

Effects of spin-orbit coupling in DMS

- anomalous Hall effect: $\mathbf{E}_{\mathrm{AH}} \propto \mathbf{E} \times \mathbf{S}$
  - skew scattering (disorder)
  - side-jump scattering (disorder)
  - Berry phases

$$\dot{\mathbf{r}}_c \equiv \frac{d}{dt} \langle \Psi | \hat{\mathbf{r}} | \Psi \rangle = \frac{\partial \epsilon}{\partial \mathbf{k}} + e\, \mathbf{E} \times \boldsymbol{\Omega}$$

$\vert\Psi\rangle$	wave packet
$\boldsymbol{\Omega}$	$\mathbf{k}$-space Berry curvature

Ferromagnetic phase, $T < T_c$, $\mathbf{B} = 0$:

$$\langle U_{\mathrm{AH}} \rangle \propto E \, \langle S_z \rangle$$

Jungwirth *et al.*, PRL **88**, 207208 (2002)

Paramagnetic phase, $T > T_c$, $\mathbf{B} = 0$:

$$\langle U_{\mathrm{AH}}(t)\, U_{\mathrm{AH}}(0) \rangle \propto E^2 \, \langle S^z(t)\, S^z(0) \rangle$$

→ noise related to spin susceptibility

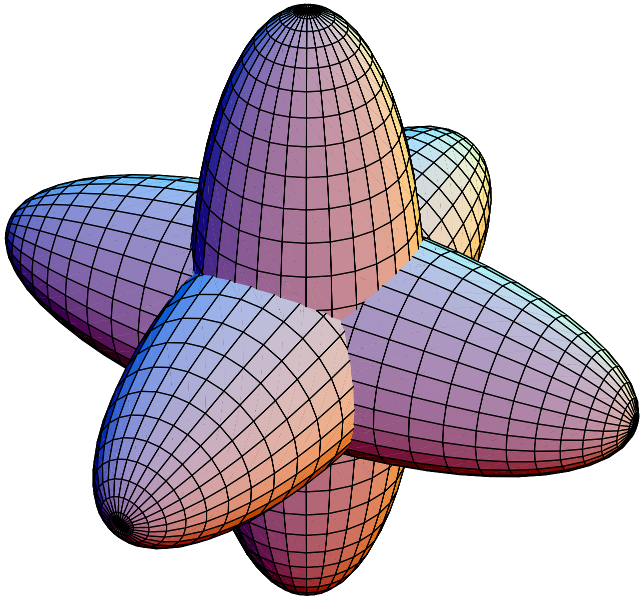
Timm *et al.*, PRB **69**, 115202 (2004)

- anisotropic spin diffusion

semiclassical Boltzmann equation

→ hole-magnetization density $\boldsymbol{\mu}_h$

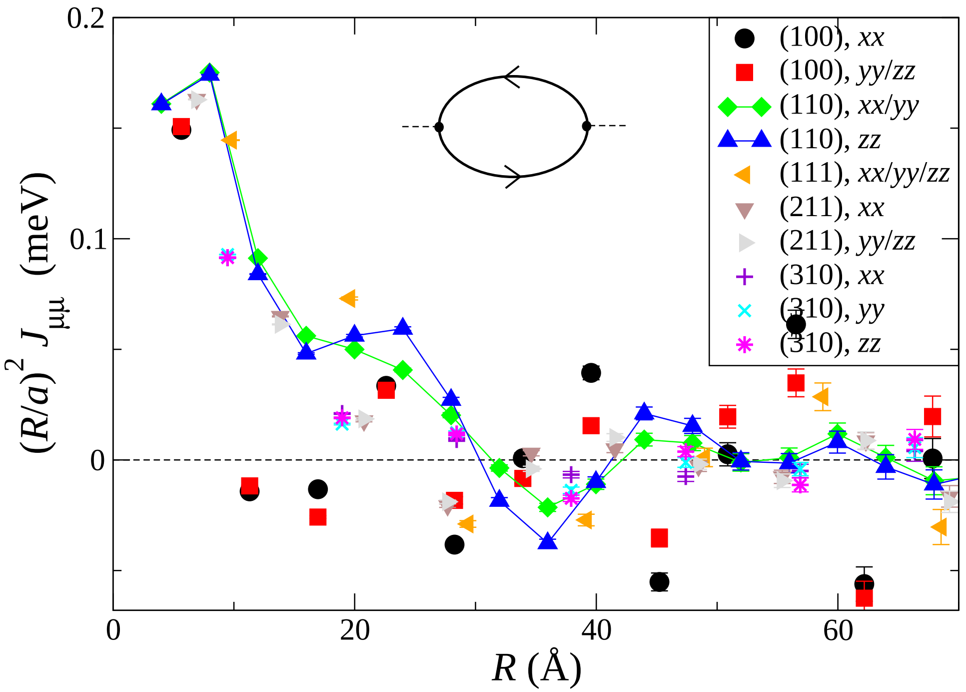
$$\frac{\partial \mu_h^z}{\partial t} = \left[-\frac{1}{\tau_s} + D \left(\mathbf{\frac{1}{5}} \frac{\partial^2}{\partial x^2} + \mathbf{\frac{1}{5}} \frac{\partial^2}{\partial y^2} + \mathbf{\frac{3}{5}} \frac{\partial^2}{\partial z^2} \right) \right] \times \left(\mu_h^z - \frac{\chi_{\mathrm{Pauli}}}{3} B_h \right) + \frac{1}{\tau_s'} \left(\mu_i^z - \chi_{\mathrm{Curie}} B_i \right)$$



Magnetic interaction between impurities

(a) RKKY interaction $-J_{\mu\nu}(\mathbf{R})\, S_1^\mu\, S_2^\nu$

- anisotropic J_{pd} & band structure
  → anisotropic in real space
- spin-orbit coupling
  → anisotropic in spin space



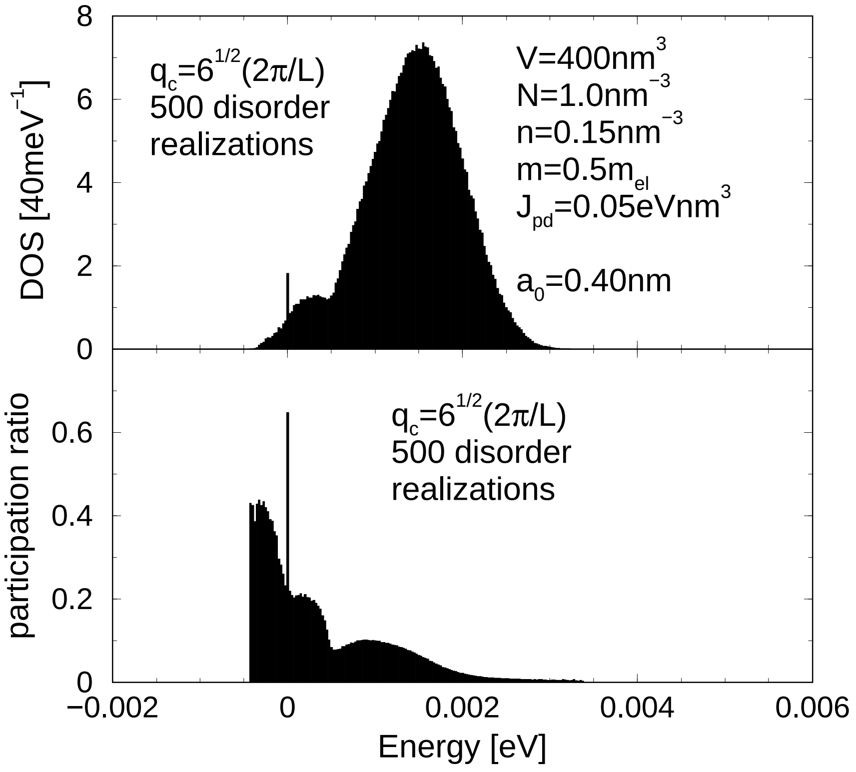
Timm & MacDonald, cond-mat/0405484

(b) NN superexchange

(c) multi-spin interactions: small

lead to frustration → non-collinear magnetization. . . but not much

Timm & MacDonald, Fiete *et al.*



Schliemann & MacDonald, PRL **88**, 137201 (2002)

Exotic quantum order

(a) Fundamental aspects

- interplay of QCP's
- Griffiths-McCoy singularities
- disorder vs. magnetism
- spin-orbit effects & local moments

(b) Practical aspects

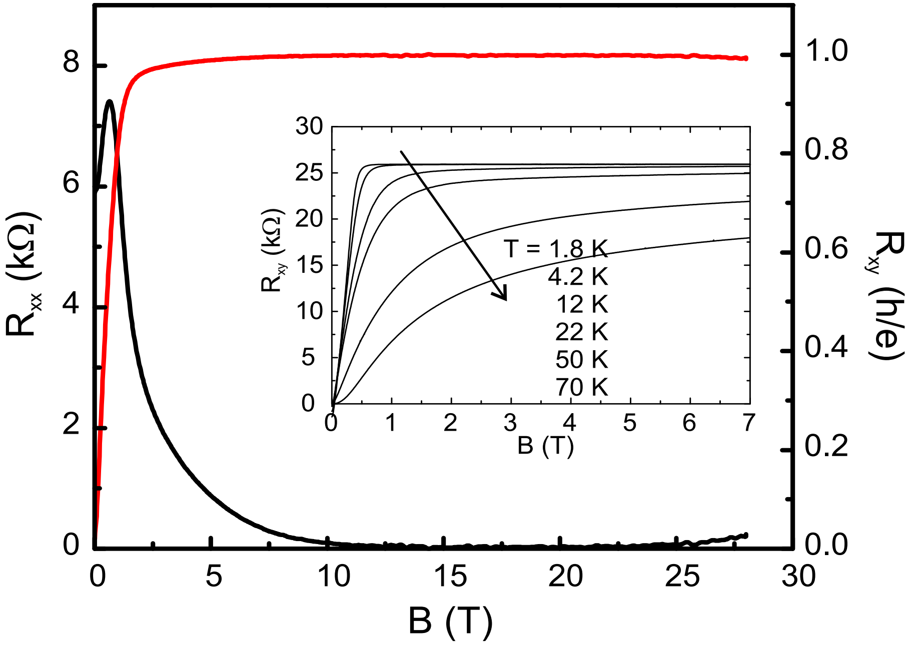
- tuneable carrier concentration
- tuneable magnetic interaction

(c) Device aspects

- carrier-spin polarizer/analyzer:
  current $\longrightarrow$ magnetization reversal
  Moriya *et al.*, cond-mat/0404663
- QHE in II-VI DMS $\mathrm{Hg}_{1-x}\mathrm{Mn}_x\mathrm{Te}$

– nearly B-independent spin splitting of Landau levels

– long $\nu = 1$ plateau for low mobility



Buhmann *et al.*, 15th Internat. Conf. on High Magnetic Fields in Semiconductor Physics, Oxford 2002

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