Spintronics
A half-time assessment

C. Gould

University of Würzburg EP3, Germany

Spintronics

-Spin injection.	Solved!
-Spin detection.	Solved!
-Memory devices.	Solved!

The original challenges of Spintronics have been solved. This is NOT a reason for the field to rest on if laurels, but rather an opportunity (and necessity) to define new goals.

The Spintronics future.

Information storage is the past and the present...

The future is information manipulation (processing and communication) as well as energy management.

Key ideas include:

-The “memristor dream“: Hybrid memory/processing device to eliminate the interconnect issue.

-GMR/TMR based antennas (STO) for efficient communication.

-Heat management (Spin-Caloritronics)

-Spin-topotronics (with potential in processing with reduced dissipation.)

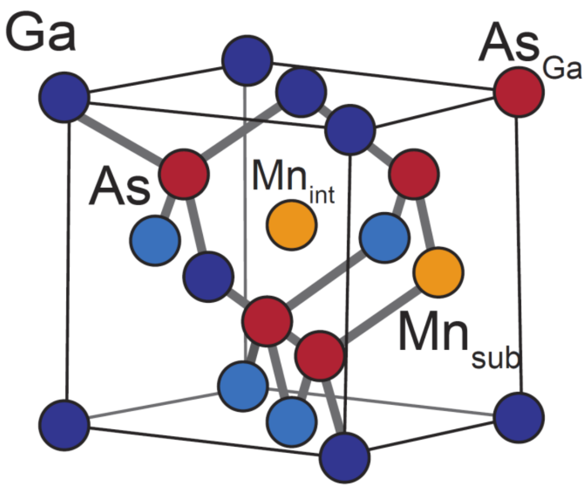
I will now show one example of each from our own research.

A memristor like idea: Electrically programmable logic device using a ferromagnetic semiconductor

S. Mark, P. Dürrenfeld, K. Pappert, L. Ebel, K. Brunner, C. Gould, L.W. Molenkamp

University of Würzburg EP3, Germany

Ferromagnetic Semiconductor

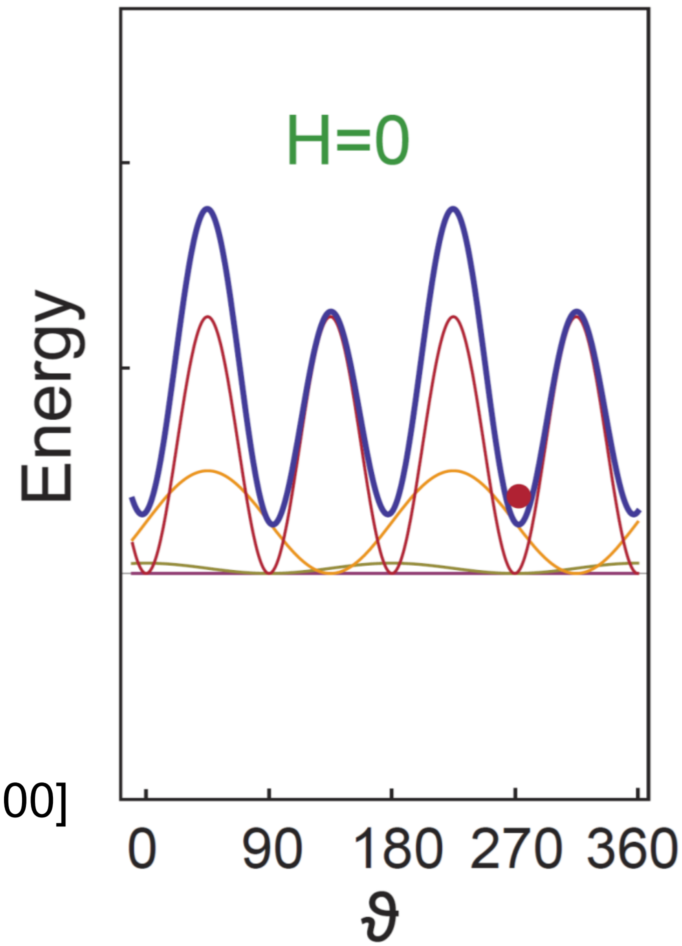


(Ga,Mn)As:

hole mediated FM,

~ 4% Mn,

T_C ~ 70 K as grown

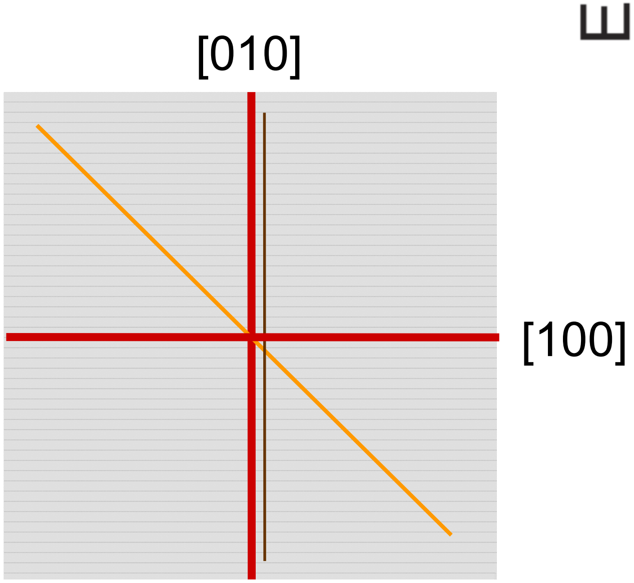


Anisotropies

100 Biaxial: [100], [010]

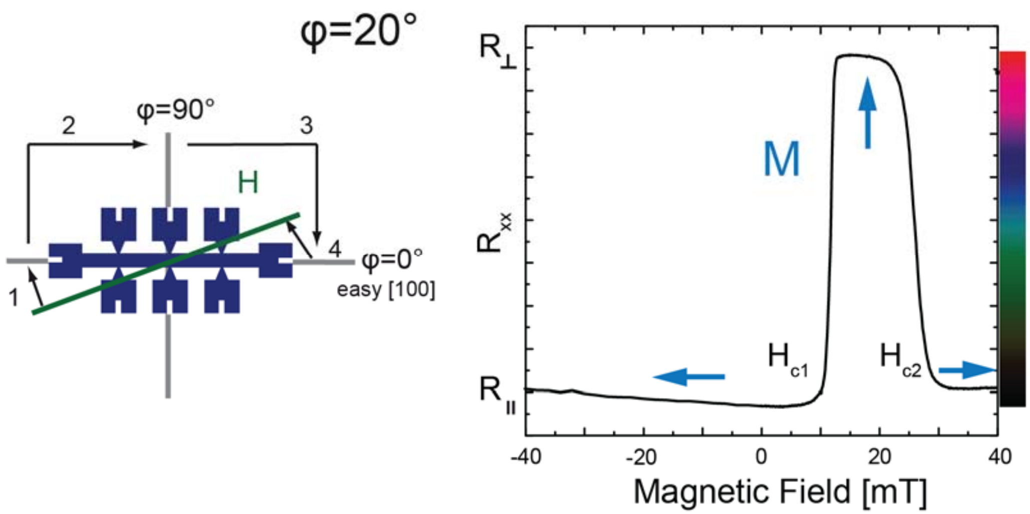
10 Uniaxial: [110]

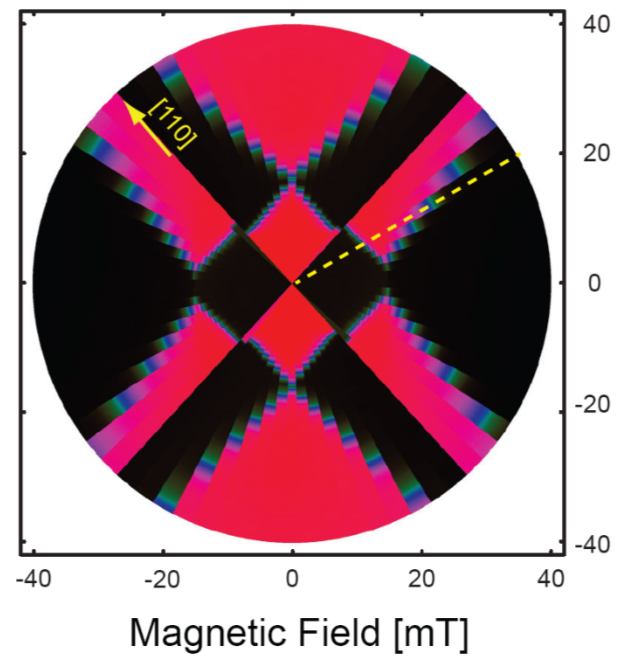
1 Uniaxial: [010]

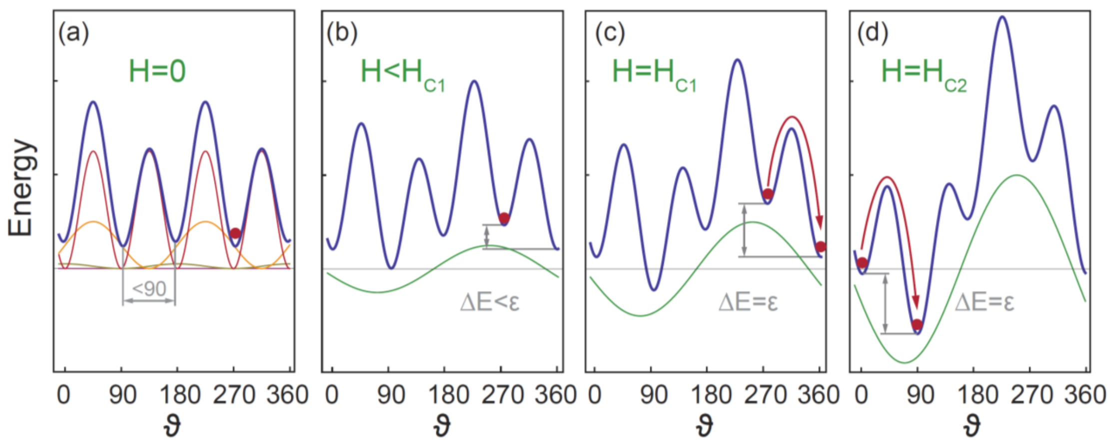


Transport Properties

$$R_{AMR} = const \bullet Cos^2(\vartheta)$$

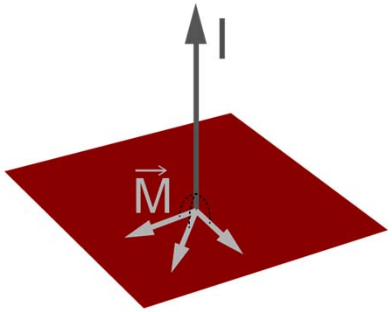


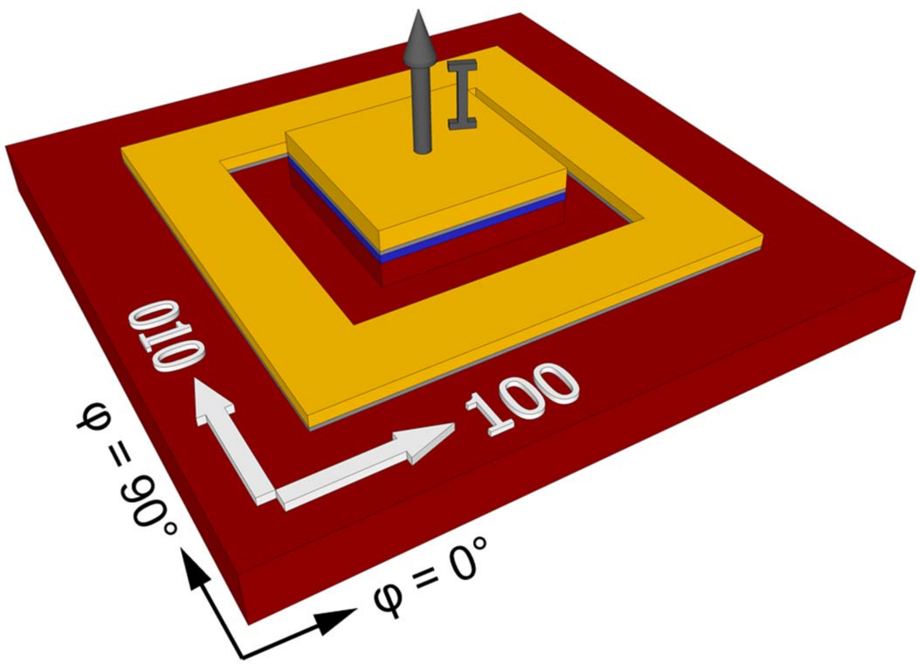


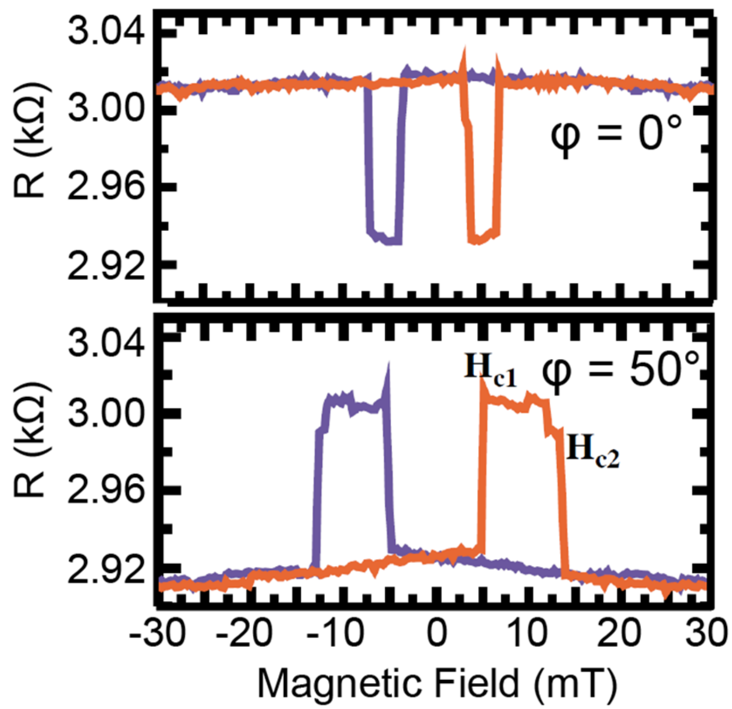


Tunneling Anisotropic Magnetoresistance (TAMR)

$$I \propto \int_{-\infty}^{\infty} DOS_{(Ga,Mn)As}(E) \cdot T(E) \cdot DOS_{Au}(E') \cdot (f_{SC}(E) - f_M(E'))dE$$

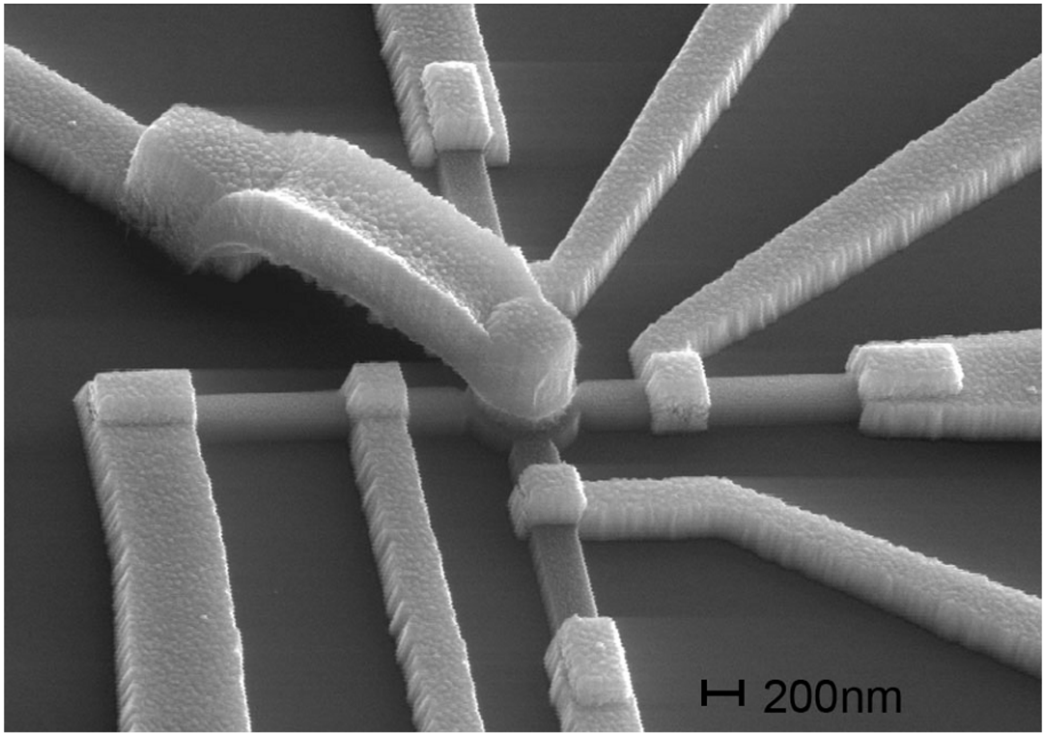


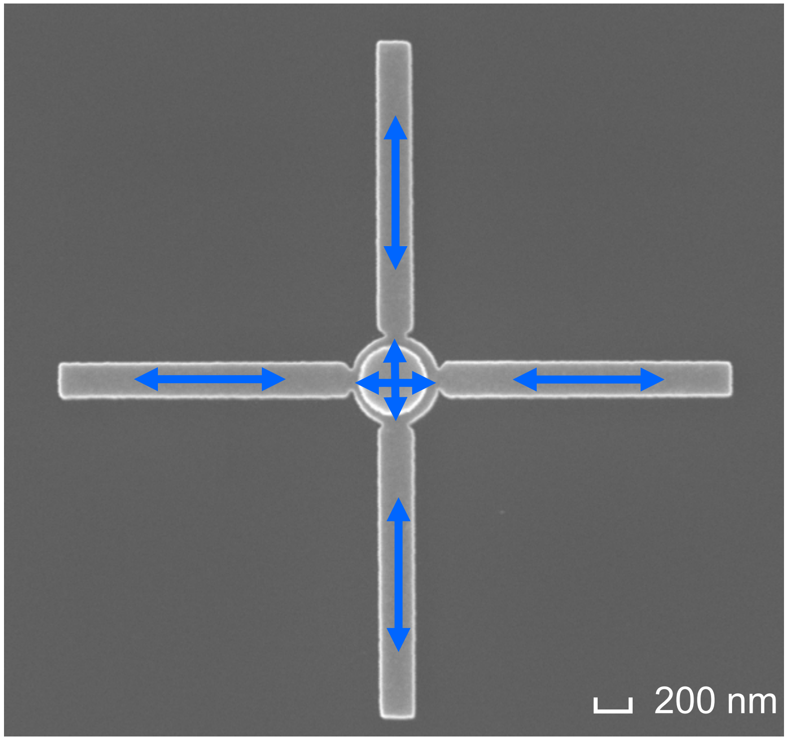




Gould et. al. PRL (2004)

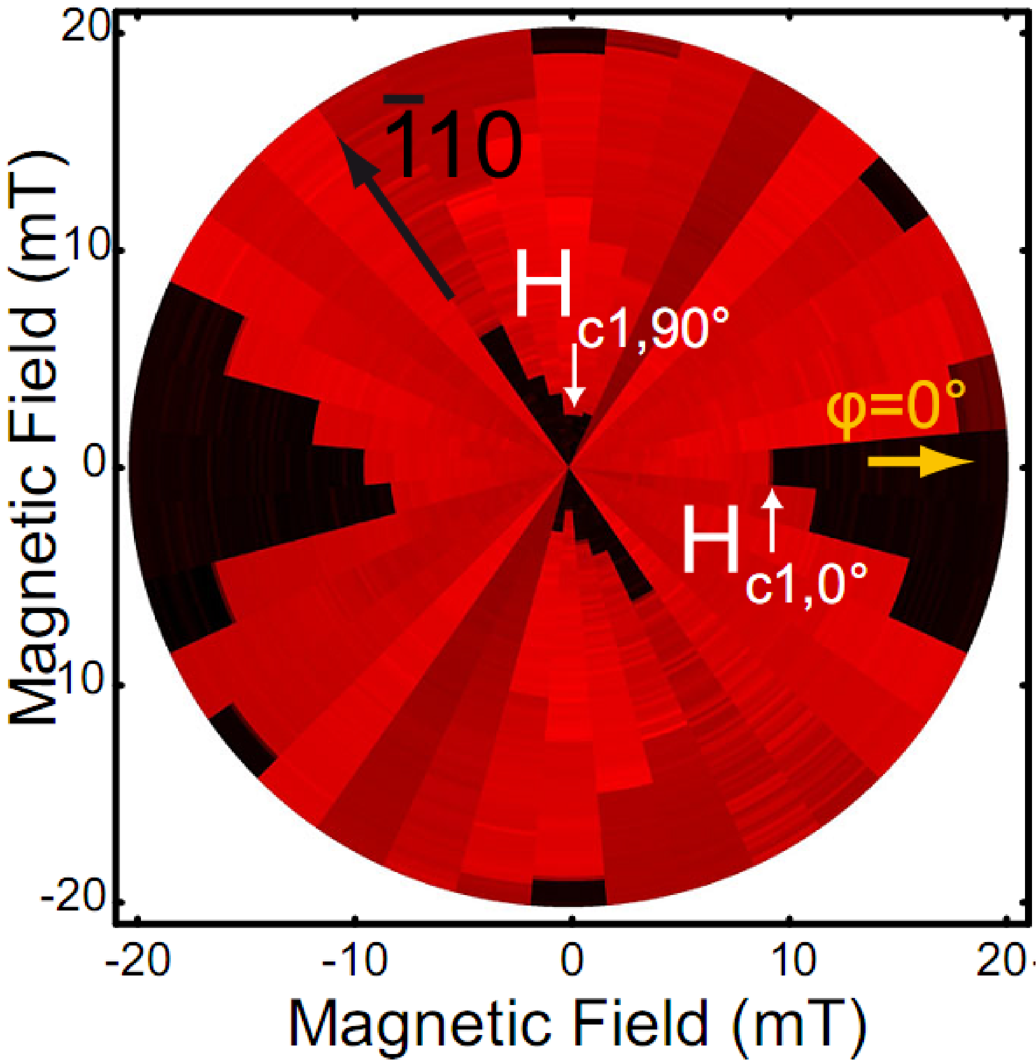
Read-Write-Device



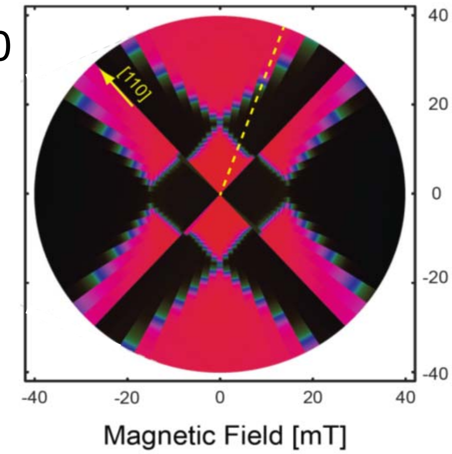


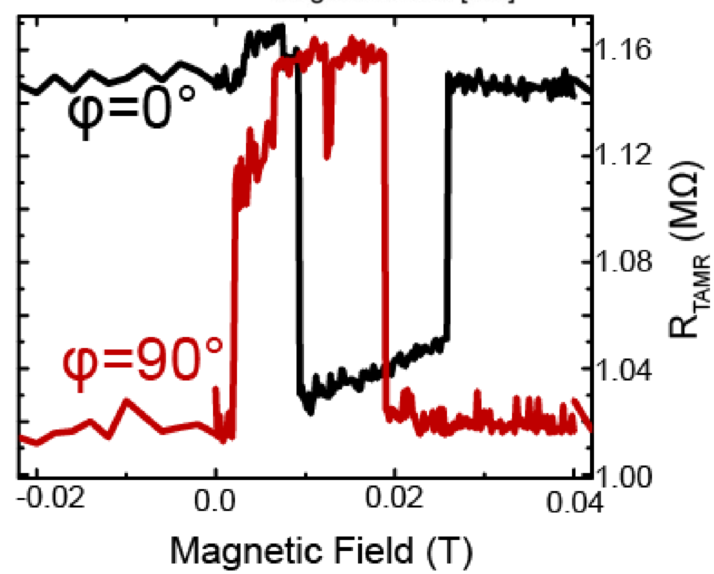
S. Mark et. al., PRL 106, 057204 (2011)

Central Disk



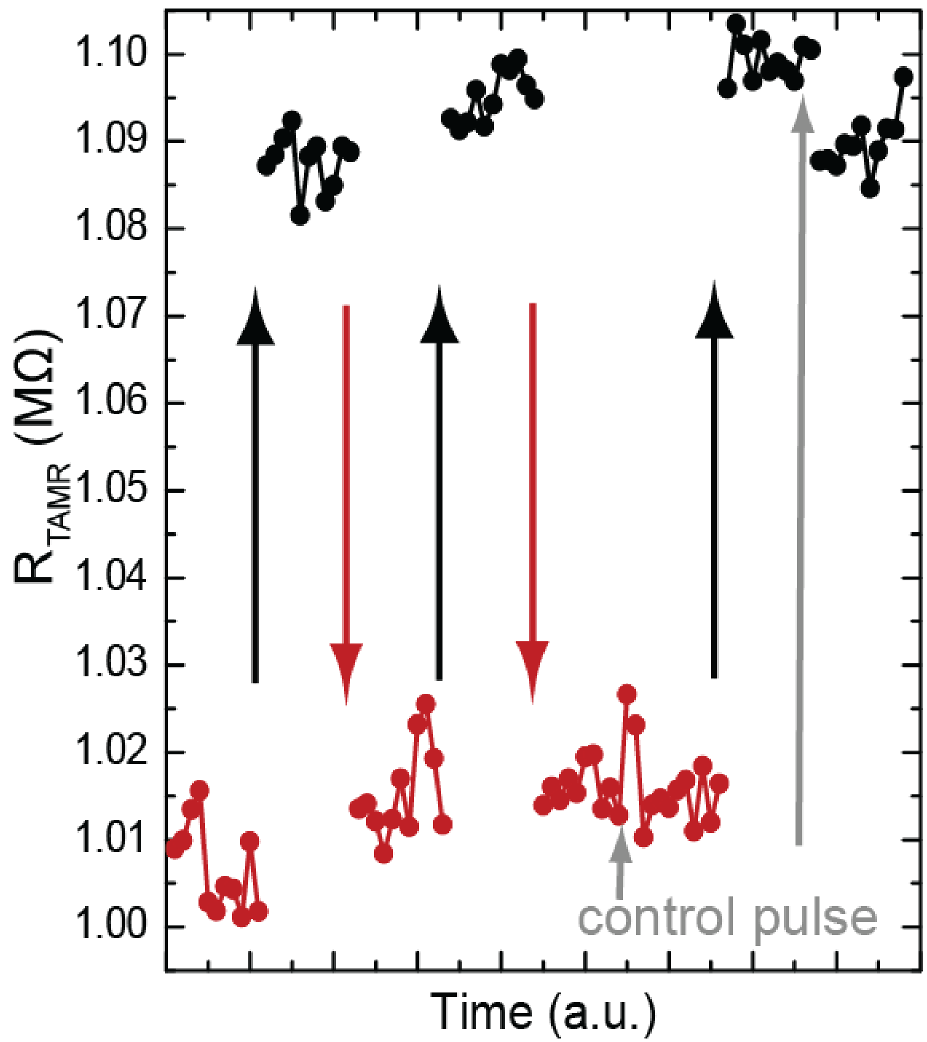
60 Biaxial 100
40 Uniaxial 10
5 Uniaxial 1

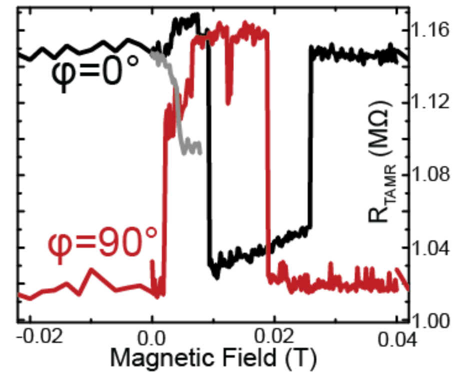


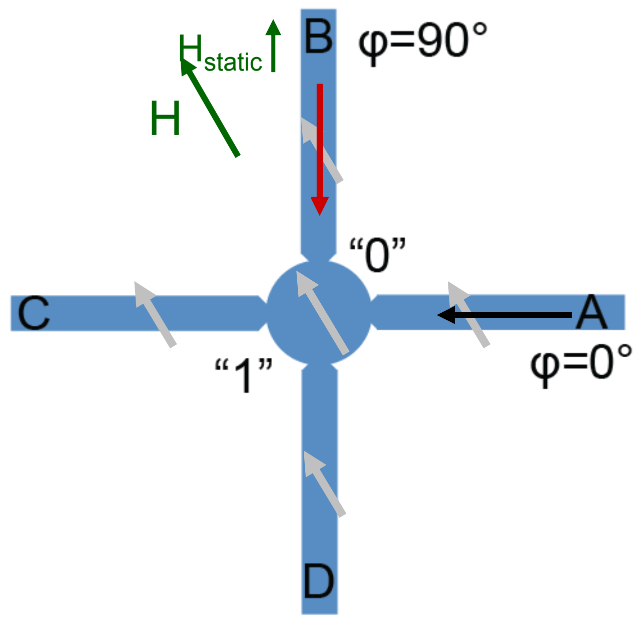


S. Mark et. al., PRL 106, 057204 (2011)

Read-Write-Device

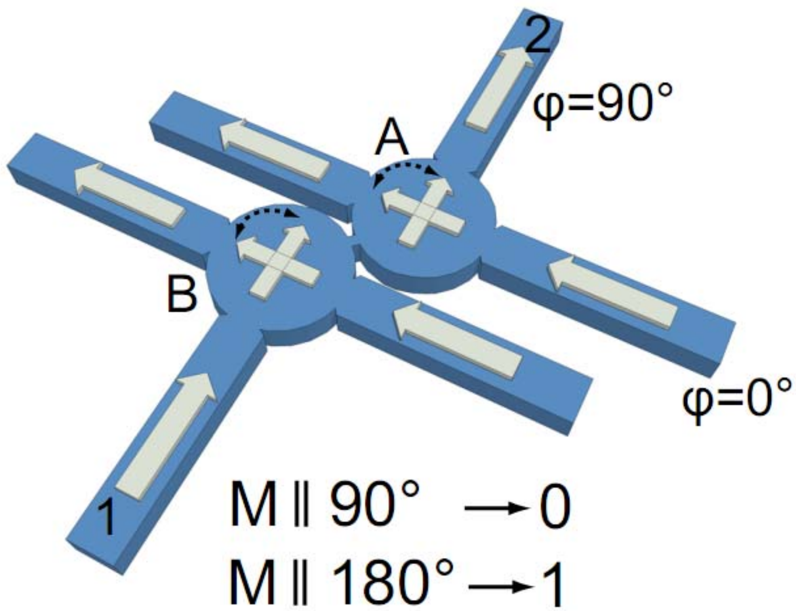


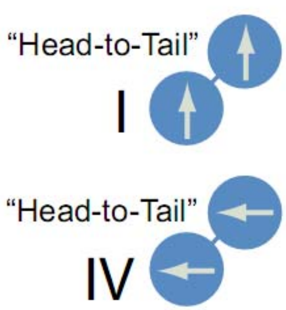




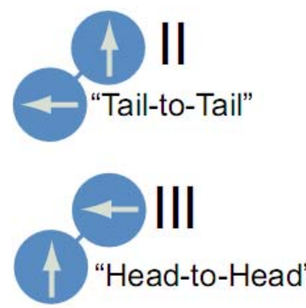
S. Mark et. al., PRL 106, 057204 (2011)

Logic Device



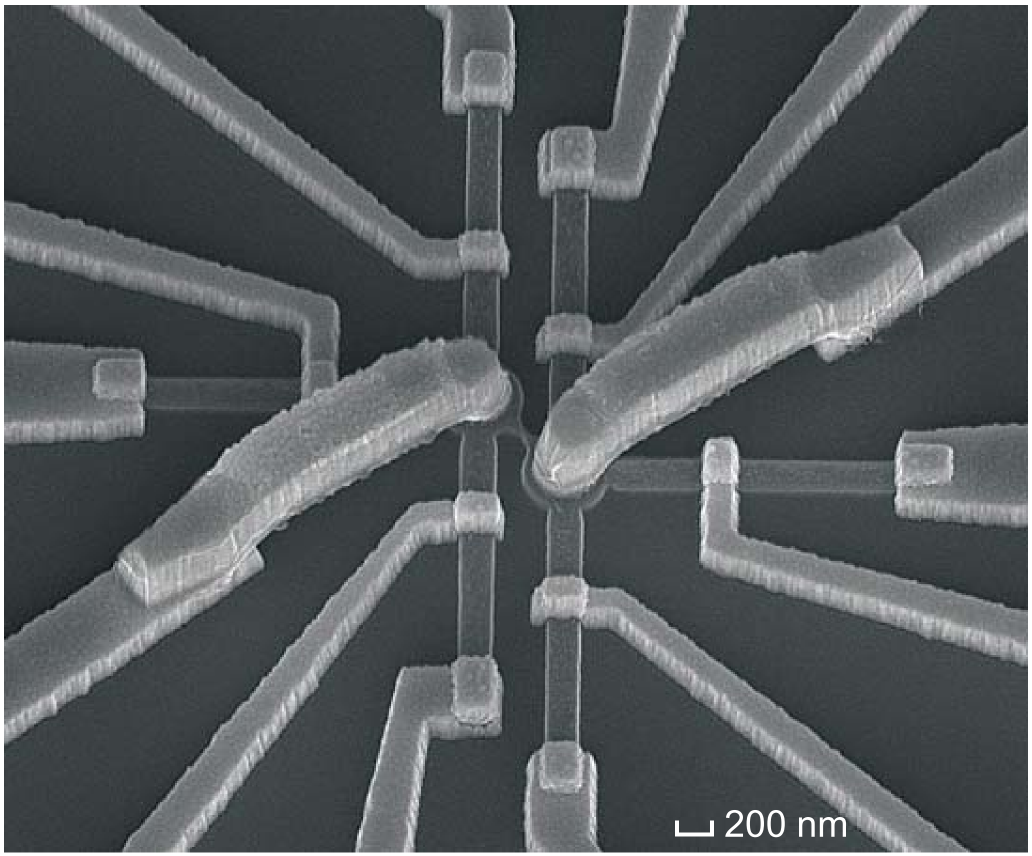


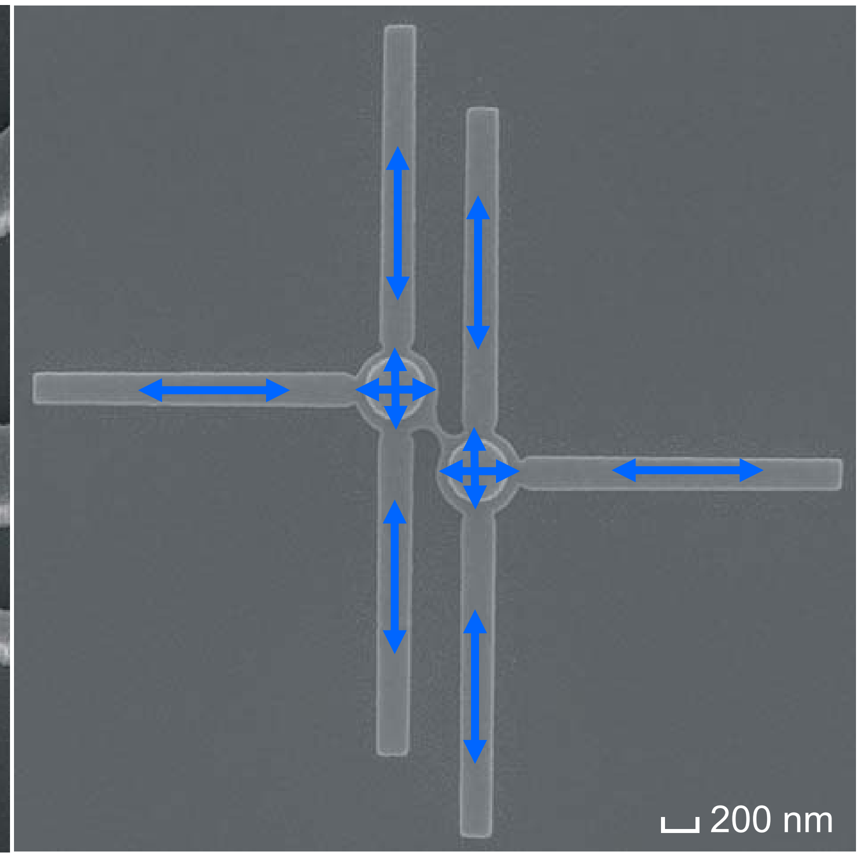
	A	B	A·B
I	0	0	0
II	0	1	1
III	1	0	1
IV	1	1	0



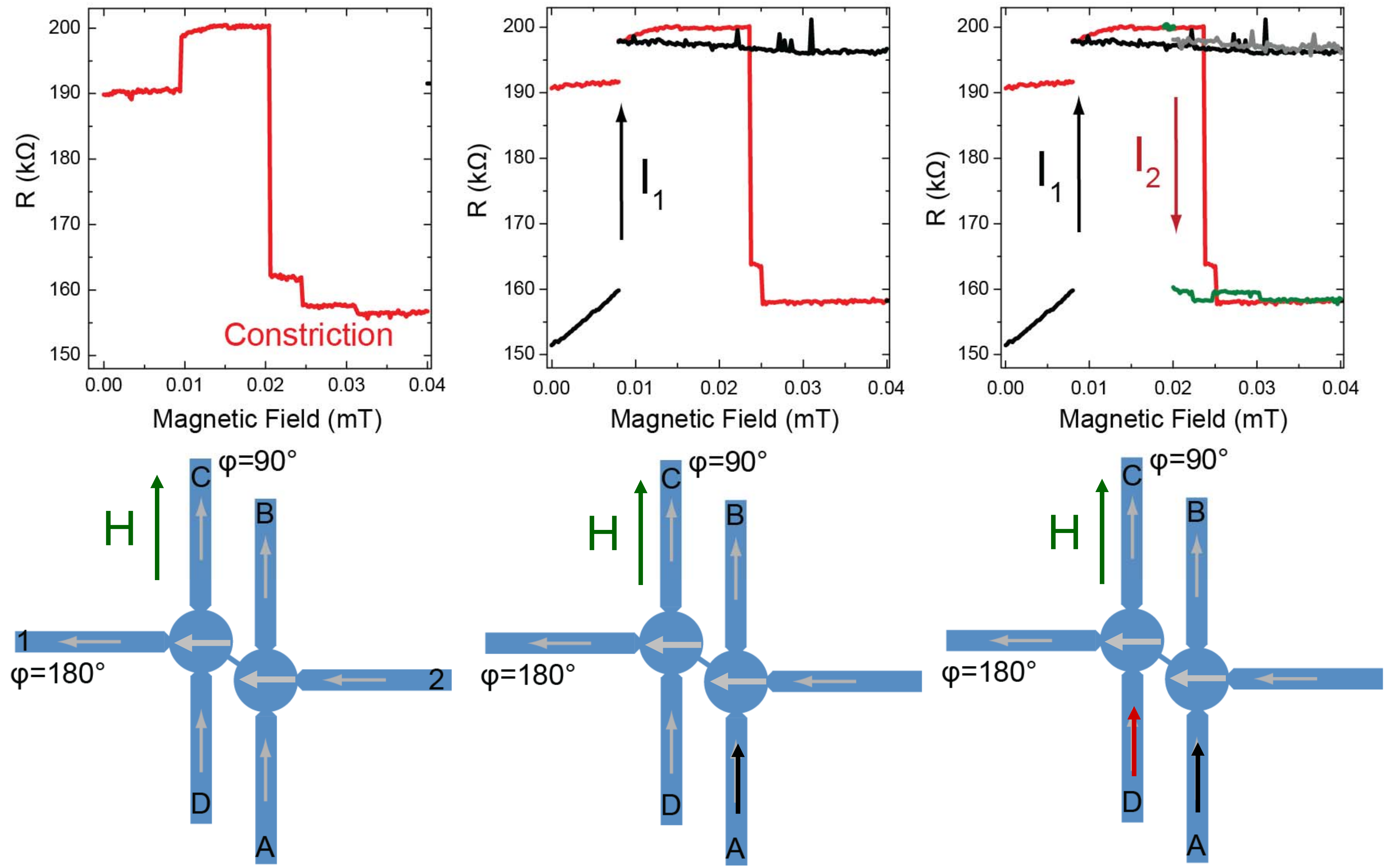
S. Mark et. al., PRL 106, 057204 (2011)

Logic Device

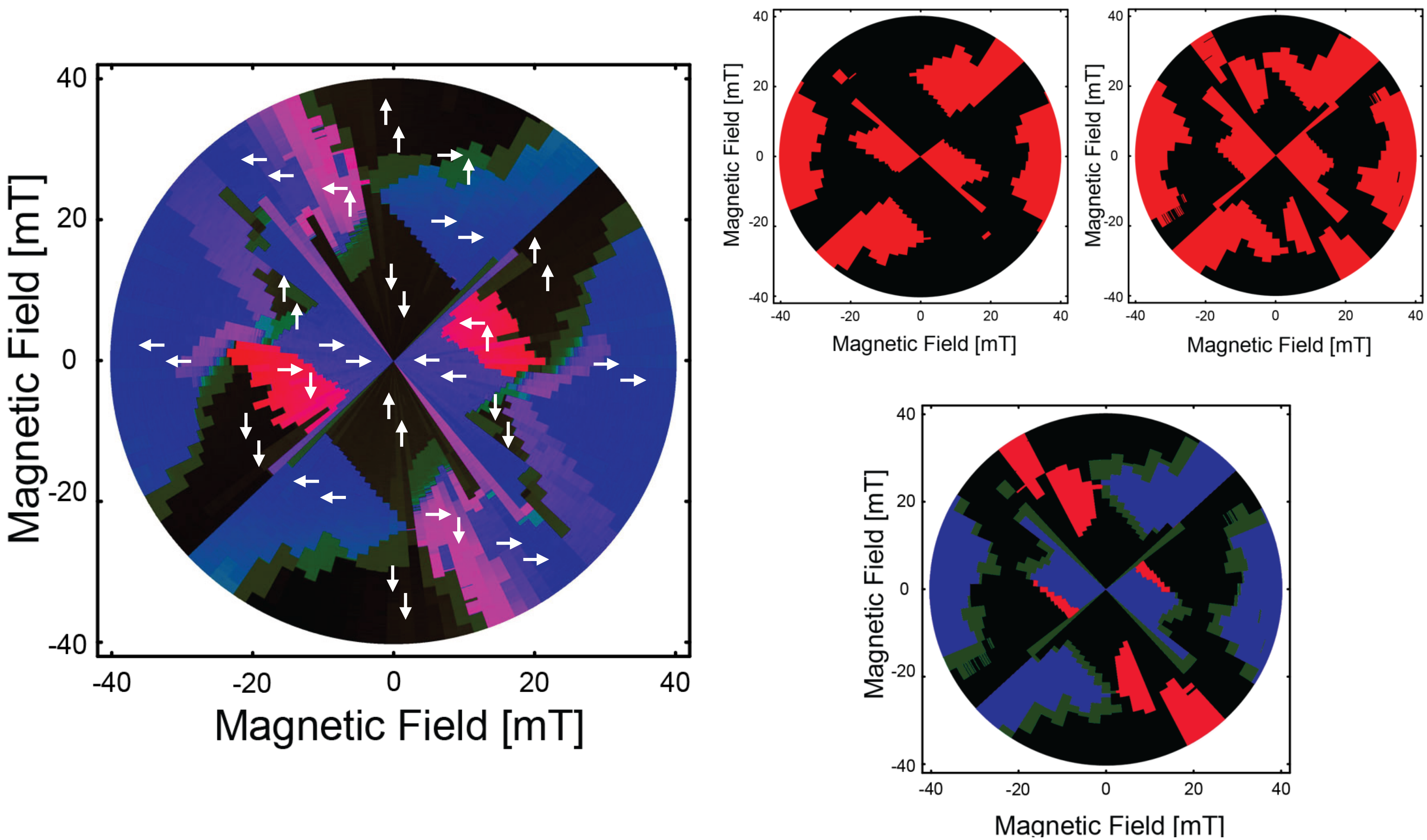




Logic Device



Logic Device



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EP3

A high Q-factor GHz emitter

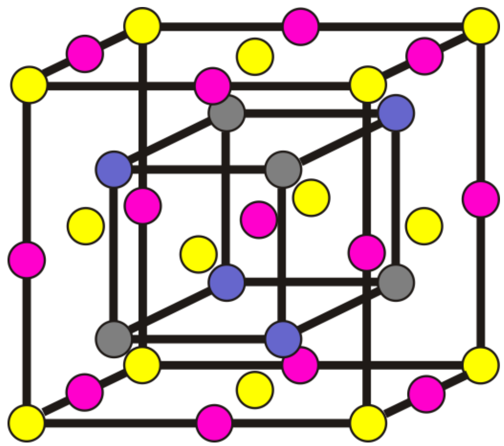
A. Riegler, F. Lochner, C. Gould, L.W. Molenkamp

University of Würzburg EP3, Germany

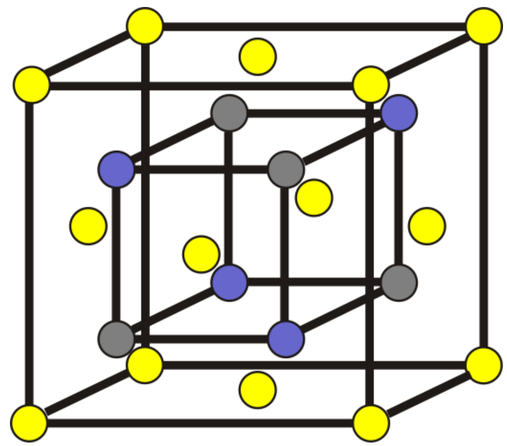
MACALO
FP7 ICT – Nanoelectronics

Crystal structure NiMnSb

F. Heusler. Verh. Deutsche Physikalische Gesellschaft **5,** (1903), S. 219ff
M.J. Otto et. al. , J. Phys. : Condens. Matter **1**, (19889 2341-2350



$L2_1$ **structure** Ni_2MnSb



$C1_b$ **structure NiMnSb**

		$L2_1$	$C1_b$
● (yellow)	A (0, 0, 0)	Ni	Ni
● (grey)	B ($^1/_4$, $^1/_4$, $^1/_4$)	Mn	Mn
● (magenta)	C ($^1/_2$, $^1/_2$, $^1/_2$)	Ni	--
● (light blue)	D ($^3/_4$, $^3/_4$, $^3/_4$)	Sb	Sb

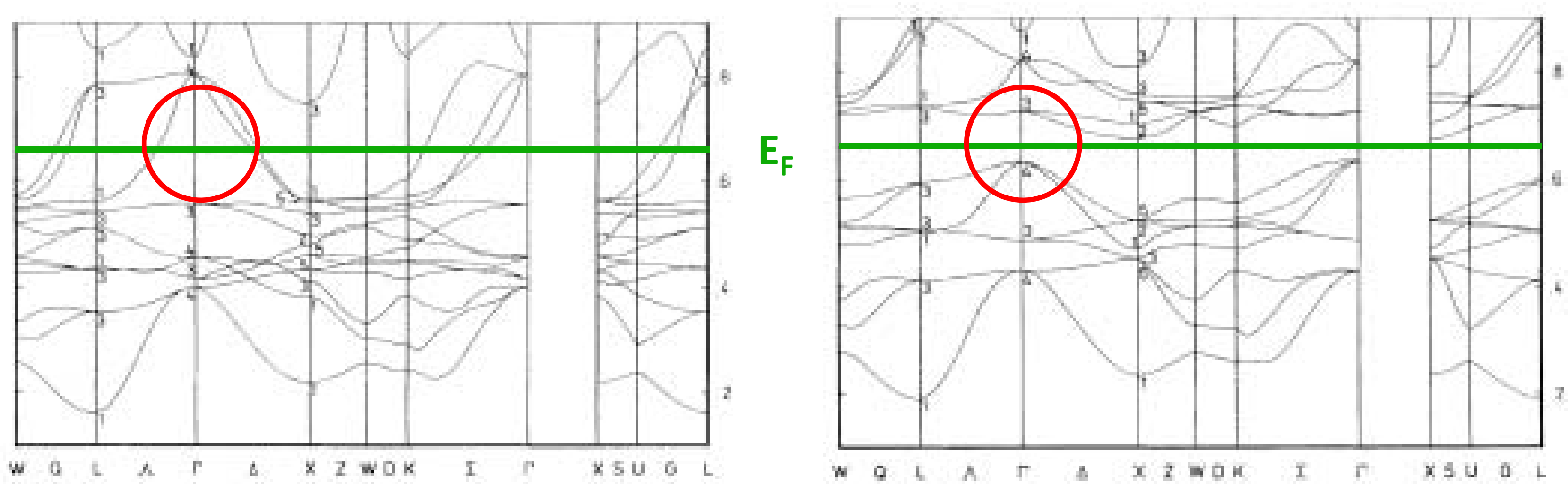
Band structure NiMnSb

*R.A. de Groot et. al., Phys. Rev. Lett. **50**, Number 25 (1983)*

as a consequence of the empty C site, the point symmetrie of the Mn sites changes from O_h ($L2_1$) to T_d ($C1_b$)

Majority-spin direction

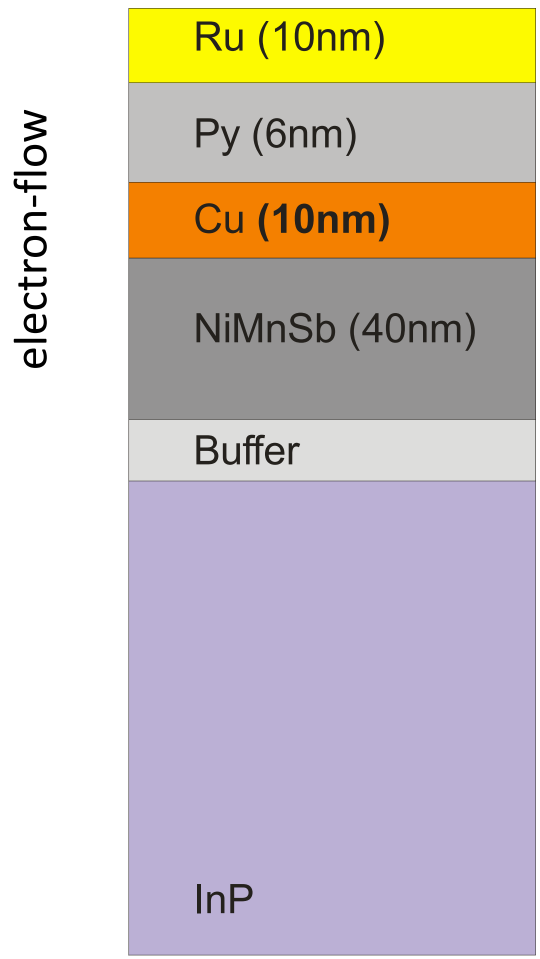
Minority-spin direction

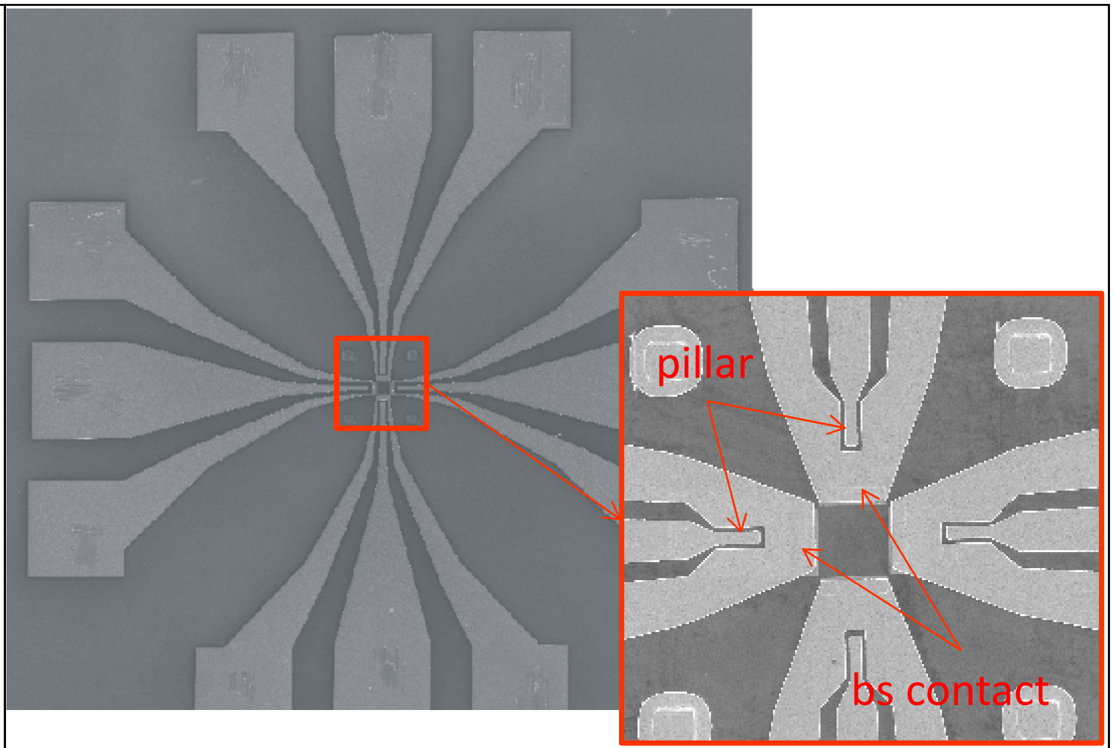


Both band structures in the **SAME MATERIAL** at the **SAME TIME** !!

- ⇨ Theoretical 100% spin-polarization
- ⇨ Half metallic ferromagnet

Spin-Torque devices

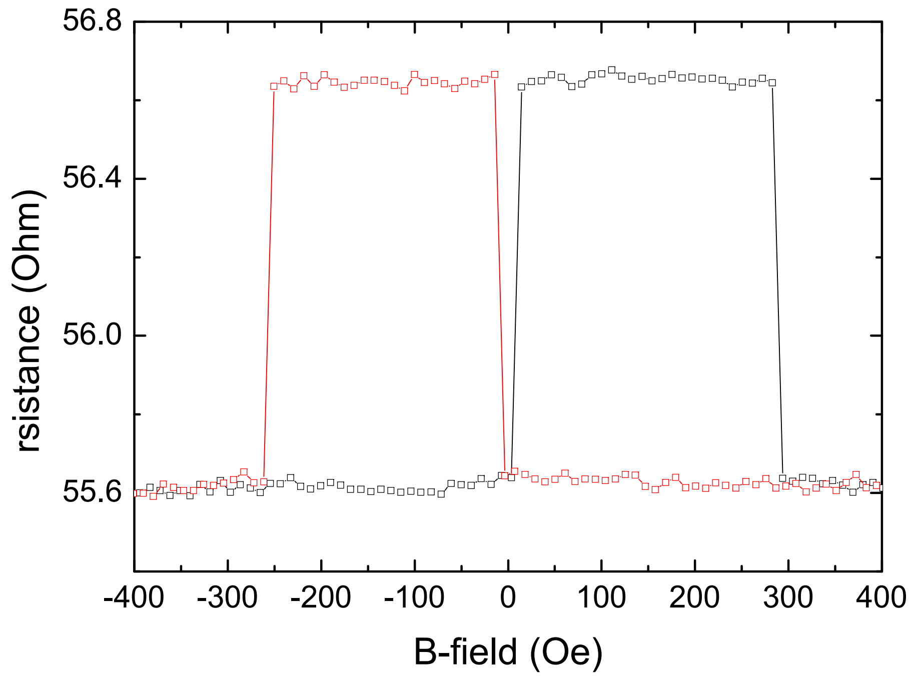


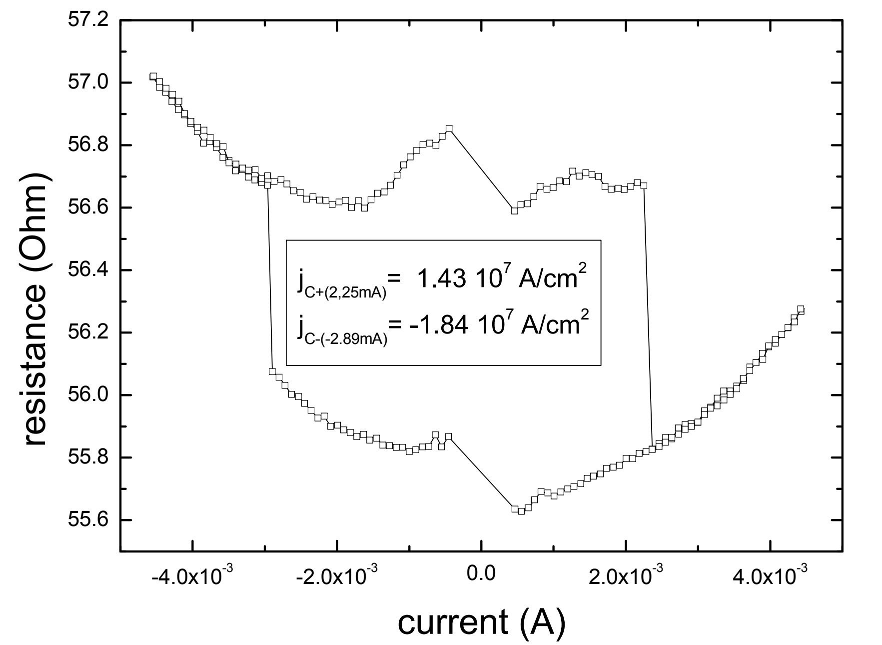


- pads in CPW geometry
- 2-point geometry

Spin-Torque devices

100nm x 200nm pillar – field along the long side



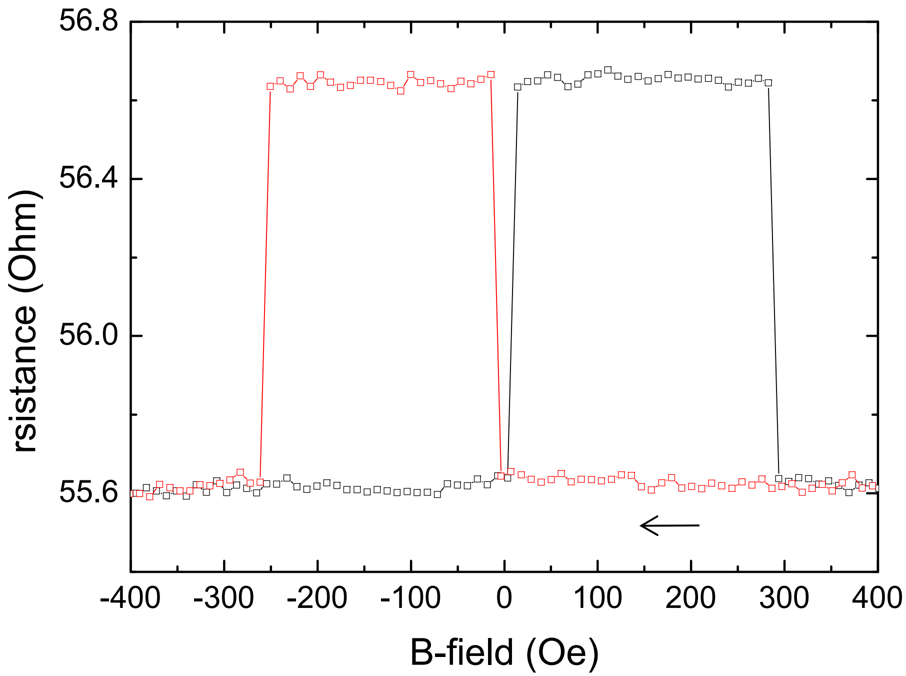


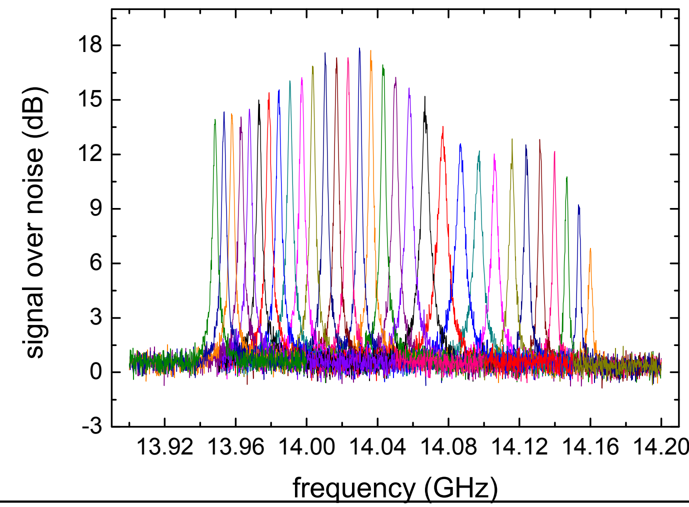
- GMR ratio of 1.7%
  (due to 2-point)

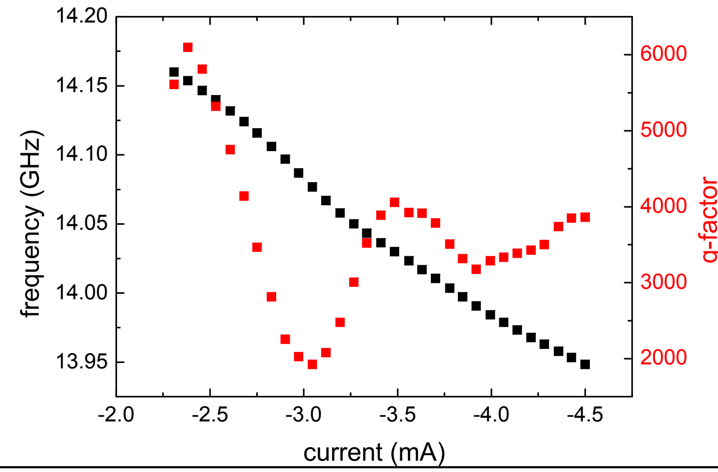
- symmetrical switching
- low current densities

Spin-Torque devices

100nm x 200nm pillar – field along the long side



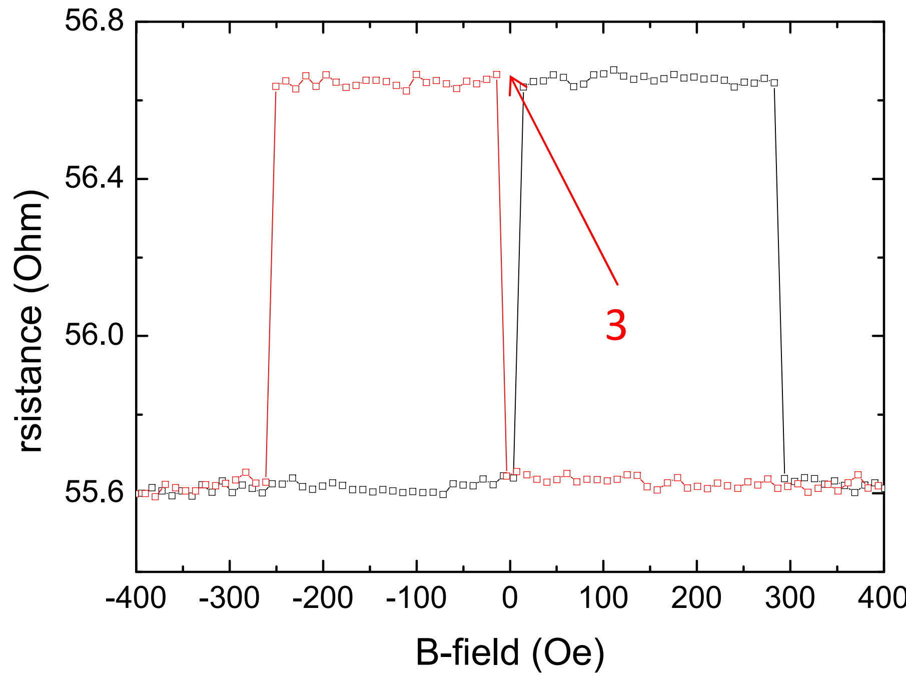




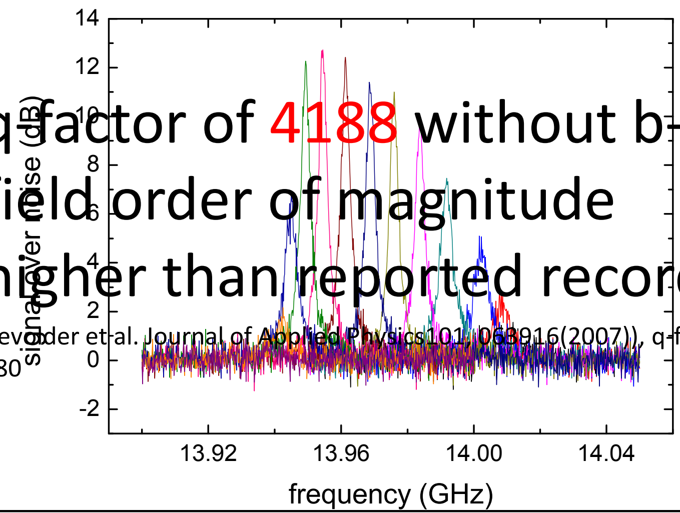
- swept from 207.1 Oe to 169 Oe
- applied different currents

Spin-Torque devices

100nm x 200nm pillar – field along the long side

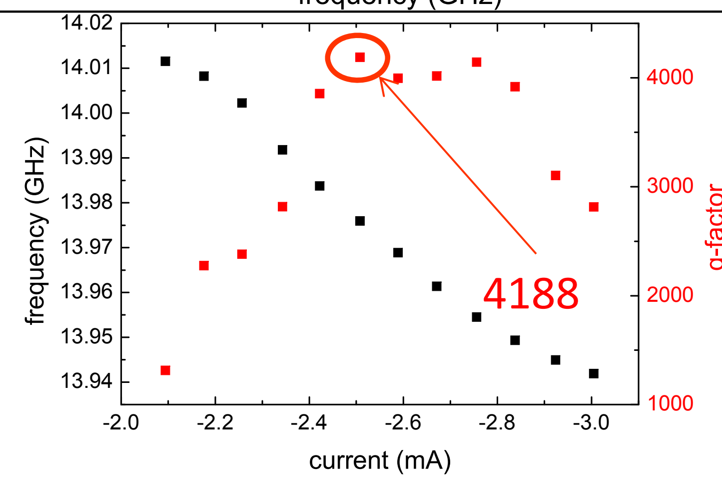


- swept from 169 Oe to 0 Oe
- still remained in the AP-state
- applied different currents



q-factor of 4188 without b-field order of magnitude higher than reported record

Devolder et al. Journal of Applied Physics101, 063916(2007)), q-factor of 280



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Spin Caloritronics: Diffusion Thermopower of (Ga,Mn)As/GaAs Tunnel Junctions

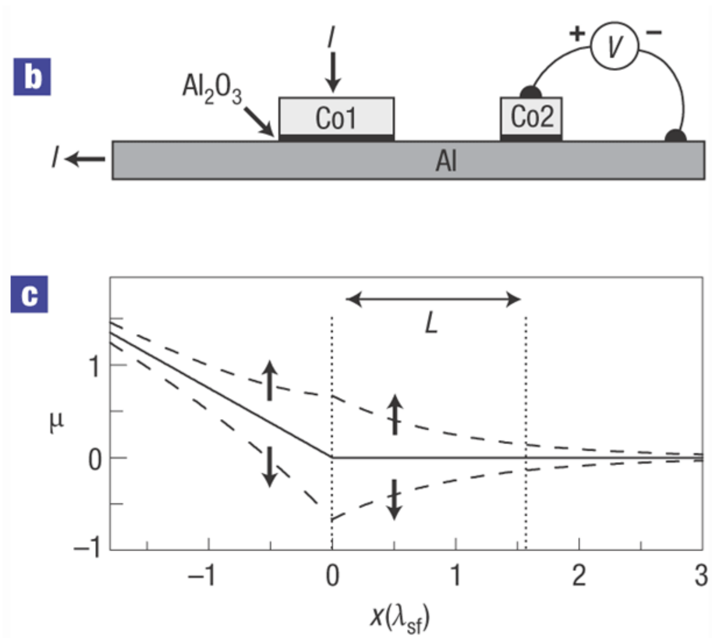
Ts. Naydenova, P. Dürrenfeld, K. Tavakoli, N. Pegard, L. Ebel, K. Pappert, K. Brunner, C. Gould, and L.W. Molenkamp

University of Würzburg EP3, Germany

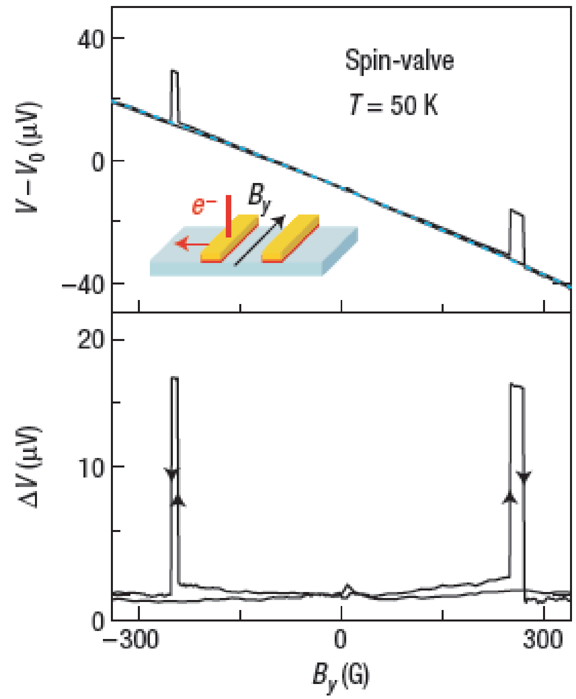
DFG

SemiSpinNet
Initial Training Network

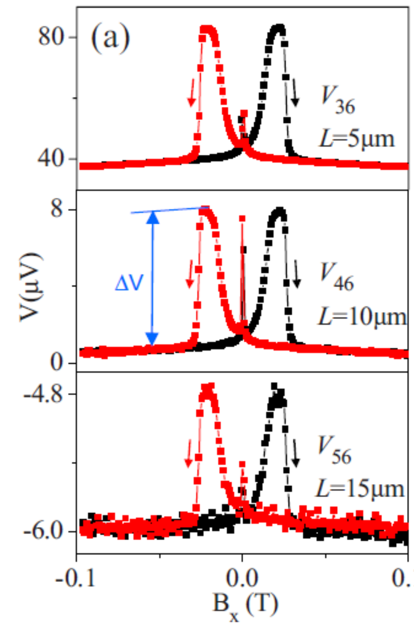
Nonlocal Technique - Experiments



Bart van Wees, *Nature* **3**, 147 (2007).

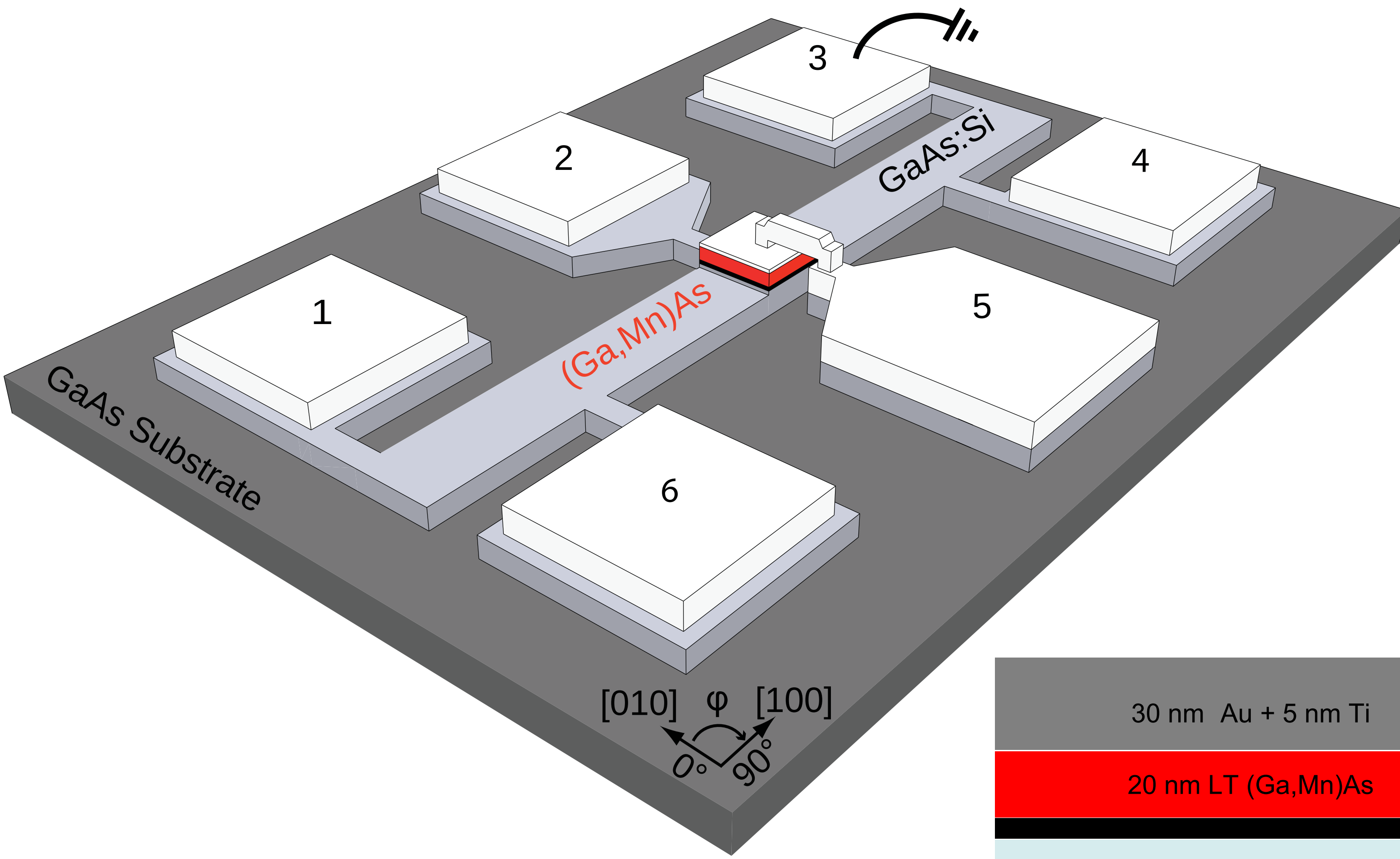


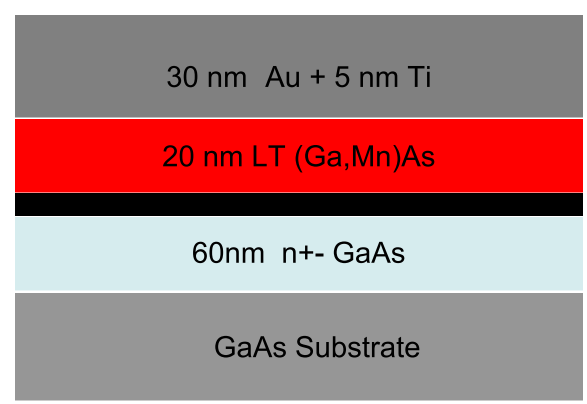
X. Lou *et al., Nature Phys.* **3**, 197 (2007).



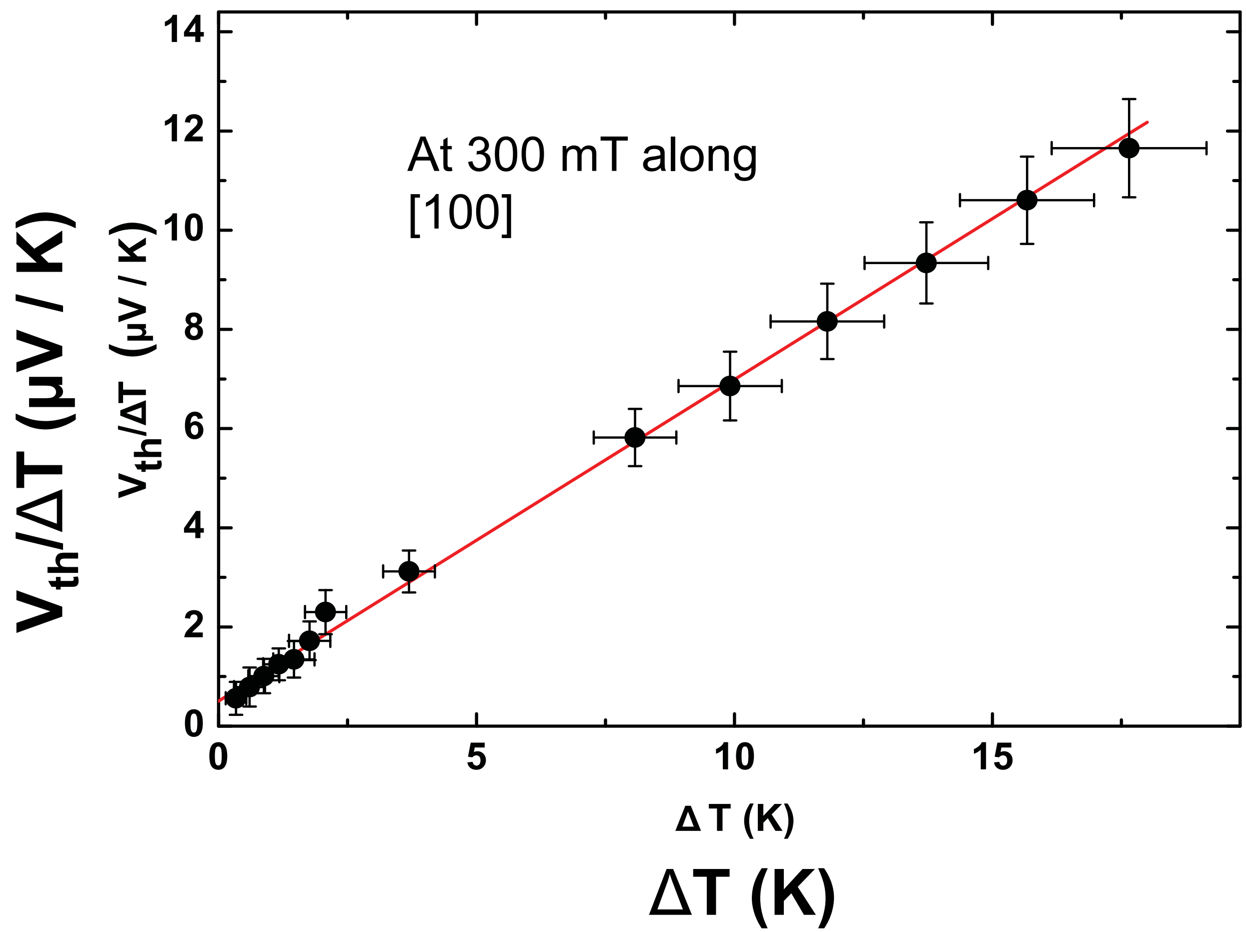
M. Ciorga et al., PRB. 79, 165321 (2009).

Sample Layout, Heating current technique

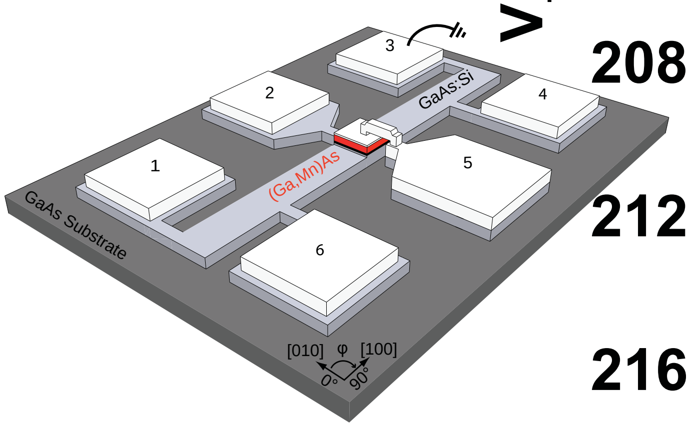


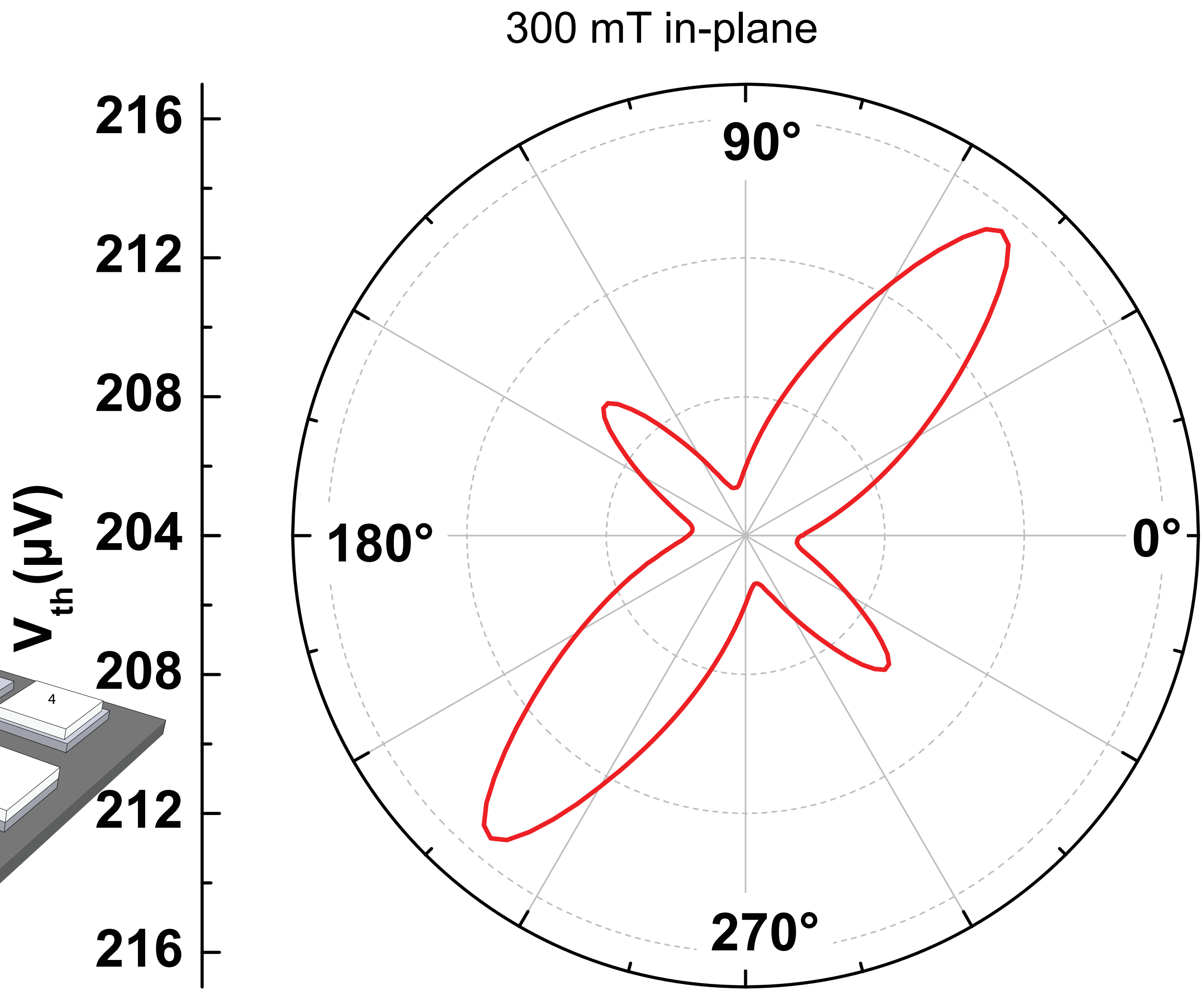


Thermopower as a function of temperature gradient



Thermovoltage phi-scan

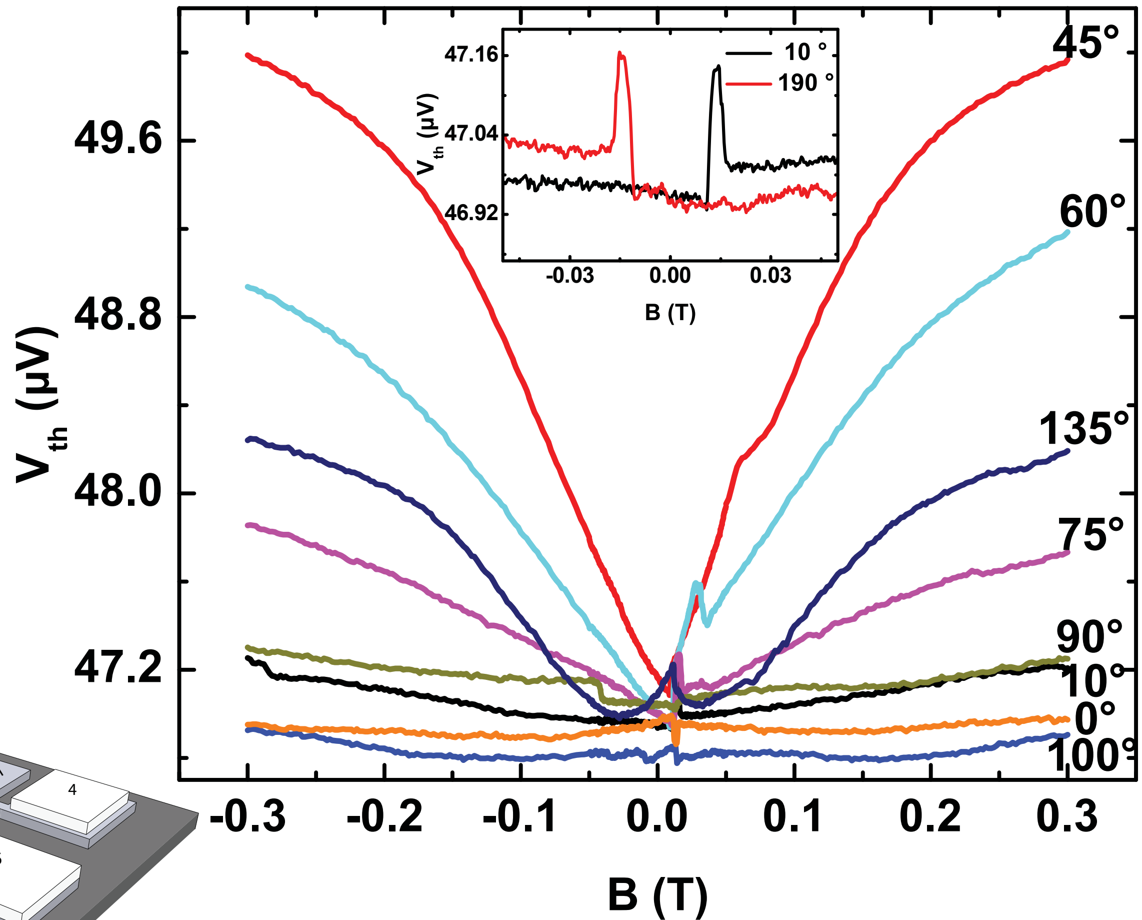


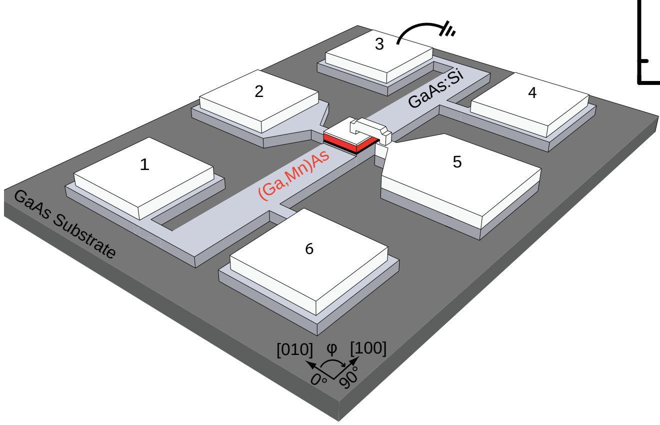


Spin-valve-like signal?

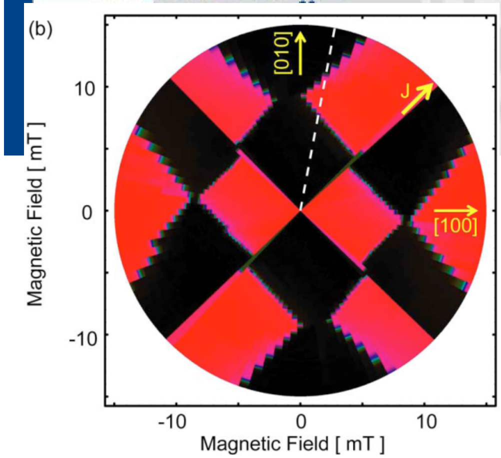
$T_{Si:GaAs}$= 12 K

$T_{(Ga,Mn)As}$= 4.2 K

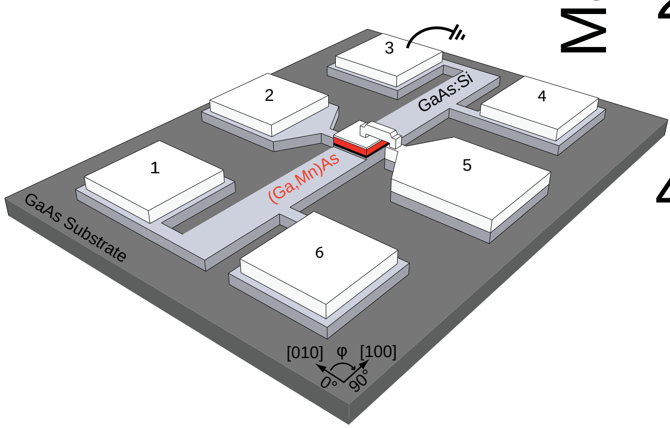


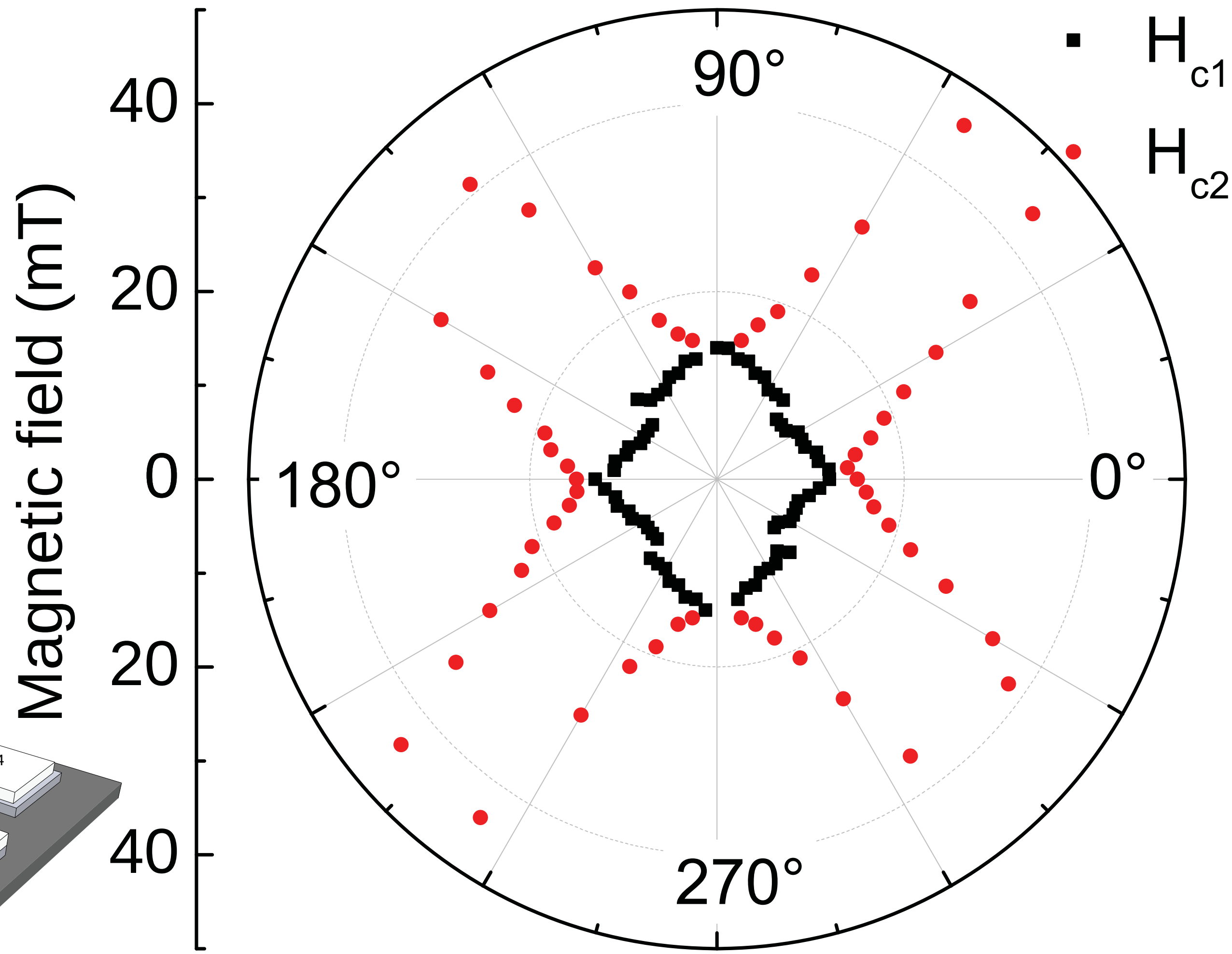


Polar Plot- look like (Ga,Mn)As

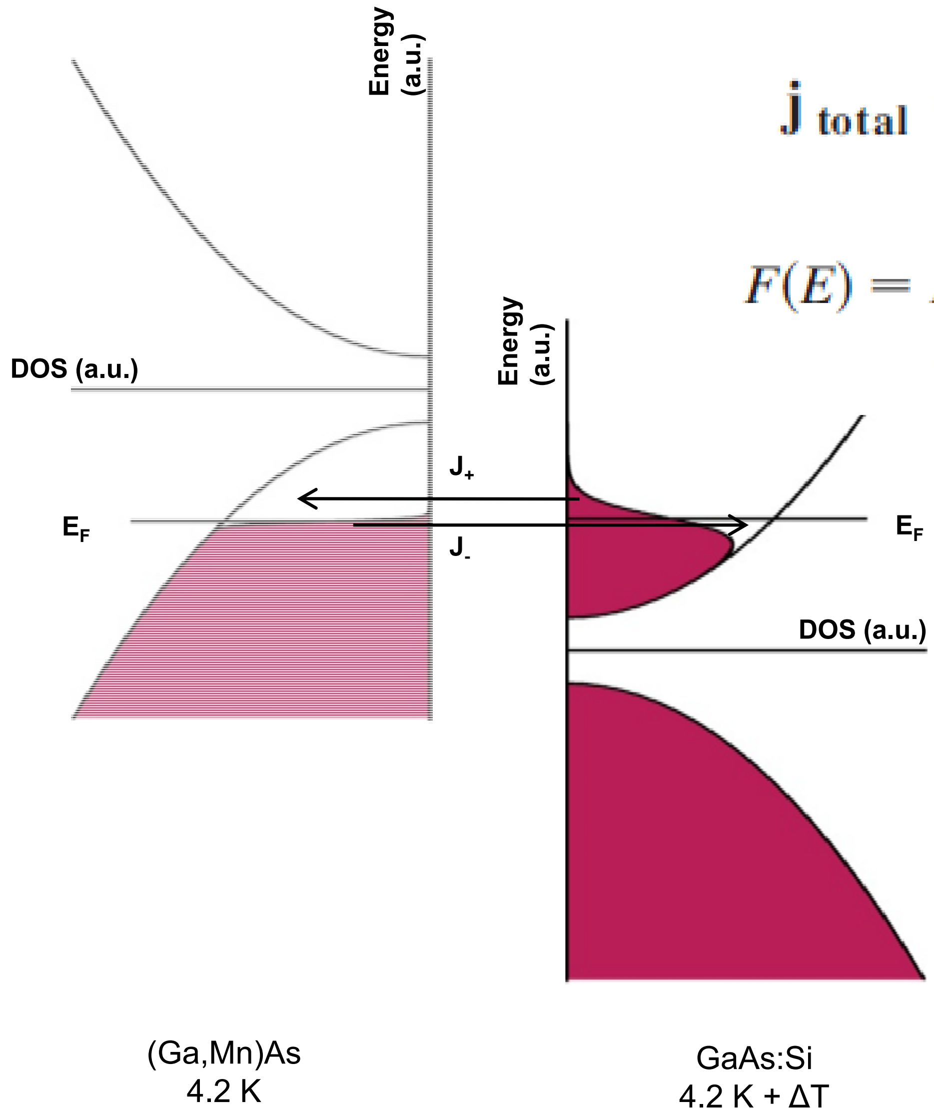


K. Pappert *et al.*, *Appl. Phys. Lett.* **90**, 062109 (2007).



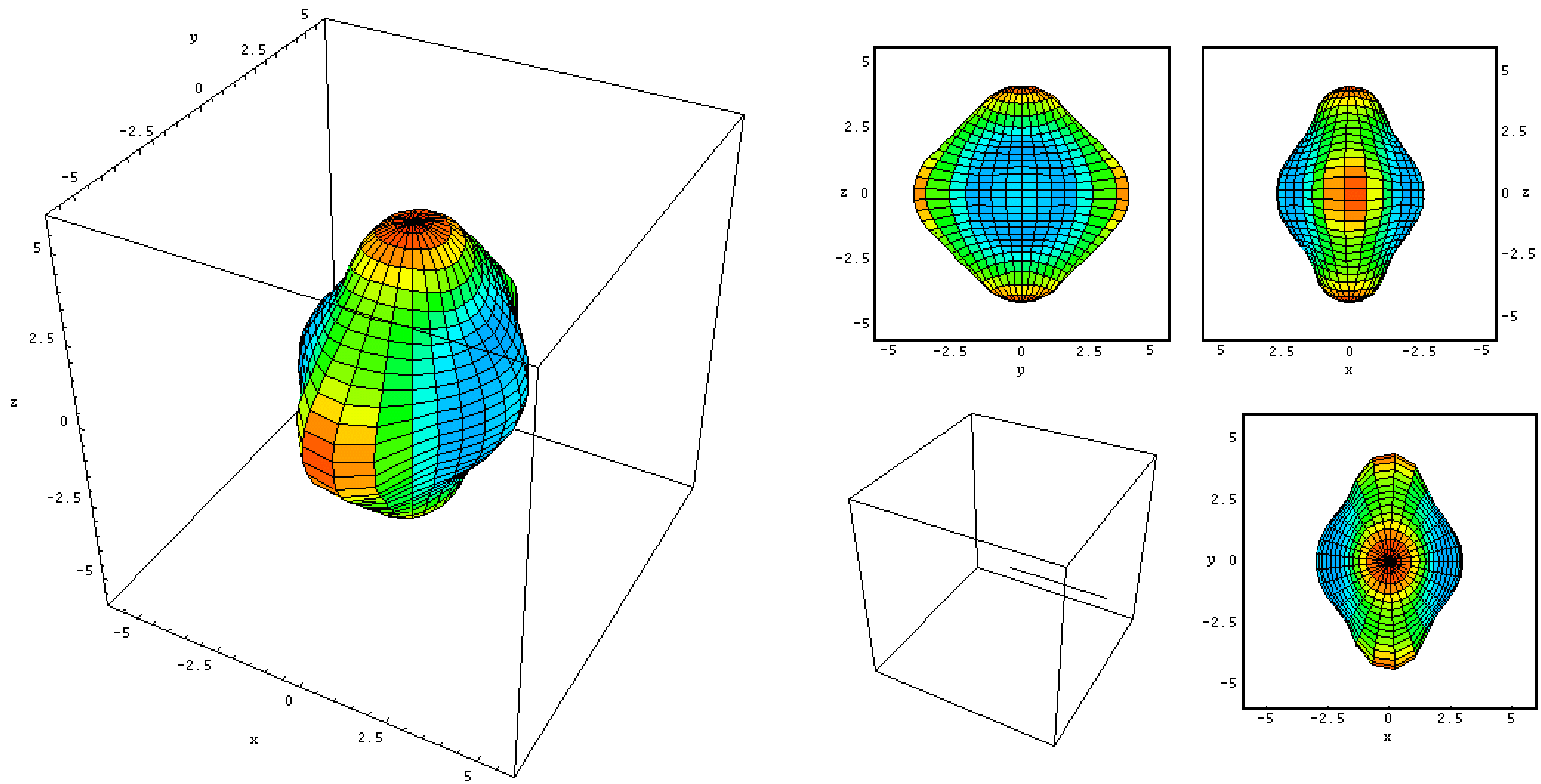


Thermopower Model and Simulation



$$j_{\text{total}} = A \int_{E_{C,\mathrm{GaAs:Si}}}^{E_{V,(\mathrm{Ga,Mn})\mathrm{As}} - eV_{\mathrm{th}}} F(E)\,dE$$

$$F(E) = D_{\mathrm{GaAs:Si}}(E) \cdot D_{(\mathrm{Ga,Mn})\mathrm{As}}(E - \mathrm{eV}_{\mathrm{th}}) \times [f_{\mathrm{GaAs:Si}}(E) - f_{(\mathrm{Ga,Mn})\mathrm{As}}(E - \mathrm{eV}_{\mathrm{th}})]$$


x
y
z
y
z
x
z
y
x

Spin Topotronics: QSHE/ISHE and spin transport in topologically protected states.

C. Brune, H. Buhmann, C. Gould, and L.W. Molenkamp

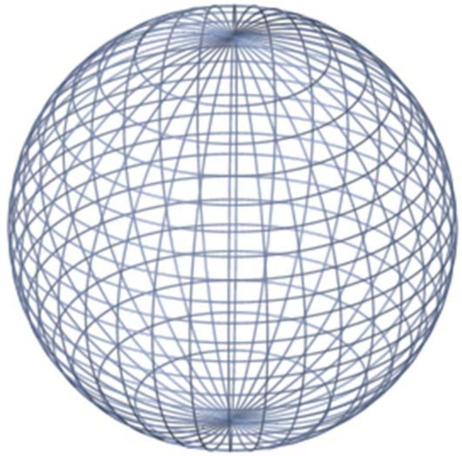
University of Würzburg EP3, Germany

Geometry and Topology

Topology describes object-properties that are preserved under a continous deformation

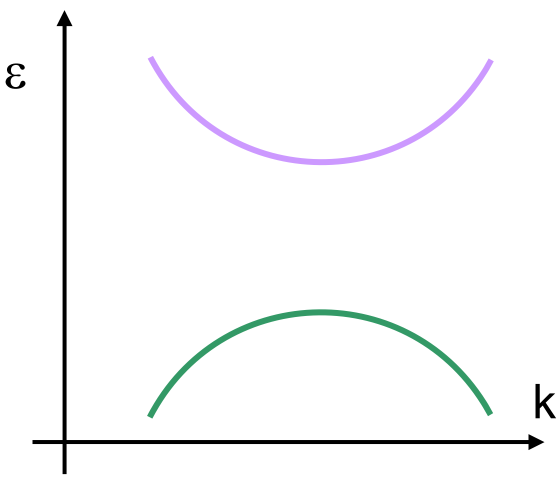
Example: Mug to Torus

But it can not be transformed to a sphere without cutting or transforming it to a point first

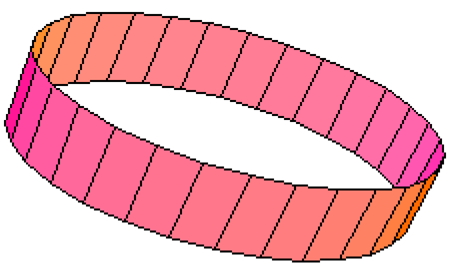


Topological Insulator States

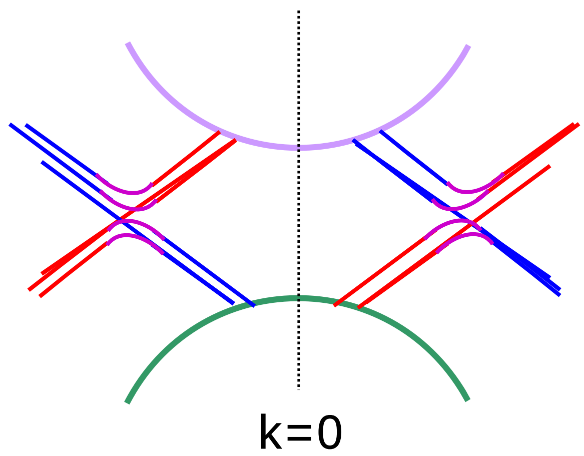
conventional insulator



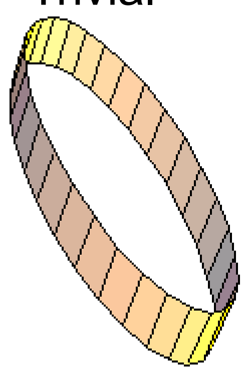
Trivial



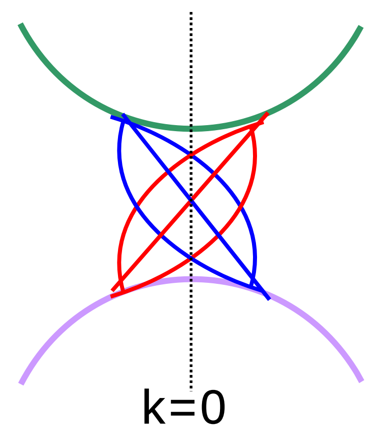
conventional insulator
with accidental surface states



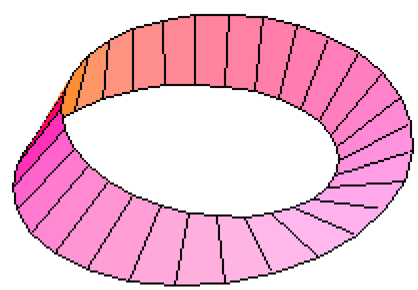
Trivial



TI



Non-trivial



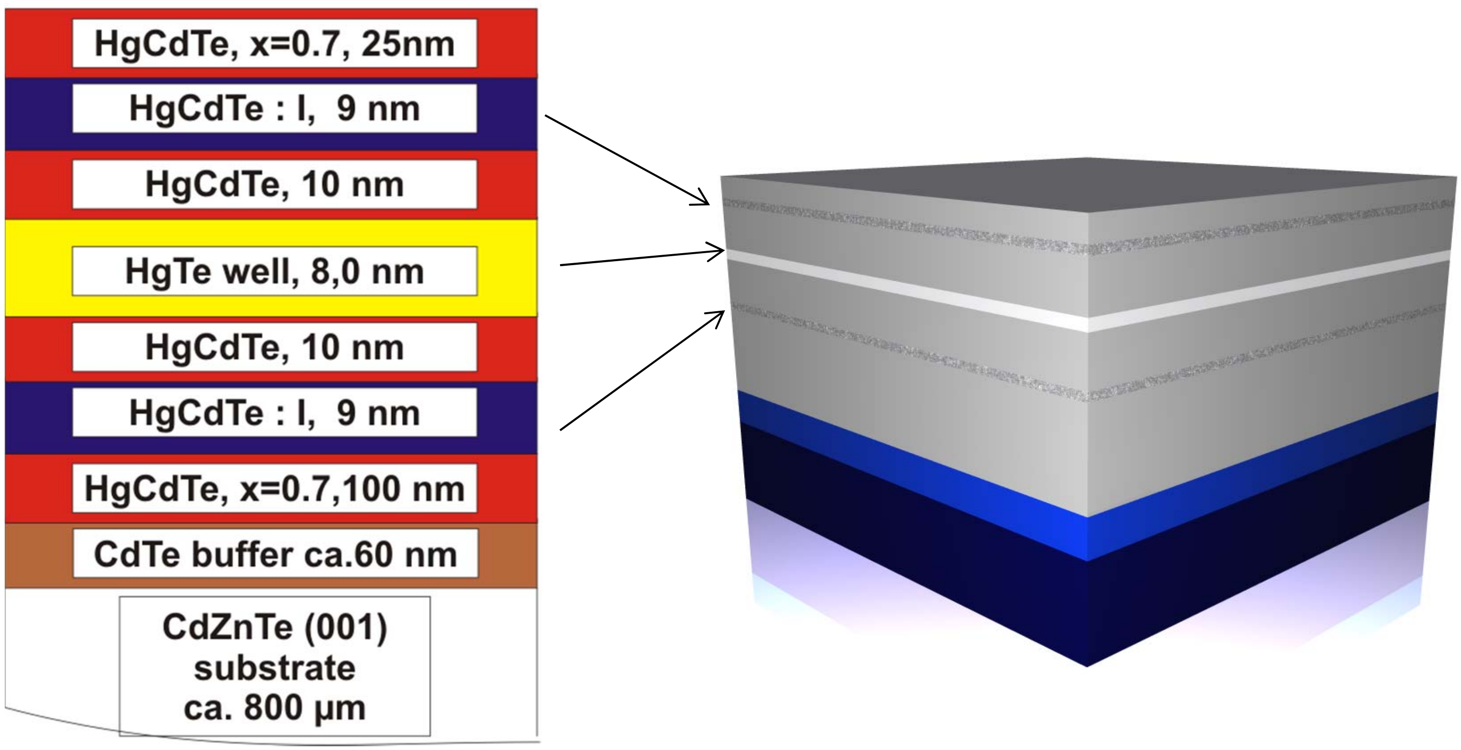
HgTe Quantum Wells

EP3

Q2220

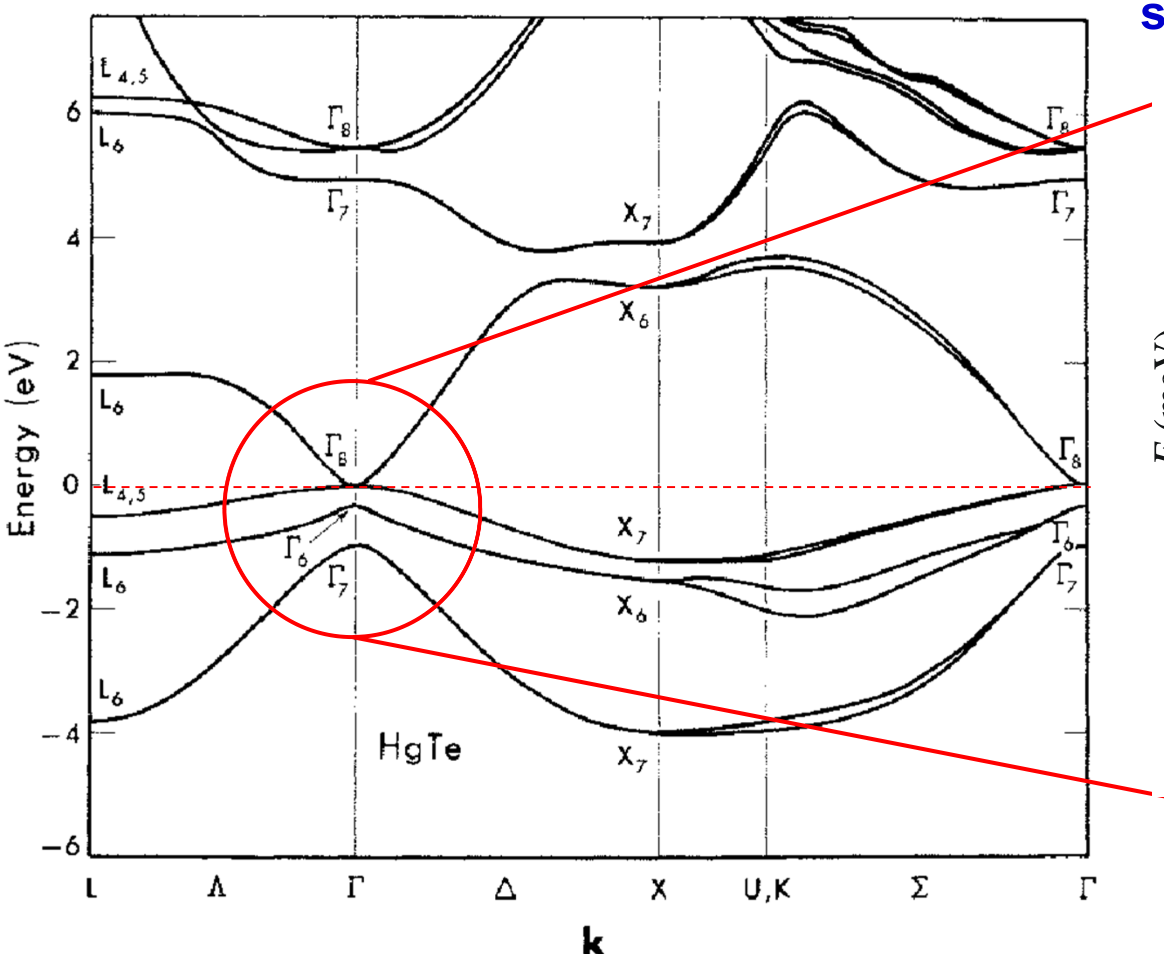
free electron gas in the QW

by donor doping of the barriers



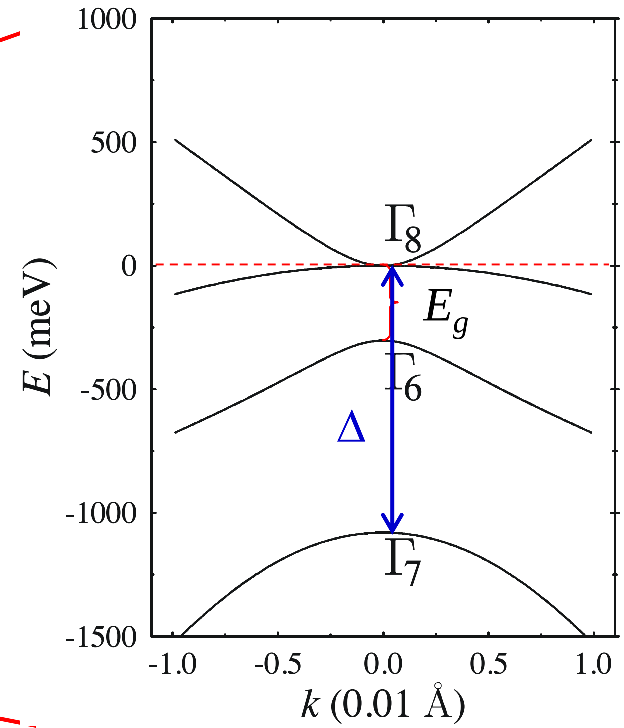
HgTe

band structure



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

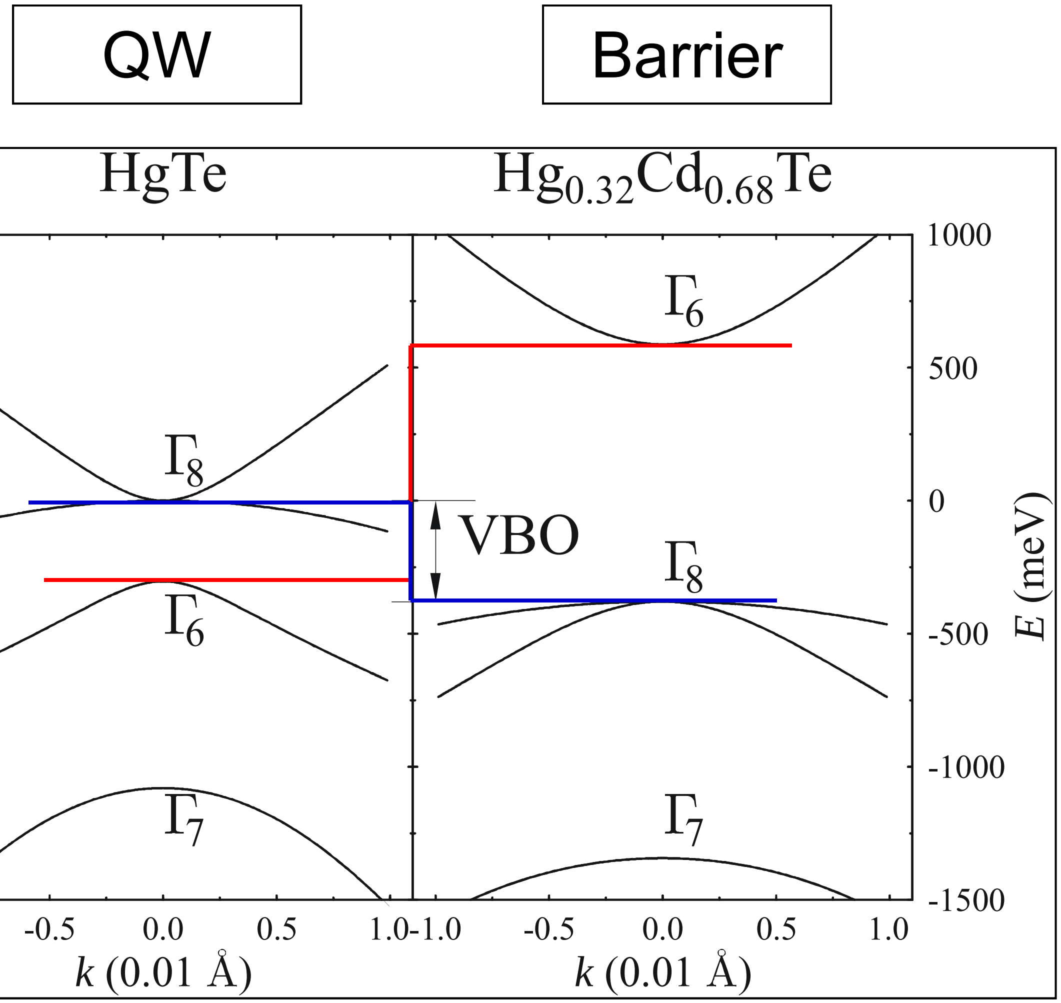
semi-metal or semiconductor



fundamental energy gap

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

HgTe-Quantum Wells

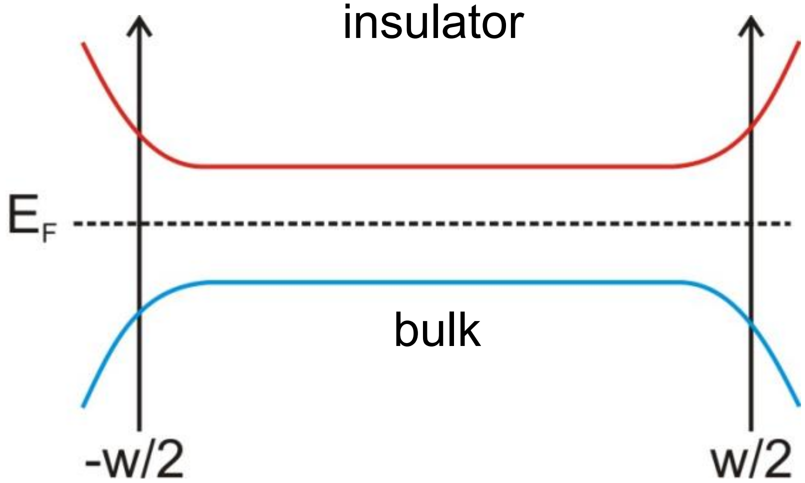


VBO = 570 meV

Simplified Picture

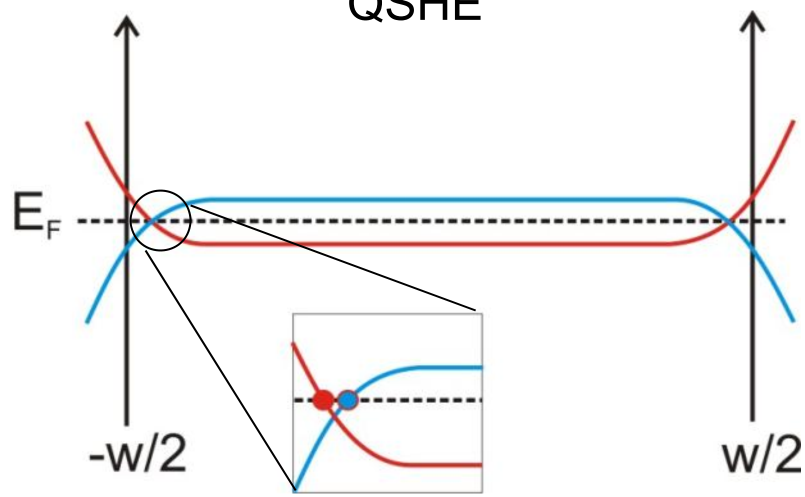
m > 0

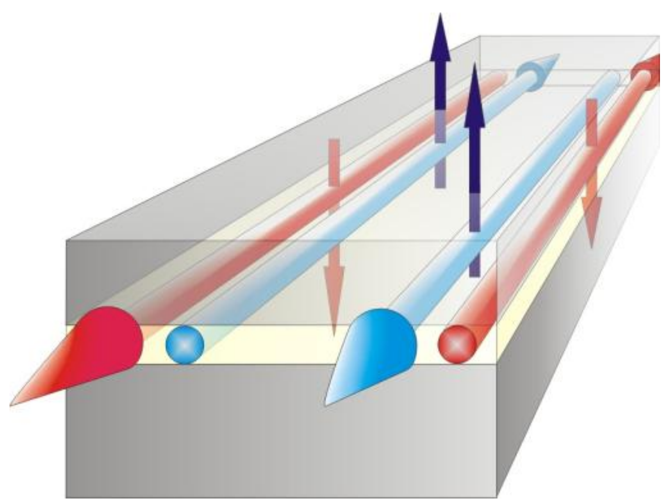
normal insulator



m < 0

QSHE





Outlook.

Spintronics is still very much a topical field which can play a leading role in developing information technology. To ensure that happens, it is important to look towards solving the present challenges, and not to continue focusing on challenges of the past (where resources are sadly still being wasted in many cases.)