Spintronic Nanostructures

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Overview

II-VI Dilute Magnetic Semiconductors

- Spin RTDs using II-VI DMSs

III-V Dilute Magnetic Semiconductors

- Tunnel AMR in GaMnAs

II-VI Narrow Gaps

- intrinsic SHE and AHE

Wide gap II-VI and FM III-V DMS

- Spin RTD: voltage adjustable spin-switch; zero field spin filter
- SADs show finite spin splitting at zero B
- TAMR results from double step switching + anisotropic dos
- Why extra anisotropy along [001]?
- gives bistable hysteresis for single FM layer; is huge for two FM layers
- Details of MI transition. Do we see the Efros-Shklovskii gap?

Collaborators:
Charles Gould, Georg Schmidt, Karl Brunner,
Peter Bach, Idriss Chado, Romain Giraud, Peter Grabs, Jian Liu, Katrin Pappert, Christian Rüster, Daniel Supp, Gisela Schott, Anatoly and Taras Slobodskyy, Tatjana Borzenko, Volkmar Hock

Michael Flatté, Pawel Hawrylak, Tomas Jungwirth, David Sanchez, Jairo Sinova

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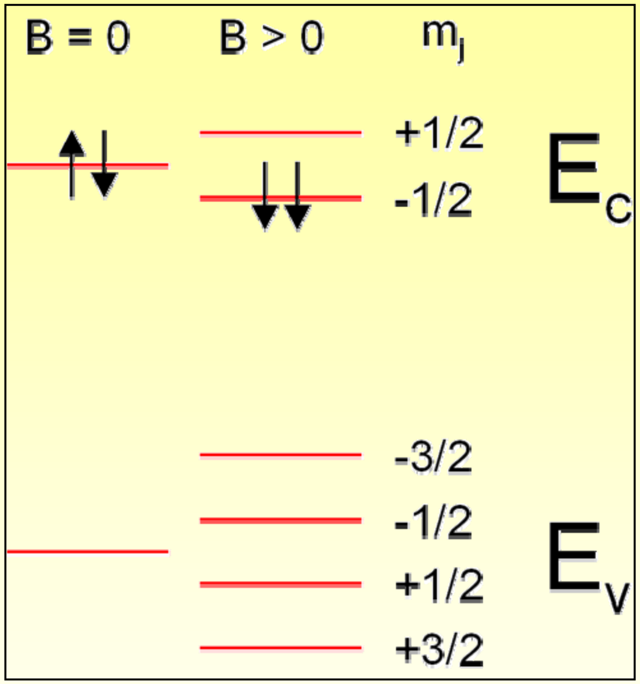
II-VI Dilute magnetic semiconductors (DMS)

The 100% spin-aligner

- II-VI Semiconductors with magnetic components (e. g. ZnMnSe), which are non-magnetic or antiferromagnetically aligned at zero B-field.
- For B ≠ 0: Finite magnetization, ‘giant’ Zeeman splitting of up to 100 meV of which 10 - 20 meV in the conduction band
- Low Fermi energy at high doping due to impurity bands: half-metallic behavior at high B-field.



$\Rightarrow \beta = 100\%$ for $kT << \Delta E_C$

$$g^* = g_0 - \frac{(\Delta E)_{\max}}{\mu_B B} B_{5/2}\left[\frac{5 g_{Mn} \mu_B B}{2 k_B T (T + T_0)}\right]$$

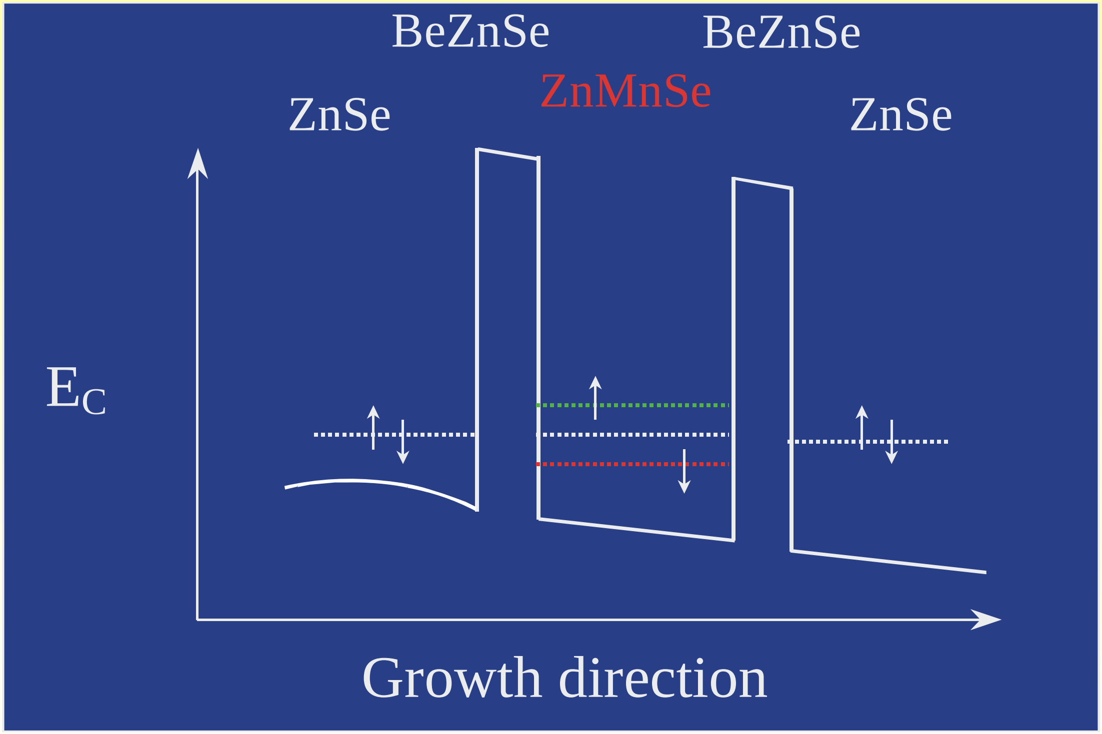
g_{Mn}: g factor for Mn

$B_{5/2}$: Brillouin function for S=5/2

$(\Delta E)_{\max}$: saturation spin splitting energy

T_0: scaling temperature (accounts for spin spin interaction)

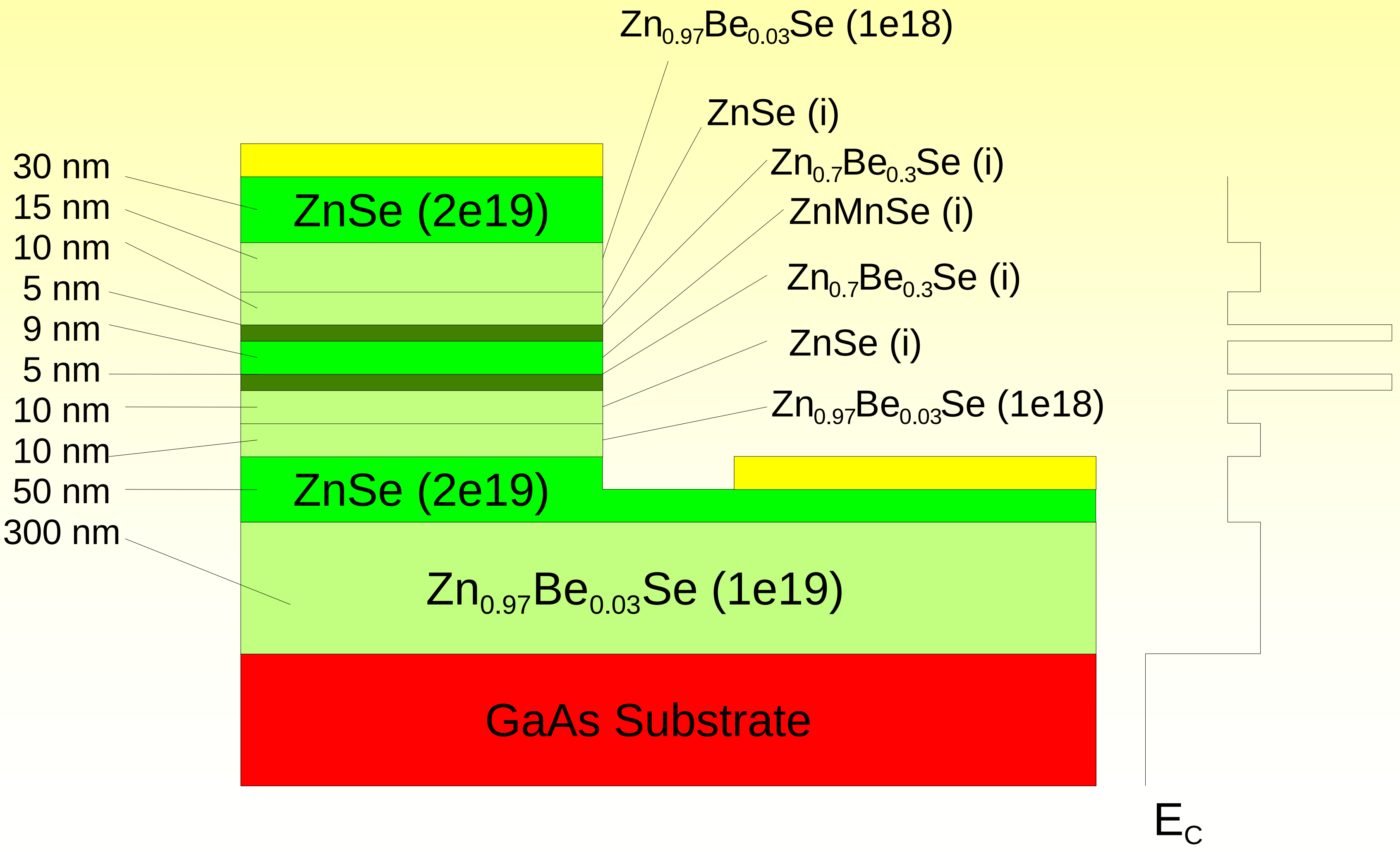
(Zn,Be,Mn)Se-based Spin-switch RTD



Voltage-adjustable spin selective injector and detector?

Spin-switch RTD in the (Zn,Be,Mn)Se-System

all doping n-type



$Zn_{0.97}Be_{0.03}Se$ (1e18)

ZnSe (i)

$Zn_{0.7}Be_{0.3}Se$ (i)

ZnMnSe (i)

$Zn_{0.7}Be_{0.3}Se$ (i)

ZnSe (i)

$Zn_{0.97}Be_{0.03}Se$ (1e18)

30 nm
15 nm
10 nm
5 nm
9 nm
5 nm
10 nm
10 nm
50 nm
300 nm

ZnSe (2e19)

ZnSe (2e19)

$Zn_{0.97}Be_{0.03}Se$ (1e19)

GaAs Substrate

E_C

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Spin-switch RTD in the (Zn,Be,Mn)Se-System

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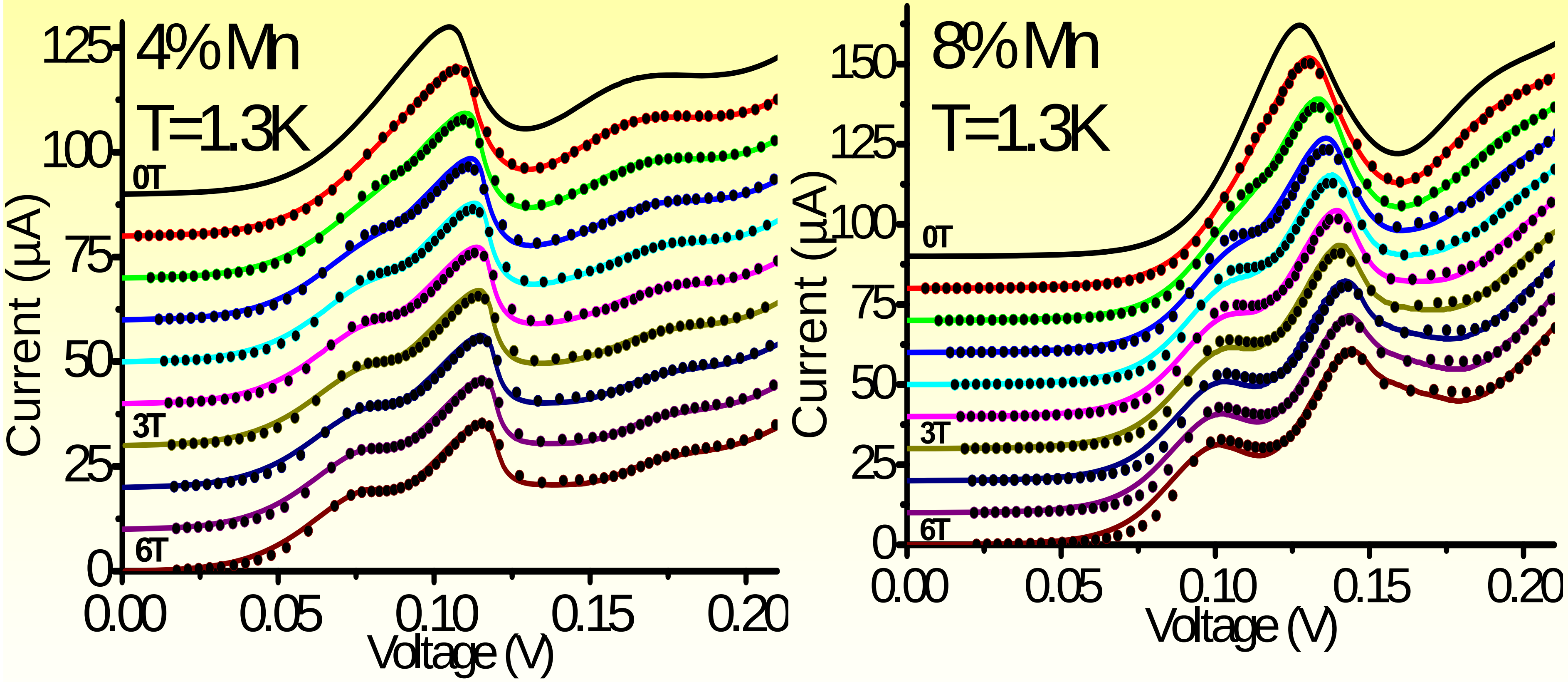
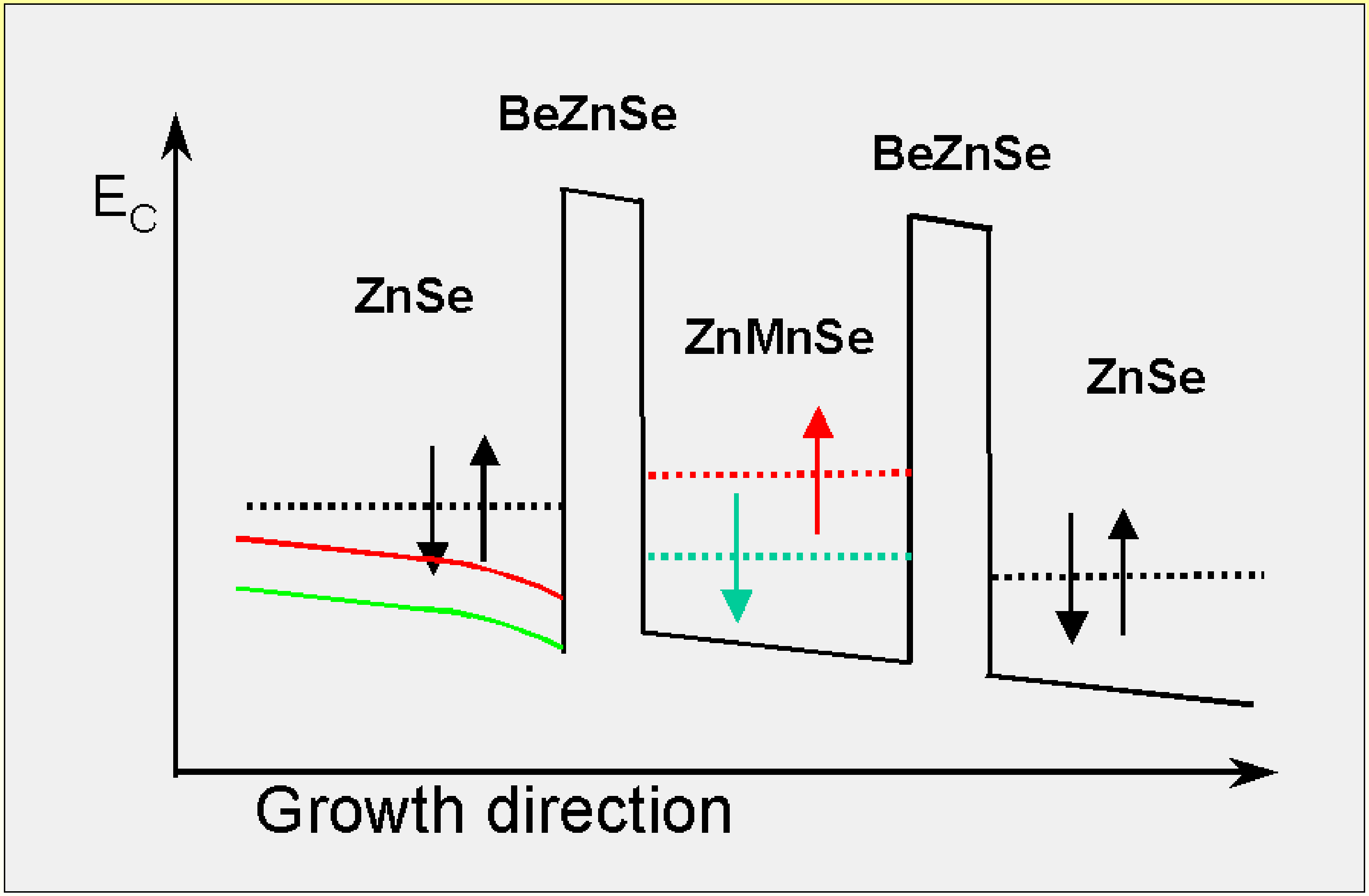
A. Slobodskyy et al., PRL 90, 246601 (2003)



The dots are fits assuming each spin-channel has the same resonance behavior as the B=0 T signal. The fits yield the exact resonance spliting.

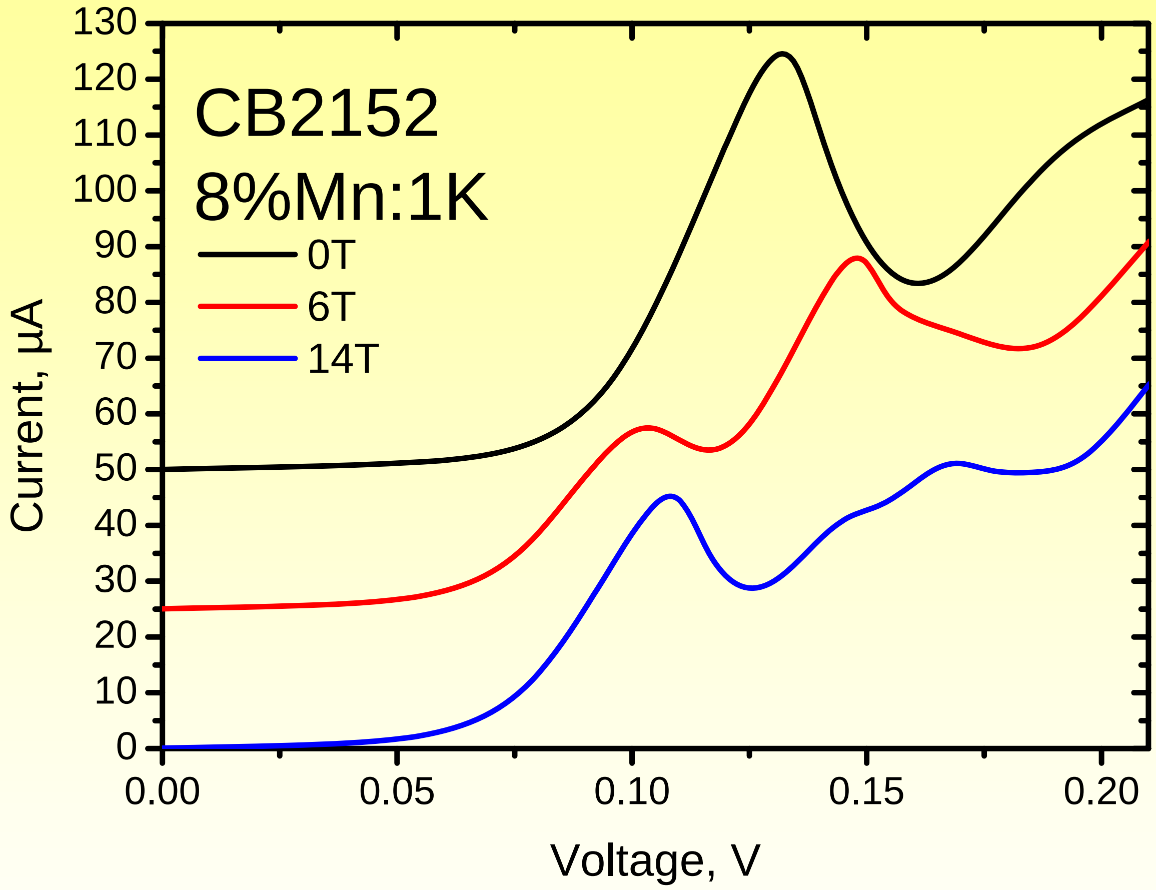
High field band structure



High fields

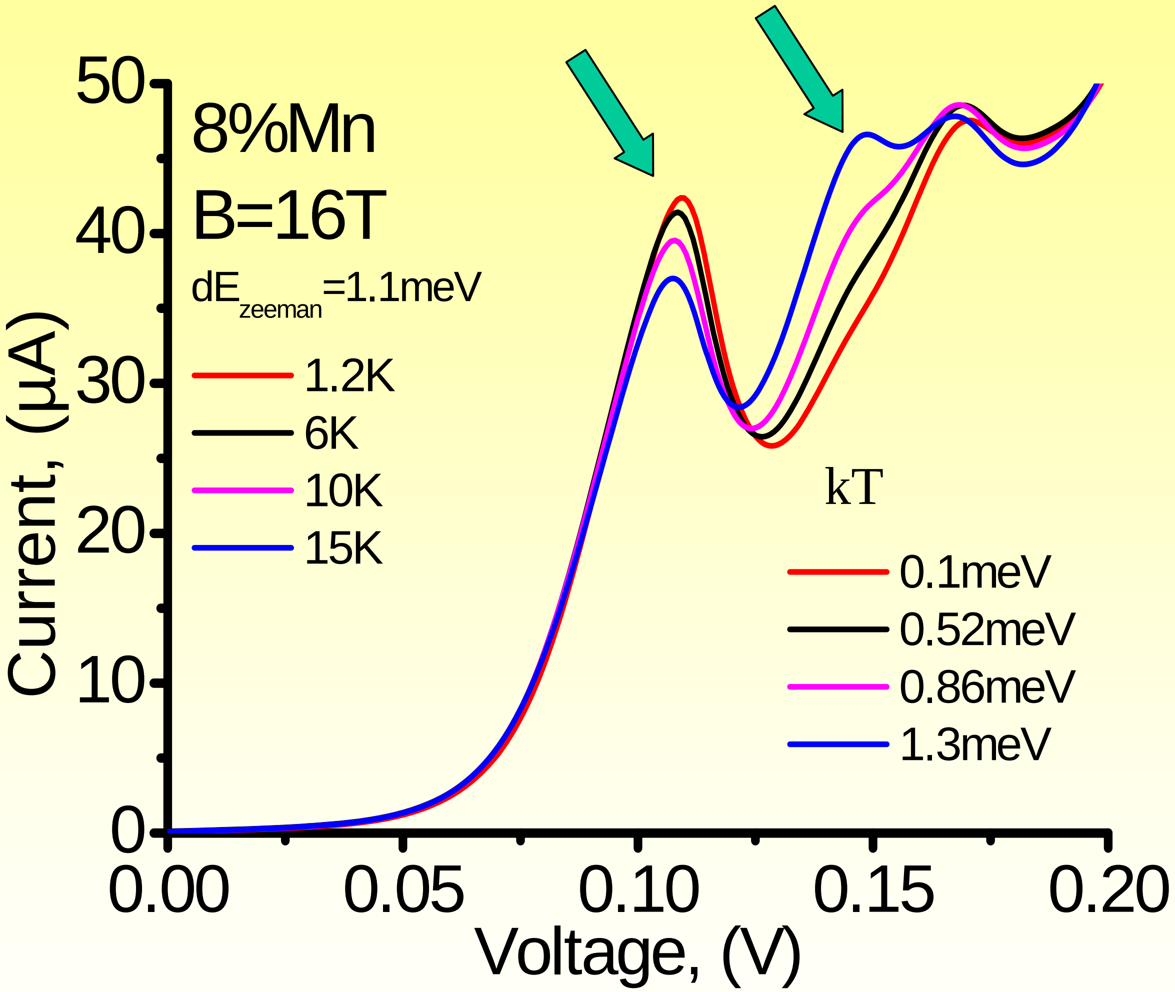
- Quantized levels show constant splitting
- Conduction band in emitter shows increasing splitting

Experiments at higher B-field



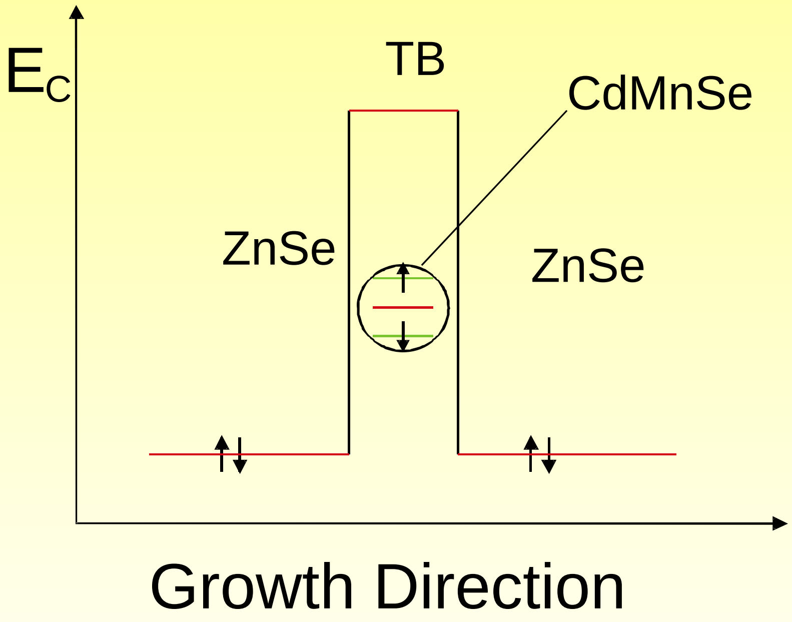
- Up to 6 T only giant Zeeman splitting is visible
- For higher fields the upper (minority) resonance is decreased due to spin polarisation in the ZnSe leads.

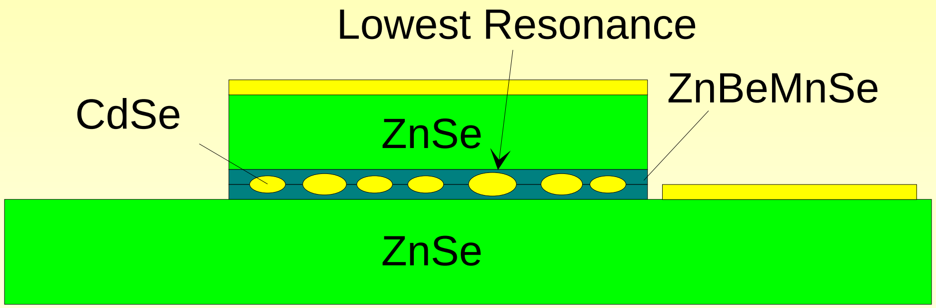
Experiments at higher B-field



I/V curves at different temperatures with constant Zeeman splitting in emitter
Modeling in collaboration with David Sanchez (University of the Baleares)
Need numbers for the spin relaxation time!

RTDs with self-assembled dots





principle

in practice: Mn in barrier

Fabricate sub-micron RTD, largest dot dominates at small bias.

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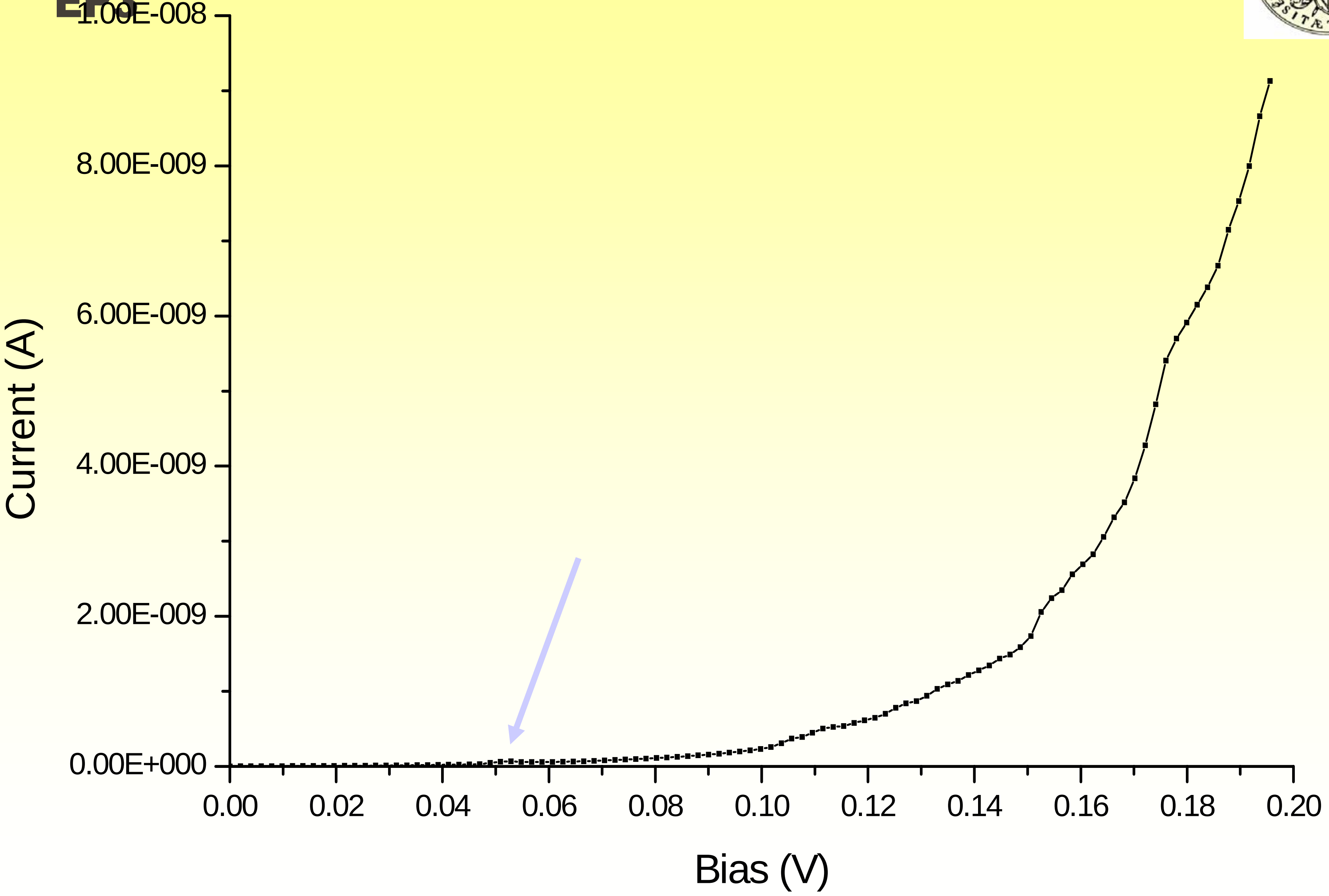
1.00E-008
8.00E-009
6.00E-009
4.00E-009
2.00E-009
0.00E+000
Current (A)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
Bias (V)

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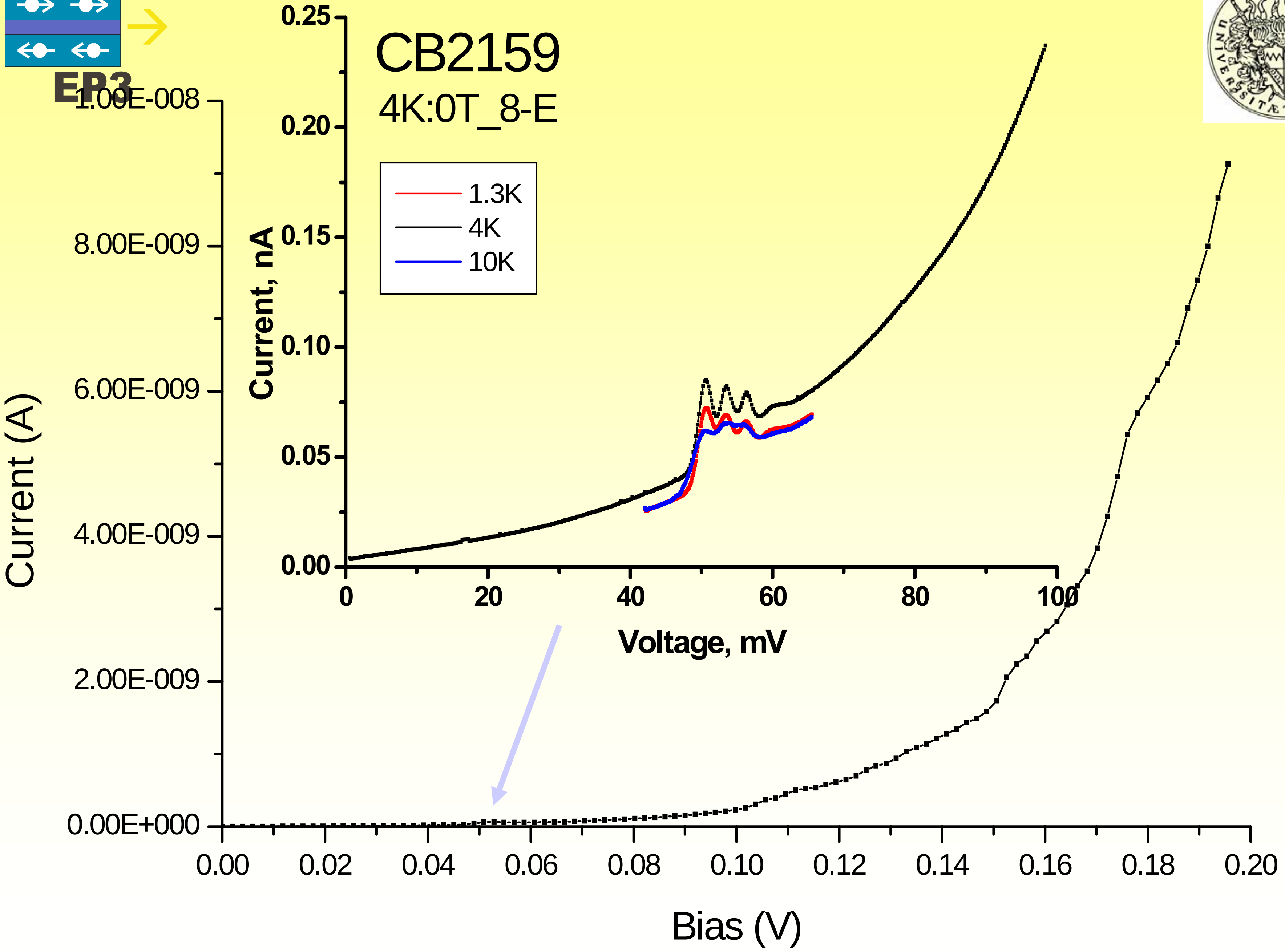
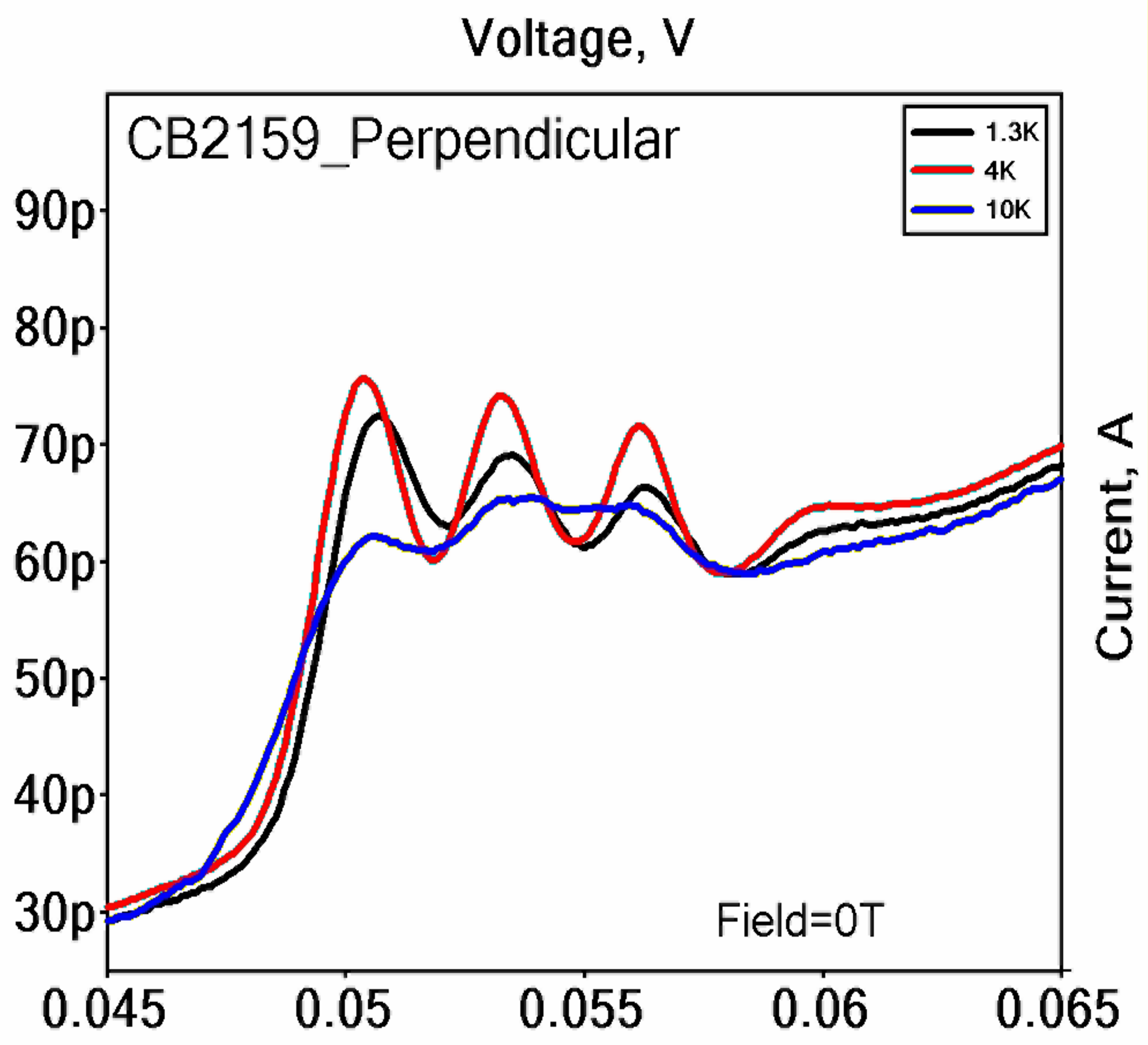
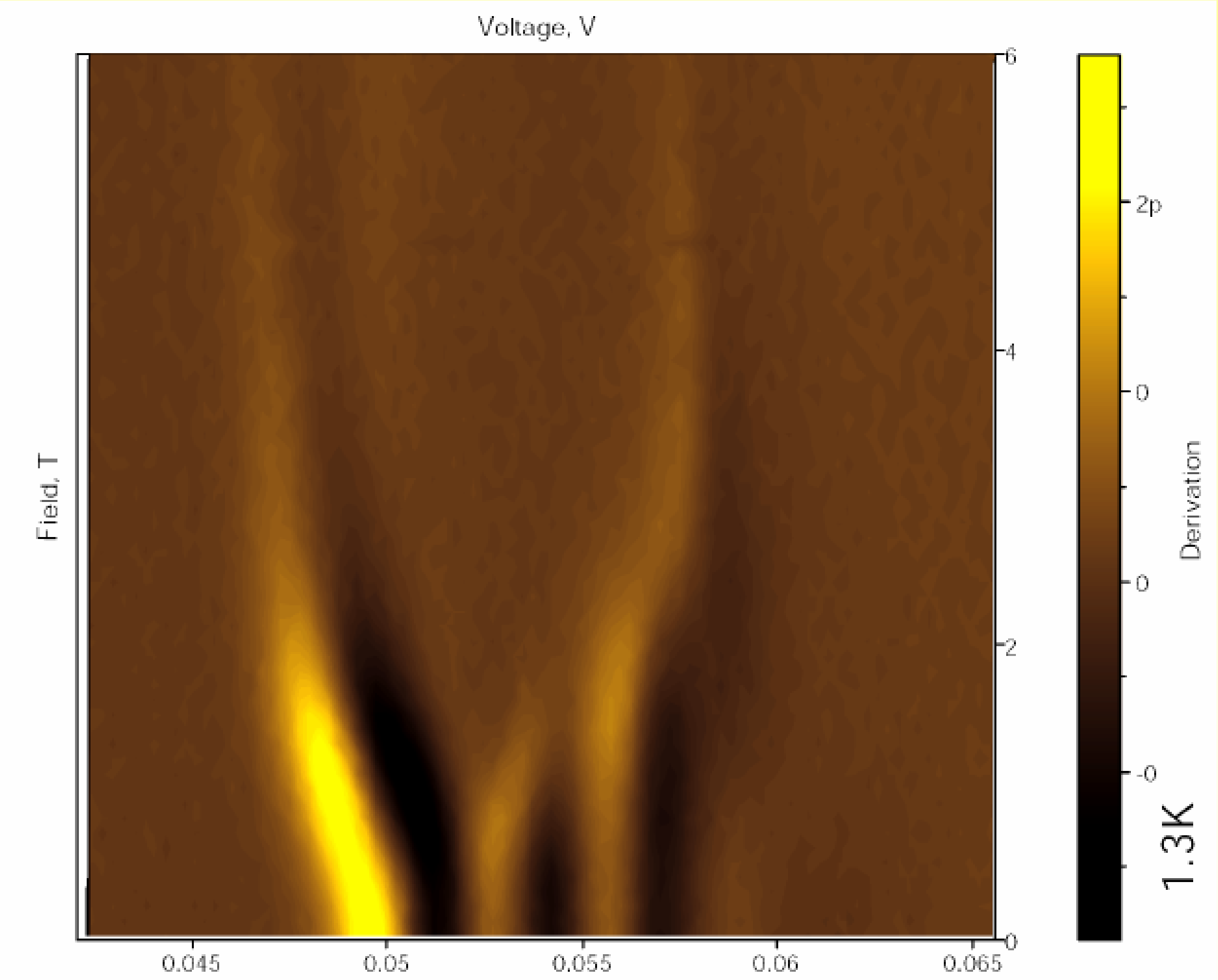

CB2159
4K:0T_8-E
1.3K
4K
10K
Current, nA
0.00
0.05
0.10
0.15
0.20
0.25
Voltage, mV
0
20
40
60
80
100
Current (A)
0.00E+000
2.00E-009
4.00E-009
6.00E-009
8.00E-009
1.00E-008
Bias (V)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20

EP3


Voltage, V
CB2159_Perpendicular
1.3K
4K
10K
90p
80p
70p
60p
50p
40p
30p
Field=0T
0.045
0.05
0.055
0.06
0.065
Current, A

EP3

RTDs with self-assembled dots



- Clear evidence that barrier Mn mixes with dot wave functions.
- Anti-crossing plus Zeeman pair imply single dot
- Single spin levels at zero field

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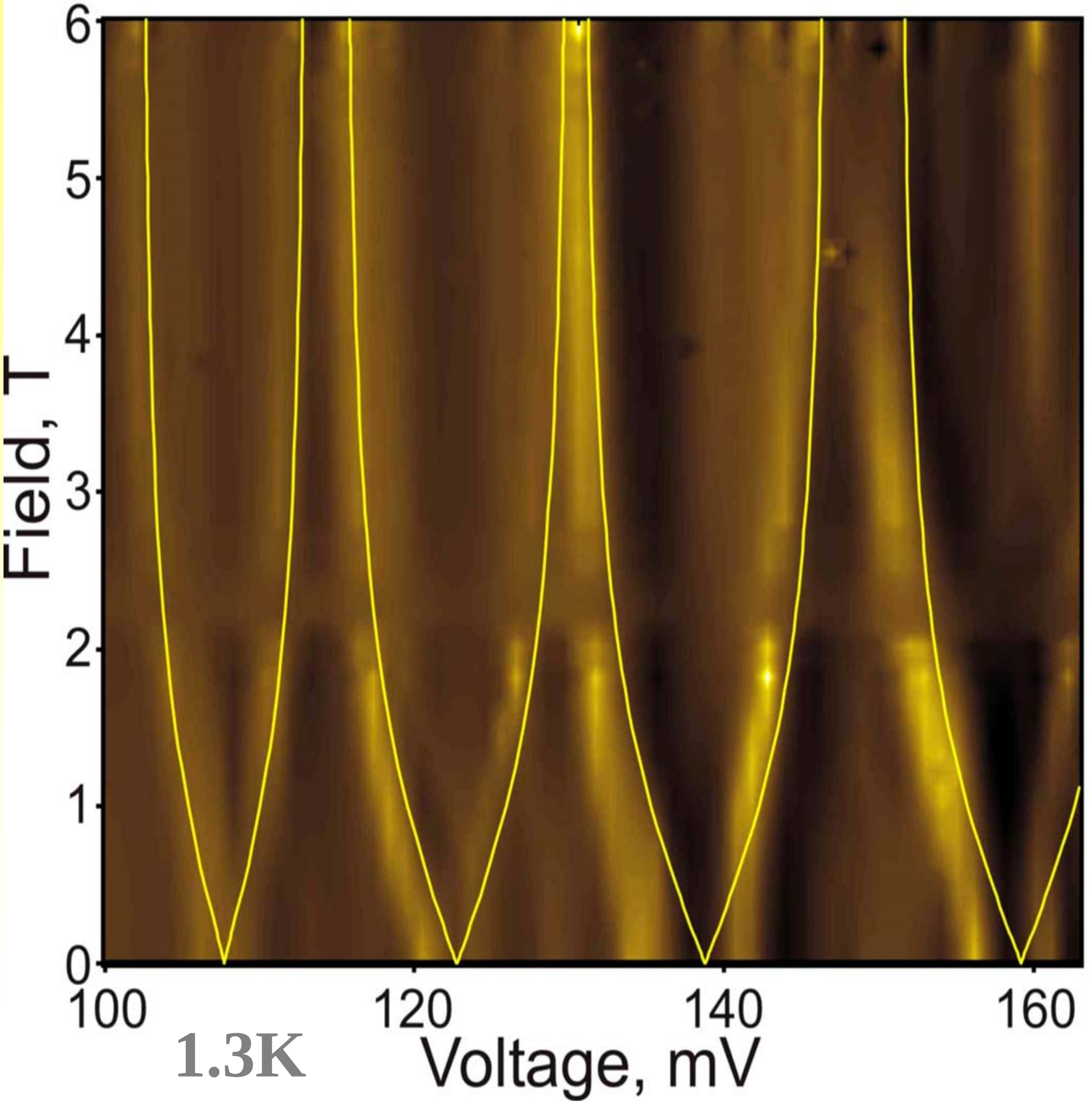
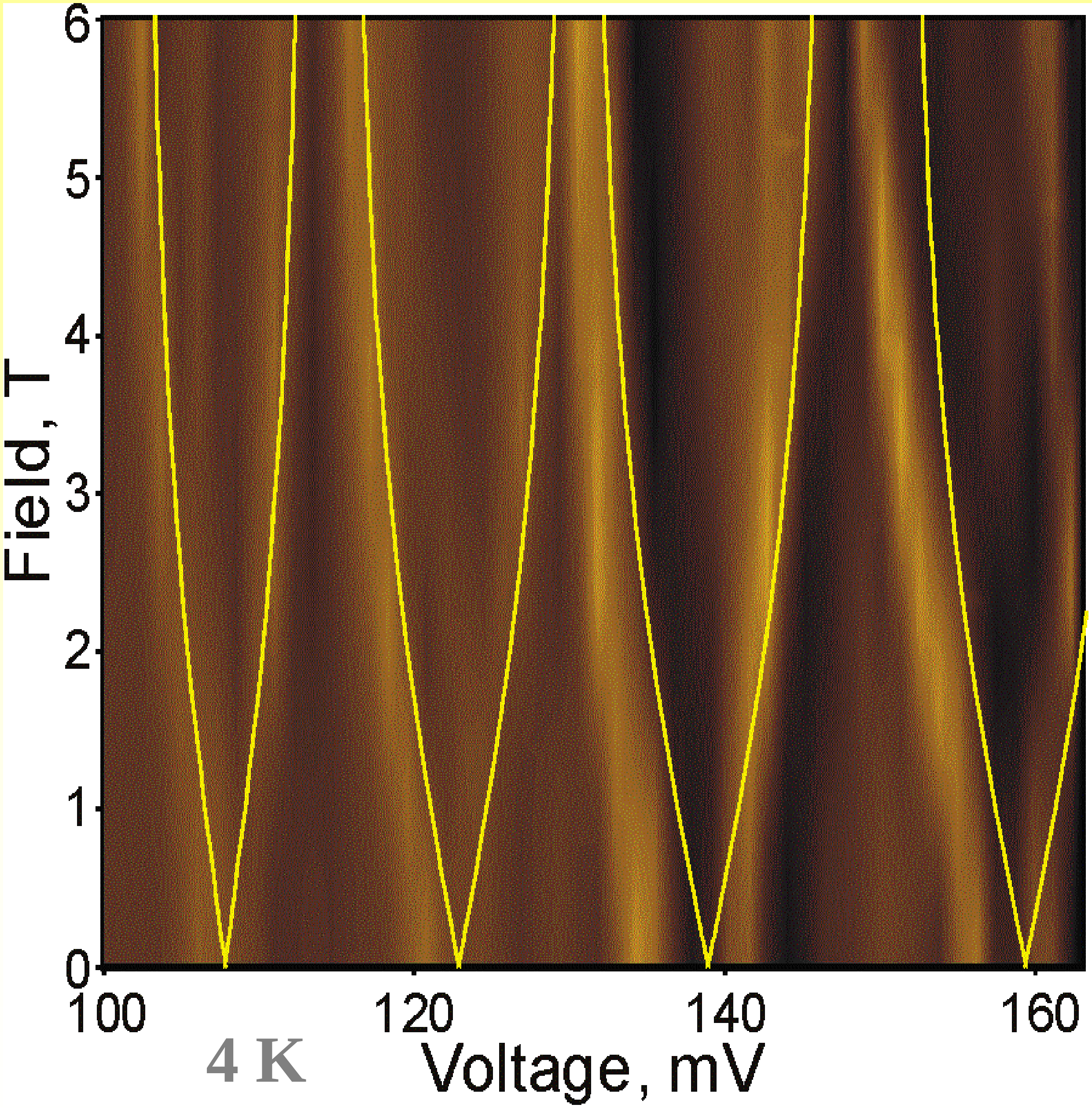
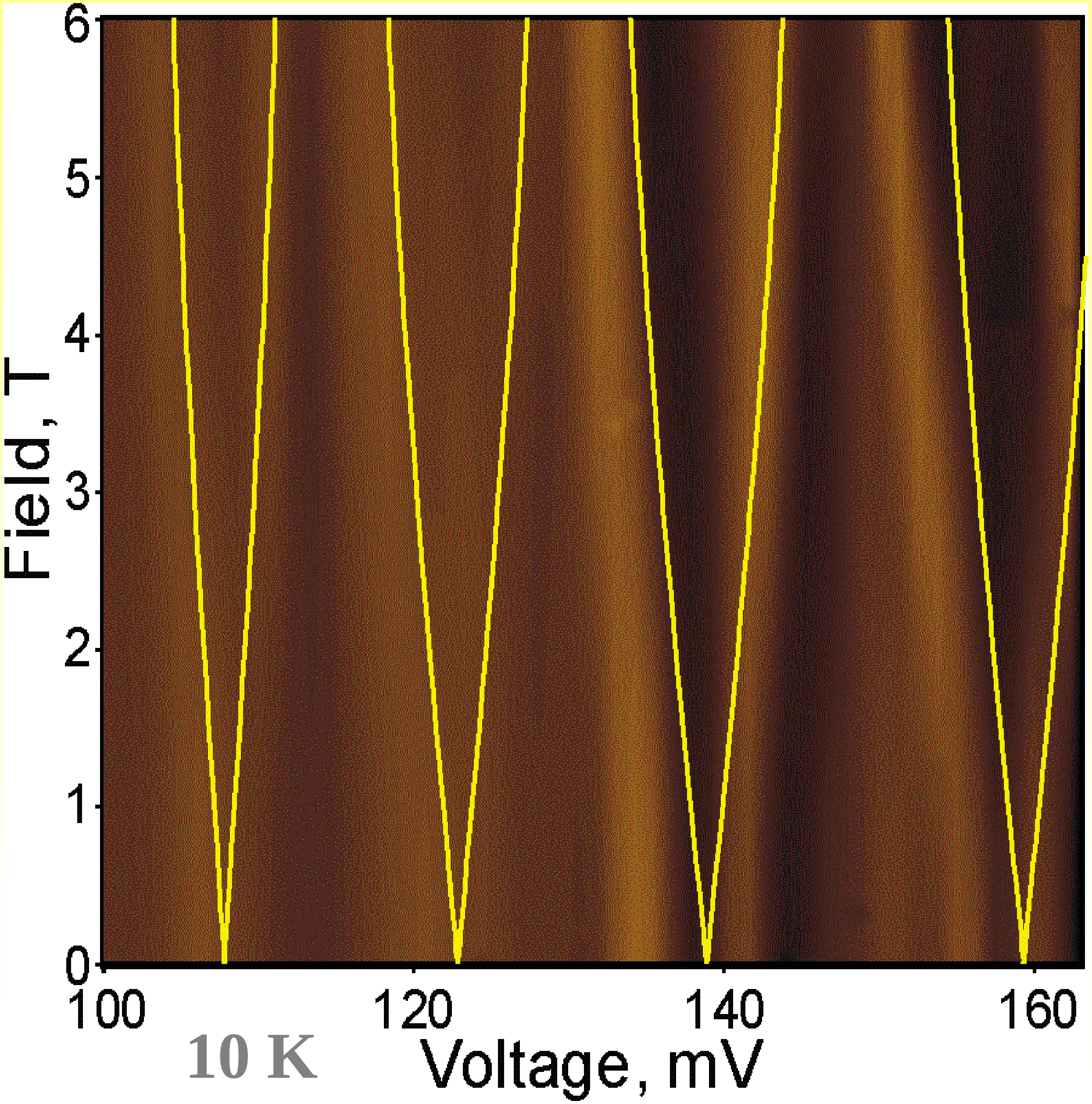


EP3



4 K

EP3

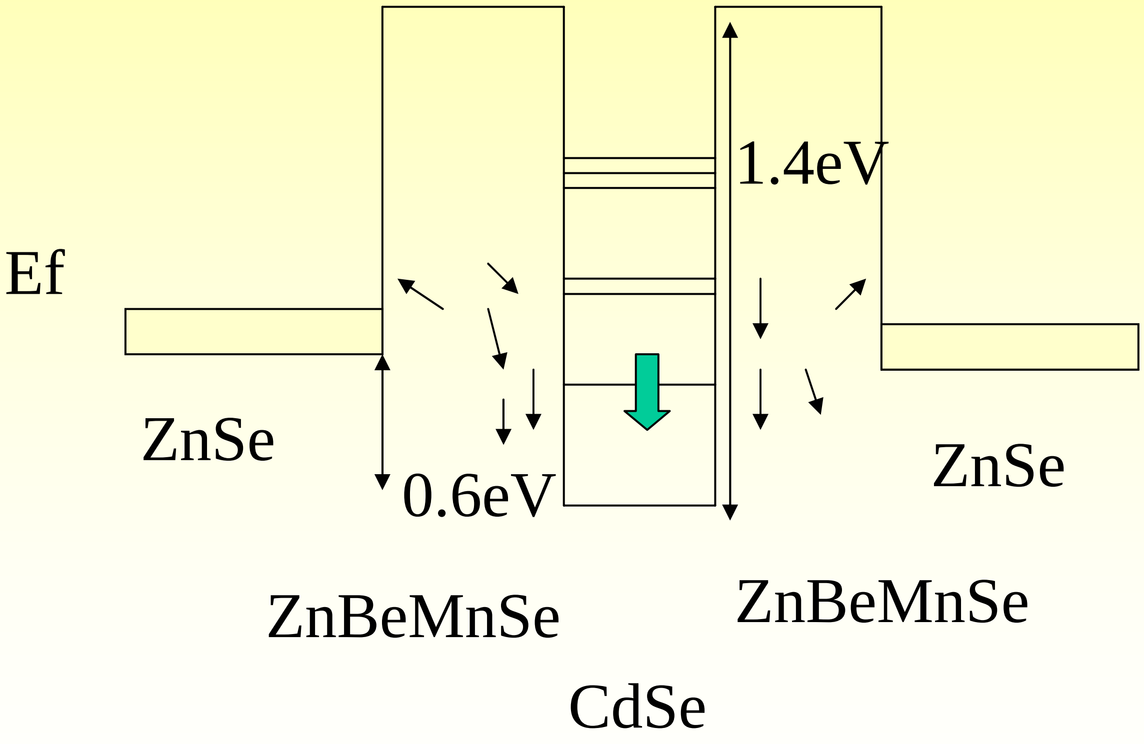


10 K

Tunneling structure

electrons in the dot lead to ferromagnetic arrangement of Mn ions

→ effective spin splitting of the tunneling structure


Ef
ZnSe
0.6eV
ZnBeMnSe
1.4eV
ZnSe
ZnBeMnSe
CdSe

Quantum dot as single
magnetic polaron

P. Hawrylak, NRC

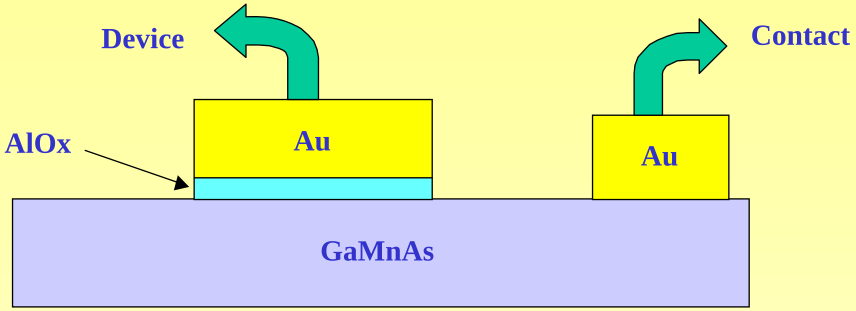
Previous theories by
A. Efros, et al., PRL
L. Brey, et al., PRL

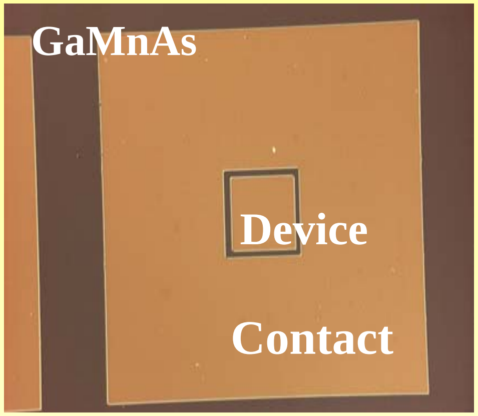
Need to extend Efros/Rashba theory to more spins.

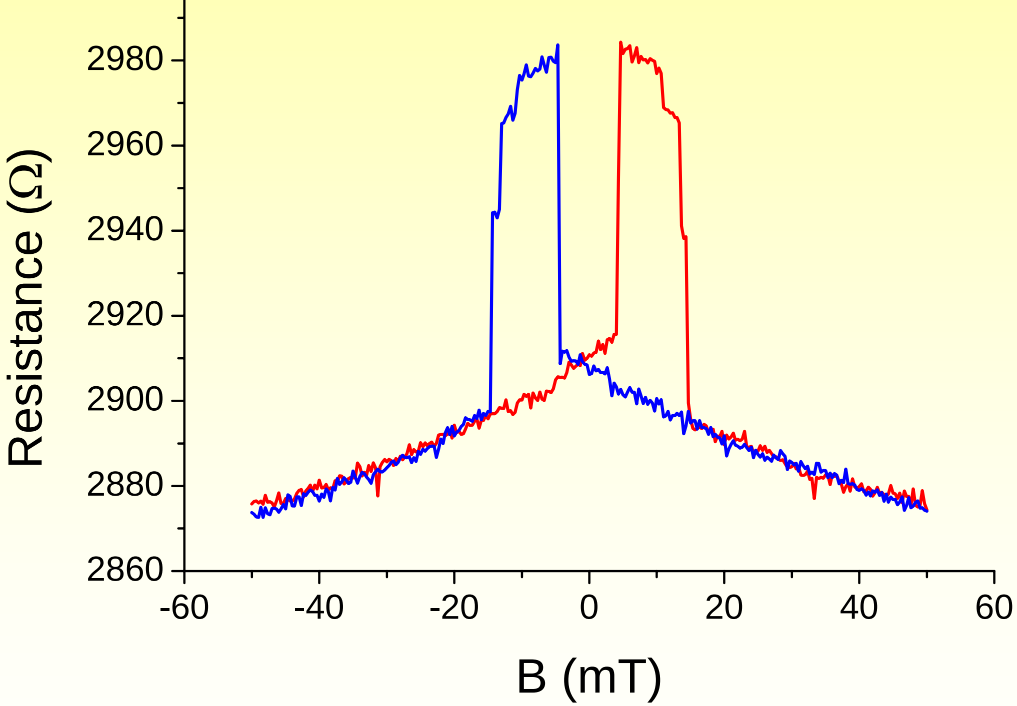
III-V DMS: (Ga,Mn)As

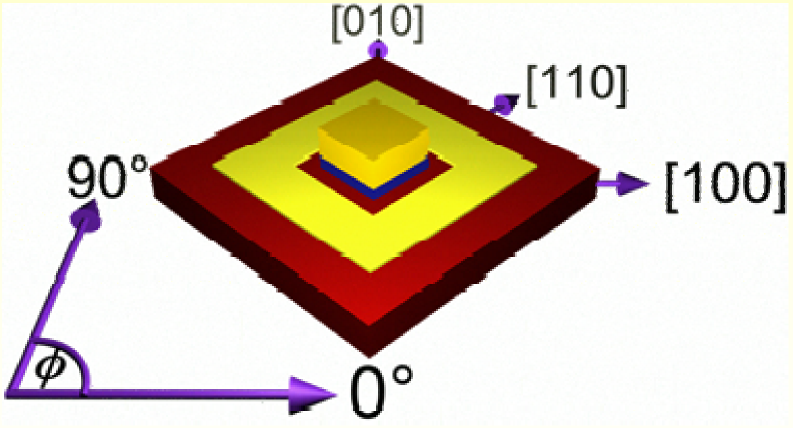
- GaAs with typically 1 to 8% Mn
- Grown at ~220° to prevent MnAs formation.
- Exhibits carrier mediated ferromagnetism.
- Mn substitues on Ga sites ☺ (acceptor) or goes in interstitially ☹ (donor)
- Tc around 70K as grown, 150 K with annealing is routine. Current WR: Nottingham 173K; Tanaka 250K in 2D layers.
- Always p-type .
- Basically metallic transport $T_{4k} \sim T_{room}$
- Complex anisotropy both in transport and magnetism.
- Very large domains (mm‘s)

TAMR in (Ga,Mn)As/AlOx/metal









A tunnel barrier between a non-magnetic metal (Au) and ferromagnetic (Ga,Mn)As can exhibit a huge magnetoresistance that can show the signature of a spin valve.

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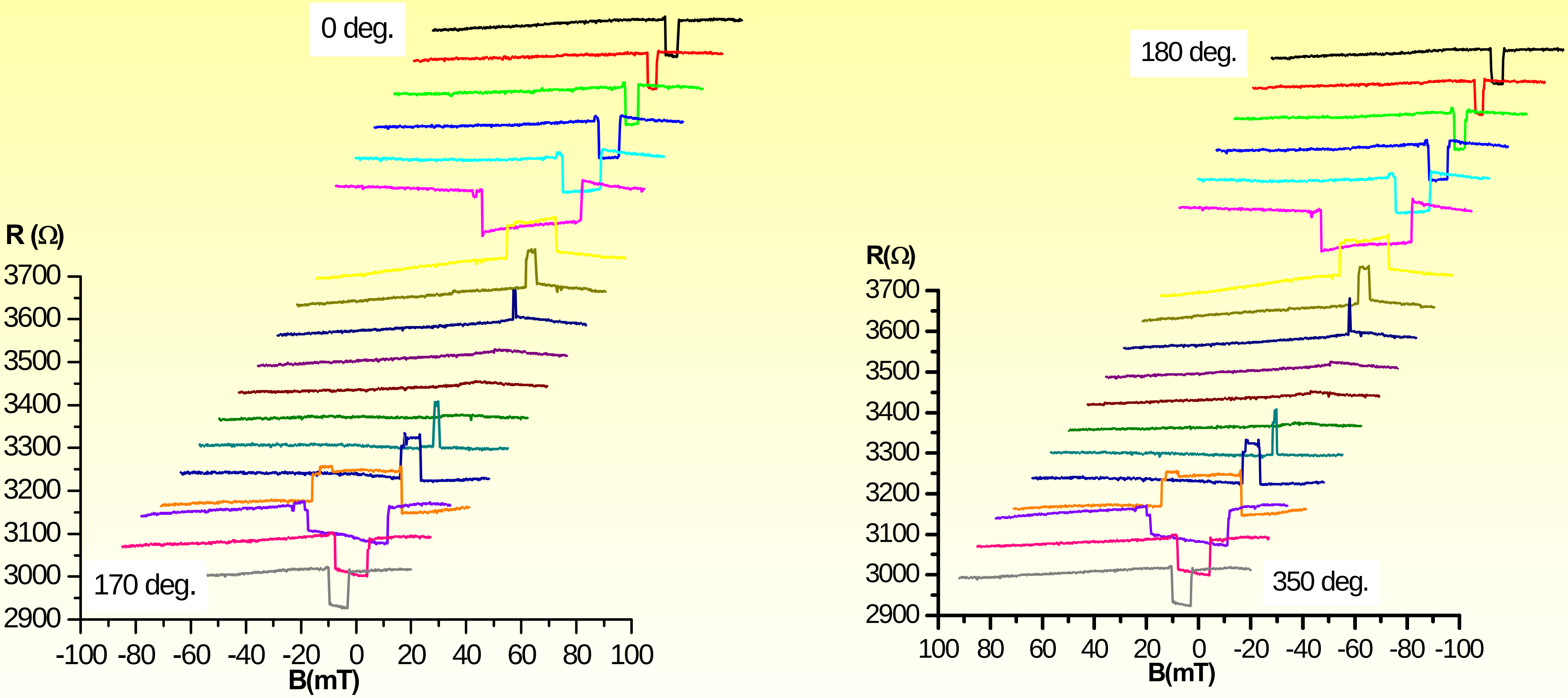
Spin-Valve like TMR in (Ga,Mn)As/AlOx/Non-magnet devices



Dependence of the magnetoresistance effect on the in-plane field angle (angle with respect to [100]).

→ (Ga,Mn)As has biaxial magnetic anisotropy

Total energy of a single domain:

$$E_m = K_u \sin^2(\theta) + K_c \sin^2(2\theta) - MH\cos(\theta - \varphi)$$

Co-linear uniaxial anisotropy

Biaxial anisotropy

Zeeman energy

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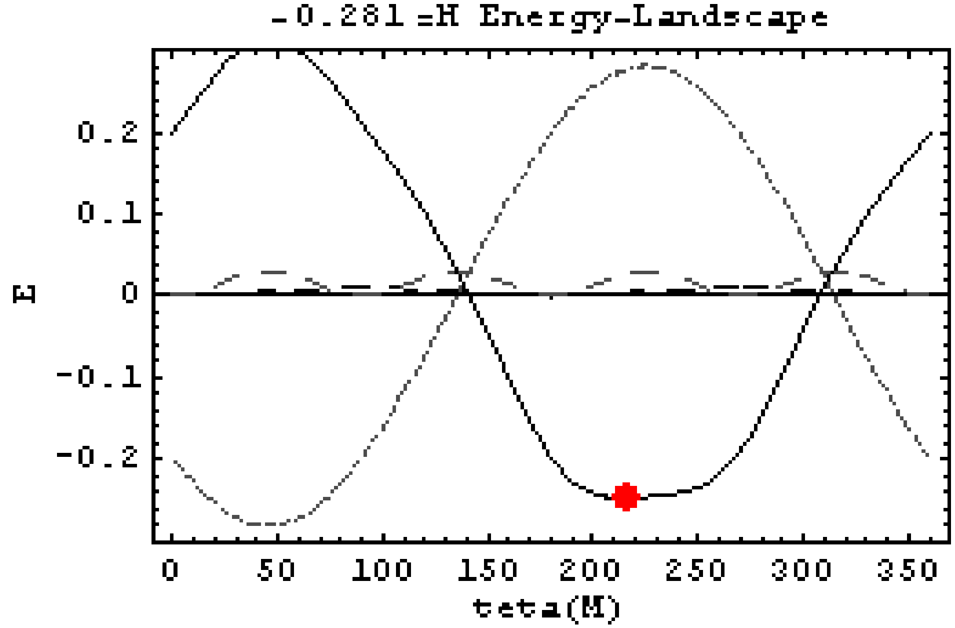
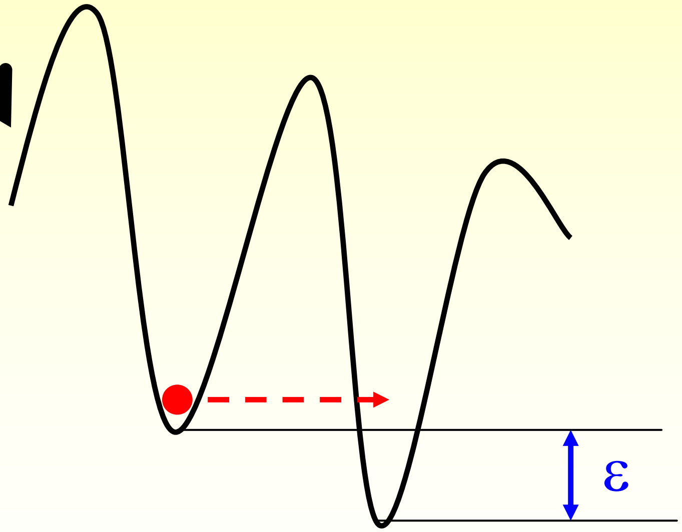
Double step switching

$$E_m = K_u \sin^2(\theta) + K_c \sin^2(2\theta) - MH\cos(\theta - \varphi)$$

-Coherent rotation a la Stoner-Wohlfarth.

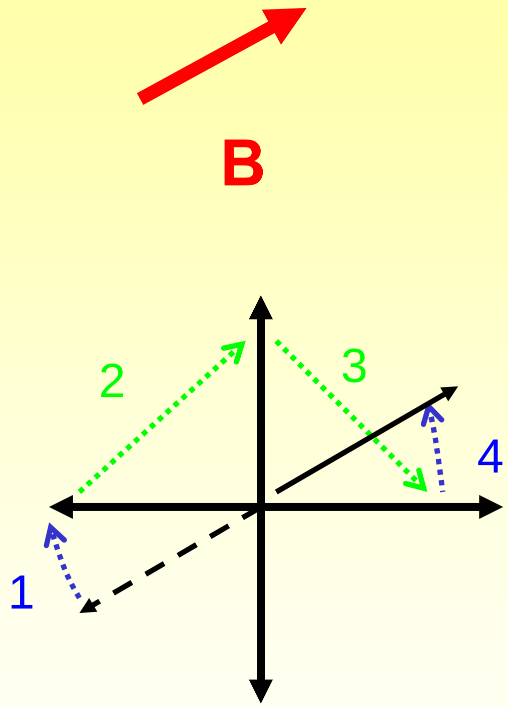
-Domain wall nucleation and propagation.

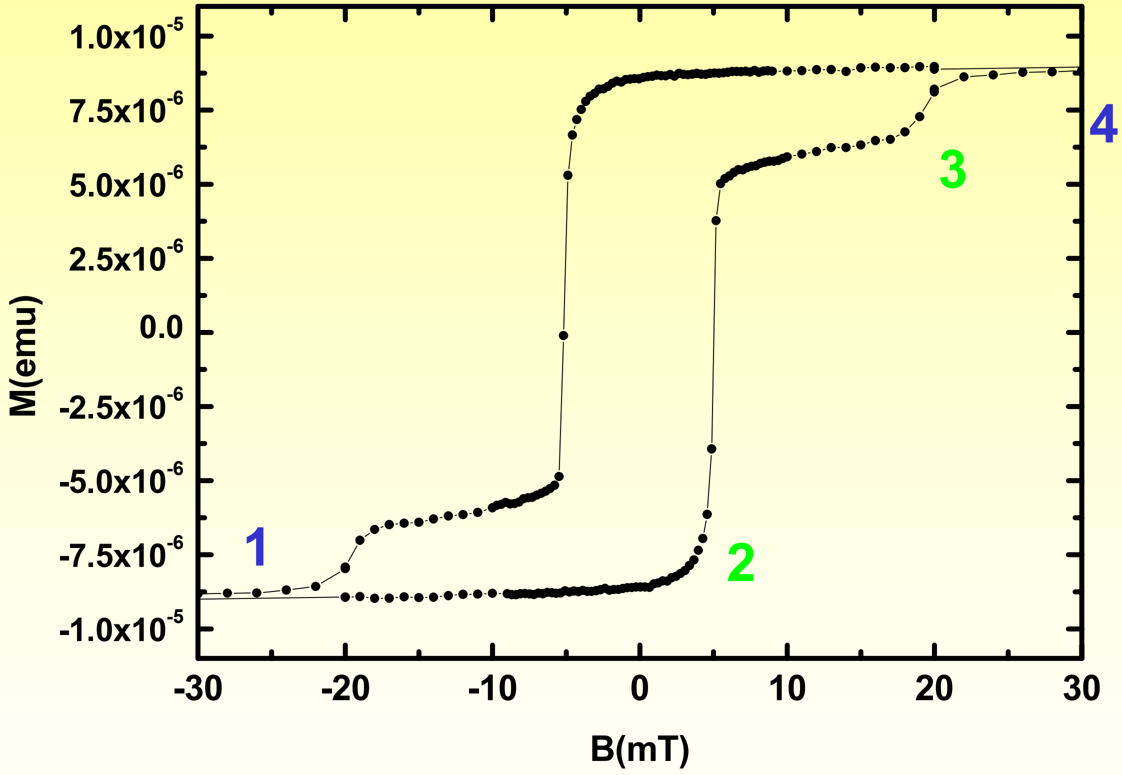




Domain wall Nucleation/propagation energy

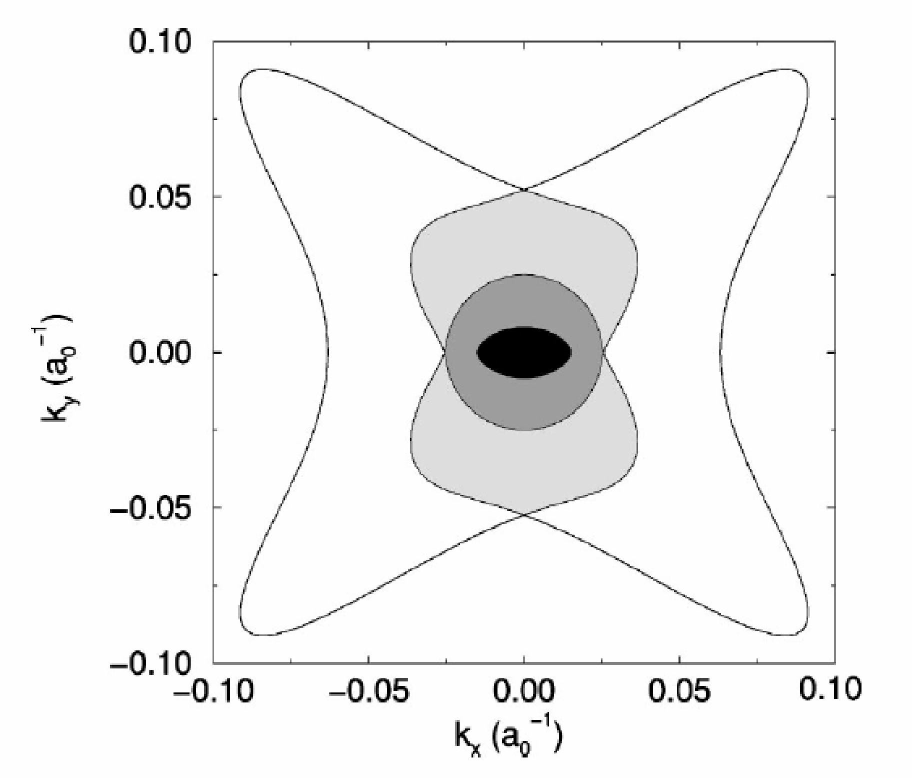
SQUID Signature



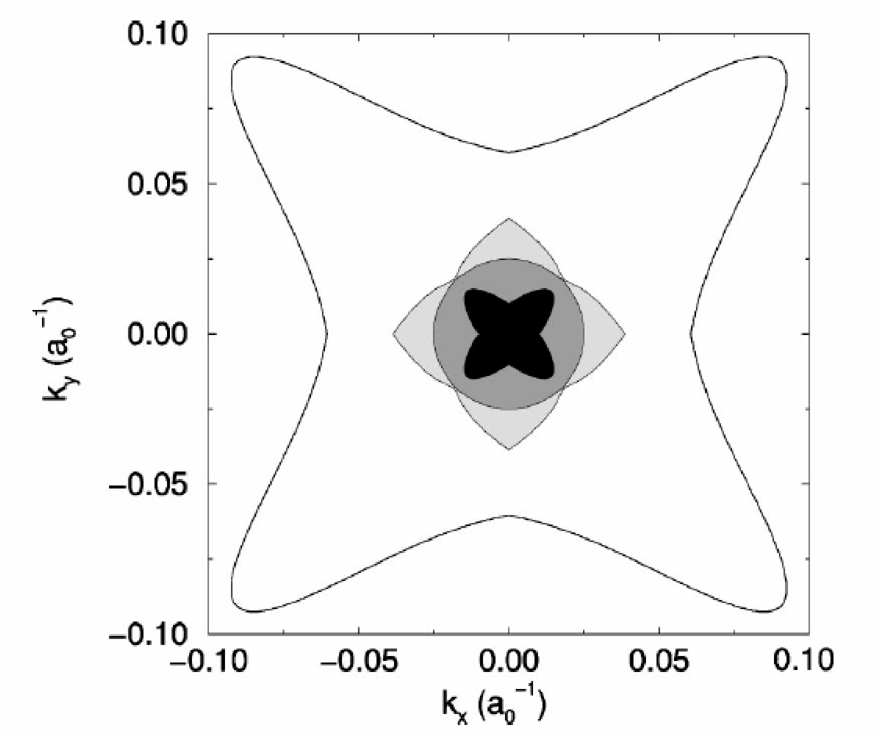


Double-step switching

Total dos of valence band strongly anisotropic.



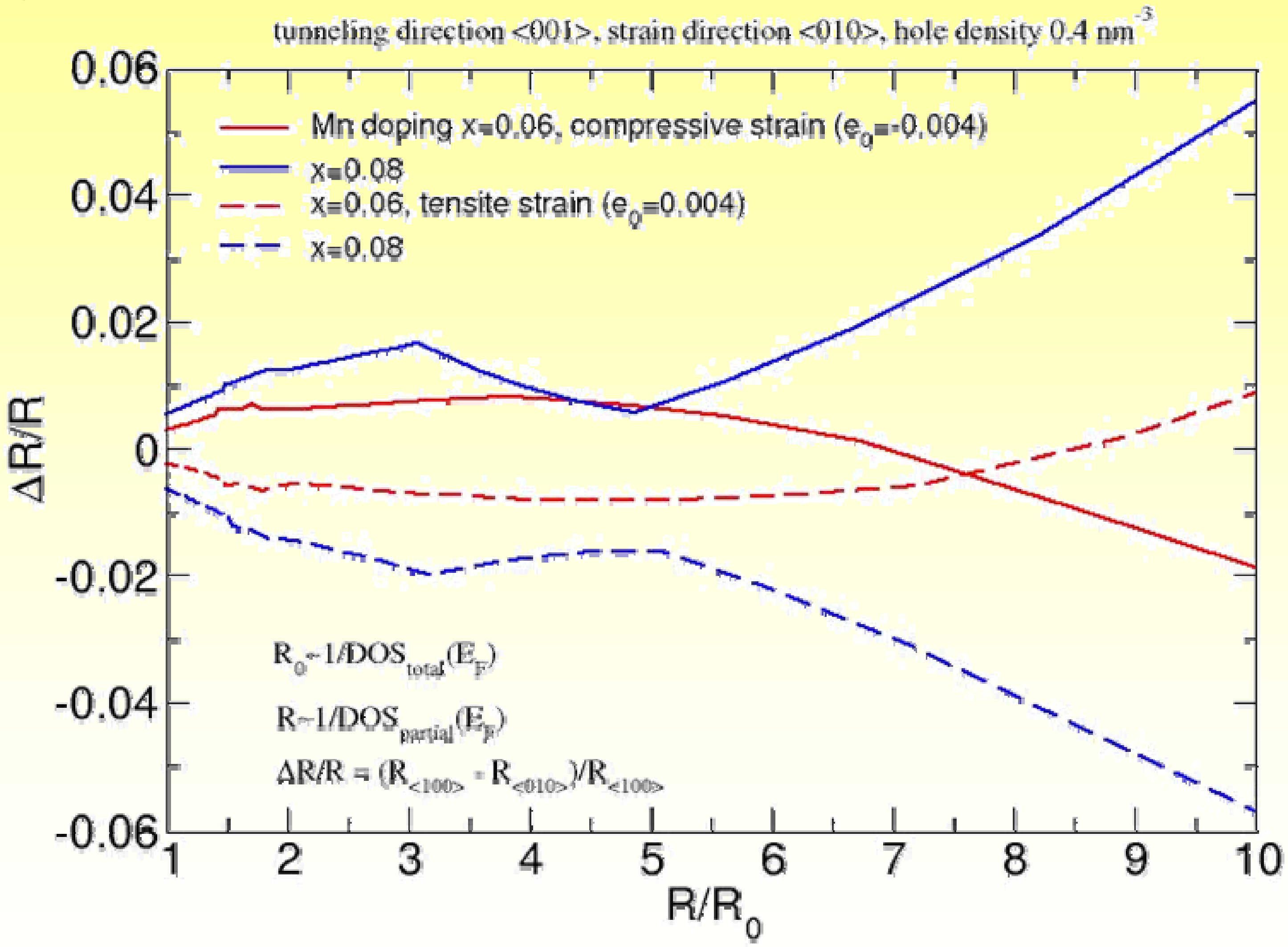
B // [100]



B // [110]

Abolfath et al., Phys. Rev. B 63, 054418 (2000).

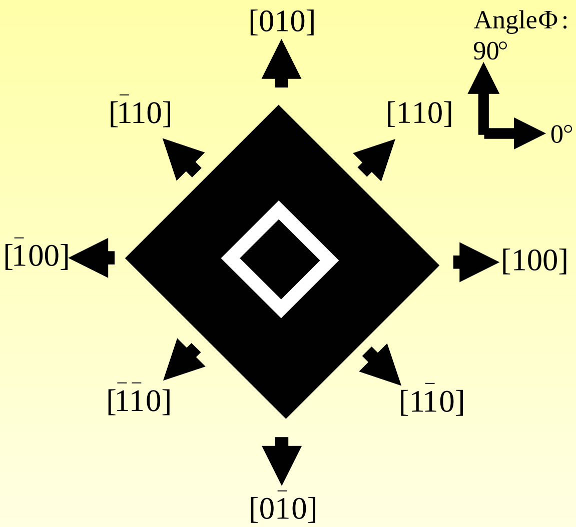
Theory: TAMR in (Ga,Mn)As/AlOx/metal devices

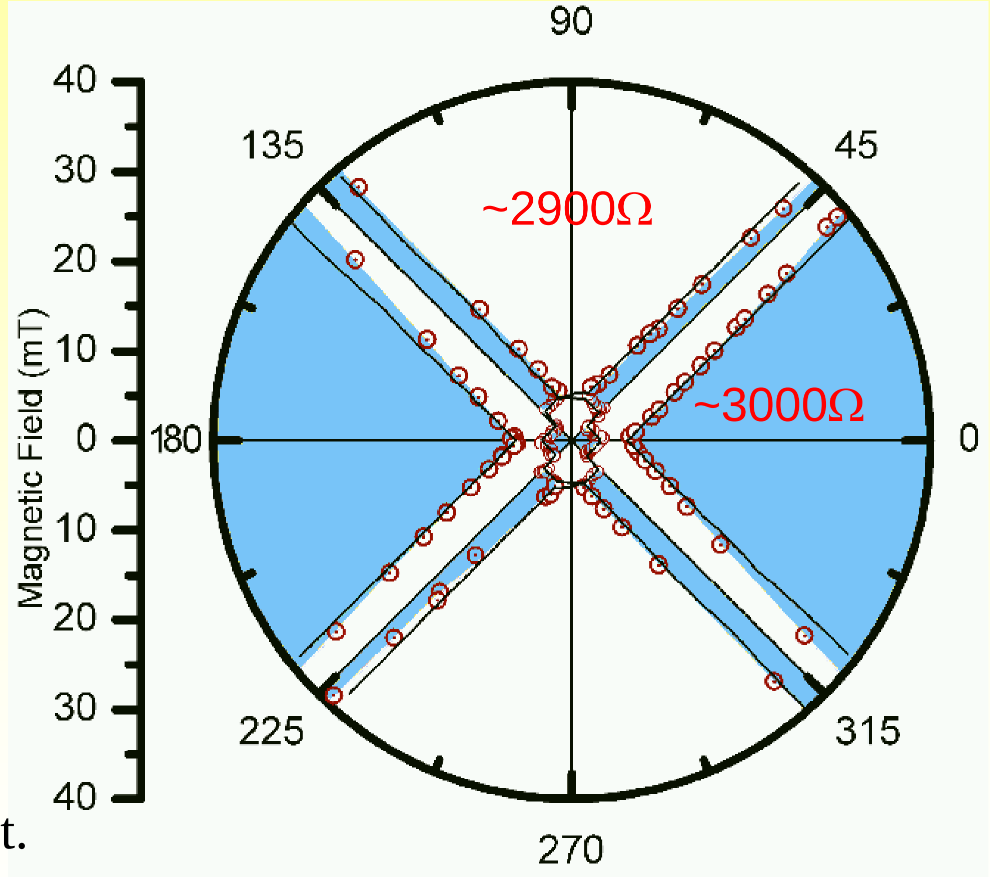


Increasing in-plane momentum conservation →

T. Jungwirth

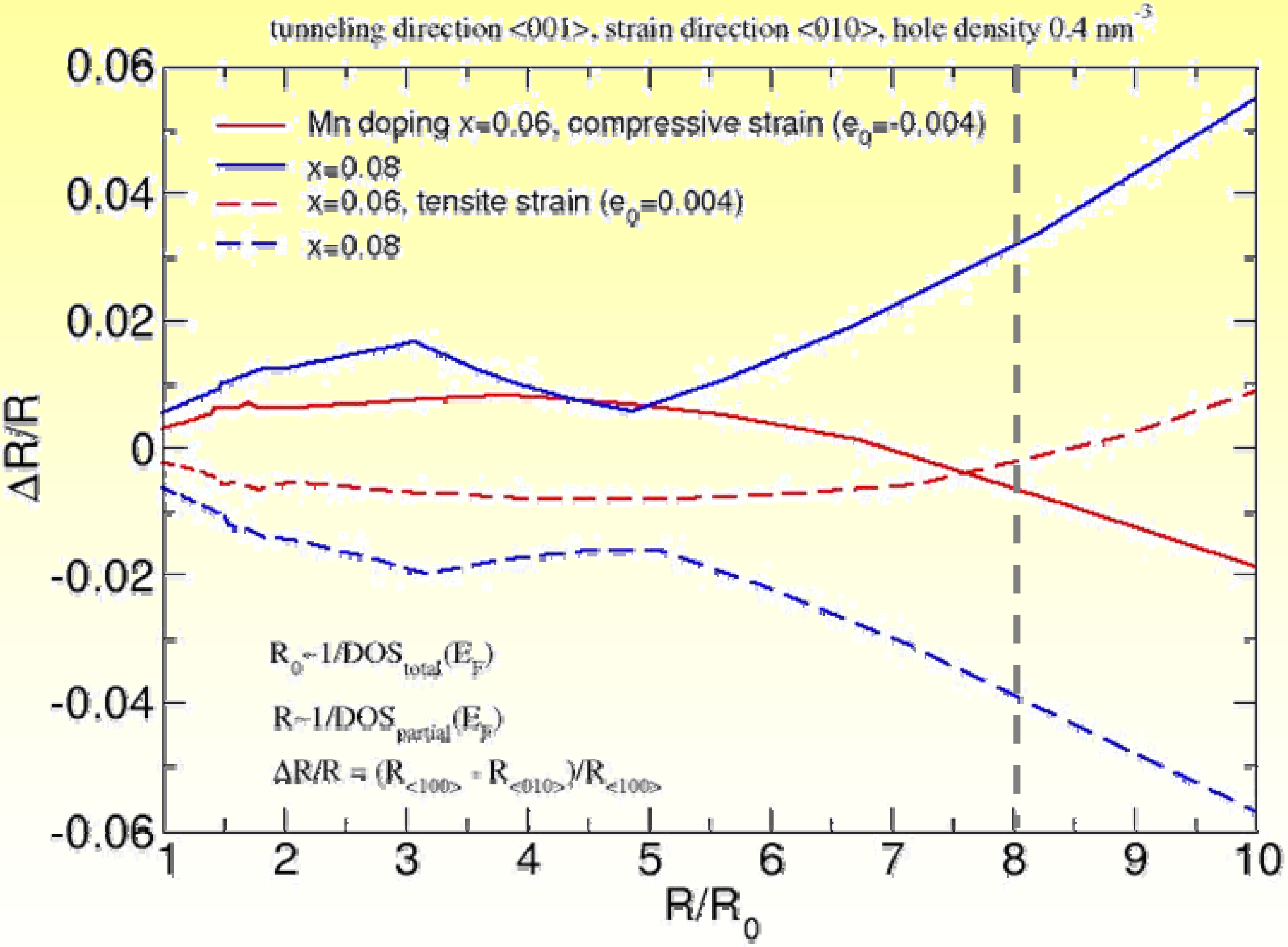
Comparing Theory and Experiment





C. Gould et al., Phys. Rev. Lett. **93**, 117203 (2004).

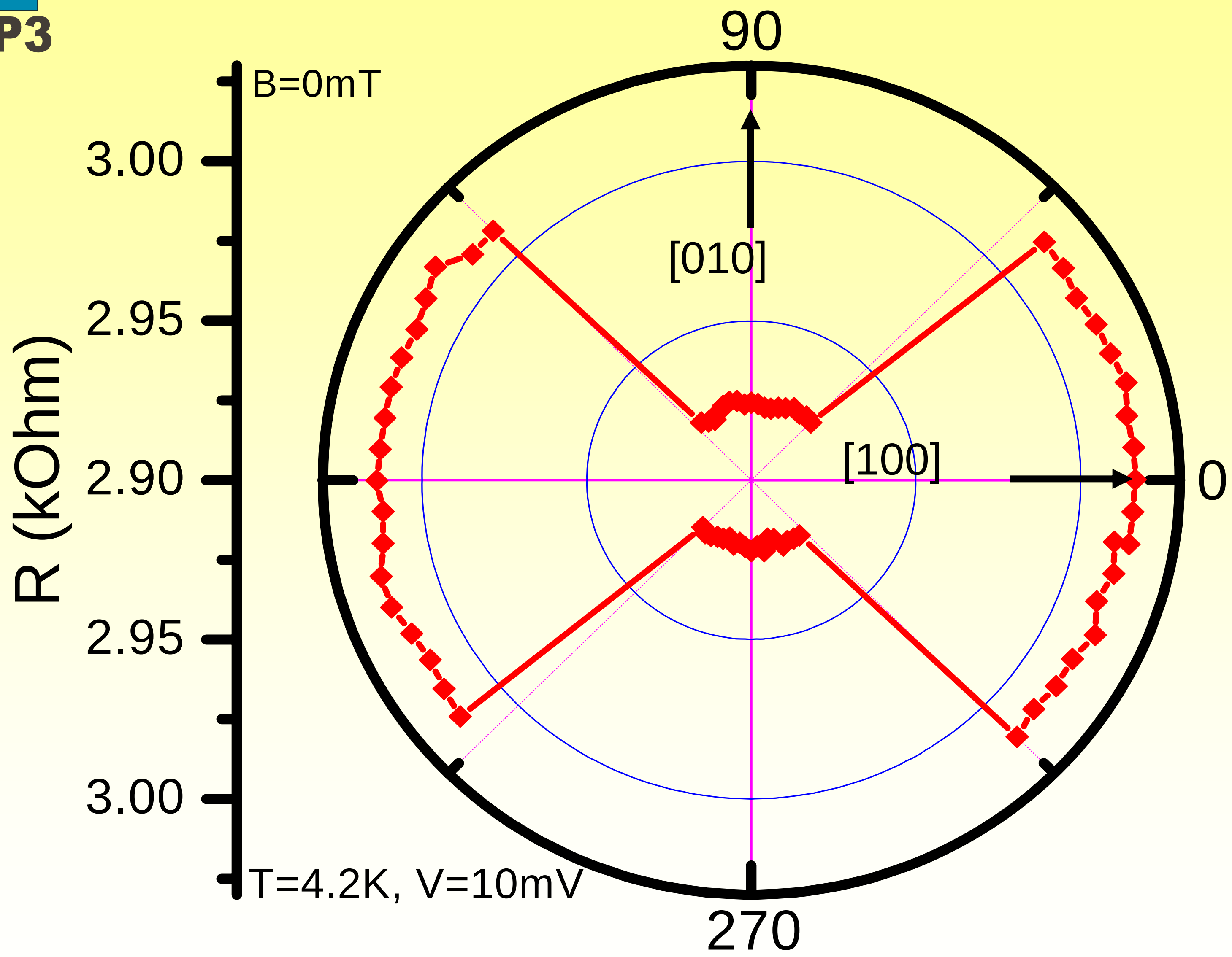
Theory: TAMR in (Ga,Mn)As/AlOx/metal devices



Increasing in-plane momentum conservation →

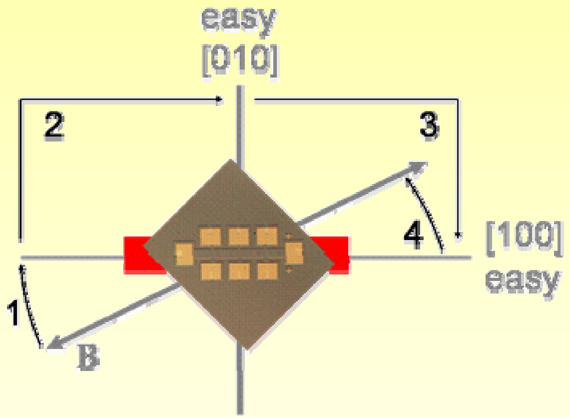
T. Jungwirth

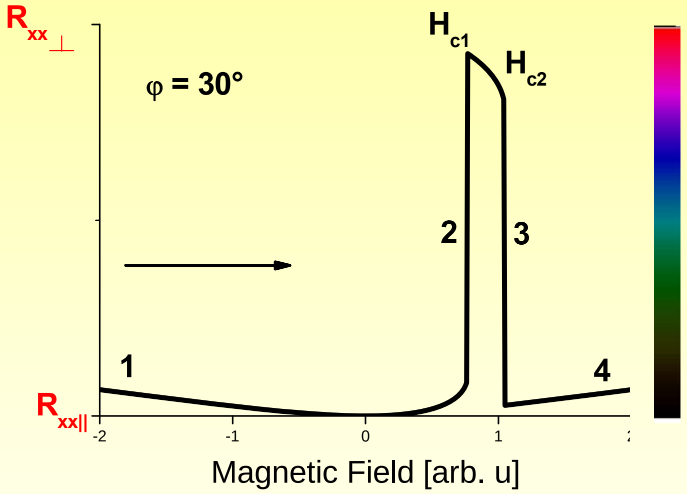
A READ-WRITE MEMORY DEVICE!

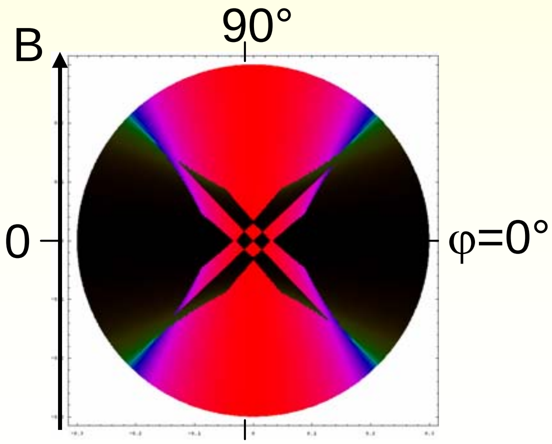


Resistance at B=0mT

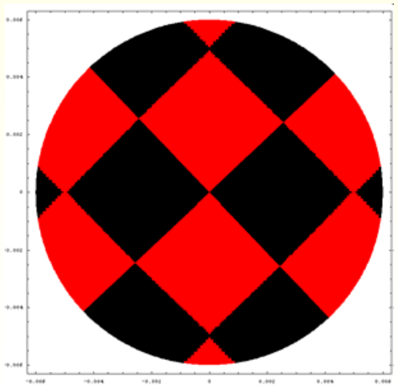
Transport Characterization of (Ga,Mn)As Magnetic Anisotropy



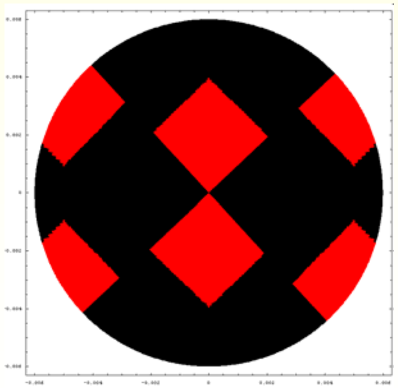




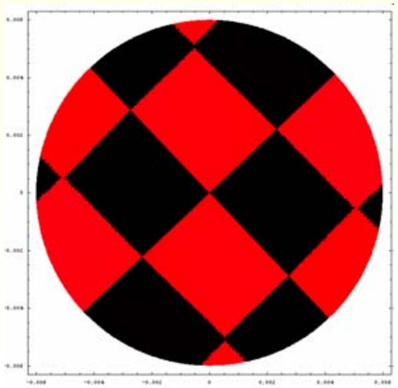
Typical at 4 K



Biaxial anisotropy

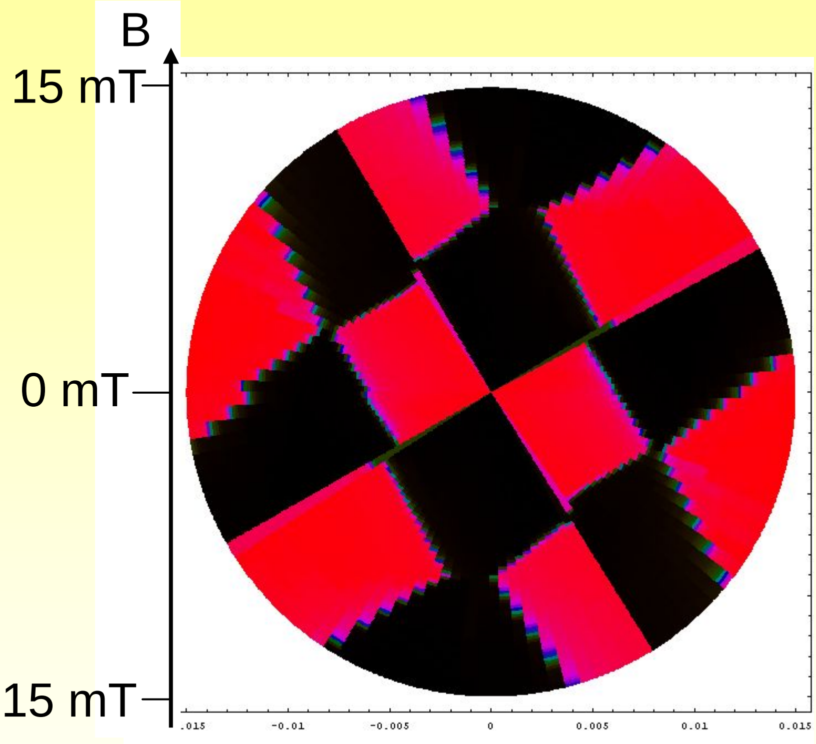


+ small uniaxial ||0°



+ uniaxial ||45°

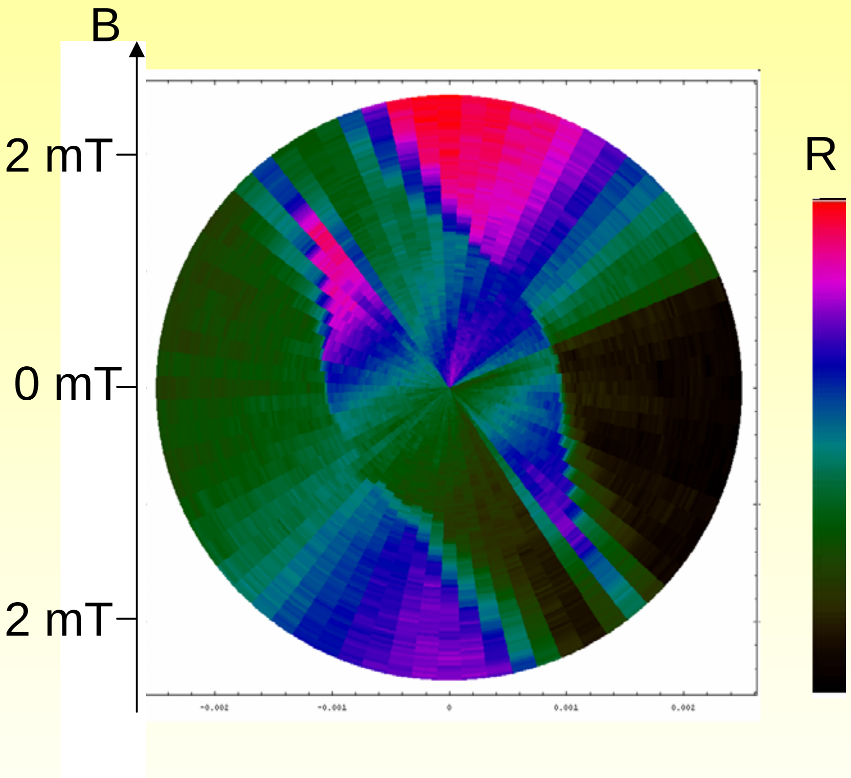
Results



4.2K

Open corners evidence [001] is indeed easier.

This is present on samples from various sources. Why is it there???



40K

The uniaxial 45° axis takes over

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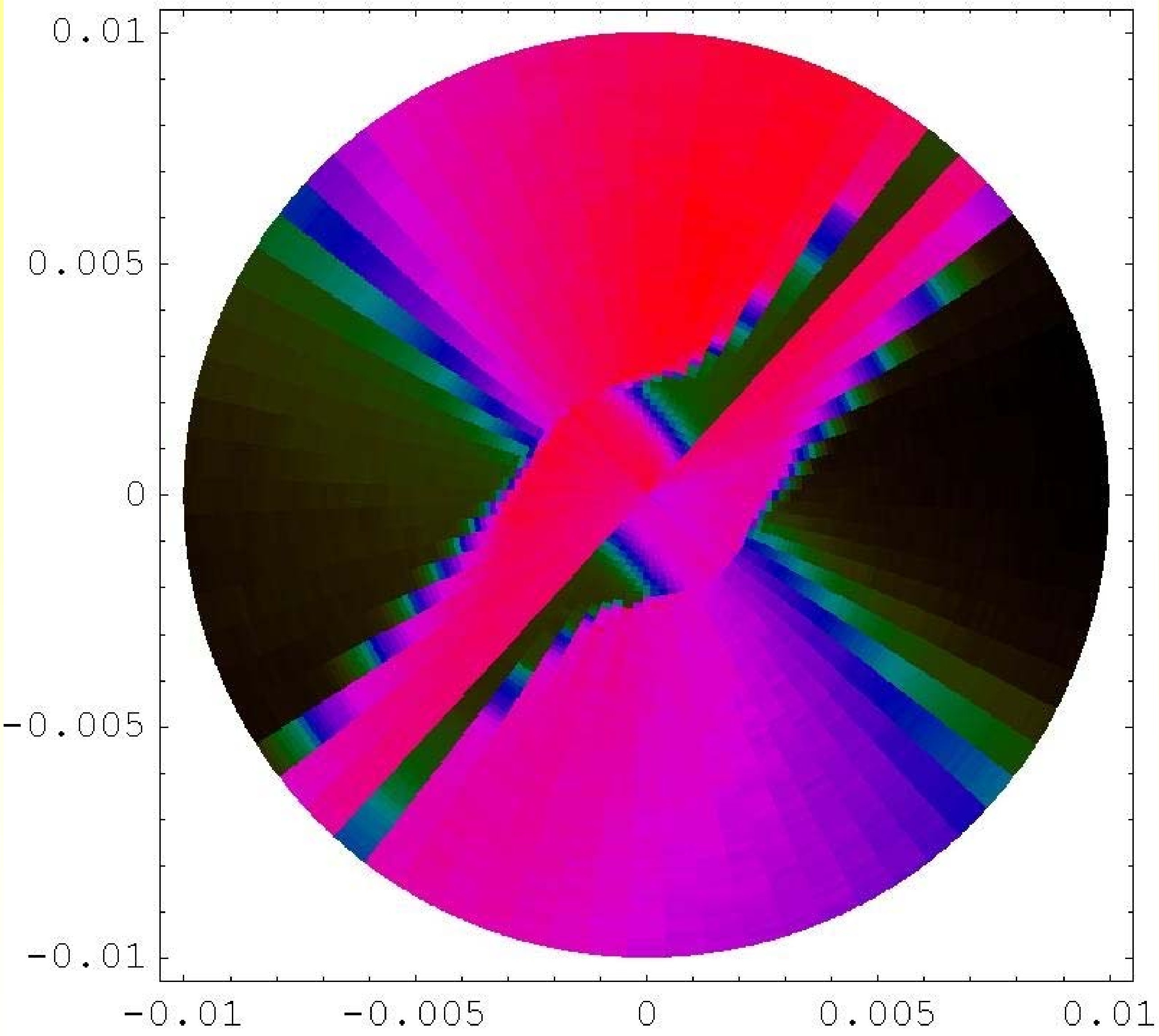

40K

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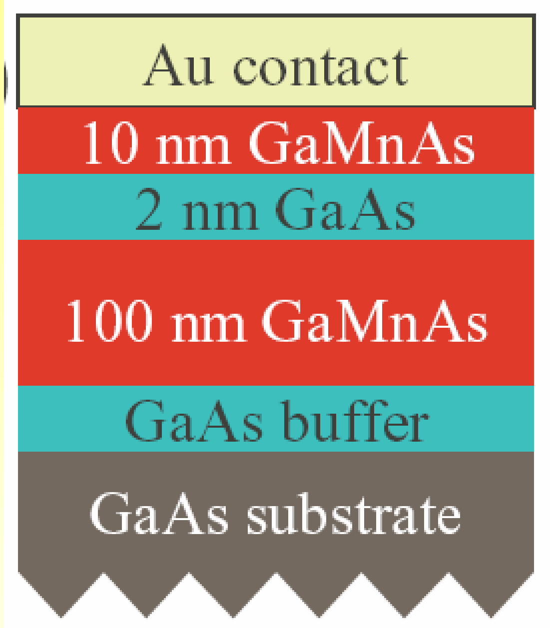
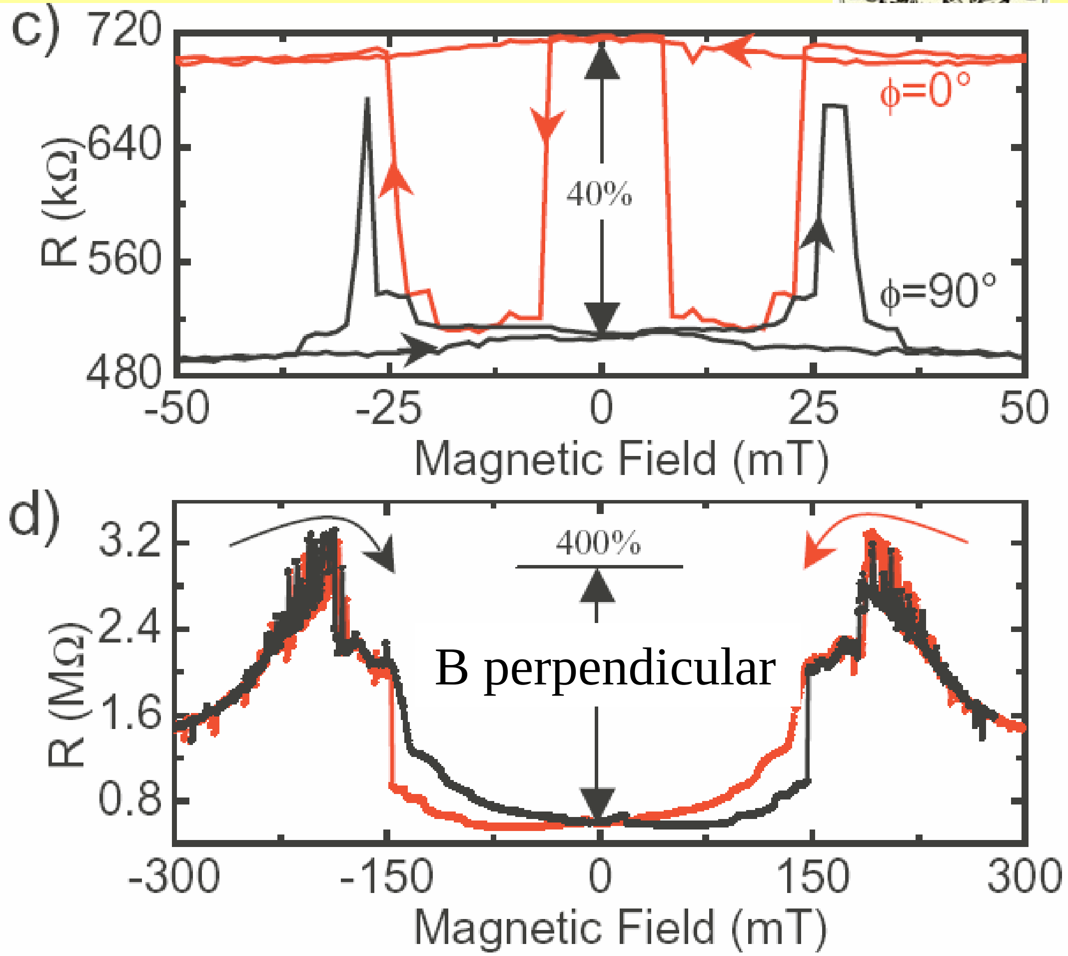
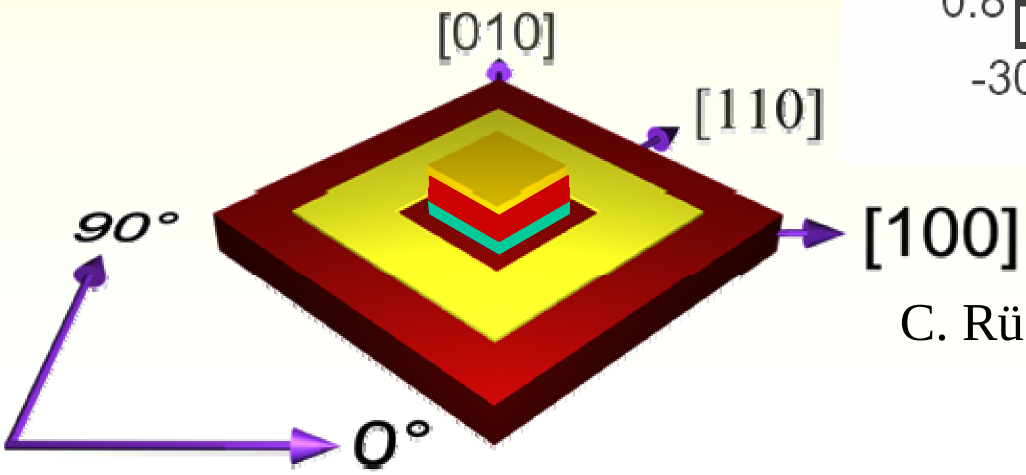
Amplifying TAMR

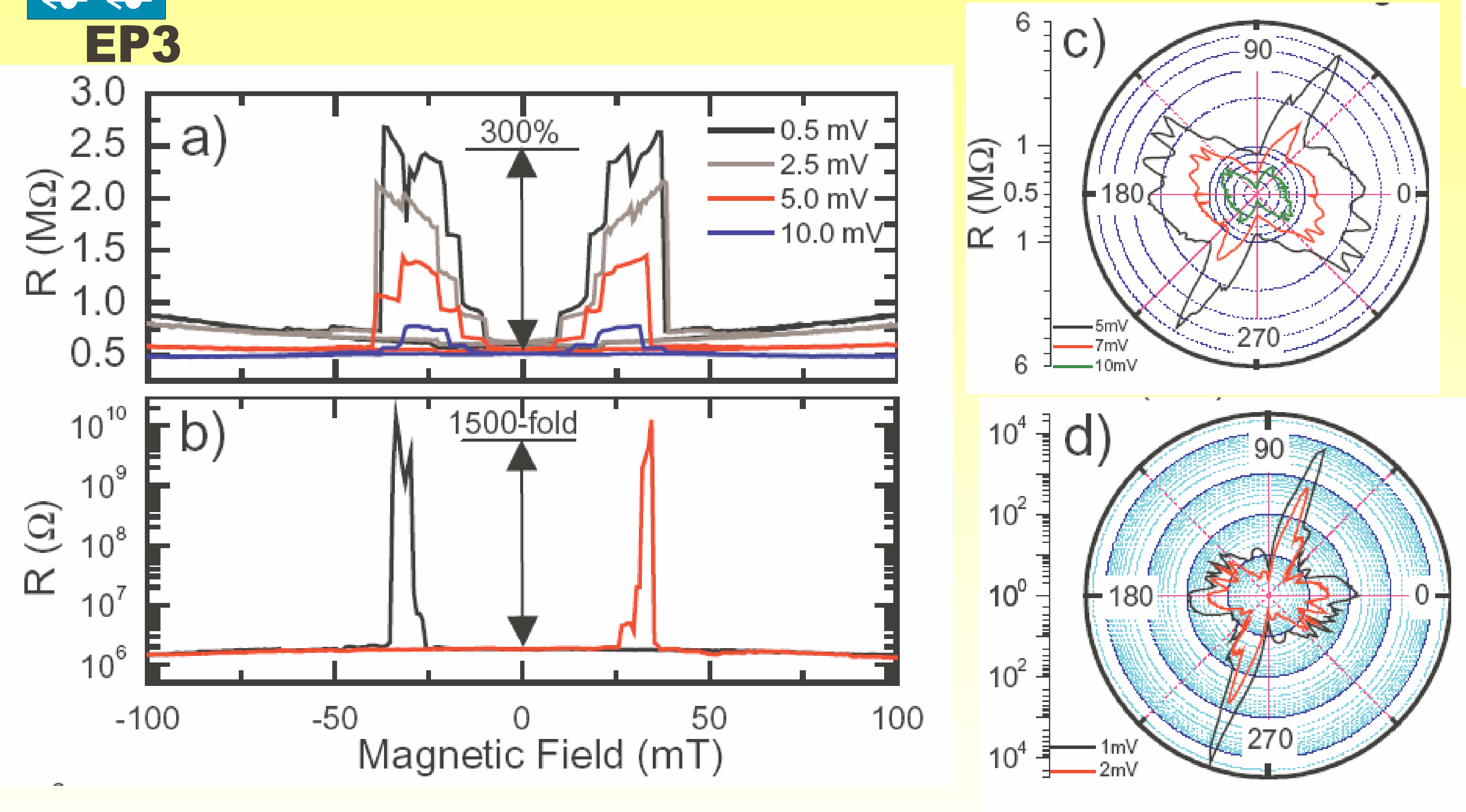

Au contact
10 nm GaMnAs
2 nm GaAs
100 nm GaMnAs
GaAs buffer
GaAs substrate





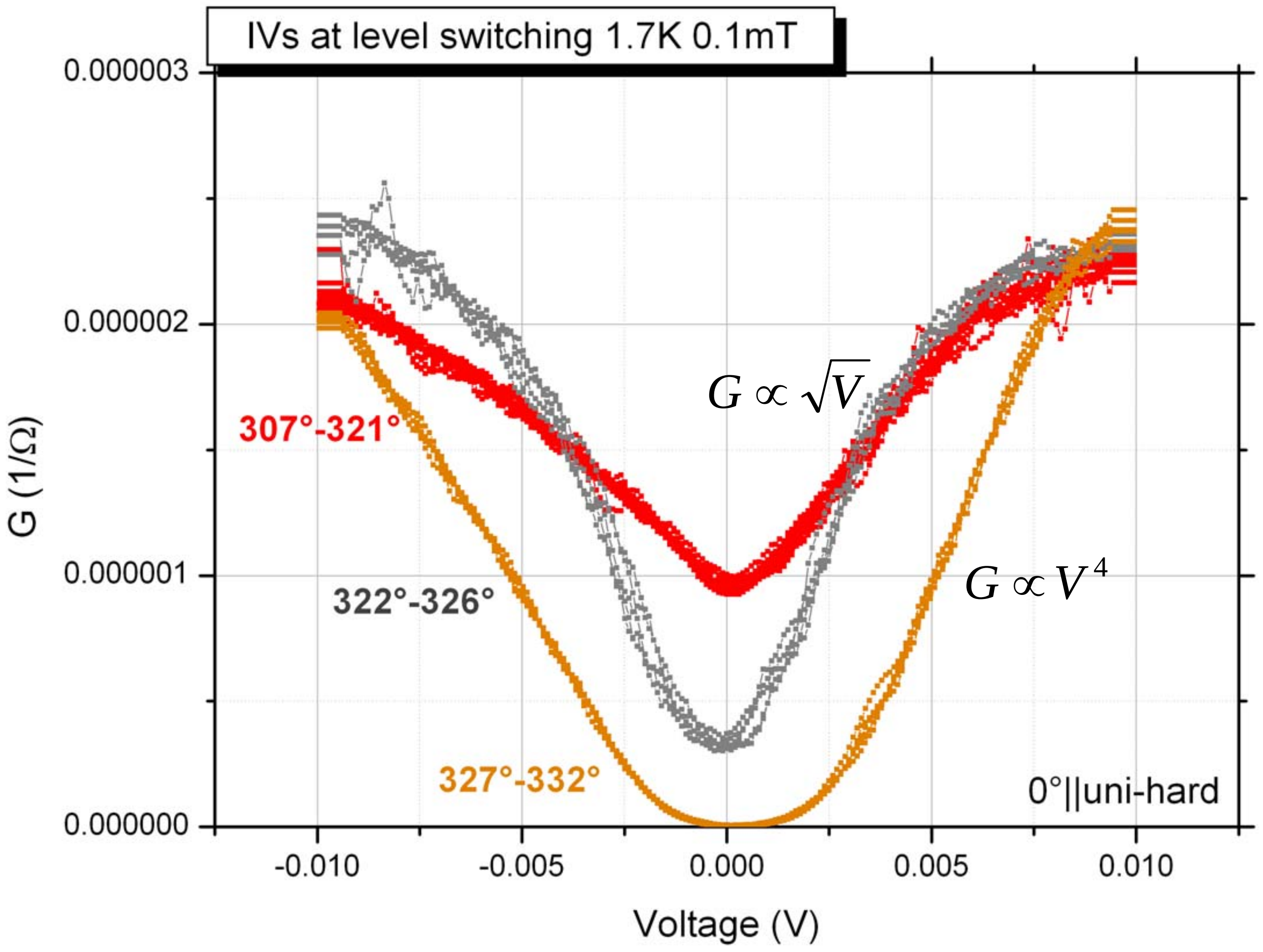
C. Rüster et al., PRL 94, 027203 (2005)

Massive amplification of TAMR



Effect blows up for low T, low bias: Efros-Shklovski gap.

Massive amplification of TAMR



G-V curves indicative of metal (insulator) for low R (high R) state.

How does the structure of the Mn-hole wavefunction vary with B-field direction? Iterative numerical solution of the Luttinger equation

Reformulation of the Luttinger equation in k-space to at iteration relation.

$$B_n(\mathbf{k}) = \frac{1}{E_b - H_{FL}^{nn}(\mathbf{k})}\left[\sum_{n'\neq n} H_{FL}^{nn'} B_{n'}(\mathbf{k}) + \int \mathcal{U}(\mathbf{k}-\mathbf{k}')B_n(\mathbf{k}')d^3\mathbf{k}'\right]$$

$H_{FL}^{nn'}(\mathbf{k})$	6 band Luttinger-Hamiltonian with SO-, PD-coupling and Strain
$\mathcal{U}(\mathbf{k}-\mathbf{k}')$	Yukawa potential in k-space
$B_{n'}(\mathbf{k})$	Bound hole wavefunction in k-space
E_b	Binding energy

Binding energy and the wavefunction will be determined at representative points.

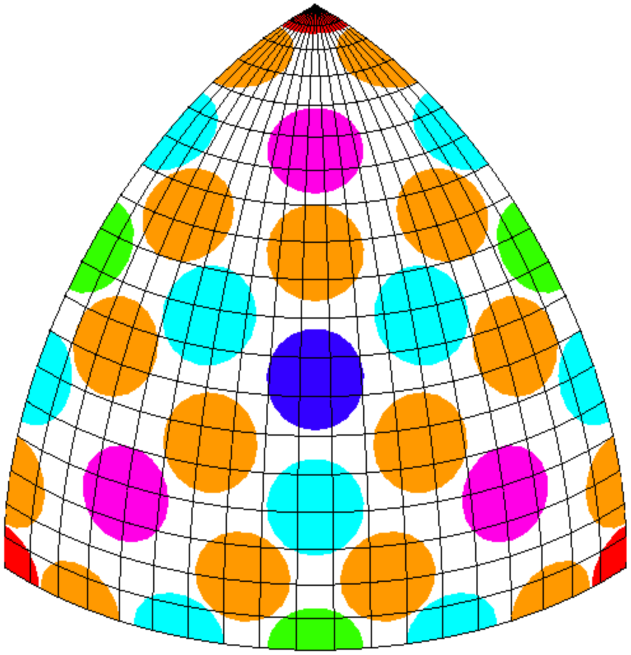
Only the ground state.

Manuel J. Schmidt, Würzburg

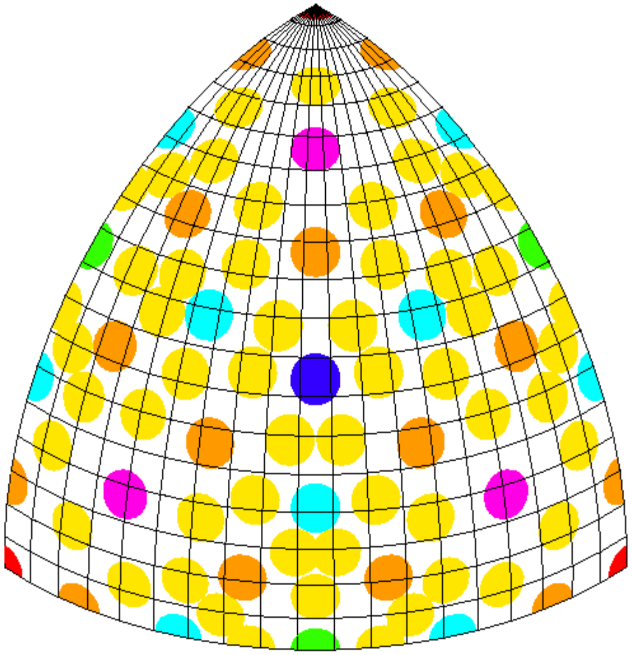
Iterative numerical solution of the Luttinger equation

The points in k-space are choosen on particular sets of rays through the origin. The directions must obey the following requirements:

- Point group invariance
- Uniform direction-distribution (as far as possible)
- Some directions are available in all stars([001],[111],[011],...)



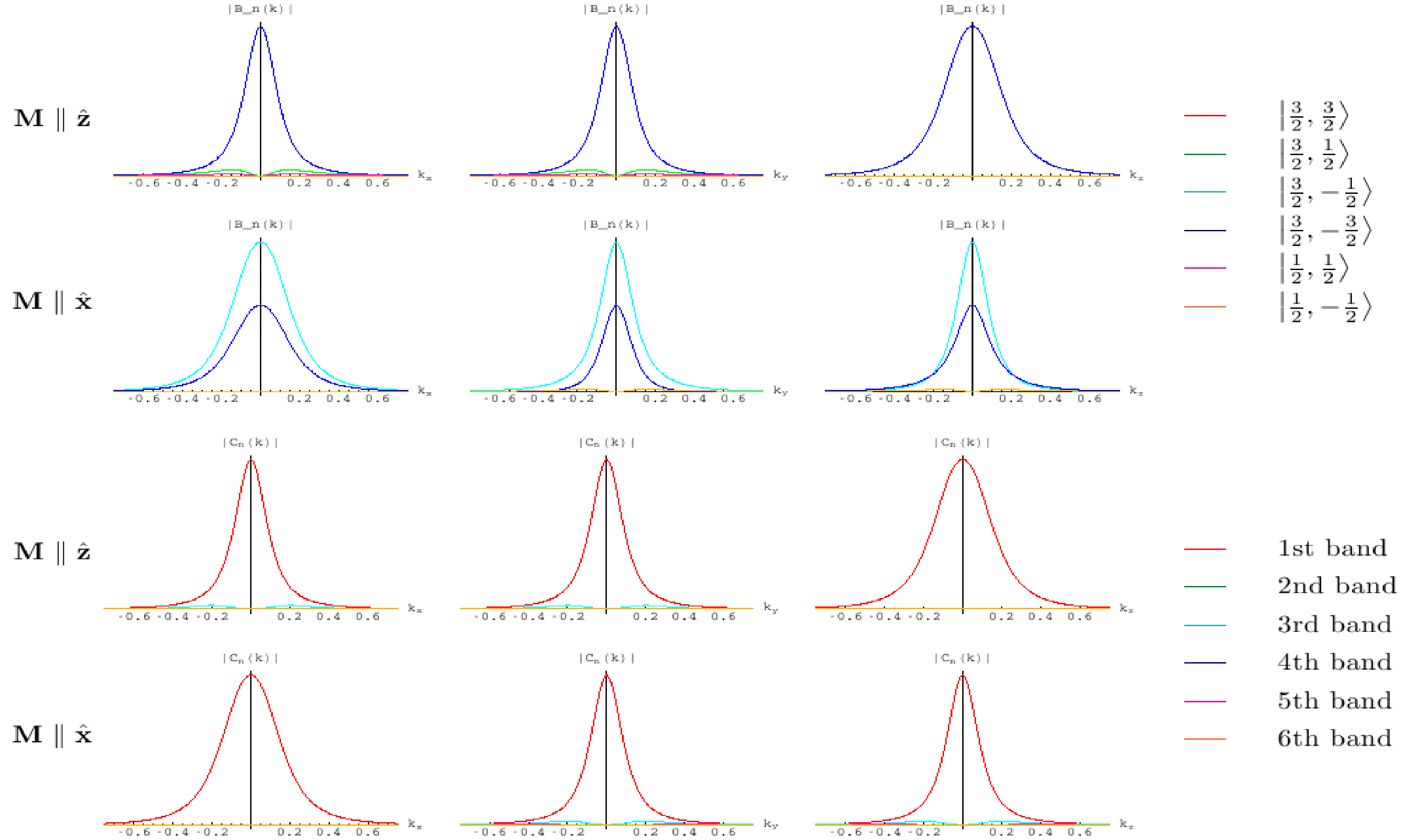
194star



602star

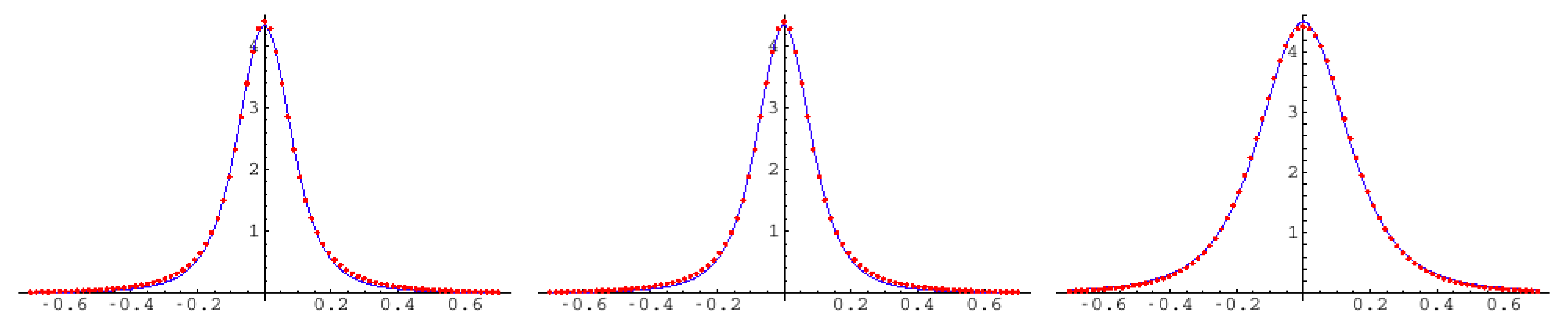
Iterative numerical solution of the Luttinger equation

Wavefunction resides mainly in the top band, as seen from a transform to the eigenbasis of the full Luttinger Hamiltonian.

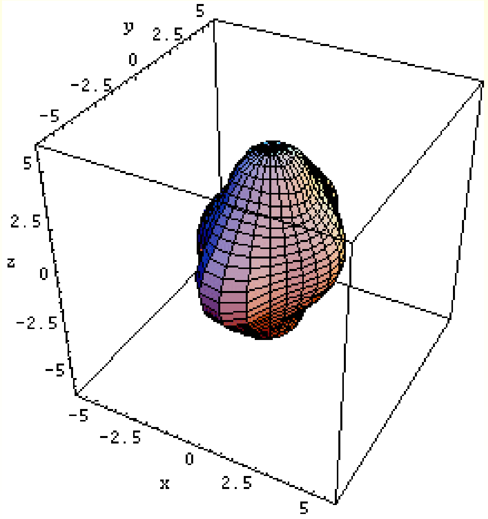


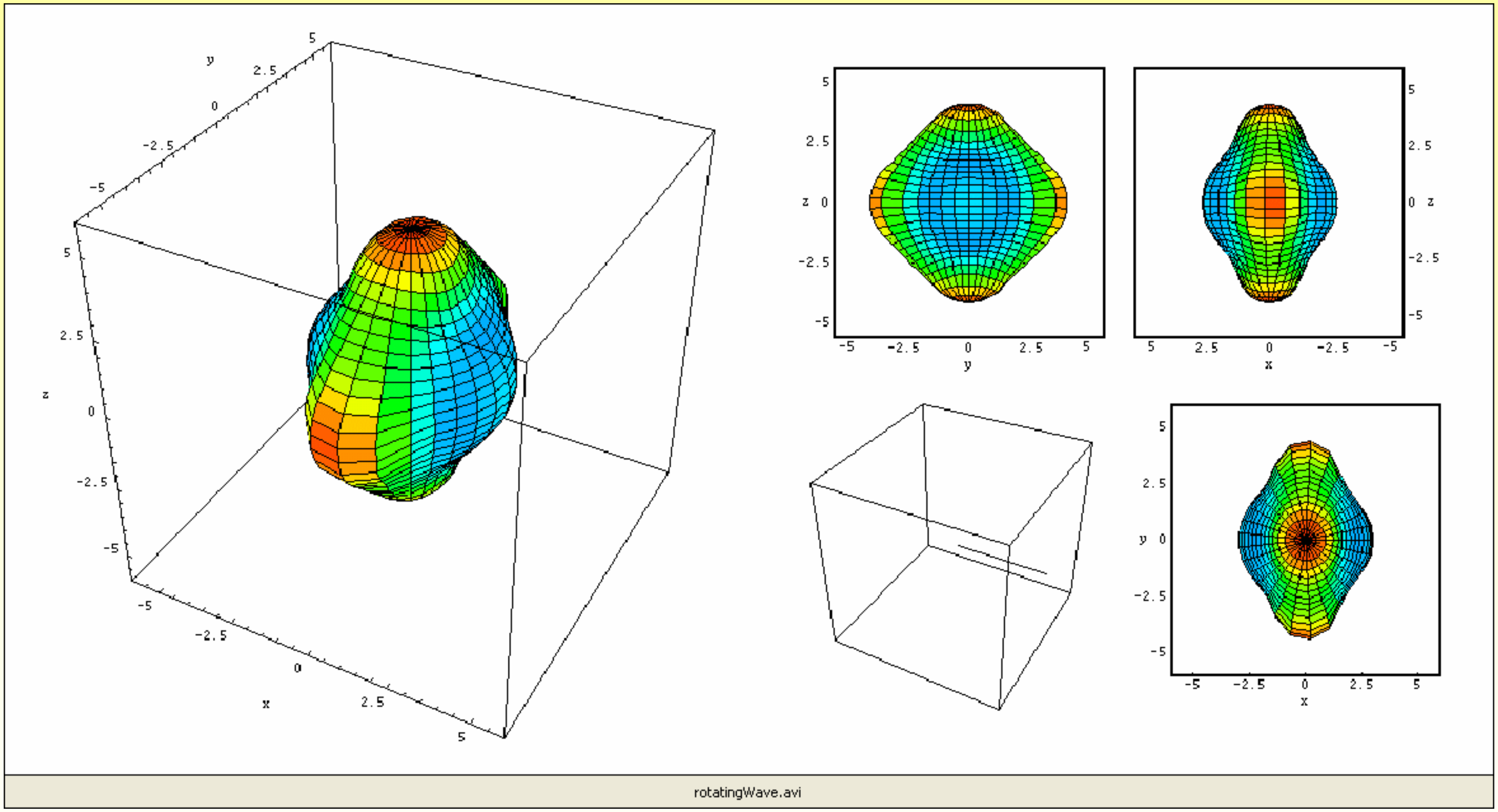
Iterative numerical solution of the Luttinger equation

Hydrogen wavefunctions in k-space can be fitted to the numerical solution for each direction in order to obtain the Bohr radius.

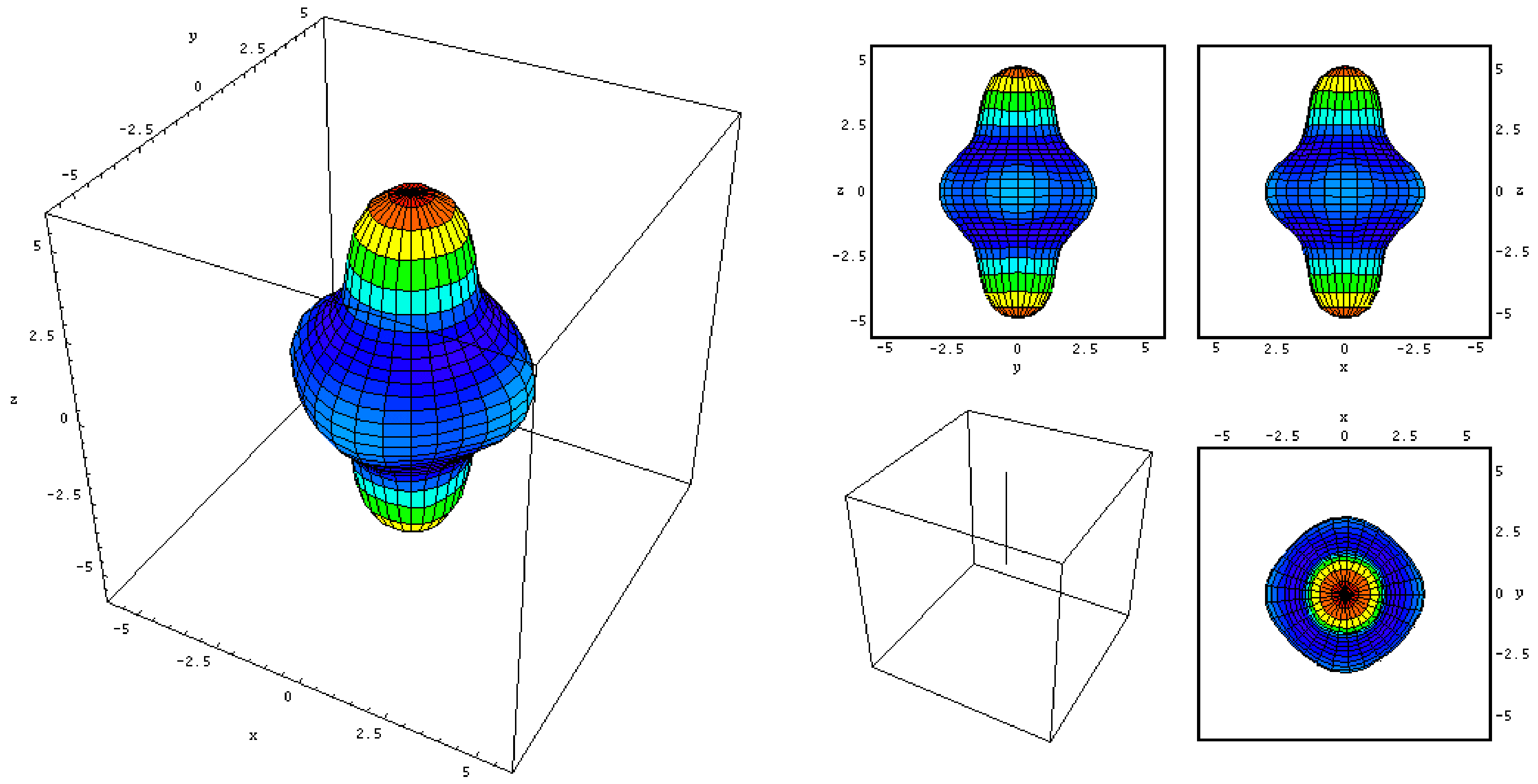


The Bohr radii for an arbitrary direction is interpolated. One can see a strong dependence on magnetization direction.





Wave function w/o strain breaking the symmetry



Including the strain (and exchange) parameters used in fitting the TAMR results.

The change in Boht radius drives the MI transition.

Evidence for insulator phase: fluctuations in hopping transport

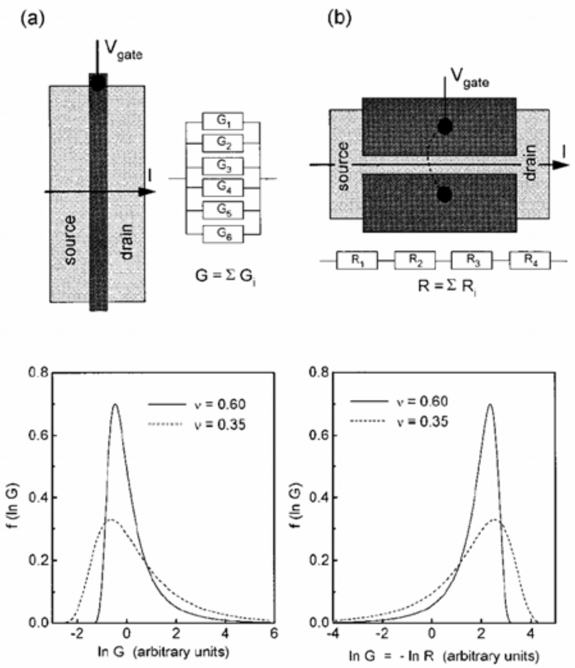


FIG. 1. Device schematics and theoretical DF's for two values of the parameter ν. (a) The 2D device behaves like a sum of parallel conductors and its DF has a tail out to high $\ln G$. (b) The 1D device behaves like a sum of series resistances with a tail on the DF towards low $\ln G$.

$$Q \equiv \ln\left(\frac{R}{R_0}\right) = \frac{\nu^{1/2}T_0}{T} \approx \left\{2\frac{T_0}{T}\ln\left[\frac{L}{\xi}\left(\frac{T_0}{T}\right)^{1/2}\ln^{1/2}\left(\frac{L}{\xi}\right)\right]\right\}^{1/2}. \tag{5}$$

The probability distribution function (DF) for the quantity Q is best written in terms of ν and a new parameter Δ. For $\nu < 1$ it is given by the following integral:

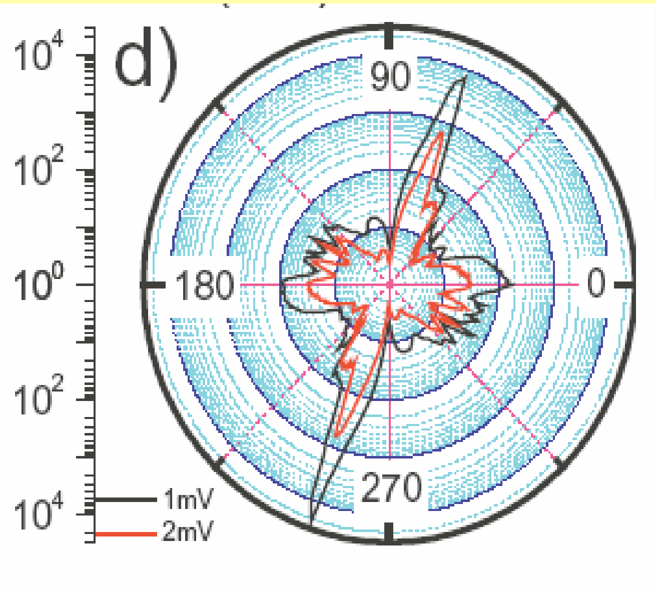
$$f(\Delta) = \frac{e^{\Delta}}{\pi}\int_0^{\infty} dx \exp\left(-x^{\nu^{1/2}}\cos\frac{\pi\nu^{1/2}}{2}\right) \times \cos\left(xe^{\Delta} - x^{\nu^{1/2}}\sin\frac{\pi\nu^{1/2}}{2}\right), \tag{6}$$

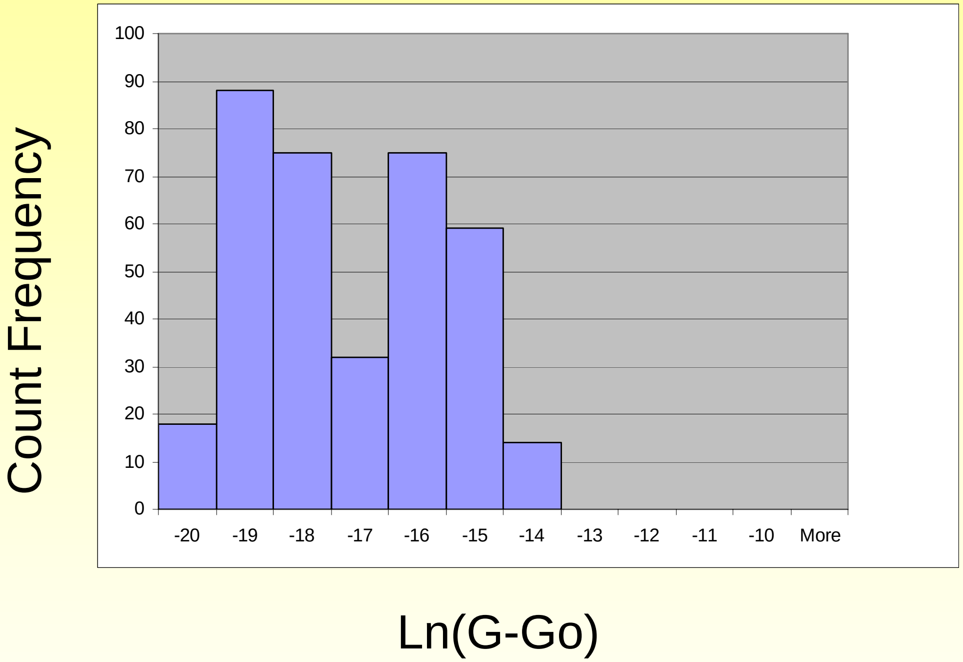
$$\Delta \equiv Q - \frac{\nu^{1/2}T_0}{T}. \tag{7}$$

[9] M. E. Raikh and I. M. Ruzin, in *Mesoscopic Phenomena in Solids*, edited by B. I. Altshuler, P. A. Lee, and R. A. Webb (Elsevier Science, Amsterdam, 1991).

[10] M. E. Raikh and I. M. Ruzin, Zh. Éksp. Teor. Fiz. **92**, 2257 (1987) [Sov. Phys. JETP **65**, 1273 (1987)].

Analysis of amplitude of experimental fluctuations





Is this at all a healthy way of analyzing our data?

How can we do better?

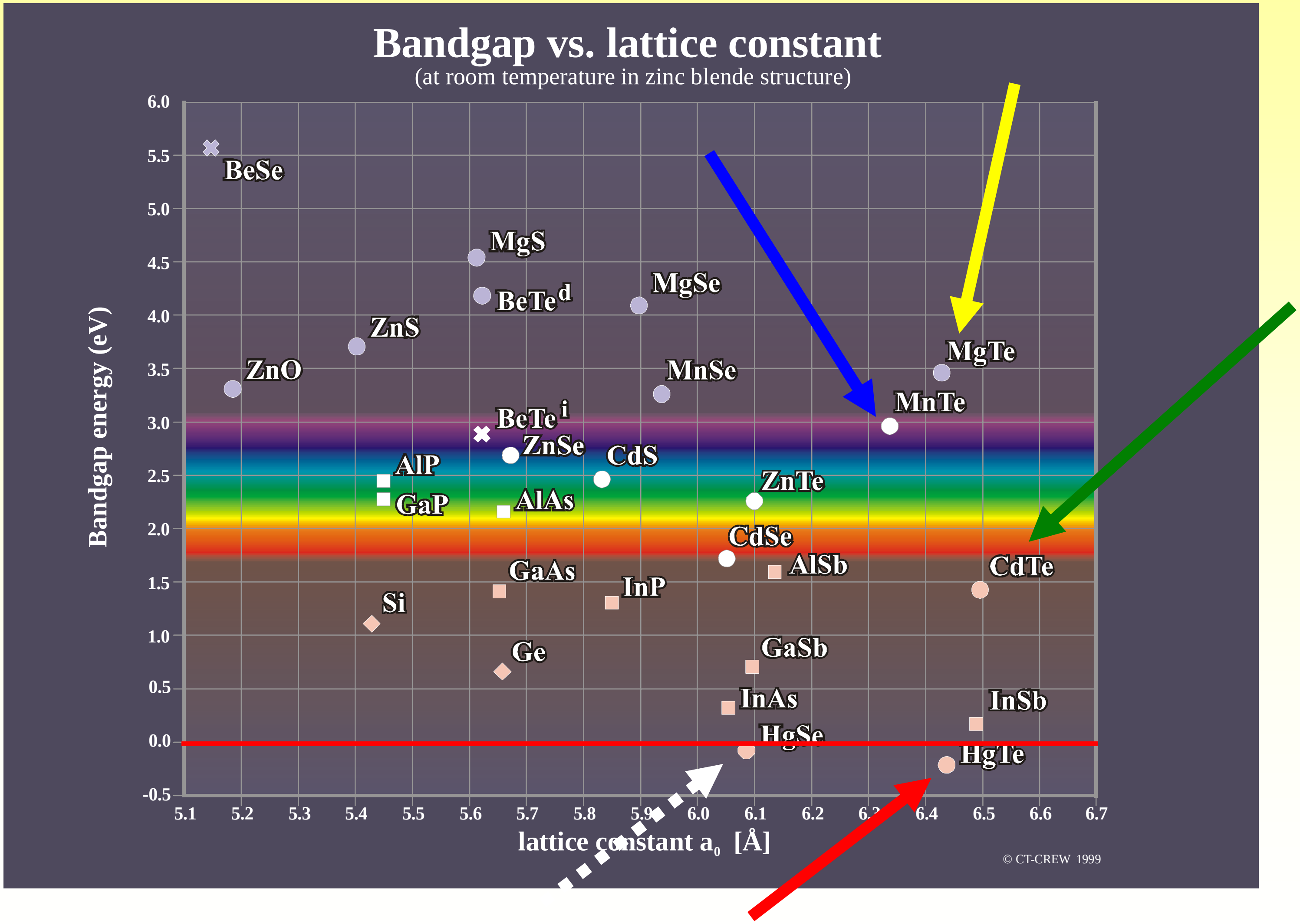
Narrow Gap II-VIs: HgMnTe

- Introduction: HgTe Quantum Wells
- Interplay Rashba/Zeeman Splitting
- Odd and Even Hall plateaus
- Nanostructured Hall bars
- Gated H-bars
- Aharonov Casher effect

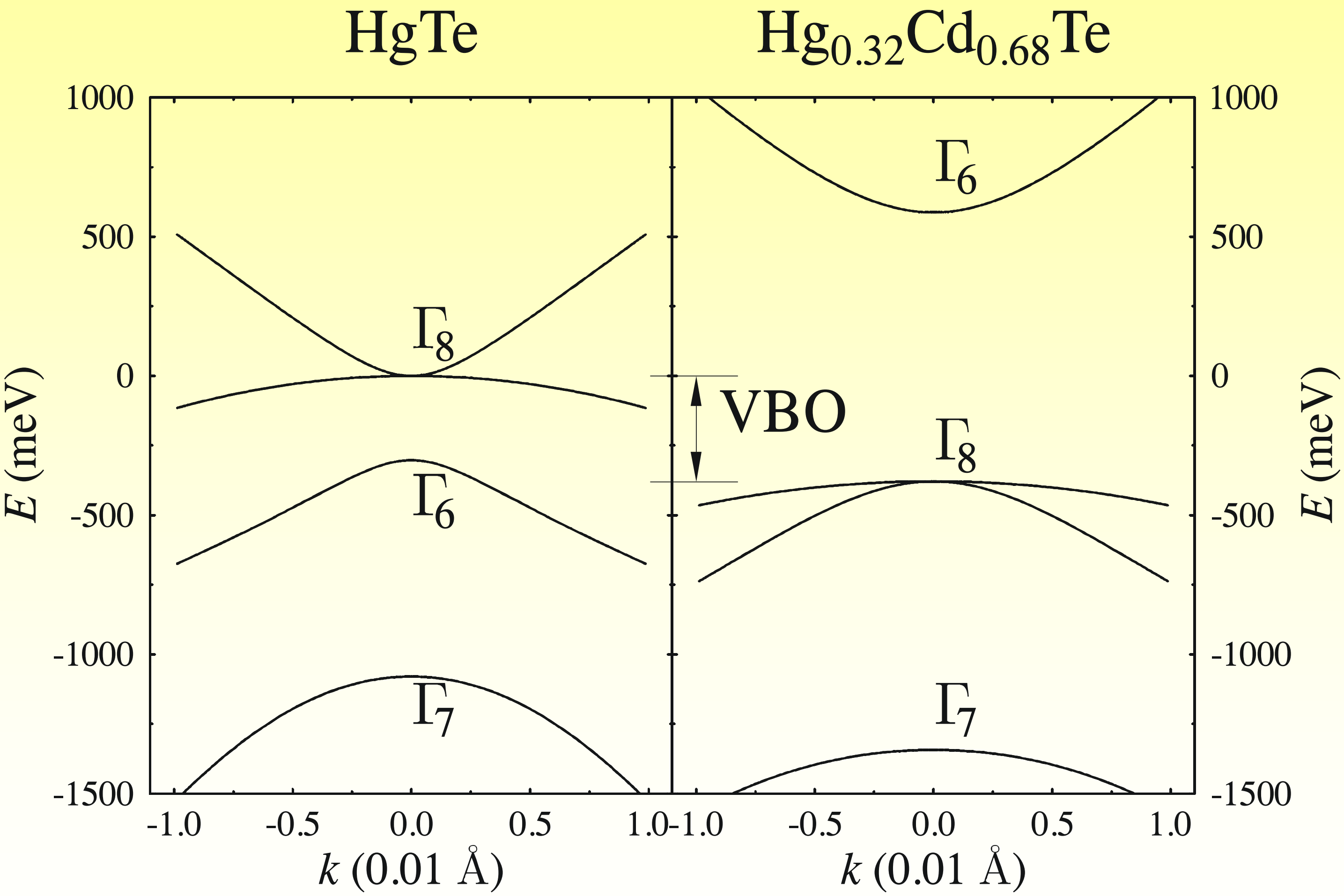
Collaborators:
Hartmut Buhmann, Charlie Becker, Volker Daumer, Yongshen Gui, Markus König, Jian Liu, Alina Novik, Matthias Schäfer

Gerrit Bauer, Junichiro Inoue
Tomas Jungwirth, Jairo Sinova, Ewelina Hankiewicz

HgTe Fabrication: MBE



HgTe Quantum-Well



VBO = 570 meV

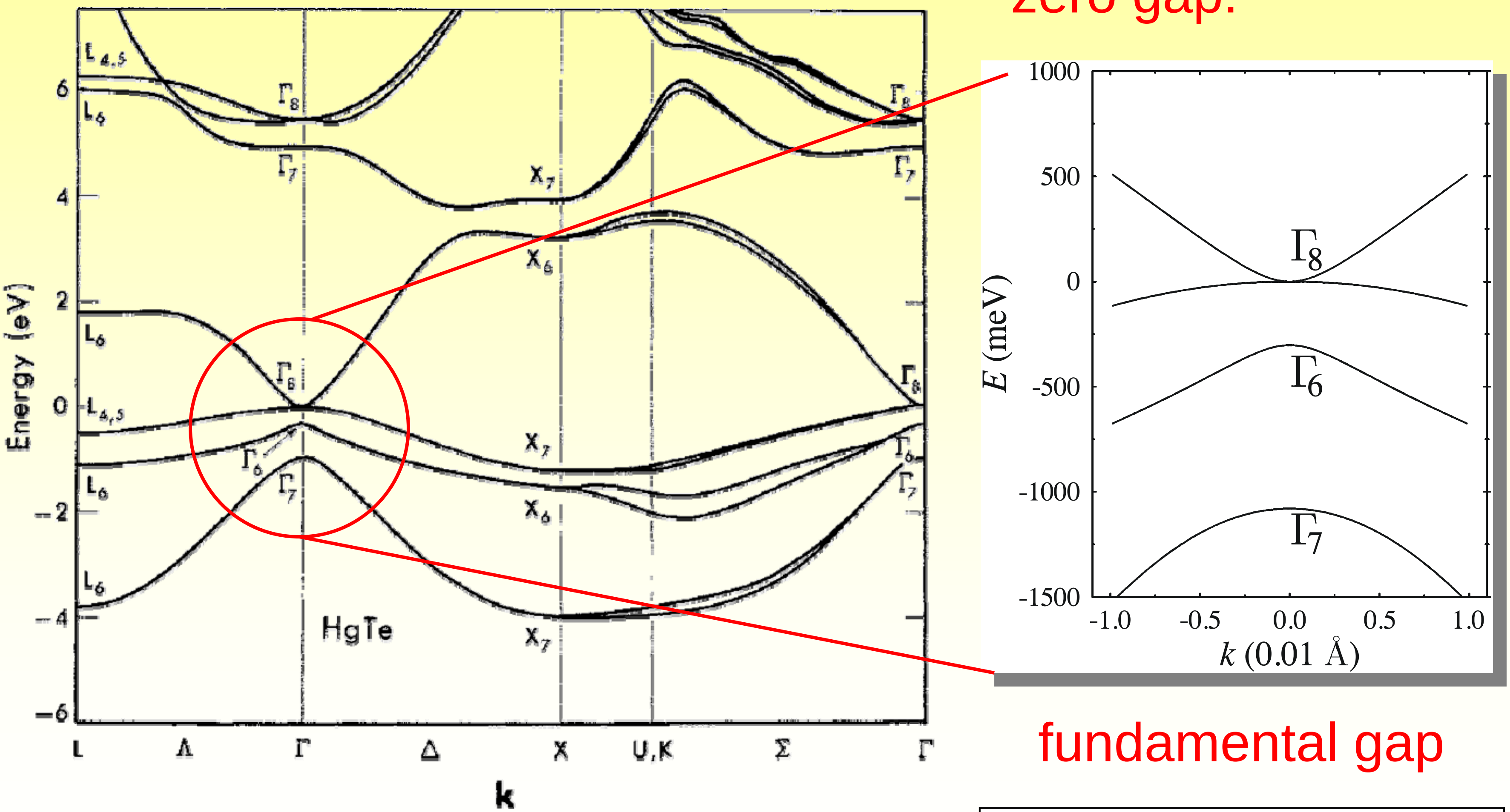
well

barrier

HgTe: Semimetal or Semiconductor

bandstructure

zero gap:

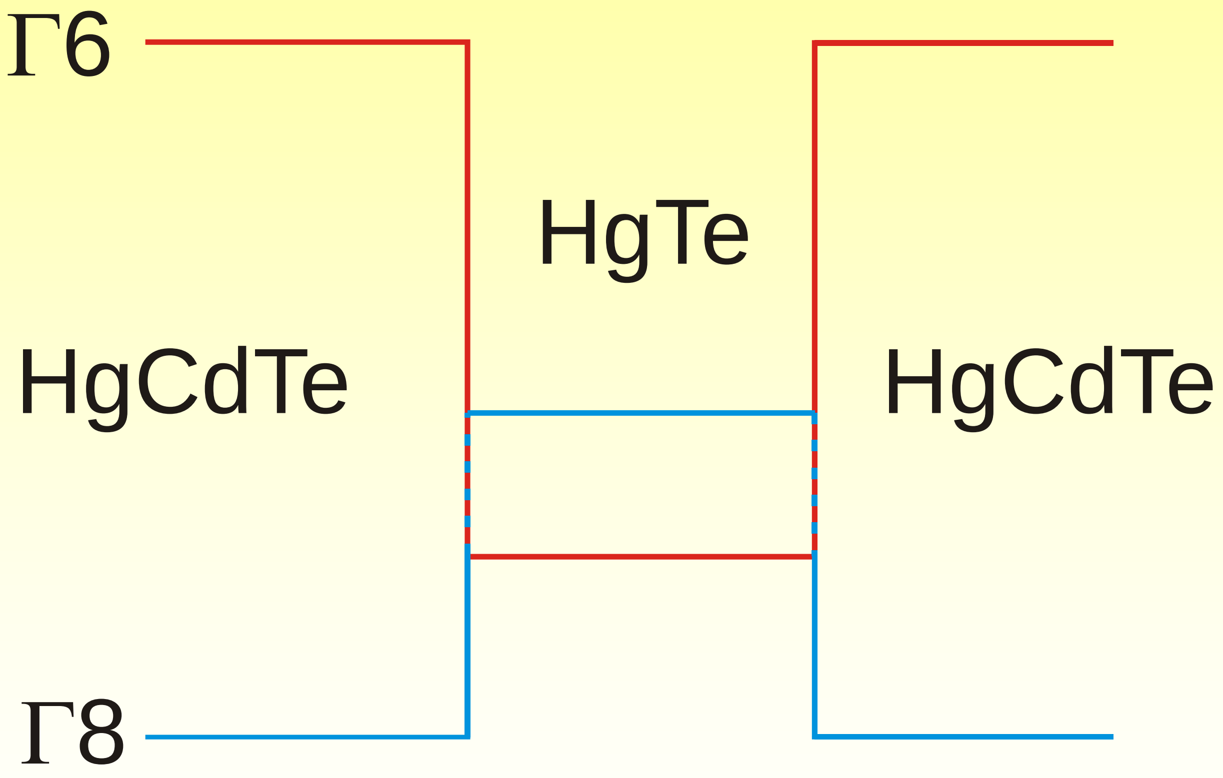


fundamental gap

D.J. Chadi et al. PRB, 3058 (1972)

$$E^{\Gamma 6} - E^{\Gamma 8} \approx -300\,\text{meV}$$

Inverted Bandstructure



Γ6

HgTe

HgCdTe

HgCdTe

Γ8

type-III QW

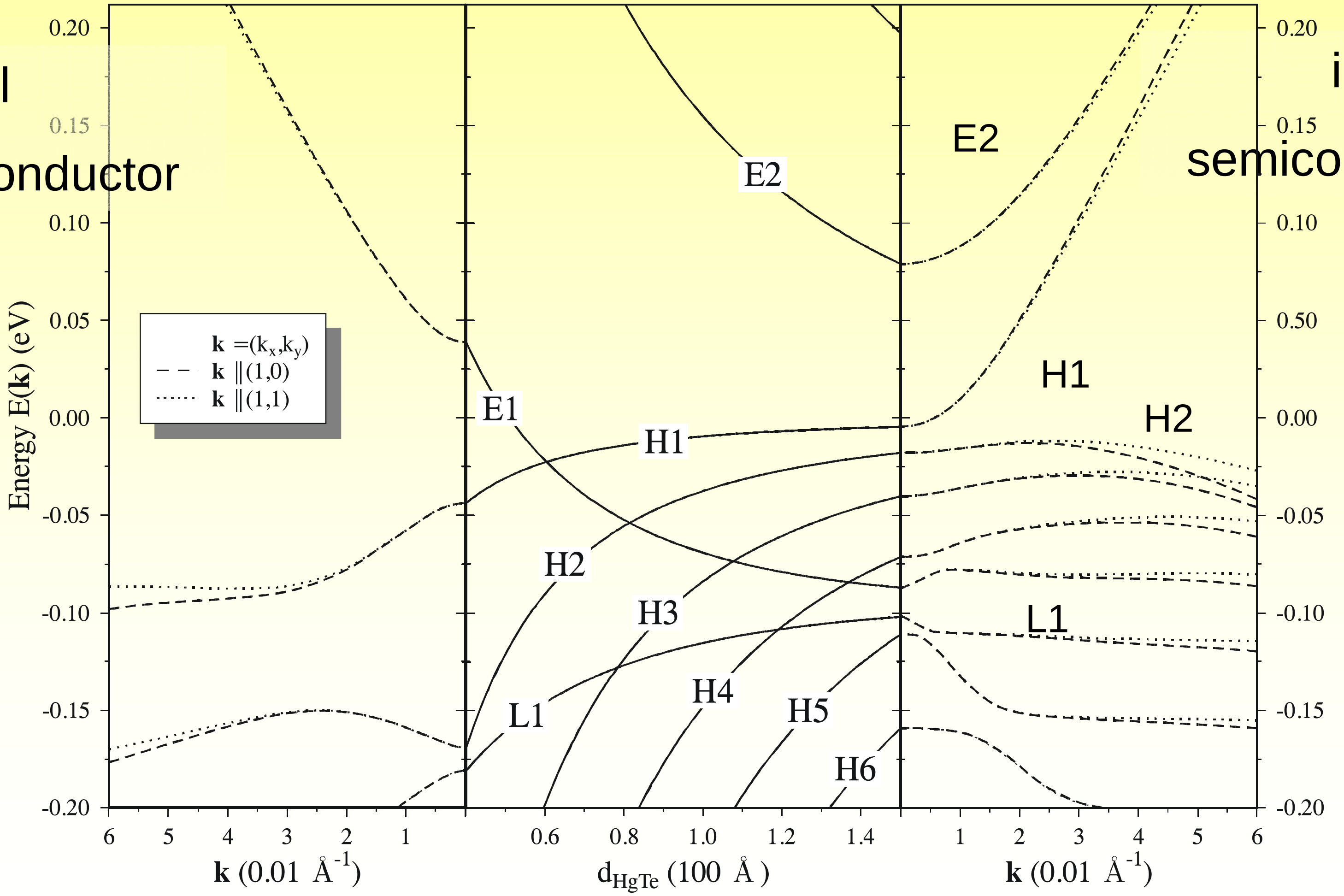
Band Structure of HgTe QWs

4 nm QW

15 nm QW

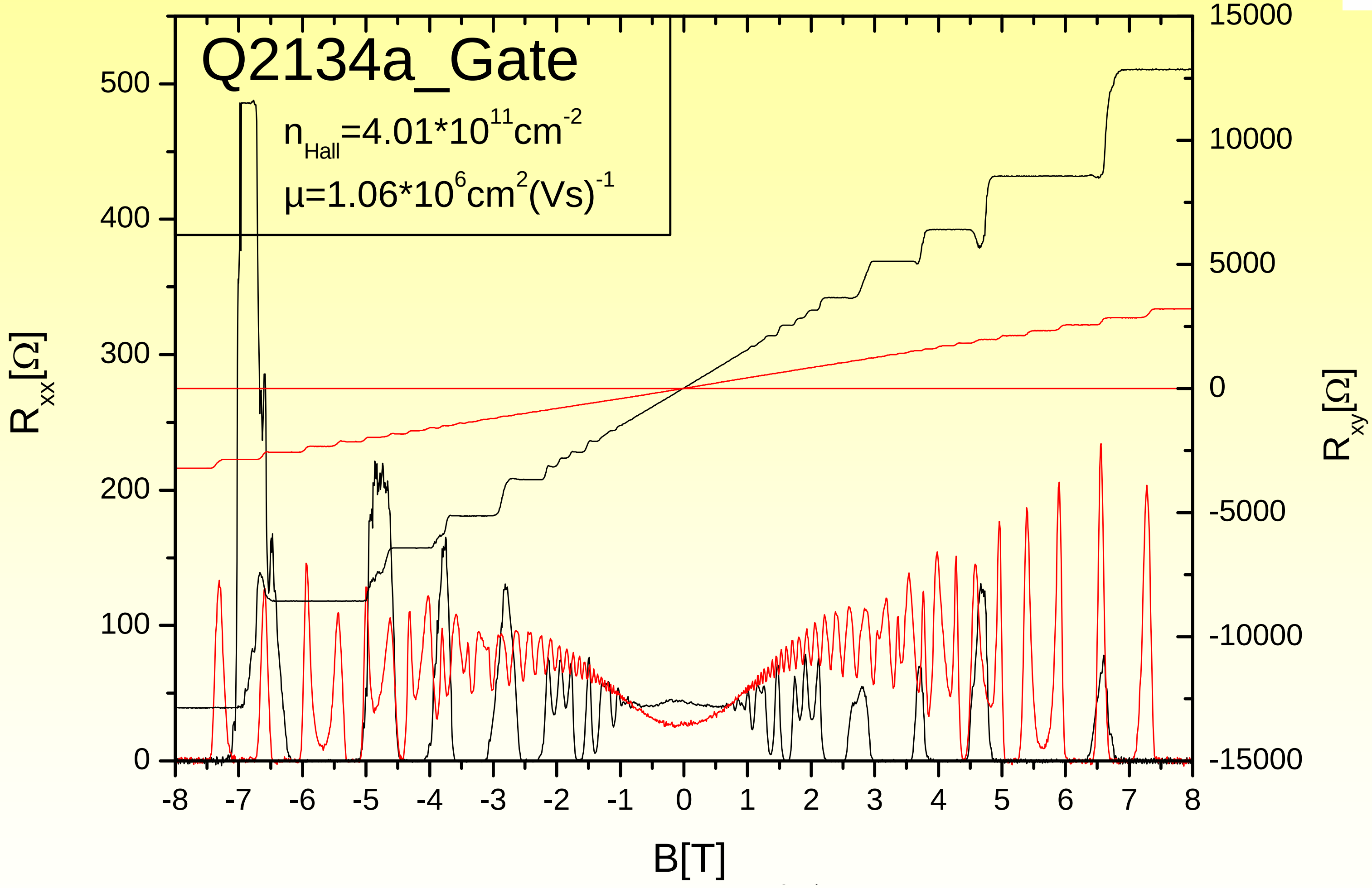
normal semiconductor

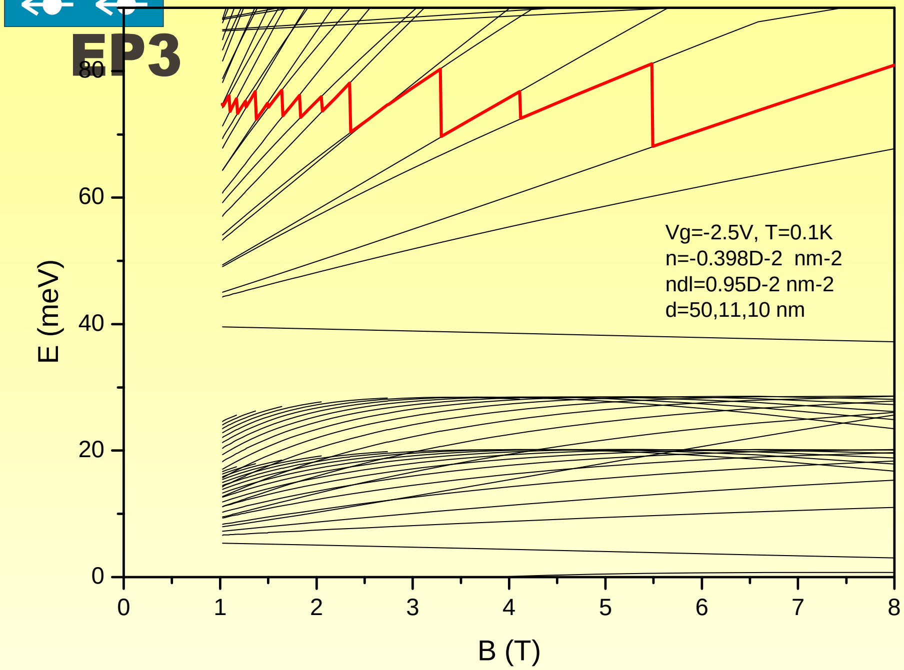
inverted semiconductor

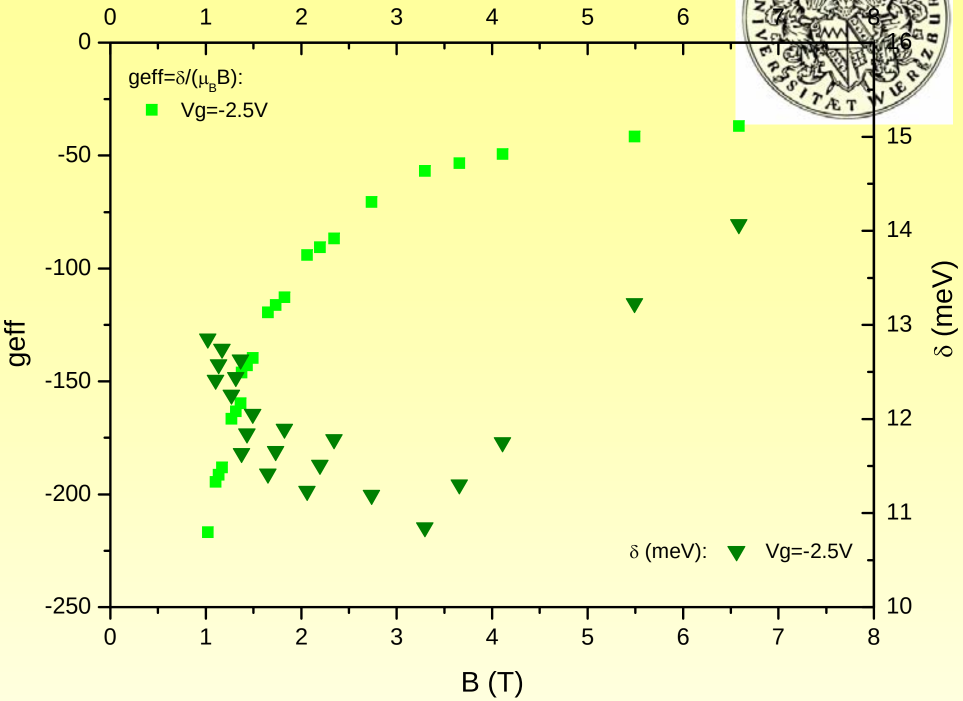


EP3

High Electron Mobility







Large spin polarisation, large Rashba - and NO (intrinsic) AHE

Inoue et al. – intrinsic AHE does not survive vertex for linear-in-k S.O.

But: Rashba in HgTe is not simply linear in k.

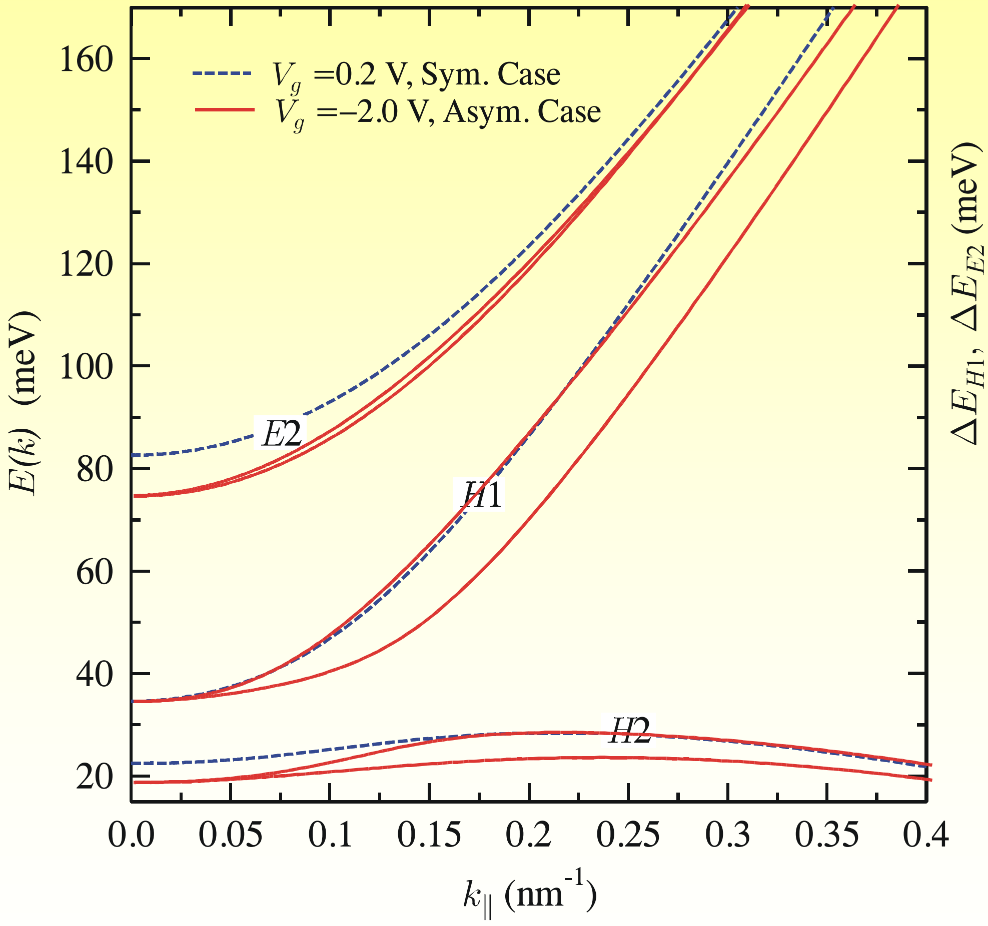
And: AHE seems also absent in HgMnTe….

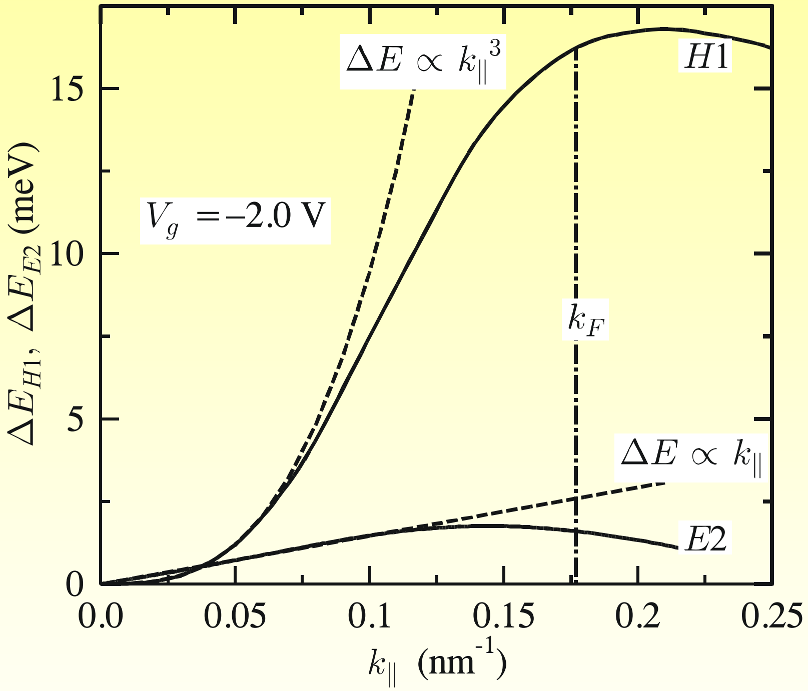
A. Novik et al., PRB 72, 035321 (2005).

Y.S. Gui et al., PRB 70, 115328 (2004).

Rashba Effect in HgTe

8 x 8 **k·p** band structure model





Rashba splitting energy

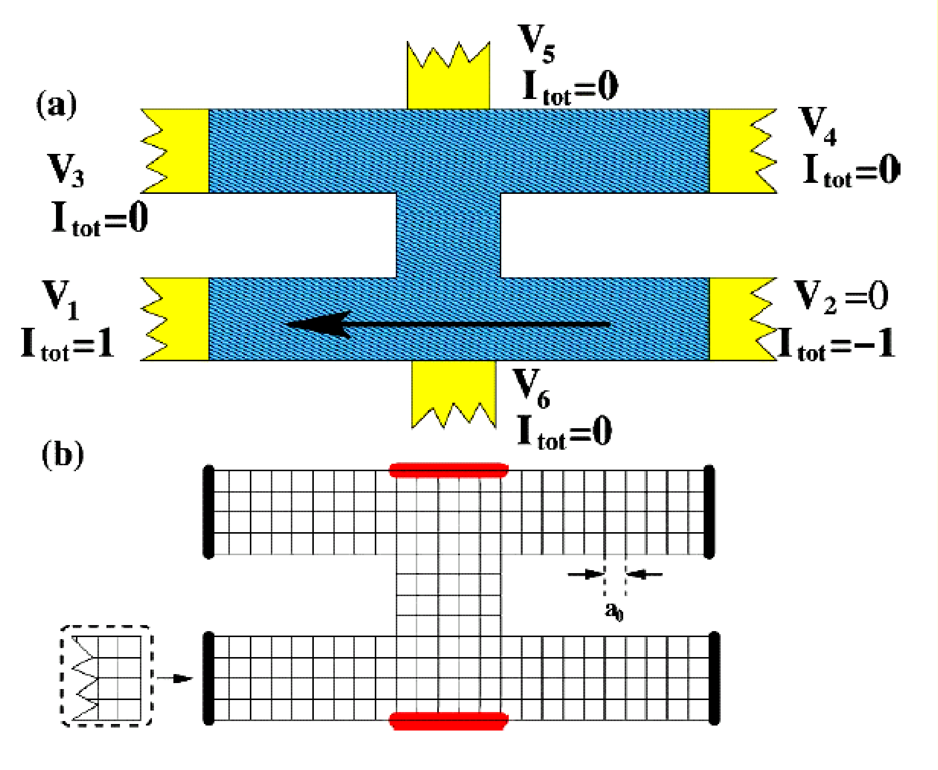
$$\Delta_{R,\max} = 30\,\text{meV}$$

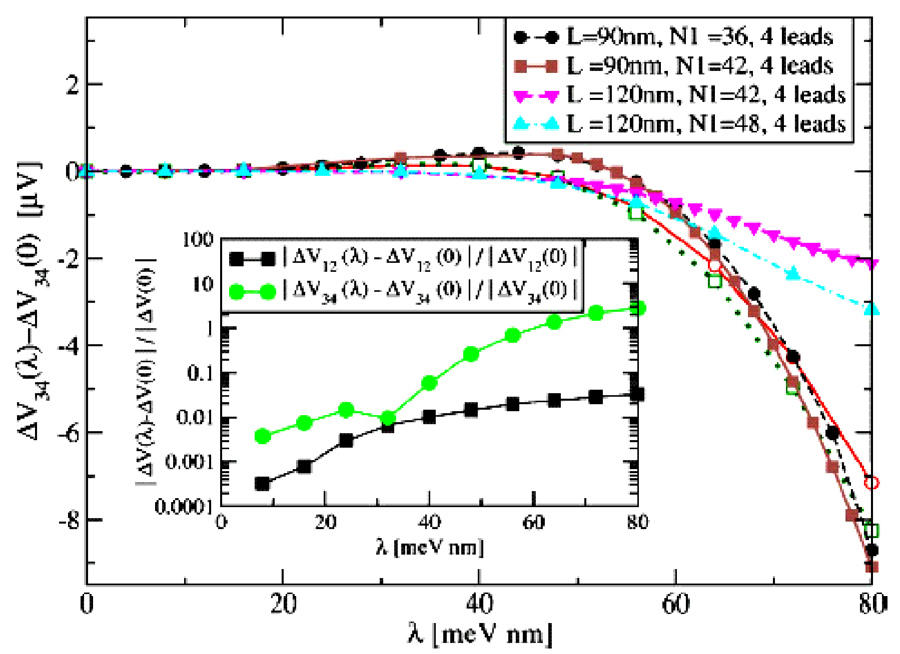
A. Novik et al., PRB 72, 035321 (2005).

Y.S. Gui et al., PRB 70, 115328 (2004).

H-bar for detection of Spin-Hall-Effect

(electrical detection through inverse SHE)





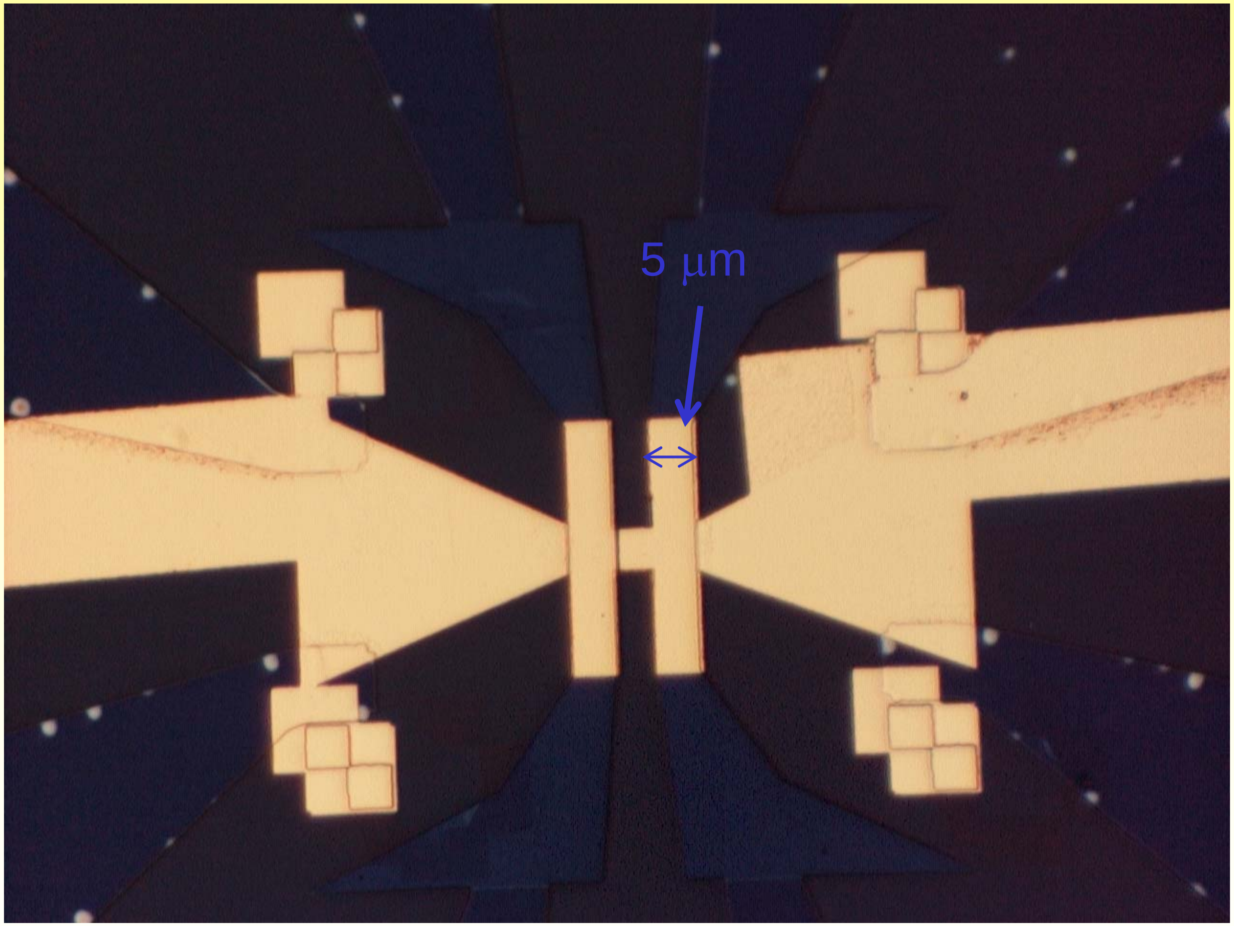
E.M. Hankiewicz et al ., PRB 70, R241301 (2004)

EP3

Actual gated H-bar sample

HgTe-QW

Δ_R = 5-15 meV



Gate-
Contact

ohmic Contacts

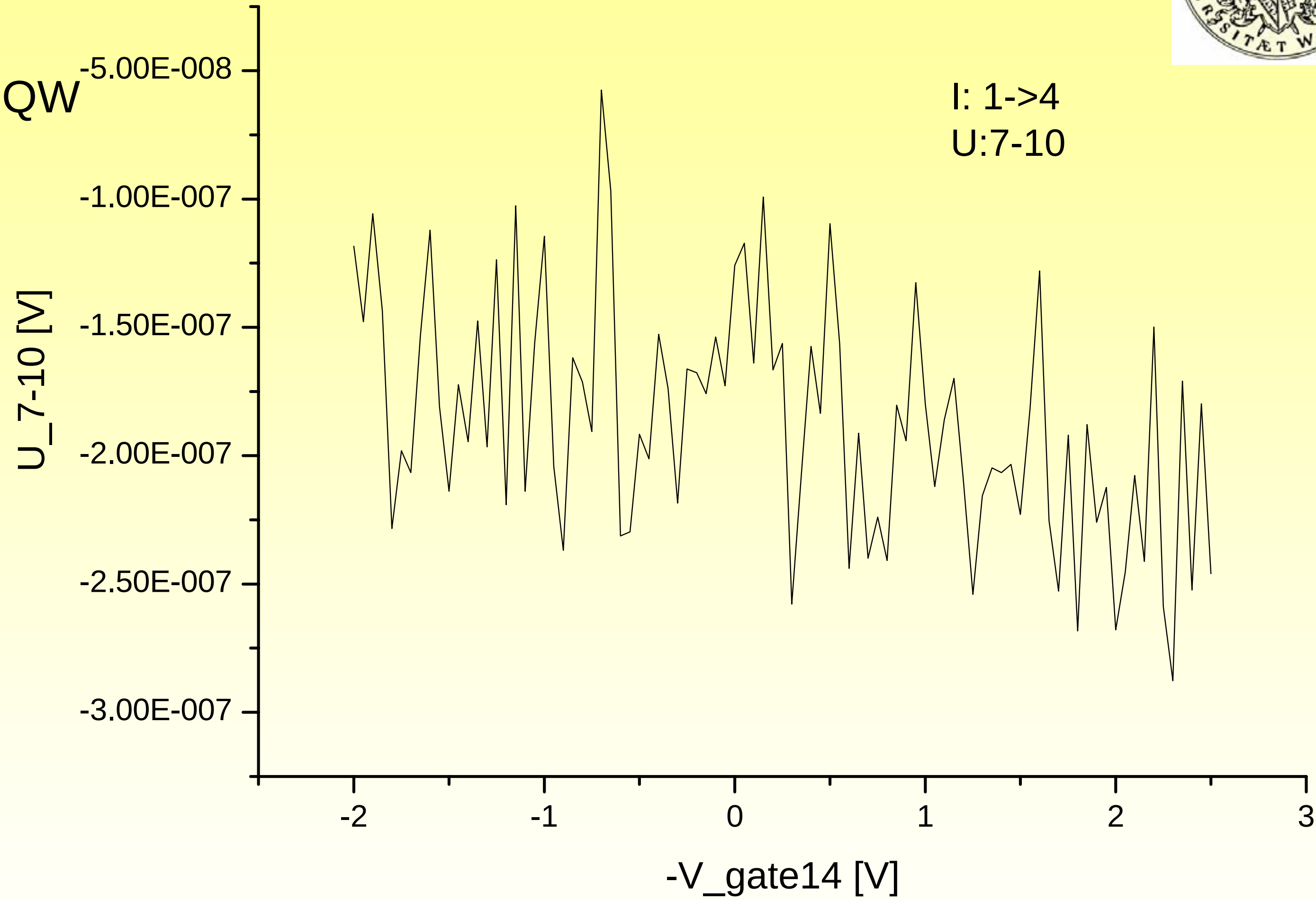
EP3

Results...

Symmetric HgTe-QW

Δ_R = 0-5 meV

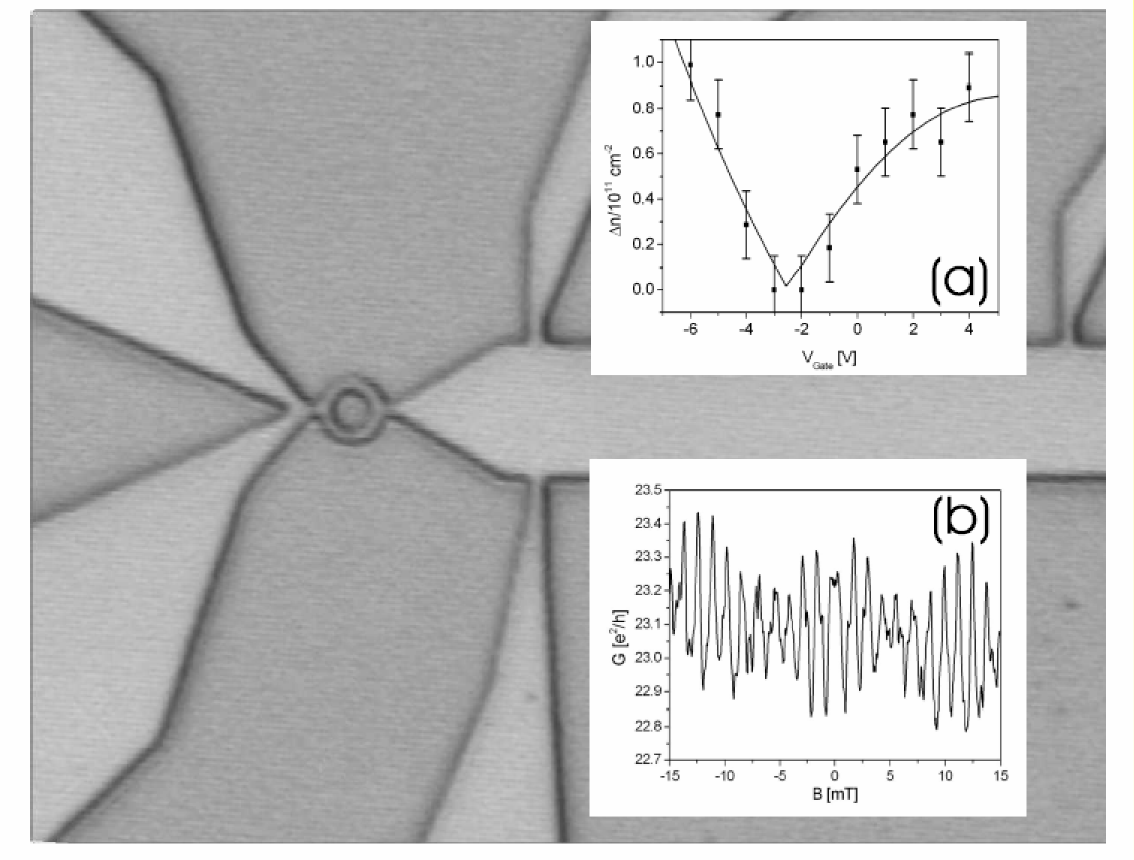
Signal less than 10^{-4}



Remember:

Rashba splitting is not simply linear in **k**

HgTe Ring-Structures



Three phase factors:

Aharonov-Bohm

Berry

Aharonov-Casher

$$\Delta\varphi_{\psi_s^+-\psi_s^-} = -2\pi\frac{\Phi}{\Phi_0} - b\pi(1-cos\theta)$$

$$\Delta\varphi_{\psi_s^+-\psi_{\bar{s}}^-} = -2\pi\frac{\Phi}{\Phi_0} - b2\pi r\frac{m^*\alpha}{\hbar^2}sin\theta$$

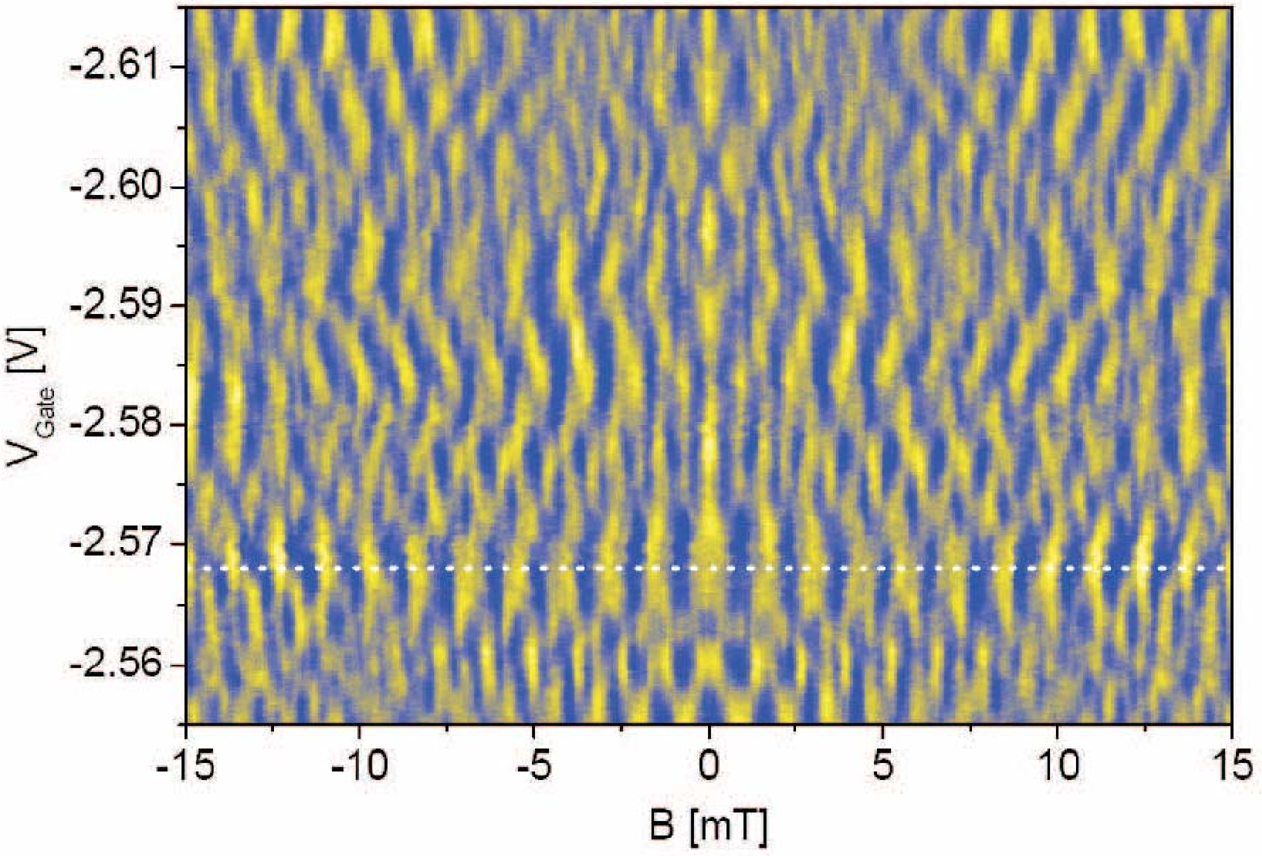
$s = \uparrow$ and $\downarrow$,

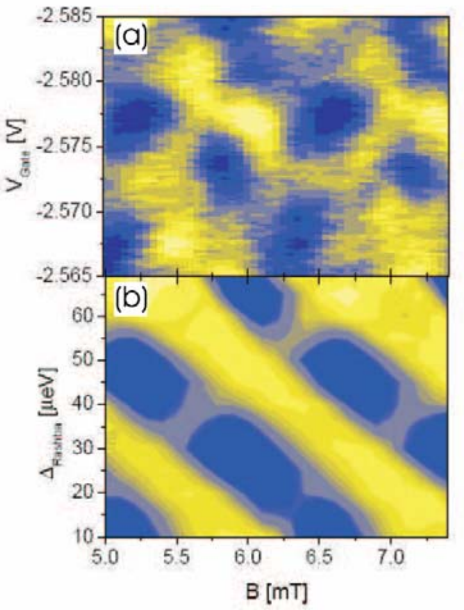
parallel and anti – parallel to B_{tot}

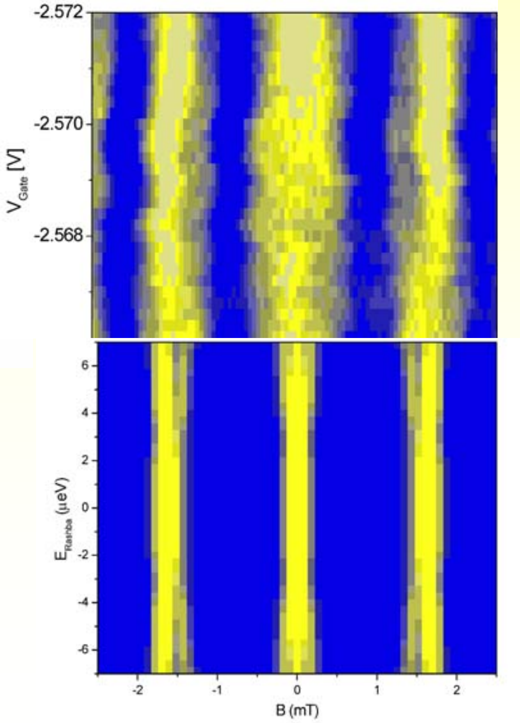
$b = \pm 1$ for $\uparrow, \downarrow$

$\theta \prec B_{ext}, B_{tot}$; $\quad B_{tot} = B_{ext} + B_{eff}$

HgTe Ring-Structures







Modeling E. Hankiewicz, J. Sinova,

Concentric Tight Binding Model (a la Nikolic)+ B-field

M. König et al., Phys. Rev.Lett. **96**, 76804 (2006).

Main questions

- SAD RTDs show finite spin splitting at zero B. Why?
- TAMR in GaMnAs: Why extra anisotropy along [001]?
- Details of MI transition in GaMnAs. Do we see the Efros-Shklovskii gap?
- Why don’t we see intrinsic SHE or AHE
- Discuss possible experiments on (quantum,insulator) SHE and AHE