MBE of II-VI semiconductors *

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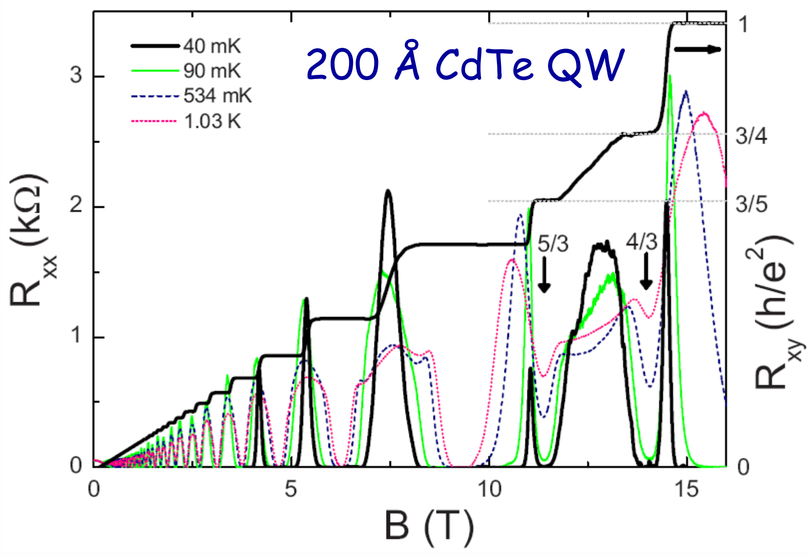
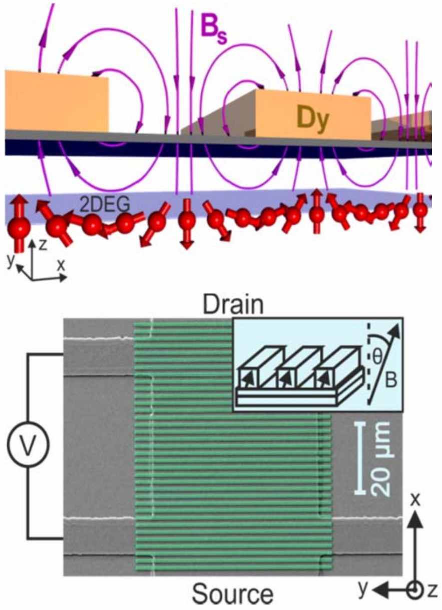
Technology

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

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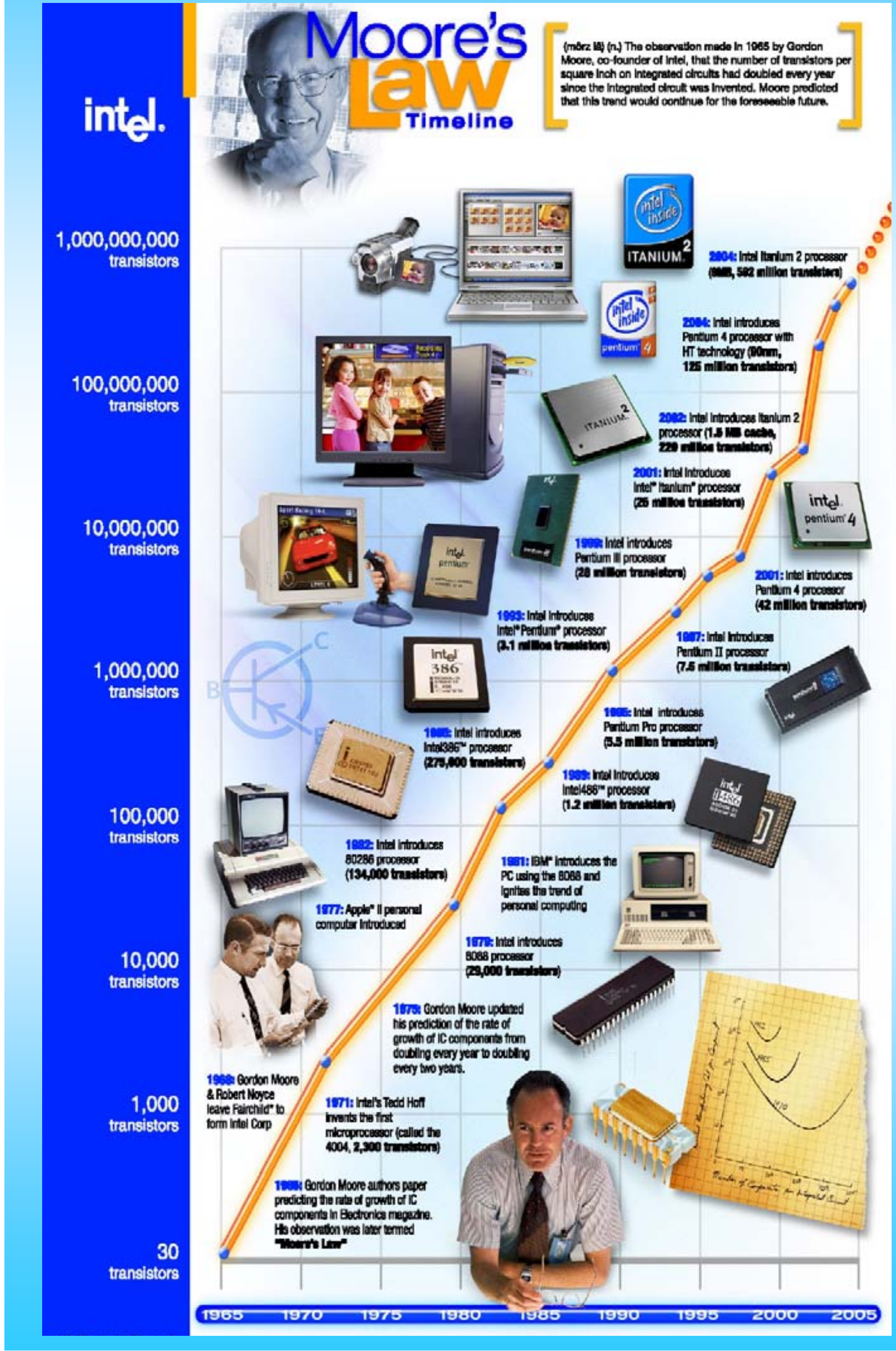
EAgLE

European Action towards Leading Centre
for Innovative Materials

How to continue progress beyond Moore's law?



Spin based electronics
"Spintronics"

T. Dietl, H. Ohno and D. Awschalom
2005 Agilent Technologies Europhysics
Prize of the European Physical Society
(semiconductor spintronics)

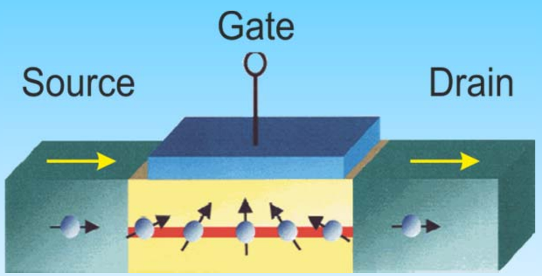
A. Fert i P. Grünberg
2007 Nobel Prize in Physics
For the discovery of giant
magnetoresistance effect
(metal spintronics)

"Bottom-up" approach

Both concepts are
under development
in the Institute and our Lab
(in combination with
"top down" approach)

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 semiconductor 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 *sp-d* interaction between localized spins of magnetic ions (e.g. Mn^{2+}) and spins of band carriers

$$E_{sp-d} = -J(\vec{j} \bullet \vec{S})$$

- for conduction electrons (direct exchange): $J = 0.2$ eV
- for valence band holes (hybridization): $J \sim -1$ eV

$$\Delta E_{spin} = xJ < S_z > \qquad \Delta E_{spin} = g^* \mu_B B$$

$$x < S_z > \sim M(B,T) \qquad g^* \sim 200$$

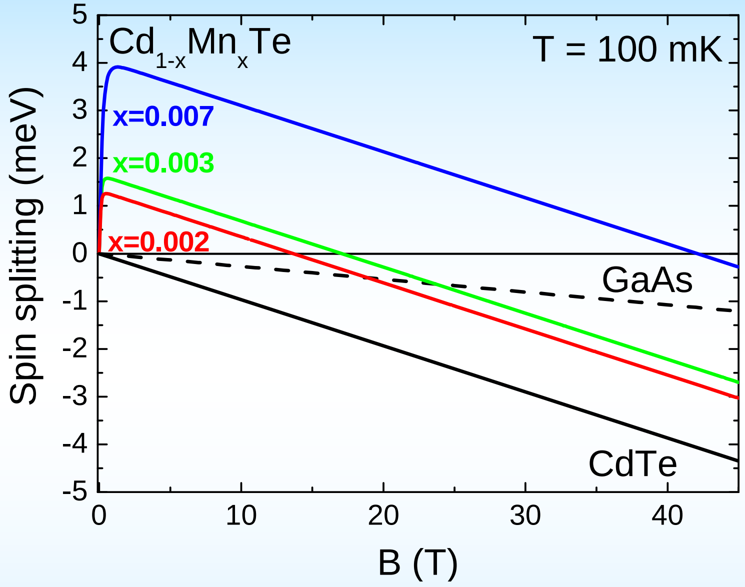
Spin splitting engineering in CdMnTe QW with 2DEG important since spintronics is all about spin

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

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

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

Temperature and field dependent



Crossing of LLs with either different or the same index possible at **various ν**

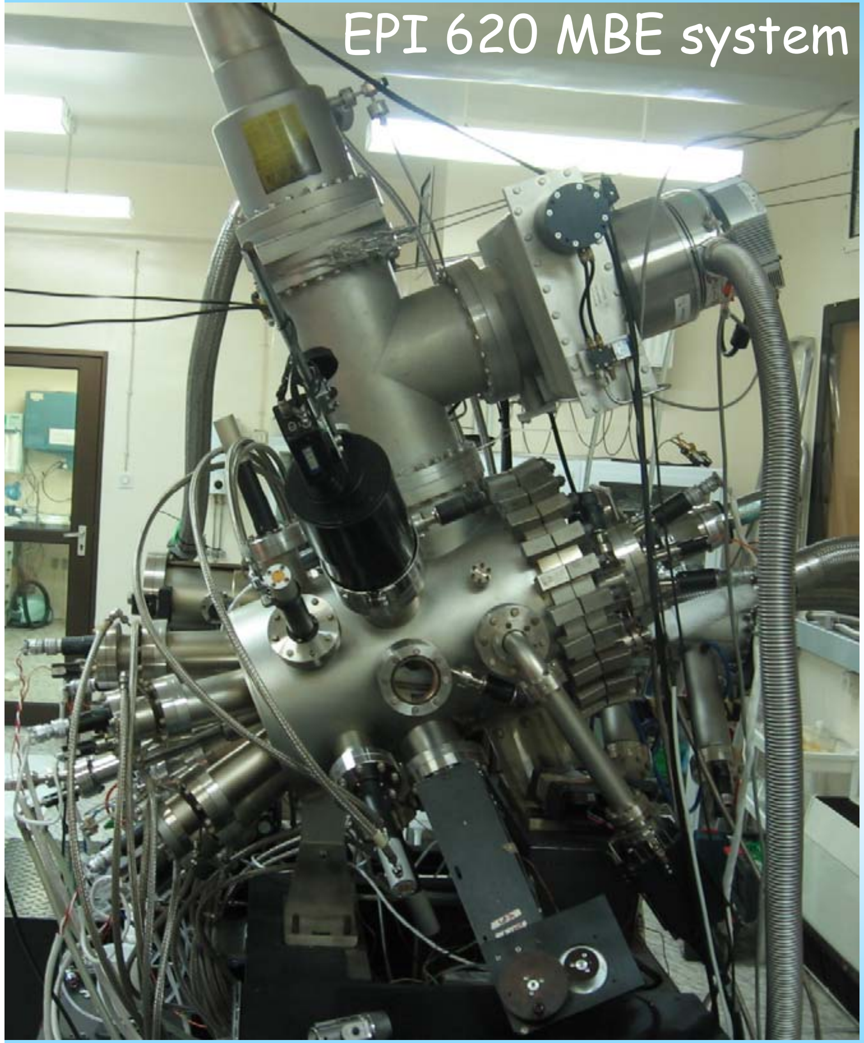
This can be used in studies of FQHE

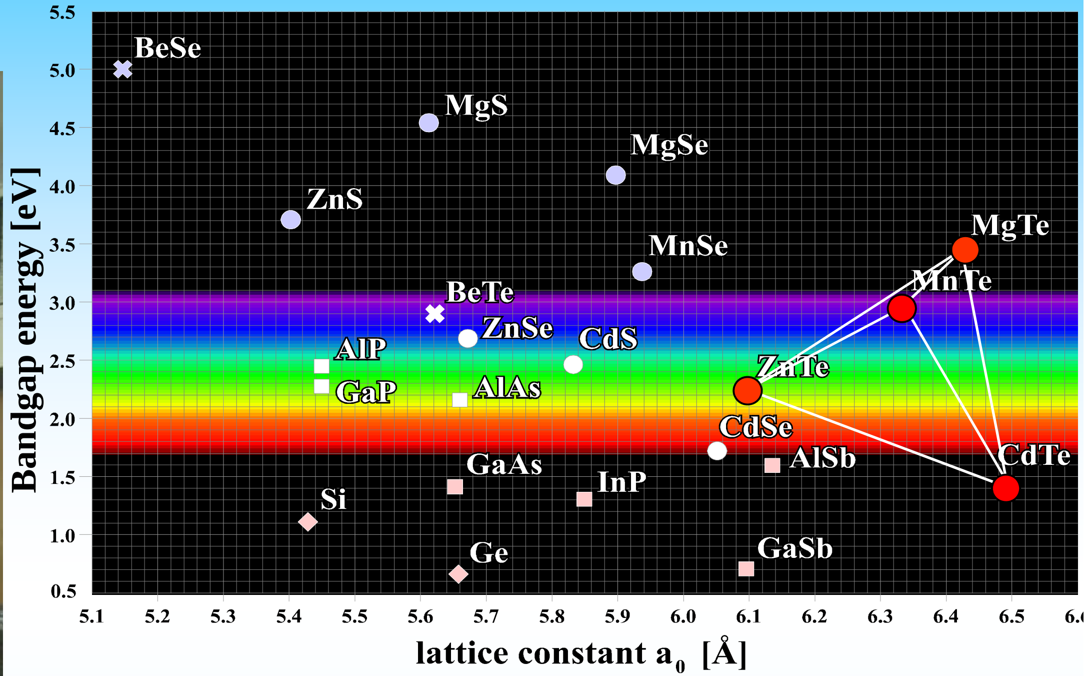
Dependence of splitting on B can be further engineered via Mn distribution in the direction of growth, e.g. in parabolic QWs made of CdMnMgTe: T.Wojtowicz *et al.* J. Cryst. Growth 214 (2000) 378

Spin splitting can be spatially engineered via local magnetic fields (nano-magnets or vortices)

Very important: Spin splitting can be externally controlled in a given structure not only by T or B but also by electric field created via gate voltage

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





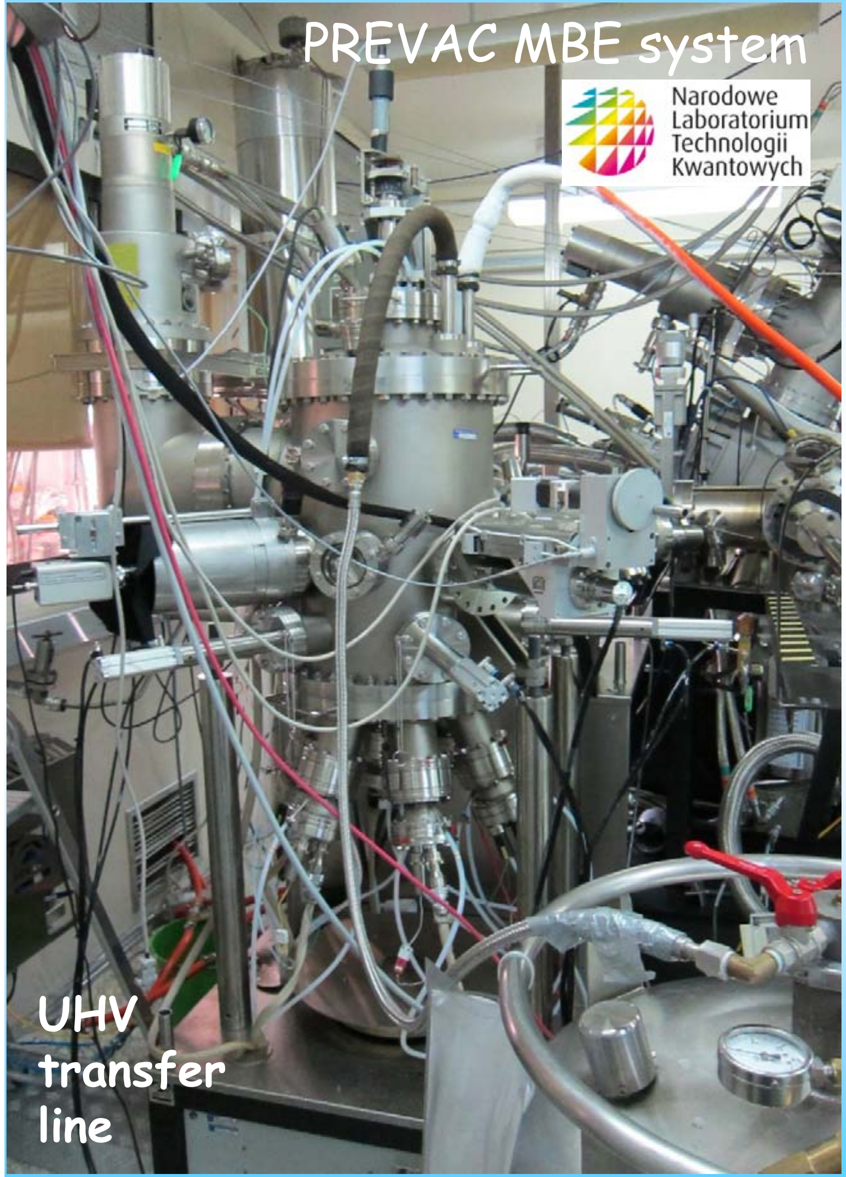
EPI 620 MBE system for II-VIs:
Cd Mg Zn Mn Te
ZnI$_2$ - „n" N plasma cell- „p"
Spare: Cr, In ...

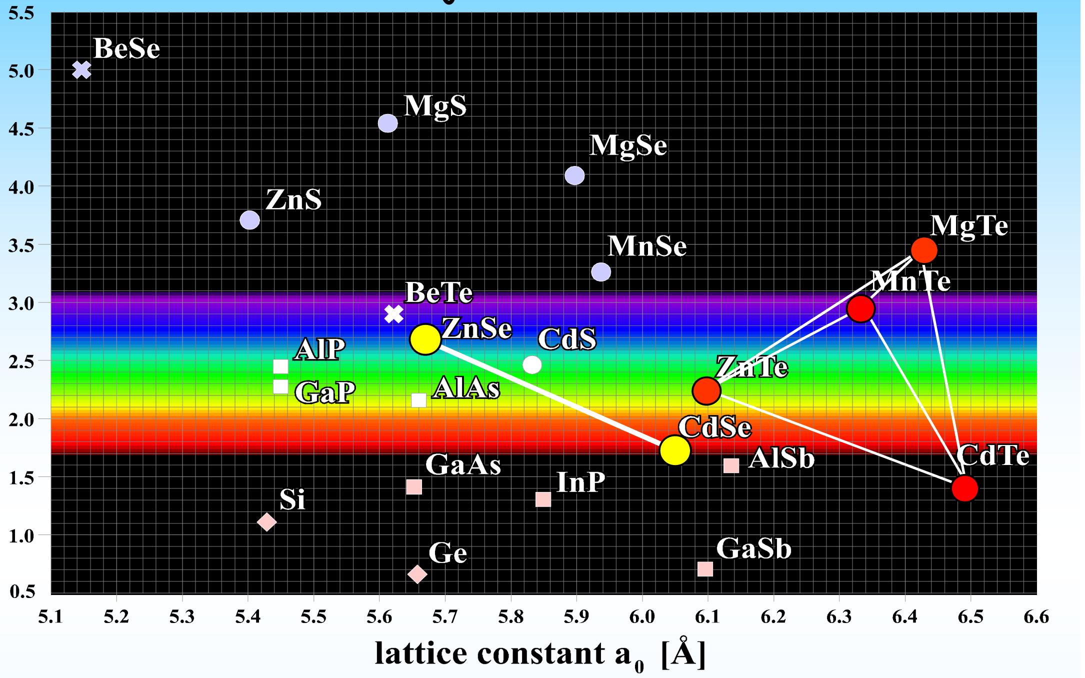
22-nd year of Lab (first growth on July 6, 1993). We have grown ≈ 6000 samples and we specialize in:

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**

Second PREVAC MBE chamber with UHV transfer line to EPI MBE chamber in the SL3 LAB

M. Wiater, K. Fronc, G. Karczewski, T. Wojtowicz





PREVAC MBE system (6 cell ports + Pyro port) prototype Prevac/SL3 FROM 5 PROJECTS

Effusion cells: **Cd, Zn, Se, Au, In,** … **Mg?**
Electron gun: **Cr, Co, Fe, Re (5d^5), Cu ...**
vs.
Mn (3d^5)

Plans:
QDs and QWs with various magnetic atoms

Just the beginning (no LN_2 phase separator, not all cells, etc.)
– some 50 growth processes

Advantages of MBE technique for the growth of II-Mn-Te DMSs (or semimagnetic semiconductors)

1. Extension of Mn concentration beyond solubility limit:
„weakly diluted magnetic semiconductors",
e.g. $Cd_{1-x}Mn_xTe$ with $x > 0.77$

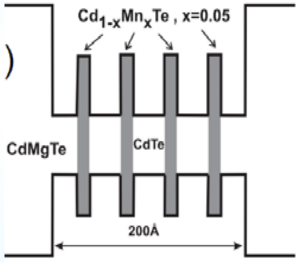
2. Materials nonexisting in the bulk form:
   a) ZB MnTe – „semiexisting semimagnetic semiconductor"
   b) ZB $Mg_{1-x}Mn_xTe$ – „double semiexisting semimagnetic semiconductor"

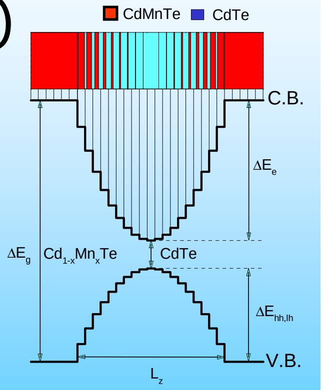
3. Flexibility in the incorporation of Mn
   a) regular random mixed crystals

   b) digital magnetic alloy = short period superlattice with magnetic component (e.g MnTe, $Cd_{1-x}Mn_xTe$)

   c) profiling of Mn concentration in the growth direction (both potential & magnetic profiling or profiling of magnetic component only in e.g. $Cd_{1-x-y}Mn_xMg_yTe$)

   d) profiling in the direction perpendicular to the growth axis





Advantages of MBE technique for the growth of Mn-based DMSs (or semimagnetic semiconductors)

Using „bottom-up" approach DMSs can be cast in such a way so that the movement of carriers is spatially confined to the regions having nanometer sizes in one, two or three directions, thus they form 2D, 1D and 0D objects (DMS quantum wells, quantum wires and quantum dots).

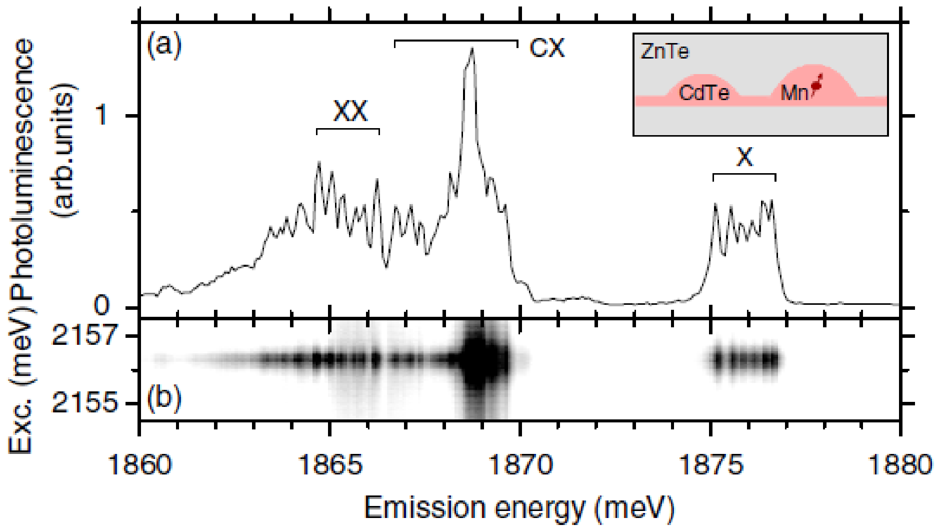
Incorporation of electrically active dopants is more efficient (say of N) and „remote" or „modulation" doping possible.

Application of MBE allows for:

- advanced g-factor/spin-splitting engineering: amplitude, sign, anisotropy and magnetic field dependence
- external control of g-factor (via temperature, light and electric field)

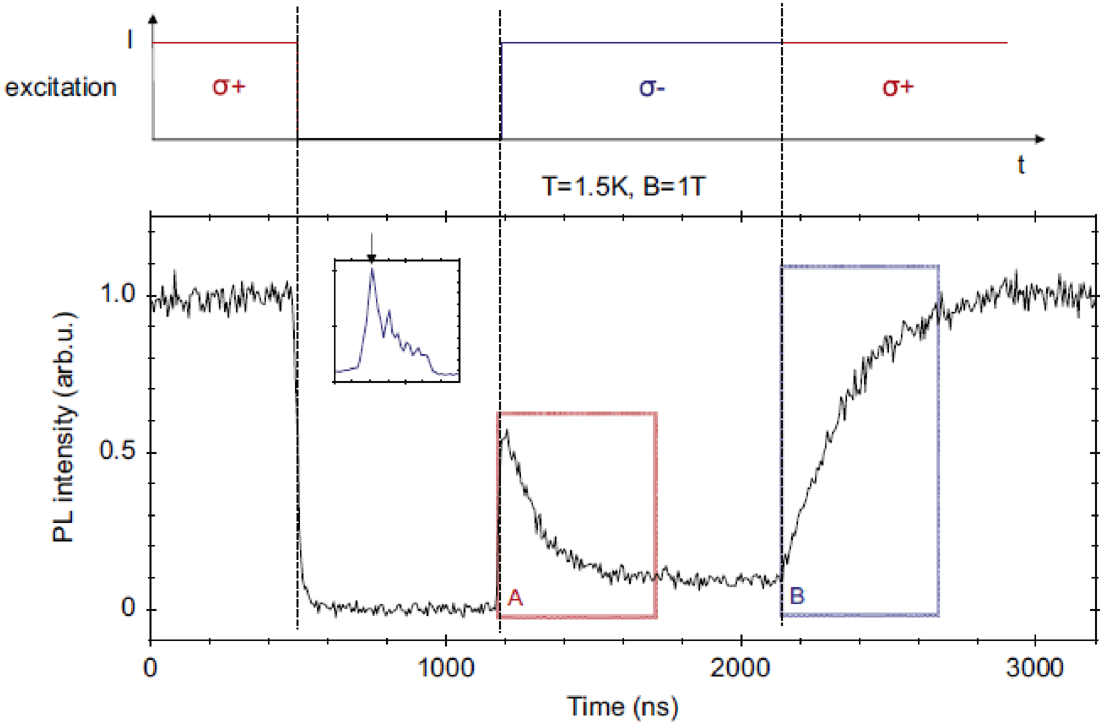
Optical manipulation of a single Mn in a CdTe QDs
Ultimate limit for information storage miniaturization

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.



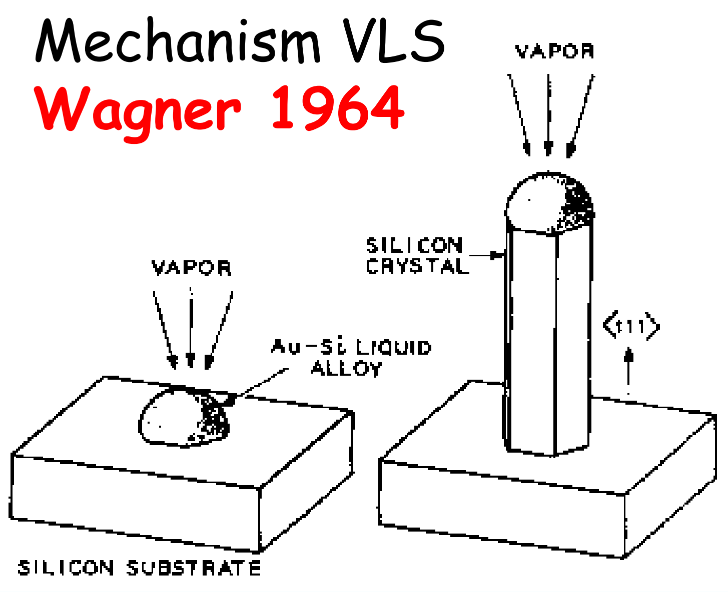
Unequal intensity of lines a measure of spin orientation

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

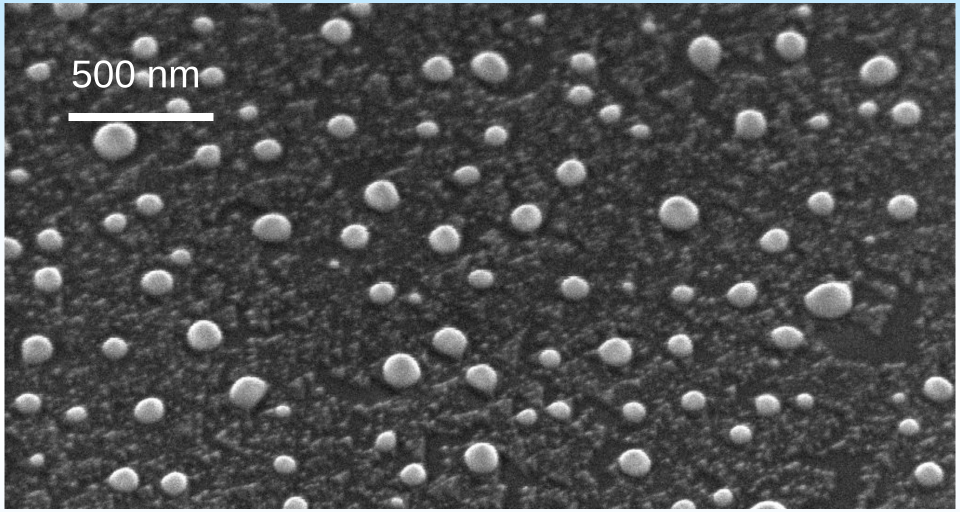
Storage time of information on Mn spin in the dark – hundreds of microseconds

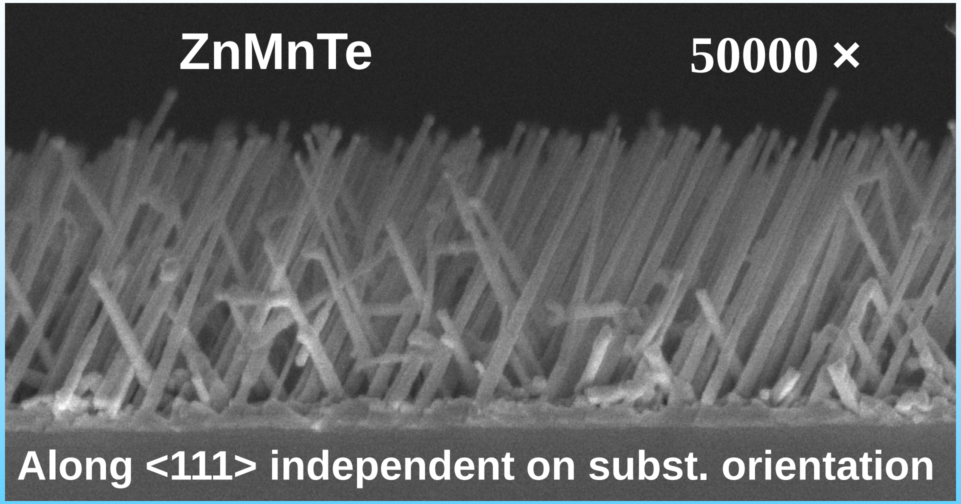
Growth of ZnMnTe nanowires: Au assisted Vapor-Liquid-Solid (VLS) growth mechnism

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



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



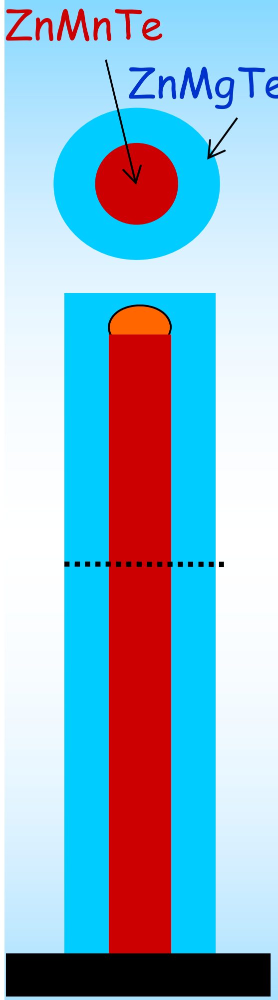


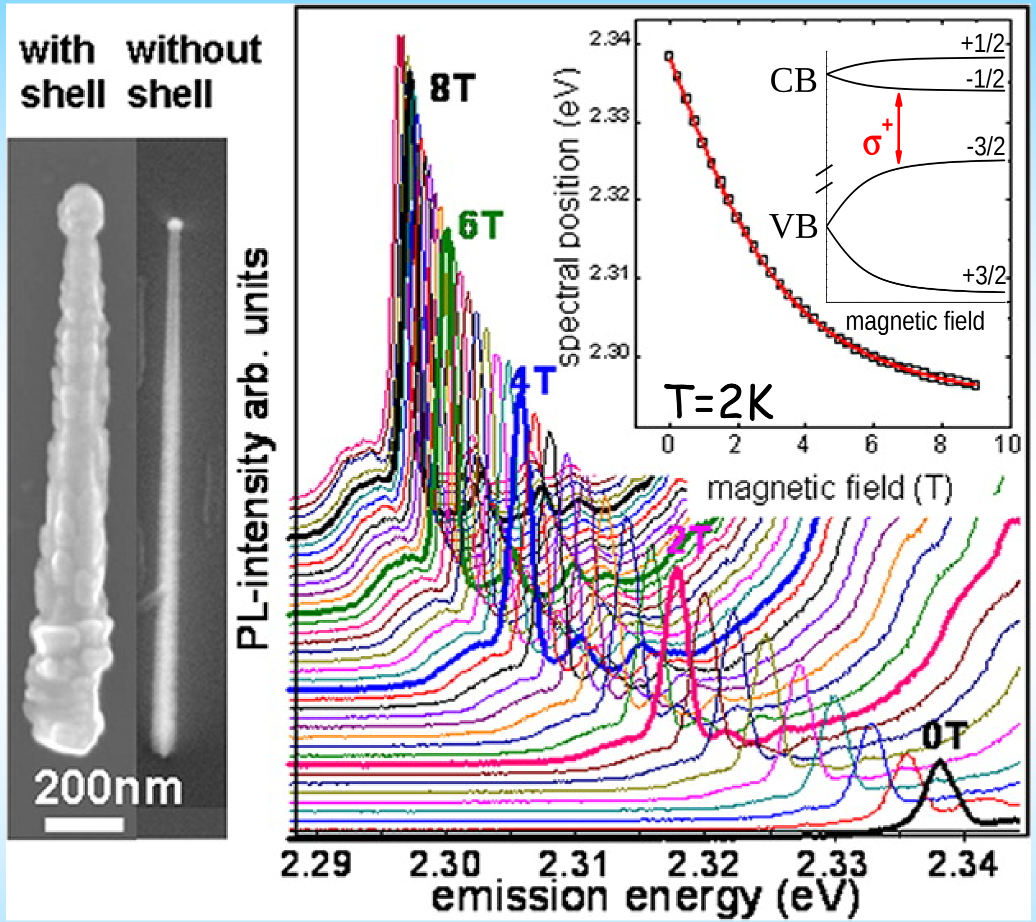
Along <111> independent on subst. orientation

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

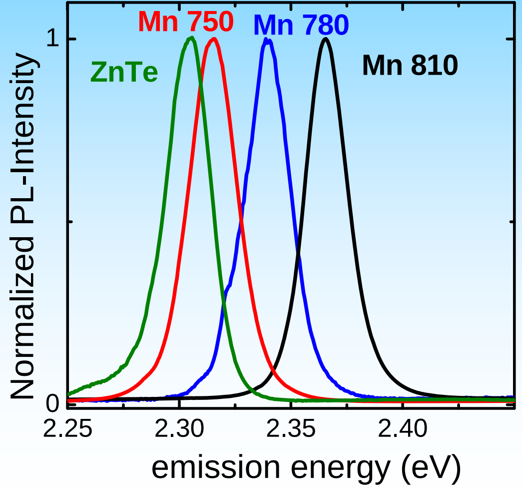
Giant spin splitting in optically active ZnMnTe/ZnMgTe core/shell nanowires

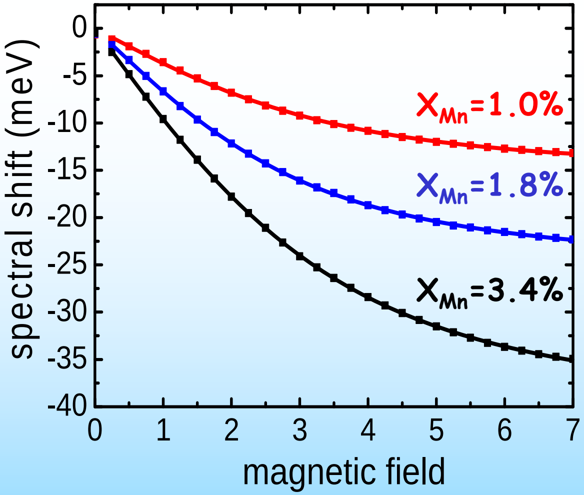
P. Wojnar, *et al.*, Nano Lett. **12** (2012) 3404





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

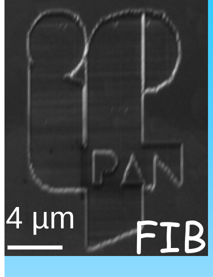




Proof of DMS nanowires

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)



Laboratory of microscopy and nanolithography joint venture of SL3 (TW) & SL2 (Prof. T. Dietl)

ZEISS Neon 40-Auriga CrossBeam Workstation & Raith Elphy Plus EBL

SEM - Schottky Field Emitter
FIB Cobra (Orsay Physics) - Gallium ions source

Resolution SEM 1.0nm at 15kV
Resolution FIB 2.5nm at 30kV
Magnification SEM: 12x –1000k x
Magnification FIB: 300x – 500k x

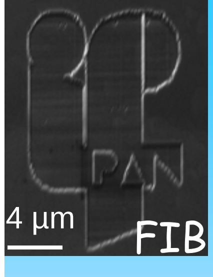
Accelerating voltage:
SEM 0.1 – 30kV
FIB 1 – 30kV

Probe current:
SEM 4pA – 80nA
FIB 1pA – 50nA
Detectors: In-lens, SE2, In-lens EsB with filtering grid for BSE detection, SI and STEM, CL.

- **Nanomanipulators** (Kleindiek, 0.5 nm resolution, with electrical probes)
- **Piezoelectric stage** (Kleindiek, 0.5 nm resolution, for EBL and FIB)
- **Gas Injection System (GIS)** for in situ etching (XeF_2) and deposition of Pt, W, SiO_2
- **EDX** (XFlash Silicon Drift Detector - Bruker) **e.g. making contacts to nanowires**

INNOWACYJNA GOSPODARKA
NARODOWA STRATEGIA SPÓJNOŚCI
UNIA EUROPEJSKA
EUROPEJSKI FUNDUSZ
ROZWOJU REGIONALNEGO
NanoBiom
Narodowe
Laboratorium
Technologii
Kwantowych
spin LAB

SL3 & SL2 Lab: SEM, low-T cathodoluminescence, Electron Beam Induced Current (EBIC)



Peltier cryostat
T: -50 C to + 50 C

Auriga SEM

Fiber to Auriga SEM

ZEISS EVO HD15 SEM:

Emitter LaB_6
Resolution 2.0nm at 30kV
Magnification SEM: 5 x –1000k x
Accelerating voltage: 0.2 – 30kV
Probe current: 0.5 pA – 5 µA
Detectors: SE and 5QBSD

HORIBA Jobin Yvon CL:

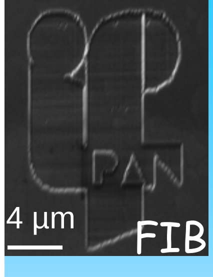
Monochromator 320mm
CCD 330-950nm
Photon counting PMT 200-860nm

Kammrath & Weiss cryostat

Temperatures down to 5K

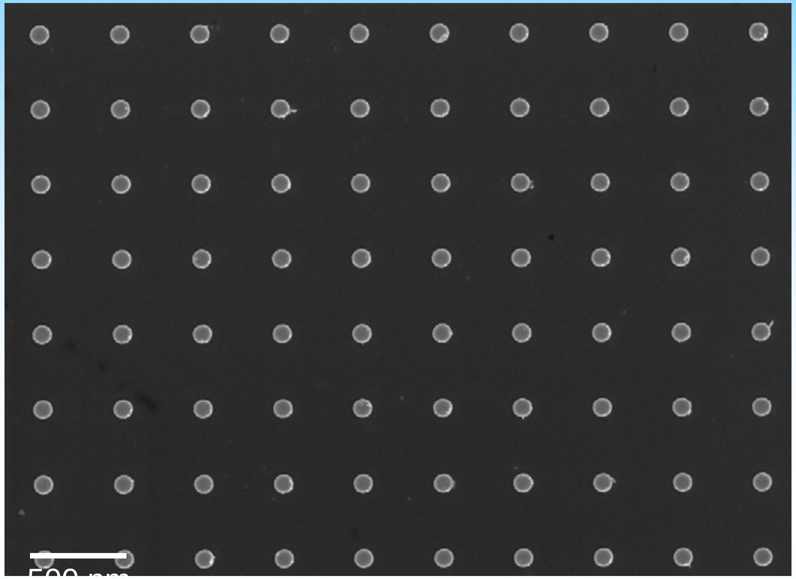
Point Electronic GmbH

Digital Image Scanning System DISS 5 EBIC with amplifier:
Gain (103 … 1010) × (0.1 … 100) V/A
Bandwidth 0.5 MHz at 109 V/A
Scan generator with max. 16,384 × 16,384 pixels
Dwell time per pixel 200 ns … 6 ms

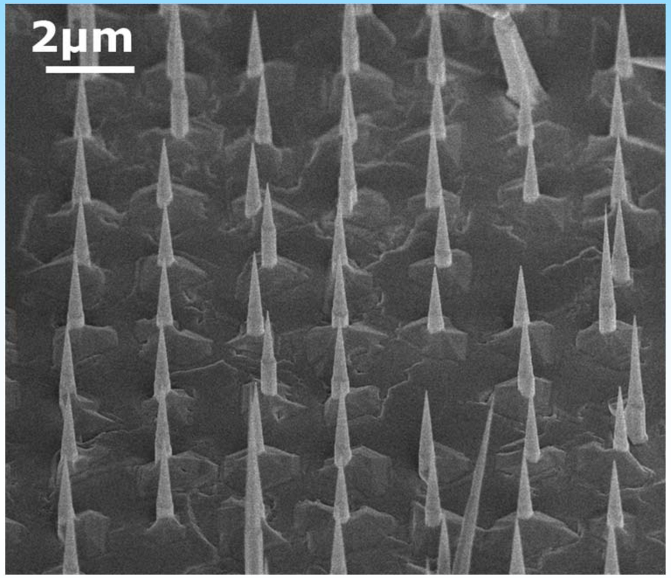


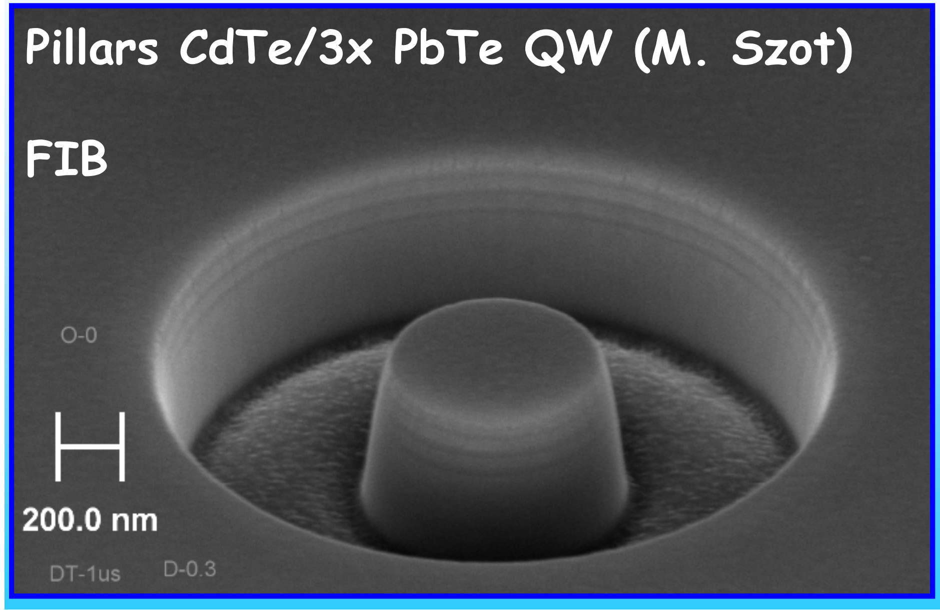
Examples of nanostructures defined by EBL & FIB in our Lab (V. Kolkovsky, T. Wojciechowski)

Au Φ =30nm na GaAs



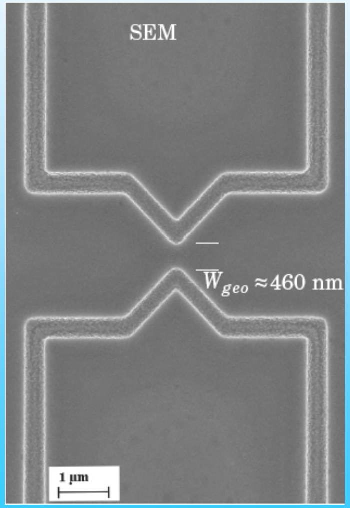
GaAs NWs on (111)-GaAs (MBE at ND)

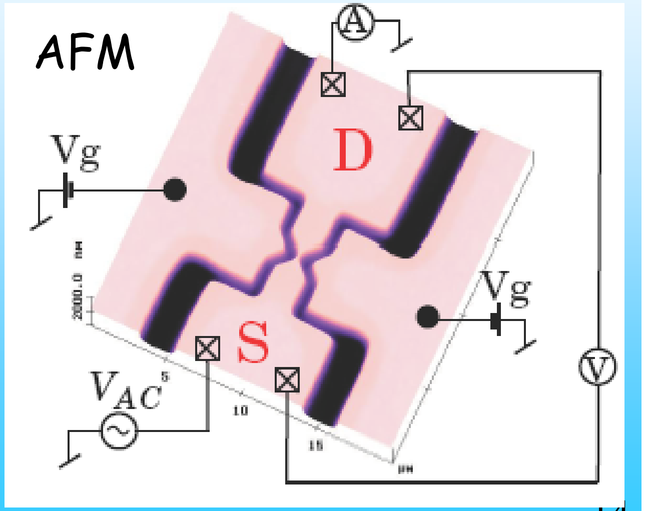



Pillars CdTe/3x PbTe QW (M. Szot)

FIB

CdTe/CdMgTe QPC , M. Czapkiewicz
M. Aleszkiewicz

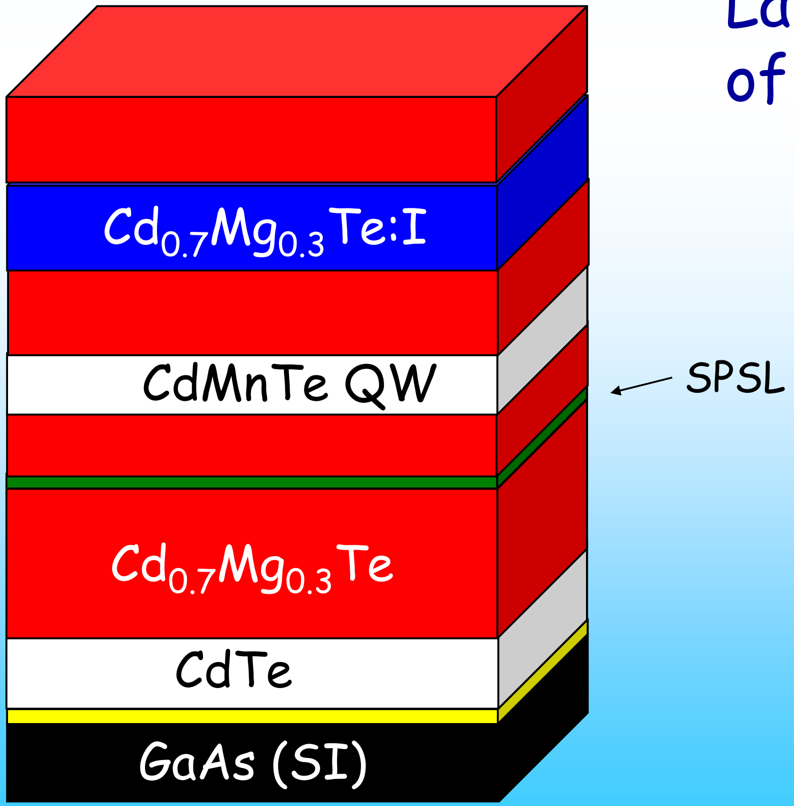




Technology of high mobility 2DEG structures made of $Cd_{1-x}Mn_xTe$ QWs with $Cd_{1-y}Mg_yTe:I$ barrier

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

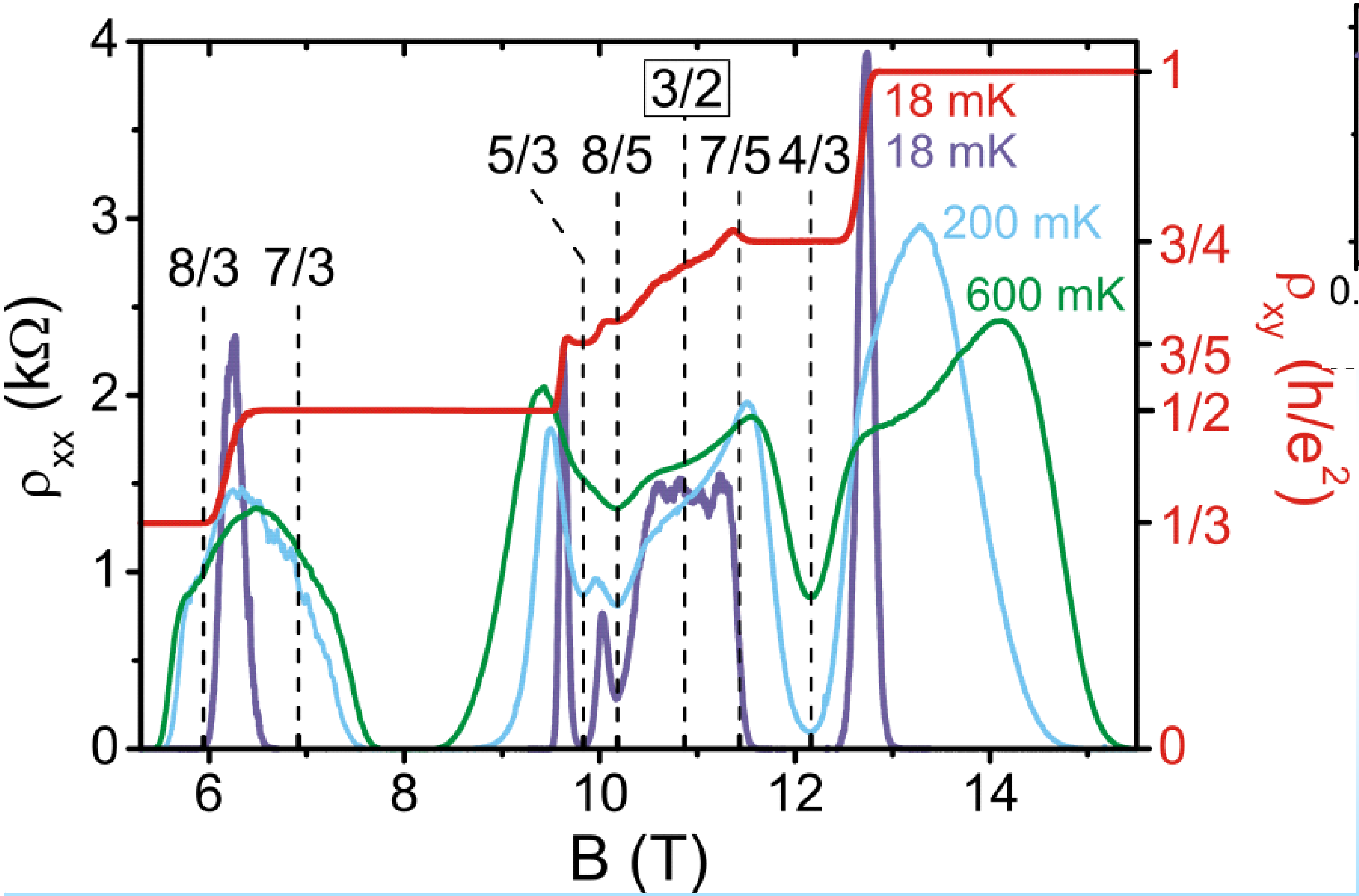
Non-bonded Molybdenum holders
Careful procedures (purity) and thick (ZnTe/CdTe/CdMgTe/SPSL) buffers

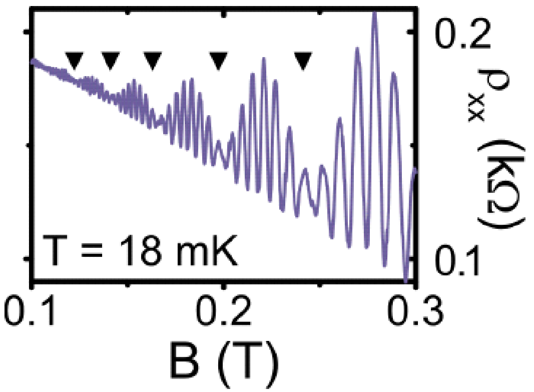


Large surface suitable for development of e-beam, AFM, FIB lithography !

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

C. Betthausen *et al.*, Phys. Rev. B **90**, 115302 (2014). $Cd_{1-x}Mn_xTe/CdMgTe:I$ 300 Å QW





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

$x \approx 0.0024$

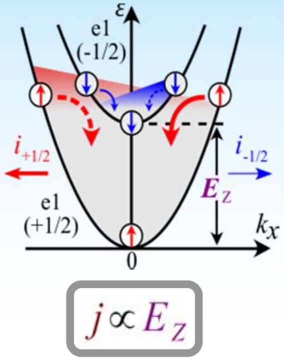
Mn does not destroy FQHE for x up to 0.01!

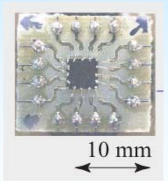
Studies of FQHE for zero Zeeman energy at any ν, taking advantage of spin-splitting engineering are feasible

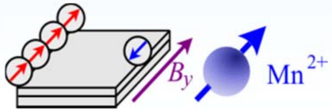
Applications of II-VI DMS nanostructures with 2DEG

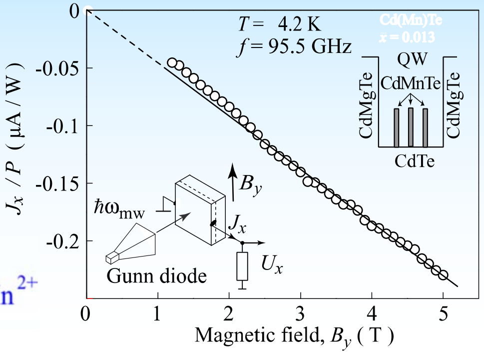
Applications based on gigant spin splitting of two-dimensional electron gas which can be engineered through structure design and externally controlled via application of magnetic or electrical filed and temperature.

Detectors of THz and microwaves radiation based on generation of generation of pure spin currents and their conversion into spin-polarized electrical currents (S. Ganichev *et al.* Phys. Rev. Lett. **102**, 156602 (2009); P. Olbrich *et al.*, Phys. Rev. B **86**, 085310 (2012))

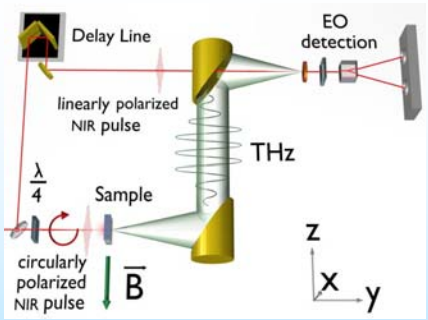


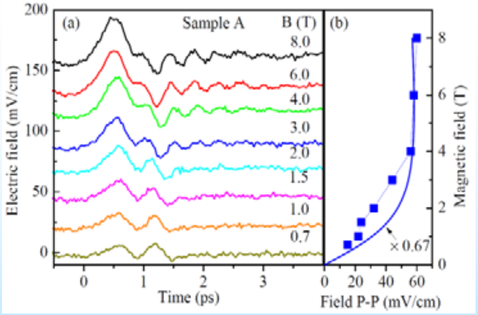




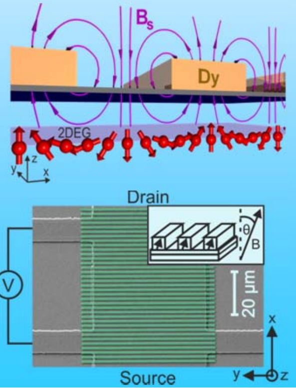


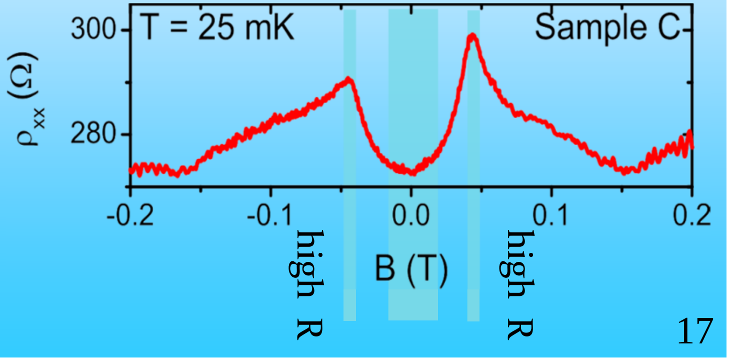
Tunable source of coherent pulses of THz radiation from spin waves excited through efficient Raman generation mechanism (R. Rungsawang *et al.*, Phys. Rev. Lett. **110**, 177203 (2013))





New type of spin transistor based on the control of spin transmission via tunable Landau-Zener transition (C. Betthausen *et al.*, Science **337**, 324 (2012))





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

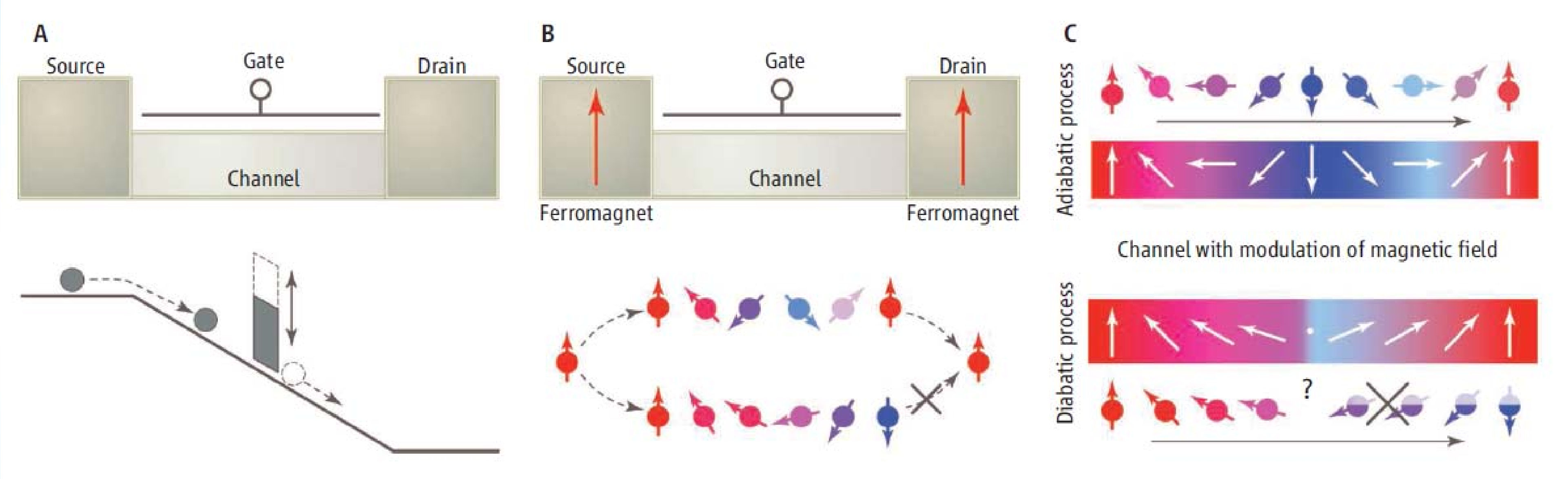
S. Datta, B. Das, App. Phys. Lett. **56** (1990) 665

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

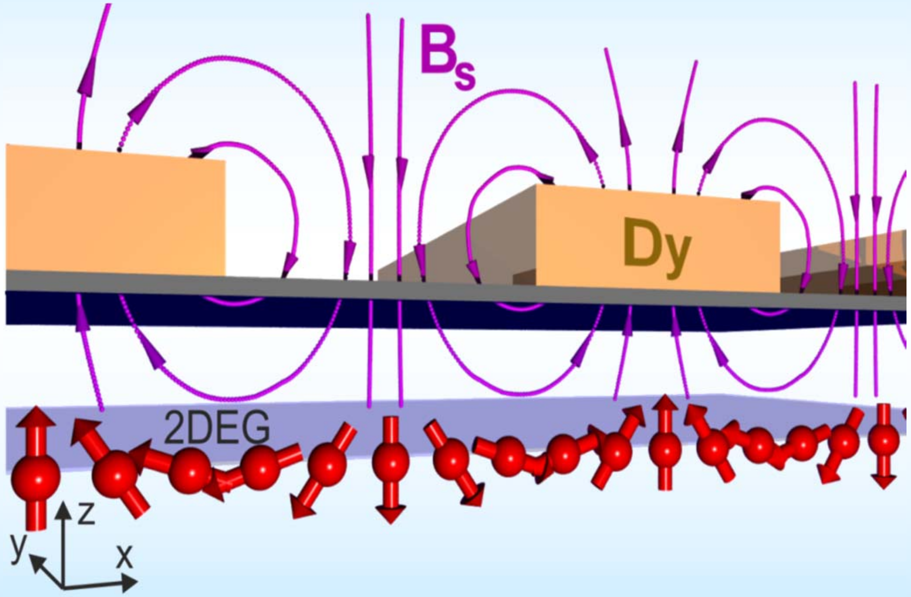
Problems:

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

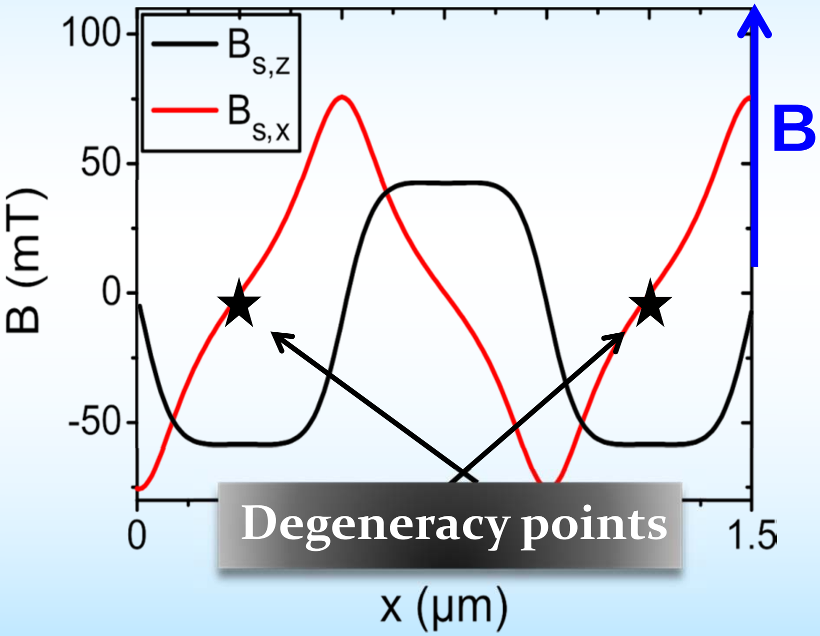
New concept of spin transistor

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

Control of spin transport adiabaticity



a = 1 µm, d = 100 nm, 75 nm Dy,



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

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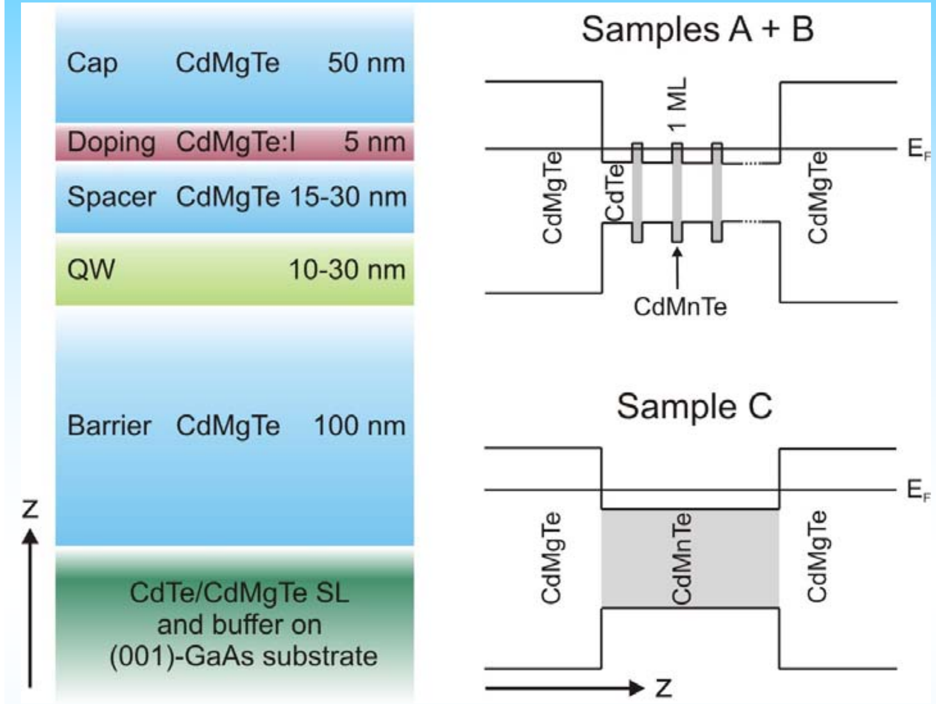
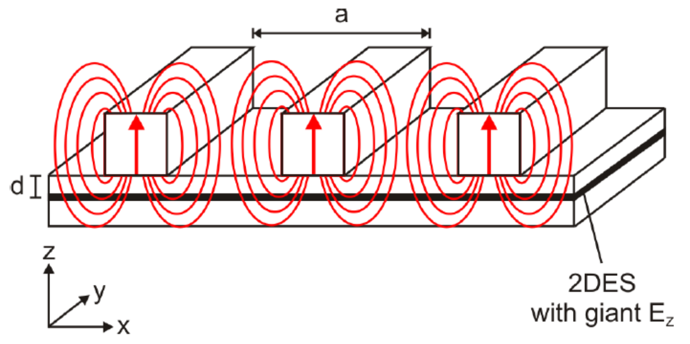
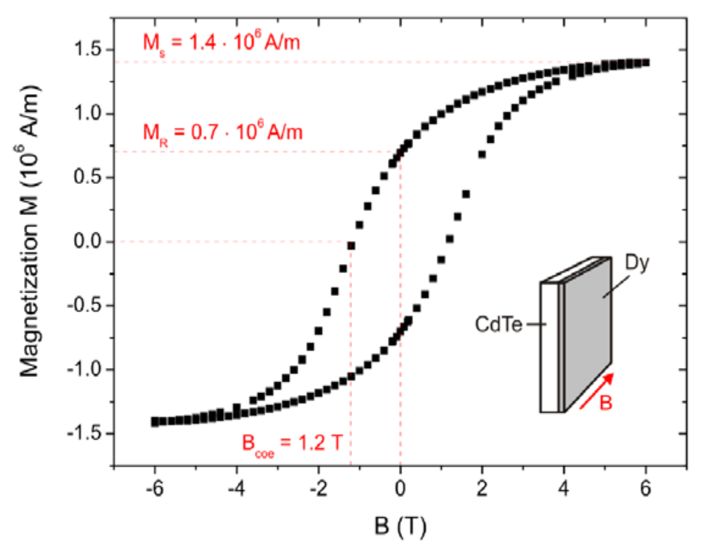


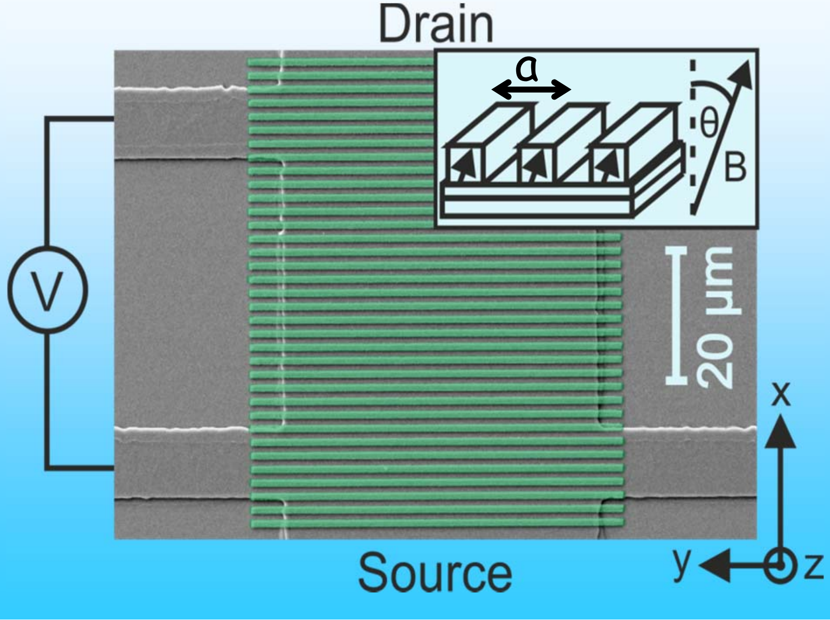


EBL + spattering + lift off

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 for sample C for various T, Θ and a

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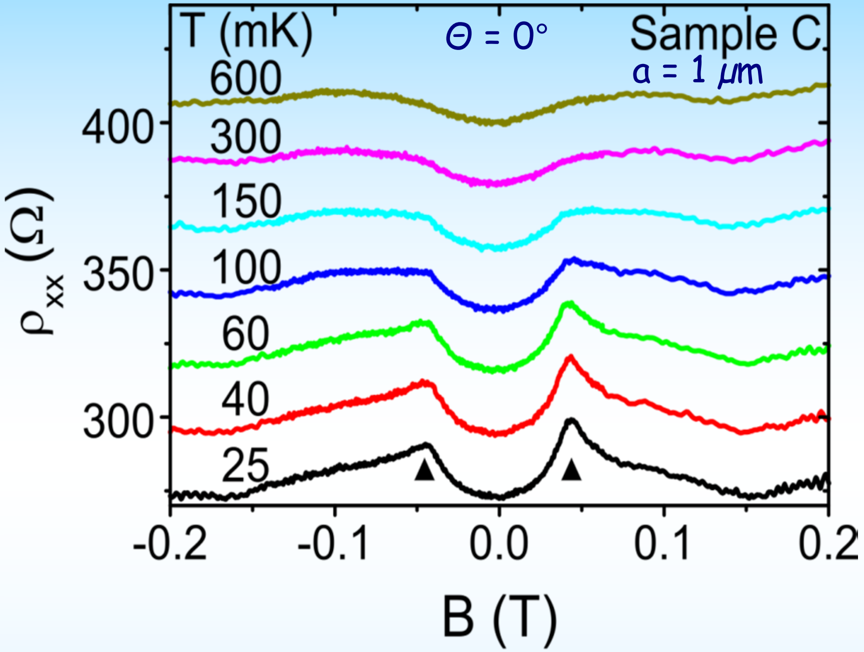
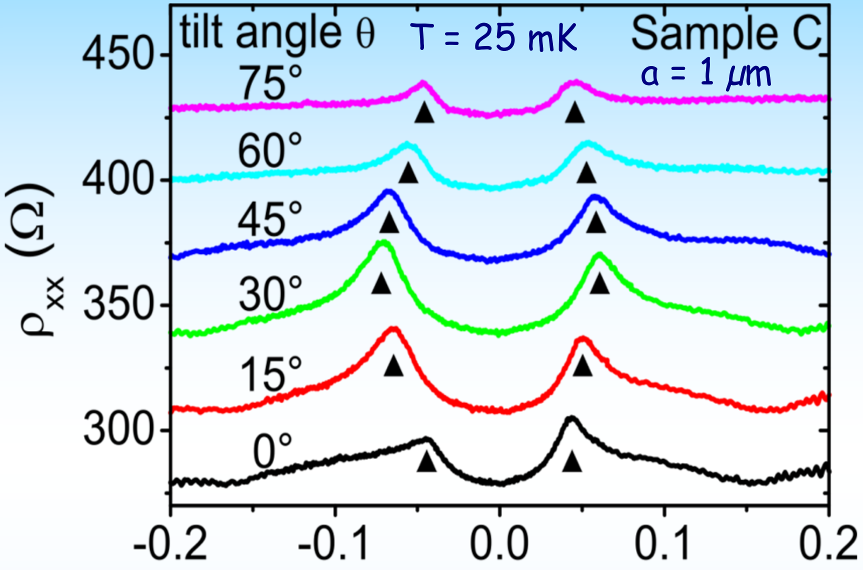
Sample C, $x = 1\%$, $\mu = 75\,000\ \mathrm{cm^2/Vs} \rightarrow l_{mfp} = 0.65\ \mu\mathrm{m}$





→ peaks vanish for T > 300 mK

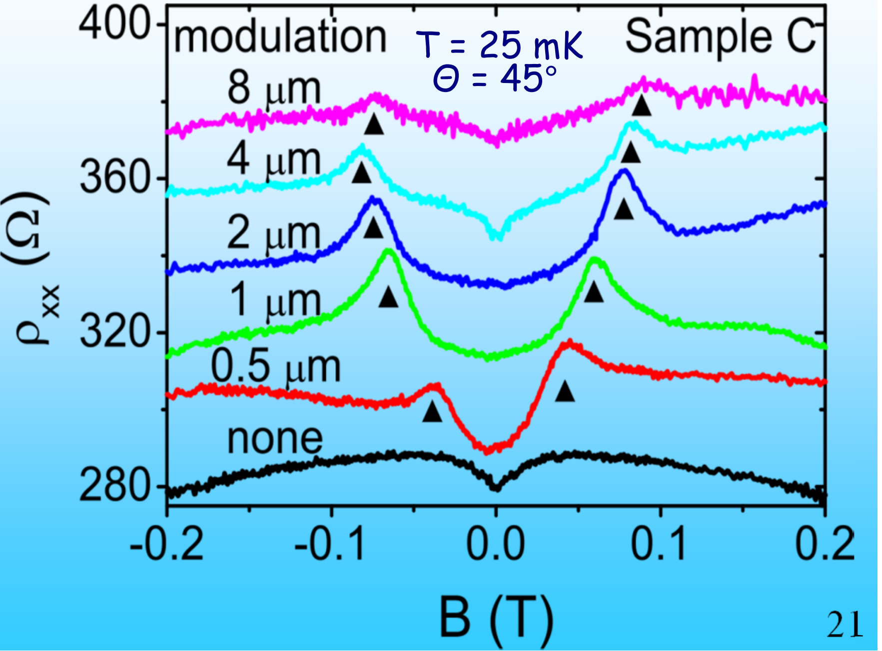
$$g^*_{eff} = g^*_{in} + \frac{\alpha M(H,T)}{g_{Mn}\mu_B^2 H}$$

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)

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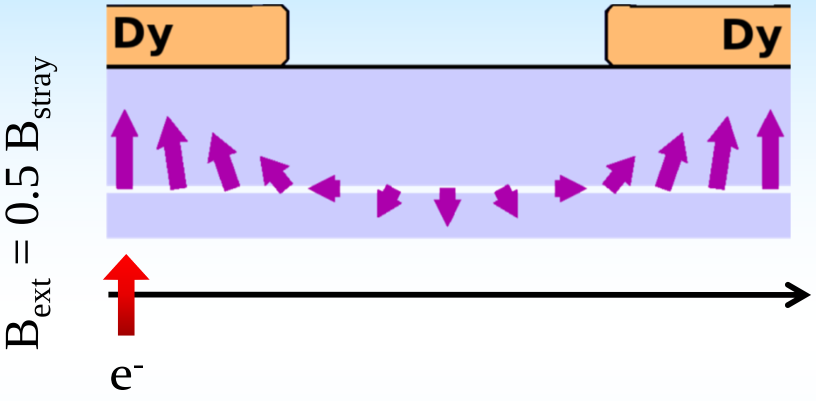
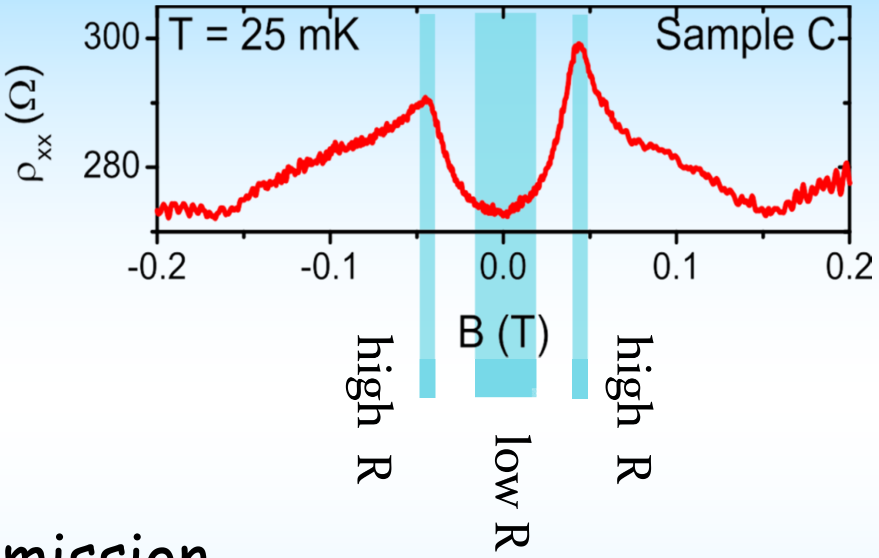
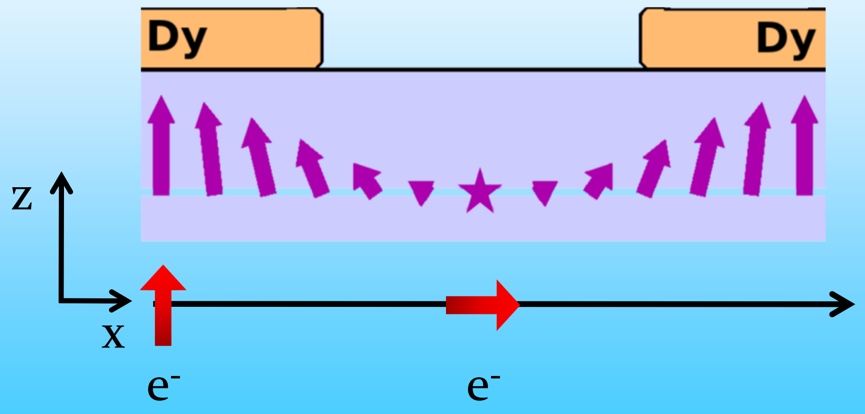
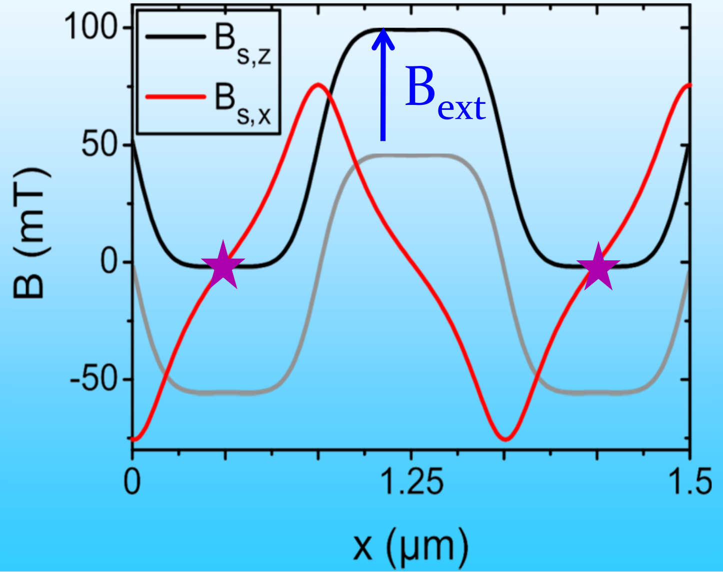
- $B_{ext} < B_{stray}$: Adiabatic spin transport



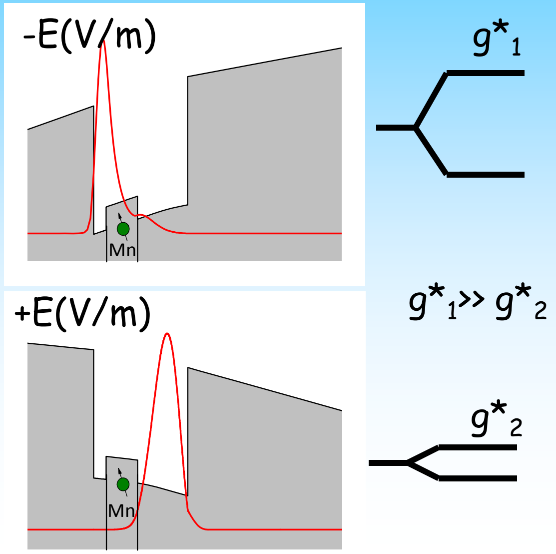


- $B_{ext} = B_{stray}$: Blocking of spin transmission

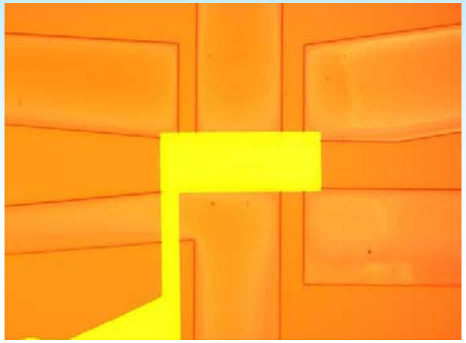




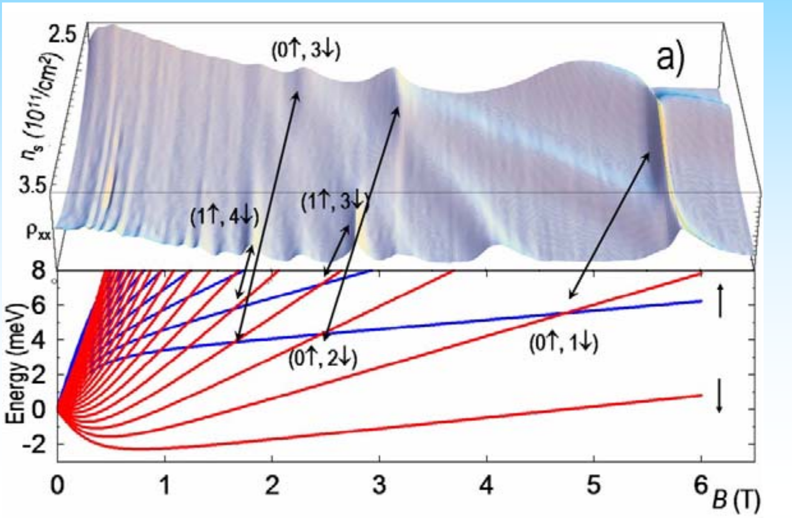
Electric field control of Lande g-factor of 2DEG in (Cd, Mn)Te QW

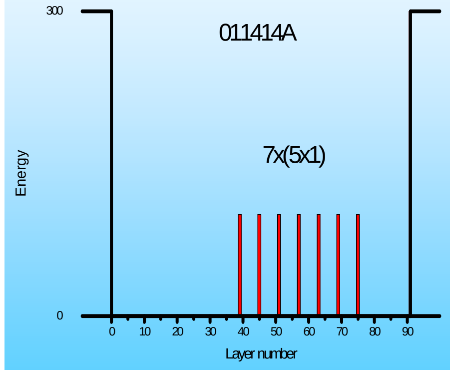


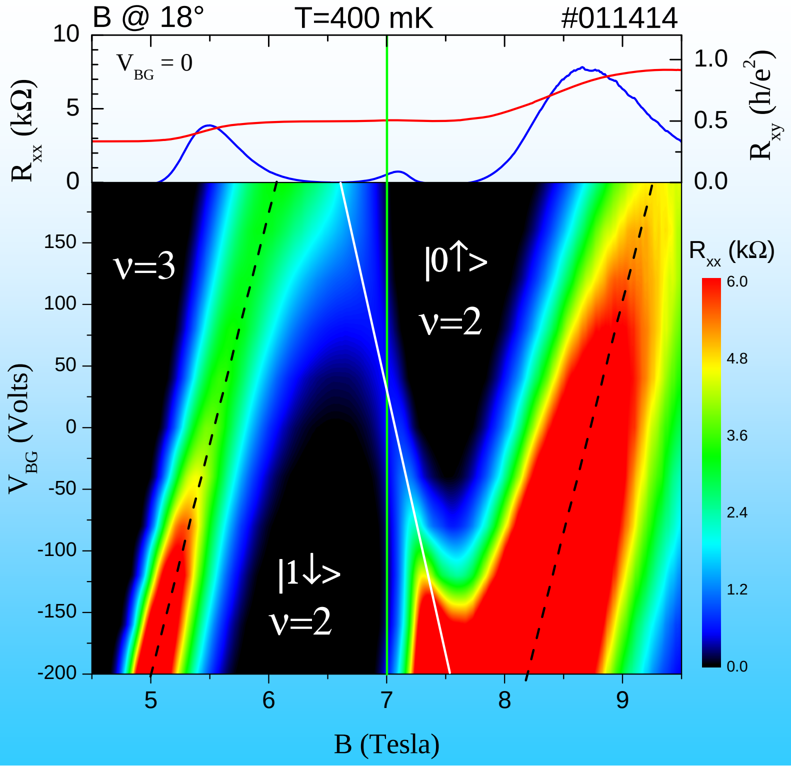
SEM of Hall bar with gate

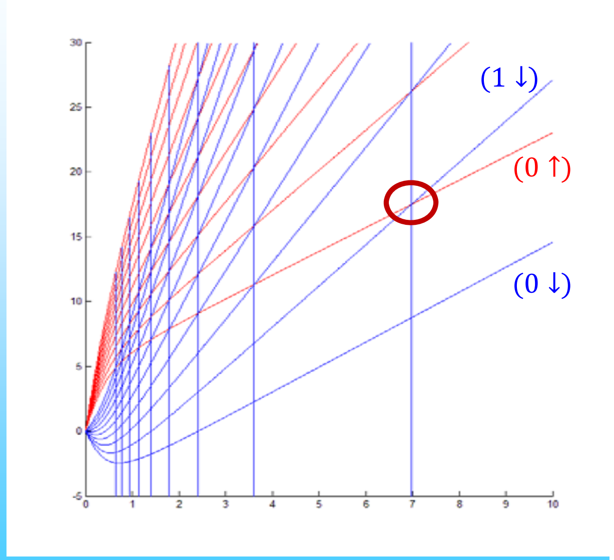


QHFm cusps as a sensitive probes of the g^*_{eff}









Conclusions

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

- creation of a new system supporting non-Abelian excitations for topologically protected quantum computations (L. Rokhinson)
- 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 and any other low-D II-VI nanostructures

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