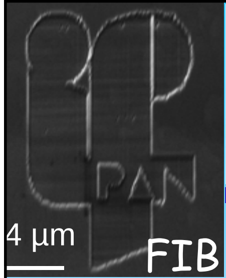


INNOWACYJNA GOSPODARKA
NARODOWA STRATEGIA SPÓJNOŚCI

NanoBiom

UNIA EUROPEJSKA
EUROPEJSKI FUNDUSZ
ROZWOJU REGIONALNEGO

European Regional Development Fund, Innovative Economy grants: POIG.01.01.02-00-008/08

II-VI Diluted Magnetic Semiconductor Nanostructures for Spintronic Research *, **

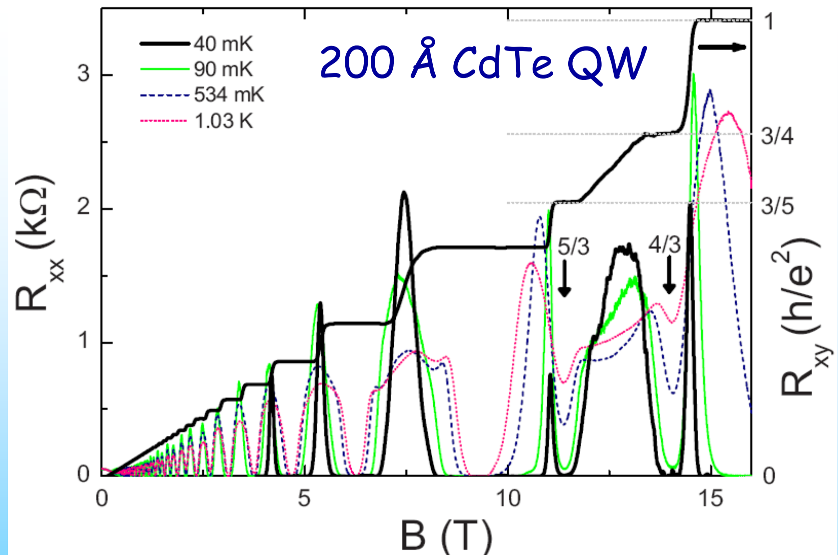
Tomasz Wojtowicz

Laboratory of growth and physics of low-dimensional crystals

Institute of Physics, PAS, Warsaw

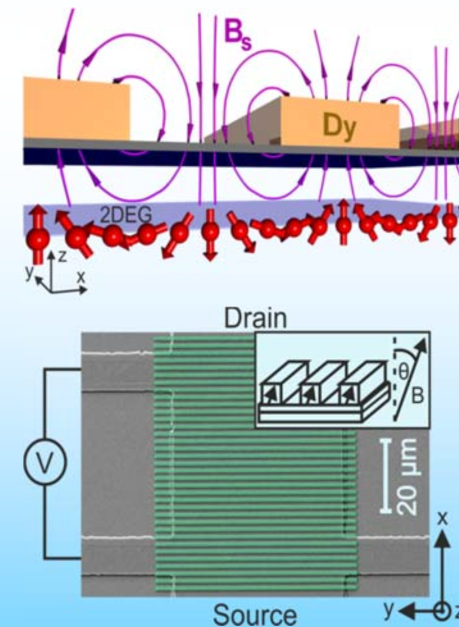
Technology

Record μ in wide gap II-Te & FQHE



B. Piot, *et al.*, Phys. Rev. B **82**, 081307 (R) (2010))

New type of spin transistor



C. Betthausen, *et al.*, Science **337** (2012) 324

* Partially supported also by the National Centre of Science (Poland) grant Maestro:DEC-2012/06/A/ST3/00247

** Plenary talk at the 20th EP2DS and 16th MSS Int. Conf., Wrocław, Poland, July 5, 2013

Outline

- Motivation for research on telluride nanostructures in context of spintronics

- QDs and NWs produced by "bottom-up" approach

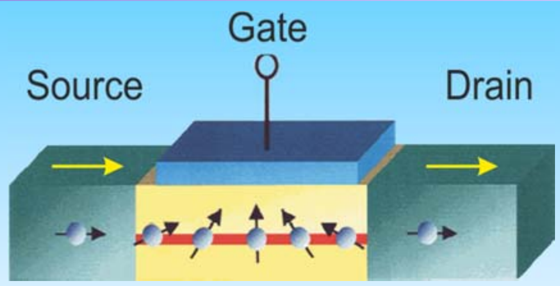
- Growth and studies which demonstrated that it is possible to improve mobility of 2DEG in CdTe and CdMnTe nanostructures (grown on 2 in hybrid substrates) by:
  - setting the new world record in 2DEG mobility of wide gap II-VI tellurides
  - the first observation of FQHE in wide gap nonmagnetic and magnetic telluride nanostructures (qualitative progress)

- Applications of CdTe- and CdMnTe-based 2DEG nanostructures for:
  - Demonstration of spin-polarization of 4/3 and 5/3 FQHE ground states
  - Observation of the enhancement of the spin gap in fully occupied two-dimensional Landau levels
  - Terahertz and microwave radiation induced generation of pure spin currents
  - Generation of terahertz radiation pulses from spin-waves
  - Demonstration of a new type of "spin transistor" action
  - Quantitative determination of an enhancement of spin-orbit field in collective spin excitations

- Conclusions

Spintronics and Diluted Magnetic Semiconductors

Spintronics is all about spin: spin is meant to be the basis of device operation



S. Datta, B. Das, App. Phys. Lett. **56**, (1990) 665

Important branch of spintronic research is related to Diluted Magnetic Semiconductors (DMSs)

DMSs - mixed crystals of nonmagnetic and magnetic semiconductor: (GaAs+MnAs=GaMnAs or CdTe+MnTe=CdMnTe)

DMSs - **characterized by very strong enhancement of all spin dependent properties** due to the exchange interaction between localized spins of magnetic ions (e.g. Mn^{2+}) and spins of band carriers

The role of "traditional" II-VI DMSs, such as tellurides with Mn, not as large as it could be.

They are not promising in the context of recent world wide quest of room temperature homogenous ferromagnetic semiconductor.

Motivation for research on 2DEG in telluride nanostructures and especially DMS

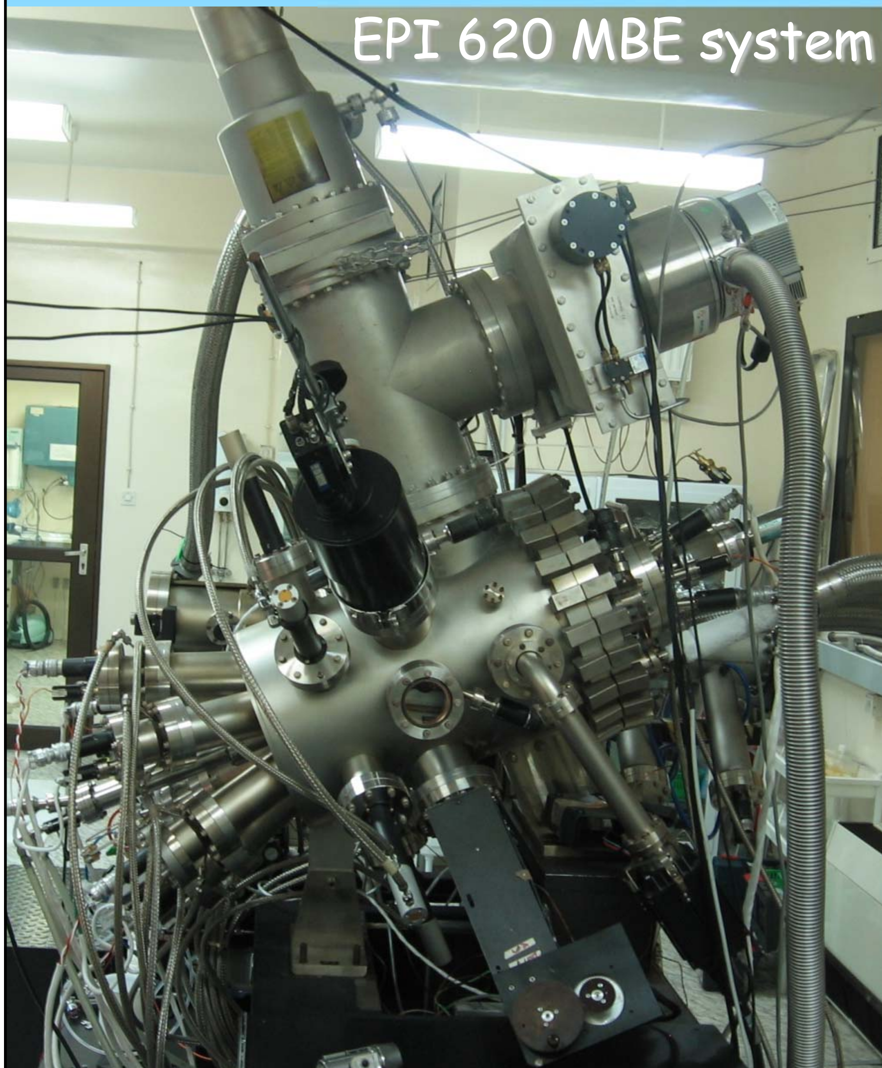
The importance of II-VIs could increase if:

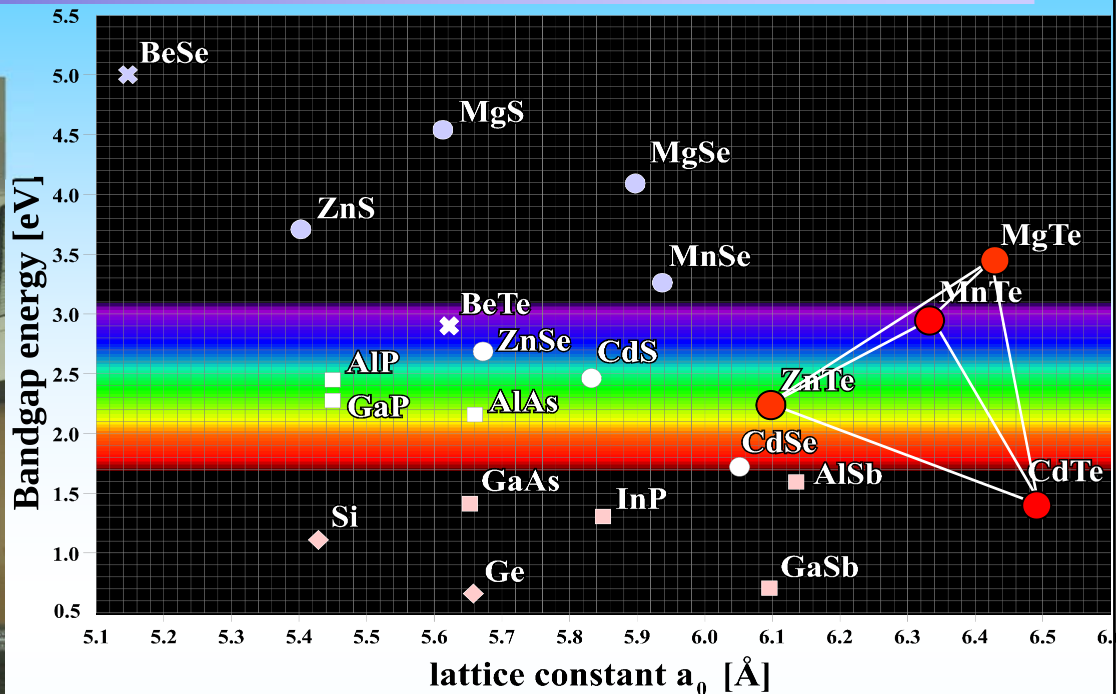
- the technology of II-VI nanostructures would be improved, especially if high mobility CdTe-based 2DEG nanostructures become available
- EB and FIB lithography of those nanostructure will be developed (so as to produce 1-D and 0-D structures within "top down" approach).

Advantages/differences of II-Mn-Te DMS nanostructures in comp. to III-Mn-Vs

- enhanced excitonic effects
- Mn can be built into lattice substitutional positions up to 100% (ZB MnTe) – no problem with interstitial Mn
- incorporation of isovalent Mn does not deteriorate excellent optical properties (as opposite to the case of GaAs where Mn is an acceptor) and should not lead to any critical reduction of 2DEG mobility
- spin splitting engineering is possible

SL3 LAB of growth and physics of low-dimensional crystals of the Institute of Physics, PAS, Warsaw





EPI 620 MBE system for II-VIs:

Cd Mg Zn Mn Te

ZnI_2 - „n" N plasma cell- „p"

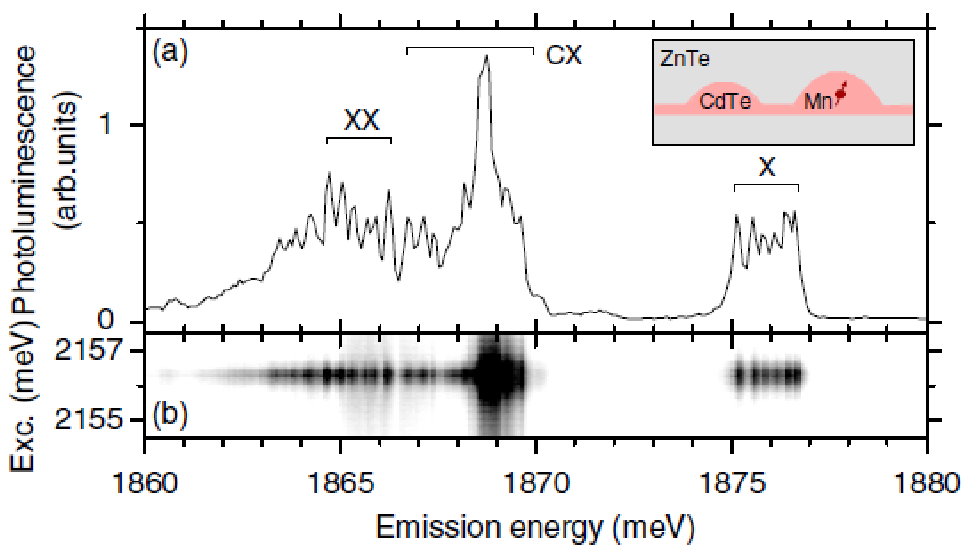
Spare: Cr, In ...

20th year of Lab (first growth on July 6, 1993). We have grown ≈ 6000 samples and we specialize in:

II-VI tellurides: **Diluted Magnetic Semiconductors** (Warsaw's tradition)
„Normal": QWs, SL, QDs **including single Mn**, sophisticated: **parabolic QWs, in-plane graded QWs, DMS nanowires, high mobility 2DEG in DMS**

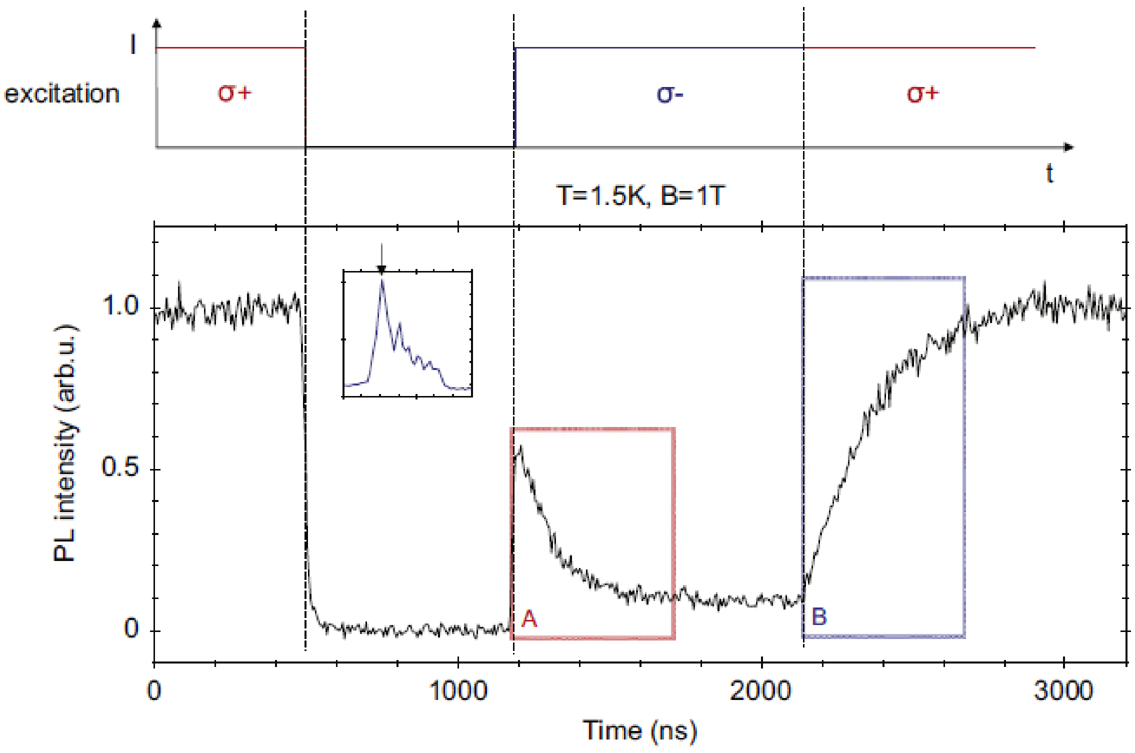
Optical manipulation of a single Mn in a CdTe QDs Ultimate limit for information storage miniaturization

M. Goryca, *et al.*, Phys. Rev. Lett. **103** (2009) 087401; Physica E **42** (2010) 2690



Optical writing of information on the spin state of Mn ion by spin polarized carriers transferred from neighboring CdTe QD

Sextuplet due to exciton-Mn exchange int.



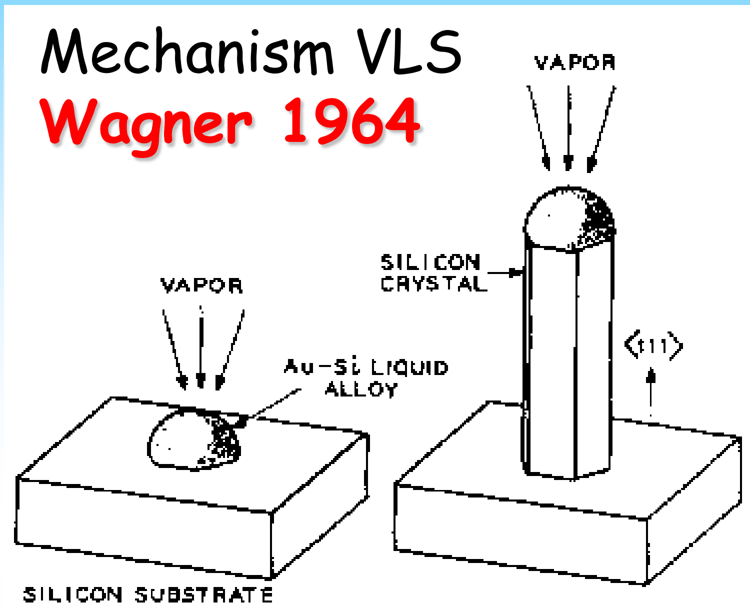
Unequal intensity of lines a measure of spin orientation

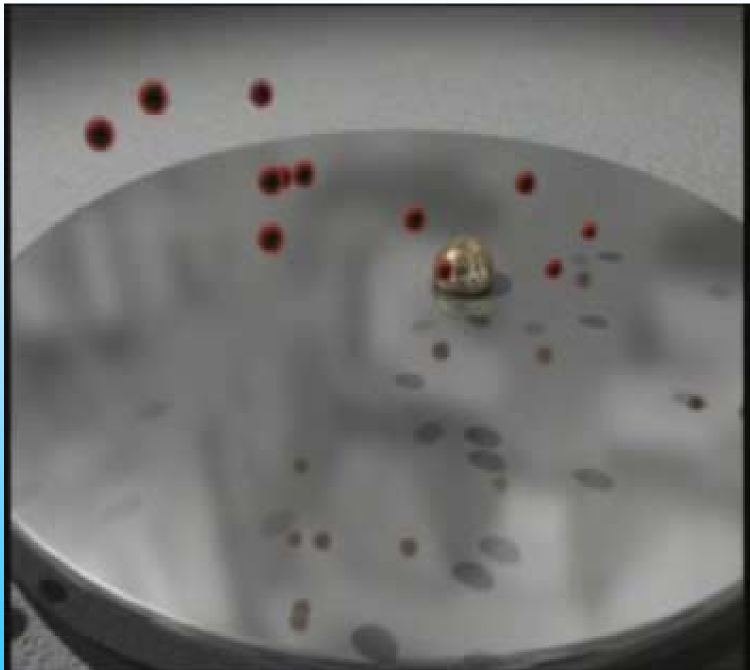
Mn orientation time 20-100 ns depending of excitation power (20-2.5 μW)

Storage time of information on Mn spin at 1T in the dark – hundreds of microseconds

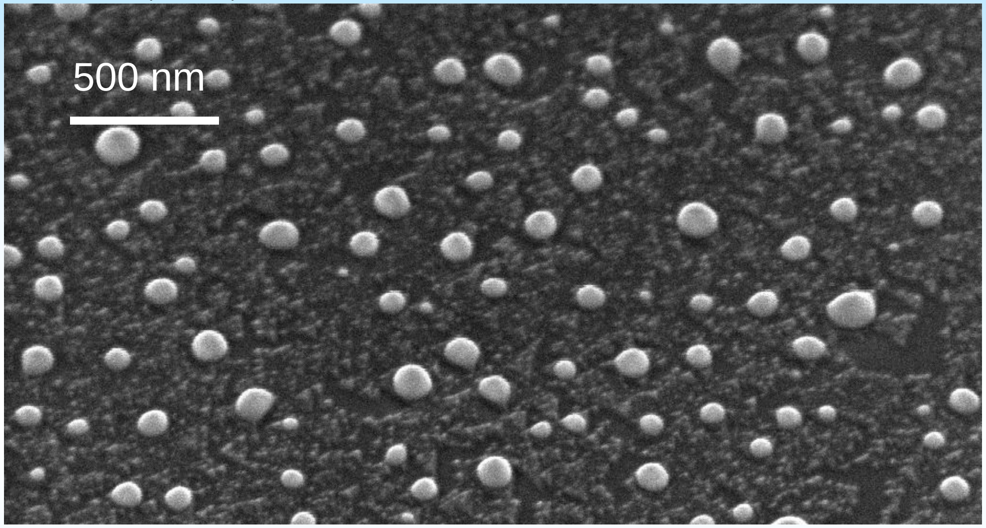
Growth of ZnMnTe nanowires: Au assisted Vapor-Liquid-Solid (VLS) growth mechnism

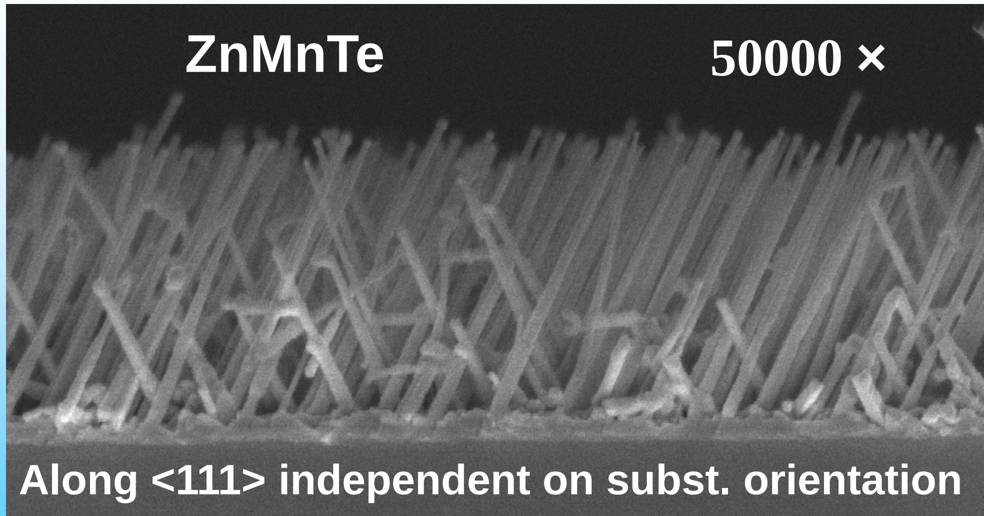
W. Zaleszczyk, *et al.*, Nano Lett. **8** (2008) 4061





Au/Ga nano-catalysts: produced thermally from a thin (1nm) Au film on GaAs

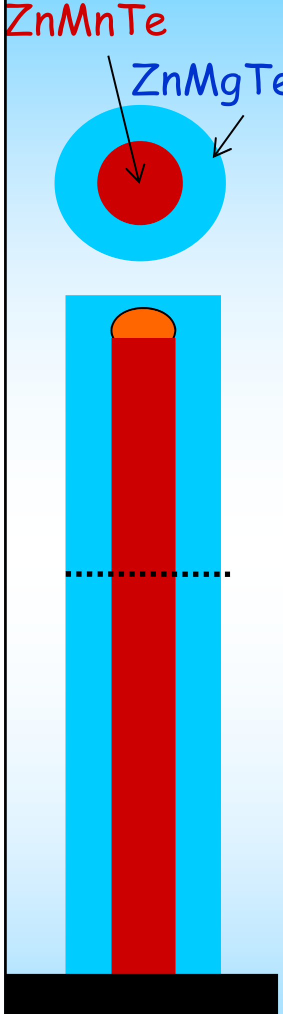


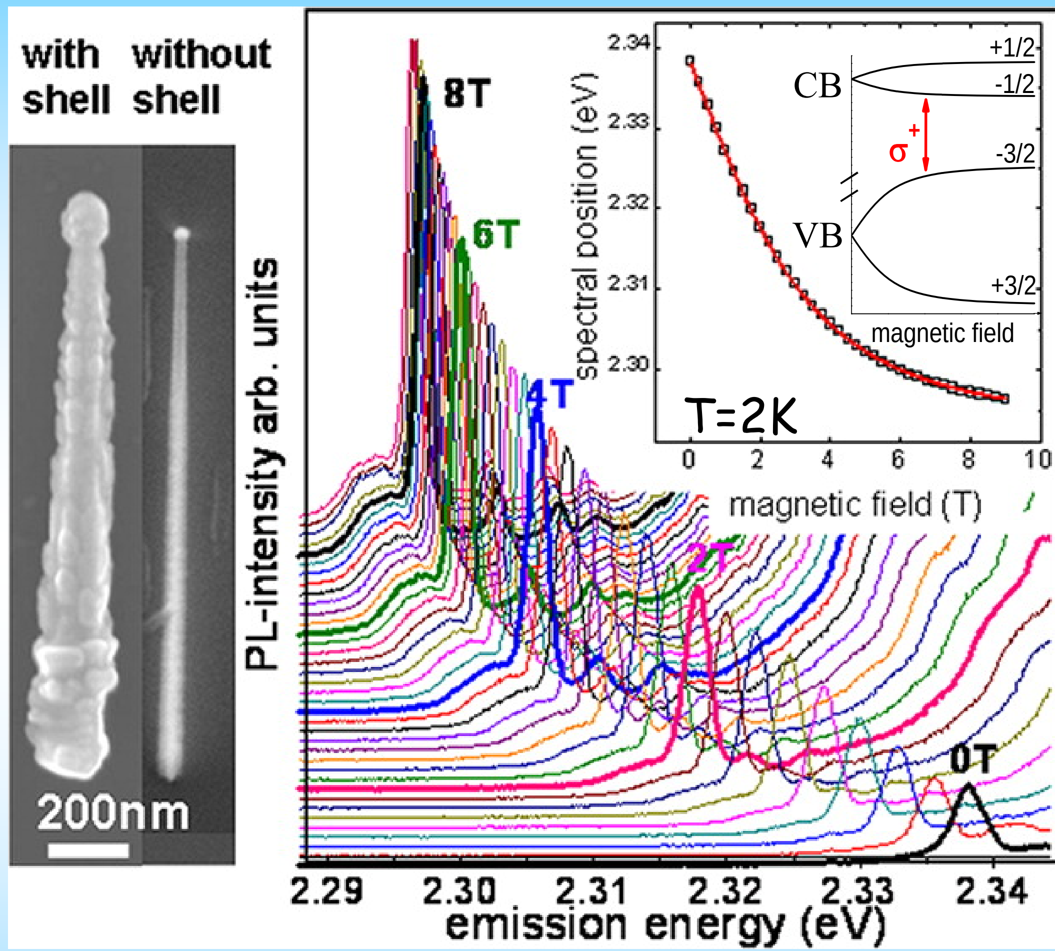


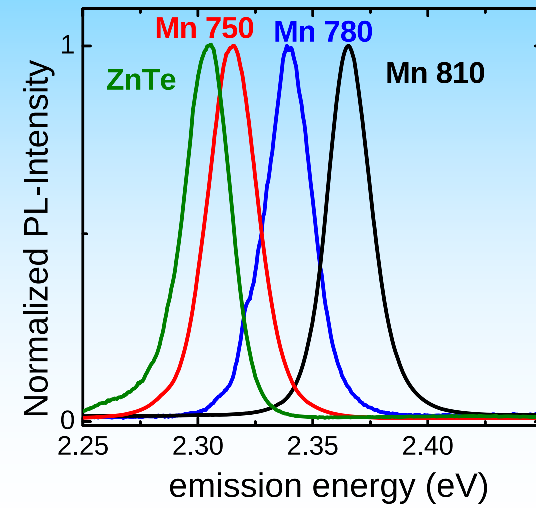
Homogenous, substitutional incorporation of Mn up to 60%: X-ray, EELS, resonant Raman, internal Mn^{2+} PL vs. T

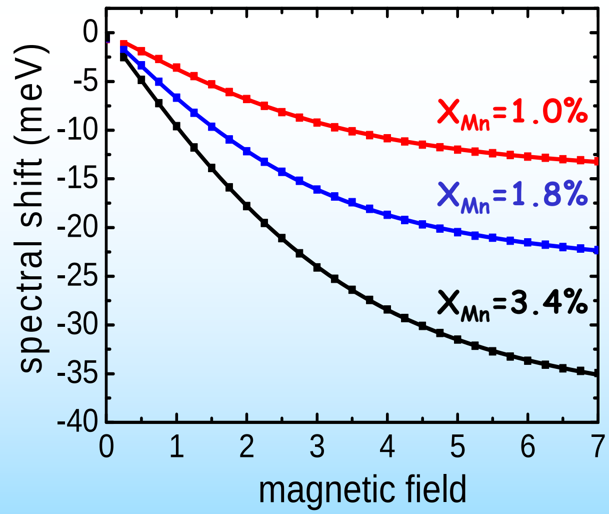
Giant spin splitting in optically active ZnMnTe/ZnMgTe core/shell nanowires

P. Wojnar, *et al.*, Nano Lett. **12** (2012) 3404









PL-lines from single NW: μ-PL spot size ~2 µm

Proof of DMS nanowires

First step toward magnetic QDs and coupled QDs inside NWs

(nonmagnetic CdTe QDs in NWs as a single photon sources already demonstrated in photon correlation experiments)

Advantages/differences of high mobility 2DEG structures based on CdTe in comp. to GaAs

Most of the 2DEG related research has been done so far on GaAs and Si based nanostructures since their technology is at much higher level than that of II-VI, however tellurides are characterized by:

- probably smaller charge metastable effects
- larger intrinsic g-factor (in CdTe g = -1.7) – four times larger Zeeman energy of 98μeV/T (interaction parameter $E_{Zeeman}/E_{Exchange}$ is ≈ 3 times larger than in GaAs)
- incorporation of isovalent Mn (as opposite to the case of GaAs where Mn is an acceptor) does not lead to any critical reduction of 2DEG mobility
- effective g-factor can be engineered by incorporation of Mn (both in sign and value, g_{eff} as high as 500 can be achieved, crossing of spin levels with B - QHFm)

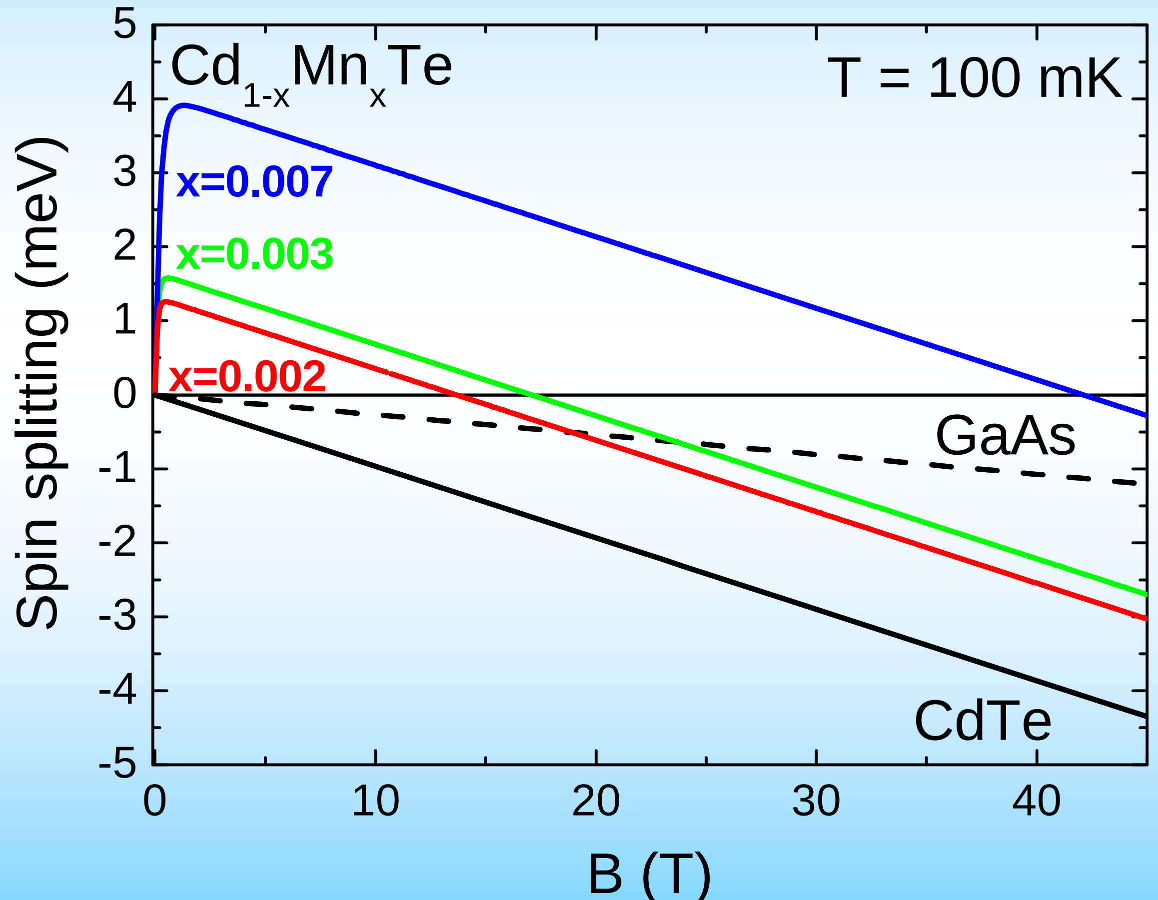
Spin splitting engineering in CdMnTe QW with 2DEG important since spintronics is all about spin

$$g^*_{eff} = g^*_{in} + \frac{\alpha M(H,T)}{g_{Mn}\mu_B^2 H}$$

$g^*_{in} = -1.7$

$g^*_{exch} \leq +500$

Temperature and field dependent



Crossing of LLs with the same index possible at various ν

This can be used in studies of FQHE

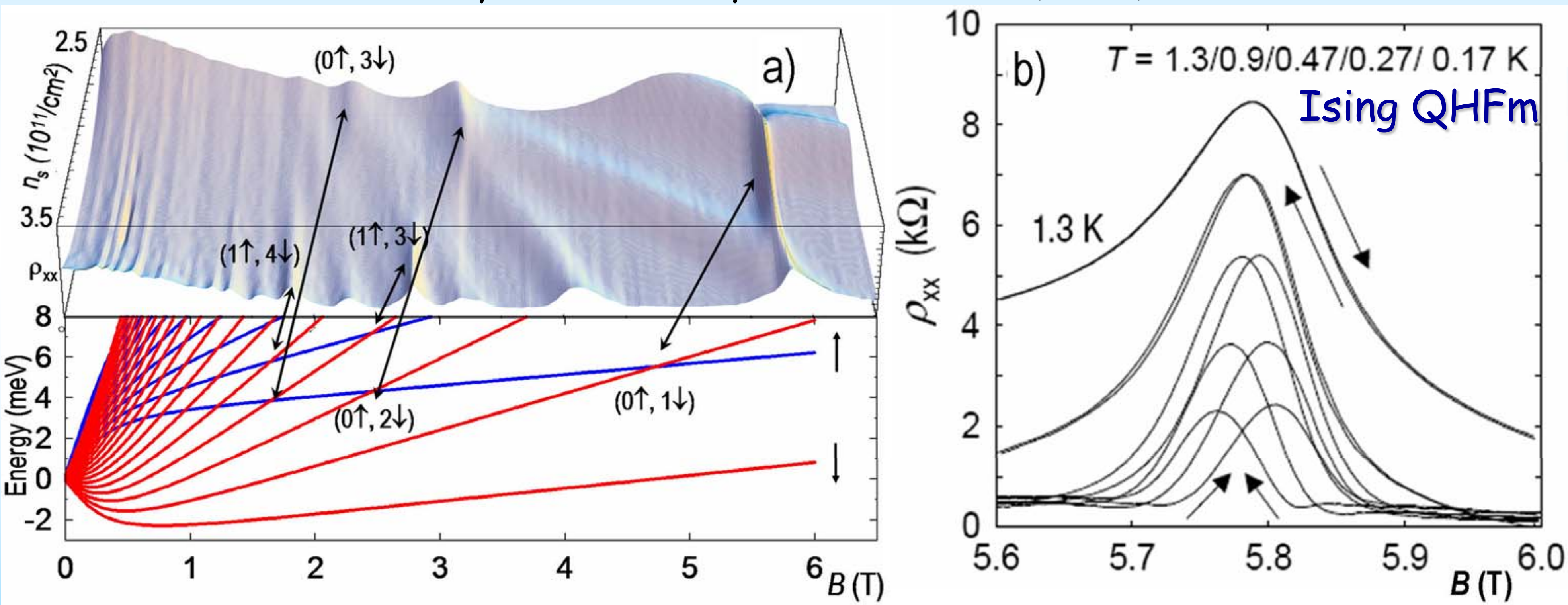
Dependence of splitting on B can be further engineered via Mn distribution in the direction of growth, e.g. in parabolic QWs made of CdMnMgTe:

T.Wojtowicz *et al.* J. Cryst. Growth **214** (2000) 378

Spin splitting engineering for the studies of Quantum Hall Ferromagnet* (QHFm)

In DMS there is a unique situation in which crossing of the spin levels can be induced by the application of solely vertical magnetic field (without in-plane component)

J. Jaroszyński, *et al.* Phys. Rev. Lett. **89** (2002) 266802



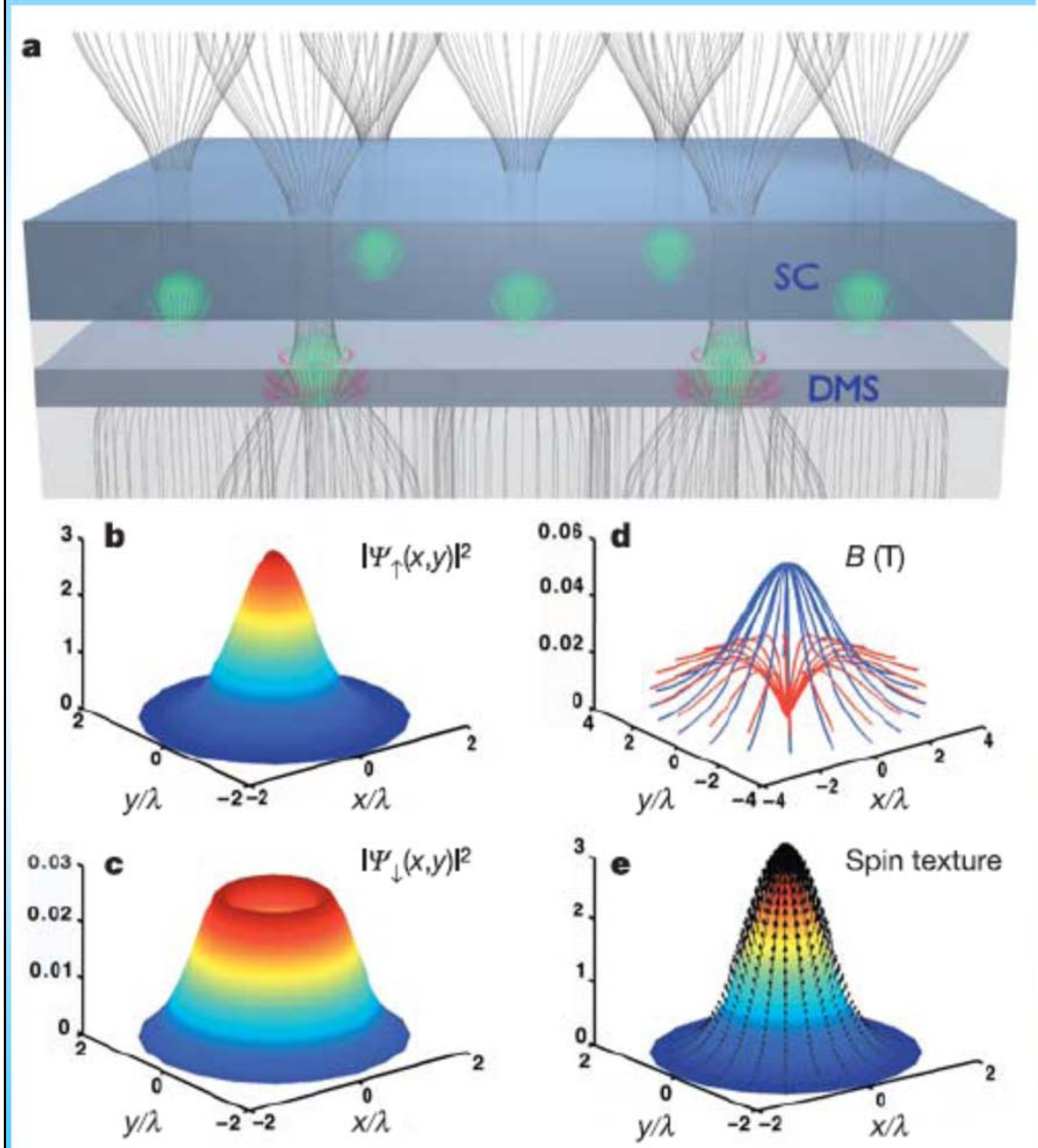
Hysteretic deeps in Hall resistance predicted by H.J.P. Freire, J.C. Egues, Phys. Rev. Lett. **99** (2007) 026801

*Quantum Hall (pseudo)ferromagnetism is a ferromagnetism of carriers when spin subbands with opposite spins are brought into degeneracy under quantum Hall effect regime (B ≠ 0 !)

Hybrid structures: local B from nanomagnets or superconducting vortices in 2DEG inside CdMnTe

NATURE | VOL 435 | 5 MAY 2005 | www.nature.com/nature

71
letters to nature

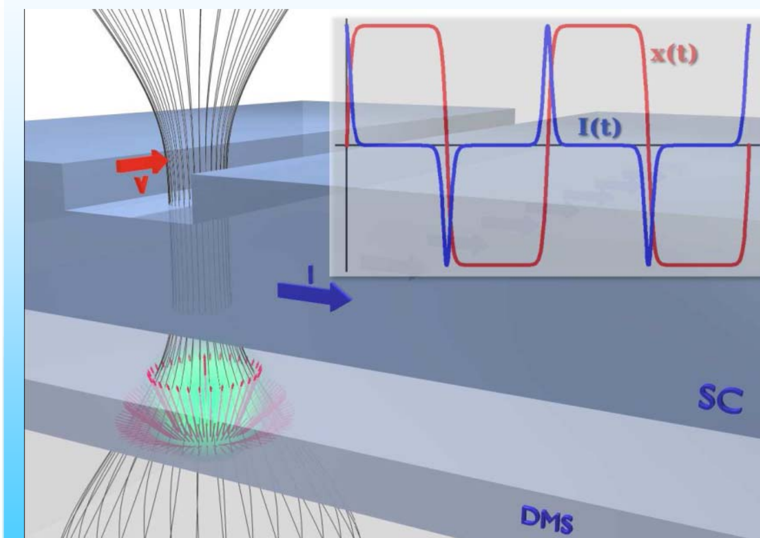


Manipulating spin and charge in magnetic semiconductors using superconducting vortices

Mona Berciu[1], Tatiana G. Rappoport[2,3] & Boldizsár Jankó[2,3]

[1] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*
[2] *Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[3] *Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

The continuous need for miniaturization and increase in device speed[1] drives the electronics industry to explore new avenues of information processing. One possibility is to use electron spin to store, manipulate and carry information[2]. All such 'spintronics' applications are faced with formidable challenges in finding fast and efficient ways to create, transport, detect, control and manipulate spin textures and currents. Here we show how



Many possible „applications“ of high mobility 2DEG structures based on CdTe

I hope that I have convinced you that :

There is a need for
CdTe and CdMnTe nanostructures
with very high mobility 2DEG !

(Cd,Mn)Te-based quantum structures with high mobility 2D electron gas for spintronic research *, **

V. Kolkovski, W. Zaleszczyk, M. Wiater, M. Czapkiewicz, P. Nowicki, T. Wojciechowski, J. Wróbel, G. Karczewski, T. Wojtowicz

Laboratory of growth and physics of low-dimensional crystals
Institute of Physics, PAS, Warsaw, Poland

P. Olbrich, C. Drexler, W. Eder, C. Zoth, P. Lutz, V. Lechner, U. Wurstbauer, D. Schuh, W. Wegscheider, S. D. Ganichev (spin current generation via THz & microwaves)
C. Betthausen, A. Vogl, D. Weiss, T. Dollinger, H. Saarikoski, K. Richter (transport mK, EBL & theory)

Department of Physics, Regensburg University, Regensburg, Germany

S.A. Tarasenko, V.V. Bel'kov, Ya.V. Terent'ev, A.N. Semenov, S.V. Ivanov, D.R. Yakovlev

A.F Ioffe Physical-Technical Institute, RAS, St. Petersburg, Russia **spin current via THz & mw)**

B. Ashkinadze (spin current via THz & mw)

Solid State Institute, Technion-Israel Institte of Technology, Haifa, Israel

*
The research is partially supported the National Centre of Science (Poland) grant Maestro:DEC-2012/06/A/ST3/00247, by the European Union within European Regional Development Fund, through Innovative Economy grants: POIG.01.01.02-00-008/08 (NanoBiom), also POIG.02.02.00-00-003/08 (NLTK for equipment), and POIG.02.02.00-00-020/09 (SpinLab for equipment).

** **Plenary talk at the 20th EP2DS and 16th MSS Int. Conf., Wrocław, Poland, July 5, 2013**

(Cd,Mn)Te-based quantum structures with high mobility 2D electron gas for spintronic research *, **

J. Kunc, B. Piot, P. Płochocka, K. Kowalik, F.J. Teran, D.K. Maude, M. Potemski (optics & transport at mK and high fields)

Grenoble High Magnetic Field Lab., MPI/FKF and CNRS, France

R. Rungsawang, D. Oustinov, J. Madéo, N. Jukam, S. Dhillon, J. Tignon (generation of THz from spin waves)

Laboratoire Pierre Aigrain – Ecole Normale Superiere, Paris, France

F. Perez, J. Gomez (generation of THz from spin waves)
F. Baboux (SO in collective spin excitations)

INSP, CNRS-University Paris 6, Paris, France

C.A. Ullrich (SO in collective spin excitations)

Department of Physics and Astronomy, University of Missouri, Columbia Missouri, USA

I. D'Amico (SO in collective spin excitations)

Department of Physics, University of York, York, United Kingdom

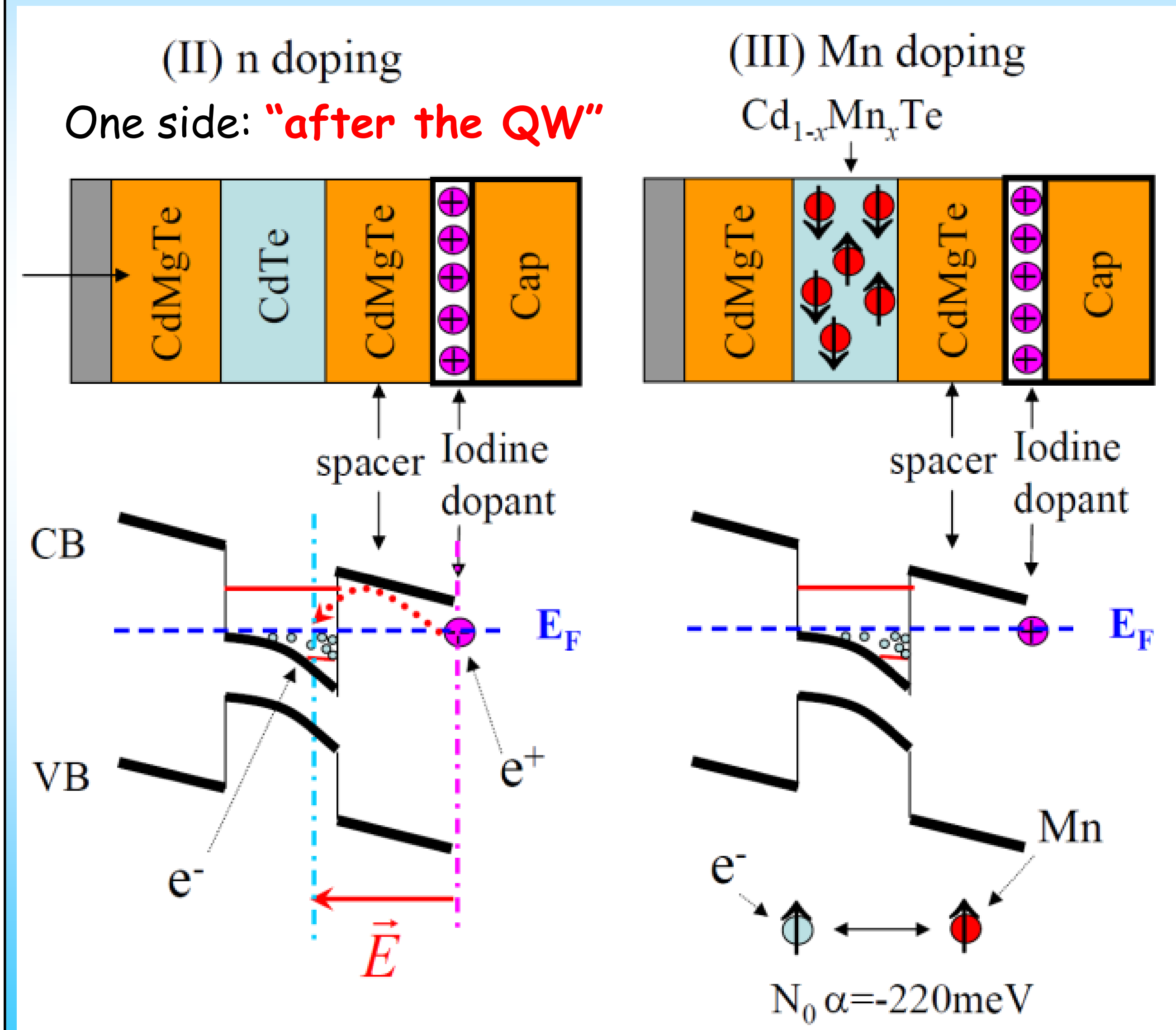
* The research is partially supported the National Centre of Science (Poland) grant Maestro:DEC-2012/06/A/ST3/00247, by the European Union within European Regional Development Fund, through Innovative Economy grants: POIG.01.01.02-00-008/08 (NanoBiom), also POIG.02.02.00-00-003/08 (NLTK for equipment), and POIG.02.02.00-00-020/09 (SpinLab for equipment).

** Plenary talk at the 20th EP2DS and 16th MSS Int. Conf., Wrocław, Poland, July 5, 2013

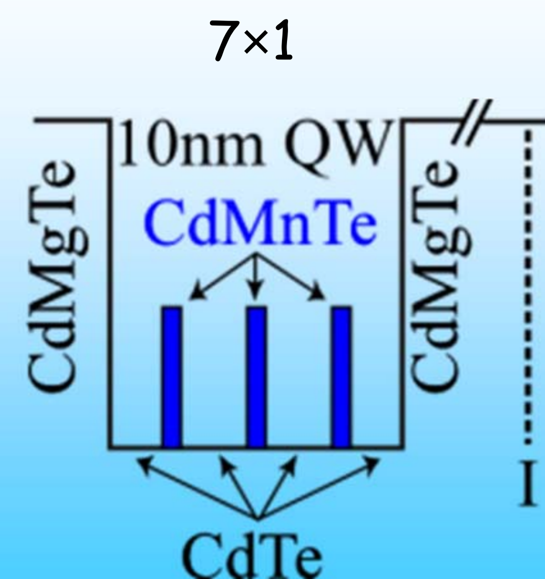
Fabrication of the CdTe-based II-VI quantum structures containing high mobility 2DEG

Idea of "modulation doping" or "remote doping".

R. Dingle, H.L. Stromer, A.C. Gossard, W. Wiegmann , Appl Phys Lett **33** (1978) 665



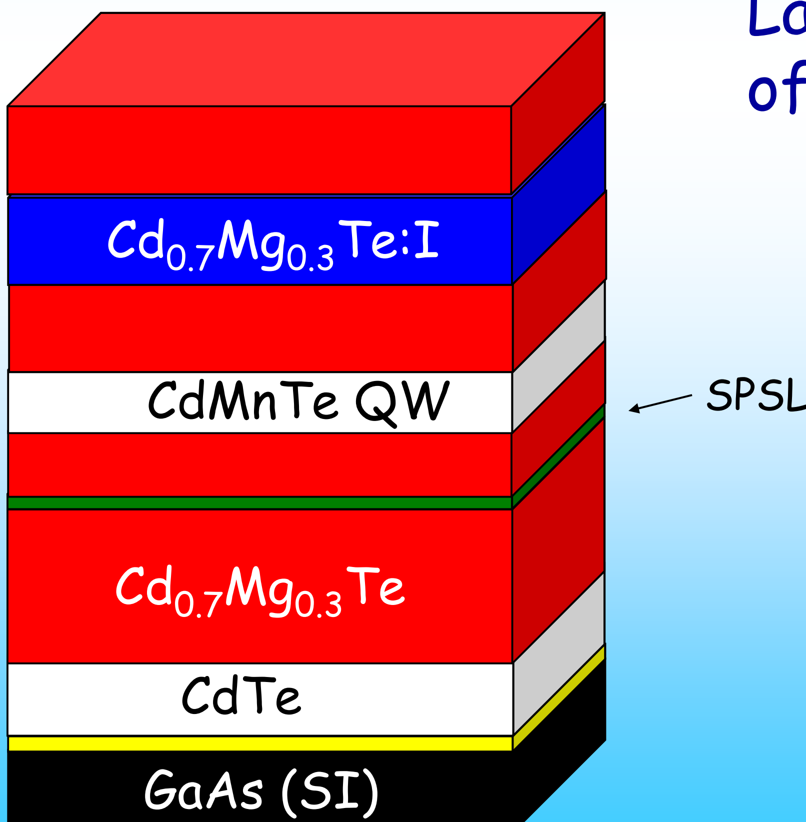
Mn atoms can be introduced either homogenously or digitally:



Technology of high mobility 2DEG structures made of $Cd_{1-x}Mn_xTe$ QWs with $Cd_{1-y}Mg_yTe$:I barrier

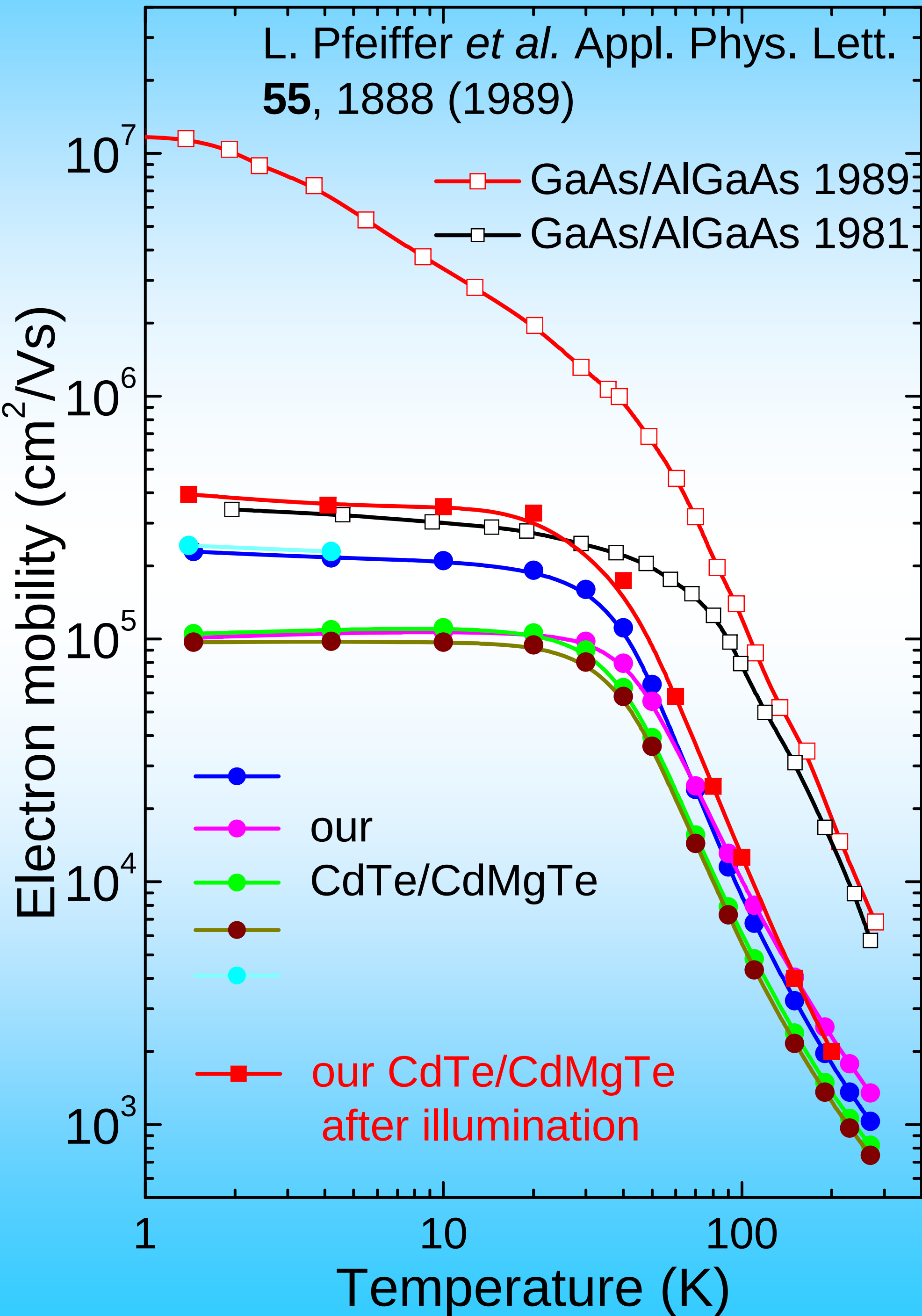
7N Cd and Te from Nikko Metal Europe GmbH (Nippon Mining & Metals)
5N Mn and Mg from Prof. A. Mycielski, Institute of Physics, PAS
5N ZnI_2 from Aldrich
GaAs (100) 2° off from AXT 2 in HYBRID SUBSTRATES

Non-bonded Molybdenum holders
Careful procedures (purity) and thick (ZnTe/CdTe/CdMgTe/SPSL) buffers



Large surface suitable for development of e-beam, AFM, FIB lithography !

Comparison of electron mobility of CdTe/CdMgTe QWs with GaAs/AlGaAs land-mark samples



GaAsAlGaAs single interface structure
70 nm spacer
after illumination

CdTe/CdMgTe QWs
20 and 30 nm wide
one side doped
20 or 30 nm spacers
without illumination

After illumination our CdTe is better than GaAs in 1981

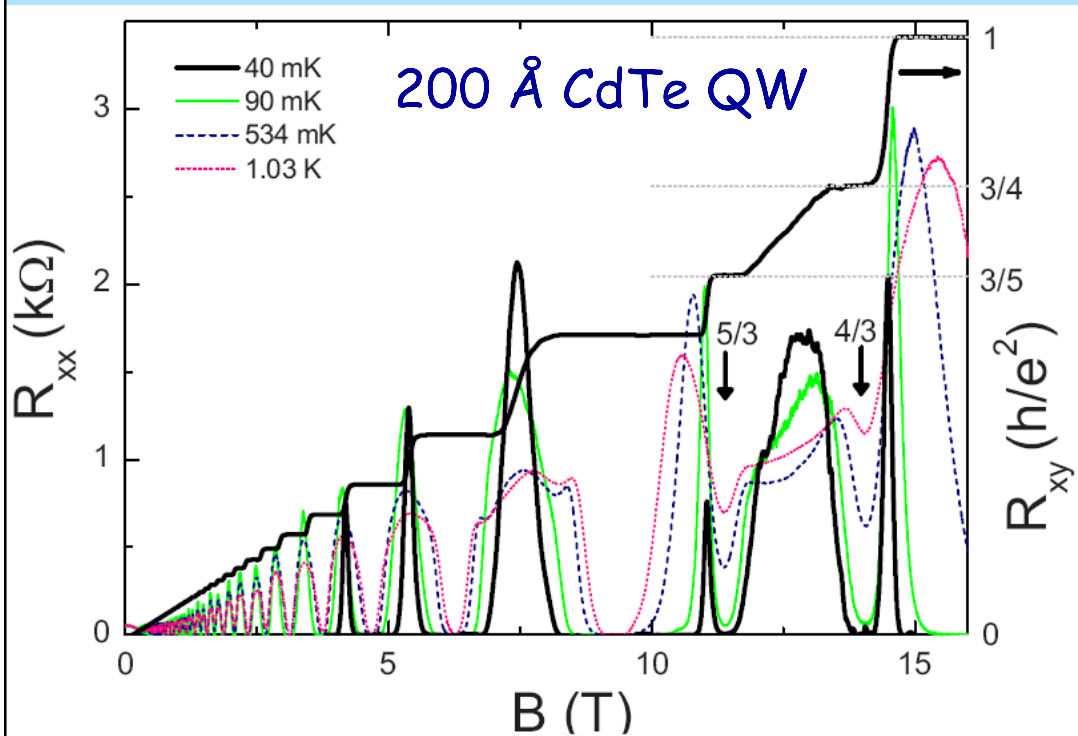
Our new record in 2DEG mobility in wide gap II-VI tellurides is now approaching 500 000 cm^2/Vs

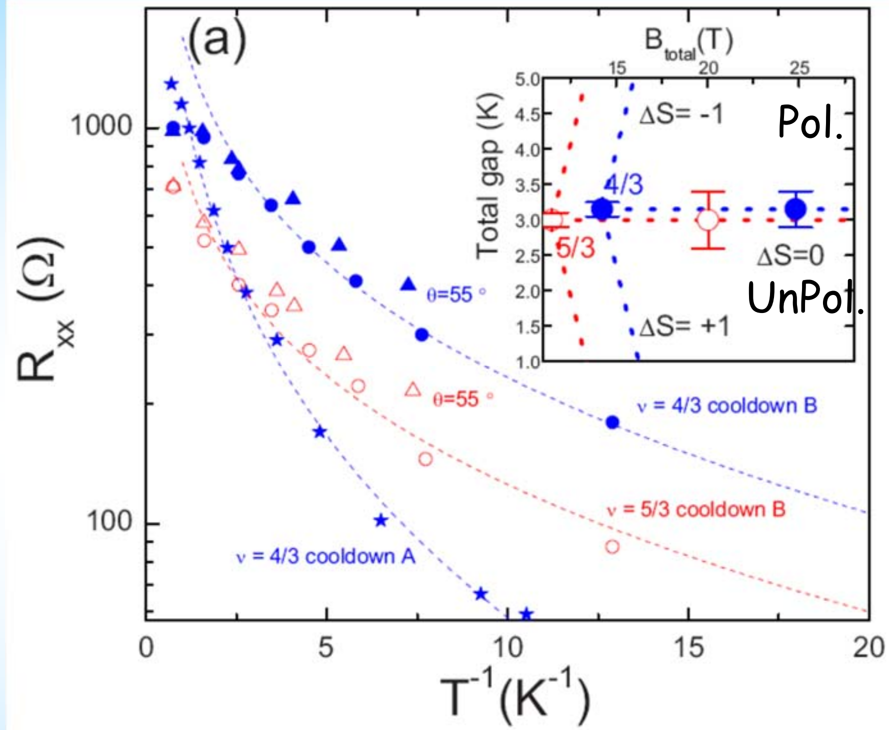
Spin-polarized fractional QHE in CdTe for filling factor 4/3, 5/3, and also for 7/3, no 5/2 FQHE

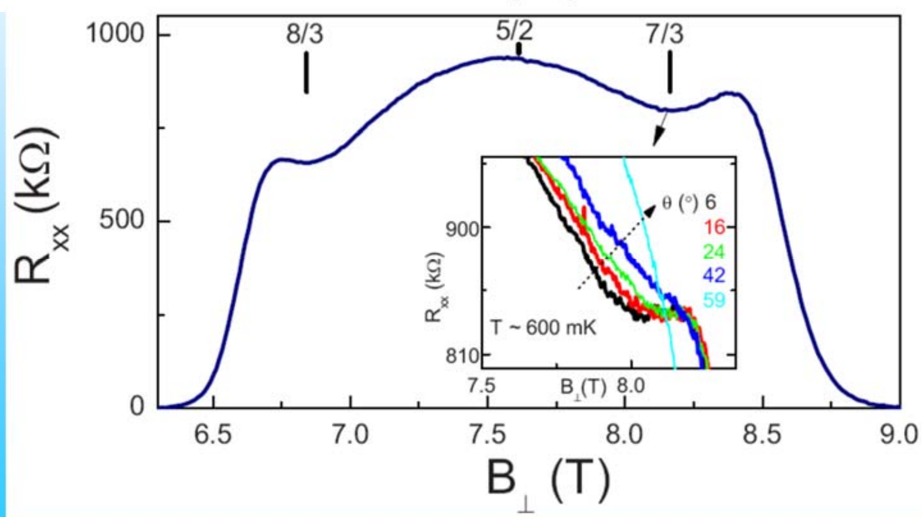
B. A. Piot *et al.*, Phys. Rev. B **82**, (2010) 081307(R)

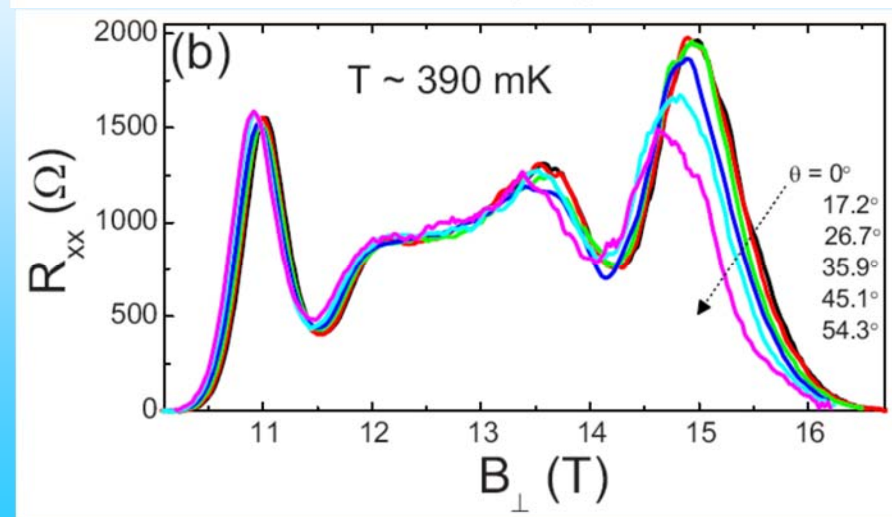
Gap not decreasing with B_{Tot} → spin polarized ground state

Gap not increasing with B_{Tot} → no spin reversed excitations



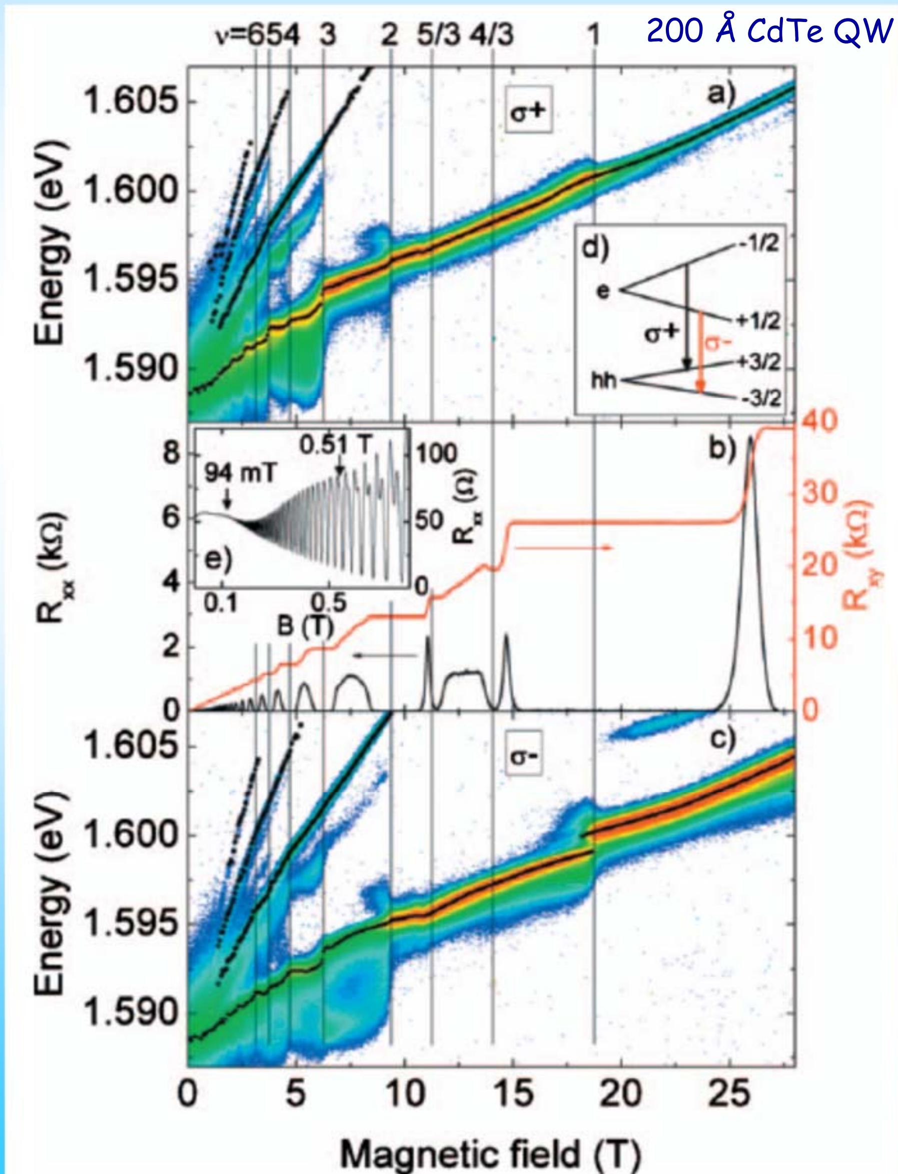




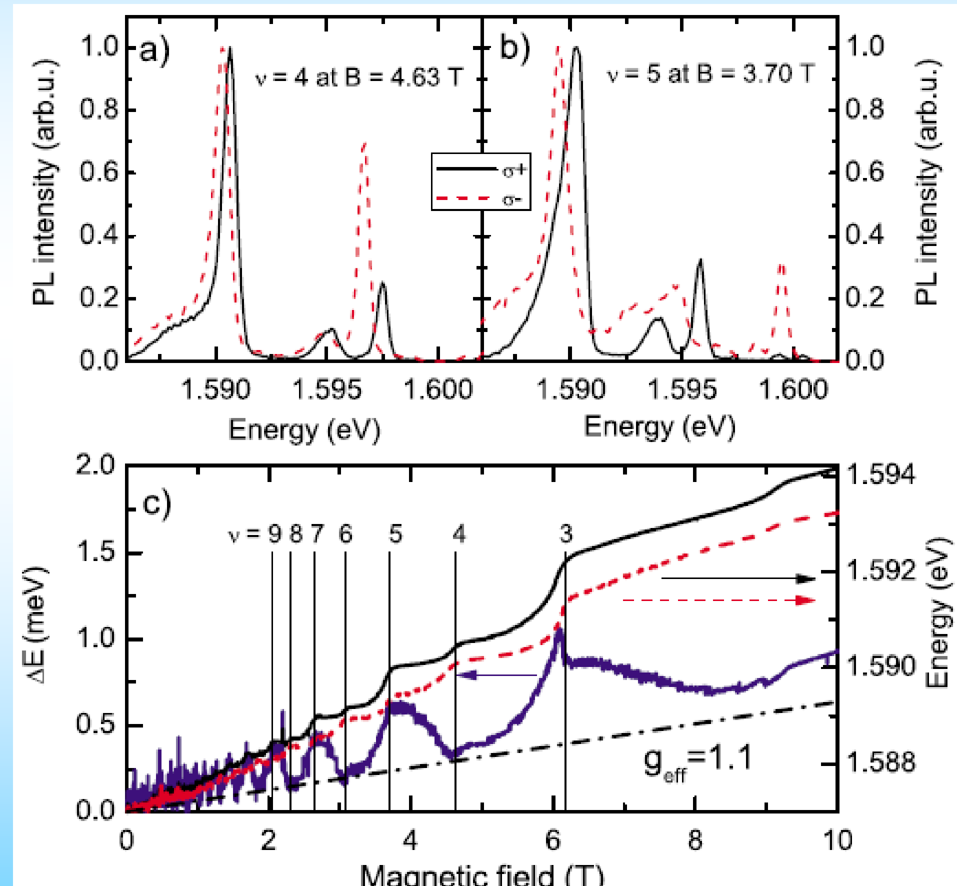


Simultaneous measurements of PL spectra and longitudinal and Hall resistance in CdTe QW

Enhancement of the spin gap in fully occupied two-dimensional Landau levels extracted from polarization resolved PL (separation of σ^+ and σ^-) for arbitrary filling factor (as determined from transport)



J. Kunc *et al.,* Phys. Rev. B **82** (2010) 113458



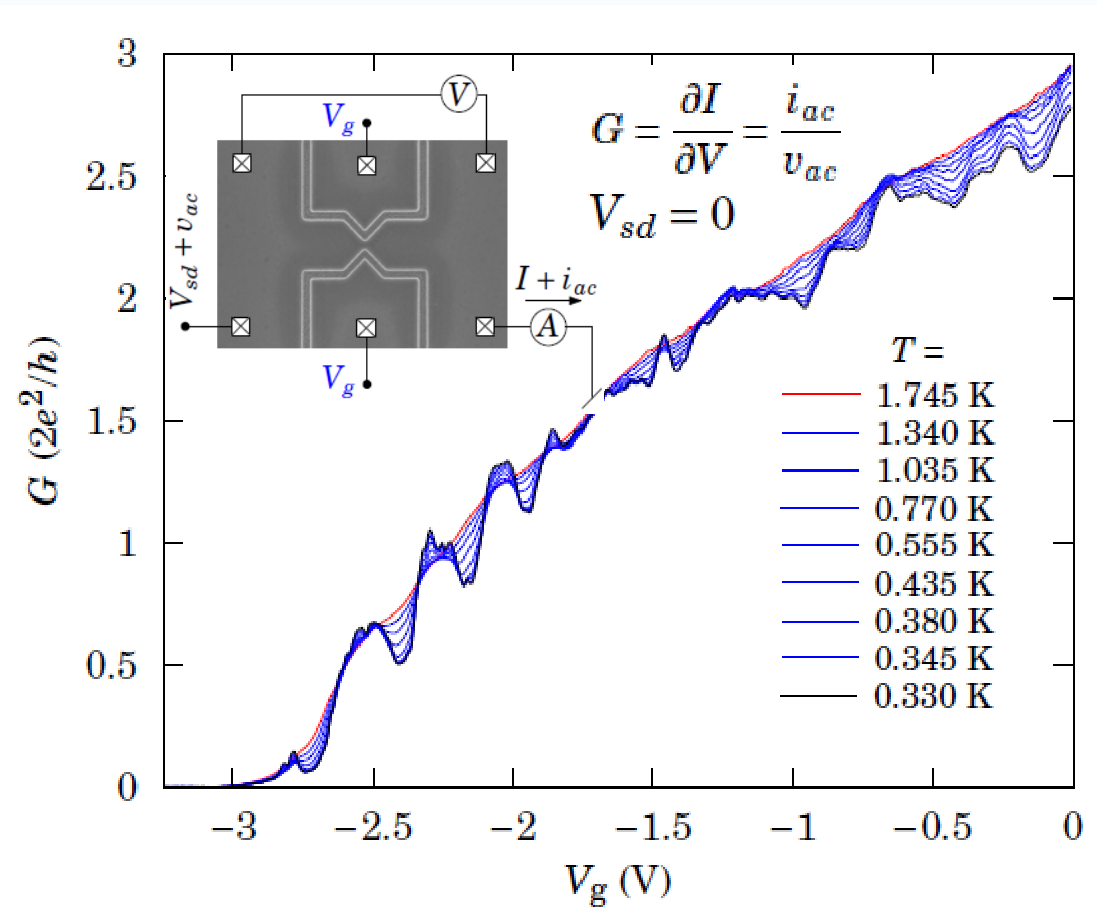
Enhancement caused by many body interaction which is shown to be driven by the spin polarization of the 2DEG

Differential conductance of CdTe/CdMgTe QPC

M. Czapkiewicz, *et al.*, Phys. Rev. B **86** (2012) 165415

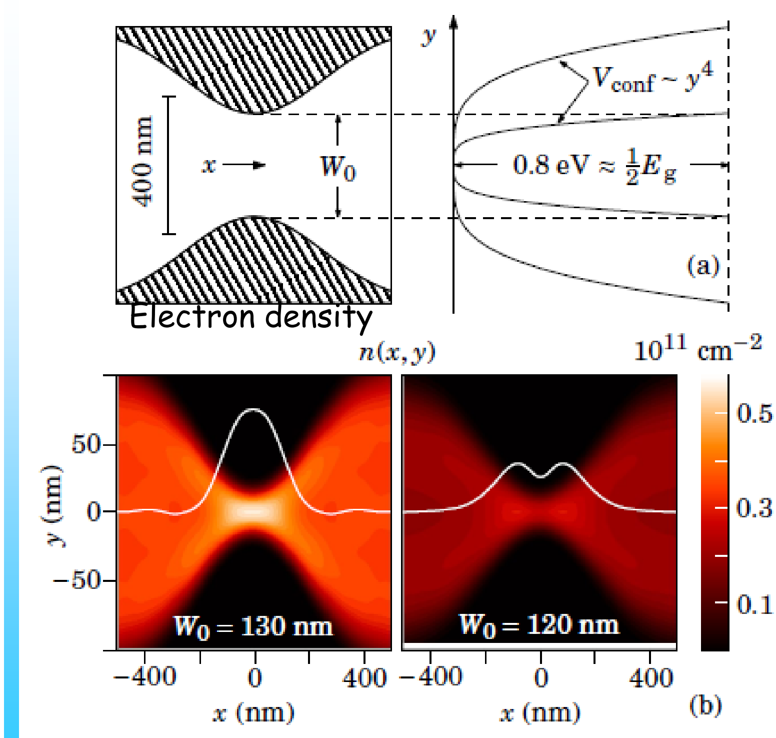
Instead of steps with flat plateaus in G quasi-periodic oscillations

- similar to that observed in GaAs QPC with centrally embedded open QD
- evidence for weakly bound state naturally formed inside constriction
- formation of QD even in short and symmetrical QPC due to the stronger e-e interaction and specific shape of the QPC confining potential



Model of external confining potential

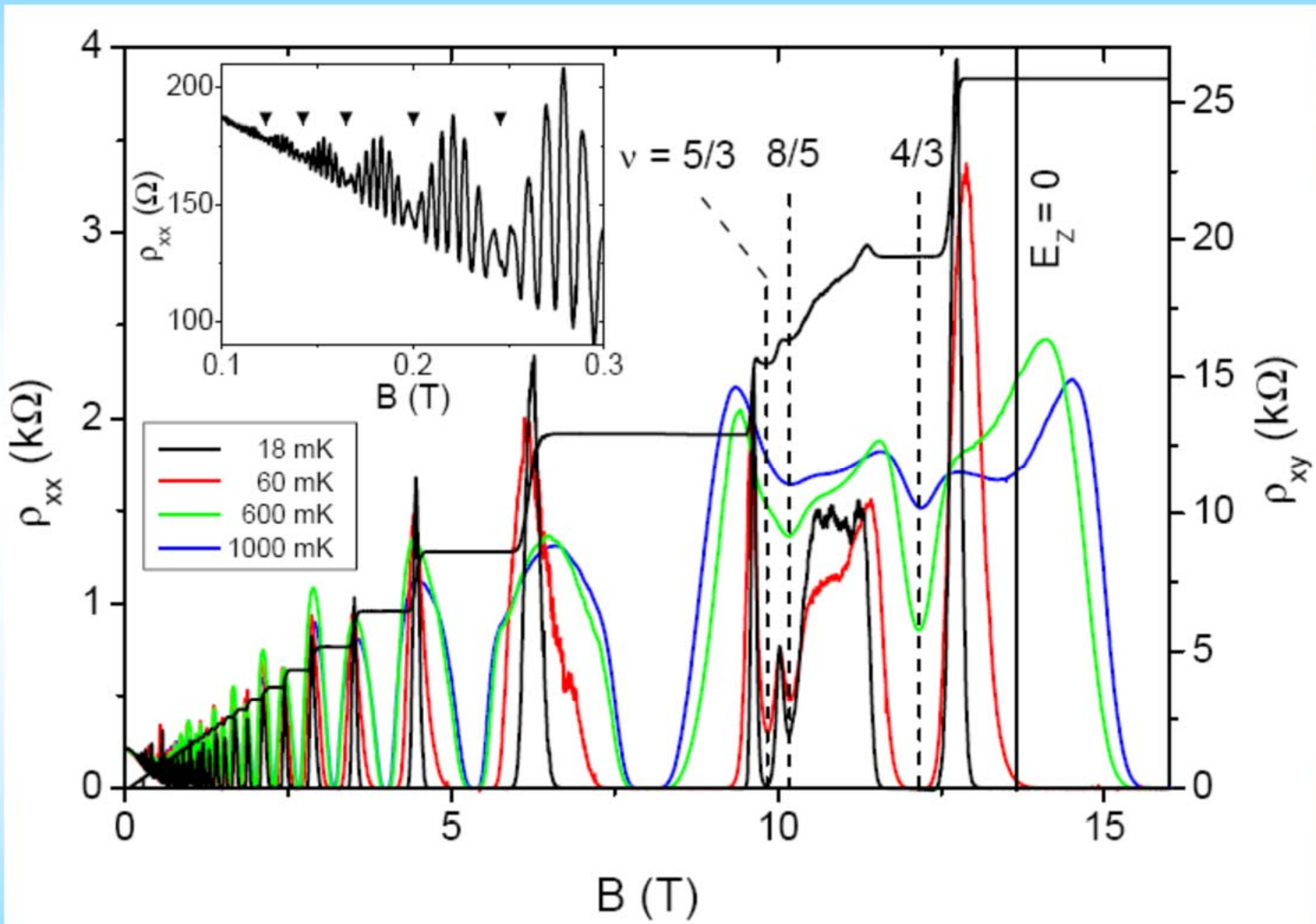
Green's function method
Hartree model (CdTe parameters)



First observation of fractional QHE in Magnetic-2DEG system made of **DMSs**

300 Å $Cd_{1-x}Mn_xTe$/CdMgTe:I QW

C. Betthausen *et al.*, unpublished.



Spacer 300 Å, homogenous Mn distribution

After illumination

$\mu_{Hall} \approx$ 200 000 cm²/Vs

n = 3.6 × 10^{11} cm^{-2}

Beating in ρ_{xx} at low B: proof of the presence of Mn

x ≈ 0.0024

Mn does not destroy FQHE for x up to 0.01!

Studies of FQHE for zero spin splitting at any ν, taking advantage of spin-splitting engineering are feasible, FQHE in double QWs with one being DMS

THz and microwave radiation induced zero-bias generation of pure spin currents:
Spin splitting engineering used to demonstrate mechanism of very efficient magnetic field induced conversion of them into spin polarized electric current.

Generation, transport and manipulation of spin polarized carriers is in the focus of research aiming at spintronic applications.

Generation of pure spin currents via zero bias spin separation

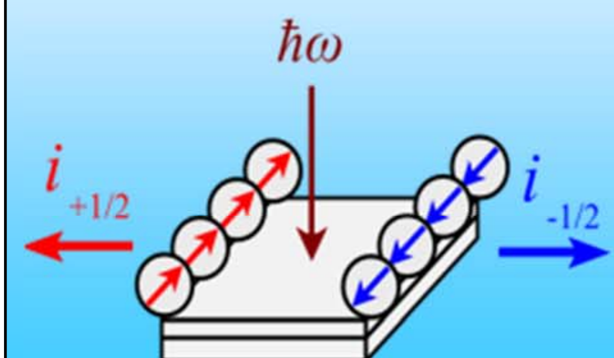
S.D. Ganichev *et al.*, Zero Bias Spin Separation, Nature Physics **2** (2006) 609

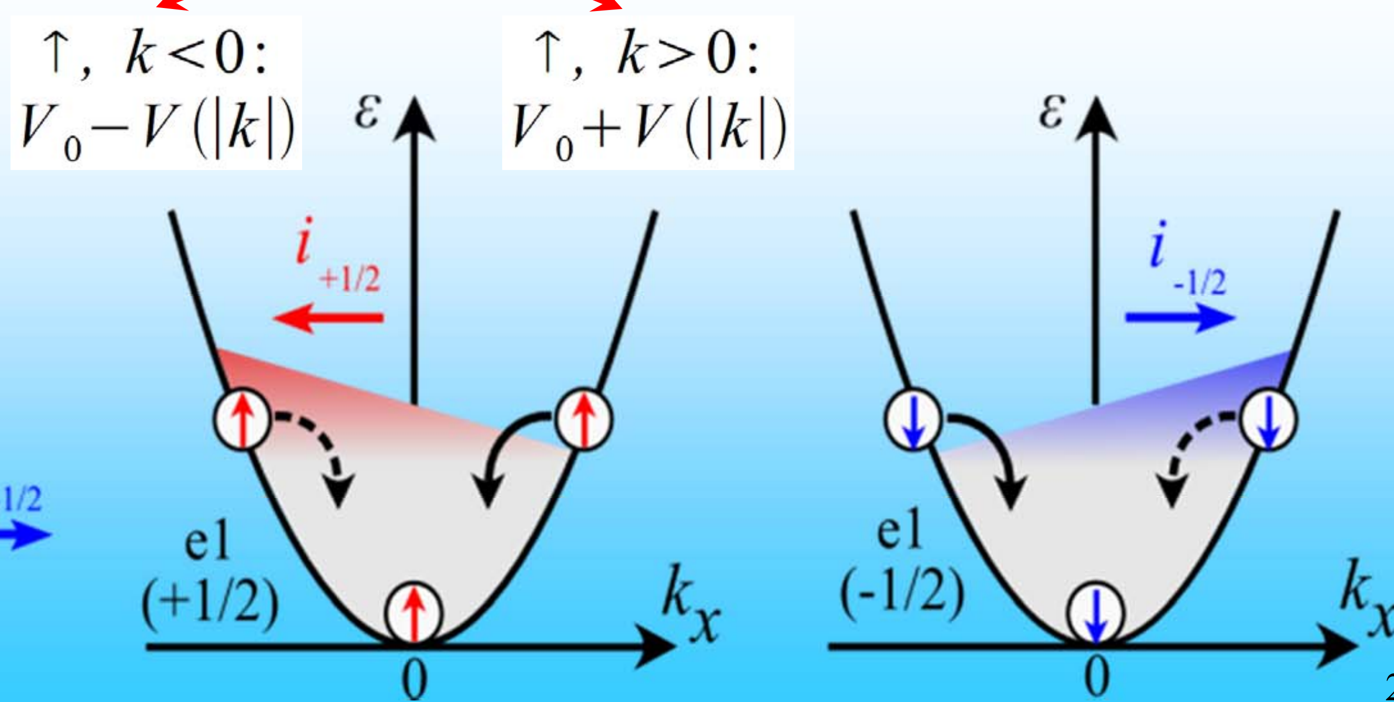
In gyrotropic media (e.g. ZB semiconductor QW) spin-orbit interaction ads an asymmetric spin-dependent term to electron scattering probability on phonons and static defects (matrix element is linear in **k** and Pauli spin matrices **σ**)

$$V_{kk'} = V_0 + \sum_{\alpha\beta} V_{\alpha\beta}\sigma_\alpha (k_\beta + k'_\beta)$$

Linear in k term stems from bulk and structure inversion asymmetry of QW

oppositely directed fluxes (↑ / ↓)

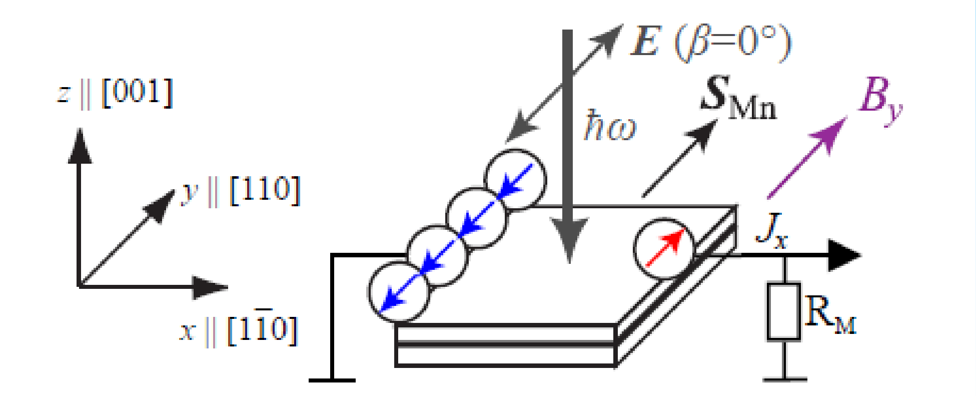




Generation of spin polarized electric current via relaxation and excitation mechanism in B (Zeeman)

$$j_z = -e\frac{E_Z}{\tilde{E}}J_{spin}$$

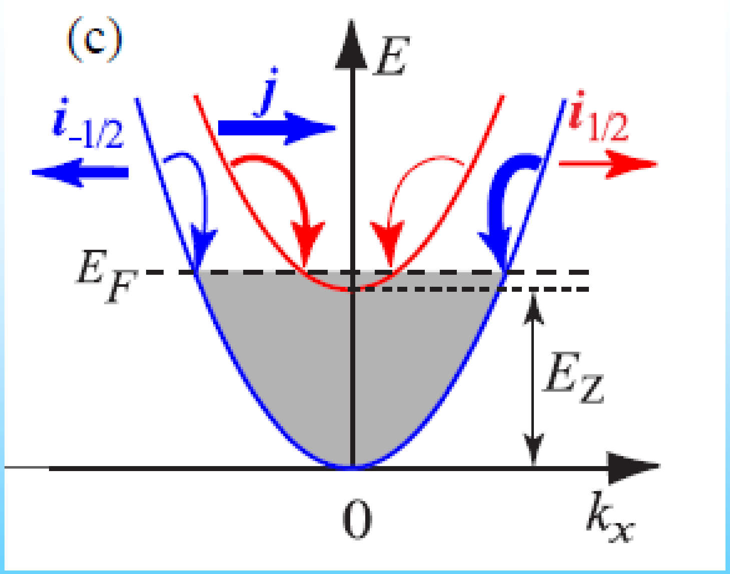
P. Olbrich *et al.*, Phys. Rev. B **86** (2012) 085310



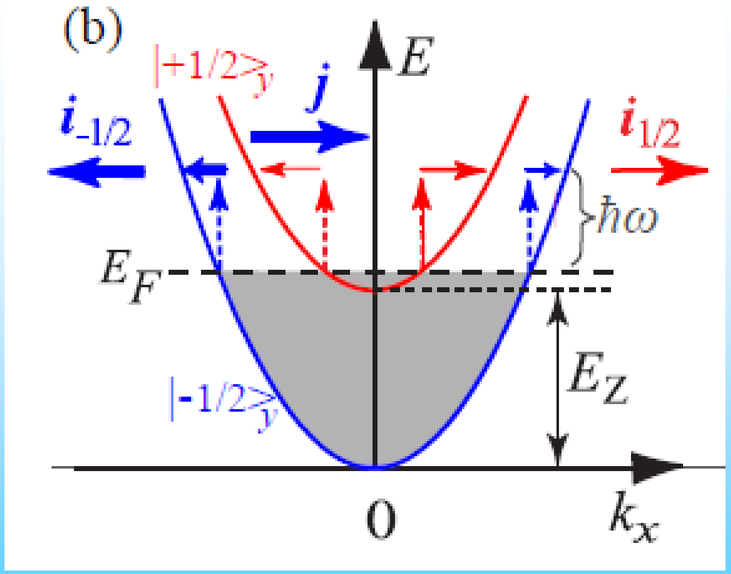
$\tilde{E} = E_F$ degenerate

$\tilde{E} = k_B T$ non-degenerate

Relaxation j_1



Excitation j_2, j_3



excitation is polarization dependent

a method to distinguish between two mechanisms

in DMS strongly enhanced !

$$j_x = j_1 + j_2 \cos 2\beta \qquad j_y = j_3 \sin 2\beta$$

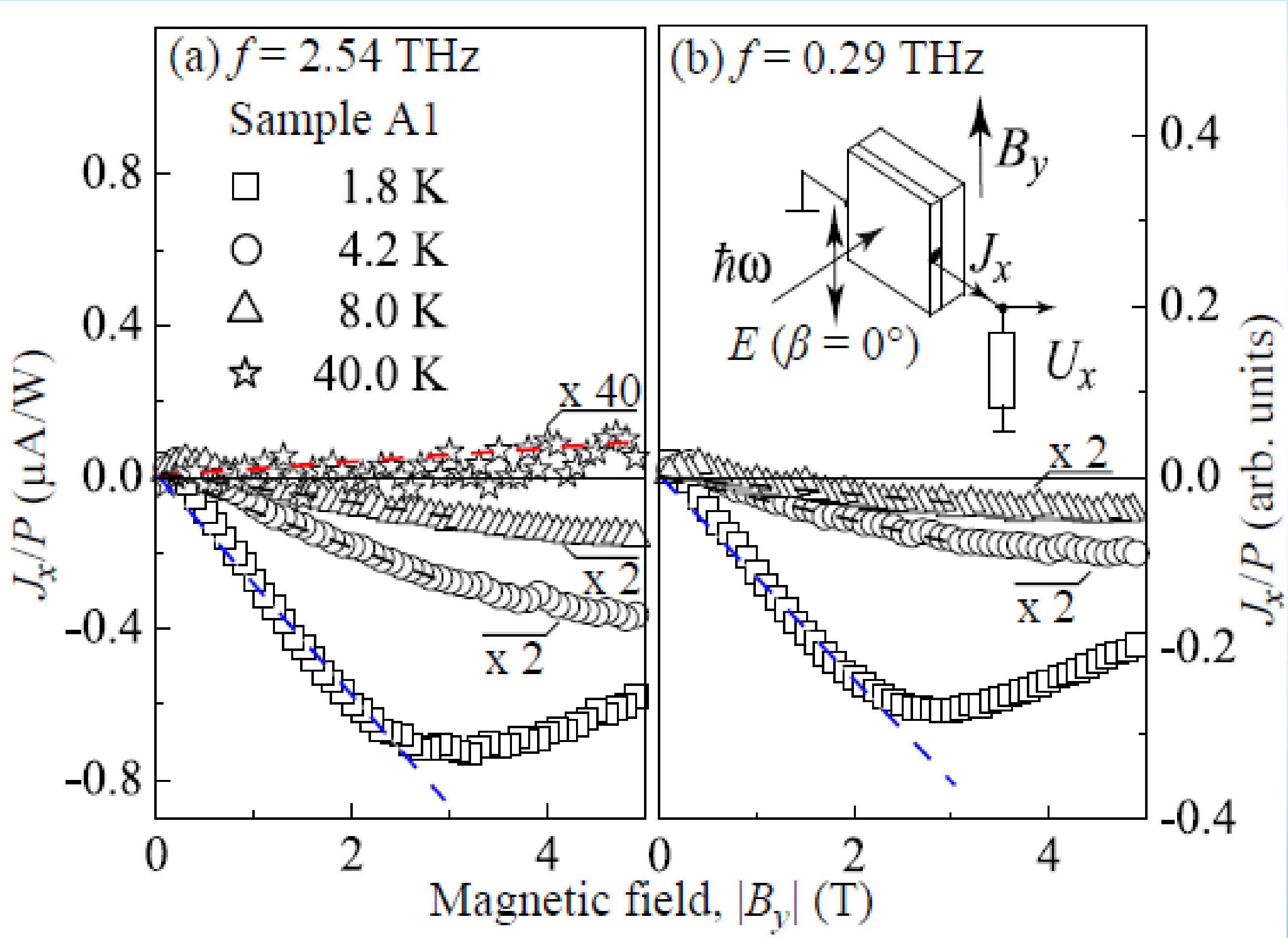
Dependence of THz induced spin polarized electric current j_x in (Cd, Mn)Te QW on B for various T

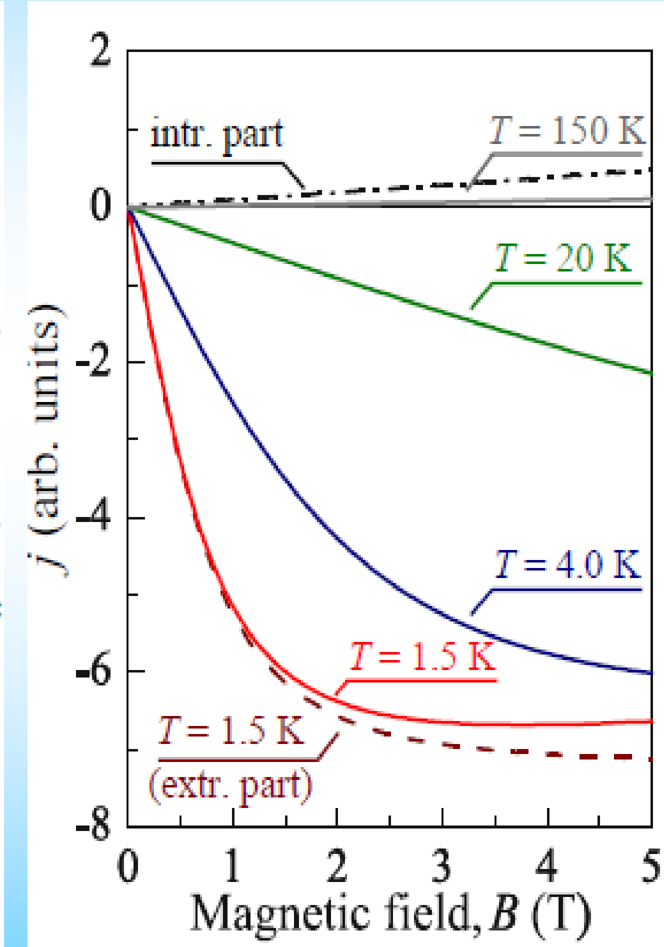
P. Olbrich *et al.*, Phys. Rev. B **86** (2012) 085310

Experiment

$$E_Z = g_{e(h)}\mu_B B + \bar{x} S_0 N_0 \alpha_{e(h)} B_{5/2}\left(\frac{5\mu_B g_{Mn} B}{2k_B(T_{Mn}+T_0)}\right)$$

Simulation



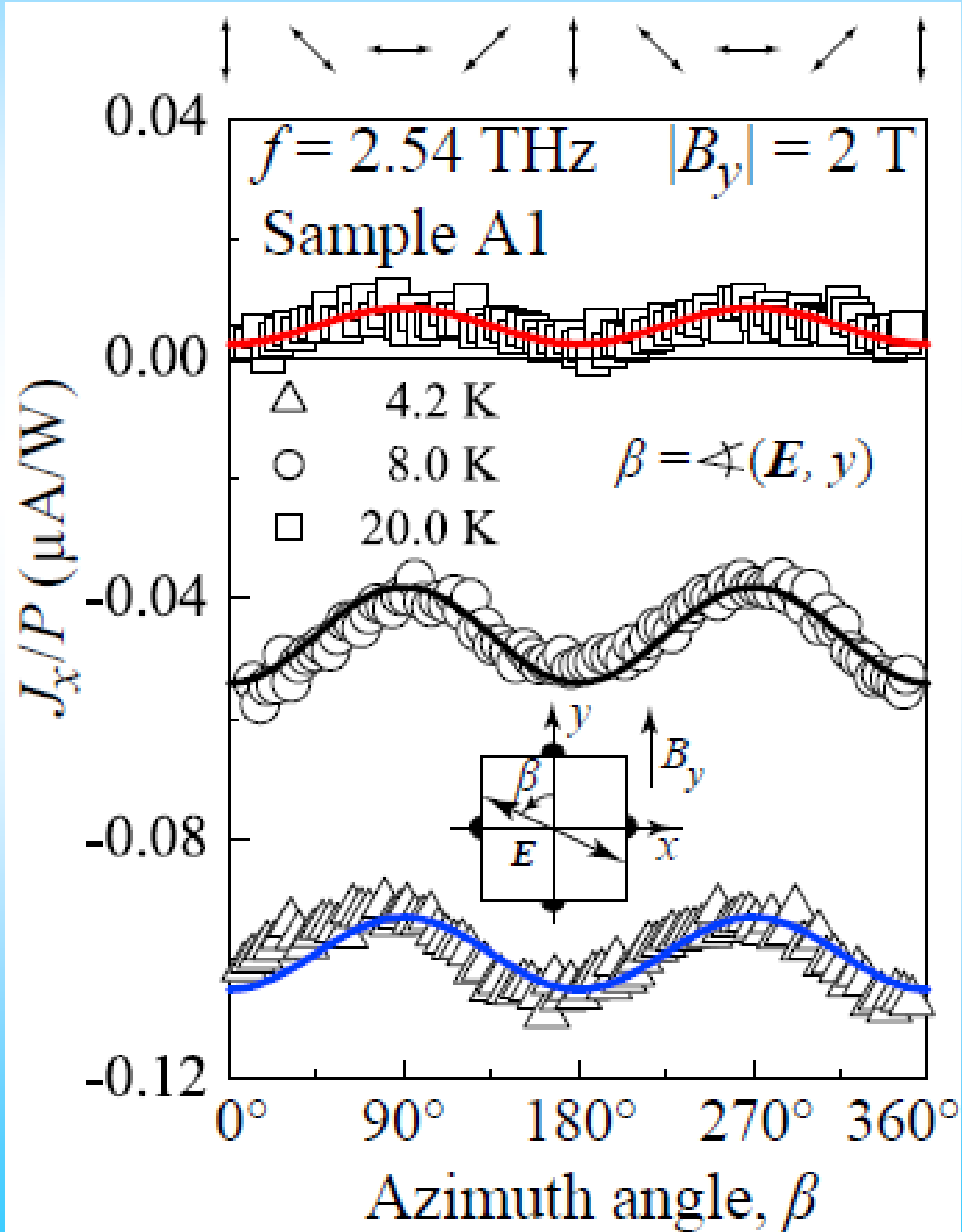


All expected features observed in experiments for THz and sub-THz

Spin-splitting engineering prove the mechanism of conversion

Experimental polarization dependence of THz induced current j_x in (Cd,Mn)Te QW for B=2 T

P. Olbrich *et al.*, Phys. Rev. B **86** (2012) 085310



J_x current is well described by the formula:

$$j_x = j_1 + j_2 \cos 2\beta$$

Again proving the mechanisms of generation of spin current and its conversion to electrical current as well revealing the contribution from **excitation mechanism j_2**

Clear demonstration of THz radiation pulses from spin-waves excited via efficient Raman generation process in $Cd_{1-x}Mn_xTe$ QW containing 2DEG.

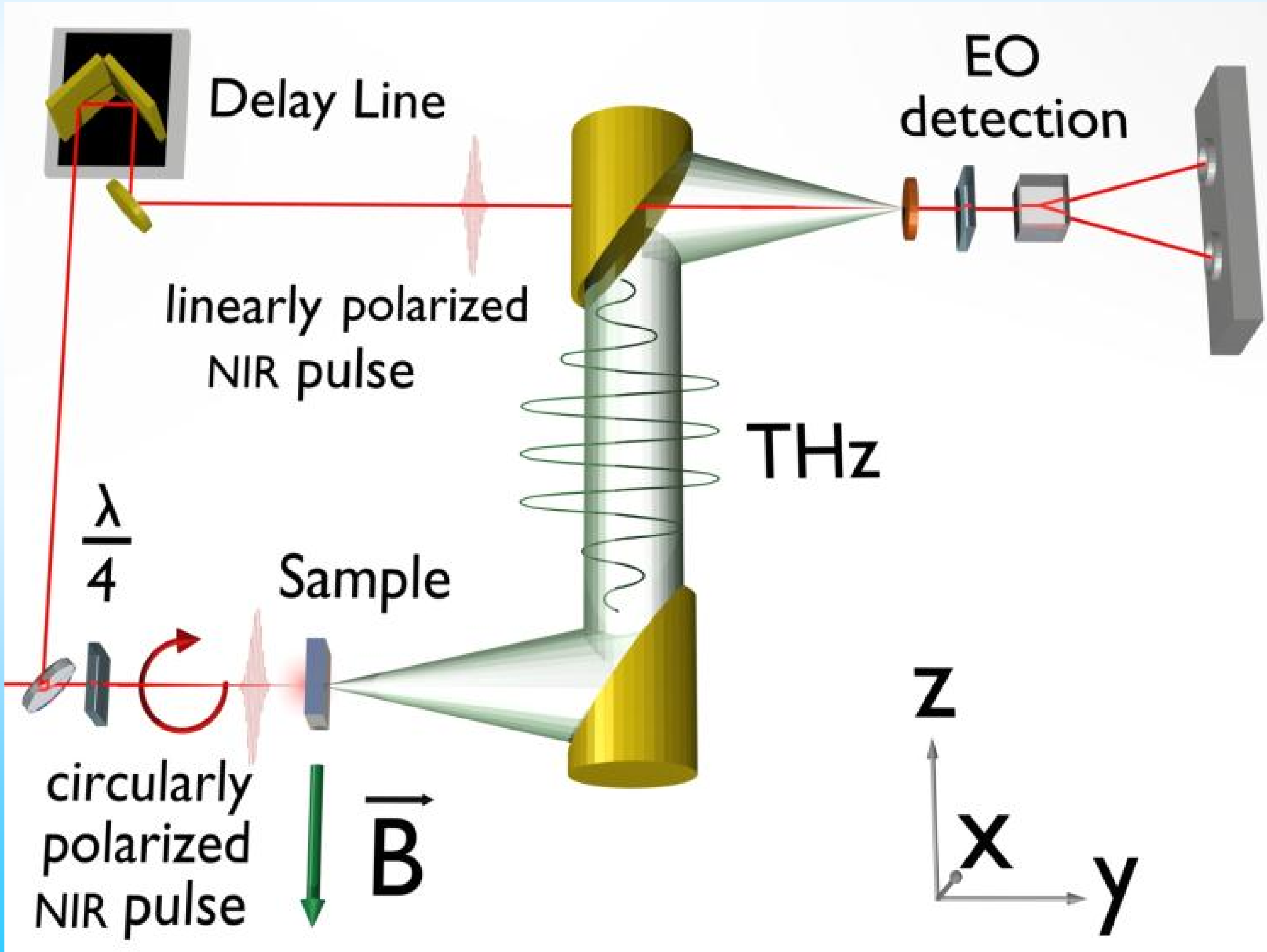
THz radiation from spin waves was previously observed in antiferromagnetic materials (e.g. NiO) and claimed in ferromagnetic GaMnAs.

The spin origin of the radiation from GaMnAs was not demonstrated:
the frequency range of observed transient did not match either acoustic or optical mode frequencies.

THz-Time Domain Spectroscopy - experimental set-up

R. Rungsawang *et al.*, Phys. Rev. Lett. **110** (2013) 177203

- Optical excitation (100fs, 763nm, circular, 5W/cm^2) mode-loced Ti:sapphire laser, 76 MHz repetition rate, 8 kHz acusto-optic modulator
- 2K ; 0-8 Tesla (modified split-coil with THz/optical access)
- multiple QW structures used (20 and 10 repetitions – more challenging than SQW)

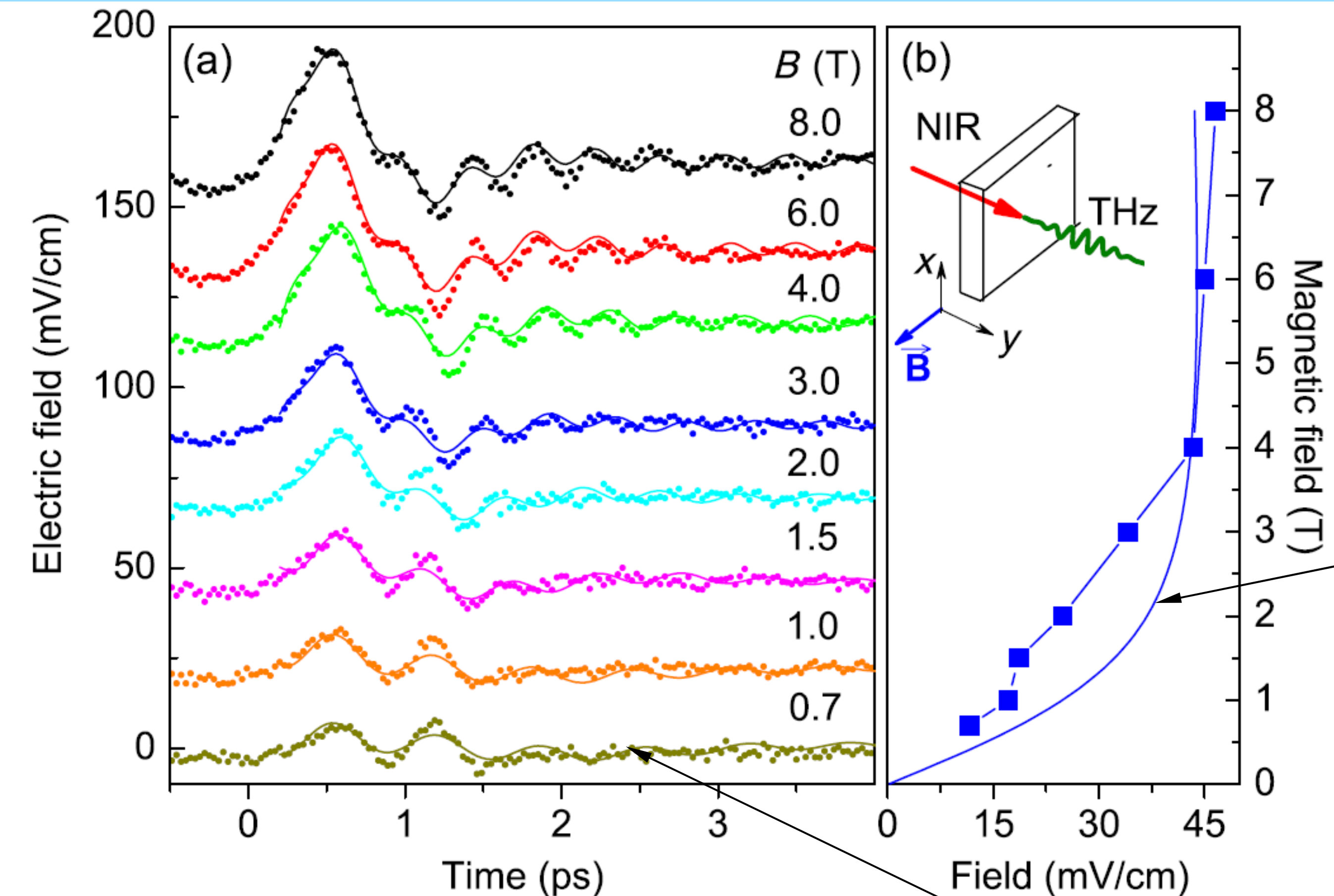


Free-space electro optic (EO) sampling with <110> ZnTe crystal set to detect electric field component parallel to B

Birefringence proportional to the amplitude of electric field (Pockels effect) of THz radiation detected by change of the linearly polarized light

THz radiation pulses from spin-waves excited in 2DEG inside $Cd_{1-x}Mn_xTe$ QW by NIR laser pulses

Radiated transient THz field at various B-field



R. Rungsawang *et al.*, Phys. Rev. Lett. **110**, (2013) 177203.

Calculated amplitude (it is proportional to macroscopic electron spin **S**, with amplitude following spin polarization)

Lines in (a) from the backward linear prediction algorithm

Energy per pulse:

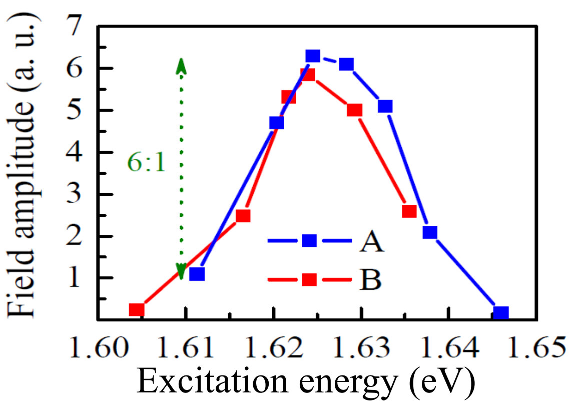
$E_P \approx 70$ nJ/cm² – in our experiments thanks to the high efficiency of the Raman generation mechanism caused by the strong spin-orbit interaction in the valence band and the possibility of using resonant Raman scattering conditions with „real" and sharp intermediate state (due to high sample quality)

$E_P \approx 400$ μJ/cm² – in $Ga_{1-x}Mn_xAs$: J.B Heroux *et al.* Appl. Phys. Lett. **88**, 221110-1 (2006)

$E_P \approx 20$ mJ/cm² – in NiO: J. Nishitani *et al.* Appl. Phys. Lett. **96**, 221906-1 (2010)

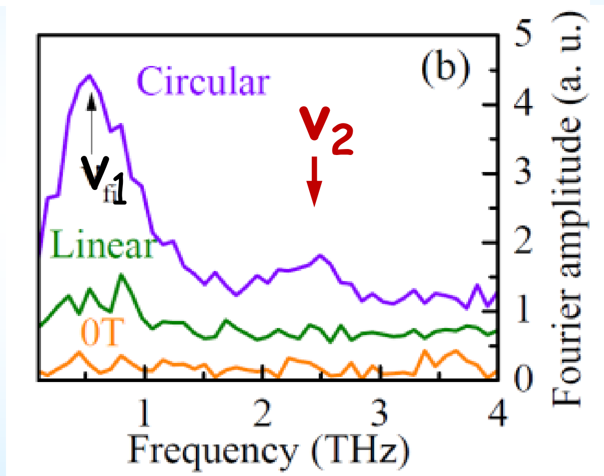
Demonstration of the spin-wave origin of THz radiation

R. Rungsawang *et al.*, Phys. Rev. Lett. **110** (2013) 177203



(i) Resonant character of excitation

• 2DEG fundamental optical transition (i.e. not a surface charge effect in GaAs or CdTe buffers)



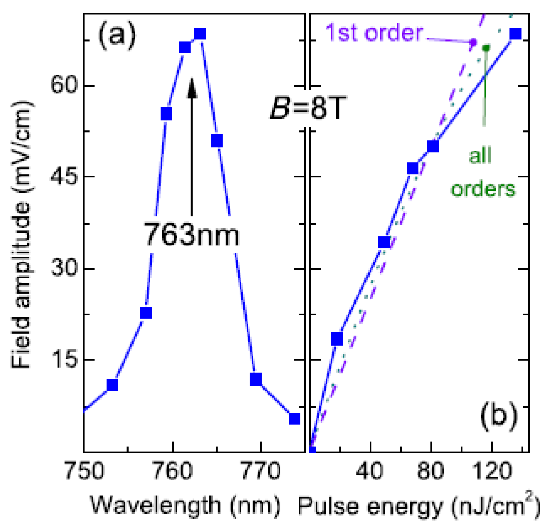
(ii) Polarization selection rules of excitation and field amplitude of THz radiation

• THz radiation detected **ONLY** with applied B **AND** circularly polarized optical pulse (linearly polarized pulse couples only to charge excitations (J.M. Bao *et al.* PRL92 (2004)).

• Radiated field polarized parallel to the equilibrium spin polarization **z** (as in the experiment).

$$\mathbf{e}_R(t) = \frac{2c\mu_0}{1+n}\frac{g_e\mu_B}{wL^2}S_x(t)\,\mathbf{z}$$

• Field amplitude agrees reasonably well with theory.

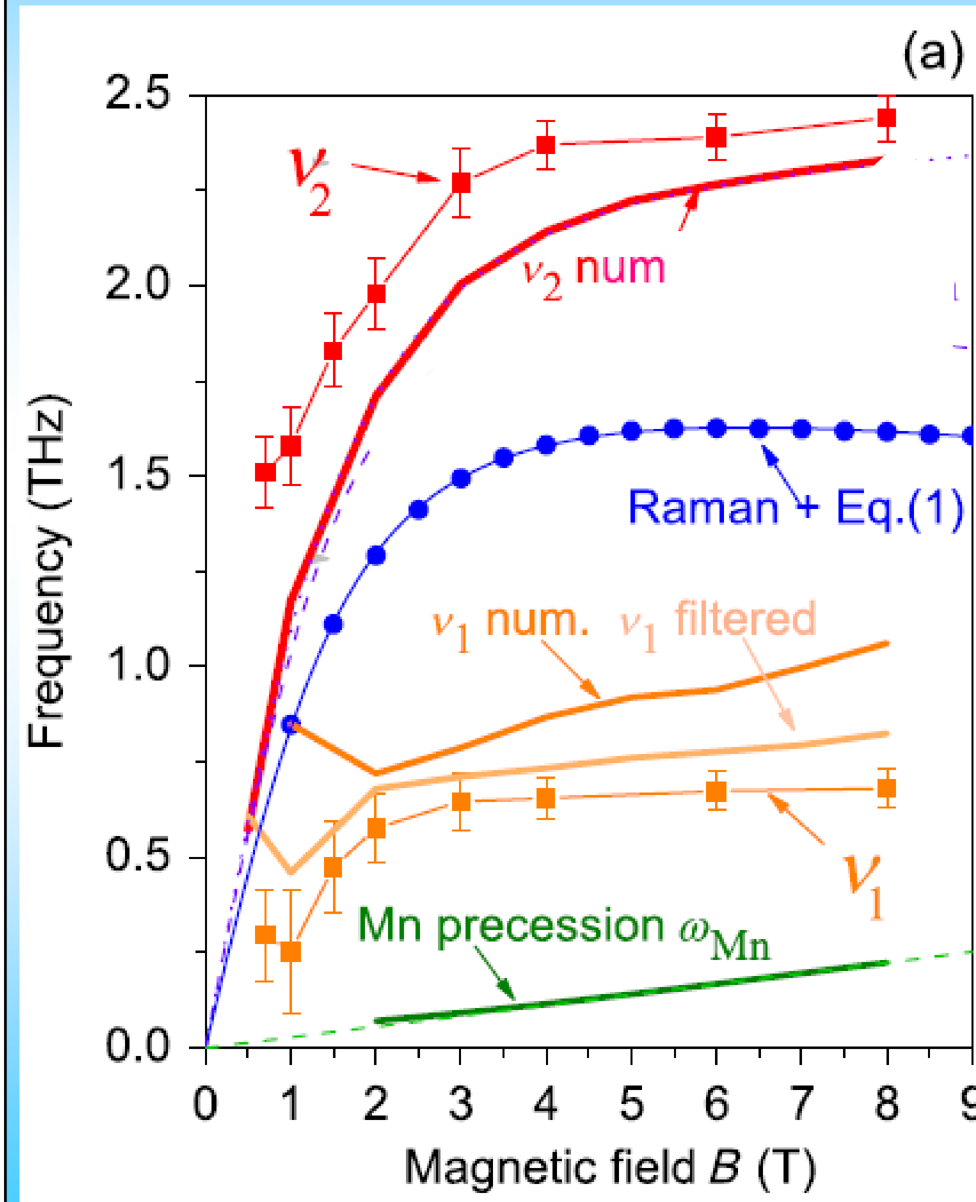


(iii) Frequency of THz radiation

• Magnetic field dependence of the two observed THz peaks frequencies can be reproduced by theory - **they are not due to inhomogeneity**.

Magnetic field dependence of the observed THz peak frequencies (ν_1 and ν_2) vs. theory

R. Rungsawang *et al.*, Phys. Rev. Lett. **110** (2013) 177203



As a result of laser pulse the macroscopic electron spin **S** starts to rotate, emitting THz radiation. However **S** is also under the influence of exchange field from macroscopic spin **M** of Mn acting as a torque α**S×M,** and also rotating around *z* axis after laser pulse, with ω_{Mn}.

This time dependent coupling between Mn and electron systems splits the observed frequencies from *Z*/*h*.

Nonlinear spin dynamic between electrons and Mn taken into account by solving coupled equations of motion for **S i M** (numerical results: ν_1 num and ν_2 num) .

Detection system acts as sharp high-pass filter with cut-off frequency around 0.3 THz:
- ω_{Mn} - not visible in experiment
- the numerical results for ν_1 and ν_2 had to be filtered with a numerical high-pass filter

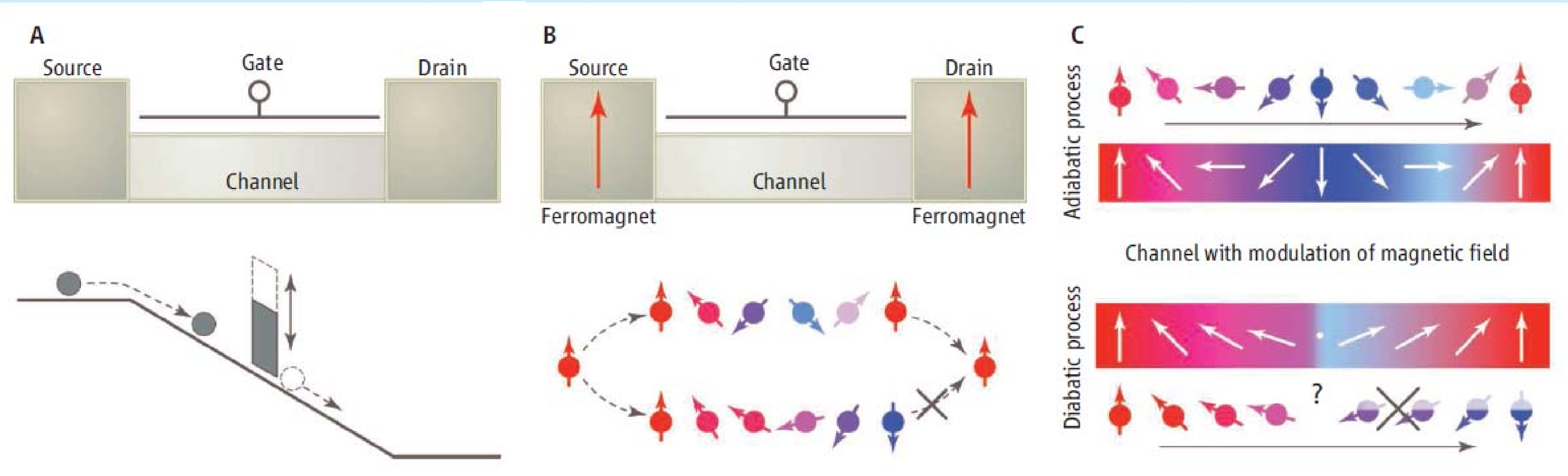
Adiabatic Spin Transistor:
controlling the spin transmission via tunable Landau-Zener transitions in spatially modulated spin-split bands.

Comparison of different types of transitsors
I. Zutic and J. Lee, Science **337** (2012) 307

S. Datta, B. Das, App. Phys. Lett. **56** (1990) 665

C. Betthausen, *et al.* Science **337** (2012) 324

Conventional FET | **Datta-Das spin T** | **Our adiabatic spin T**



V_g controls electron flow

V_g controls SO field
"on" – electron spin parallel
"off" – electron spin anti-parallel

"on" – gradual (adiabatic) change of magnetic field B
"off" – abrupt (diabatic) change of B – back reflection

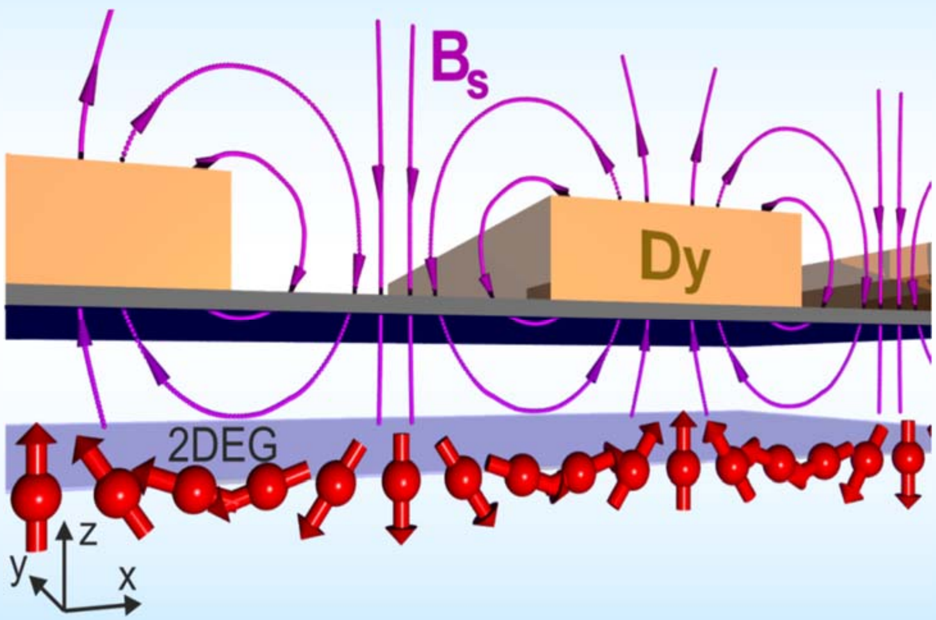
Problems:

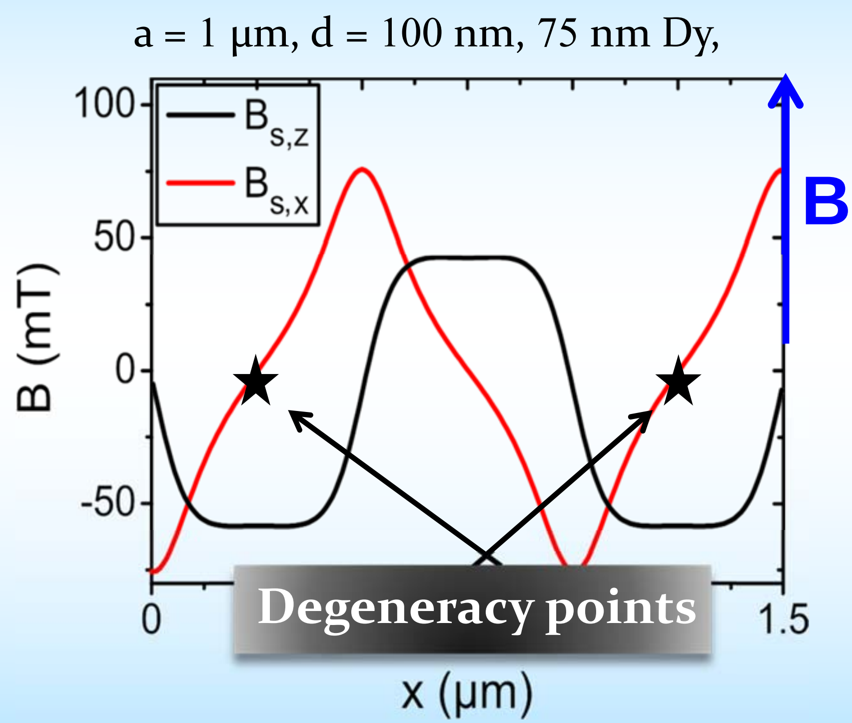
- Injection of spins (conductivity mismatch)
- Propagation of spins (limited spin lifetime)

New concept of spin transistor

C. Betthausen, *et al.* Science **337** (2012) 324

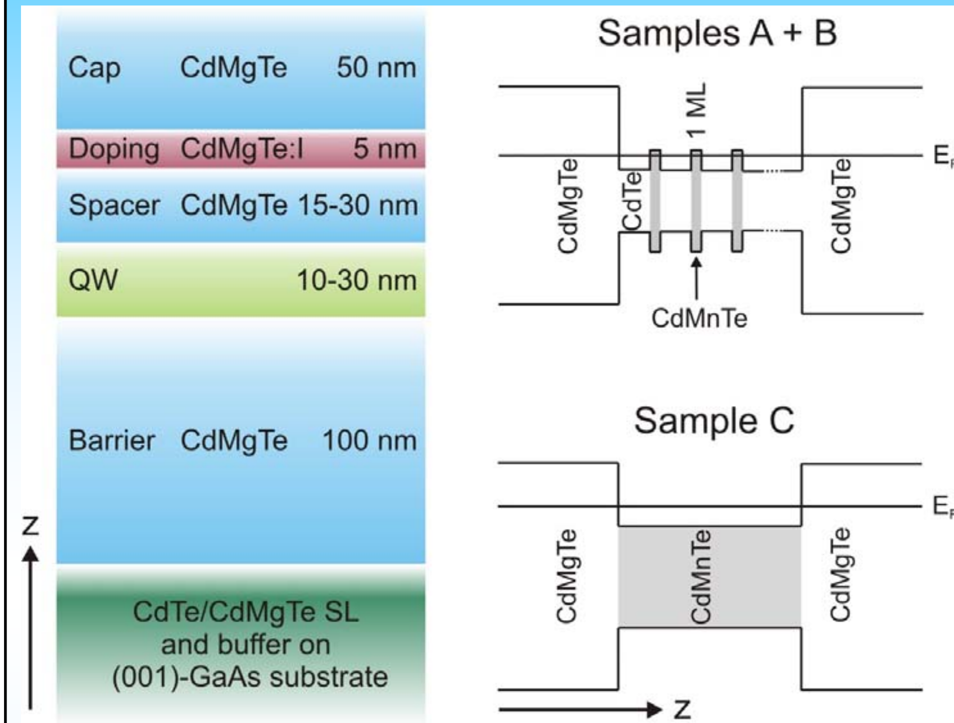
Control of spin transport adiabaticity



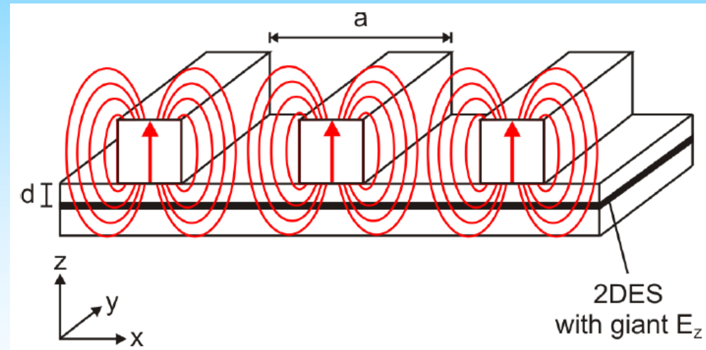


1. Polarize: large Zeeman splitting → $Cd_{1-x}Mn_xTe$
2. Propagate adiabatically: slowly varying stray field → spin helix
3. Regulate: external field tunes adiabaticity of spin transport → back-reflection

Hybrid structures made of high mobility 2DEG in CdMnTe



C. Betthausen, *et al.*, Science **337** (2012) 324

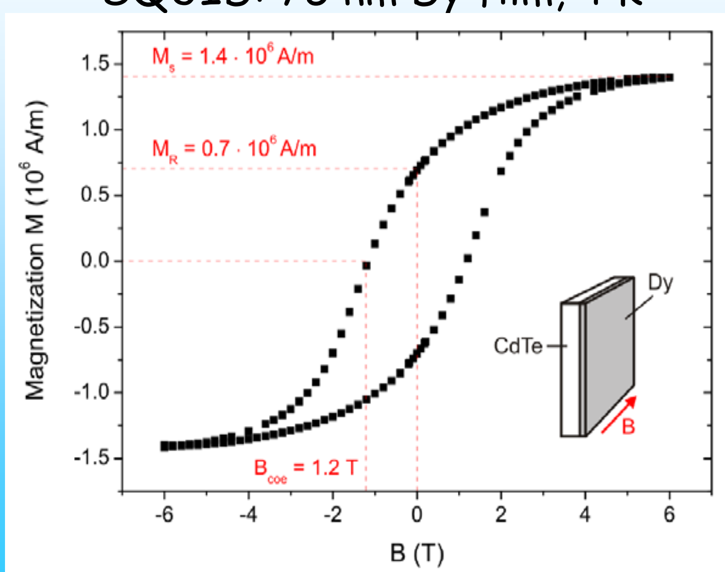


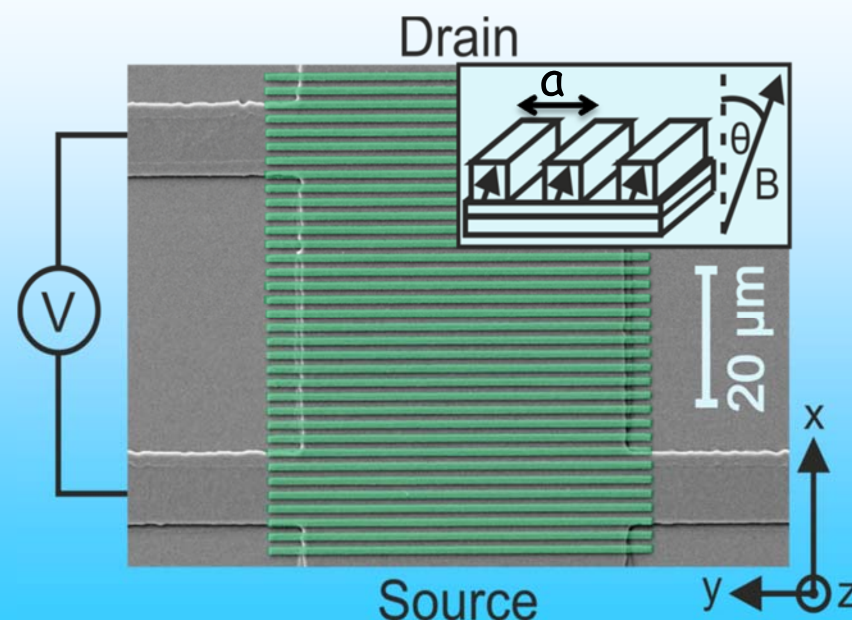
EBL + spattering + lift off

Dy thickness 75 nm + 6 nm Al protection

period a = 0.5, 1, 2, 4, 8 μm, stripes a/2 wide

SQUID: 75 nm Dy film, 4 K





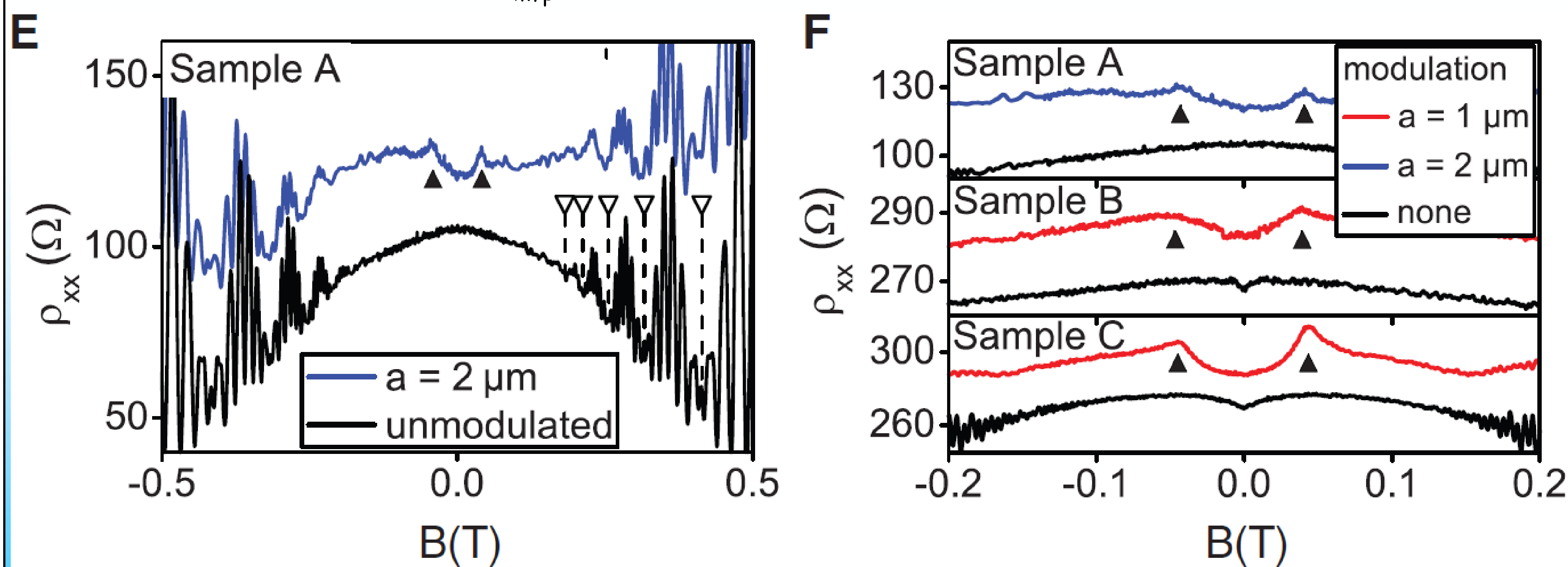
Experimental results: overview

C. Betthausen, *et al.*, Science **337** (2012) 324

Transport experiments: ramping B up to 8 T at angle θ in order to magnetize Dy stripes and data taken on the sweep back to - 0.5 T

T = 25 mK, B ⊥ 2DEG, e.a. θ = 0

Sample A, x = 0.55%, a = 2 μm,
μ = 130 000 cm^2/Vs → l_{mfp} = 1.39 μm

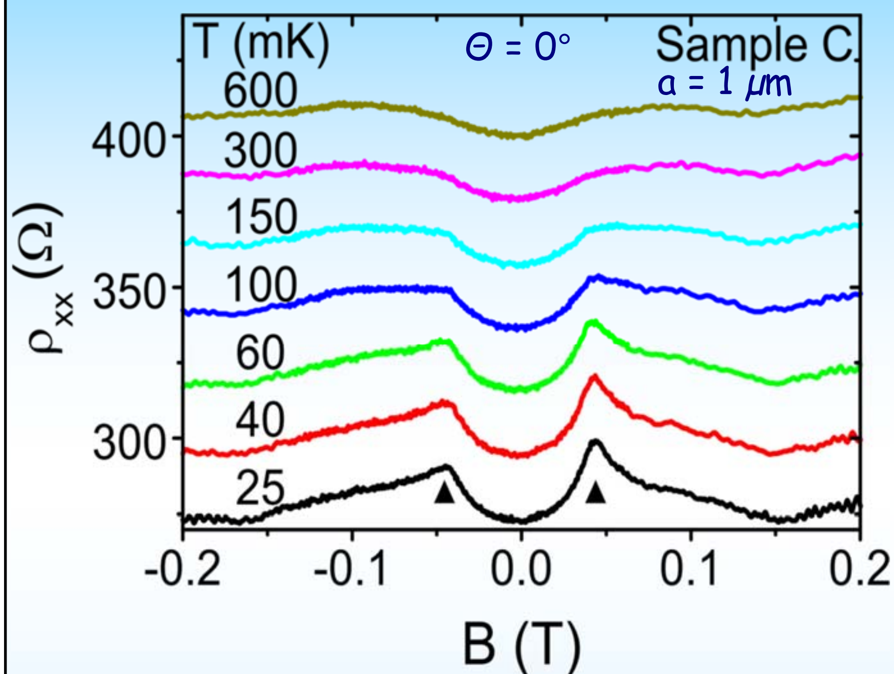


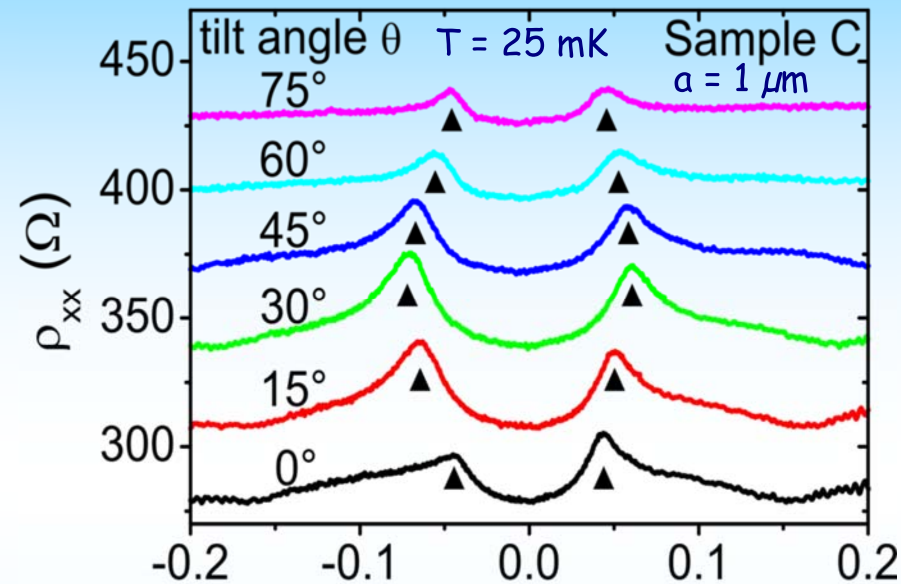
→ MR-peaks at ± 50 mT (= ± B_{stray})

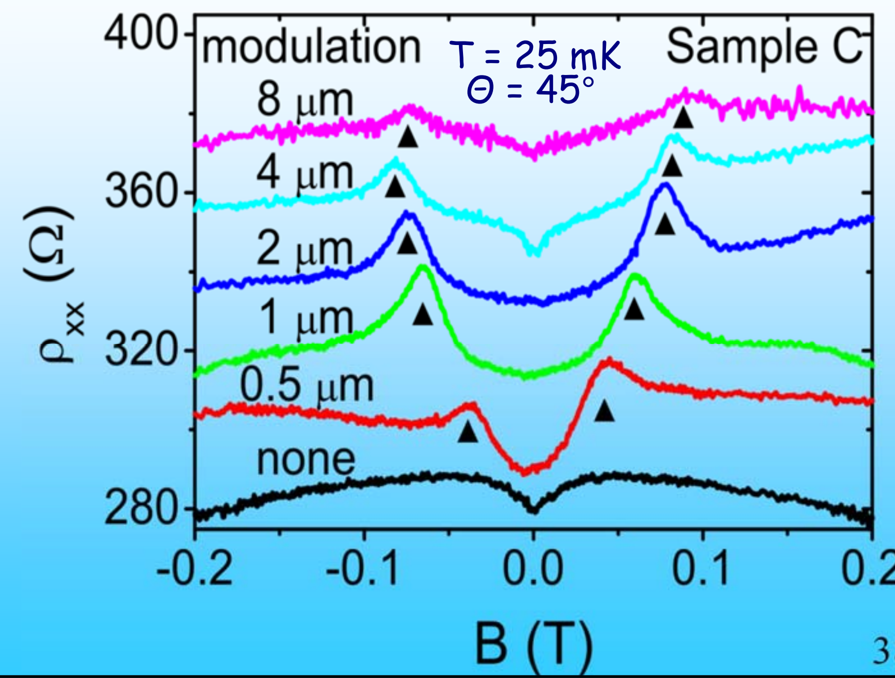
Experimental results for sample C for various T, Θ and a

C. Betthausen, *et al.*, Science **337** (2012) 324

Sample C, x = 1%, μ = 75 000 cm^2/Vs → l_{mfp} = 0.65 μm







→ peaks vanish for T > 300 mK

T-scaling of MR-peaks amplitude and $B_{5/2}$-function is identical → spin

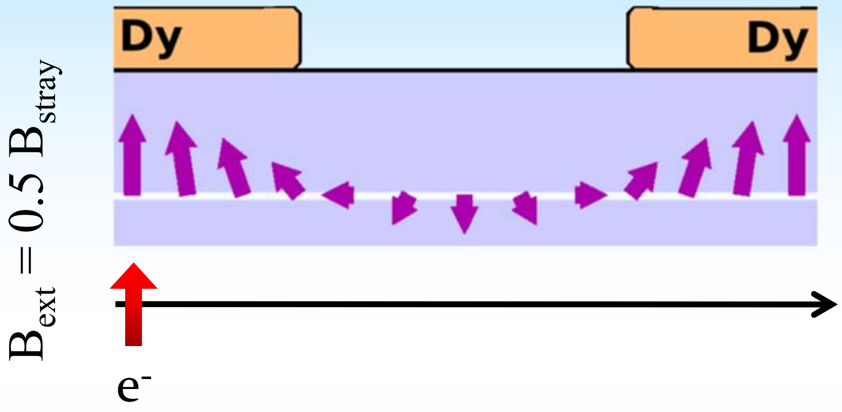
→ symmetry around θ = 45°
→ peak positions shift with period

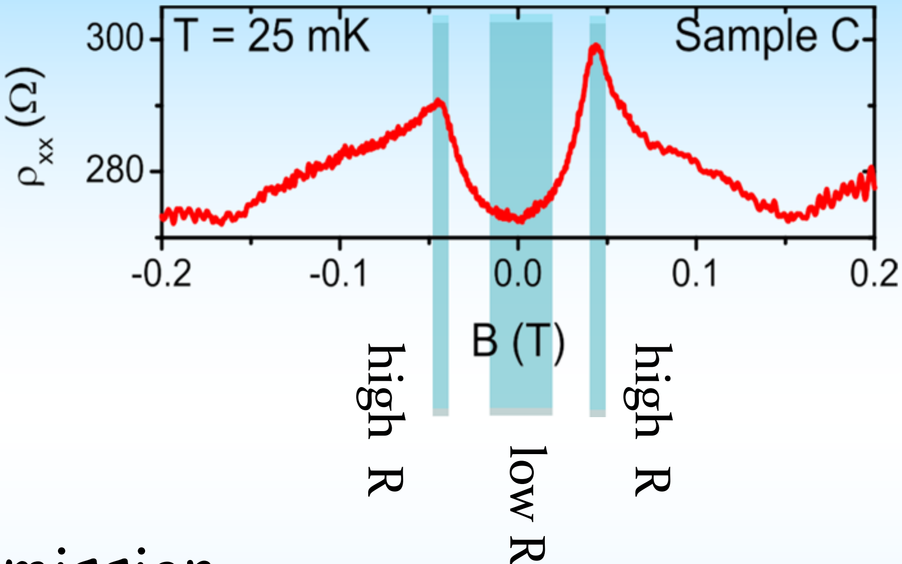
links MR-peaks to stray field

Interpretation: simple model (confirmed by theoretical device modeling)

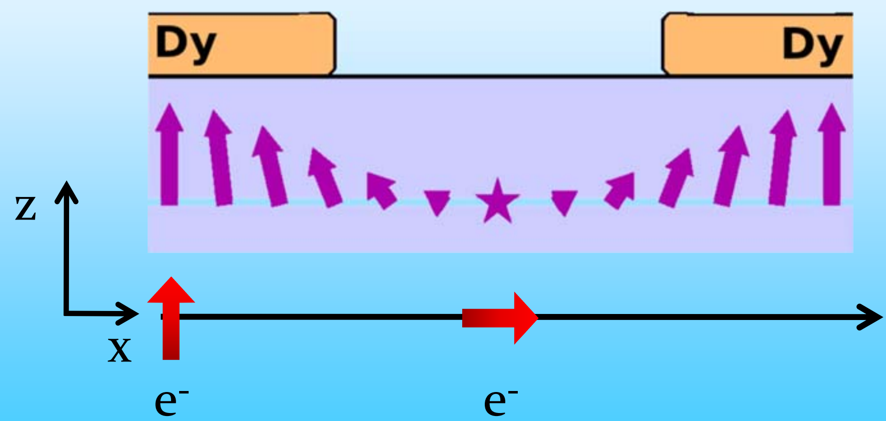
C. Betthausen, *et al.*, Science **337** (2012) 324

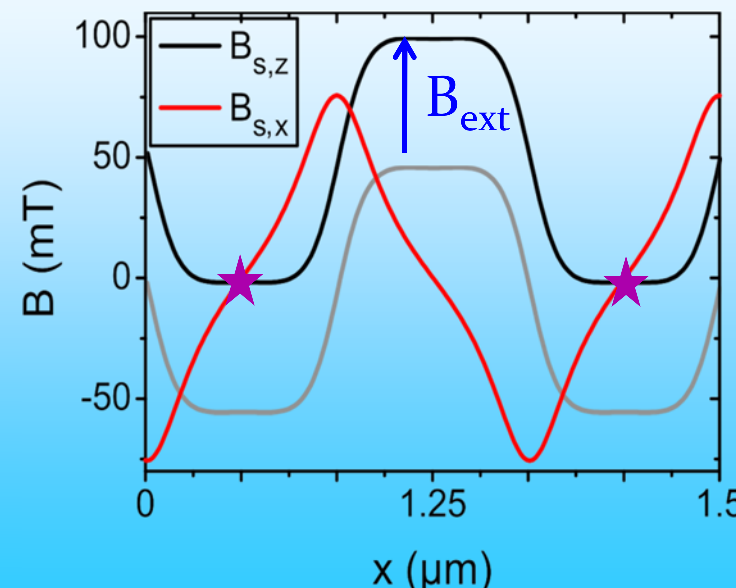
- $B_{ext} < B_{stray}$: Adiabatic spin transport





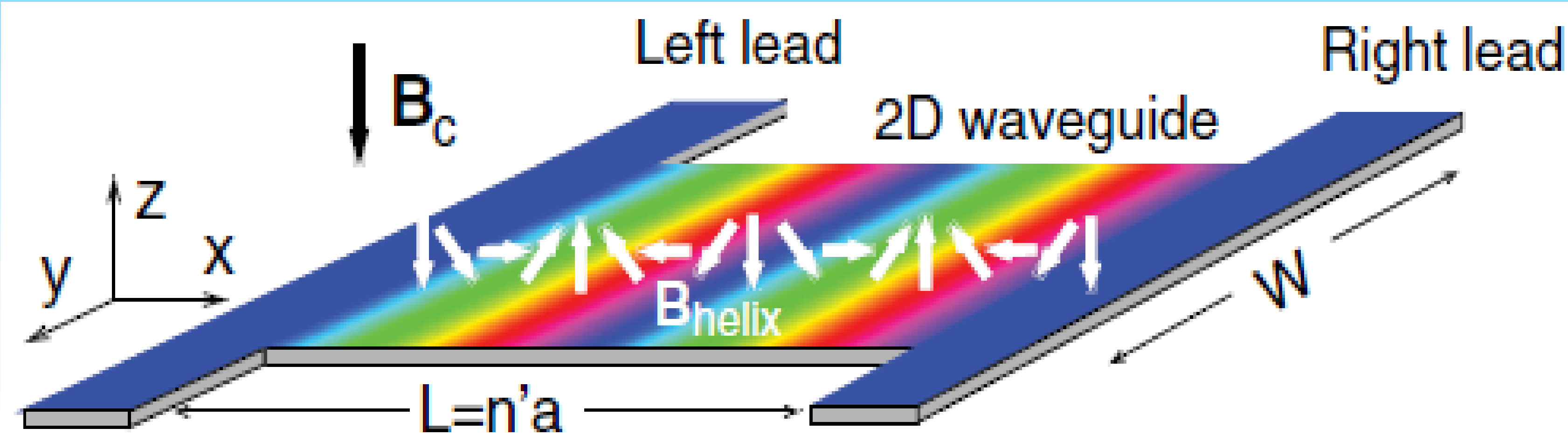
- $B_{ext} = B_{stray}$: Blocking of spin transmission





Theoretical modeling of adiabatic spin transistor (H. Saarikoski, T. Dollinger, K. Richter)

H. Saarikoski, *et al.*, Phys. Rev. B. **86** (2012) 165407



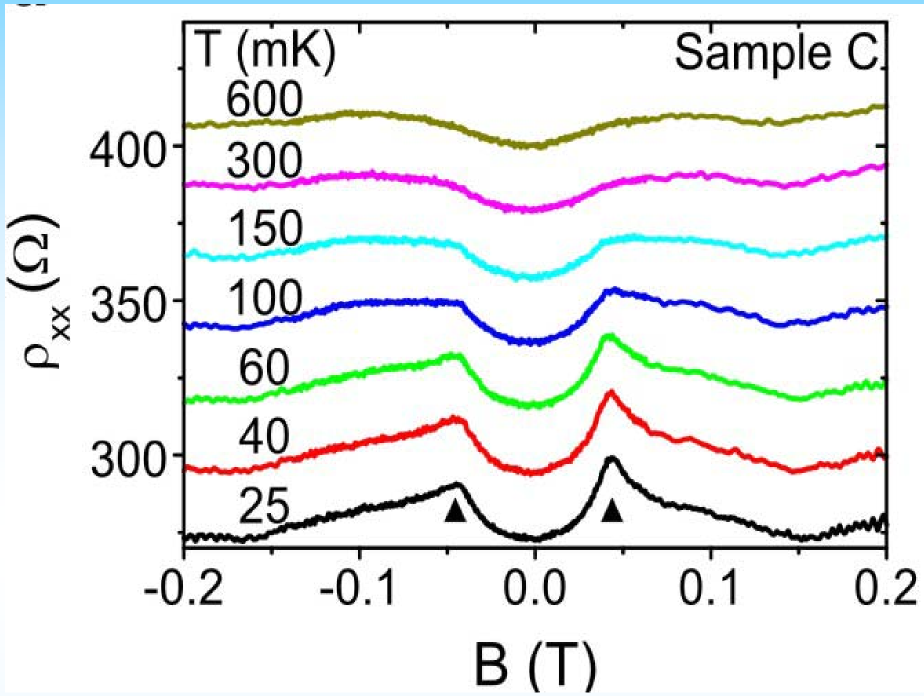
Spin-dependent magnetoconductance through magnetically modulated waveguides using Landauer-Buttiker formalism.

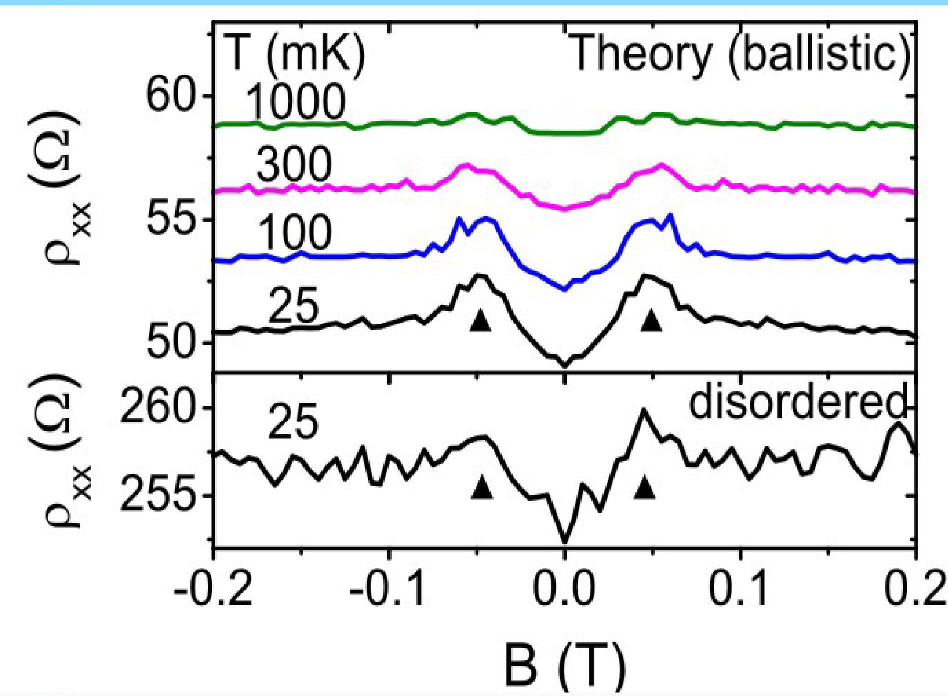
Two levels of approximation were used:

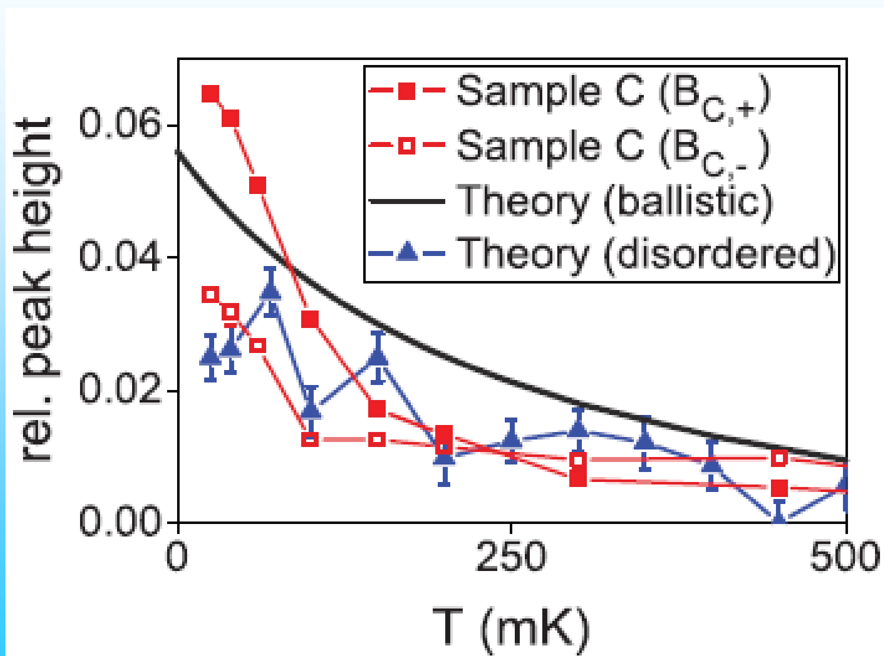
- A ballistic model with decoupled transverse channels and treating spin flips within the Landau-Zener theory
- Large-scale numerics: a recursive Green's function technique based on a tight-binding discretization for both ballistic and disordered systems

Comparison of experiments for sample C and theoretical device modeling vs. T

C. Betthausen, *et al.*, Science **337** (2012) 324

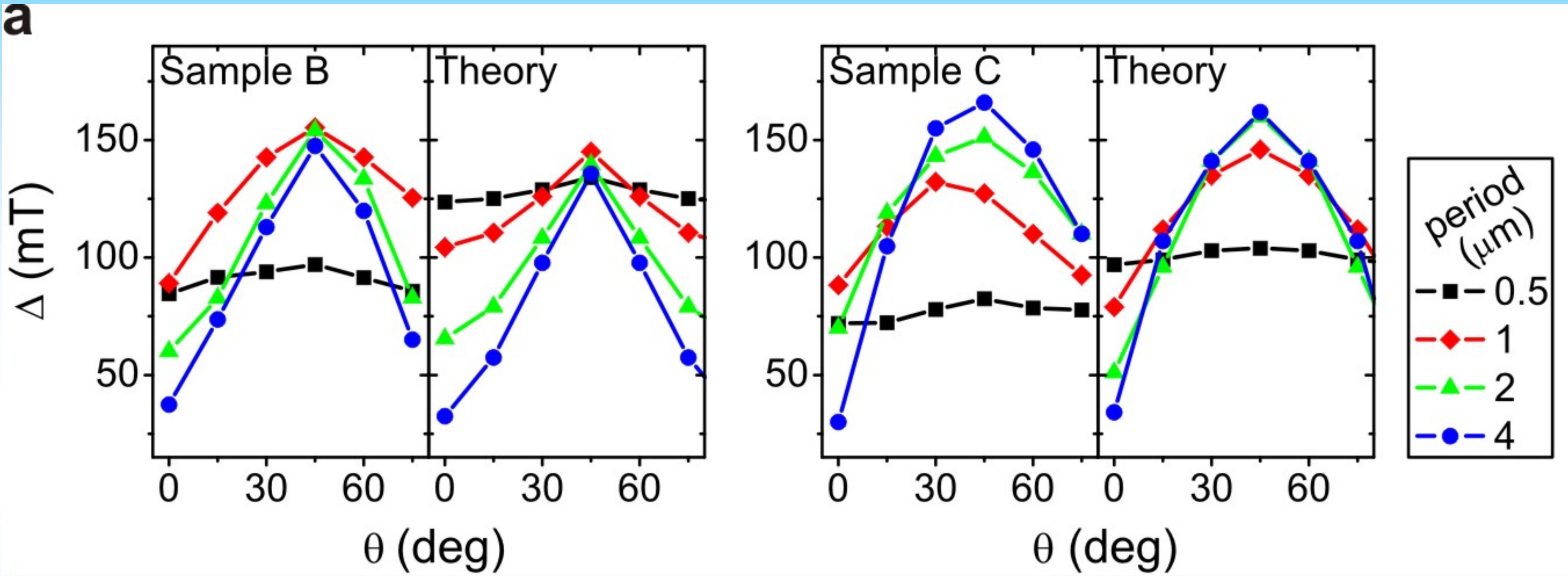


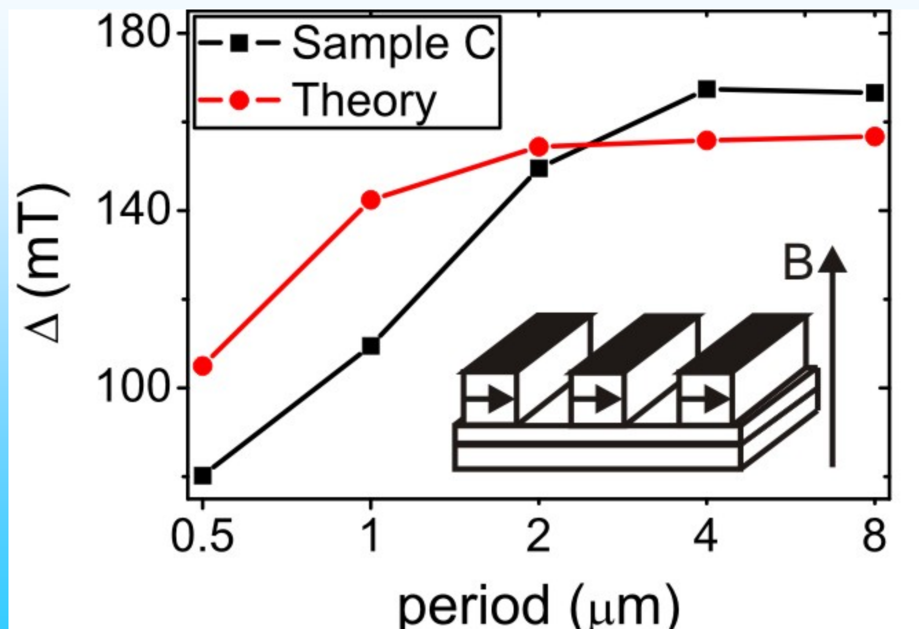




Comparison of experiments and theoretical device modeling vs. θ and stripes' period

C. Betthausen, *et al.*, Science **337** (2012) 324





$\mathbf{B}_{measr.} \perp \boldsymbol{M}$

Organization and enhancement of SO field in collective spin excitations

F. Baboux, *et al.*, Phys. Rev. B. **87** (2013) 121303(R)

SO field in the intrasubband spin-flip waves (SFW) of a spin-polarized electron gas.

It has been predicted
C.A. Urlich and M.E. Flatte, Phys. Rev. B. **68** (2003) 235310
and recently shown experimentally
F. Baboux, *et al.*, Phys. Rev. Lett. **109** (2012) 166401
that **intersubband spin-plasmon** of a GaAs quantum well, is *intrinsically* protected from D'yakonov-Perel' decoherence.

The Coulomb interaction rearranges the distribution of SO fields, so that all electronic spins precess in synchronicity about a single ***collective SO field***. Moreover SO field was discovered to be **drastically enhanced** with respect to the one acting on individual electrons: $\mathbf{B}^{coll}_{SO}(\mathbf{q}) \approx 5\,\mathbf{B}_{SO}(\mathbf{q})$

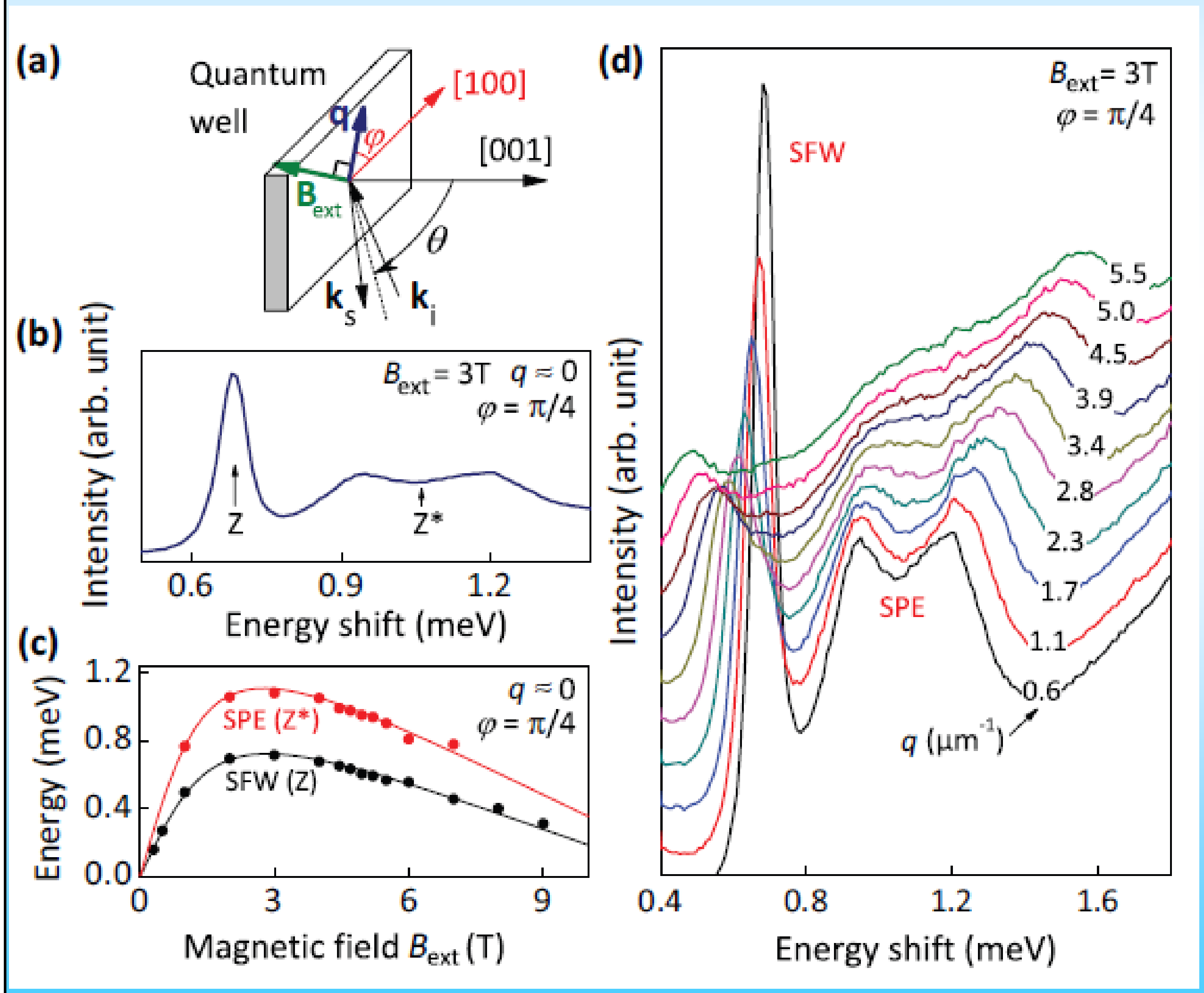
Question: is this general to collective spin excitations of any conducting system?

CdMnTe system provides a much simpler demonstration of these effects; here, in contrast to paper reporting data for GaAs, direct observations of the SO field at both single-particle and collective level is possible.

Intrasubbend spin excitations in CdMnTe QWs studied by inealstic light scattering (ILS)

F. Baboux, *et al.*, Phys. Rev. B. **87** (2013) 121303(R)

ILS is a powerful tool to transfer a momentum **q** to the spin excitations of the two-dimensional electron gas (2DEG).



q can be varied both in amplitude and in-plane orientation $|\mathbf{q}| \approx 4\pi/\lambda \sin\theta$, where λ = 771 nm is the incoming wavelength

$\mathbf{B}_{ext}$ - in the plane of the QW, perpendicular to **q** at angle ϕ with [100]

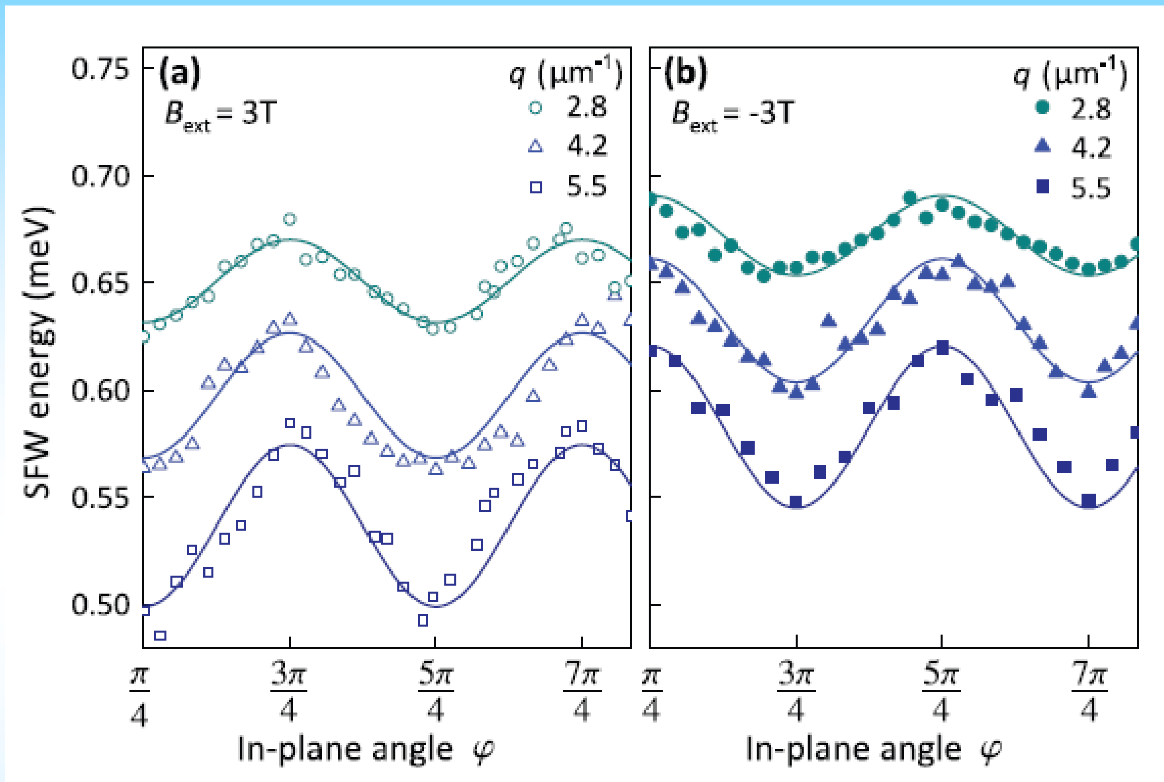
The incoming and scattered light polarizations are crossed- the required selection rule to address spin-flip excitations.

$\mathbf{k}_i$ and $\mathbf{k}_s$ are the incoming and scattered light wave vectors

SFW – Spin Flip Waves, SPE- Single Particle Excitations

Spin-orbit induced modulation of the spin-flip wave energy

F. Baboux, *et al.*, Phys. Rev. B. **87** (2013) 121303(R)



$$\widetilde{\beta} = 31.6 \pm 4.5 \text{ meV\AA}.$$

$$\widetilde{\alpha} = 19.9 \pm 2.5 \text{ meV\AA}$$

To analyze the data the model assuming that SFW behave as macroscopic quantum object of spin magnitude 1, subject to a collective SO field proportional to the excitation momentum q (shown to be valid for intersubband spin-plasmon in F. Baboux, *et al.*, Phys. Rev. Lett. 109 (2012) 166401):

$$\mathbf{B}_{\mathrm{SO}}^{\mathrm{coll}}(\mathbf{q}) = 2\widetilde{\alpha}\,(q_y, -q_x) + 2\widetilde{\beta}\,(q_x, -q_y)$$

$\hat{x} \parallel [100]$ and $\hat{y} \parallel [010]$

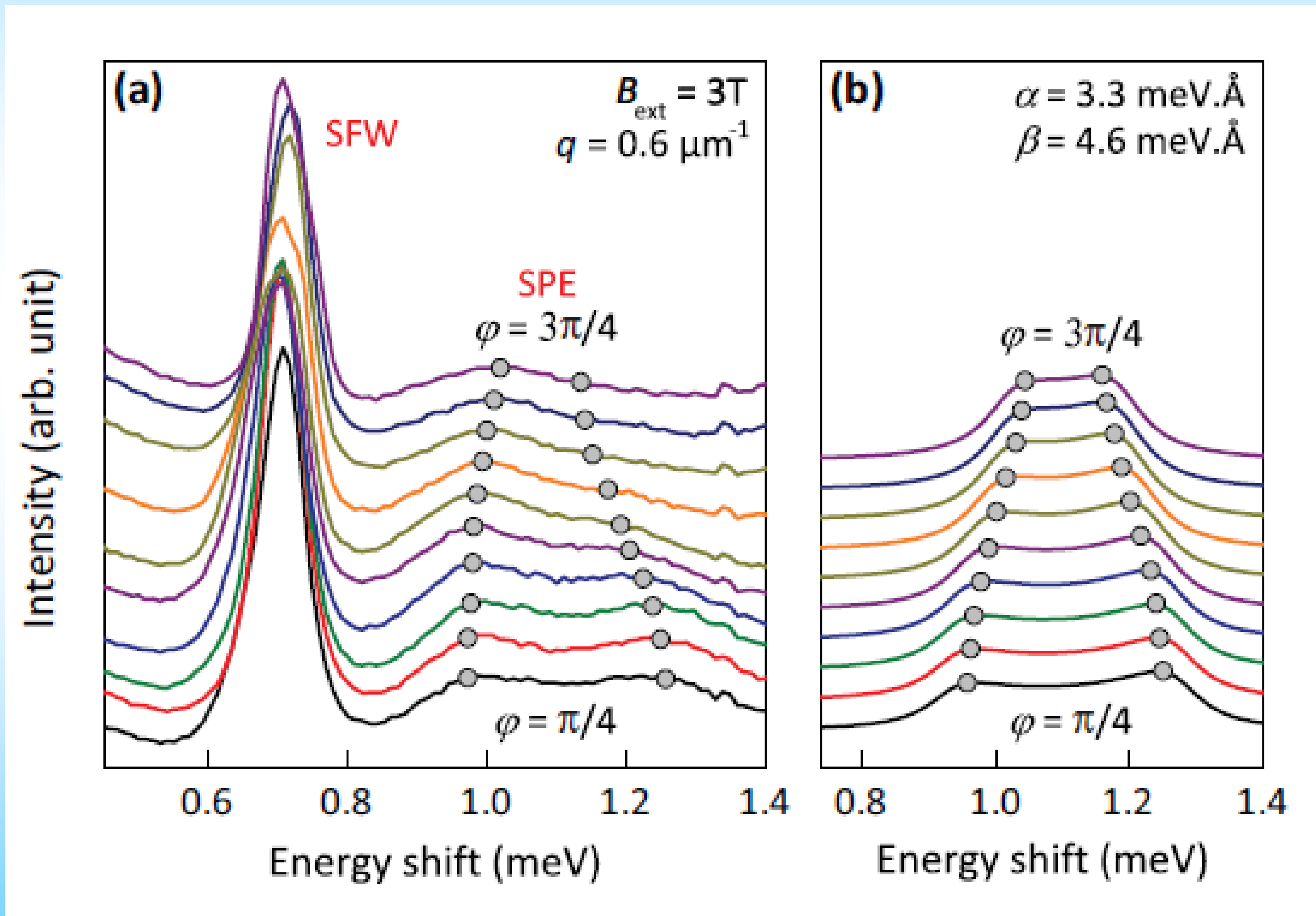
collective Rashba–SIA + linear Dresselhaus-BIA

the SFW energy for B>0 and B<0 is: $E_{\pm}(q,\varphi) = |Z - f q^2| \mp 2\widetilde{\alpha} q \mp 2\widetilde{\beta} q \sin 2\varphi$

Determination of spin-orbit coupling constants for single particle excitations (SPE)

F. Baboux, *et al.*, Phys. Rev. B. **87** (2013) 121303(R)

To extract α and β , we calculate the spin-flip Lindhard polarizability whose imaginary part describes the shape of spip-flip SPE line at transferred momentum q.



$$\alpha = 3.3 \text{ meVÅ},$$

$$\beta = 4.6 \text{ meVÅ}$$

$$\eta = 0.05 \text{ meV}$$

The fitted disorder parameter η is at least three times lower than for previously investigated samples, confirming a very high sample quality.
First ILS observation of SO splitting of the SPE line in DMS.

Comparison of spin-orbit coupling constants for SPE and SFW

The separation between two shoulders in SPE reflects the spread of single-particle SO fields due to their momentum dependence, in strong contrast with the SFW, which produces a sharp line. This provides a clear manifestation of the organization of SO fields at the collective level.

The interplay of Coulomb and SO interactions produces a striking boost of the Rashba and Dresselhaus effects at the collective level, while preserving the balance between both.

$$\mathbf{B}_{\mathrm{SO}}^{\mathrm{coll}}(\mathbf{q}) \simeq 6.5\, \mathbf{B}_{\mathrm{SO}}(\mathbf{q}).$$

Our results provides a strong indication of the universality of the immunity against dephasing, and giant enhancement of SO effects at the collective level.

Conclusions

Our results create a basis for further progress in technology of telluride 2D quantum structures and brings hope for many interesting physical and technological results to be obtained in the near future:

- physics of FQHE
- physics of QHFm
- spin textured systems (including superconductor/DMS)
- electrically defined magnetic QDs
- three terminal ballistic nano-junction spin filters
- etc. …….

We are eager to collaborate and we welcome new ideas on possible applications of CdTe-based 2DEG system