Spin-related transport phenomena in low dimensional magnetic semiconductors

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FunDMS

MARIE CURIE ACTIONS

Alexander von Humboldt

LECTURE II

SUMMARY – lecture I

1. Exchange interactions between carriers and localized spins
   - -- potential exchange (intra atomic)
   - -- kinetic exchange (involves neighbor anions)
2. Leads to
   - -- giant spin-splitting of band states
   - -- spin-disorder scattering of band carriers
   - -- coupling between localized spins
     - -- superexchange (AF or FM)
     - -- sp-d Zener mechanism (FM)

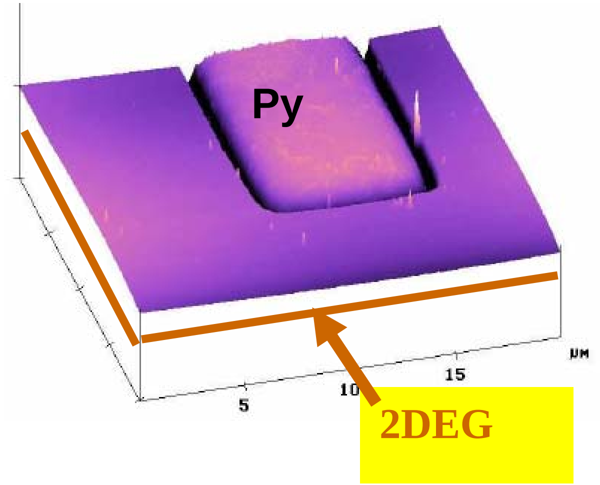
Spintronics -- materials aspect

Why to do not combine capabilities of ferromagnets and semiconductors?

- hybrid ferromagnetic metal/semiconductor structures

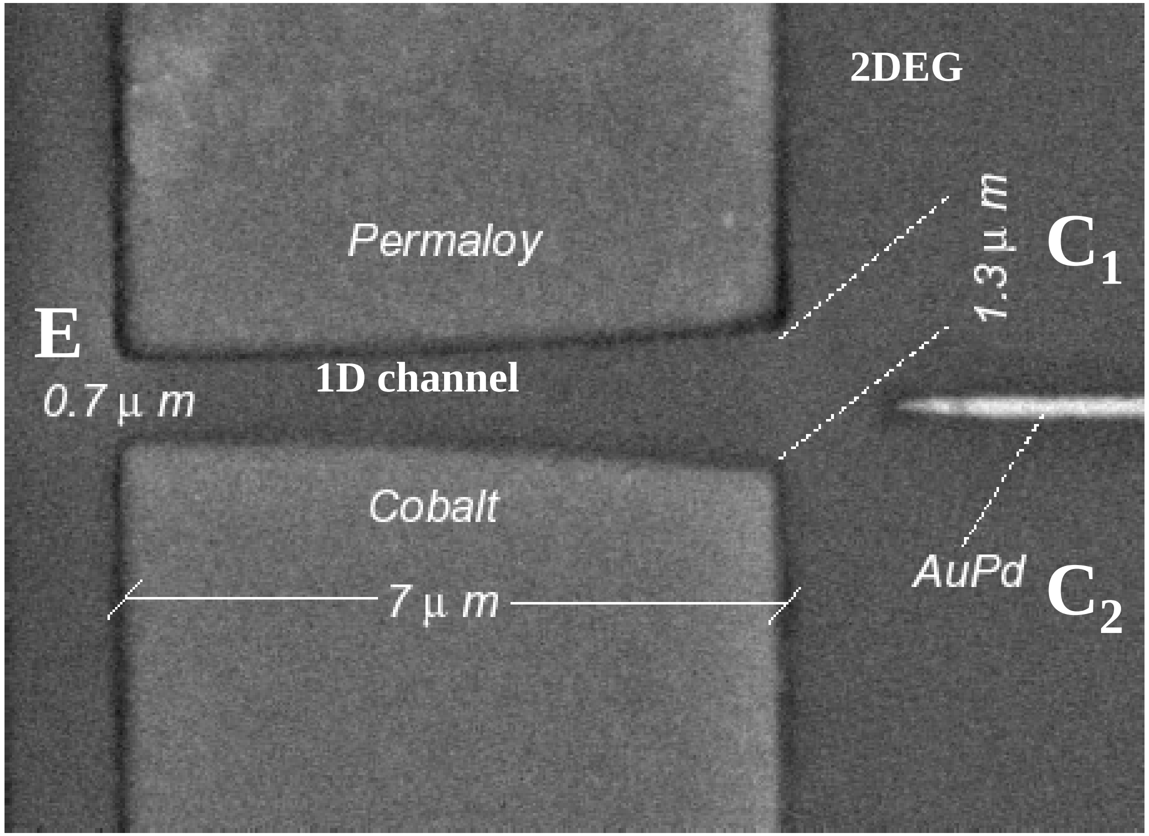
The Stern-Gerlach device

GaAs/AlGaAs



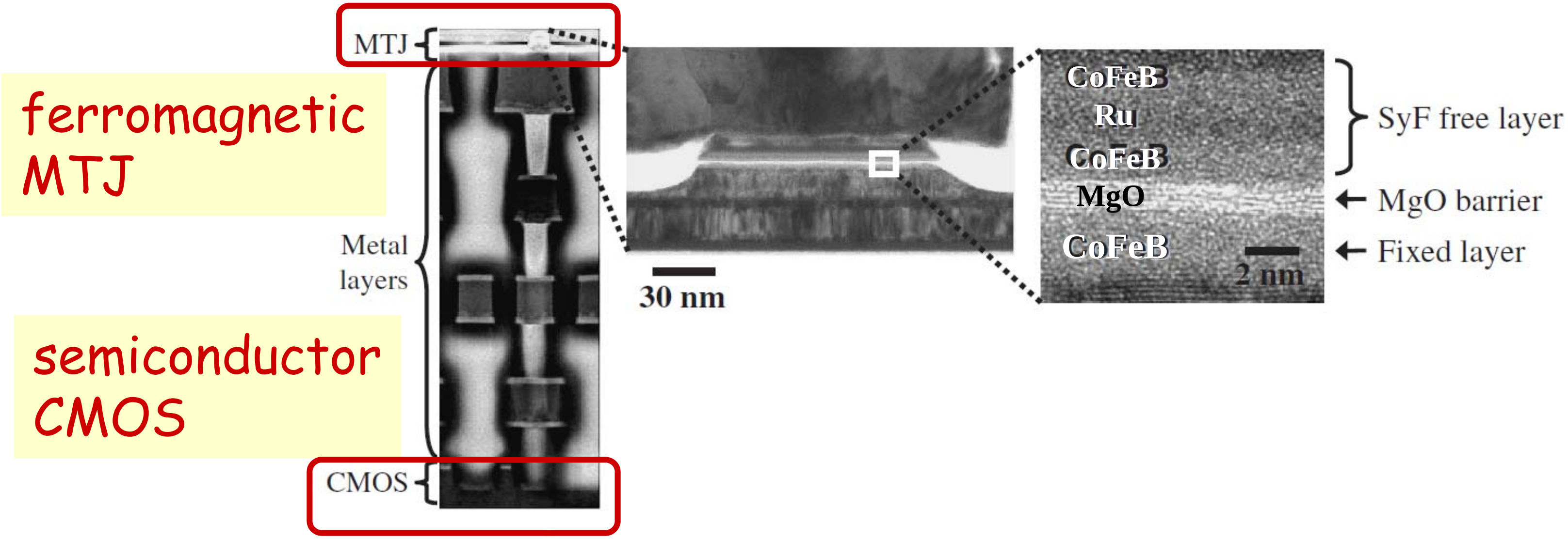
center of magnetic film at 2DEG

GaAs/GaAlAs,



J. Wróbel, T.D., ..., PRL'04

Low-power logic-in-memory

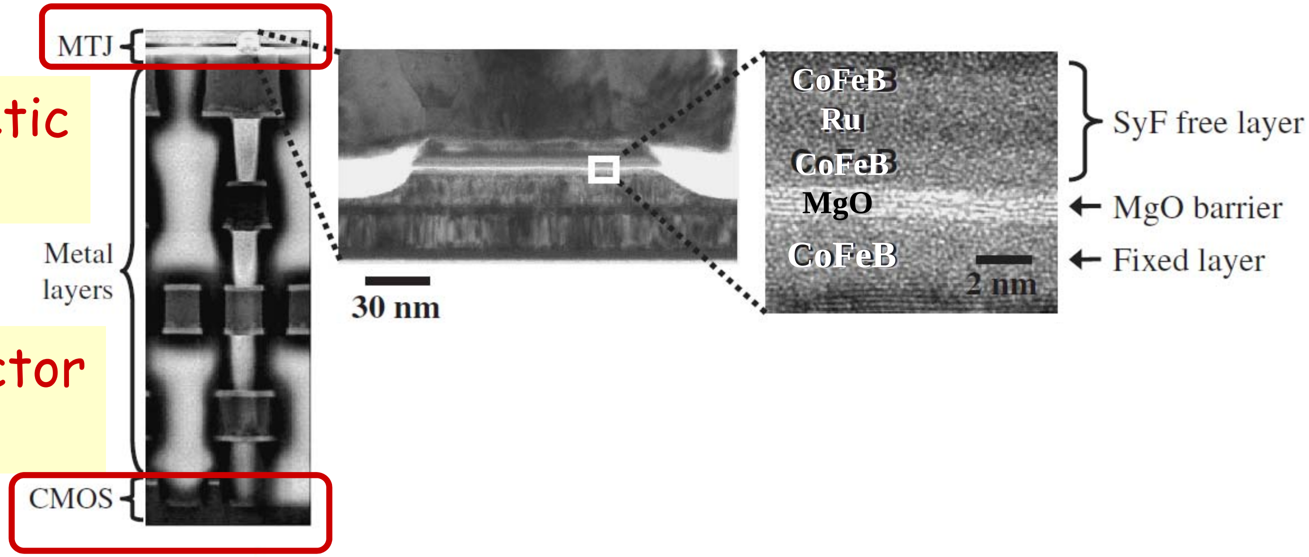


S. Matsunaga et al. (Tohoku) APEX'08

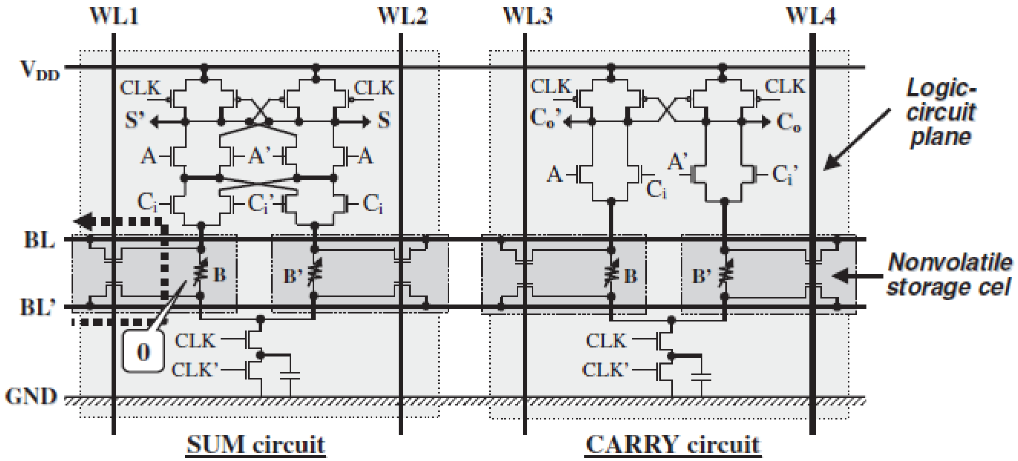
Low-power logic-in-memory

ferromagnetic
MTJ

semiconductor
CMOS



4 MTJs + 32 MOSs



Adder:
power consumption
4 times reduced

S. Matsunaga et al. (Tohoku) APEX'08

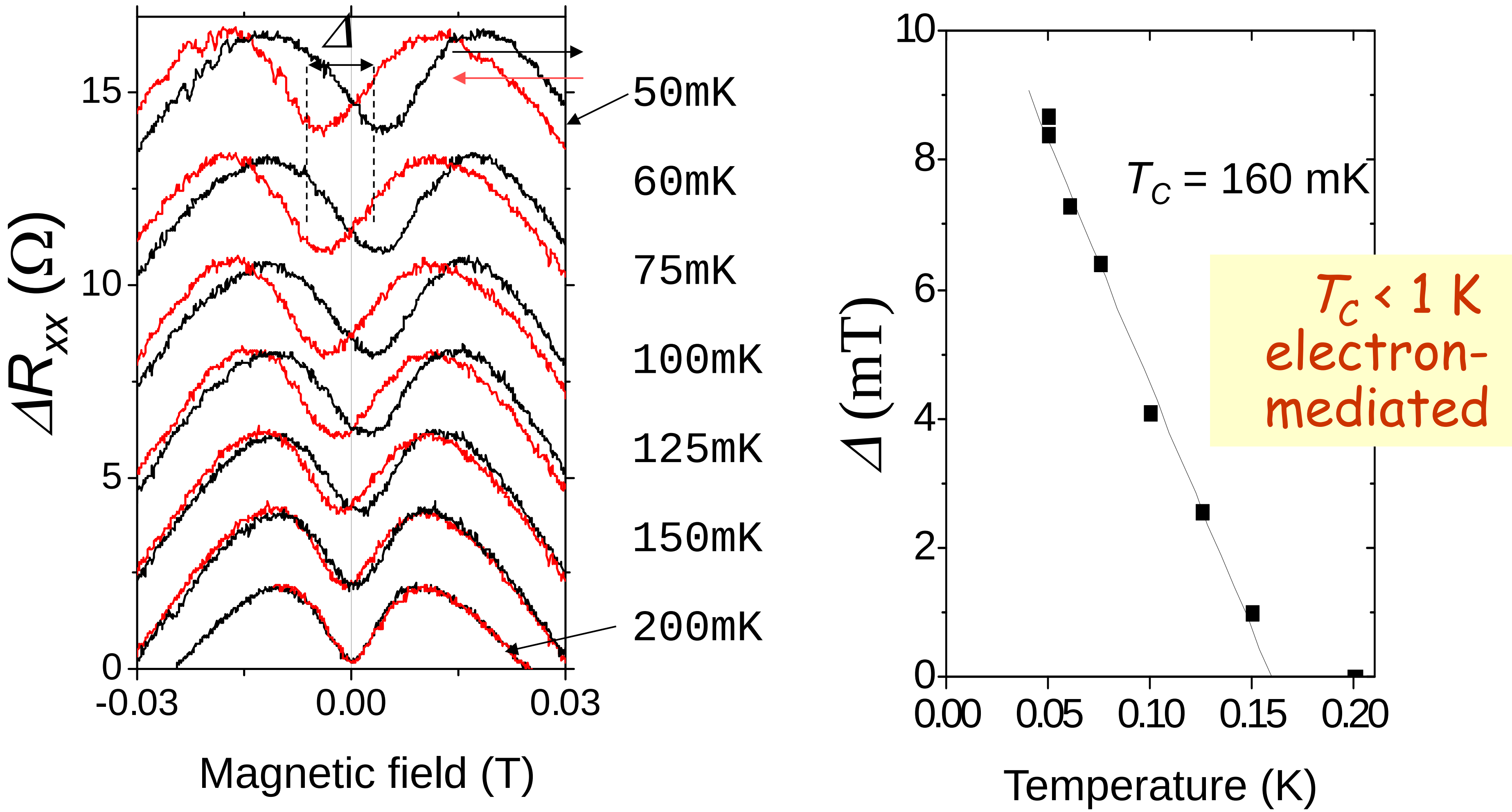
Spintronics -- materials aspect

Why to do not combine capabilities of ferromagnets and semiconductors?

- hybrid ferromagnetic metal/semiconductor structures
- ferromagnetic semiconductors

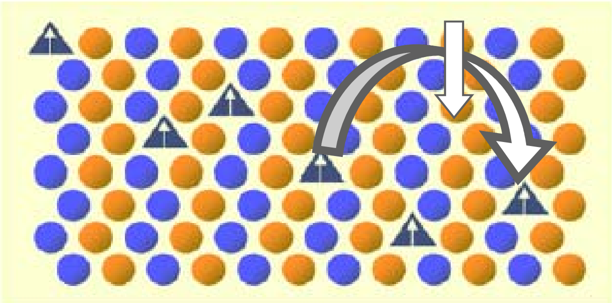
Electron-mediated ferromagnetism

Magnetoresistance hysteresis n-$Zn_{1-x}Mn_xO$:Al, $x = 0.03$



T. Andrearczyk et al. [Warsaw, Yokohama] ICPS'00

Making DMS ferromagnetic – p-type doping



holes mediate ferro coupling in DMS

source of holes in Mn-based DMSs, x < 10%:

- Mn itself III-V

(In,Mn)As; (Ga,Mn)As *H. Ohno et al. [IBM, Tohoku] PRL'92, APL'96* — T_C up to 190 K

$(Sb,Mn)_2Te_3$; $(Bi,Mn)_2Te_3$ *Choi et al. [Ulsan] pps(b)'04* — T_C up to 20 K

- acceptor impurities

(Cd,Mn)Te:N, (Zn,Mn)Te:P — T_C up to 5 K

TD, Cibert et al. [Grenoble, Warsaw] PRB'97, PRL'97, PRL'03

$(K,Ba)(Zn,Mn)_2As_2$ *et al. [Beijing, Columbia U.] Nat. Commun.'13* — T_C up to 180 K

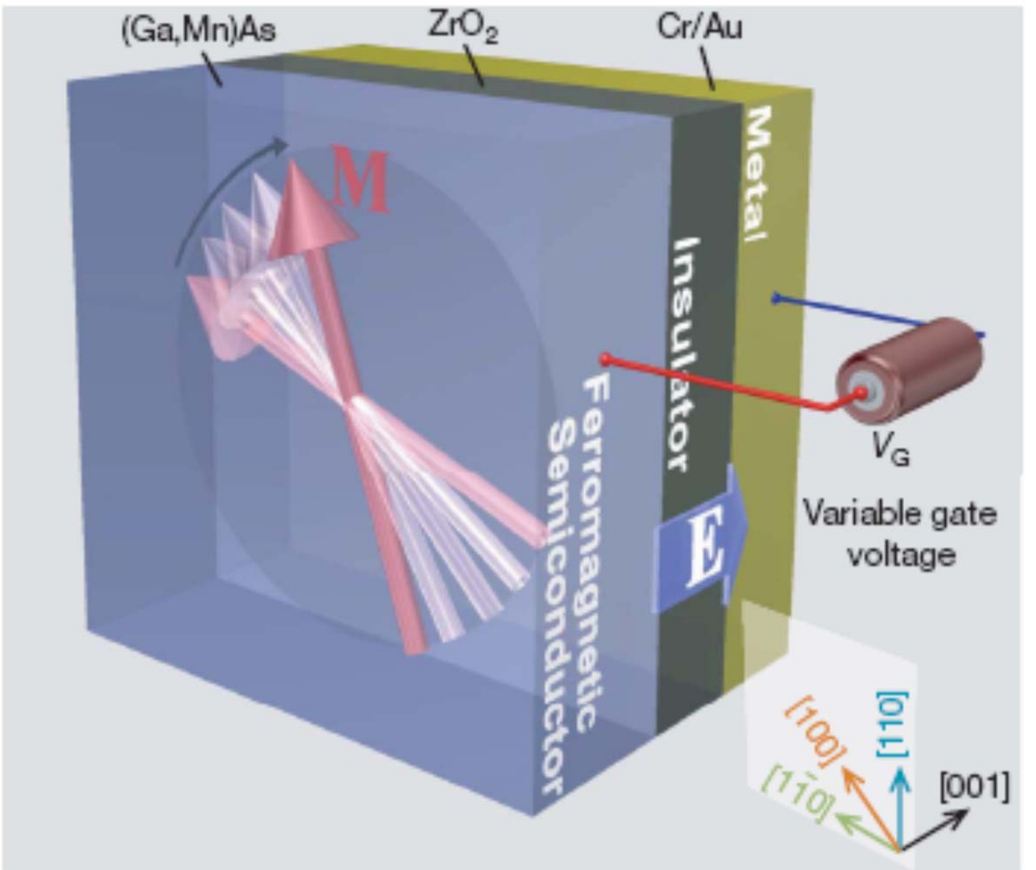
- cation vacancies IV-VI, [I-II]-V

(Pb,Sn,Mn)Te *T. Story et al. [Warsaw] PRL'86* — T_C up to 10 K

(Ge,Mn)Te *Y. Fukuma et al. [Yamaguchi] APL'08* — T_C up to 190 K

[Li(Zn,Mn)]As *Z. Deng et al. [Beijing, Columbia,Tokyo, Vancouver] Nature Comm.'11* — T_C up to 50 K

(Ga,Mn)As - novel functionalities: an example



low-power magnetization switching

exp:. Chiba et al. [Tohoku, Warsaw] Nature'08
theory: Birowska et al. [Warsaw] PRL'12

now FeCo

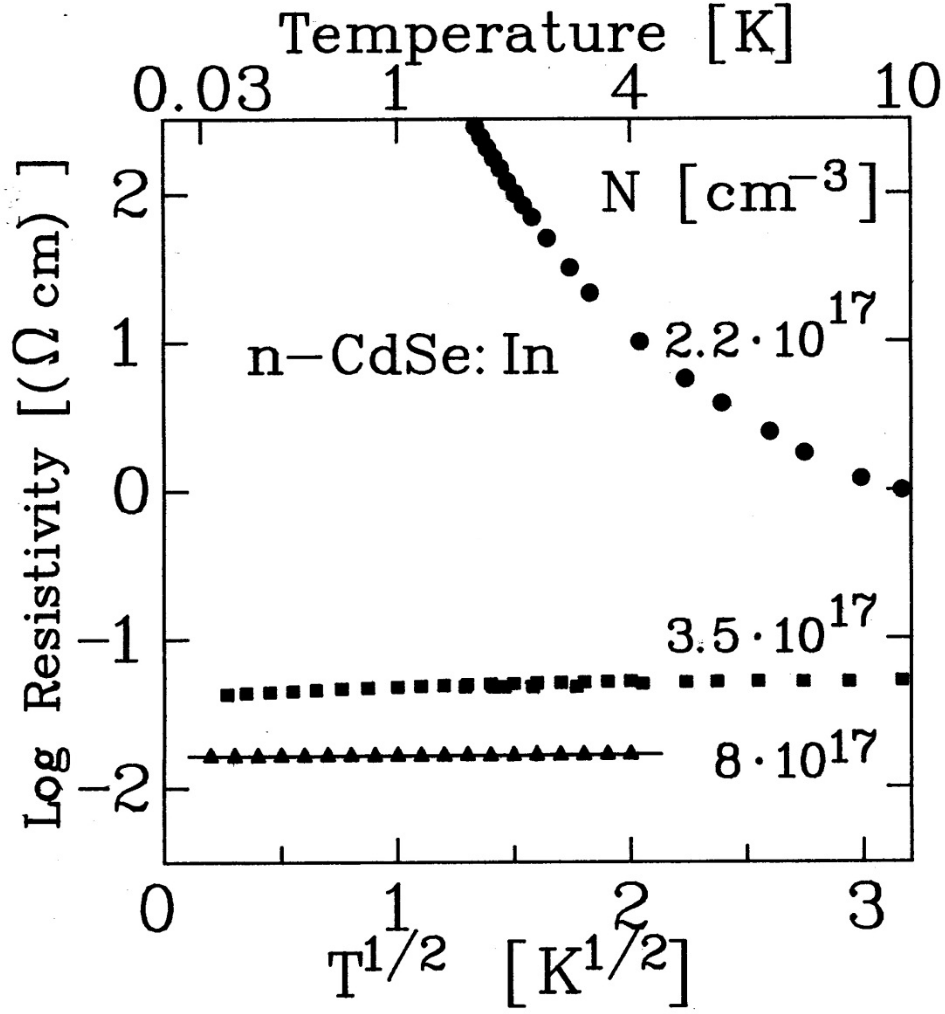
Shiota et al. [Osaka] Nature Mat.'11

Spin-related transport phenomena in magnetic semiconductors

Quantum localization phenomena dominate properties of charge transport in magnetically doped semiconductors

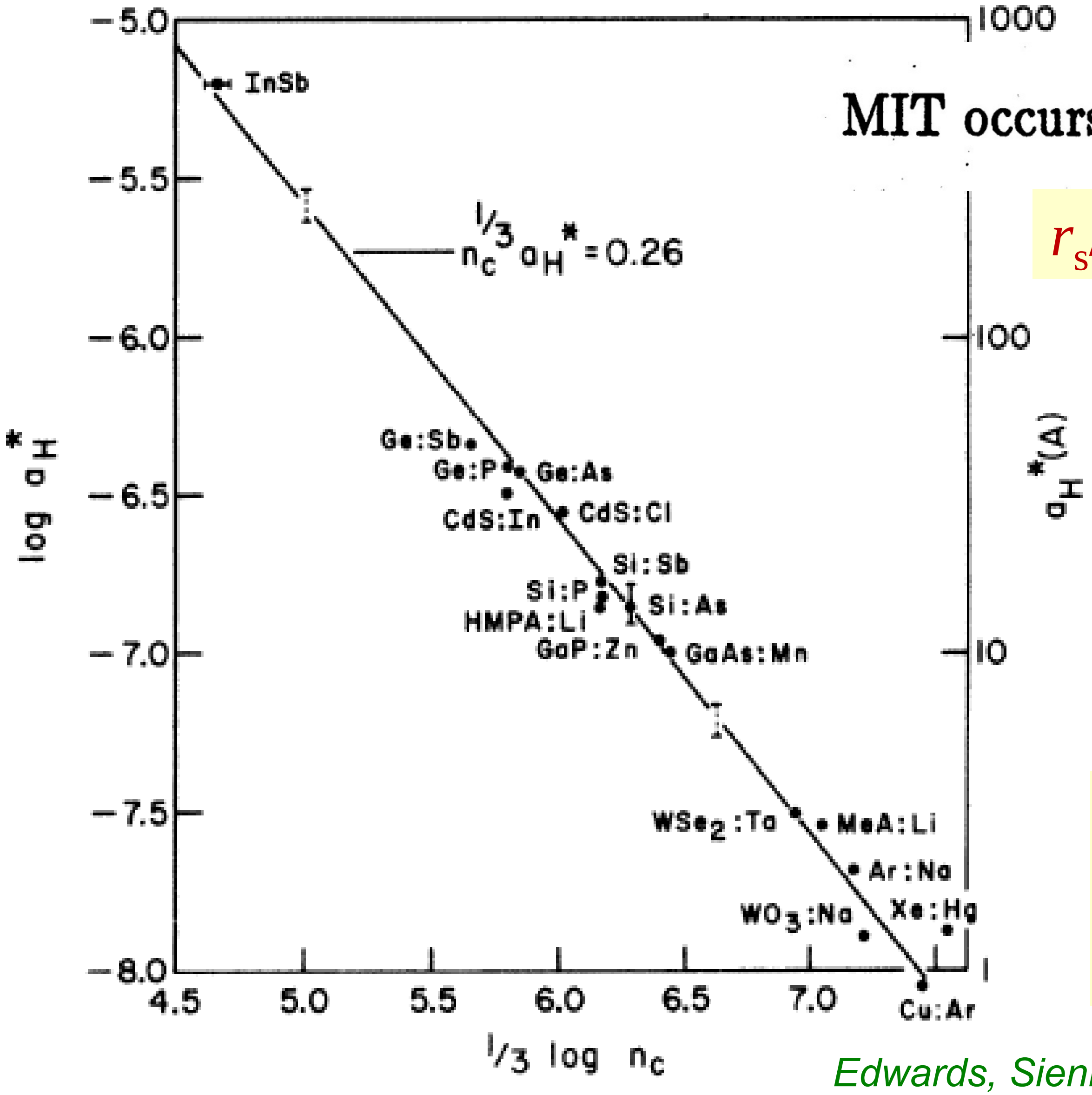
Influence of spin effects on quantum localization

MIT in doped semiconductors



J. Jaroszynski , T.D. et al.'81

Critical concentration for MIT *vs.* Bohr radius a_B*



MIT occurs for: $n_c^{1/3} a_B^* \approx 0.25$

$r_s/a_B^* = [3/(4\pi n_c)^{1/3}]/a_B^* \approx 2.5$

For hydrogenic-like donors:

$a_B^* = a_B\, \varepsilon_S/(m^*/m_o)$

More general:

$a_B^* = \hbar/(2E_I m^*)^{1/2}$

$a_B^* = e^2/(2\varepsilon_S\, E_I^*)$

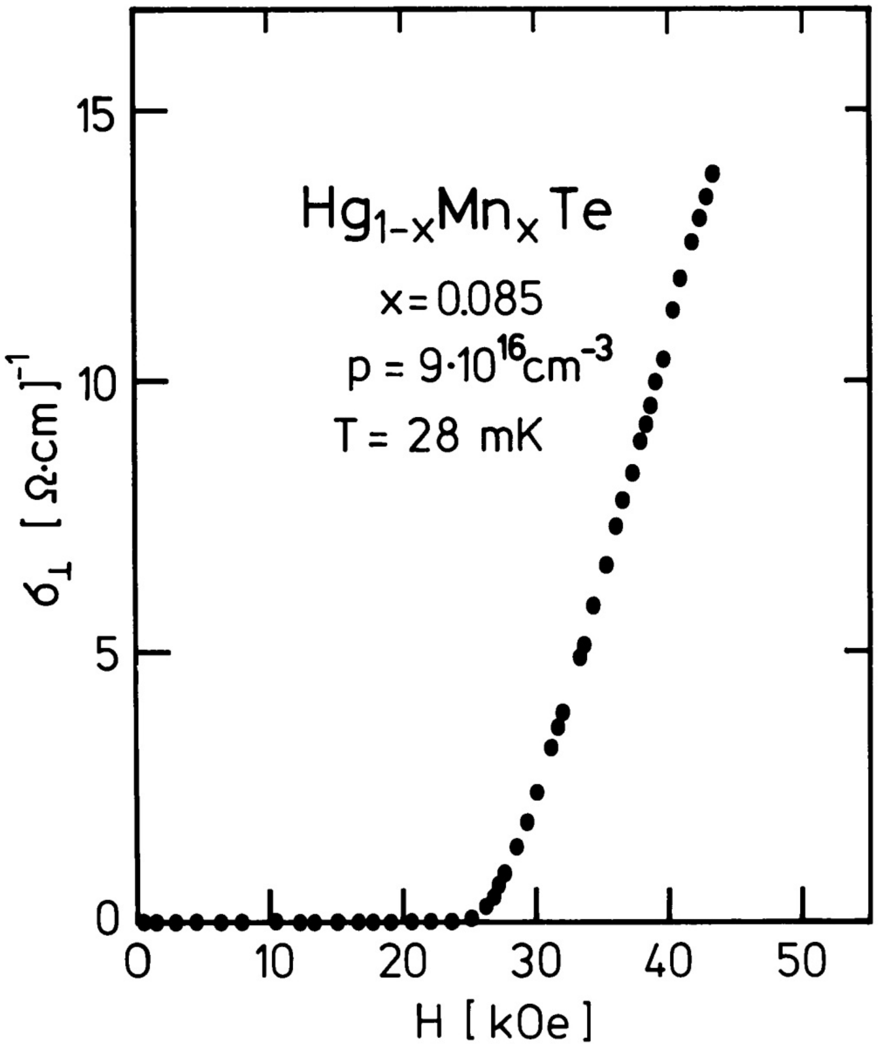
Another parameter: $k_F l$

at $r_s/a_B^* = 2.5$, $k_F l = 5.8(1\text{-}K)/(1 + K)$

K - compensation

Edwards, Sienko, PRB'78

MIT in p-(Hg,Mn)Te -- disorder (scattering by Mn spins) reduced by the magnetic field



T. Wojtowicz, T.D. et al. PRL'86

MIT in doped semiconductors

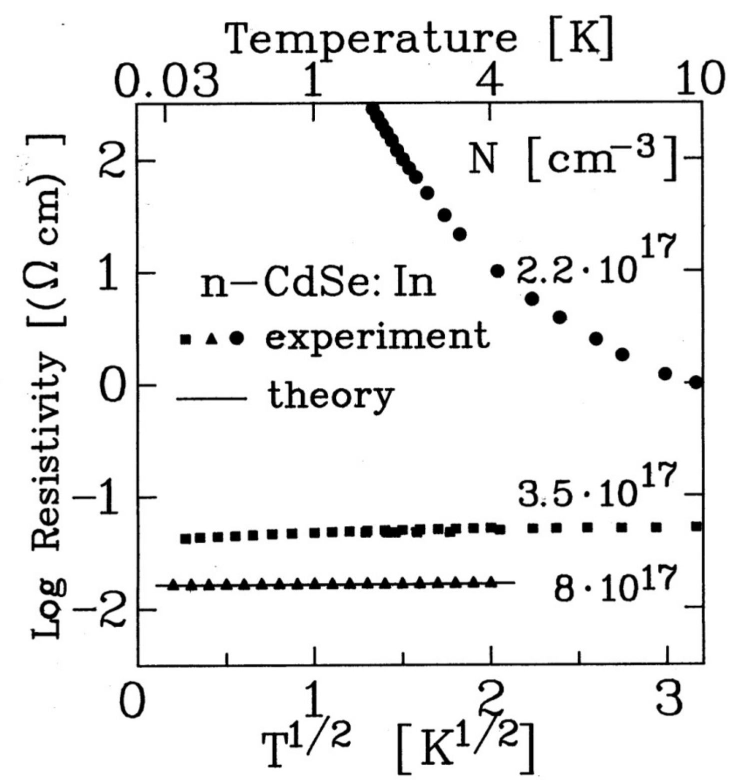
- no theory for n_c
- no theory for σ
- innaccesible by available *ab initio* methods

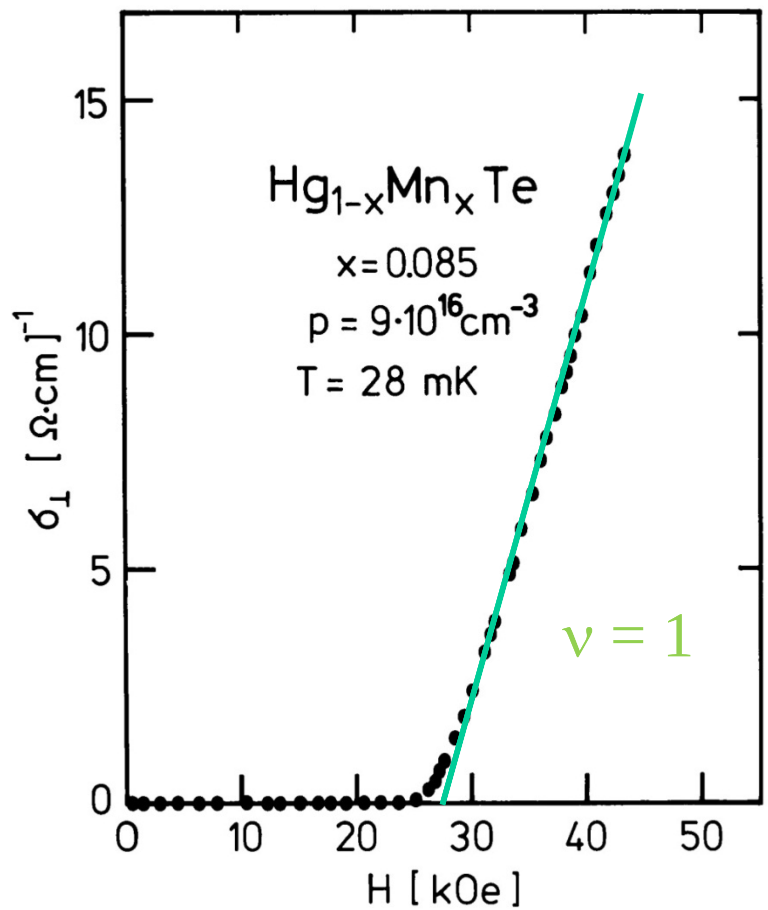
MIT in doped semiconductors

What we know

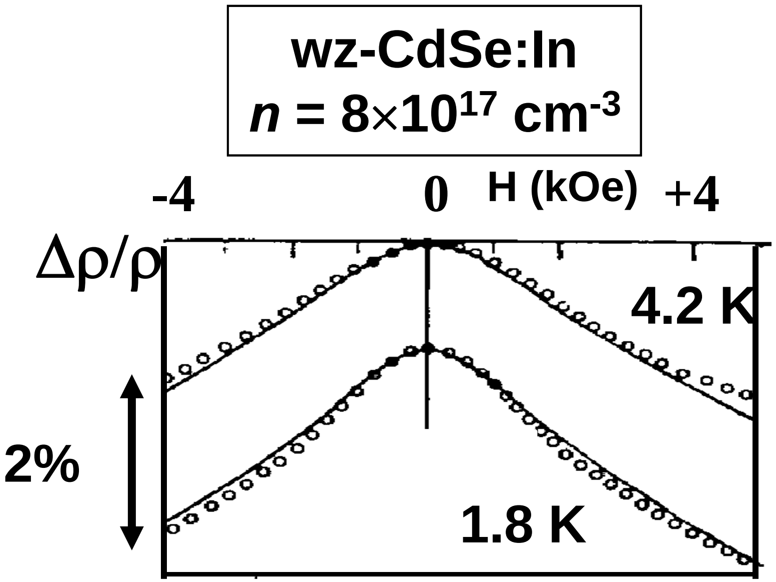
- both disorder *and* disorder-modified electron-electron interactions important ➔ Anderson-Mott transition
- quantum interference crucial – sensitive to symmetry lowering perturbations (various universality classes)
- in the weakly localized regime, $n > n_c$, $\Delta\sigma(T, \omega, H, \omega_s, \tau_s, \tau_{so})$ - known

MIT in doped semiconductors





Negative MR in semiconductors

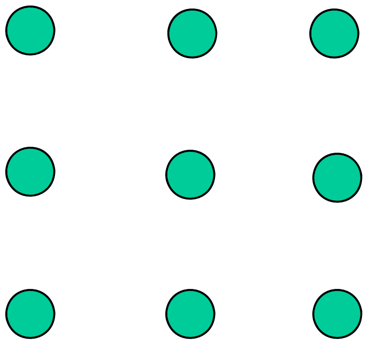


Theory: Hikami, Khmielnitskii, Kawabata, Fukuyama, … 1980-1982

not Kondo effect!

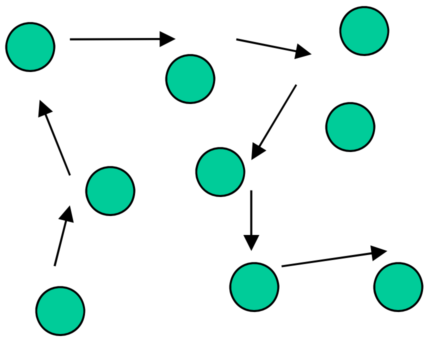
Particle/wave propagation in solids

Crystals
(periodic potential)



Quantum particles: (electrons, photons,...)
scatterring + interferences ➔
Energy bands: quasi-free (ballistic) propagation
Energy gaps: regions of evanescent waves

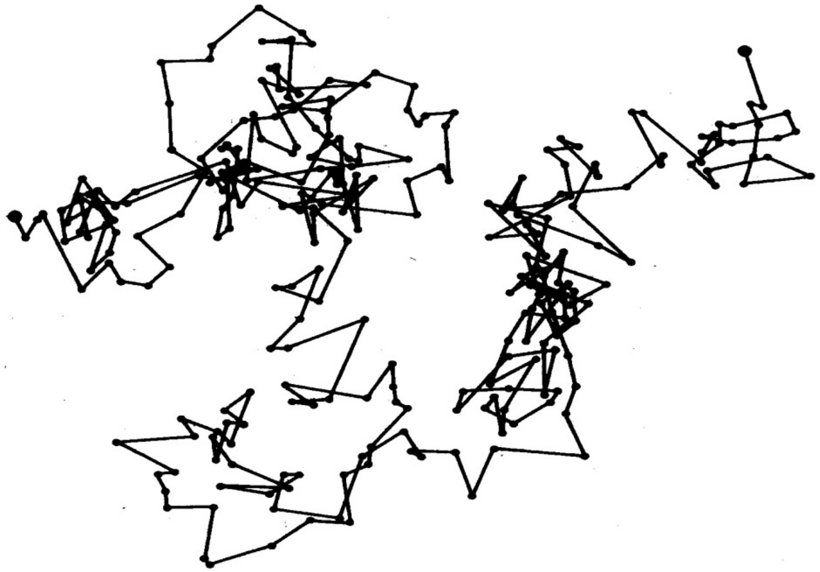
Disordered solids

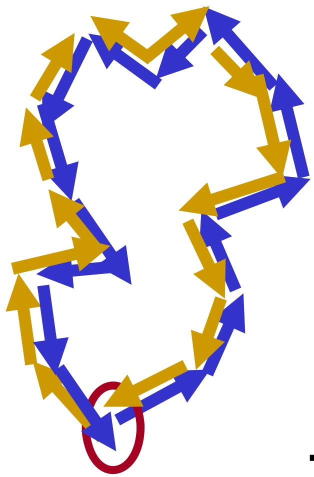


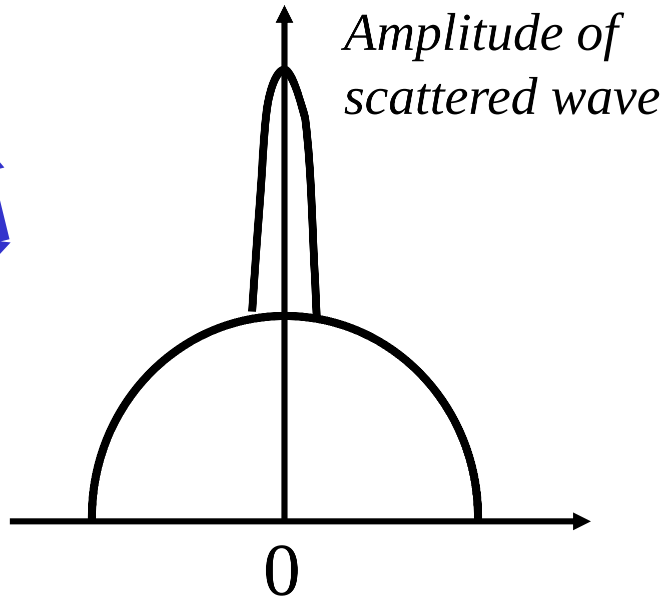
Quantum particles: (electrons, photons,...)
scattering + interferences ➔
diffusions + localisation

Probability of returning to the starting point

diffusing electron







$$P_{\text{return}} = |t_r|^2 + |t_l|^2 + 2|t_r t_l|\cos(\varphi_r - \varphi_l)$$

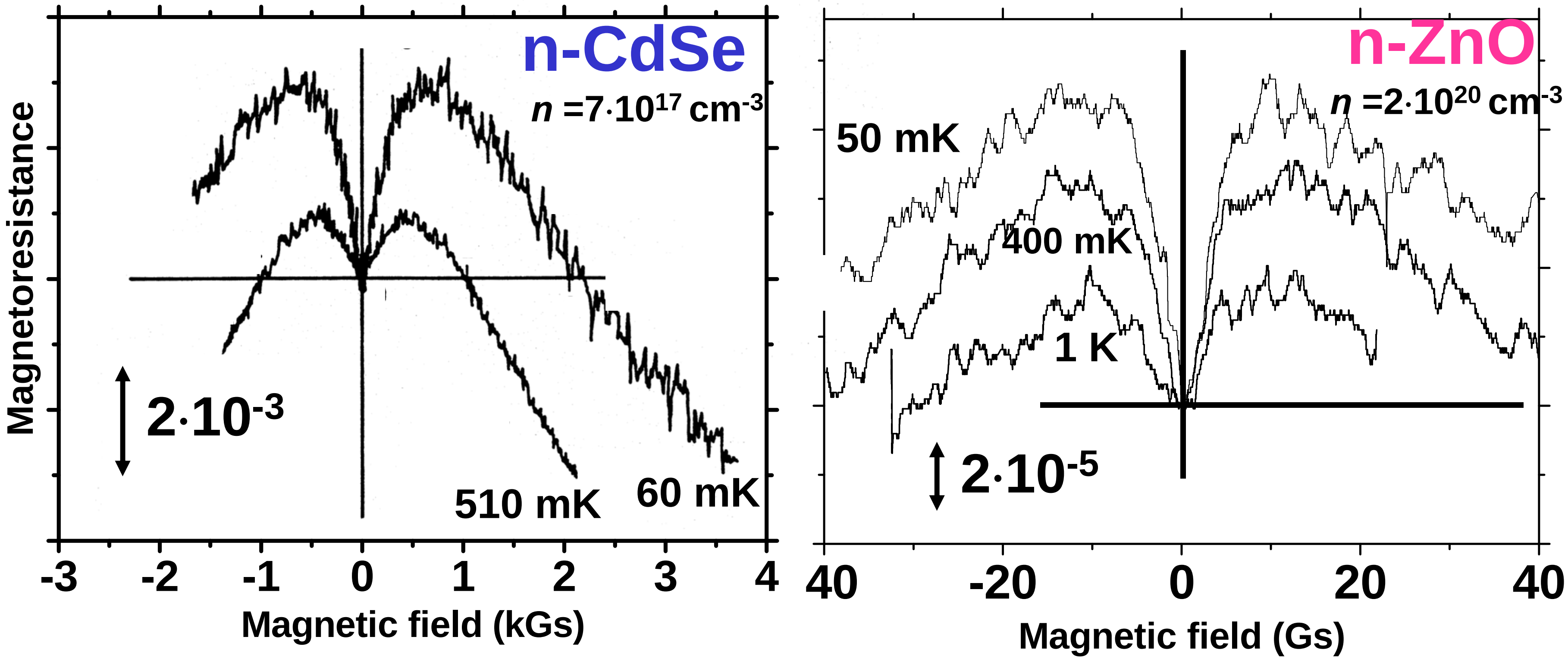
$\varphi_r - \varphi_l = 0$ if no magnetic field and spin or inelastic scattering

Factor of two enhancement over classical value

➔ magnetic field, spin-dependent scattering, and temperature *enhance* diffusion (reduce localization)

Abrahams, Khmelnitskii, Larkin, Altshuler, Aronov, ...

Observation of antilocalization in n-wz-CdSe and -ZnO



M. Sawicki, T.D., …, PRL'86

T. Andrearczyk, T.D,... PRB'05

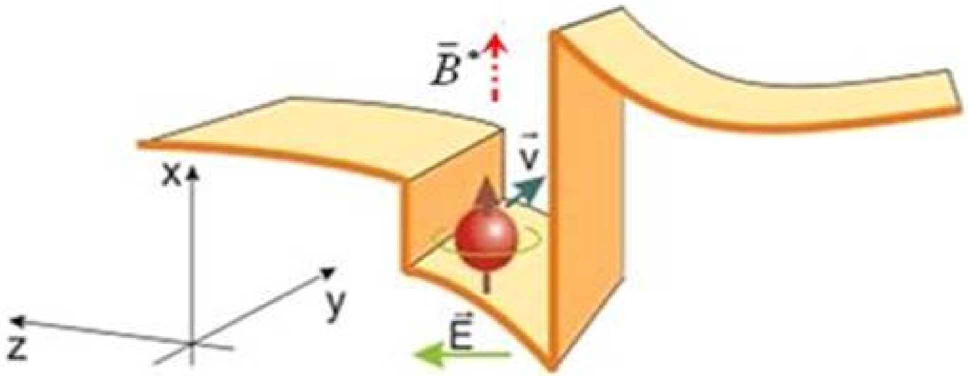
Smaller amplitude, smaller magnetic field
➔ weaker spin-orbit coupling

cf. lectures by J. Nitta, K. Richter

Capri 2013

Manifestations of spin-orbit interaction in transport phenomena

Rashba effect in nanostructures



$\mathbf{B} = (\mathbf{v} \times \mathbf{E})/c^2$

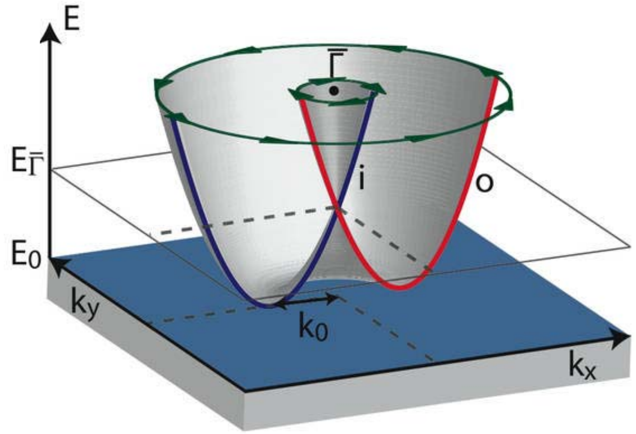
$\mathcal{H}_{so} = g\mu_B \mathbf{s}(\mathbf{v} \times \mathbf{E})/c^2$

wrong

inversion symmetry broken and
time reversal symmetry conserved

kp, TBA, … ➔

$\mathcal{H}_R = \alpha'_{so} (\mathbf{s} \times \mathbf{k})\, \check{z}$

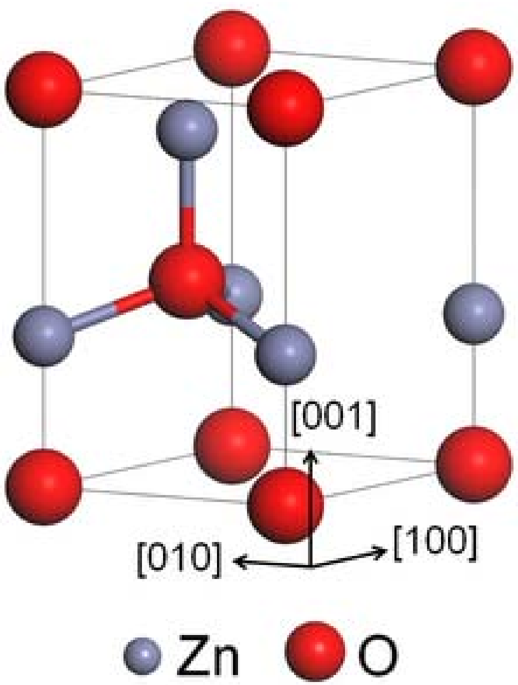


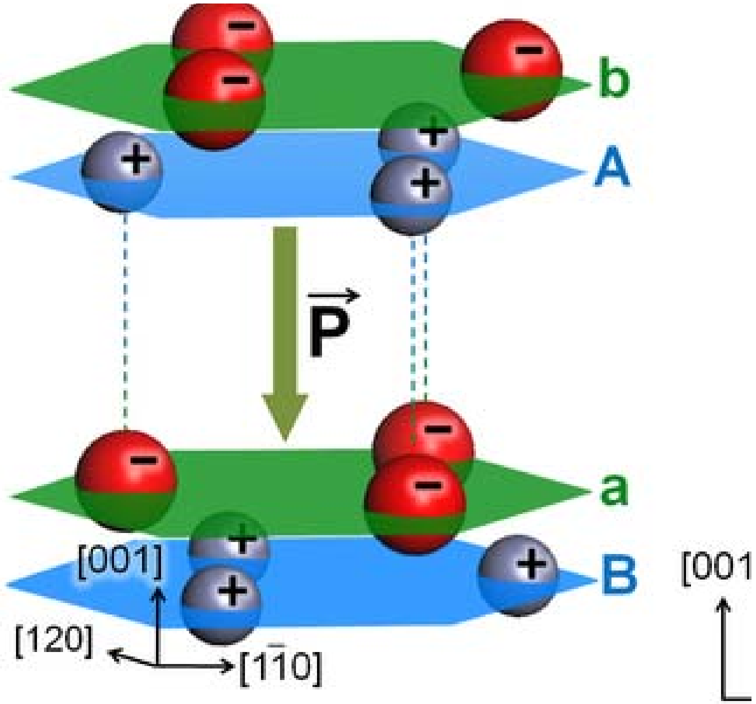
Yu. Bychkov, E. Rashba, J. Phys. C'84
Pffefer, Zawadzki, PRB'99

cf. lecture by J. Nitta

Rashba term – wurtzite structure

ZnO, GaN, CdSe, …



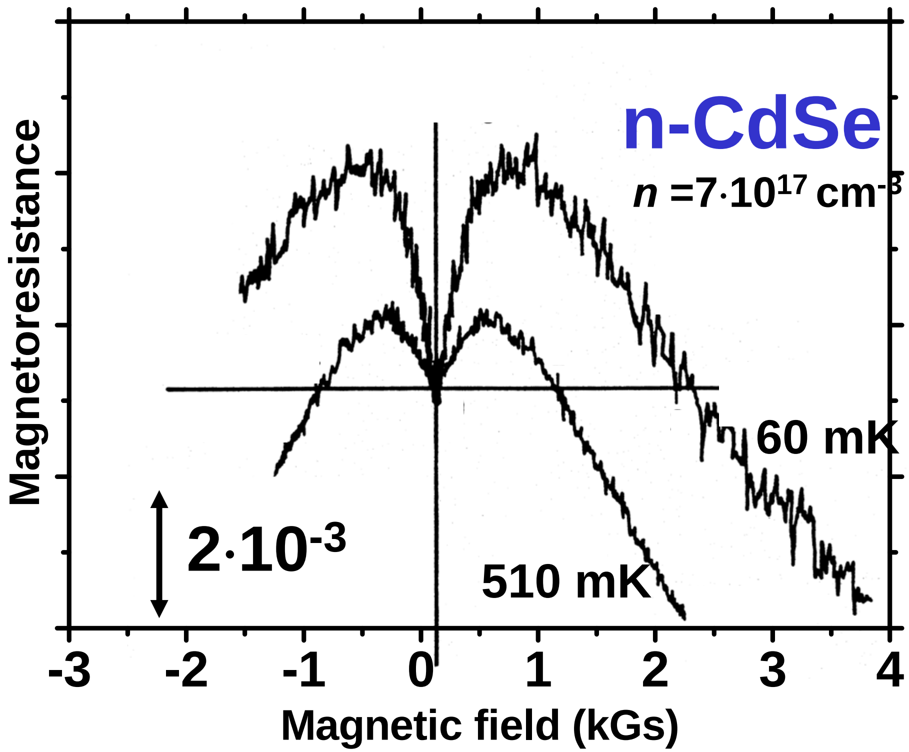


inversion symmetry broken and
time reversal symmetry conserved ➔

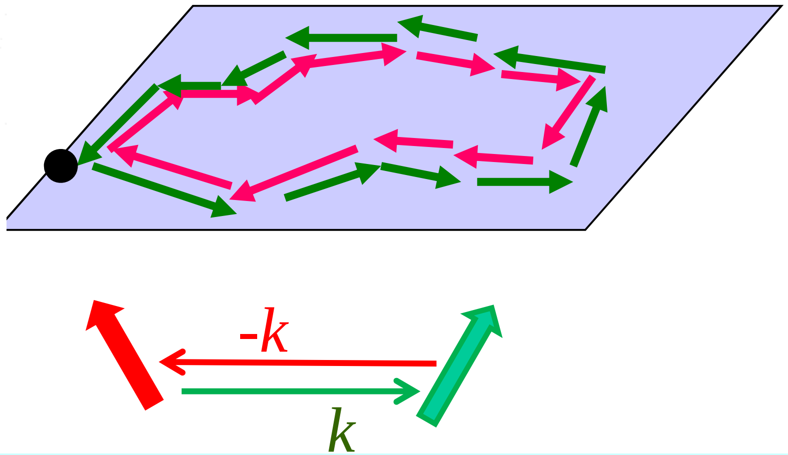
$\mathcal{H}_R = \lambda_{so}(\boldsymbol{s} \times \boldsymbol{k})\ \hat{\boldsymbol{c}}$

E. I. Rashba, V. I. Sheka (FTT, 1959); B. C. Casella (IBM – PRL, 1960)

Weak anti-localization MR in wz-CdSe



M. Sawicki, T.D., …, PRL'86



$\mathcal{H}_R = \lambda_{so}(\boldsymbol{s} \times \boldsymbol{k})\,\hat{\boldsymbol{c}}$

➔ additional ***k***-dependent field $\boldsymbol{B}_R$ rotating the spin

rotation angle = – *rotation angle*

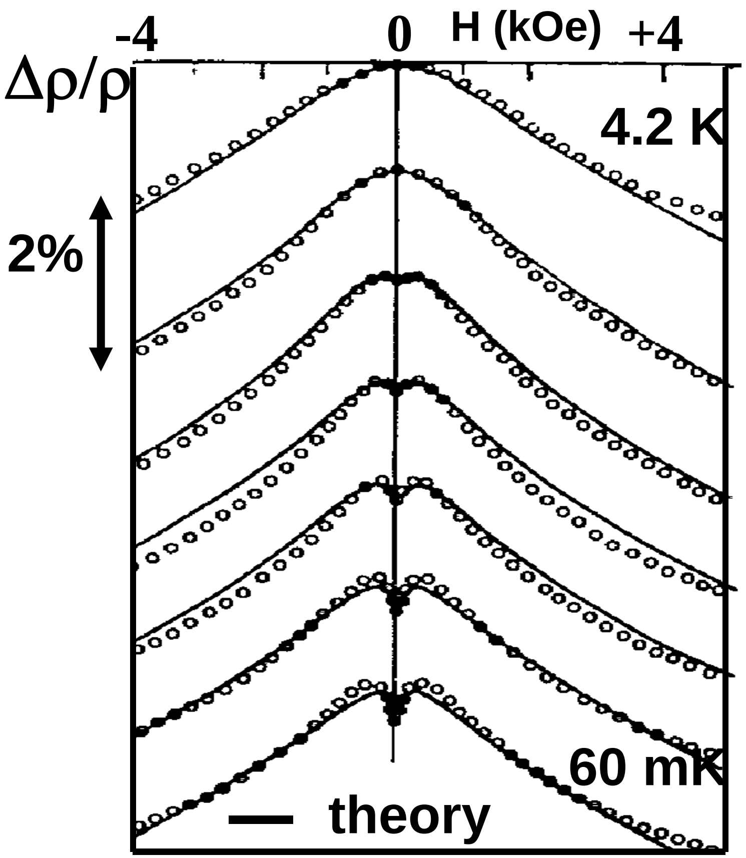
➔ additional phase shift reducing localization

➔ reduced by external magnetic field

➔ positive MR

Weak localization and anti-localization MR

wz-CdSe:In
n **= 8×10¹⁷ cm⁻³**



M. Sawicki, T.D., …PRL'86

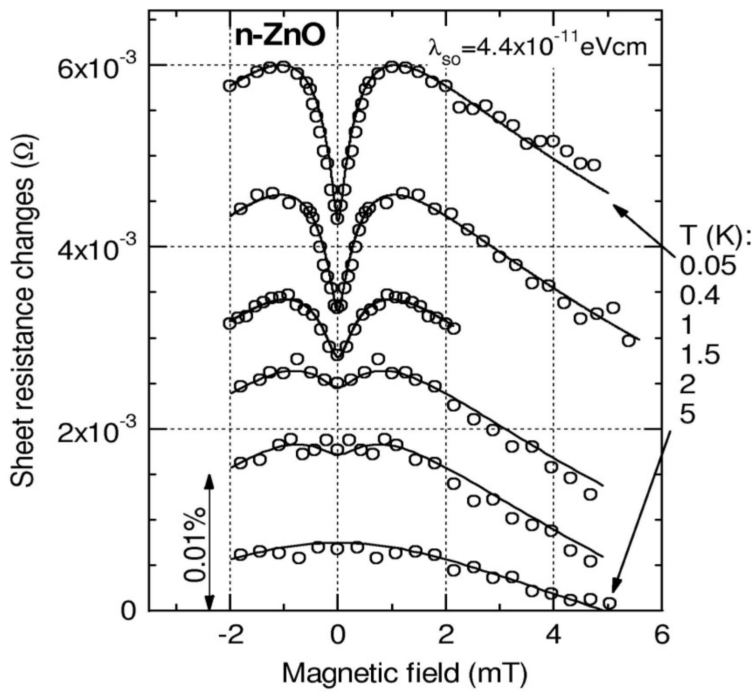
Fitting parameters:

λ_{so}

$\tau_{\varphi} \sim T^{-3/2}$

Theory of weak anti-localization in n-ZnO

Magnetoresistance in the weakly localized regime



T. Andrearczyk, …, T.D., PRB‘05

$H_{so} = \lambda_{so} (\boldsymbol{s}\times\boldsymbol{k})\, \hat{\boldsymbol{c}}$

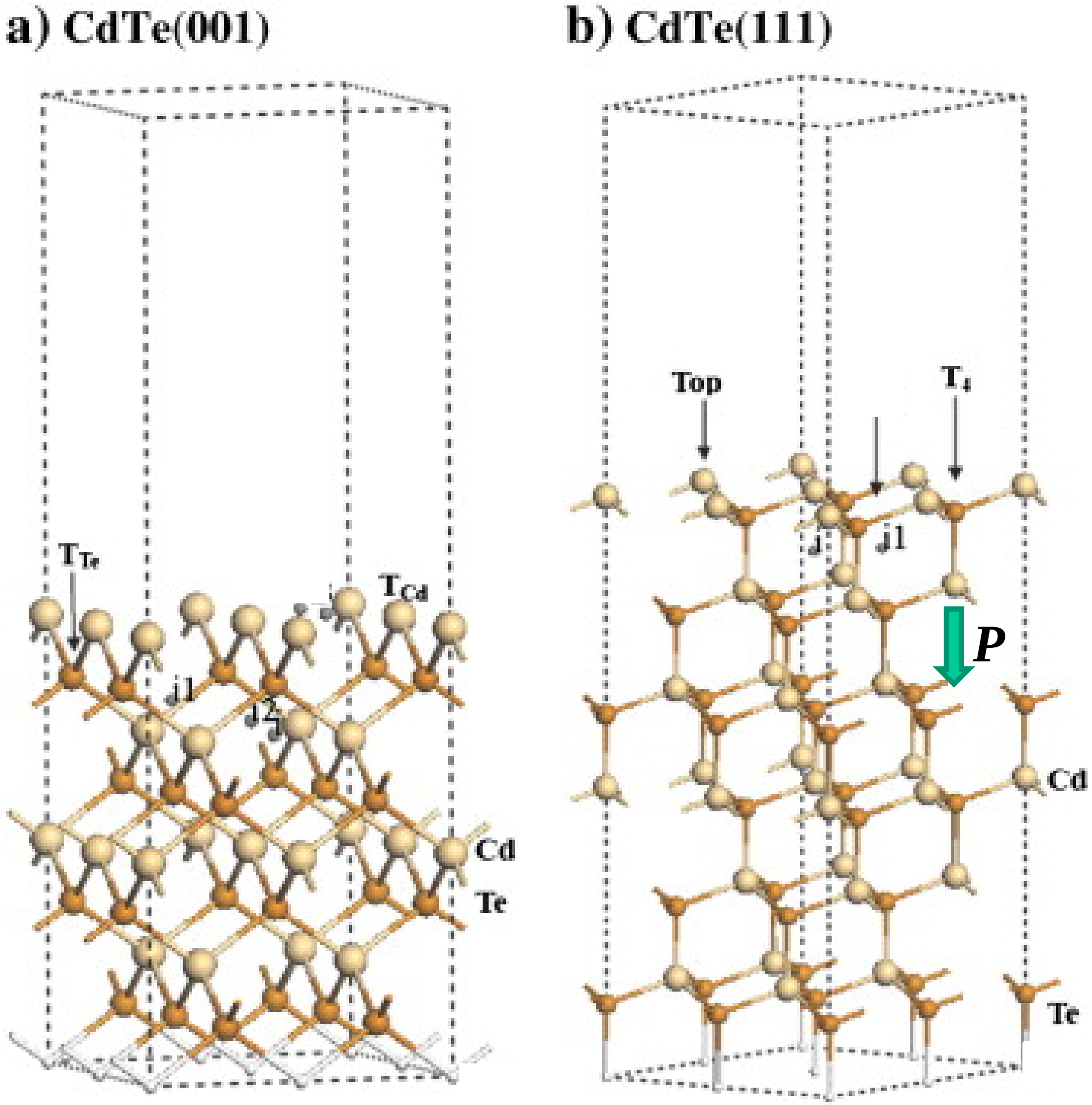
$\tau_{sox}^{-1} = \lambda_{so}^2 k_F^2 \tau /12$

$B_m \propto \lambda_{so}^2 m^{*2}$

Dyakonov-Perel; Fukuyama, Hoshino

λ_{so}[meVÅ]	CdSe	ZnO	
WLR	50±10	4.4±0.4	
optics	60±25		*Dobrowolska et al. PRB’84*
LMTO-LSD	60	1.1	*Voon et al. (Stuttgart, Aarhus) PRB’96*

Spin-orbit effects in zinc-blende structure

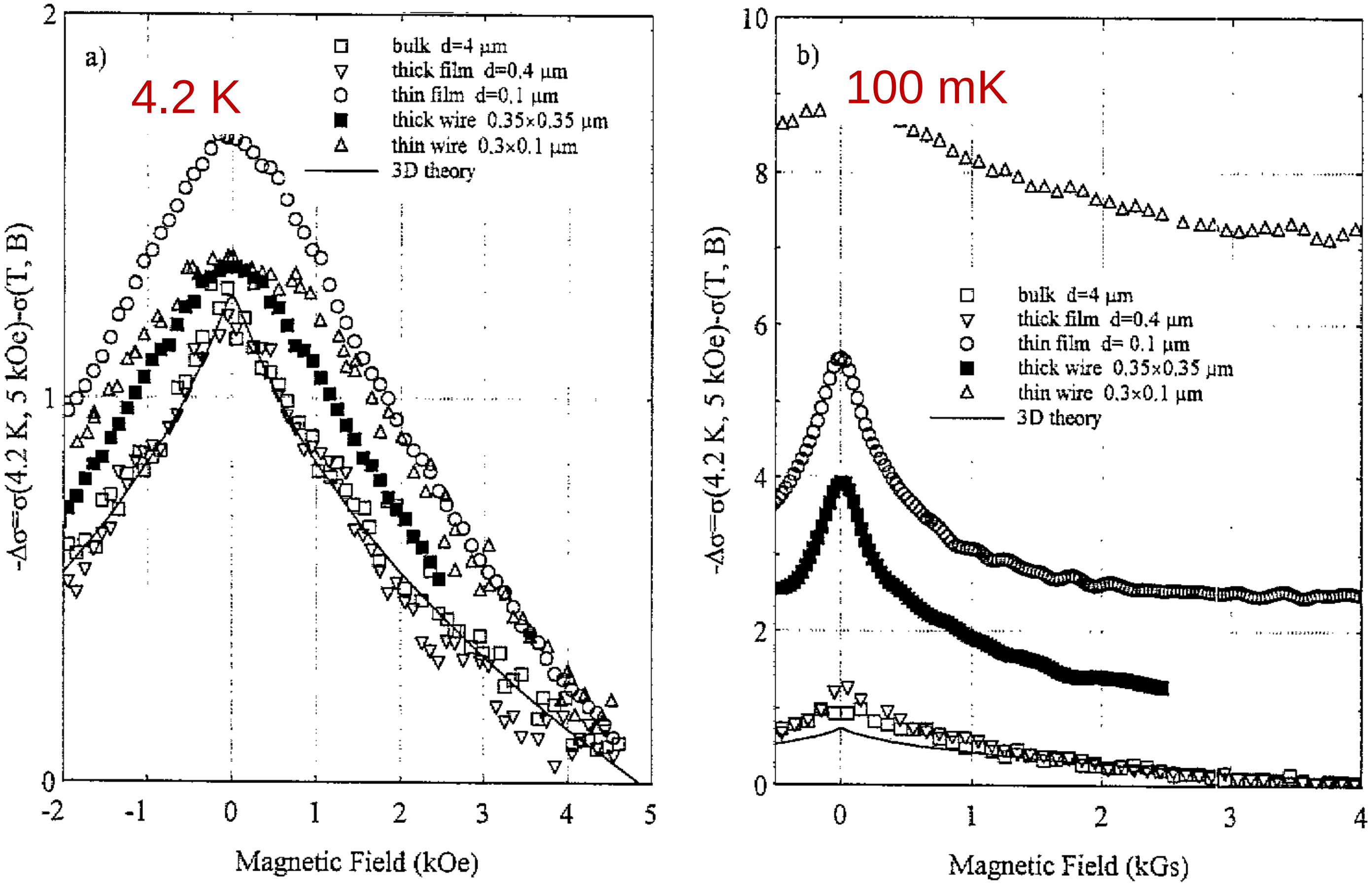


$H_{so} = \mathbf{s}\boldsymbol{\Omega}(\boldsymbol{k})$ $\boldsymbol{\Omega}(\boldsymbol{k}) = \beta k^3$

Dresselhaus hamiltonian

cf. lectures by J. Nitta

WLR MR in n-CdTe



J. Jaroszynski, T.D. et al. TSF'97

no anti-localization visible but better fit with

L_{so} = 1.3 ± 0.2 μm for n = 9.7x10^{17} cm^{-3}

L_{so} = 0.8 ± 0.1 μm for n = 2.0x10^{18} cm^{-3}

β value within 20% of calculated

M. Cardona et al., PRB'88

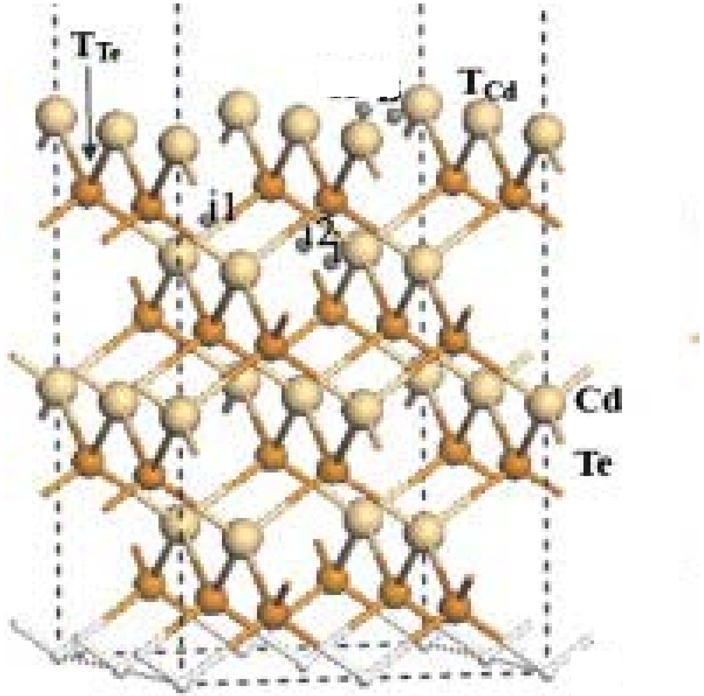
Linear in *k* terms for holes

- Rashba-like terms reduced by HH-LH splittings due to confinement

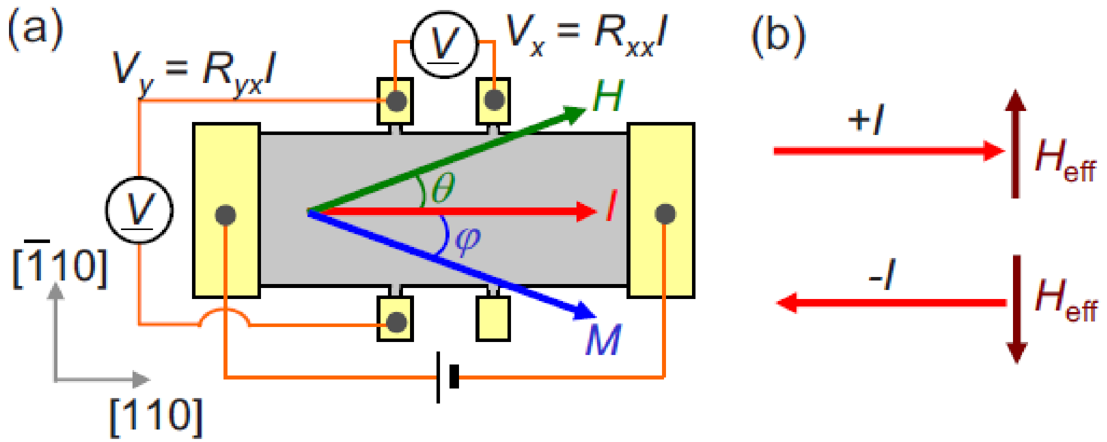
- Strain-induced symmetry lowering +
  \+ Dresselhaus cubic terms results in *k*-linear terms

  - biaxial strain
  - uniaxial strain

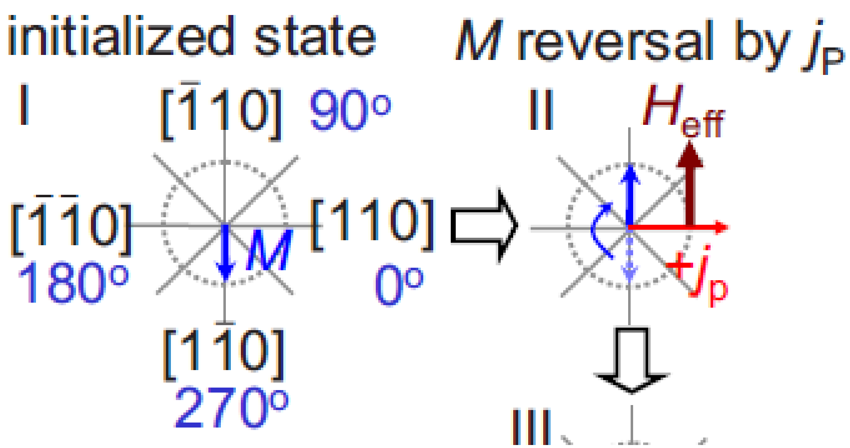
E. Ivchenko, book'95
R. Winkler, book'03



Magnetization switching by current in (Ga,Mn)As



$H = 0$



A. Chernyshov et al. [Purdue] Nat. Mater.'08

M. Endo et al. [Tohoku] APL'10

Non-magnetic semiconductors - summary

- **positive MR in weak fields**

  spin-orbit weak anti-localization effect

  quantitatively understood

- **negative MR in higher fields**

  weak localization orbital effect

  quantitatively understood

Non-magnetic semiconductors - summary

- **positive MR in weak fields**

  spin-orbit weak anti-localization effect

  quantitatively understood

- **negative MR in higher fields**

  weak localization orbital effect

  quantitatively understood

Provide:

λ_{so}, β - understood

$\tau_{\varphi} = a_d T^{-d/2}$ - understood

MR of DMSs

Trademarks of magnetic semiconductors

- Complex MR including colossal negative MR
- Temperature dependent localization (MIT)
- Giant critical scattering
- …

Key suggestion:

Quantum localization effects account for these properties

Magnetic semiconductors - new ingradients

- **giant spin splitting** $\hbar\omega_s \propto M(T,H)$

  spin polarization and spin currents

- **spin-disorder scattering** $1/\tau_s \propto T\chi(T,H)$

  dynamics

Magnetic semiconductors - new ingradients

- **giant spin splitting** $\hbar\omega_s \propto M(T,H)$

  spin polarization and spin currents

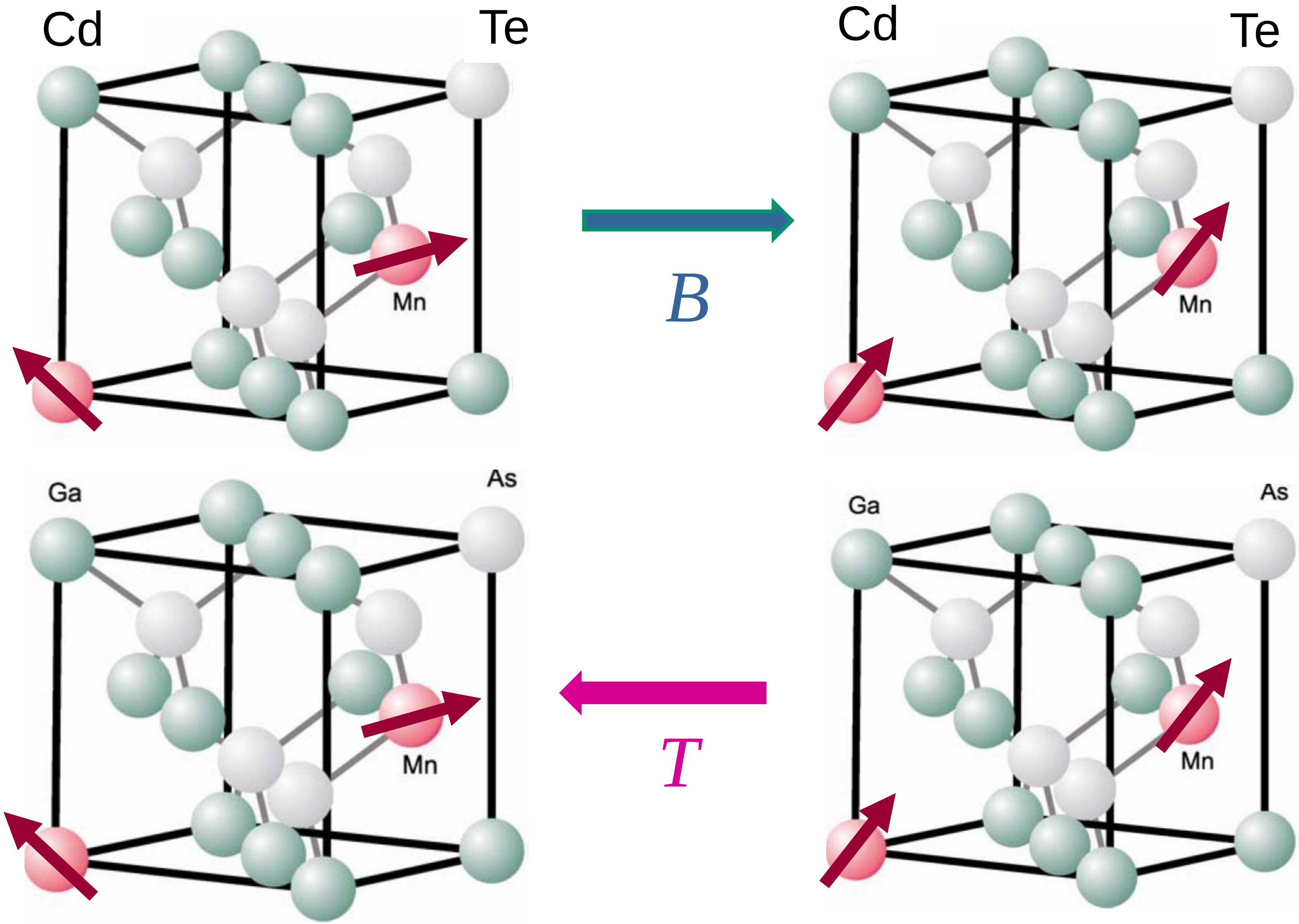
  today

- **spin-disorder scattering** $1/\tau_s \propto T\chi(T,H)$

  dynamics

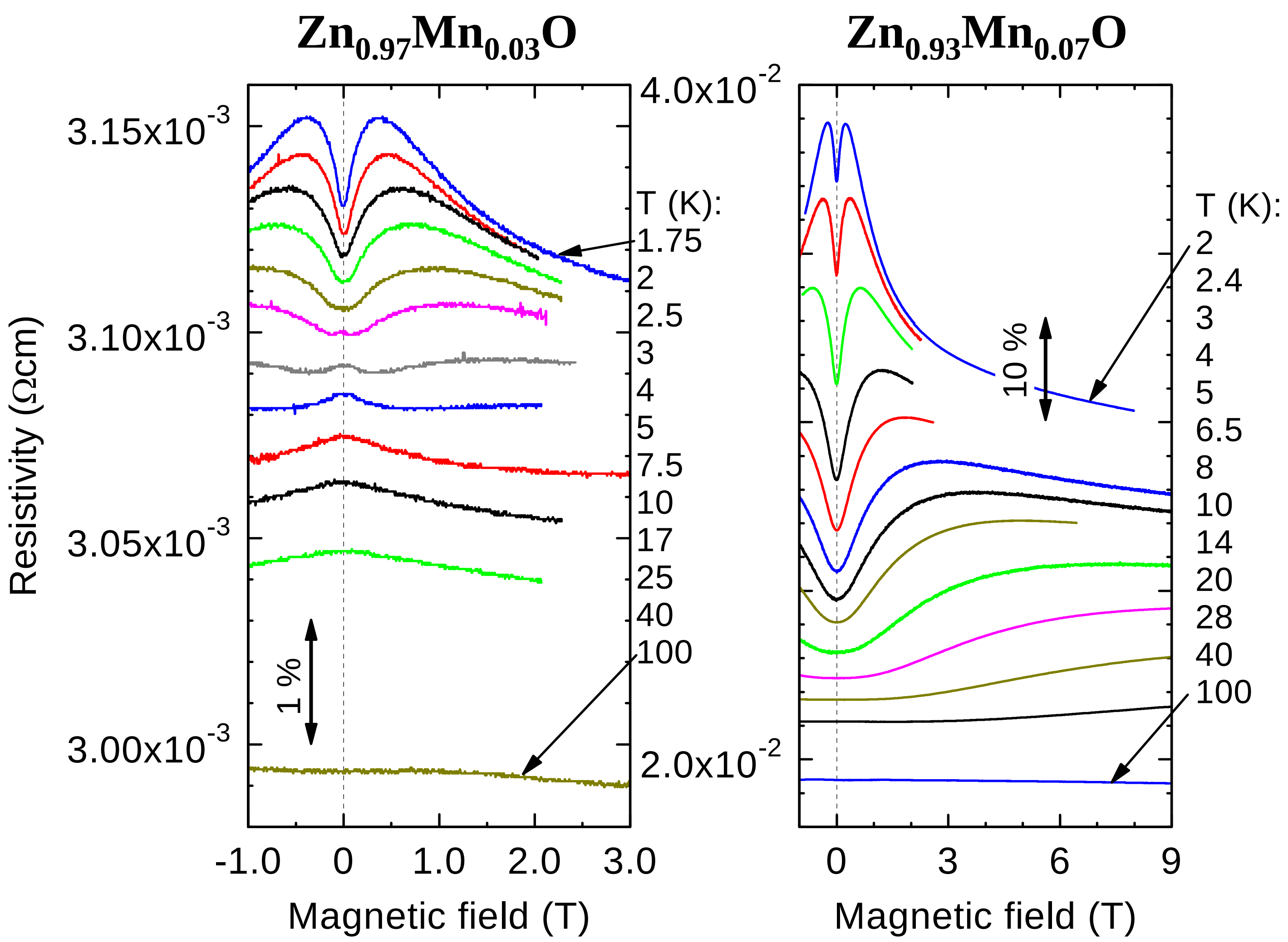
  tomorrow

Two families of DMSs: non-ferromagnetic and ferromagnetic



Non-ferromagnetic DMSs

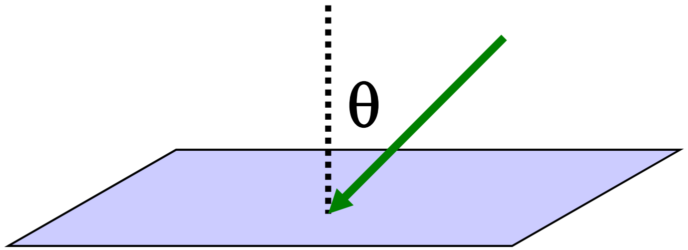
MR in n-(Zn,Mn)O at various temperatures



T. Andrearczyk, …, T.D., PRB'05

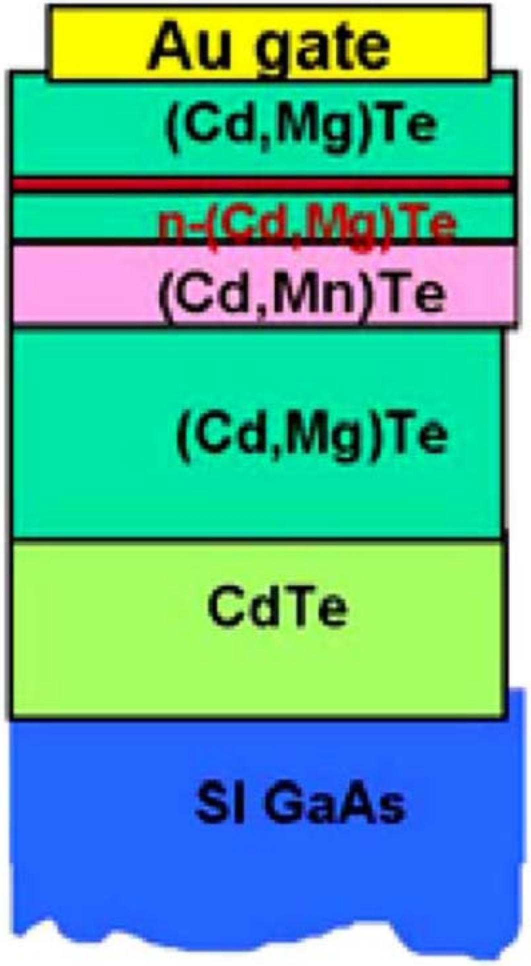
Giant anti-localization!?

2D systems can tell between orbital and spin effects



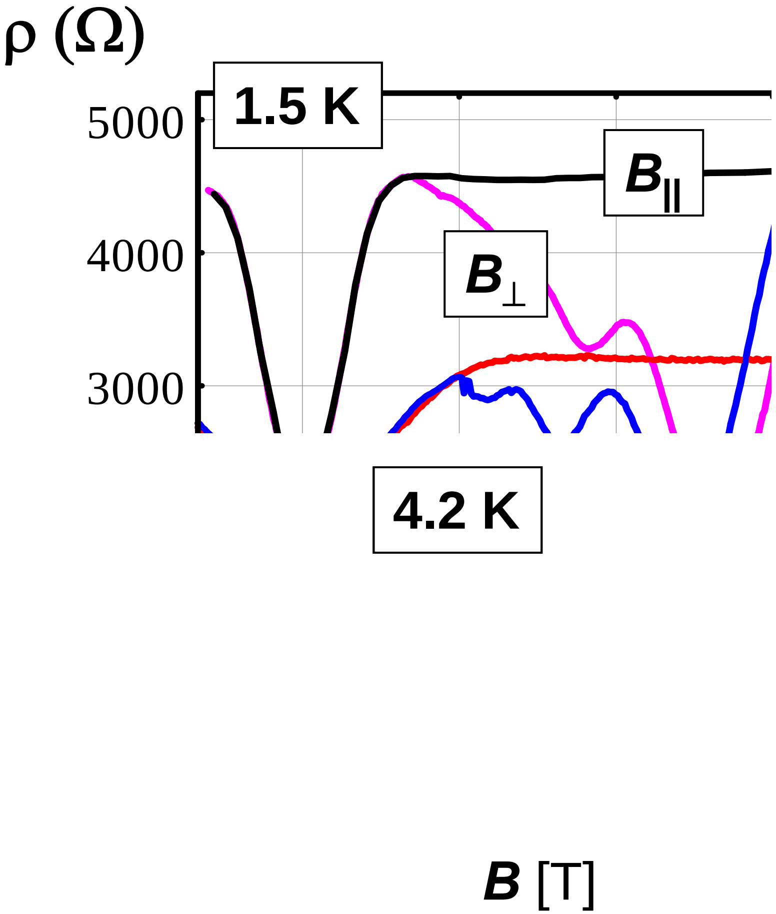
MR dependent on θ
➔ orbital effect

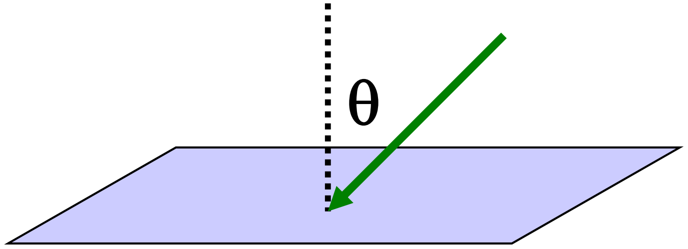
MR independent of θ
➔ spin effect



T. Wojtowicz et al. (Warsaw)

MR – n-(Cd,Mn)Te/(Cd,Mg)Te heterostructure



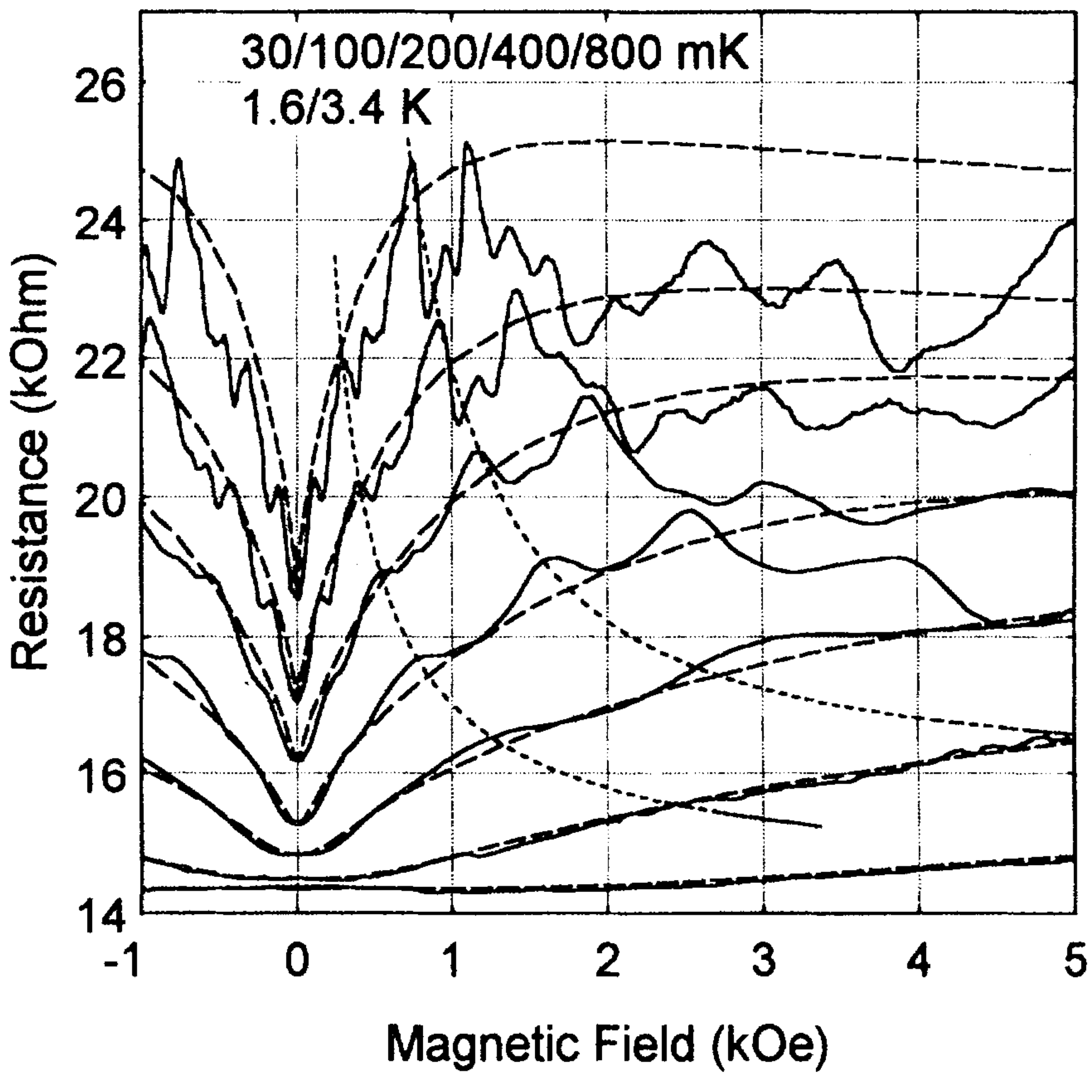


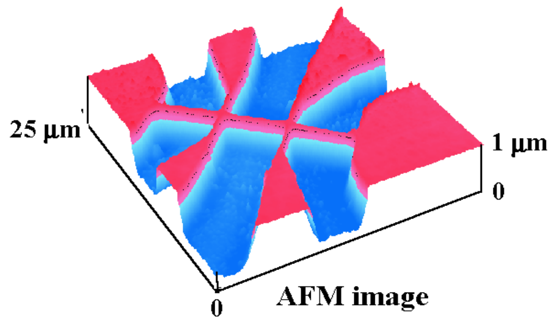
positive MR independent of θ

➔ <u>spin effect</u>

T. Andrearczyk ... T.D., Physica E'02

MR – n-(Cd,Mn)Te quantum wire





----- theory

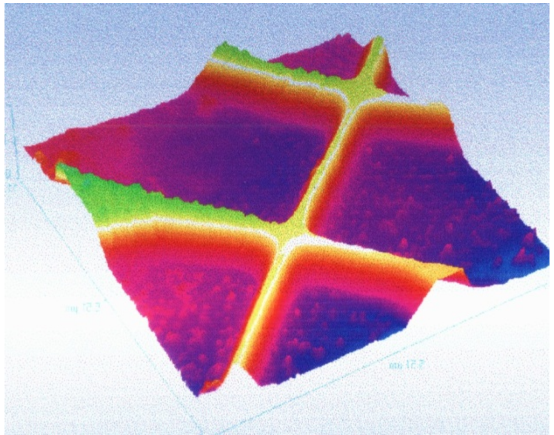
Fitting parameter:

Landau's FL parameter

$A_F \equiv 1 + F/2 = 2.2$

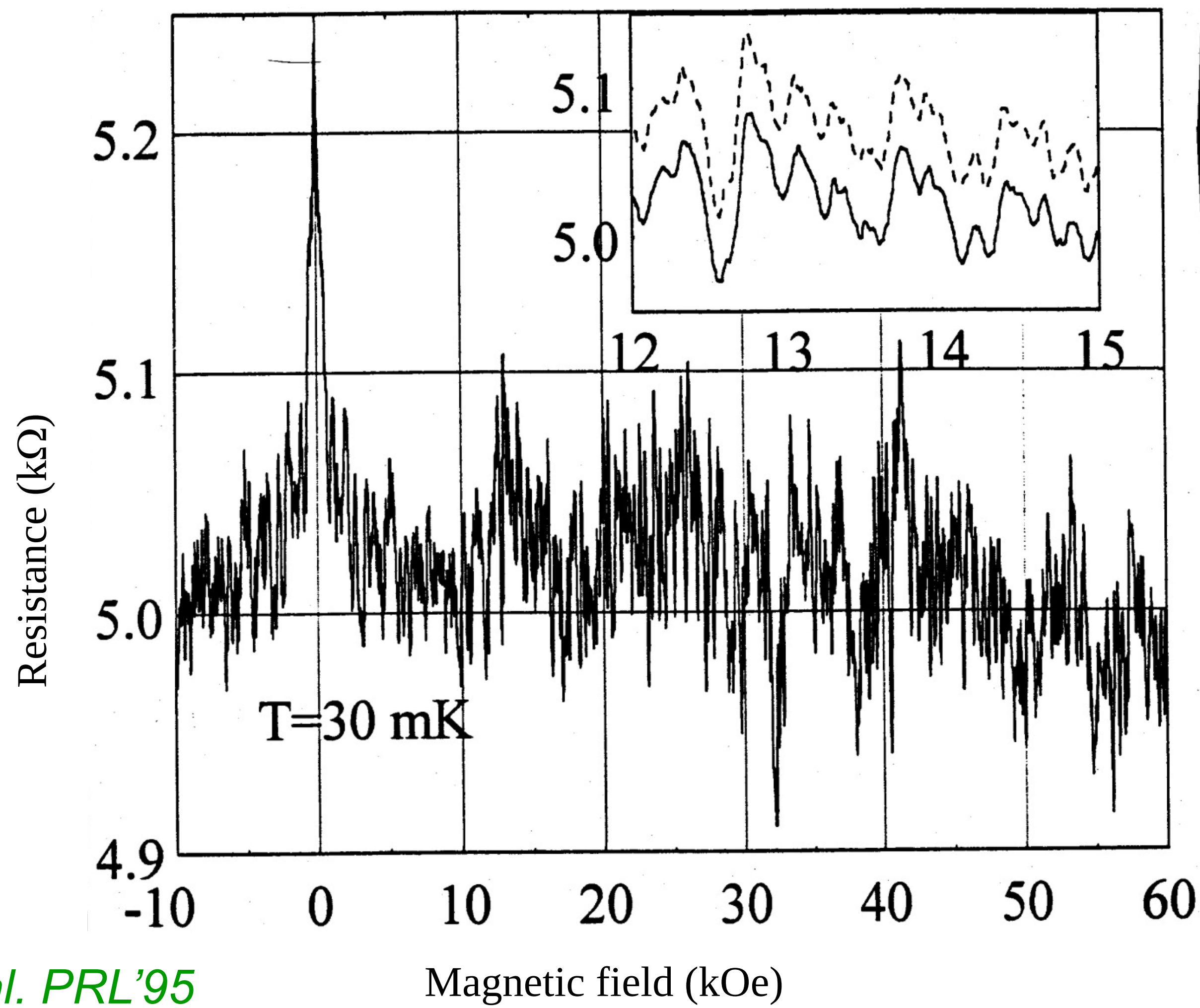
J. Jaroszyński ... T.D., PRL'95

Weak localization MR and aperiodic conductance fluctuations in a n-zb-CdTe quantum wire



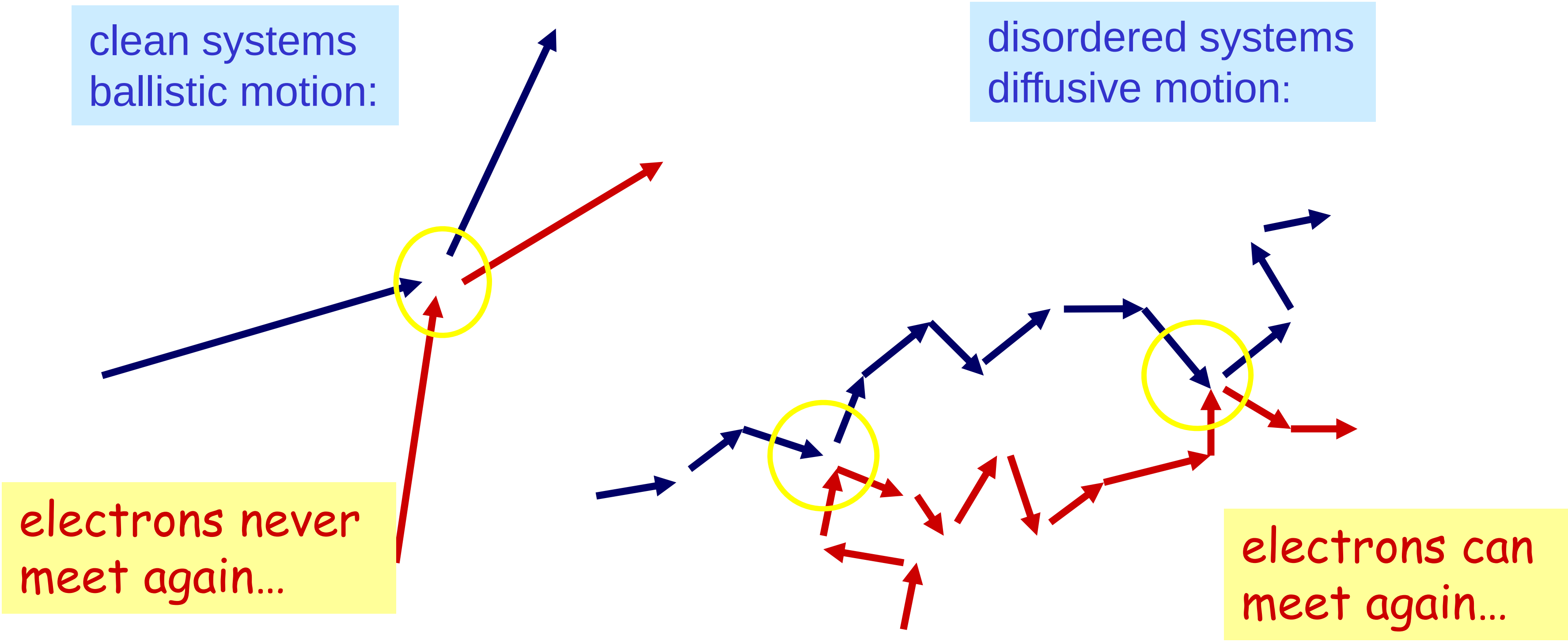
CdTe:In

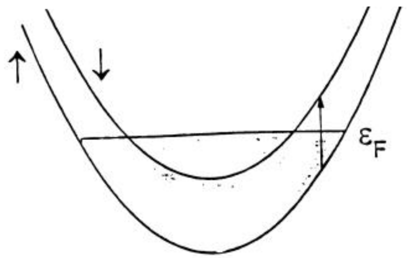
$W \approx 350$ nm



J. Jaroszynski, T.D. et al. PRL'95

Electron-electron scattering





interference of e-e scattering amplitudes

$$T_{\sigma\sigma'} = |t_\sigma|^2 + |t_{\sigma'}|^2 + 2|t_\sigma t_{\sigma'}|\cos(\varphi_\sigma - \varphi_{\sigma'})$$

same spins: diffusion reduced

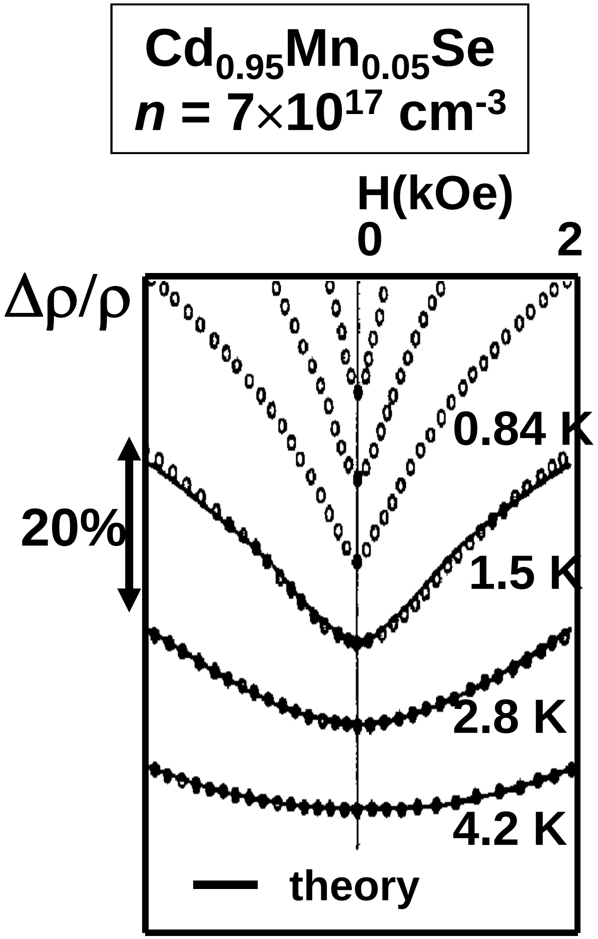
opposite spins: diffusion enhances

spin-splitting and spin-disorder scattering perturb interference

if $\hbar\omega_s \neq 0$ ➔ $k_\downarrow \neq k_\uparrow$ ➔ phase shift ➔ positive MR

Altshuler, Aronov, Fukuyama, Lee, Ramakrishnan, …

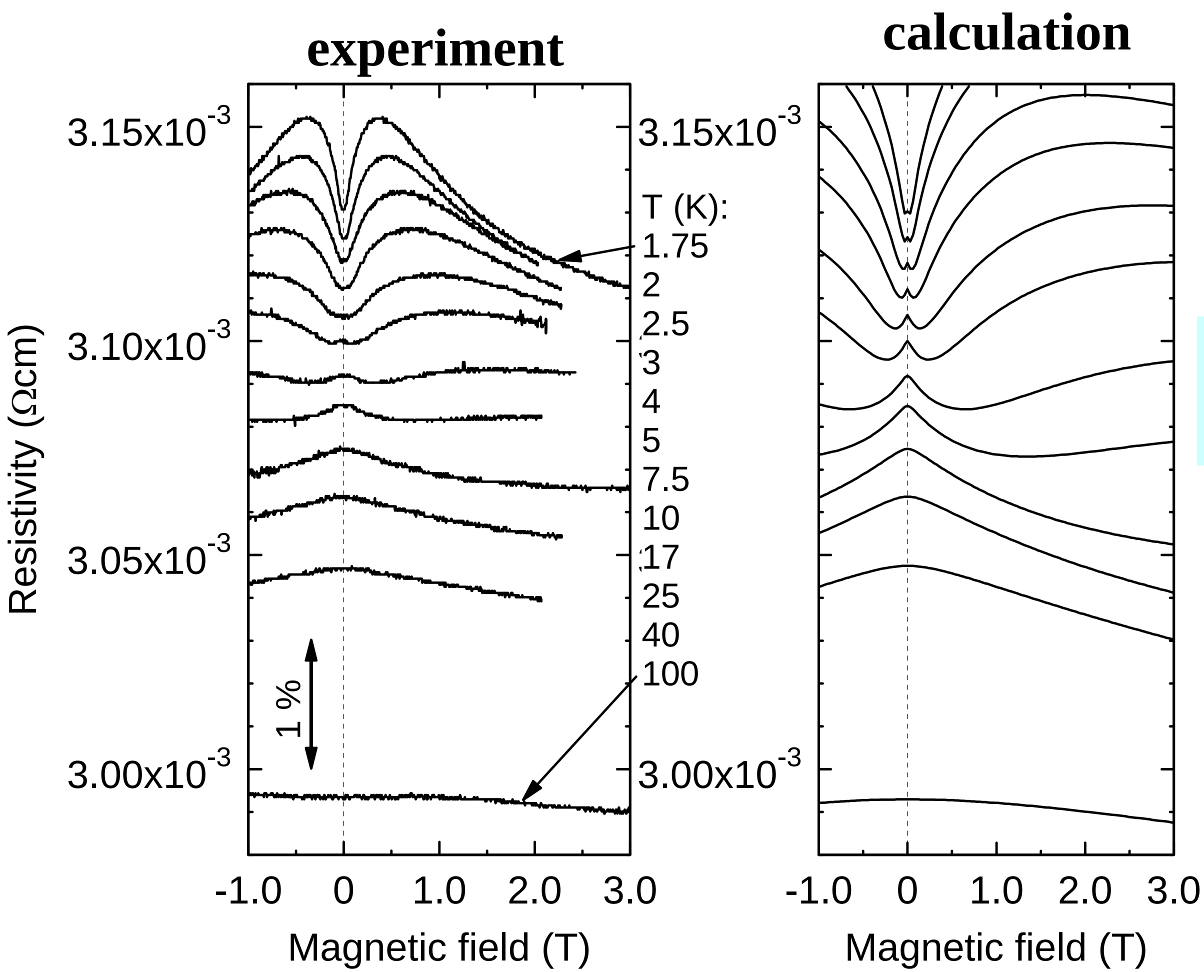
Positive MR driven by the effect of giant spin-splitting on disorder-modified e-e interaction



M. Sawicki, T.D., …PRL'86.

Landau's FL parameter
$A_F \equiv 1 + F/2 = 2.4$

Comparison of experimental and calculated MR for $Zn_{0.97}Mn_{0.03}O$



Landau's FL parameter

$A_F \equiv 1 + F/2 = 2.4$

$k_F l \approx 2.4$

T. Andrearczyk, …, T.D., PRB'05

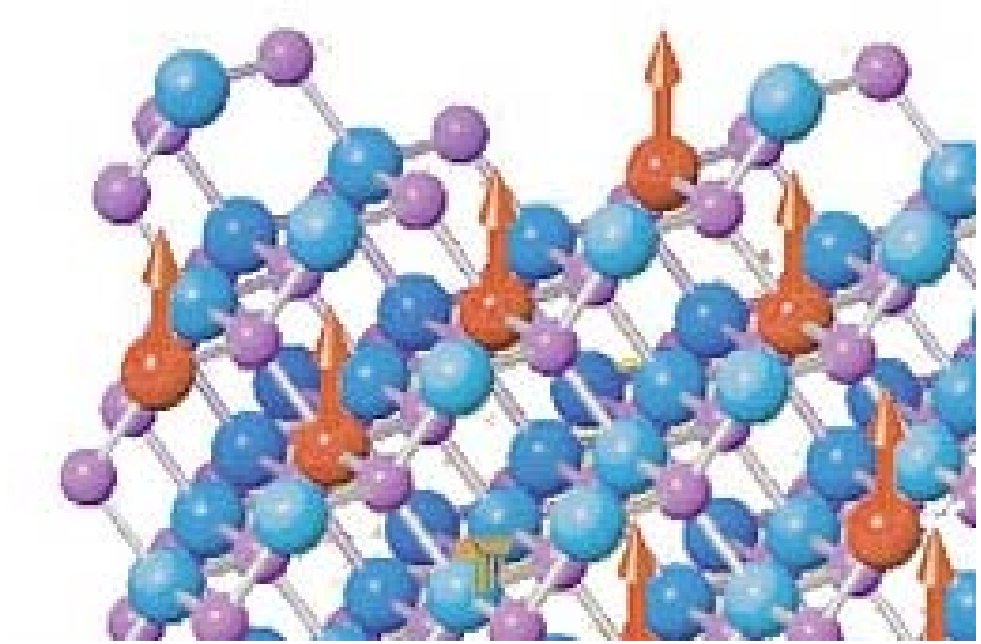
WLR in DMSs - summary

- **positive MR in non-ferro DMSs**

  effect of spin-splitting on e-e interactions

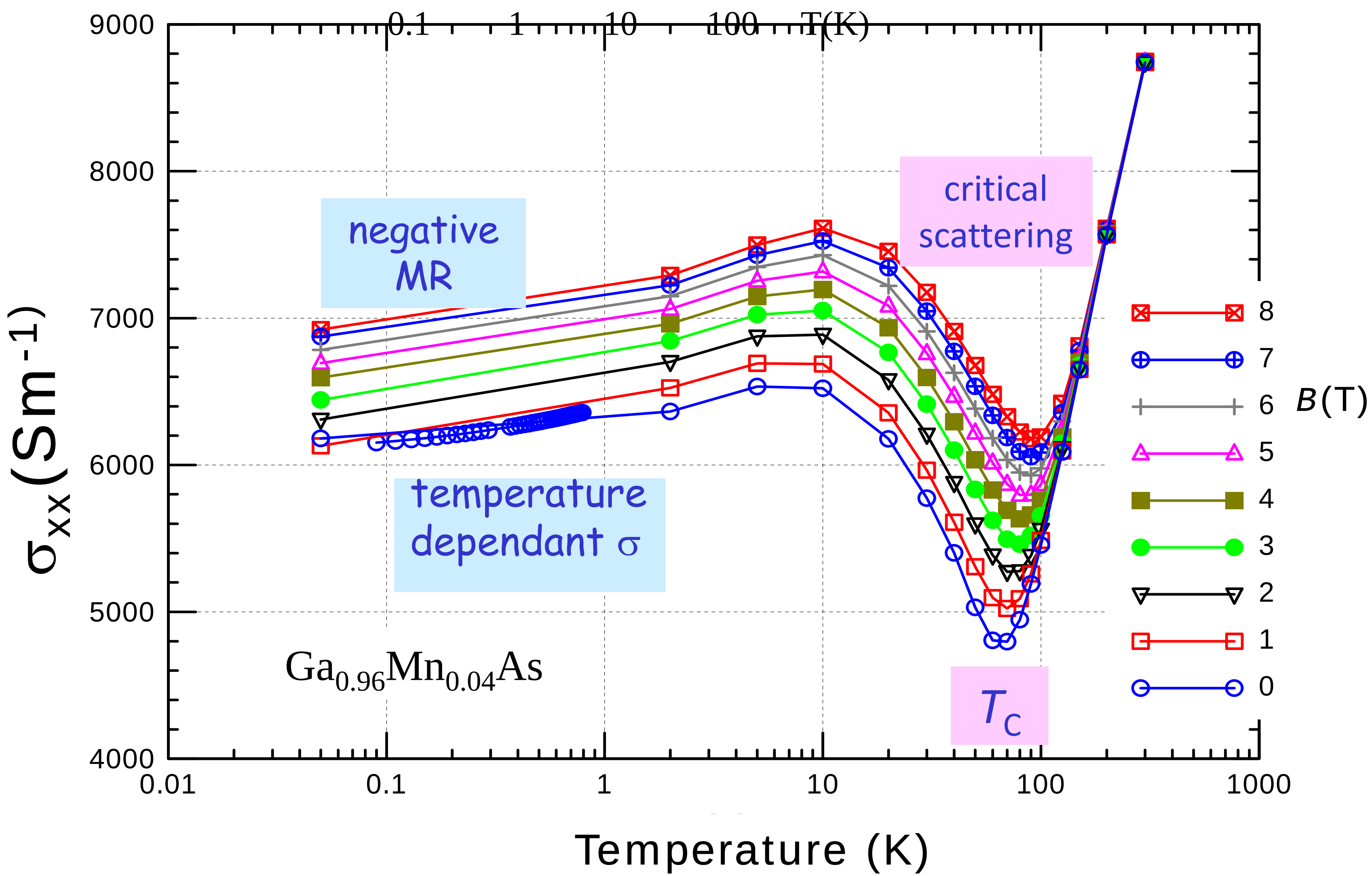
  quantitatively understood

Ferromagnetic DMSs at $T << T_C$



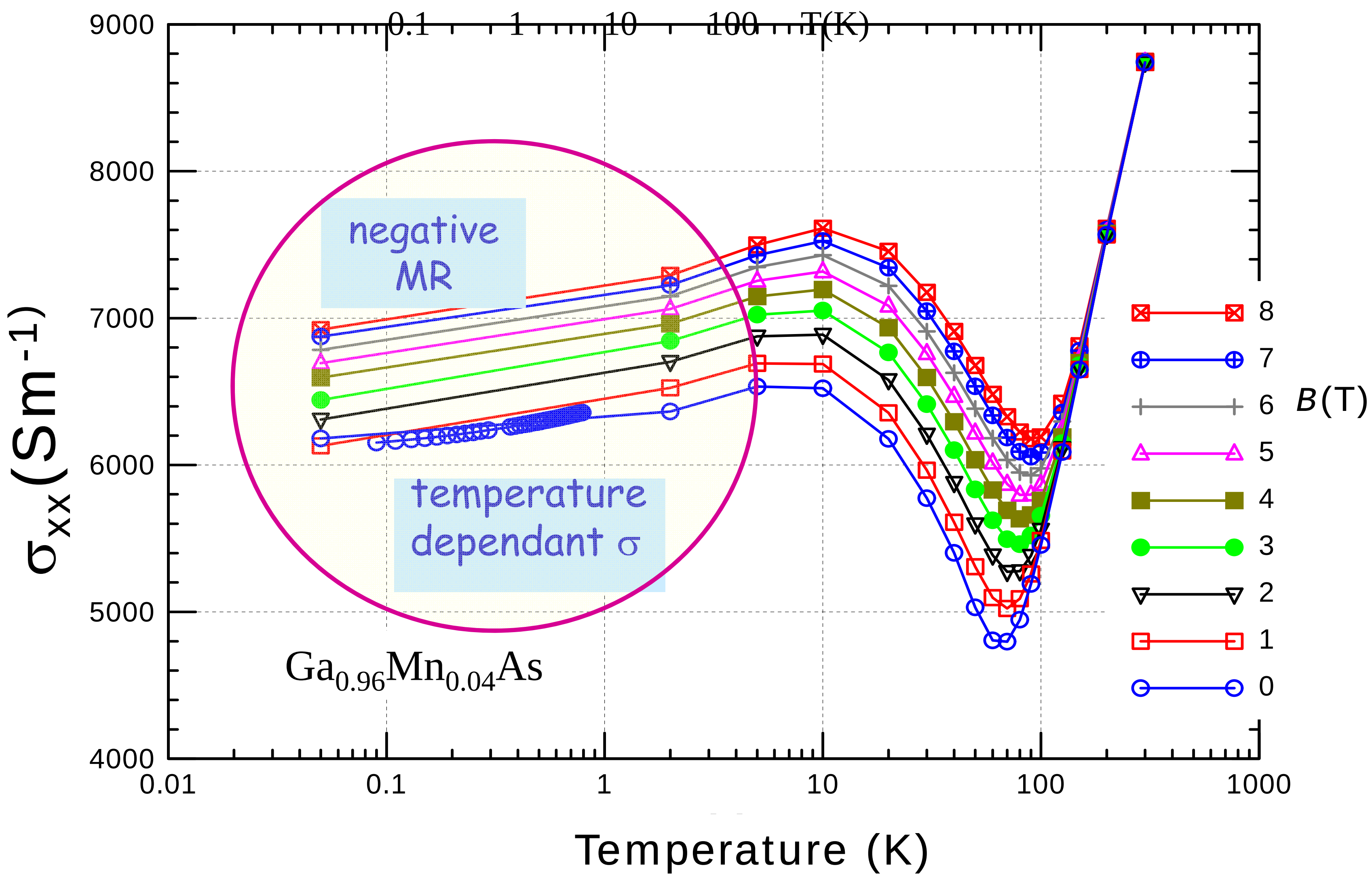
spin dynamics frozen

Temperature dependence of conductivity in various magnetic fields in (Ga,Mn)As



F. Matsukura, … T.D. et al. (Warsaw, Tohoku)'04,'05

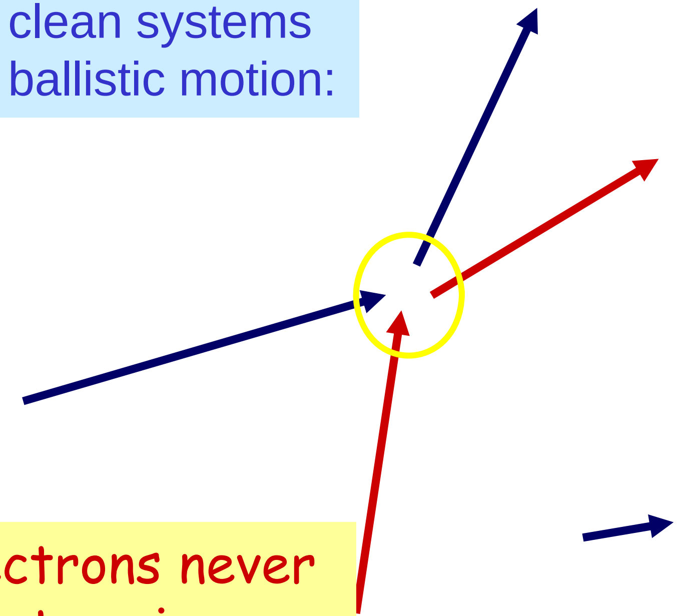
Temperature dependence of conductivity in various magnetic fields in (Ga,Mn)As



F. Matsukura, … T.D. et al. (Warsaw, Tohoku)'04,'05

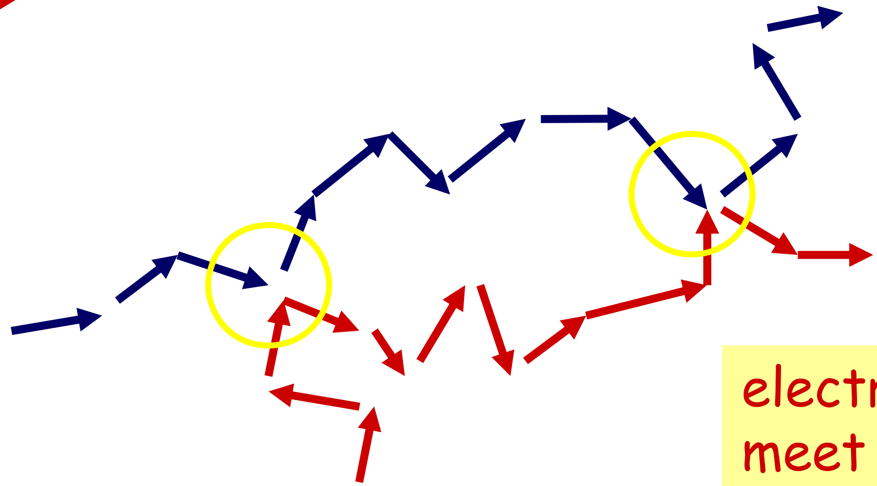
Electron-electron scattering –effect of temperature

clean systems
ballistic motion:



electrons never meet again…

disordered systems
diffusive motion:



electrons can meet again…

interference of e-e scattering amplitudes

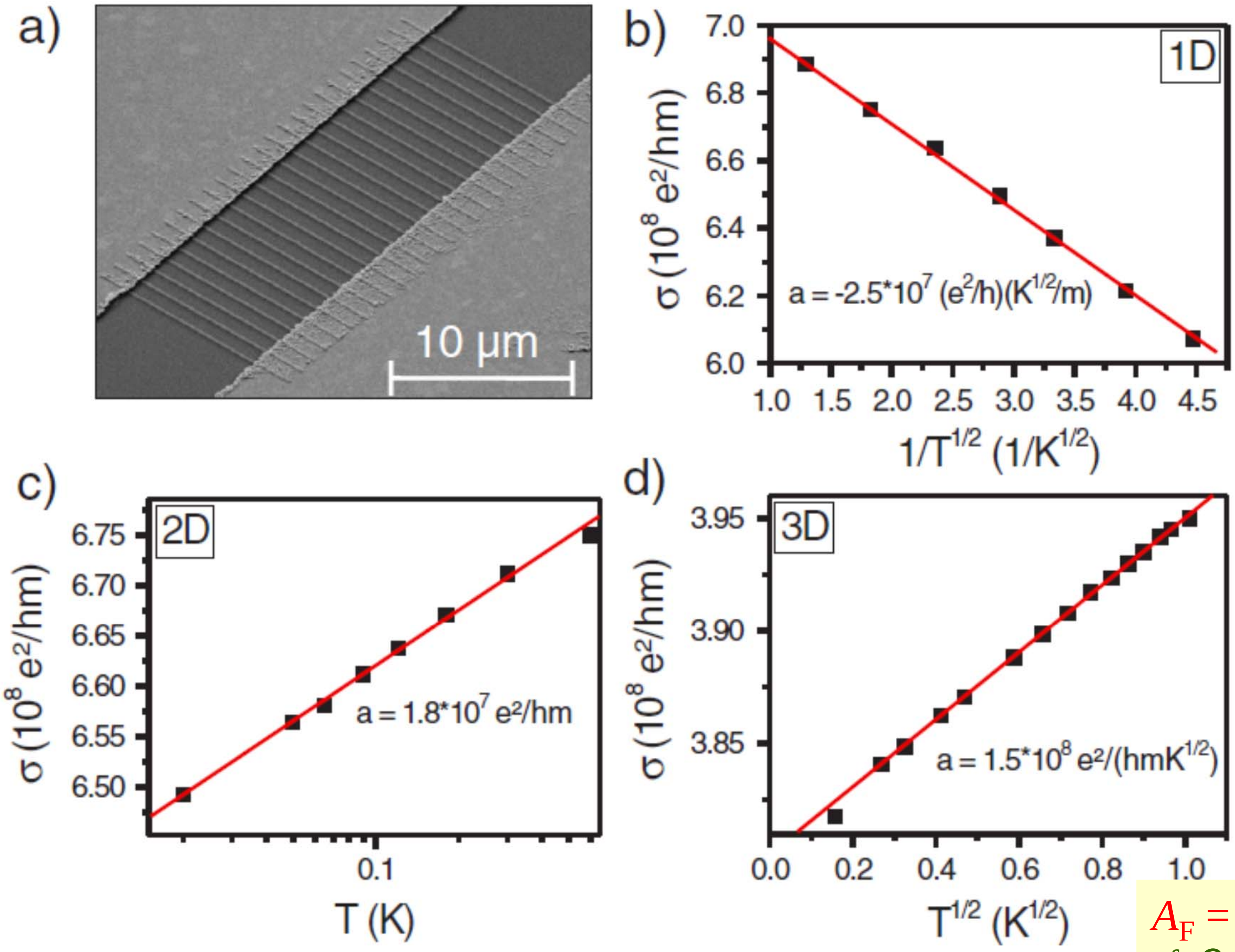
$$T_{\sigma\sigma'} = |t_\sigma|^2 + |t_{\sigma'}|^2 + 2|t_\sigma t_{\sigma'}|\cos(\varphi_\sigma - \varphi_{\sigma'})$$

effect of temperature:

two electrons can have different energy:
interference reduced

Altshuler, Aronov, Fukuyama, Lee, Ramakrishnan, …

Temperature dependence of conductance below 1 K in (Ga,Mn)As – dimensionality effects

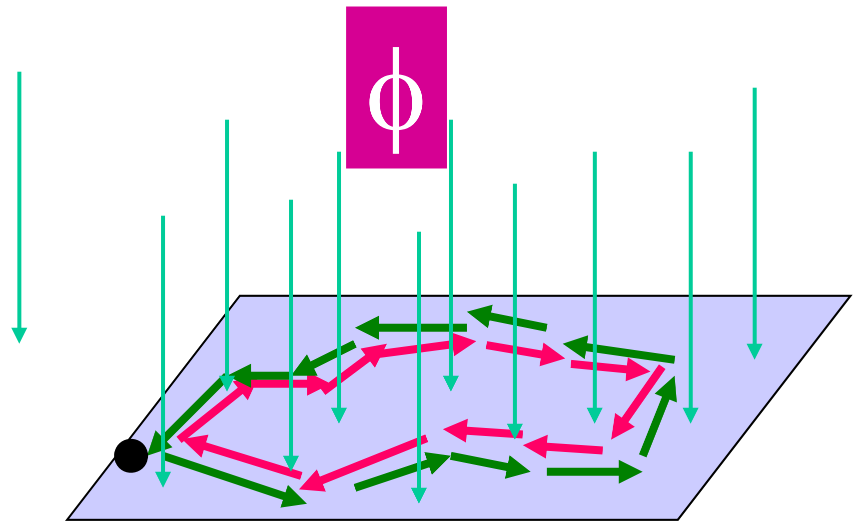


D. Neumaier et al. (Regensburg)' PRL'09

$A_F = 1.2$

cf. *C. Sliwa, T.D.,PRB'11*

Probability of returning in the magnetic field

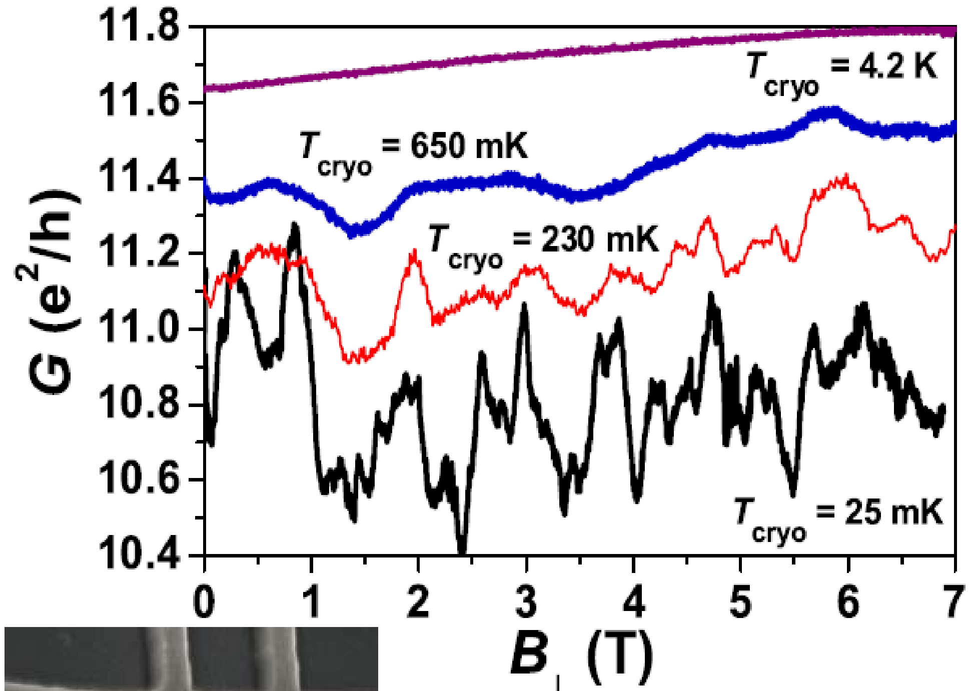


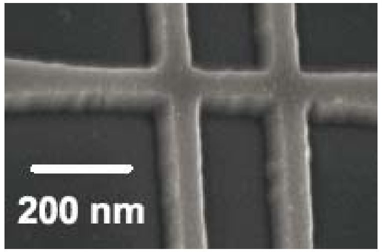
$$P_{\text{return}} = |t_r|^2 + |t_l|^2 + 2|t_r t_l|\cos(4\pi\phi/\phi_0)$$

for $L < L_\varphi$

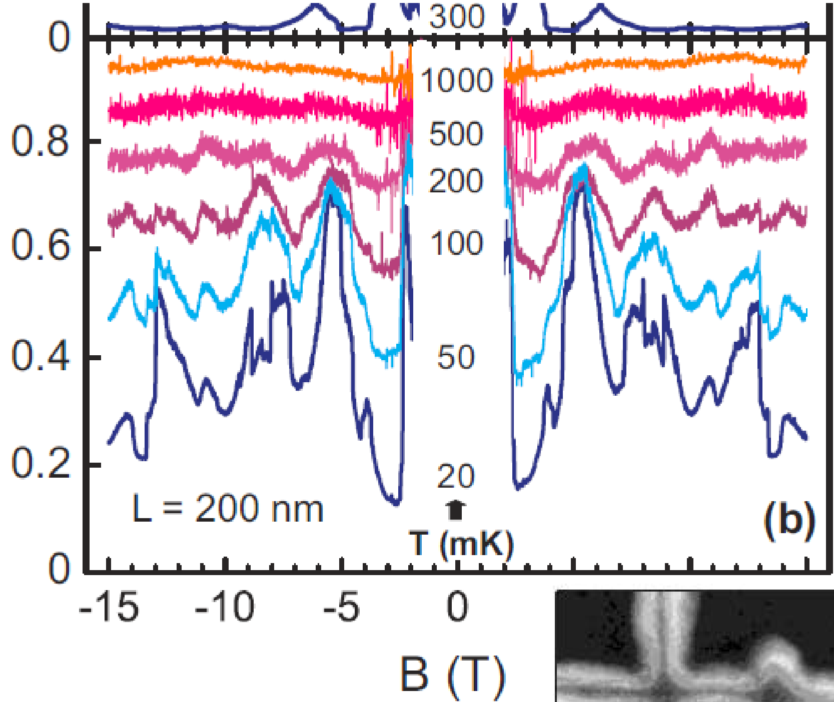
Abrahams, Khmelnitskii, Larkin, Altshuler, Aronov, ...

Coherence length L_φ in (Ga,Mn)As from UCF

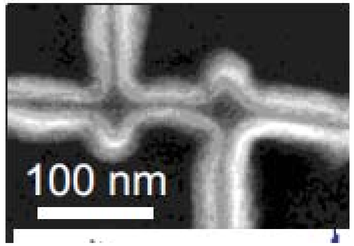




L. Vila et al. (CNRS) PRL'07



K. Wagner (Regensburg) PRL'06

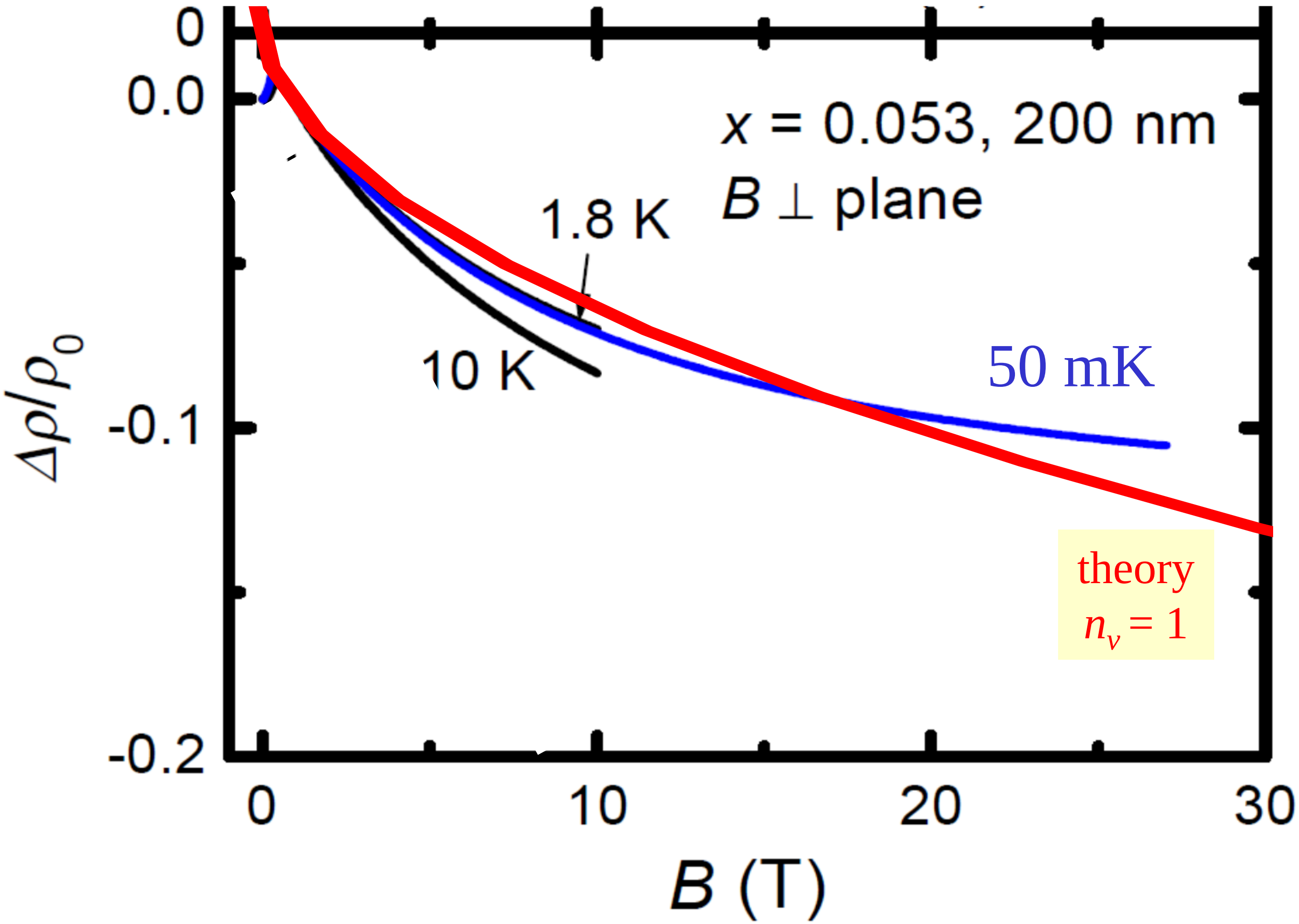


$L_\varphi \approx$ 100 nm at 100 mK

$L_\varphi \approx$ 30 nm at 100 mK

$L_B = (\hbar/eB)^{1/2} > L_\varphi$ for $B > 0.7$ T

(Ga,Mn)As: low temperature negative magnetoresistance



Y. Omiya, F. Matsukura … T.D. (Tohoku, Warsaw) Physica'01, '04

$$\Delta\rho/\rho = -n_v e^2 C_o \rho (eB/\hbar)^{1/2}/(2\pi^2\hbar), \quad \text{for } L_B < L_\varphi$$

A. Kawabata et al., (Tokyo) JPSJ'80

WLR in DMSs - summary

- **positive MR in non-ferro DMSs**

  effect of spin-splitting on e-e interactions

  quantitatively understood

- **temperature dependence at $T \ll T_C$**

  effect of thermal broadening on e-e interactions

  quantitatively understood

Provide:

A_F - Landau's enhancement of carrier magnetic susceptibility

- **negative MR at $T \ll T_C$**

  weak localization MR (orbital effect)

  quantitatively understood