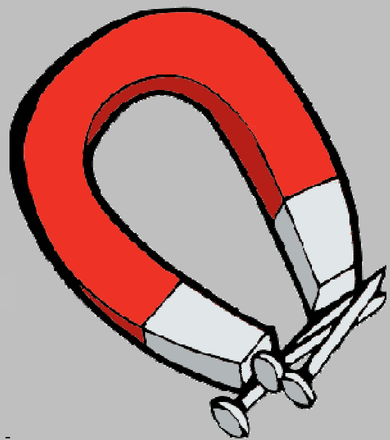
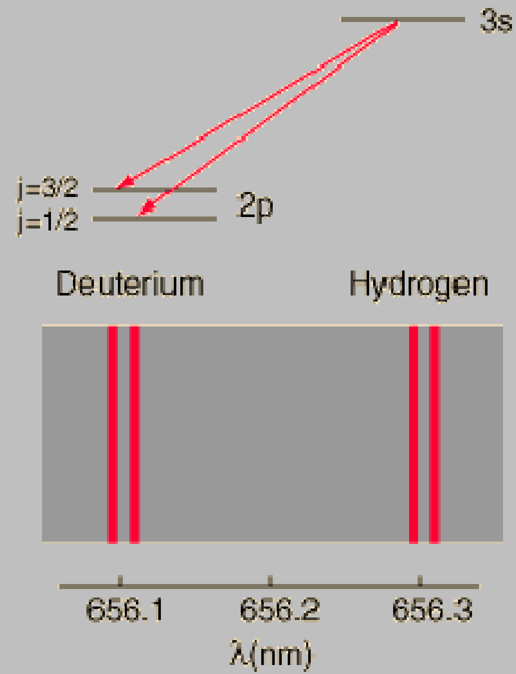
Magnetism and Spin-Orbit Interaction: Some basics and examples





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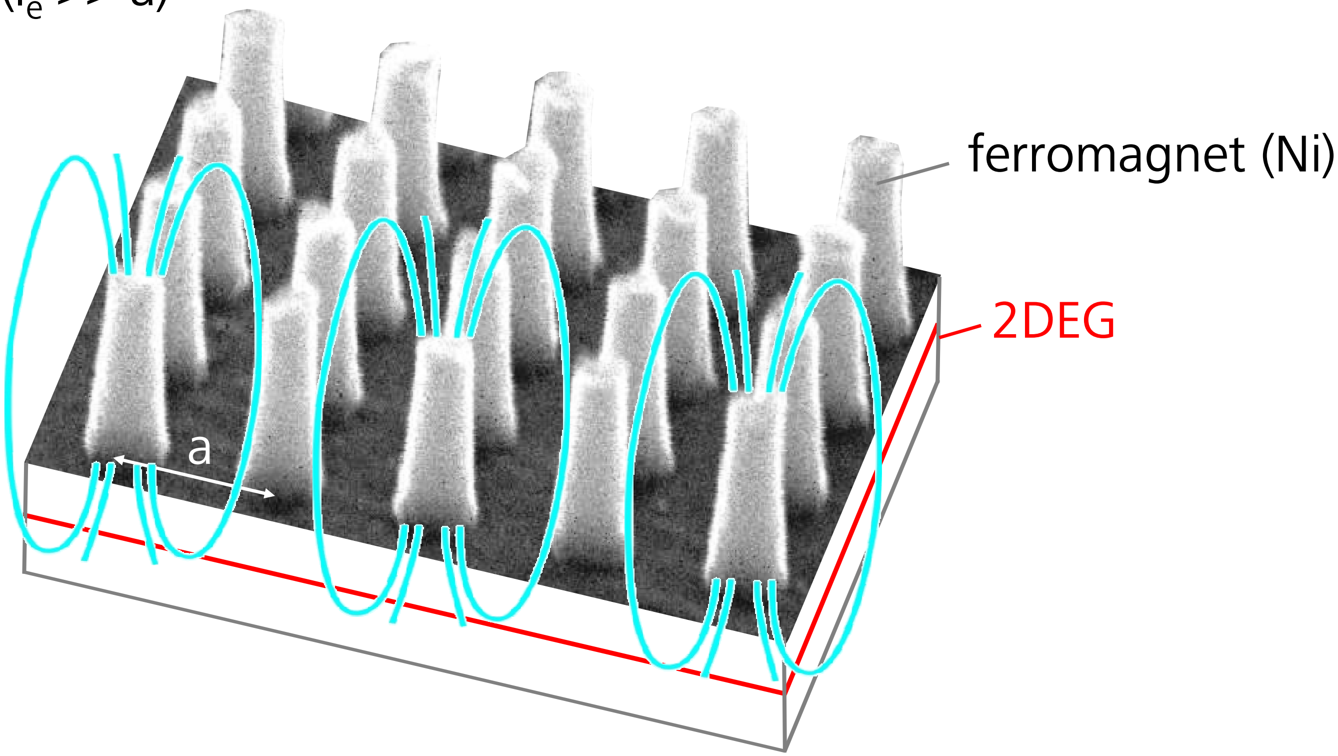
(Our initial) Motivation

Transport in a two-dimensional electron gas with superimposed periodic magnetic field ($l_e \gg a$)



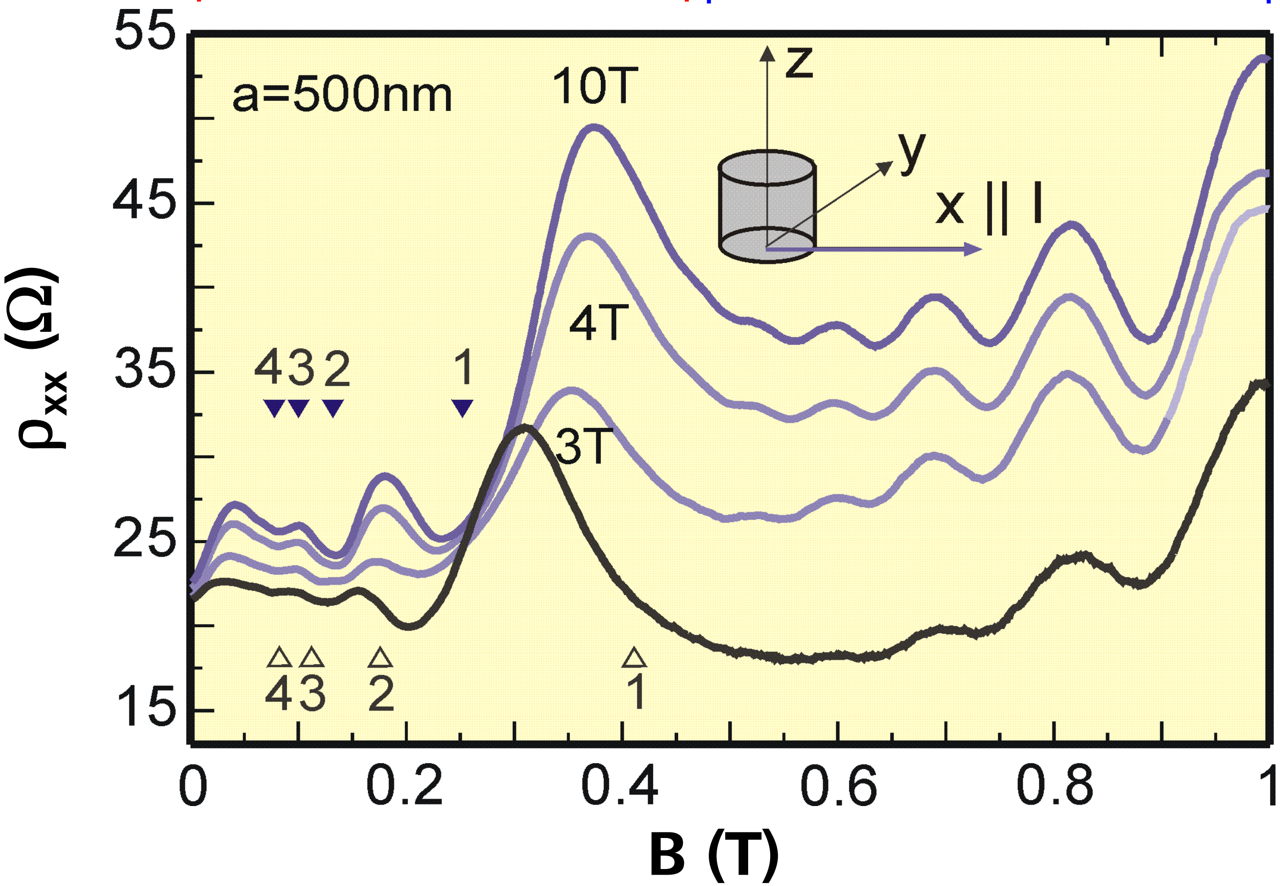
Magnetization pattern of ferromagnet determines stray field

Transport in a periodic magnetic field

Commensurability (Weiss) Oscillations:

$$2R_C = \left(n \pm \frac{1}{4}\right)a$$

SdH oscillations

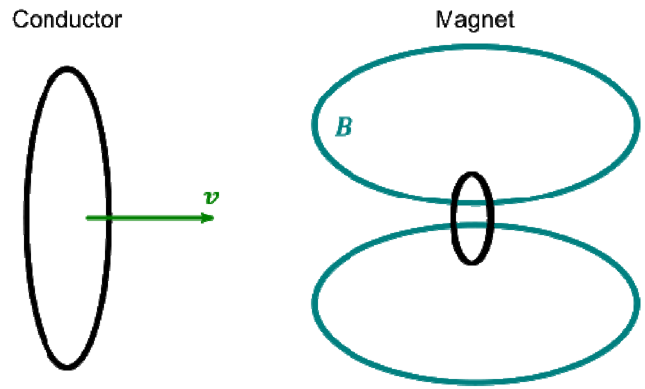


see, e.g., P.D. Ye PRL **74**, 3013 (1995)

A little bit of history

Hans Christian Ørsted

1820: Electric current generates magnetic field



Albert Einstein

1905: On the electrodynamics of moving bodies
Magnetic field stems from Lorentz contraction of moving charges

Magnetism and Spin-Orbit Interaction:

Magnetism

<u>Basic concepts</u>

magnetic moments, susceptibility, paramagnetism, ferromagnetism
exchange interaction, domains, magnetic anisotropy,

<u>Examples:</u>

detection of (nanoscale) magnetization structure
using Hall-magnetometry, Lorentz microscopy and MFM

Spin-Orbit interaction

<u>Some basics</u>

Rashba- and Dresselhaus contribution, SO-interaction and effective magnetic field

<u>Example:</u>

Ferromagnet-Semiconductor Hybrids: TAMR involving epitaxial Fe/GaAs interfaces

Magnetism and Spin-Orbit Interaction:

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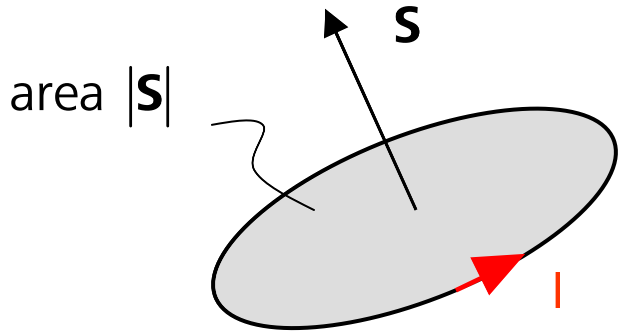
Magnetic moment and angular momentum

Current in a loop generates magnetic moment μ, constitutes magnetic dipole



$$\boldsymbol{\mu} = I\mathbf{S}$$

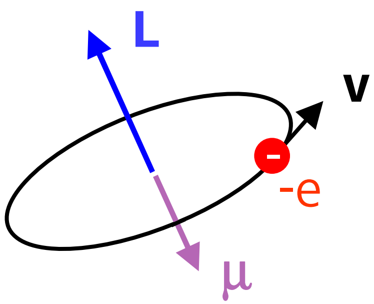
As mass is transported around the loop $\Rightarrow$ $\boldsymbol{\mu}$ is connected to angular momentum

$$\boldsymbol{\mu} = \gamma \mathbf{L} \quad [\mathrm{Am}^2] \qquad \gamma = \text{gyromagnetic ratio}$$

Size of atomic magnetic moment

$$I = \frac{-e}{T} = \frac{-ev}{2\pi r} \Rightarrow \mu = -\frac{1}{2} evr = -\frac{1}{2}\frac{e}{m} L = --\mu_B \frac{L}{\hbar}$$

$$\boldsymbol{\mu} = -\frac{\mu_B}{\hbar}\mathbf{L} \text{ with } \mu_B = \frac{e\hbar}{2m} = \text{Bohr Magneton}$$



Magnetization **M**: magnetic moments / volume [A/m]

Angular momentum: quantum mechanical picture

Total angular momentum of an atom is composed of angular momentum of all occupied electron states **L** and of all corresponding spins **S**

Total angular momentum (L-S coupling):

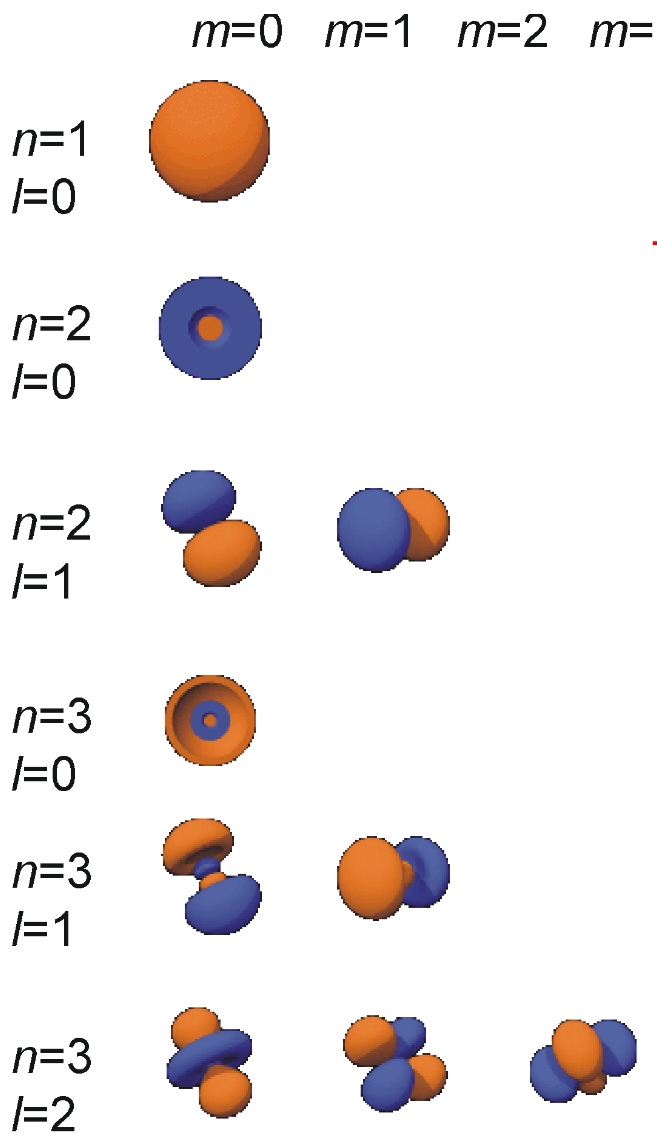
$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

Connection between μ and **J**

$$\boldsymbol{\mu} = -\frac{g\mu_B}{\hbar}\mathbf{J}$$

with Landé factor

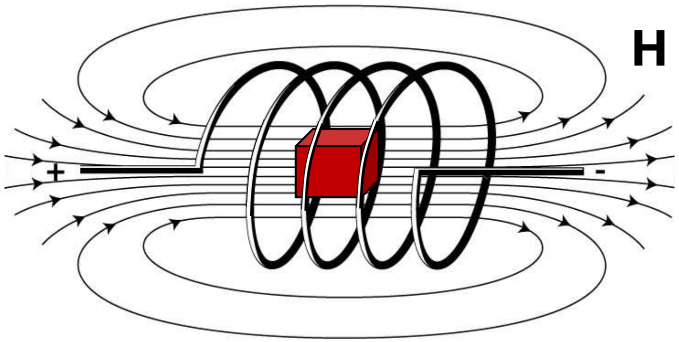
$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$



http://www.orbitals.com/orb/ov.htm

Susceptibility

Connection between field H (e.g. generated by coil) and magnetization **M**:



Linear materials:

$$\mathbf{M} = \chi \mathbf{H}$$

diamagnetic if $\chi < 0$
paramagnetic if $\chi > 0$

χ: magnetic susceptibility

Connection between B and H field: $\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$ (for $M << H$)

$$\Rightarrow \mathbf{B} = \mu_0 (\mathbf{H} + \chi \mathbf{H}) = \mu_0 (1 + \chi) \mathbf{H}$$

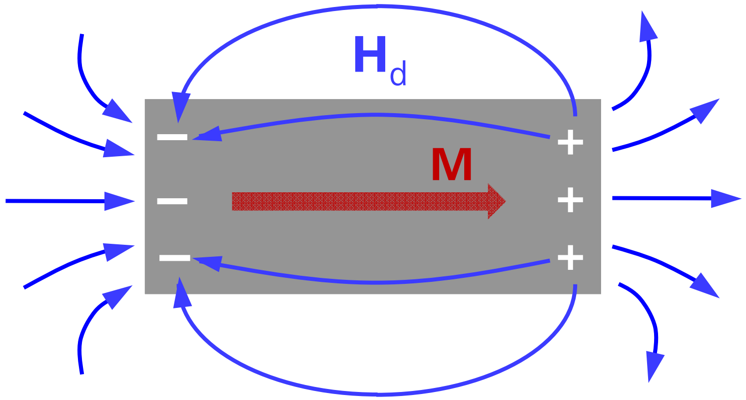
μ_0: permeability of free space

Not the whole story!

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{H}_d + \mathbf{M})$$

$\mathbf{H}_d$: demagnetizing field or stray field (important for ferromagnets)

Demagnetizing field

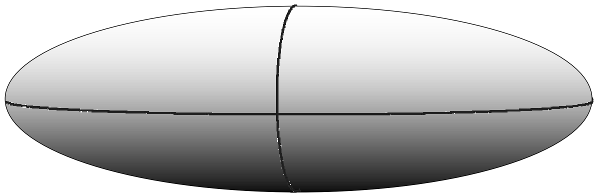


$$\nabla \cdot \mathbf{B} = \nabla \cdot [\mu_0(\mathbf{H}_d + \mathbf{M})] = 0$$

$$\nabla \cdot \mathbf{H}_d = -\nabla \cdot \mathbf{M}$$

Any divergence of **M** creates a magnetic field – can be seen as sort of (bound) magnetic charges

Easy expression for strayfield (demagnetizing field) $\mathbf{H}_d$ only for ellipsoids:

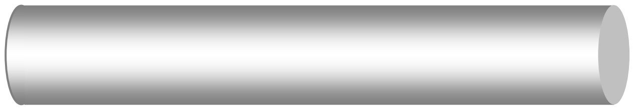


$$\mathbf{H}_d = -\begin{pmatrix} N_{xx} & 0 & 0 \\ 0 & N_{yy} & 0 \\ 0 & 0 & N_{zz} \end{pmatrix} \mathbf{M}$$

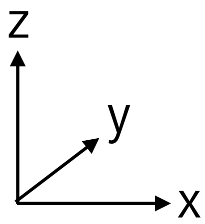
with $N_{xx} + N_{yy} + N_{zz} = 1$

Some examples:

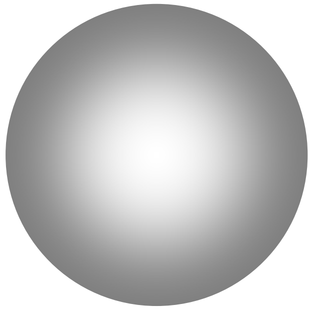
$$N_{xx} = 0,\ N_{yy} = N_{zz} = \tfrac{1}{2}$$



long cylindrical rod



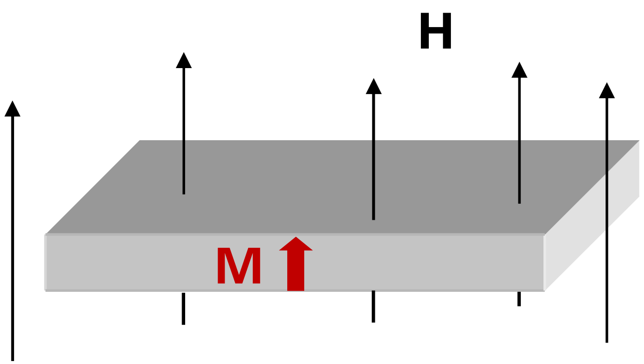
$$N_{xx} = N_{yy} = N_{zz} = \tfrac{1}{3}$$



sphere

$$N_{xx} = N_{yy} = 0,\ N_{zz} = 1$$

flat plate



$$\mathbf{H}_d = -\mathbf{M} \Rightarrow$$

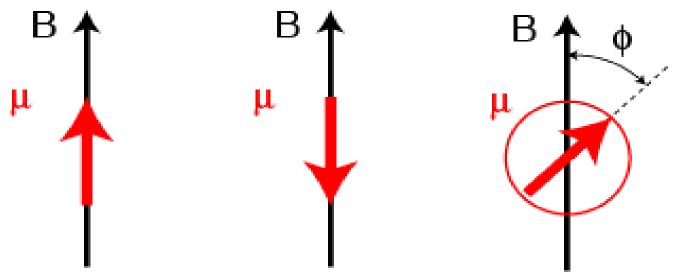
$$\mathbf{B} = \mu_0 \left(\mathbf{H} + \mathbf{H}_d + \mathbf{M} \right) = \mu_0 \mathbf{H}$$

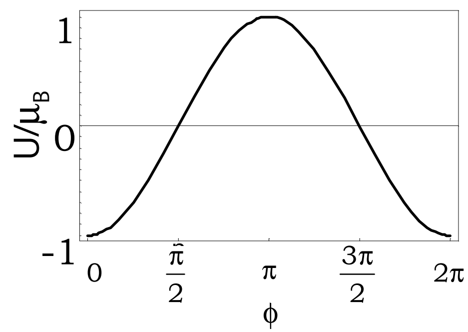
Paramagnetism (of isolated magnetic moments)

Requisite: Atoms with non-vanishing angular momentum J

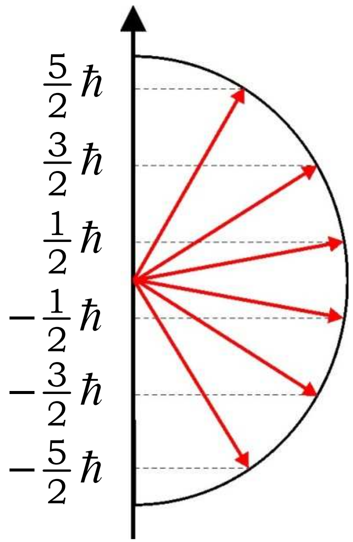
Energy of magnetic moment $E = -\boldsymbol{\mu} \cdot \mathbf{B}$

Classically: arbitrary values and orientation of $\boldsymbol{\mu}$





Quantum mechanically: discrete values and orientations of $\boldsymbol{\mu}_J$, e.g. $J = 5/2$



$$\mu_z = -\frac{g\mu_B}{\hbar} J_z = -m_J g \mu_B \qquad m_J = J, J-1, \ldots -(J-1), -J$$

$$\uparrow$$

$$J_z = m_J \hbar$$

2J+1 discrete values
(and hence energy levels)

Associated energy levels $E_{m_J} = \underbrace{m_J g \mu_B}_{-\mu_z} B$
get thermally occupied

Magnetization (thermal average)

Magnetization $M = NgJ\mu_B B_J(x)$ J: total angular momentum

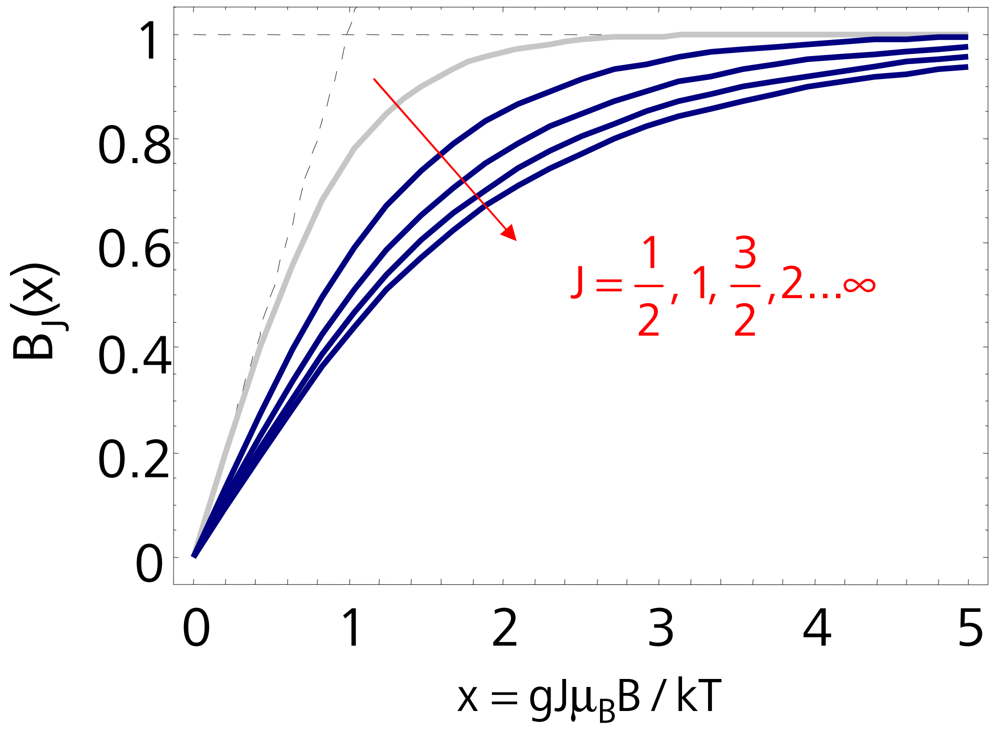
Brillouin function $B_J(x) = \frac{2J+1}{2J}\coth\left(\frac{2J+1}{2J}x\right) - \frac{1}{2J}\coth\left(\frac{x}{2J}\right)$; with $x = \frac{gJ\mu_B B}{k_B T}$

Saturation:

for $x >> 1$: $B_J \to 1$

and $M \to NgJ\mu_B = M_S$

N: Density of magnetic atoms



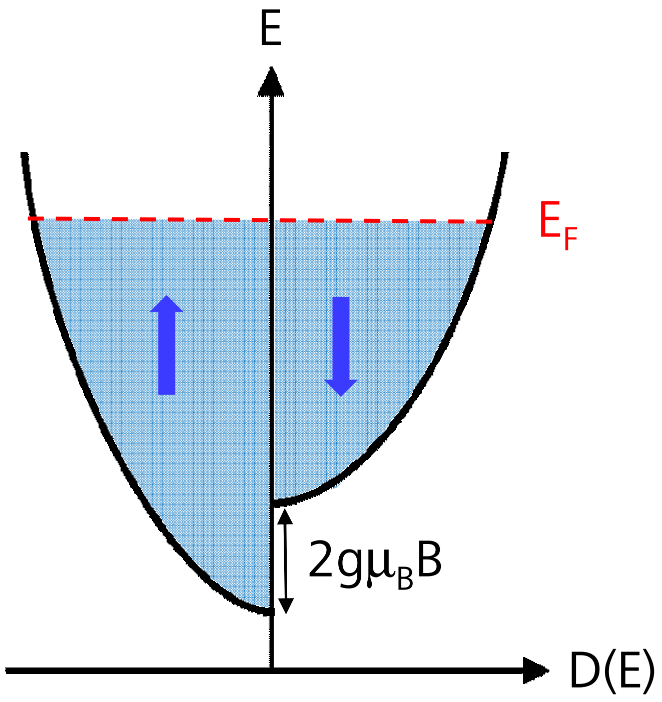
"High – T":

$x << 1 \Rightarrow \coth(x) \approx \frac{1}{x} + \frac{x}{3} - \ldots$

$\Rightarrow B_J \approx \frac{J+1}{J}\frac{x}{3}$

$M = NgJ\mu_B B_J(x) \approx N\frac{g^2 J(J+1)\mu_B^2}{3k_B T}B = N\frac{g^2 J(J+1)\mu_B^2}{3k_B T}\mu_0 H \Rightarrow \chi = \frac{M}{H} \approx N\frac{g^2 J(J+1)\mu_B^2\mu_0}{3k_B}\frac{1}{T}$

Paramagnetism (of free electrons)



Magnetization: $M = \left(N_\uparrow - N_\downarrow\right)\mu_B = \Delta N \mu_B$

$$\Delta N = \frac{1}{2} D\left(E_F\right) \cdot 2g\mu_B B = \frac{3}{2}\frac{N}{E_F} g\mu_B B$$

$D\left(E_F\right) = \frac{3}{2}\frac{N}{E_F}$ in 3D

Resulting magnetization:

$$M = \frac{3}{2}\frac{N}{E_F} g\mu_B^2 B = \underbrace{\frac{3}{2}\frac{N}{k_B T_F} g\mu_B^2\mu_0}_{\chi} H$$

Taking into account diamagnetism of free electrons ($M_{dia} = -\frac{1}{3}M_{para}$)

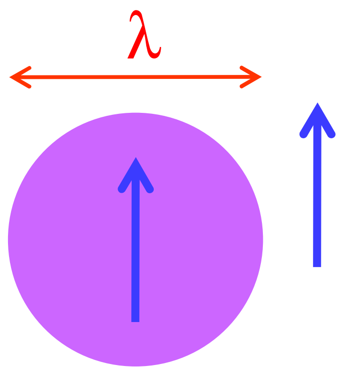
$$\chi = \frac{N}{k_B T_F} g\mu_B^2\mu_0$$

Independent of temperature!

Exchange Interaction (a la Heisenberg)

Exchange due to Pauli exclusion principle and Coulomb repulsion

An electron pushes a second electron with the same spin orientation out of a region with diameter $\lambda \rightarrow$ exchange hole forms



Exchange hole

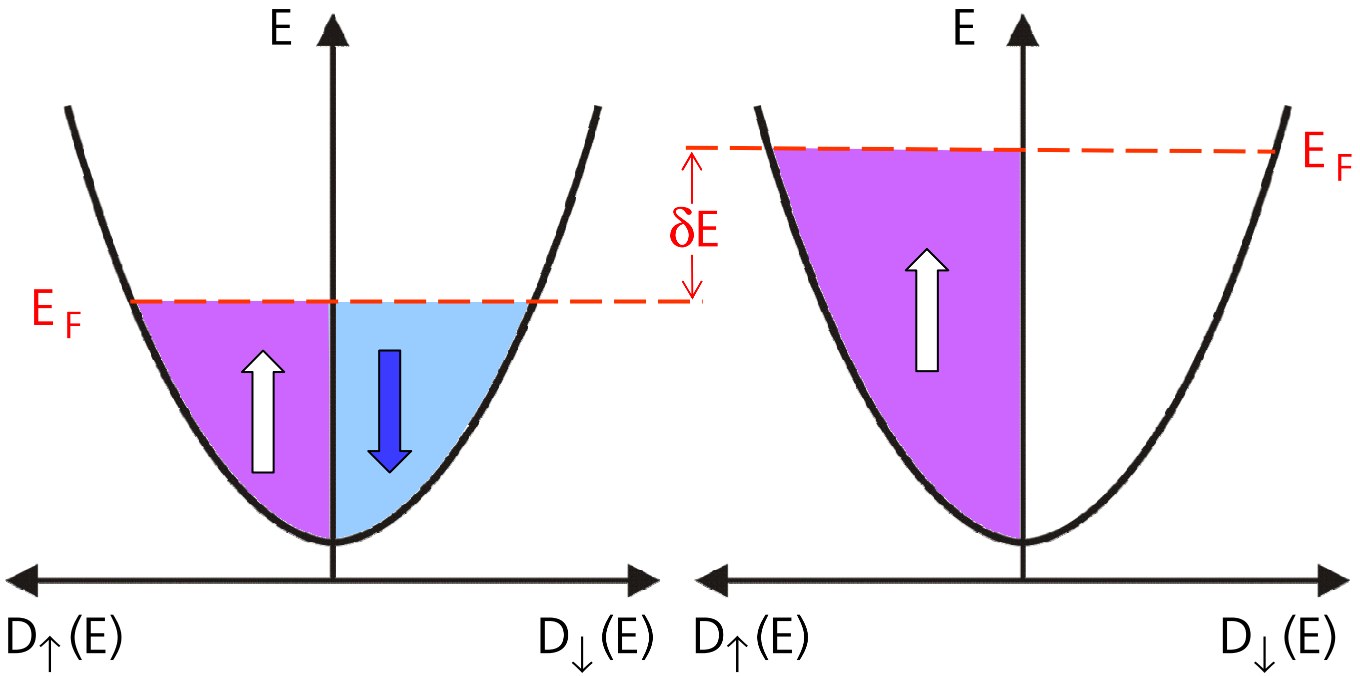
Consequences of spin arrangement for total energy

- For parallel orientation, e.g., $|\uparrow\uparrow\rangle$ potential energy gets reduced compared to anti-parallel arrangement, e.g., $|\uparrow\downarrow\rangle$ since Coulomb-repulsion is reduced due to larger average interparticle distance.

- On the other hand kinetic energy is larger for $|\uparrow\uparrow\rangle$ since Fermi-energy increases due to fixed electron number.

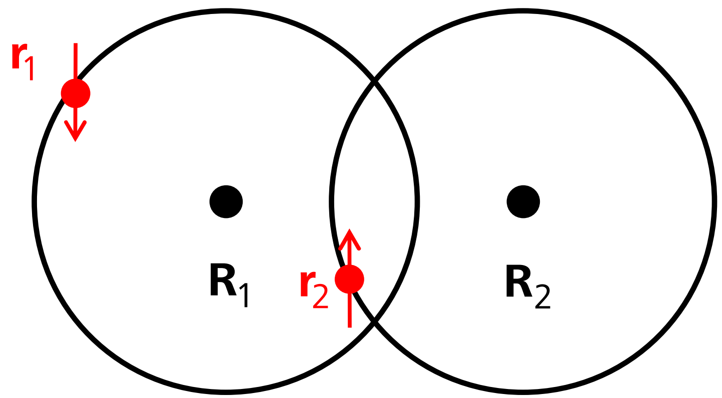
delicate interplay!

Increase of kinetic energy (example)



Fermi energy E_F of a free electron gas increases if, for fixed electron density only one spin species is permitted

Exchange Interaction (a la Heisenberg)



Two electron wave function of hydrogen molecule like system:

$$\hat{\mathbf{H}}\psi = -\frac{\hbar^2}{2m}\left(\nabla_1^2 + \nabla_2^2\right)\psi + V(\mathbf{r}_1,\mathbf{r}_2)\psi = E\psi$$

Fermi-Dirac statistics requires that

$\psi(\mathbf{r}_1,\mathbf{r}_2) = -\psi(\mathbf{r}_2,\mathbf{r}_1)$ exchange of electrons

Construction of Ψ with Heitler-London approximation:

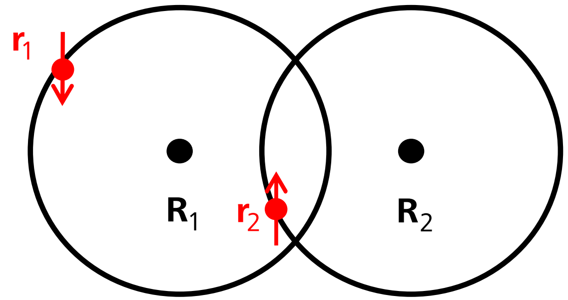
Spin of both electrons anti-parallel (Singulett, S=0)

$$\psi_S(\mathbf{r}_1,\mathbf{r}_2) = \underbrace{\left[\varphi_1(\mathbf{r}_1)\varphi_2(\mathbf{r}_2) + \varphi_1(\mathbf{r}_2)\varphi_2(\mathbf{r}_1)\right]}_{\text{symmetric}}\underbrace{\chi_S}_{\text{anti-symmetric under particle exchange}}$$

Spin of both electrons parallel (Triplett, S=1)

$$\psi_T(\mathbf{r}_1,\mathbf{r}_2) = \underbrace{\left[\varphi_1(\mathbf{r}_1)\varphi_2(\mathbf{r}_2) - \varphi_1(\mathbf{r}_2)\varphi_2(\mathbf{r}_1)\right]}_{\text{anti-symmetric}}\underbrace{\chi_T}_{\text{symmetric under particle exchange}}$$

Spin wave function χ



	S	m_s	χ	$\mathbf{S}_1 \cdot \mathbf{S}_2$	
Triplett	1	1	$\lvert\uparrow\uparrow\rangle$	$\frac{1}{4}$	
	1	0	$\lvert\uparrow\downarrow\rangle + \lvert\downarrow\uparrow\rangle$	$\frac{1}{4}$	χ_T symmetric
	1	-1	$\lvert\downarrow\downarrow\rangle$	$\frac{1}{4}$	
Singulett	0	0	$\lvert\uparrow\downarrow\rangle - \lvert\downarrow\uparrow\rangle$	$-\frac{3}{4}$	χ_S anti-symmetric

see, e.g. Stephen Blundell *Magnetism in Condensed Matter* Oxford University Press

Exchange splitting

exclusively due to the exchange of the two electrons

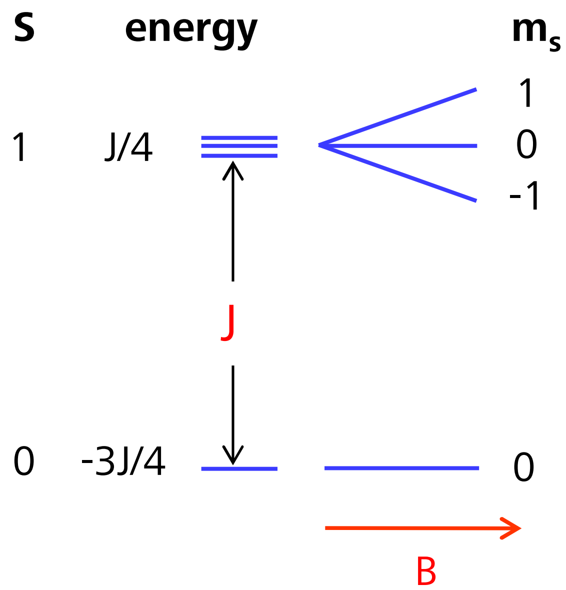
$\psi_S(\mathbf{r}_1,\mathbf{r}_2)$ and $\psi_T(\mathbf{r}_1,\mathbf{r}_2)$ have different energy E_S and E_T

$$E_S - E_T = \frac{\langle \psi_S | \hat{H} | \psi_S \rangle}{\langle \psi_S | \psi_S \rangle} - \frac{\langle \psi_T | \hat{H} | \psi_T \rangle}{\langle \psi_T | \psi_T \rangle} \ldots\ldots\ldots$$

Ashcroft, Mermin

$$= \underbrace{2\int d\mathbf{r}_1 d\mathbf{r}_2 \left[\varphi_1(\mathbf{r}_1)\varphi_2(\mathbf{r}_2)\right]\left(\frac{e^2}{|\mathbf{r}_1-\mathbf{r}_2|}+\frac{e^2}{|\mathbf{R}_1-\mathbf{R}_2|}-\frac{e^2}{|\mathbf{r}_1-\mathbf{R}_1|}-\frac{e^2}{|\mathbf{r}_2-\mathbf{R}_2|}\right)\left[\varphi_1(\mathbf{r}_1)\varphi_2(\mathbf{r}_2)\right]}$$

exchange integral J



sign of J determines spin ground state

$J > 0 \Rightarrow E_S > E_T \Rightarrow$ spins parallel

$J < 0 \Rightarrow E_S < E_T \Rightarrow$ spins anti-parallel

Heisenberg Hamiltonian

Expressing spin Hamiltonian with Eigenvalues E_S and E_T in terms of $\mathbf{S}_1$ and $\mathbf{S}_2$:

$$\hat{\mathbf{H}} = \tfrac{1}{4}(E_S + 3E_T) - (E_S - E_T)\hat{\mathbf{S}}_1 \cdot \hat{\mathbf{S}}_2$$

$$\hat{\mathbf{S}}_1 \cdot \hat{\mathbf{S}}_2 = \begin{cases} +\tfrac{1}{4} & S = 1 \\ -\tfrac{3}{4} & S = 0 \end{cases}$$

using that $\hat{\mathbf{S}}^2 = S(S+1)$

$\hat{\mathbf{H}}$ has Eigenvalue E_T for triplett ($\uparrow\uparrow$ or $\downarrow\downarrow$) and

E_S for singulett ($\uparrow\downarrow$ or $\downarrow\uparrow$)

Shift of origin results in usual form of Heisenberg Hamiltonian

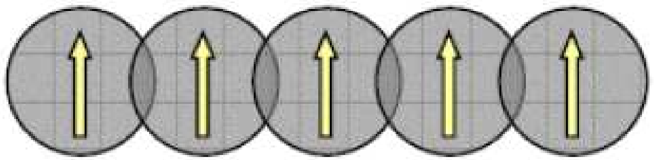
$$\hat{\mathbf{H}} = -(E_S - E_T)\hat{\mathbf{S}}_1 \cdot \hat{\mathbf{S}}_2 = -J\hat{\mathbf{S}}_1 \cdot \hat{\mathbf{S}}_2$$

Generalisation for many spins: $\hat{\mathbf{H}} = -\sum_{i,j} J_{ij}\hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j$

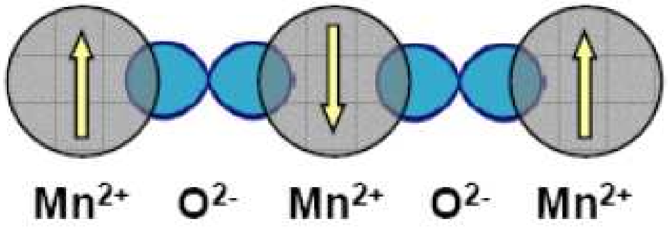
Exchange integral between spin i and spin j

Forms of exchange interaction

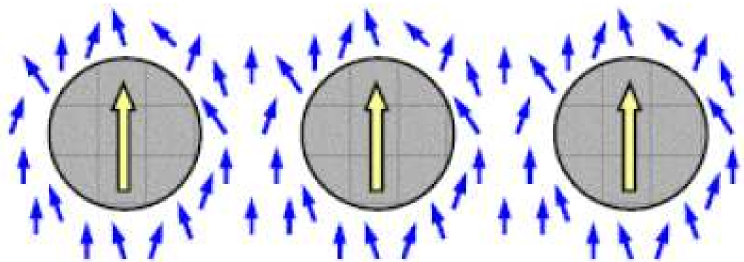
Direct exchange interaction
from direct overlap



Superexchange
mediated by paramagnetic atoms
or ions

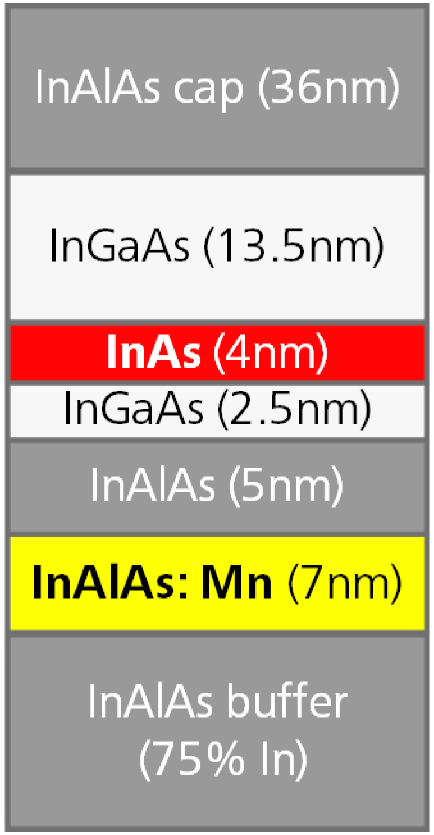


RKKY Interaction
(After M.A. Rudermann, C. Kittel, T. Kasuya, K. Yosida)
coupling mediated by mobile charge carriers

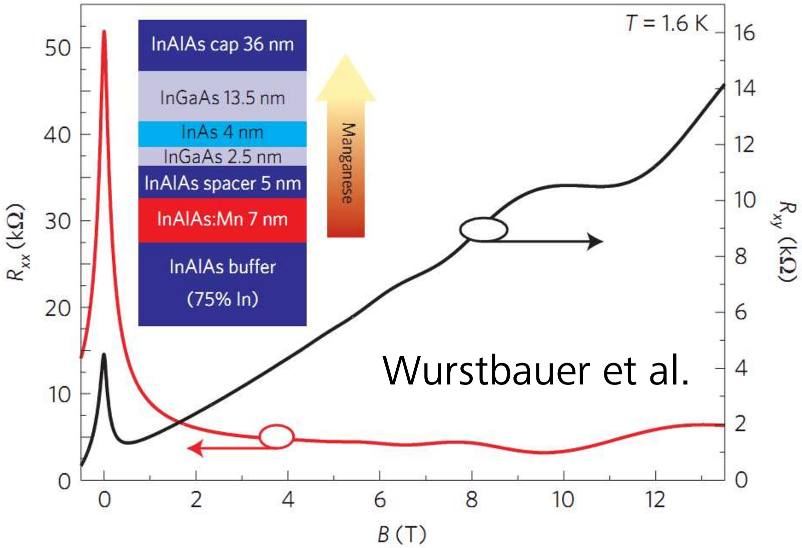


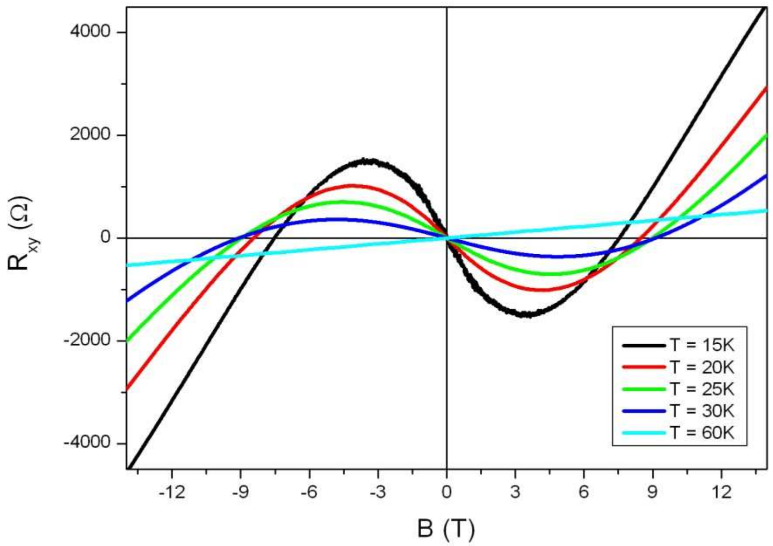
Example: p-d exchange interaction in a 2DHG

Mn (S=5/2) in two-dimensional hole gas



Nature Physics
6, 955 (2010)



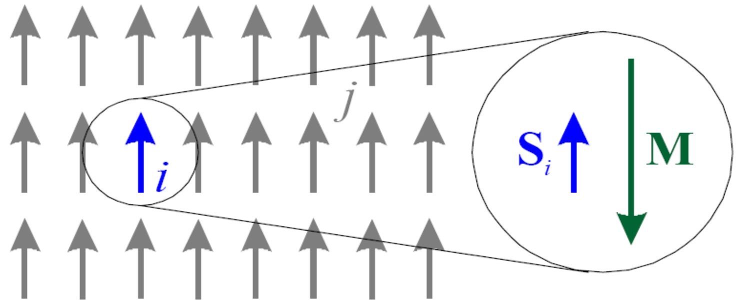


see: **WP-20** Anomalous Hall effect in Mn doped,p-type InAs quantum wells
C. Wensauer, D. Vogel et al.

Weiss molecular field

Pierre Weiss 1907

Idea: Replace interaction of a given spin with all other spins by interaction with an effective field (molecular field)



Sum of all $\mathbf{S}_j$ act on one particular spin $\mathbf{S}_i$

magnetic moment $\boldsymbol{\mu}_i$ of spin $\mathbf{S}_i$

$$E_{ex} = -2\mathbf{S}_i \cdot \sum_j J_{ij}\mathbf{S}_j ,$$

$$\boldsymbol{\mu}_i = \frac{-g\mu_B \mathbf{S}_i}{\hbar} \Rightarrow \mathbf{S}_i = -\frac{\boldsymbol{\mu}_i \hbar}{g\mu_B}$$

$$E_{ex} = 2\frac{\boldsymbol{\mu}_i \hbar}{g\mu_B} \cdot \sum_j J_{ij}\mathbf{S}_j = -\boldsymbol{\mu}_i \cdot \left(\frac{2\hbar^2}{(g\mu_B)^2} \langle \boldsymbol{\mu}_i \rangle \sum_j J_{ij} \right) = -\boldsymbol{\mu}_i \cdot \mathbf{B}_M$$

$= \lambda \mathbf{M}$

Weiss molecular field $\mathbf{B}_M$

$\vec{S}_j$ replaced by constant moment: $\langle \boldsymbol{\mu}_j \rangle = -g\mu_B \langle \mathbf{S}_j \rangle / \hbar \Rightarrow \langle \mathbf{S}_j \rangle = -\hbar \langle \boldsymbol{\mu}_j \rangle / g\mu_B$

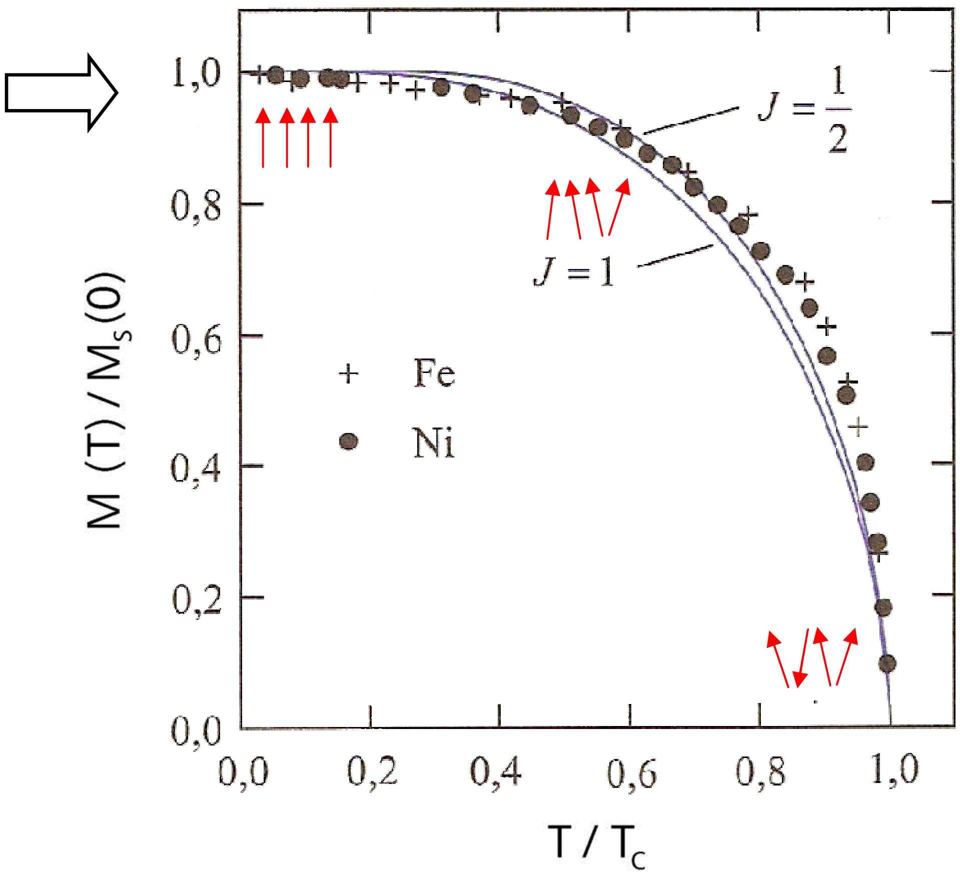
Magnetic moments get aligned in an effective field $\mathbf{B}_{eff} = \mathbf{B}_0 + \mathbf{B}_M >> \mathbf{B}_0$

Ferromagnetism within the molecular field picture

Molecular field $B_m = \lambda M$ allows to map ferromagnetism onto paramagnetism

$$M = N g_J J \mu_B \left[\frac{2J+1}{2J} \coth\left(\frac{2J+1}{2J} x \right) - \frac{1}{2J} \coth\left(\frac{x}{2J} \right) \right] \quad \text{with} \quad x = \frac{g_J J \mu_B (B + \lambda M)}{kT}$$

M on both sides of equation:
graphical or numerical solution



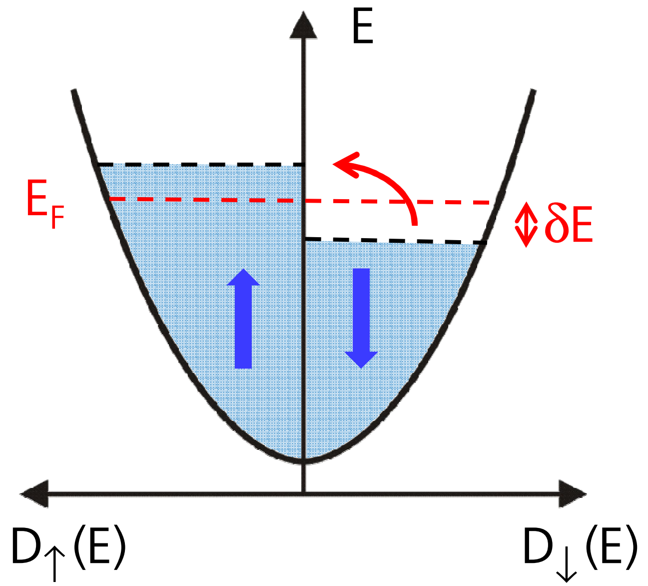
$$T_C = \frac{g_J \mu_B (J+1) \lambda M_S}{3 k_B}$$

Für $T_C \sim 10^3 K$ und $J = 1/2 \Rightarrow$

$B_M = \lambda M_S \sim 1500T$

Band magnetism and Stoner criterion

Heisenberg Model unable to describe all aspects of ferromagnetism e.g. moment of iron is 2.2 μ_B. Stoner picture:



Redistribution of spins: Energy cost E_{kin}

$$\Delta E_{kin} = \frac{1}{2} D(E_F)\delta E^2$$

Resulting magnetization

$$M = \left(n_\uparrow - n_\downarrow\right)\mu_B = D(E_F)\mu_B \delta E$$

Energy of electron's magnetization dM in effective (Weiss) field B_{eff} of other electrons

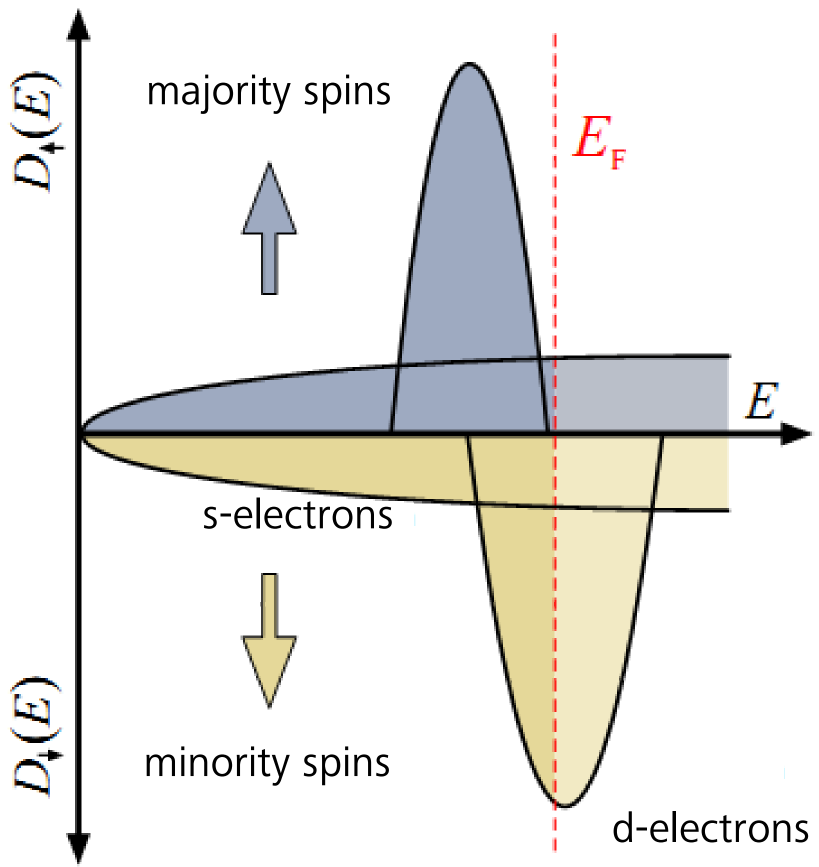
$$dEpot = -dM \cdot B_{eff} \rightarrow \Delta E_{pot} = -\int_0^M dM'\lambda M' = -\lambda \frac{M^2}{2} = -\frac{1}{2}\lambda\mu_B^2 D(E_F)^2 \delta E^2$$

Energy gain if $\Delta E_{kin} + \Delta E_{pot} = \frac{1}{2} D(E_F)\delta E^2 [1 - \lambda\mu_B^2 D(E_F)] < 0$

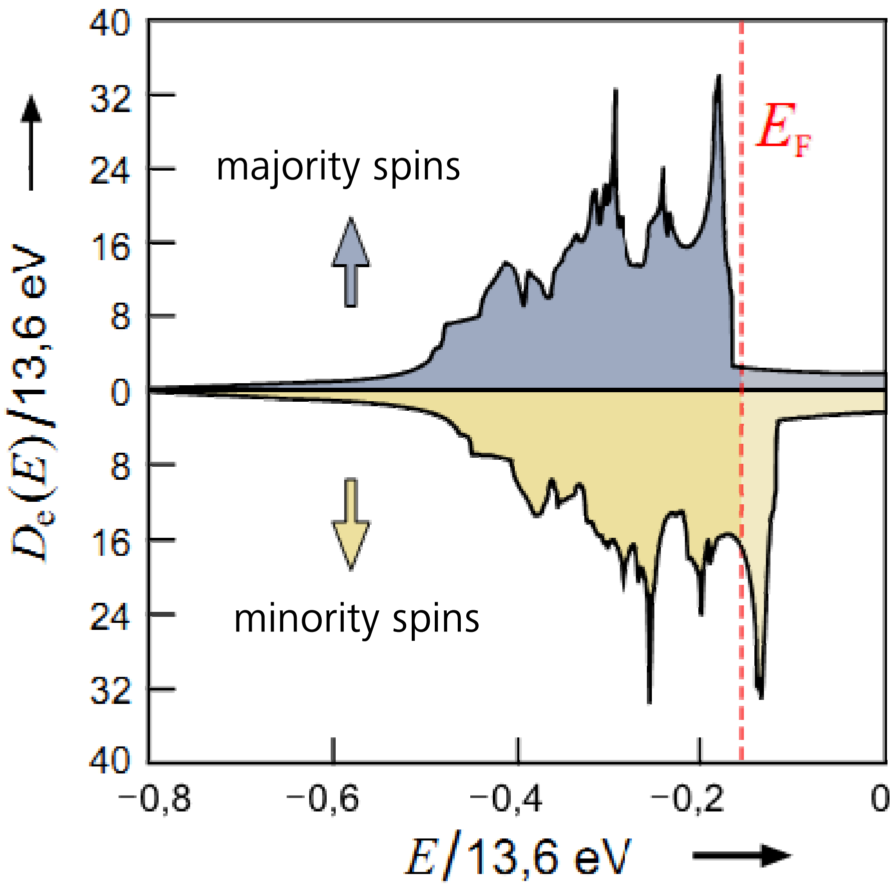
Ferromagnetism occurs if $\lambda\mu_B^2 \cdot D(E_F) \geq 1$ **Stoner criterion** (holds for Fe, Ni, Co)

Ferromagnet: Density of States D(E)

Schematic

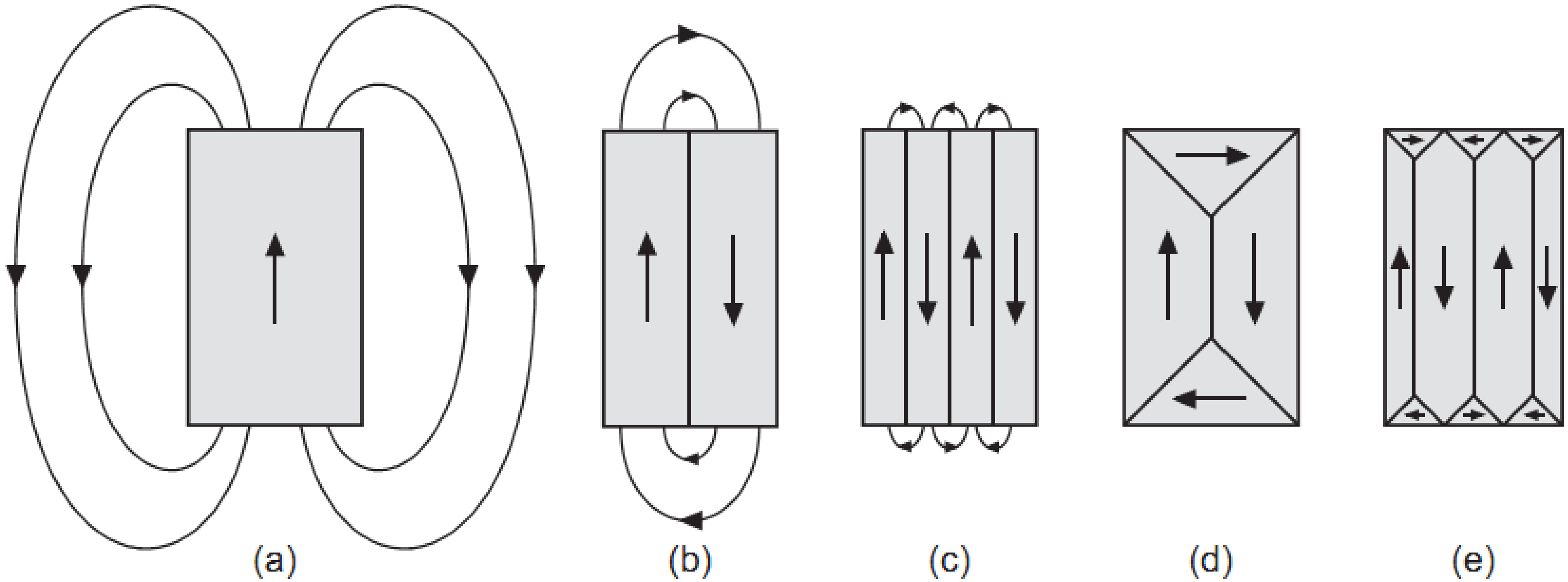


Nickel



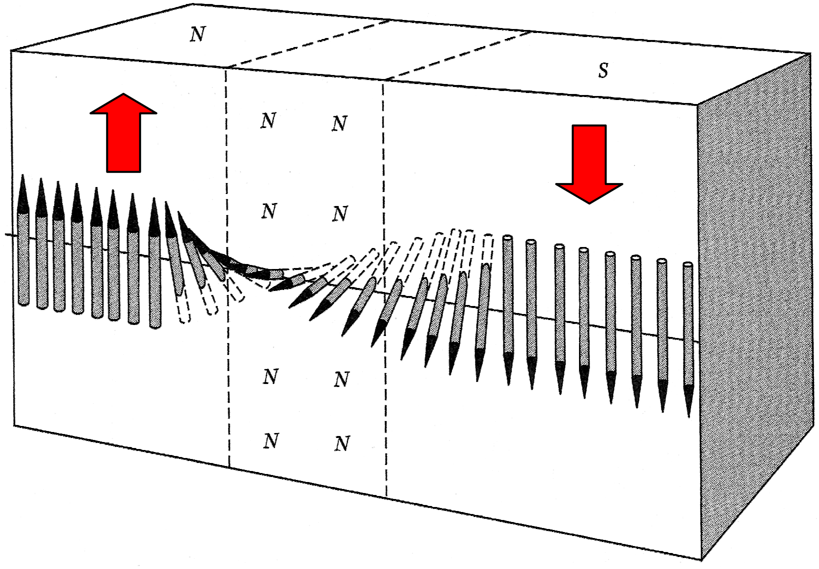
Magnetic Domains

Energy of stray field $\mathbf{H}_d$: $E_d = \frac{1}{2}\mu_0 \int_{\text{space}} \mathbf{H}_d^2 \, dV = -\frac{1}{2}\mu_0 \int_{\text{sample}} \mathbf{H}_d \cdot \mathbf{M} \, dV$



Formation of domains reduces stray field energy!

Width of a Bloch wall



Classical Heisenberg Hamiltonian

$$E_{ex} = -2J\mathbf{S}_1 \cdot \mathbf{S}_2 = -2JS^2 \cos\theta$$

$$\theta = 0 \rightarrow E_{ex} = -2JS^2$$

Energy to rotate spin by angle θ

$$\theta \neq 0 \rightarrow \Delta E_{ex} = JS^2\theta^2 \quad \text{for } \theta << 1$$

Spin rotation by π over N sites $\Rightarrow \theta = \frac{\pi}{N} \Rightarrow$ energy cost per line : $\Delta E_{ex} = JS^2 \frac{\pi^2}{N}$

Energy per unit area $\varepsilon_{ex} = \frac{\Delta E_{ex}}{a^2} = JS^2 \frac{\pi^2}{Na^2}$

a: lattice constant

$\Rightarrow$ best $N \rightarrow \infty$?

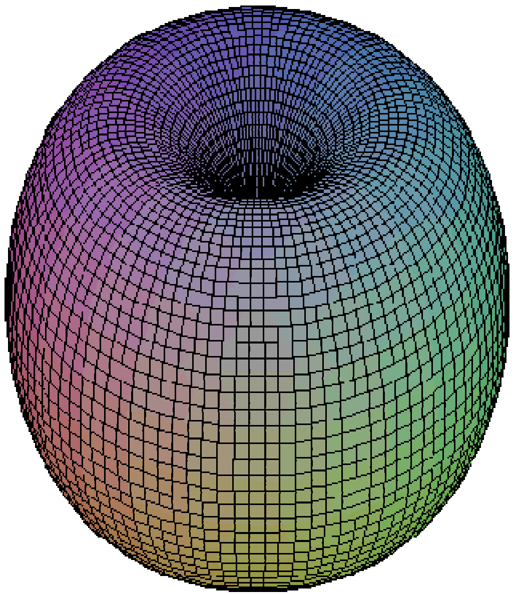
Magnetocrystalline anisotropy

Ferromagnetic crystals have easy and hard axes. Along some crystallographic directions it is easy to magnetize the crysal, along others harder. Reflects the crystal symmetry.

Extra energy associated with magnetocrystalline anisotrpy:

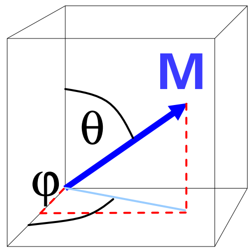
uniaxial anisotropy (e.g. Co)

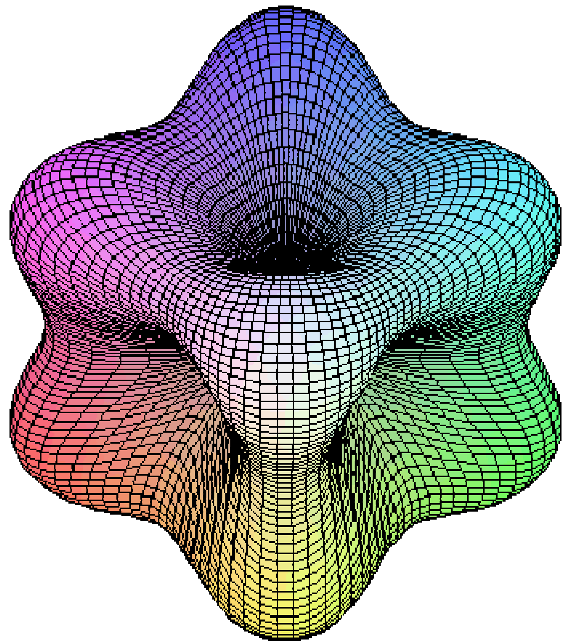
$$E = K_1 \sin^2(\theta) + K_2 \sin^4(\theta) + \ldots$$



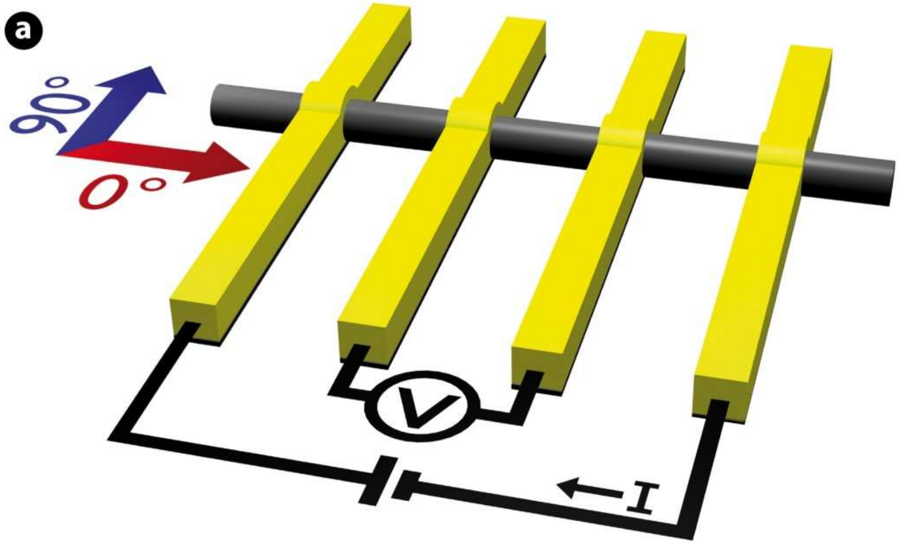
cubic anisotropy (e.g. Fe)

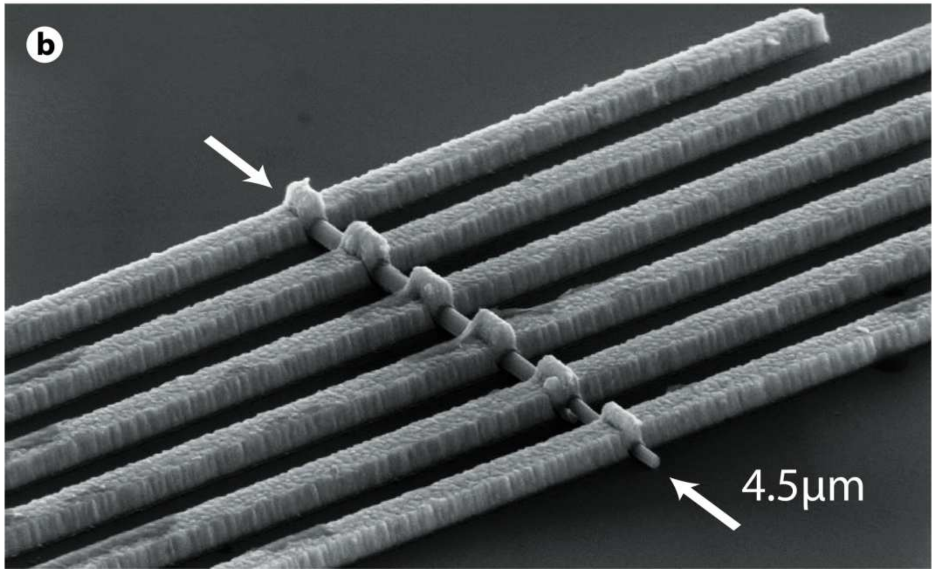
$$E = K_1 \left(\tfrac{1}{4} \sin^2(\theta) \sin^2(2\varphi) + \cos^2(\theta) \right) \sin^2(\theta) + \ldots.$$



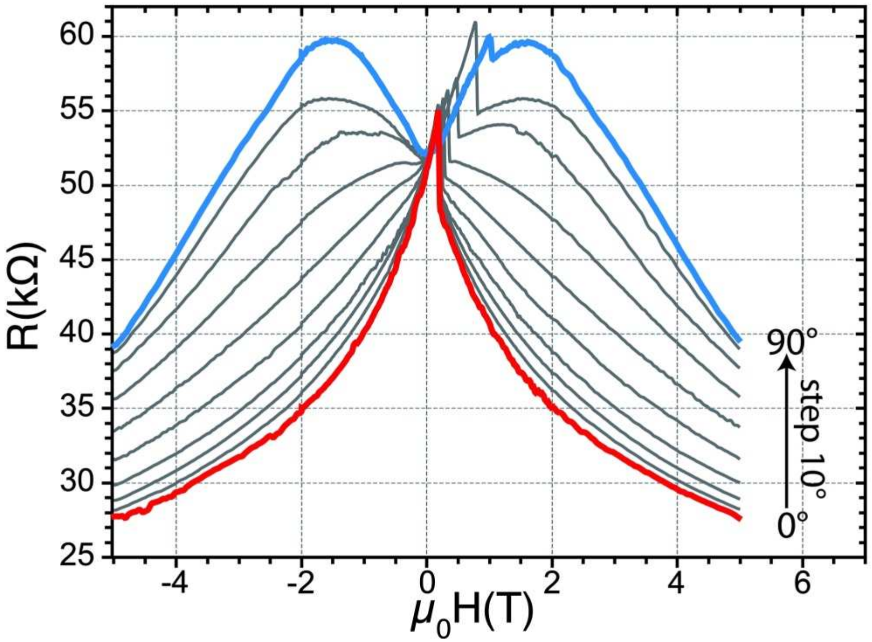


Example: GaMnAs core-shell nanowires



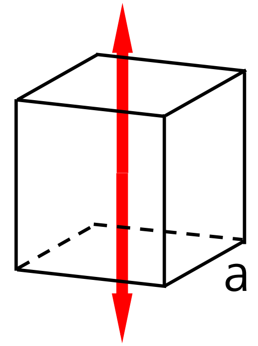


system with very strong uniaxial anisotropy



see: **WP-22**, C. Butschkow et al.

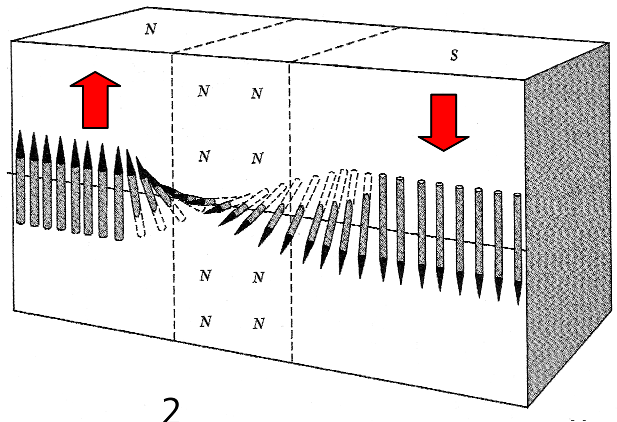
Width of a Bloch wall, continued



assume simple form of anisotropy energy

$$E_{ani} = K\sin^2(\theta); \quad K > 0$$

energy cost of rotation out of easy direction



$$\sum_{i=1}^{N} K\sin^2\theta_i \approx \frac{N}{\pi}\int_0^{\pi} K\sin^2\theta \, d\theta = \frac{NK}{2}$$

energy per unit area $= \frac{NKa}{2}$

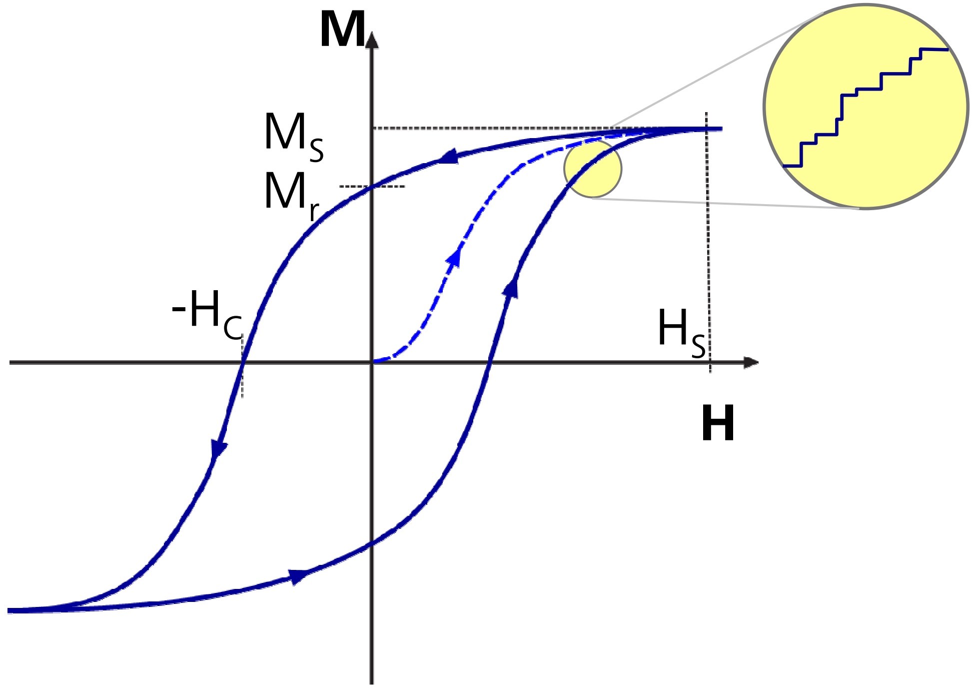
exchange energy + anisotropy energy $\varepsilon_{BW} = \frac{NKa}{2} + JS^2\frac{\pi^2}{Na^2}$

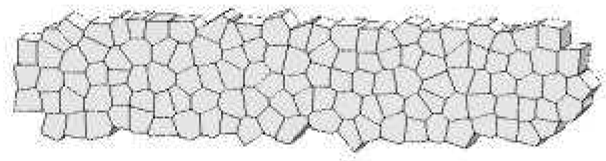
From $d\varepsilon_{BW}/dN = 0 \Rightarrow N = \pi S\sqrt{\frac{2J}{Ka^3}} \Rightarrow Na = \pi S\sqrt{\frac{2J}{Ka}}$

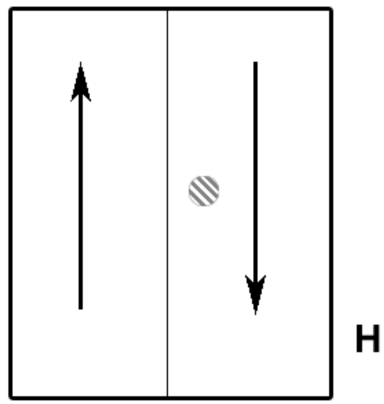
domain wall width

Reversal of magnetization: Hysteresis

macroscopic bulk material consisting of many domains



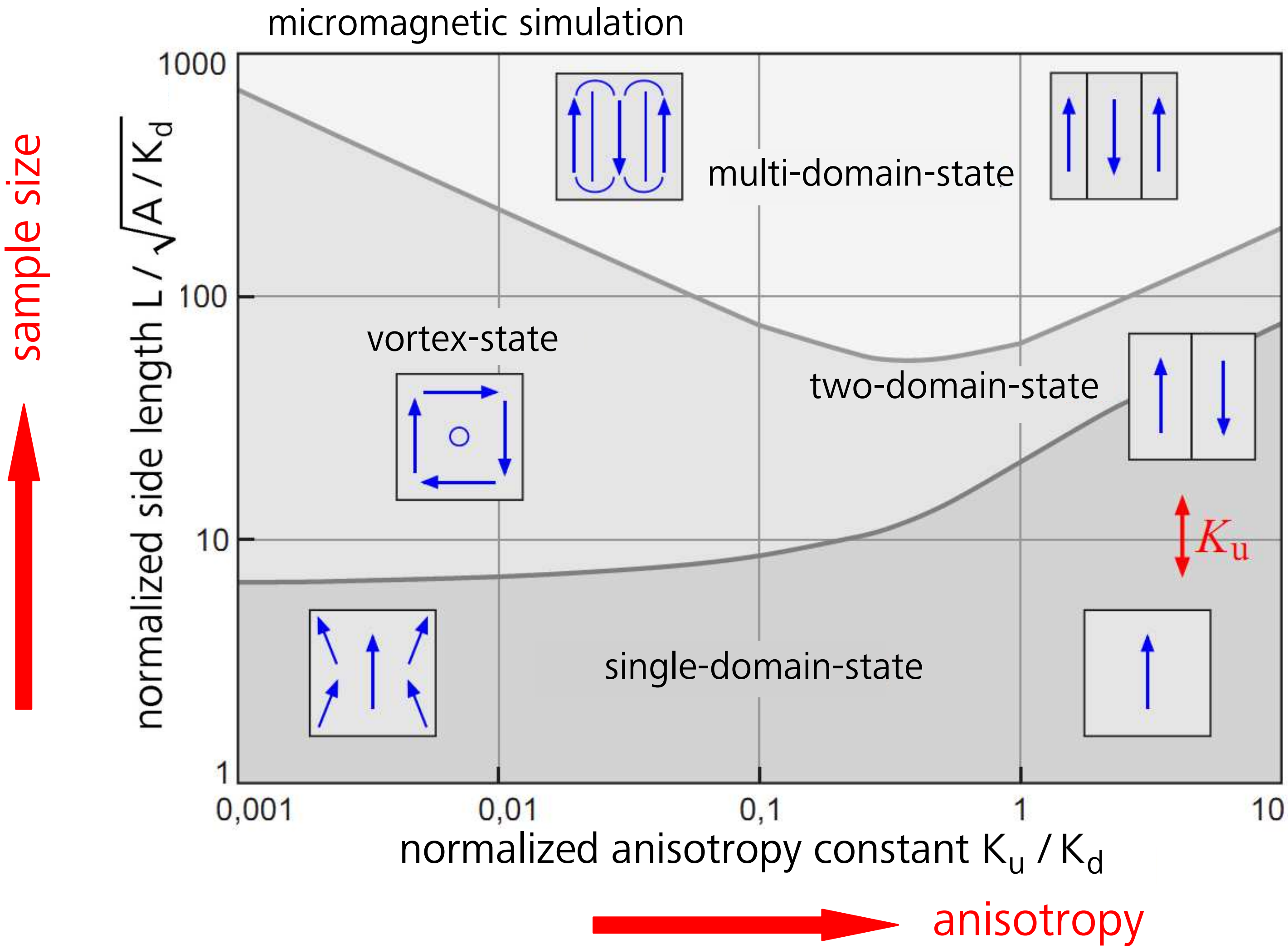


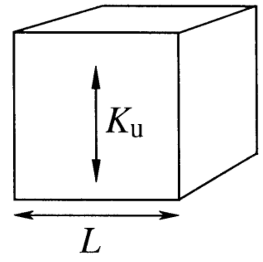


Processes

1. Shift of domain walls (reversible and irreversible)
2. Domain rotation towards nearest easy axis
3. Coherent rotation at high fields

Magnetization of a cube with uni-axial anisotrpy





W. Rave, K. Fabian, A. Hubert, JMMM **190**, 332 (1998)

Magnetism and Spin-Orbit Interaction:

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Basic concepts

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exchange interaction, domains, magnetic anisotropy,

Examples:

detection of (nanoscale) magnetization structure
using Hall-magnetometry, Lorentz microscopy and MFM

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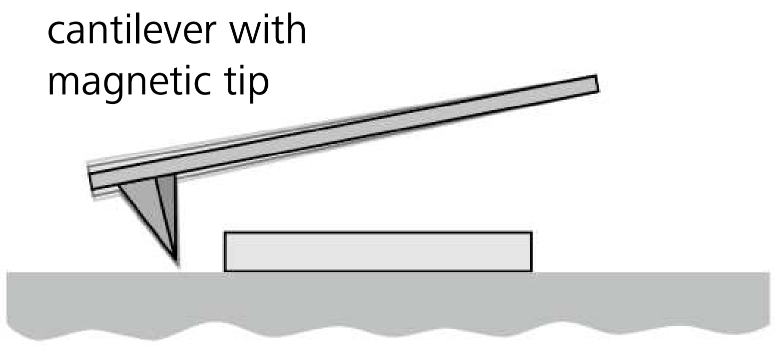
Rashba- and Dresselhaus contribution, SO-interaction and effective magnetic field

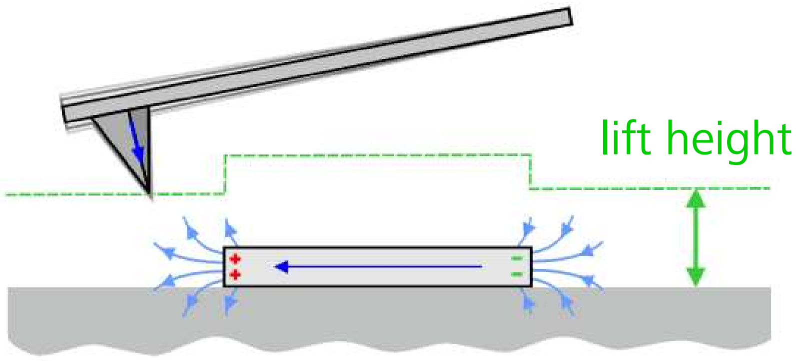
Example:

Ferromagnet-Semiconductor Hybrids: TAMR involving epitaxial Fe/GaAs interfaces

Measurement of domains: magnetic force microscopy

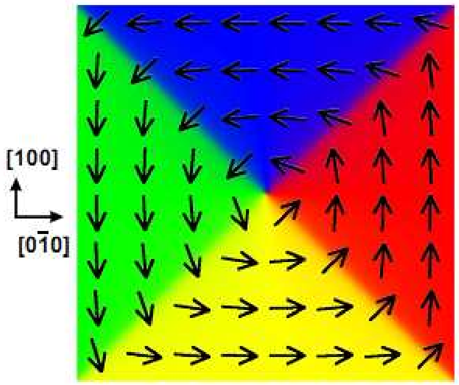


1. topography scan

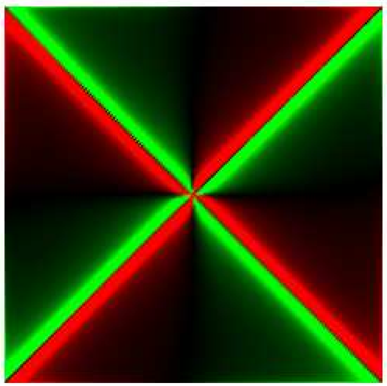


2. MFM scan (lift mode)

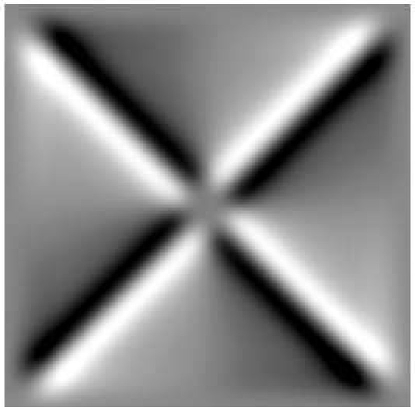
MFM measures „magnetic charges“



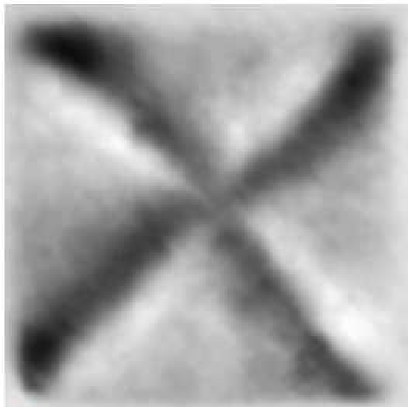
magnetization **M**



div **M**



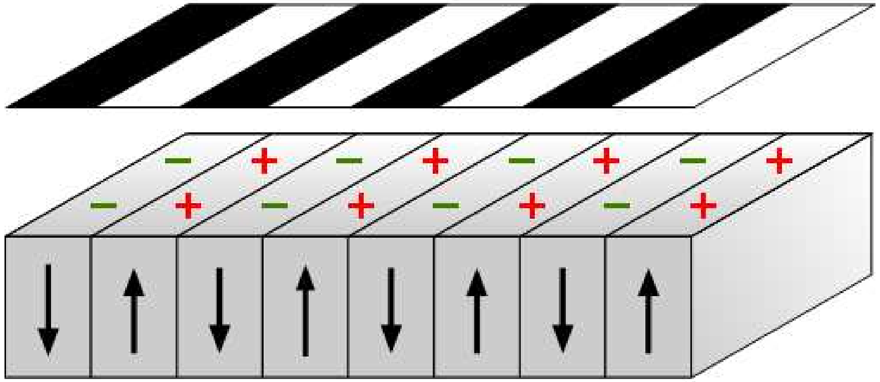
sim. MFM picture

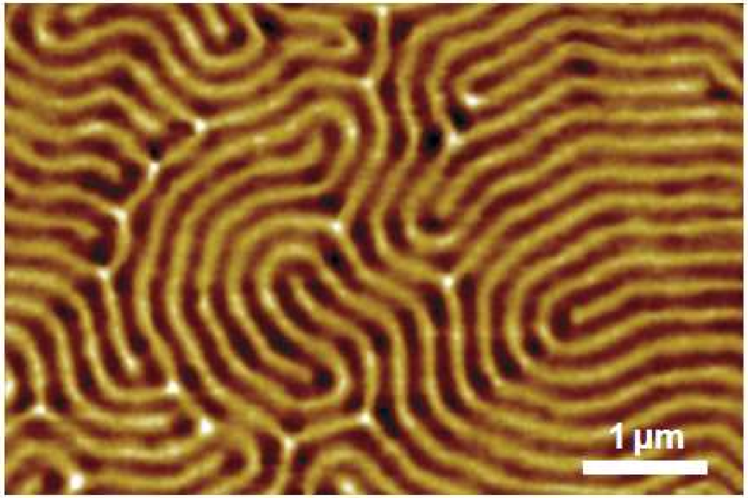


real MFM picture

Domains, measured by MFM

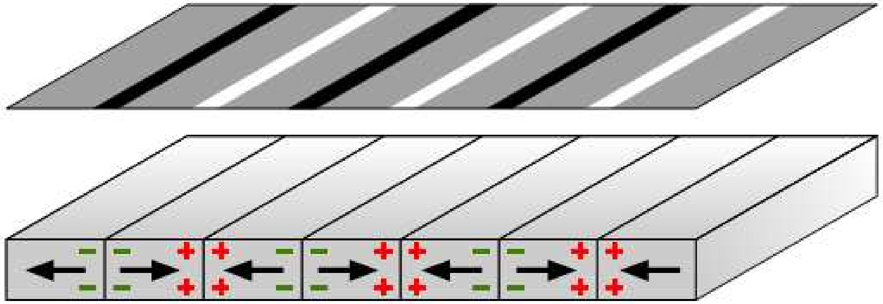
Perpendicular magnetization

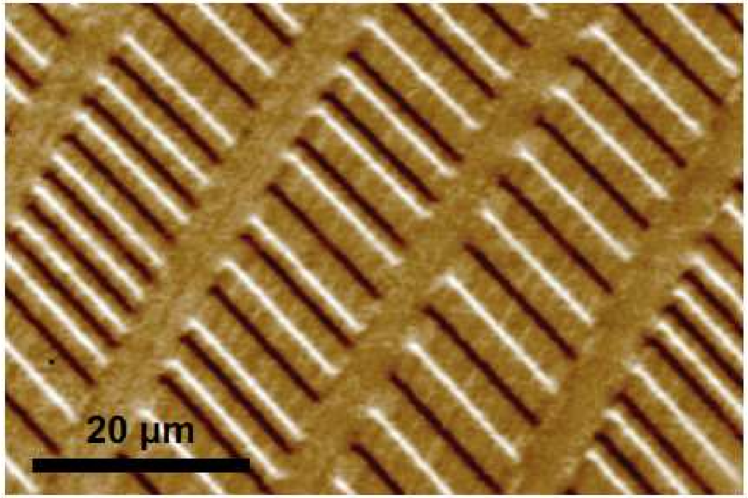




4Å Fe / 4Å Gd (75 layers)

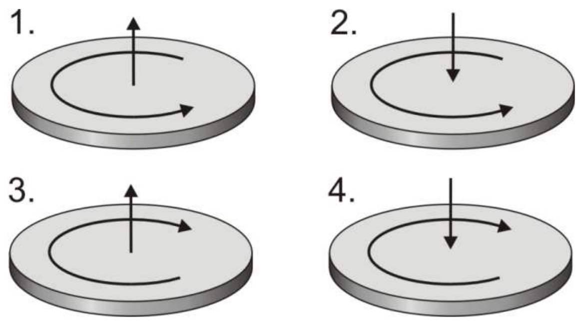
in-plane magnetization





50 Mbyte hard drive

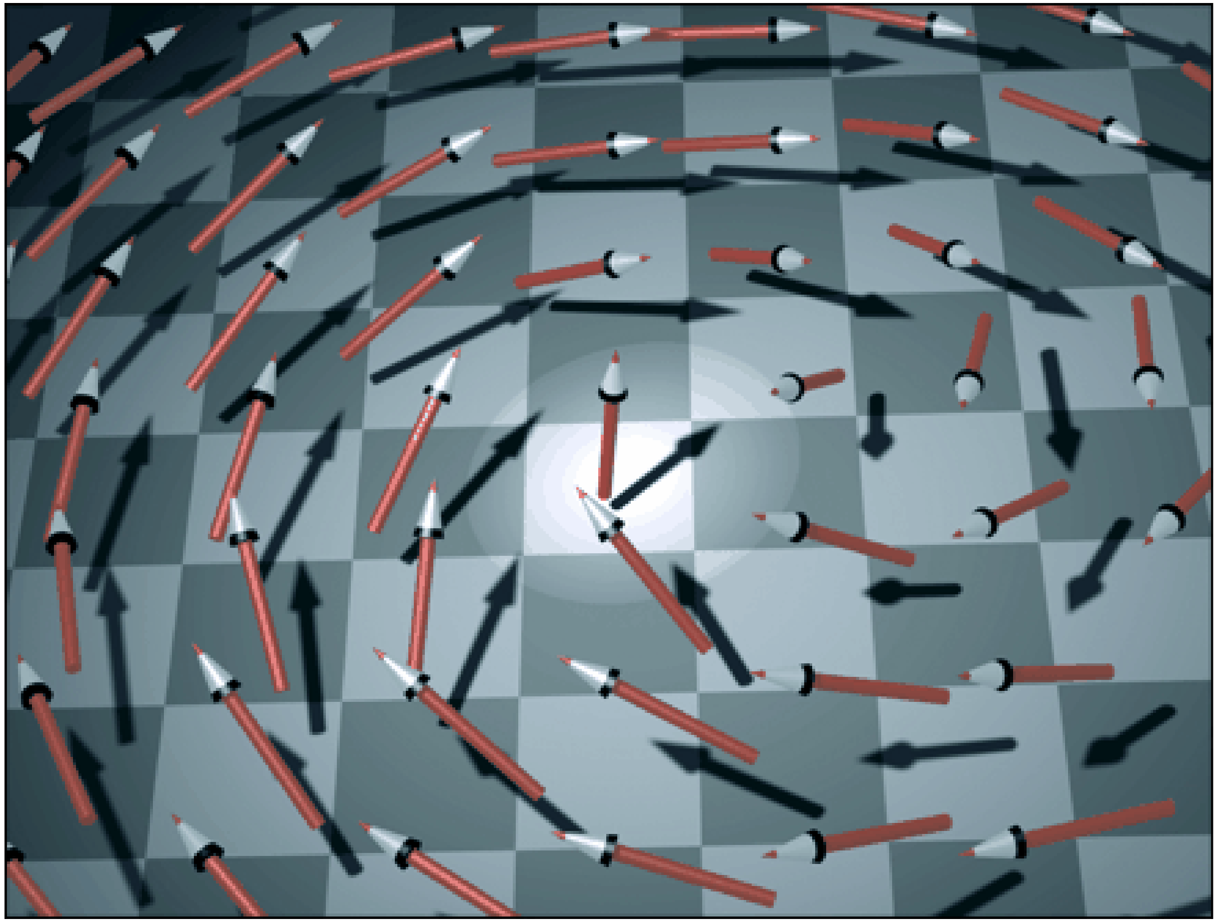
Between multidomain and single-domain state: vortex structure



4 ground state configurations

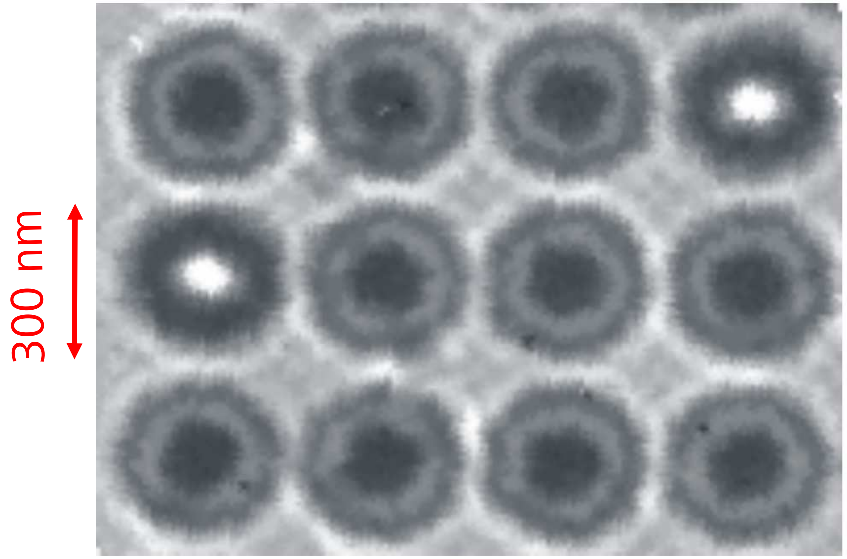
in-plane and out-of plane magnetization component can be switched independently!

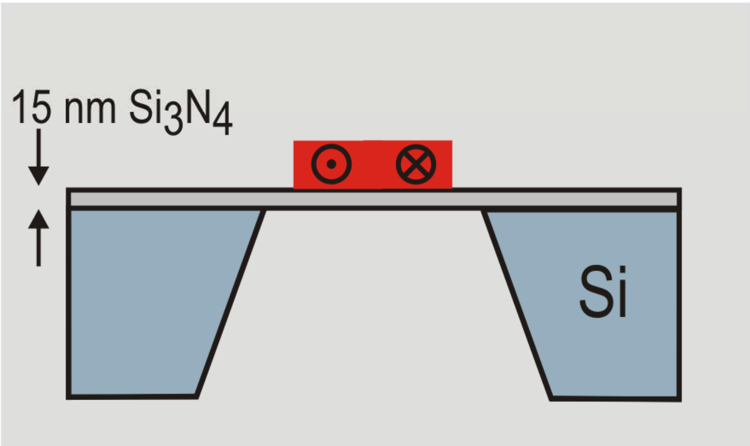
Picture: Ref [3)]

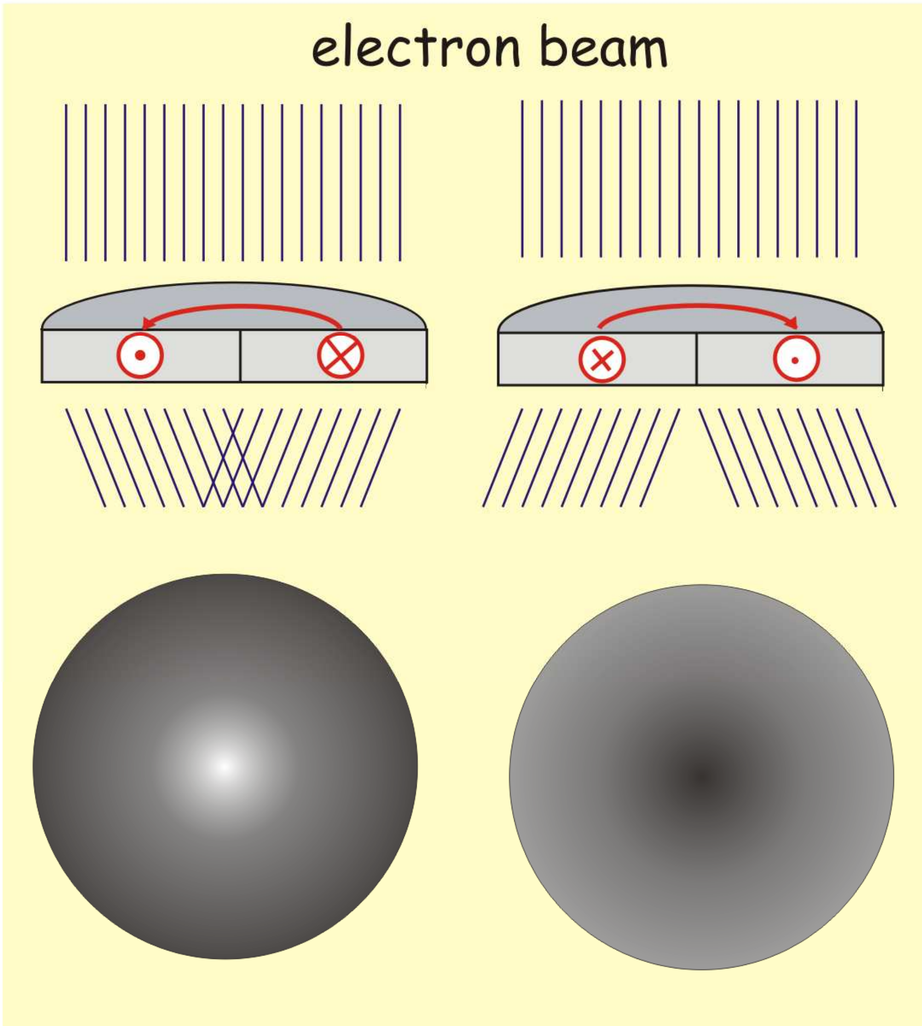


[1)] J. Raabe, R. Pulwey et al., J. Appl. Phys. **88**, 4437 (2000)
[2)] T. Shinjo et al., Science 289, 930 (2000)
[3)] A. Wachowiak et al., Science **298**, 577 (2002)

Detection of in-plane vortex



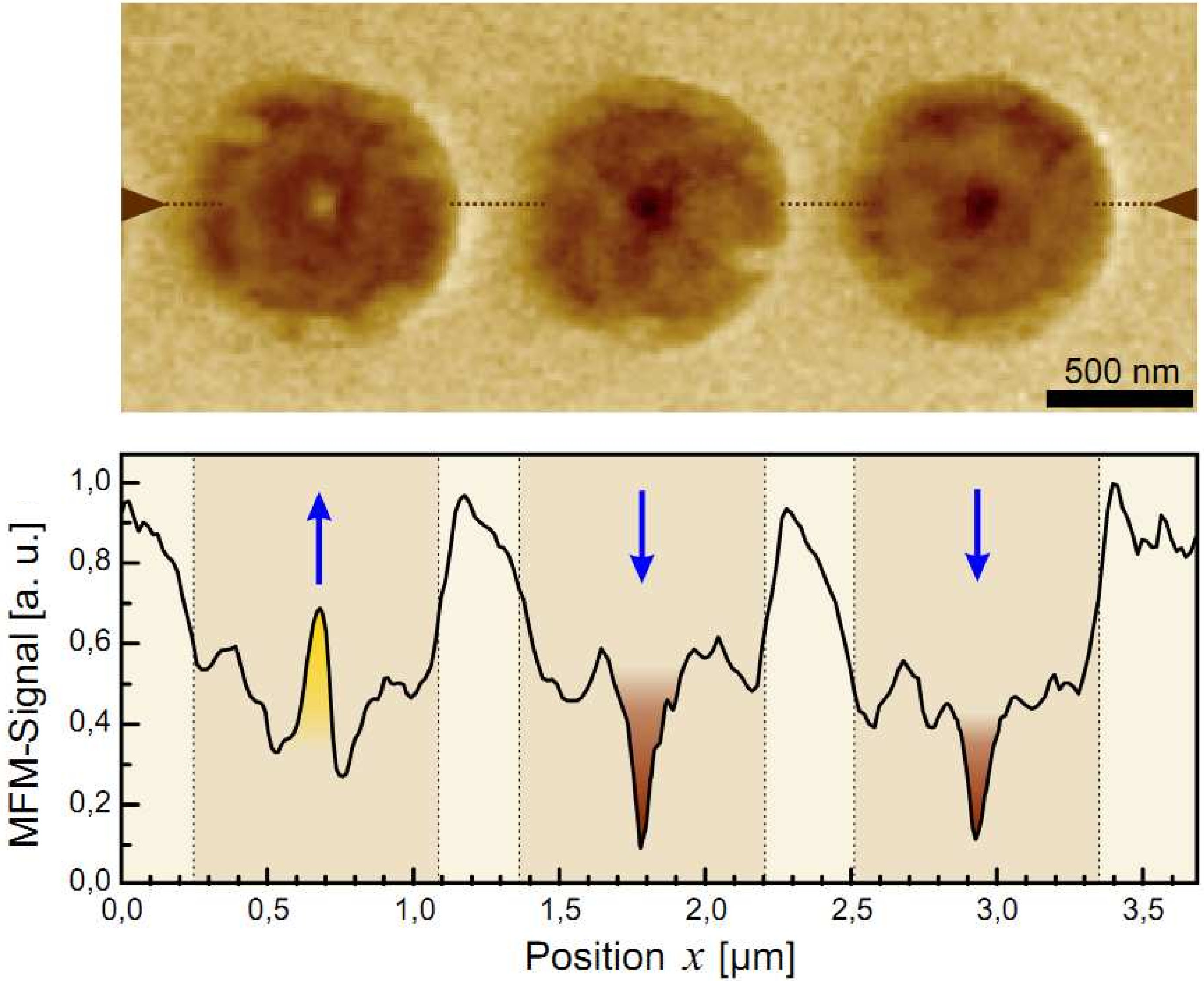




Lorentz-microscopy probes in-plane magnetization…

J. Raabe, R. Pulwey et al., J. Appl. Phys. **88**, 4437 (2000)

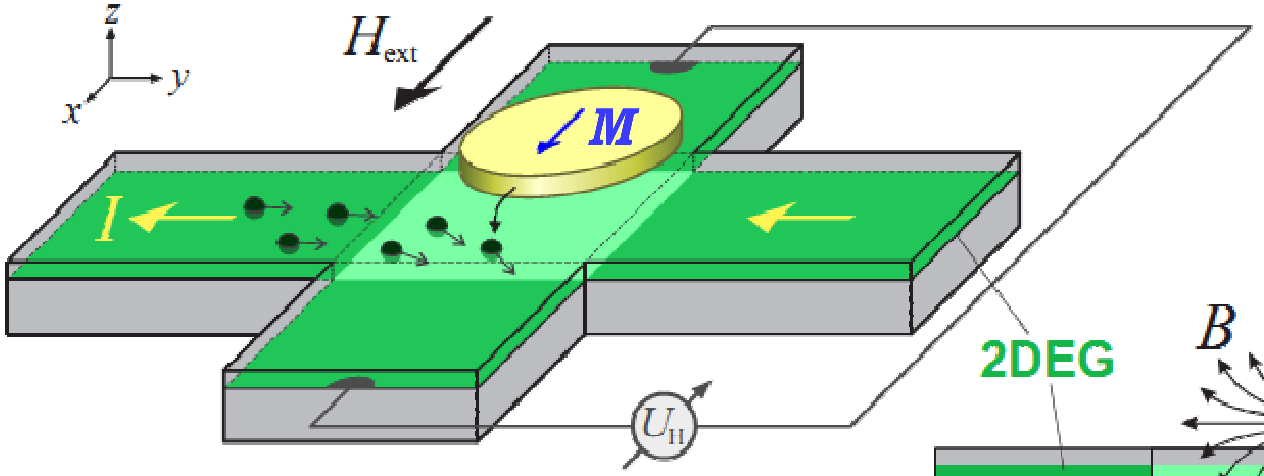
Detection of vortex singularity

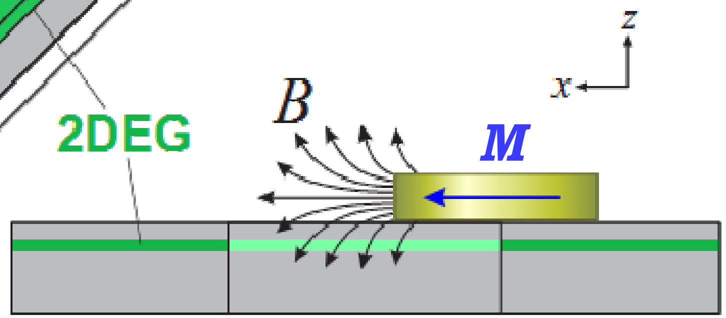


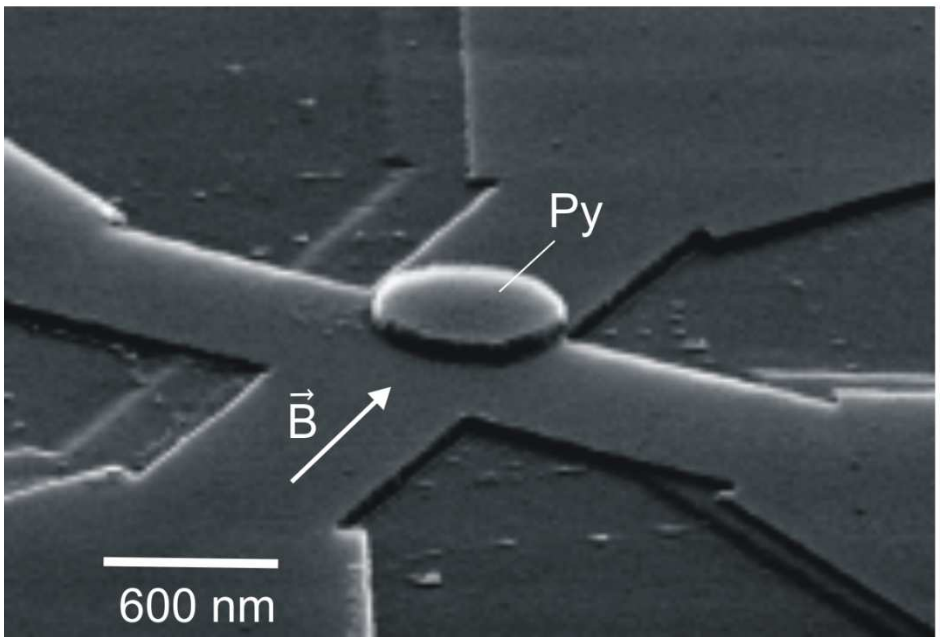
J. Raabe, R. Pulwey et al., J. Appl. Phys. **88**, 4437 (2000)

Another technique: Micro Hall magnetometry

allows to measure hysteresis traces



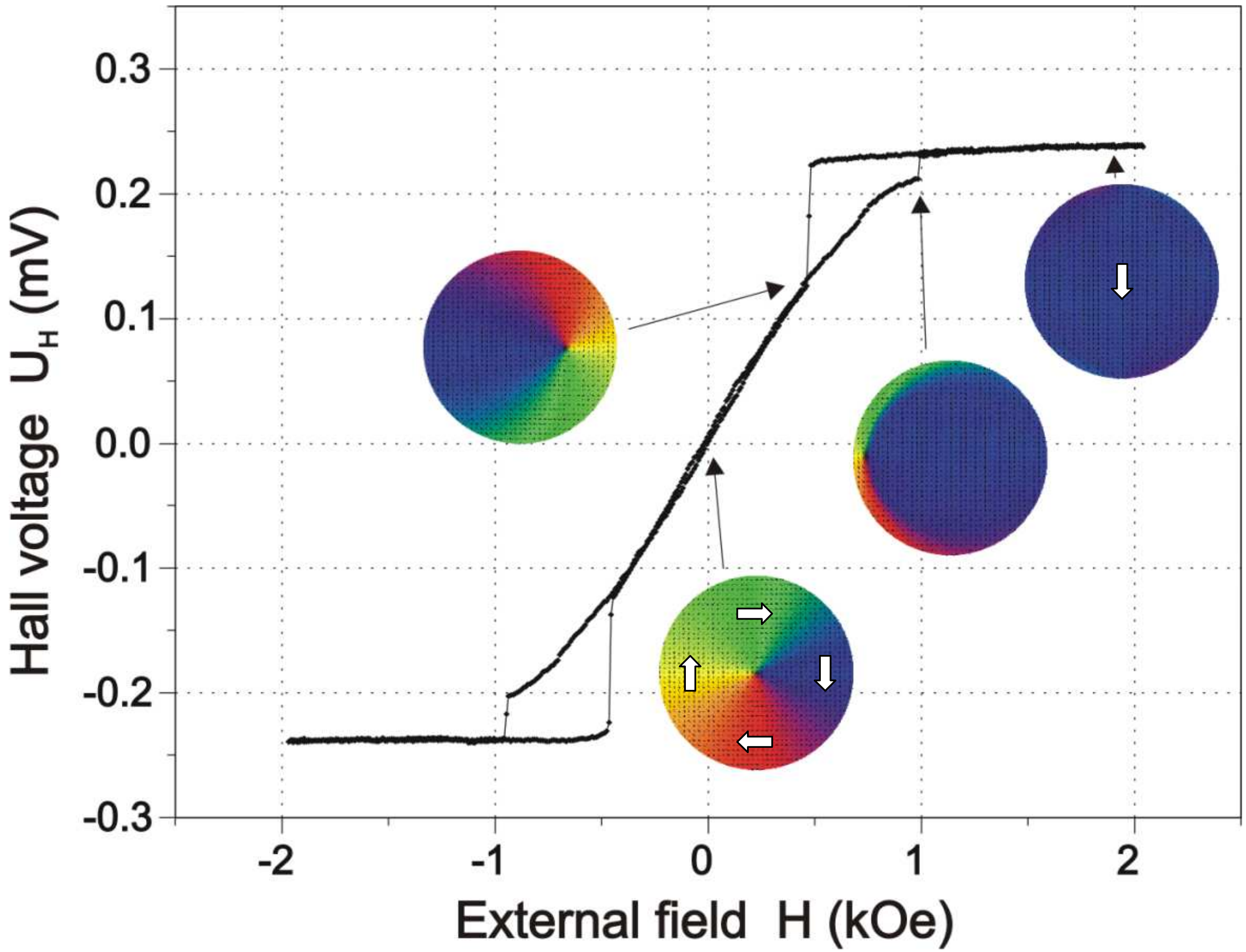




Measures directly the stray field, averaged over the central area of the Hall junction

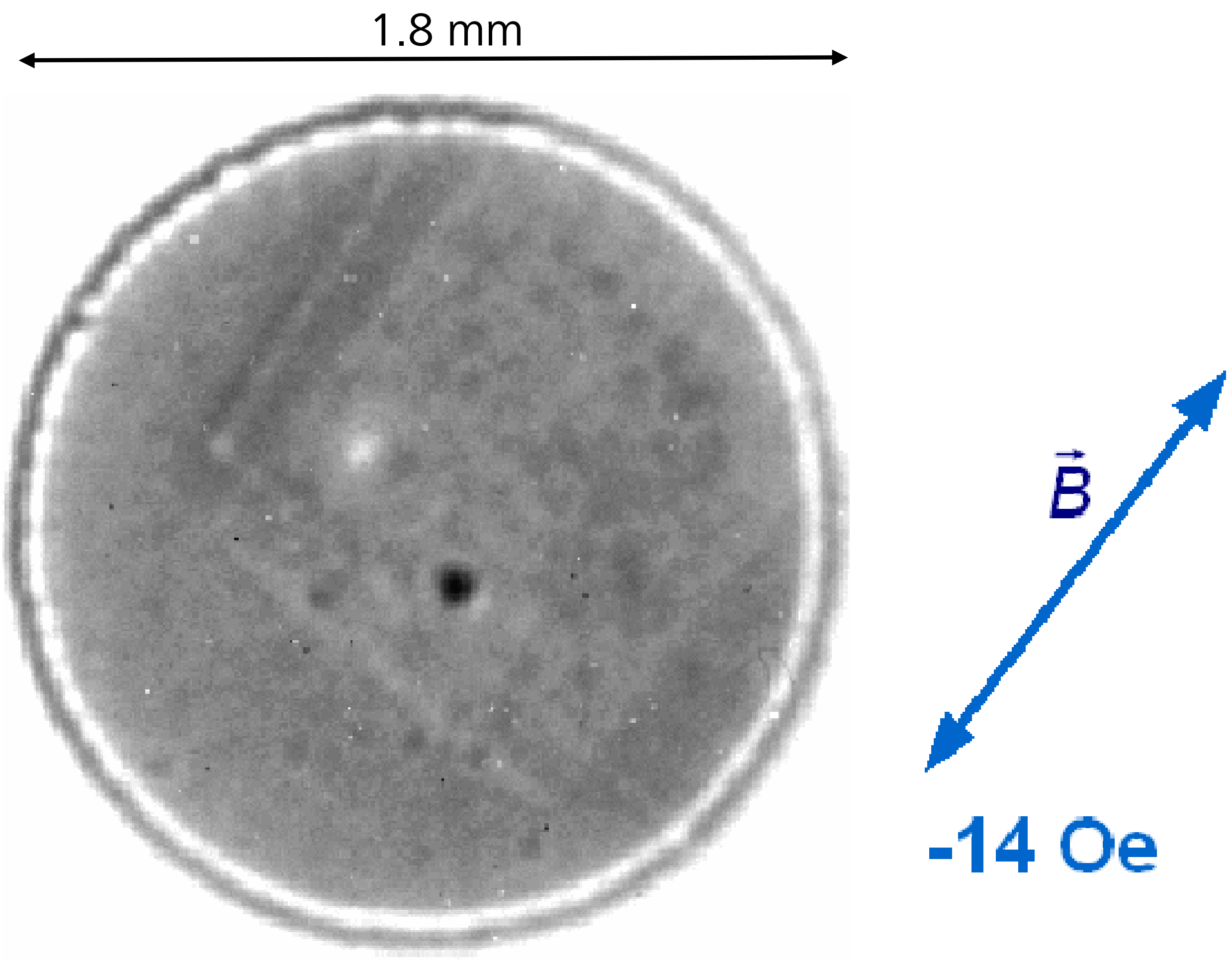
$$U_H = \frac{I}{en_s}\langle B \rangle$$

Hysteresis trace of a vortex state



M. Rahm et al., J. Appl. Phys. **93**, 7429 (2003)

Vortex-Golf



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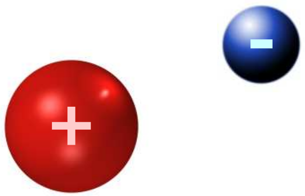
Origin of spin-orbit (SO) interaction

Spin-orbit interation $E = -\mu_B B_{eff}$ due to orbital motion

magnetic moment of electron

electron

nucleus



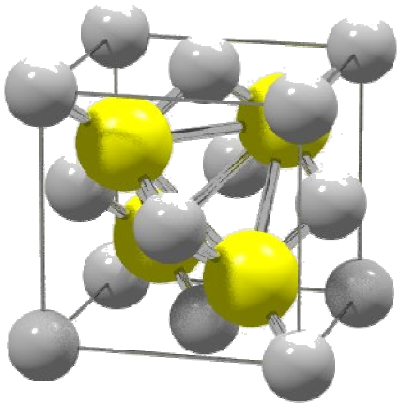
$$\hat{H}_{SO} = -\mu_B \hat{\boldsymbol{\sigma}} \cdot \left[\frac{\mathbf{E} \times \mathbf{p}}{2mc^2} \right]$$

vector of Pauli spin matrices

$$\mathbf{B}_{eff} = \frac{\mathbf{E} \times \mathbf{p}}{2mc^2}$$

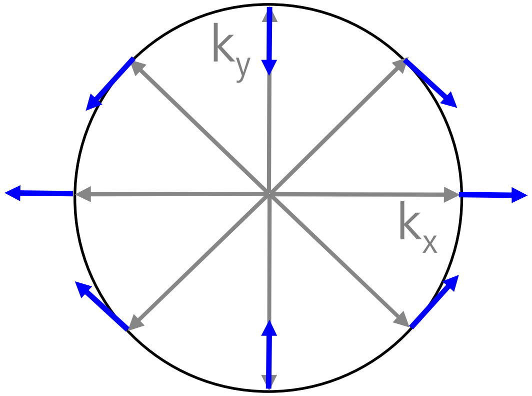
$$\hat{H}_{Zeeman} = -\mu_B \hat{\boldsymbol{\sigma}} \cdot \mathbf{B}$$

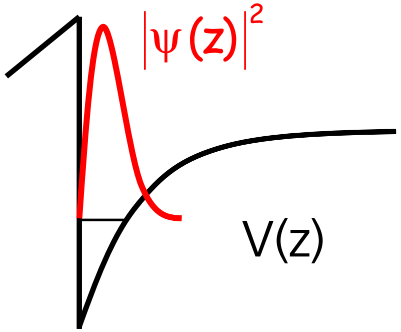
Electric field E in solids



Bulk inversion asymmetry (BIA)
Lack of inversion symmetry in III-V semiconductors
"Dresselhaus contribution γ"

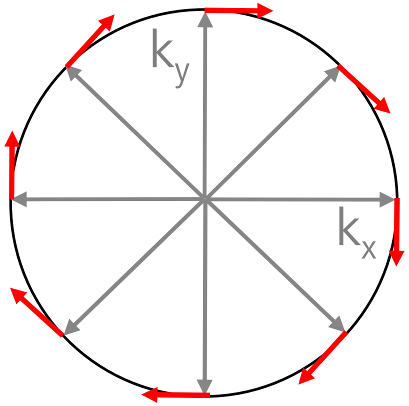
$$B_{BIA} \propto \gamma \begin{pmatrix} k_x \\ -k_y \end{pmatrix}$$





Structure inversion asymmetry (SIA) due to macroscopic confining potential: "Rashba contribution α". Tunable by external electric field!

$$B_{SIA} \propto \alpha \begin{pmatrix} k_y \\ -k_x \end{pmatrix}$$



SO interaction in 2DEG: Rashba & Dresselhaus terms

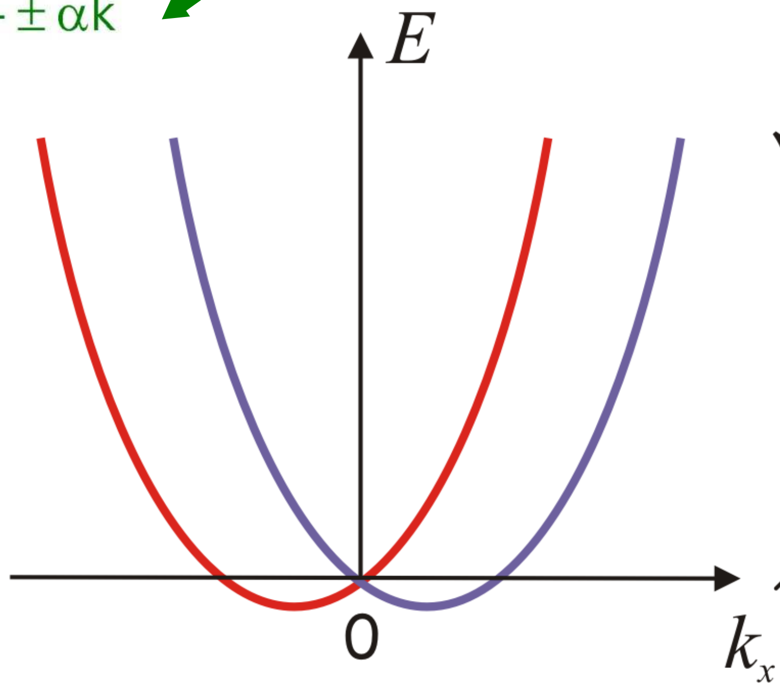
$$\hat{\mathbf{H}} = \frac{\hbar^2 k^2}{2m} + \hat{\mathbf{H}}_{SO} \quad \text{with}$$

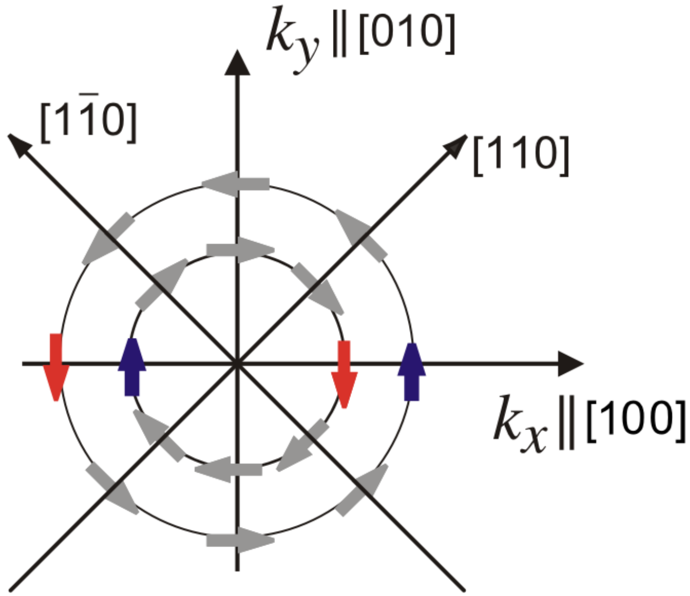
tunable by gate voltage

Pauli spin matrix

$$\hat{\mathbf{H}}_{SO} = \underbrace{\alpha(\boldsymbol{\sigma}_x k_y - \boldsymbol{\sigma}_y k_x)}_{\text{Rashba}} + \underbrace{\gamma(\boldsymbol{\sigma}_x k_x - \boldsymbol{\sigma}_y k_y)}_{\text{Dresselhaus}}$$

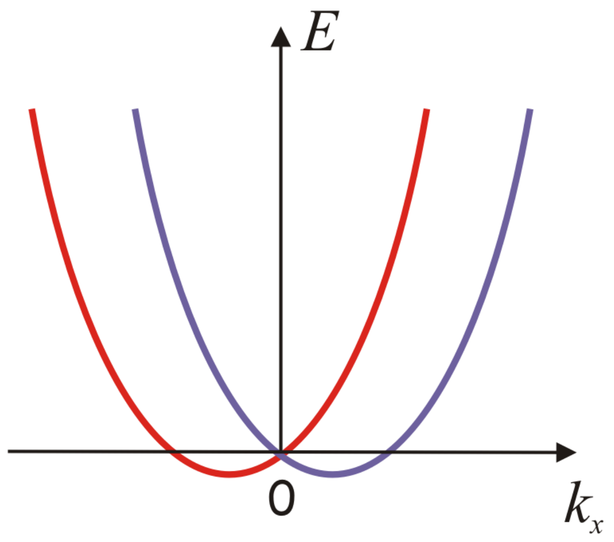
$$E = \frac{\hbar^2 k^2}{2m} \pm \alpha k$$





Calculation of Eigenvalue

$$E = \frac{\hbar^2 k^2}{2m} \pm \alpha k$$



$$\hat{\mathbf{H}}_{SO}^{Rashba} = \alpha(\boldsymbol{\sigma}_x k_y - \boldsymbol{\sigma}_y k_x)$$

$$\hat{\boldsymbol{\sigma}}_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}; \; \hat{\boldsymbol{\sigma}}_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}; \; \hat{\boldsymbol{\sigma}}_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Pauli Spin matrices

$$\hat{\mathbf{H}}_{SO}^{Rashba} = \alpha(\boldsymbol{\sigma}_x k_y - \boldsymbol{\sigma}_y k_x) =$$

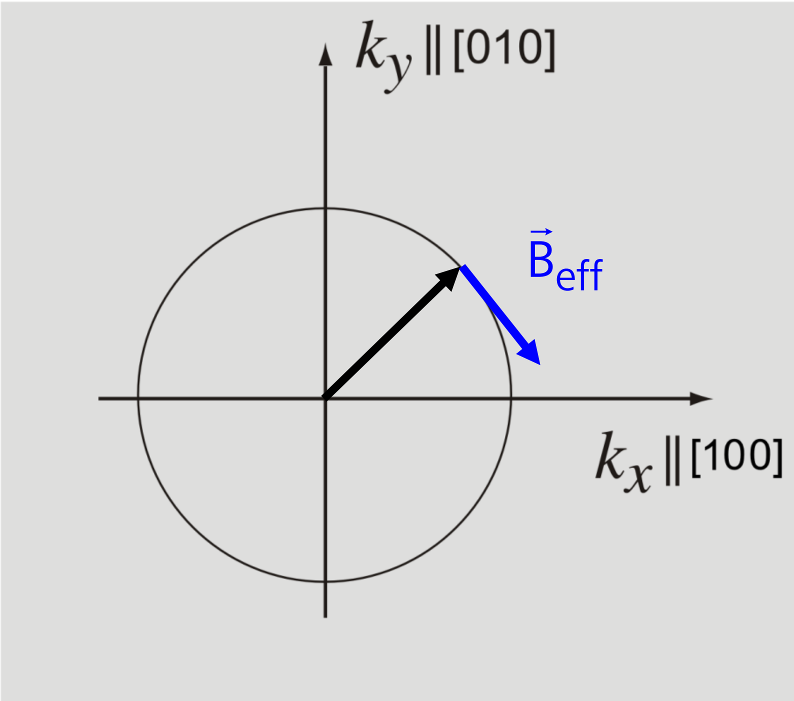
$$= \begin{pmatrix} 0 & \alpha k_y \\ \alpha k_y & 0 \end{pmatrix} - \begin{pmatrix} 0 & -i\alpha k_x \\ i\alpha k_x & 0 \end{pmatrix} = \begin{pmatrix} 0 & \alpha(k_y + ik_x) \\ \alpha(k_y - ik_x) & 0 \end{pmatrix}$$

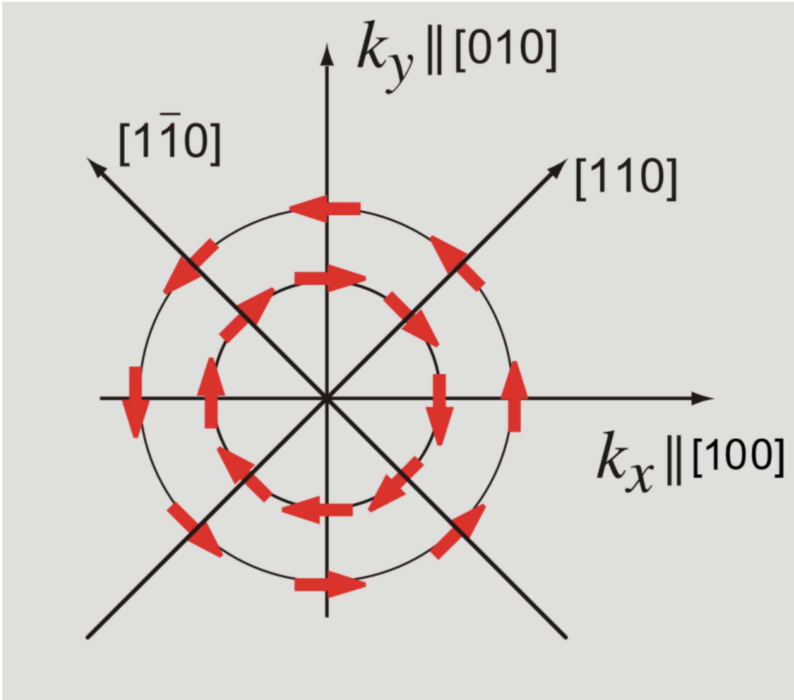
Eigenvalues of the matrix : $\pm\alpha\sqrt{k_x^2 + k_y^2} = \pm\alpha k_{\|}$

Description of zero-field spin splitting by B_{eff}

$$\hat{H}_{SO} = \underbrace{\alpha(\sigma_x k_y - \sigma_y k_x)}_{\text{Rashba}} + \underbrace{\gamma(\sigma_x k_x - \sigma_y k_y)}_{\text{Dresselhaus}} \sim \hat{\sigma}\cdot\vec{B}_{eff}; \quad \hat{\sigma}\cdot\vec{B}_{eff} = \sigma_x B_x + \sigma_y B_y + \sigma_z B_z$$

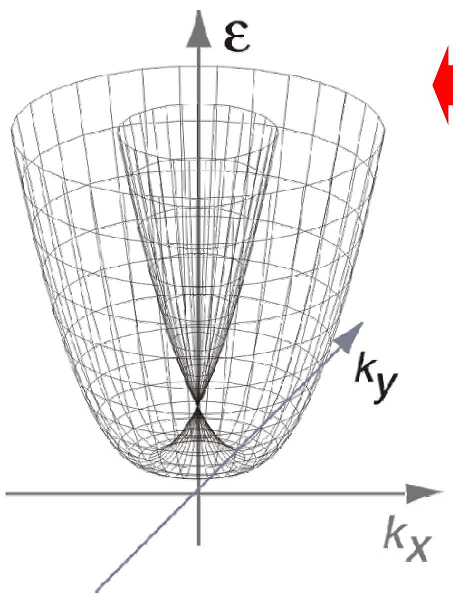
Comparison of coefficients. E.g. only Rashba contribution: $\vec{B}_{eff} \propto \alpha \begin{pmatrix} k_y \\ -k_x \end{pmatrix}$





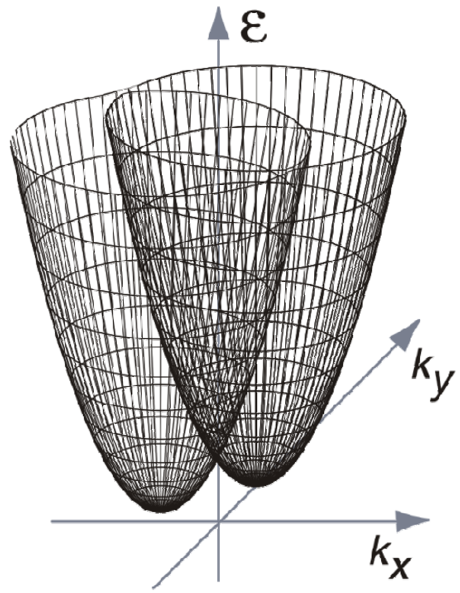
E.A. de Andrada e Silva PRB **46**, 1921 (1992)

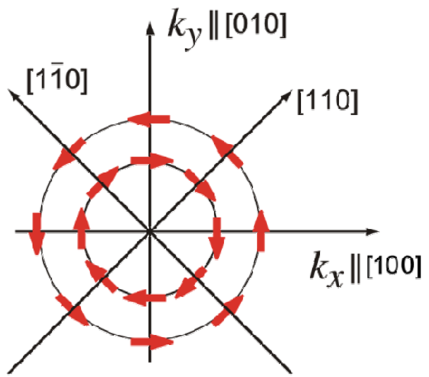
Presence of Rashba & Dresselhaus contributions



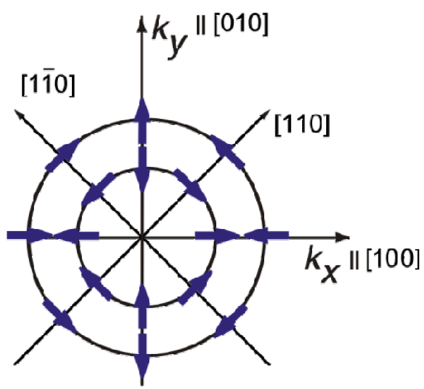
Rashba or Dresselhaus

Rashba and Dresselhaus



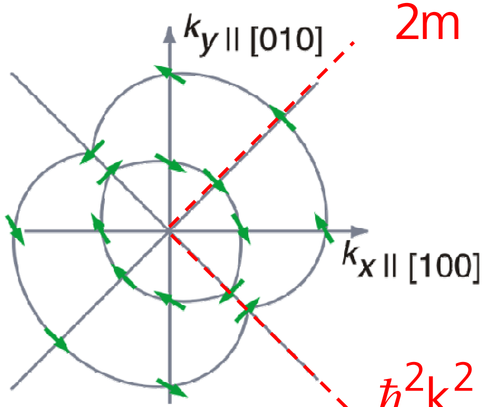


BIA=0
SIA≠0



BIA≠0
SIA=0

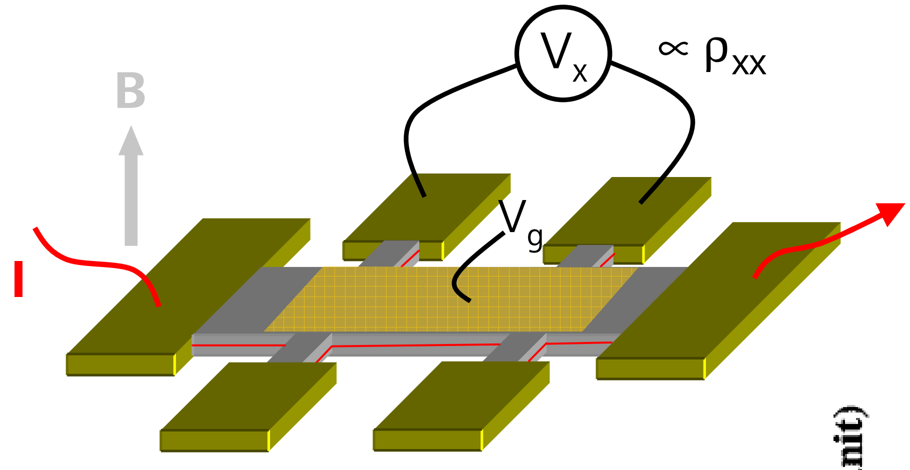
$$E = \frac{\hbar^2 k^2}{2m} \pm (\alpha + \gamma)\left|\vec{k}\right|$$

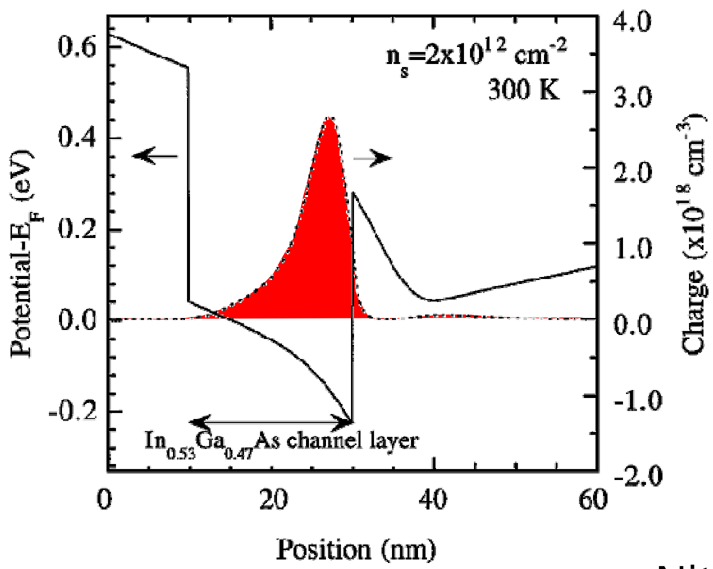


$$E = \frac{\hbar^2 k^2}{2m} \pm (\alpha - \gamma)\left|\vec{k}\right|$$

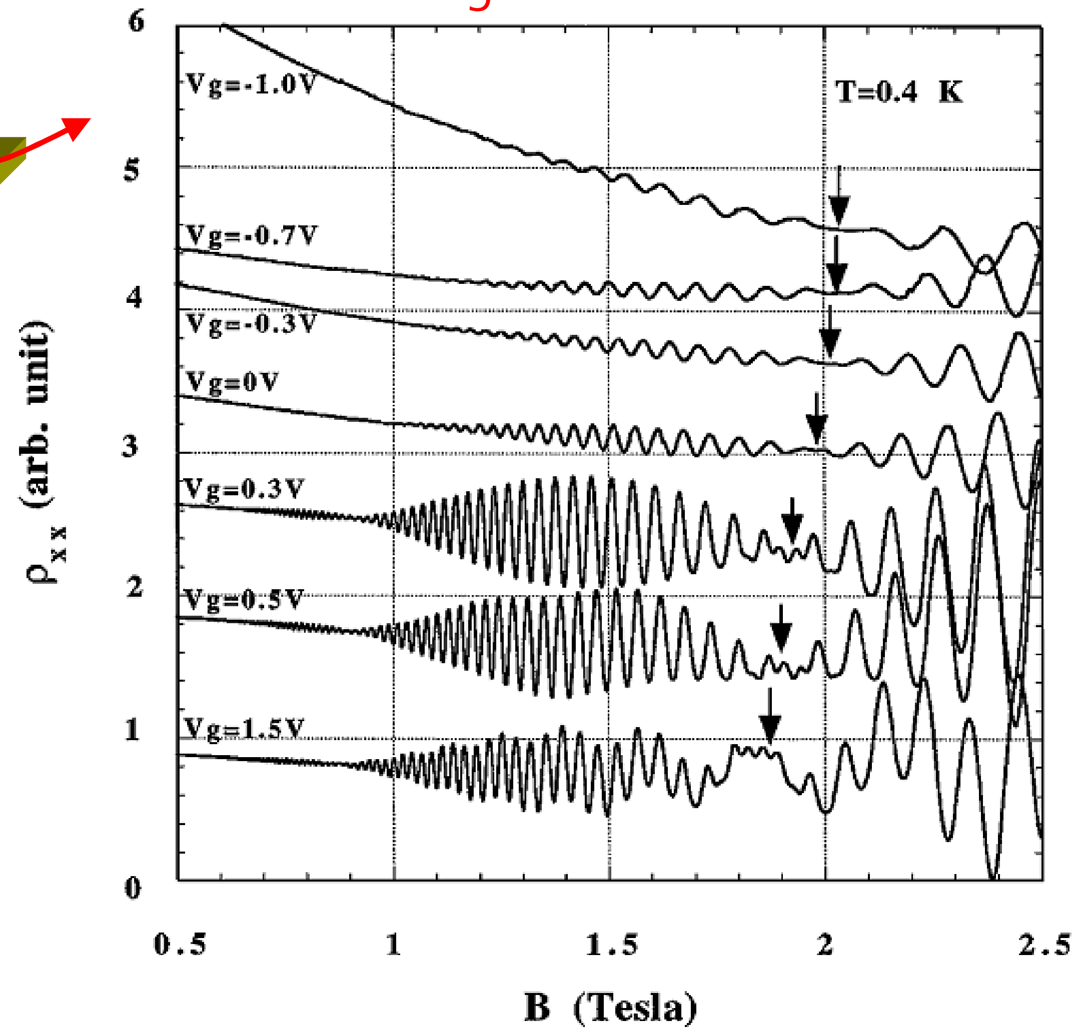
BIA ≠ SIA

SO-interaction in a InGaAs quantum well



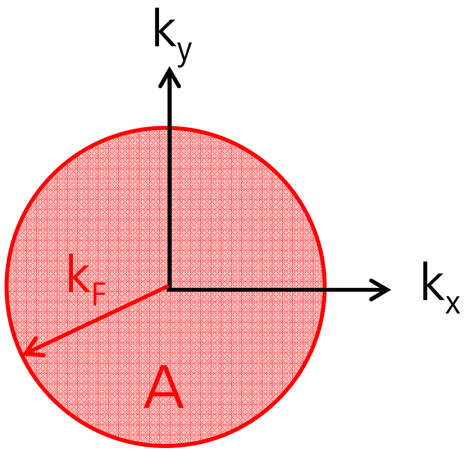


Beating of SdH-oscillations



Nitta et al., Phys. Rev. Lett **78**, 1335 (1997)

Quantum oscillations (SdH) reflect k-space area

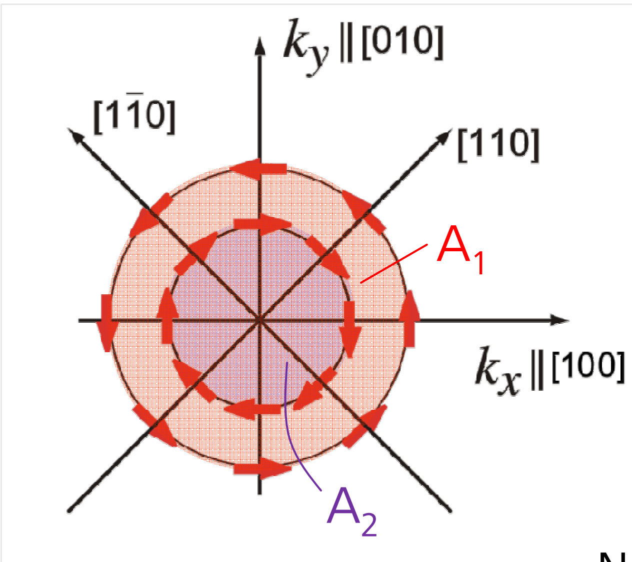


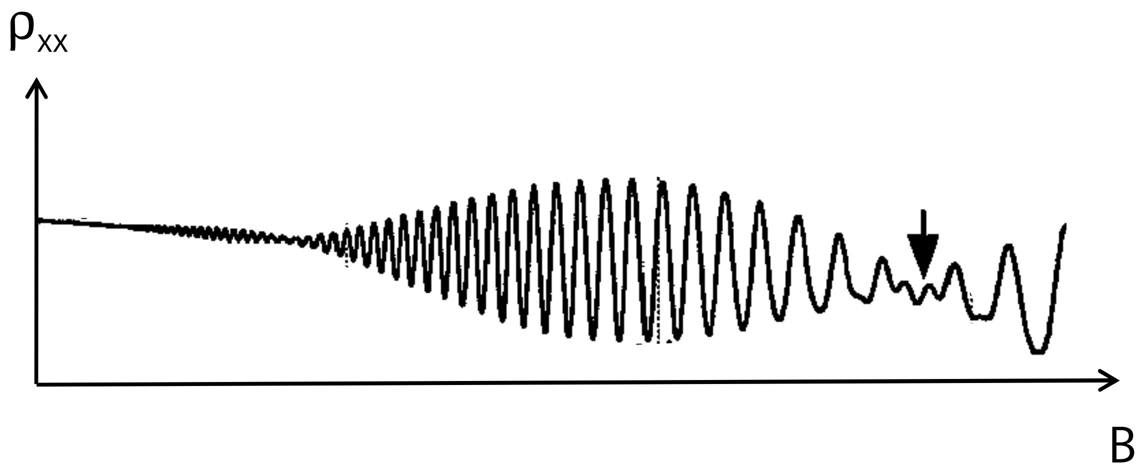
Periodicity of Shubnikov-de Haas (SdH) oscillations

$$\Delta\left(\frac{1}{B}\right) = \frac{2\pi e}{\hbar A}$$

Note that $A = \pi k_F^2 = 2\pi^2 n_s$

Origin of beating: two periodicities due to two k-space areas A_1 and A_2

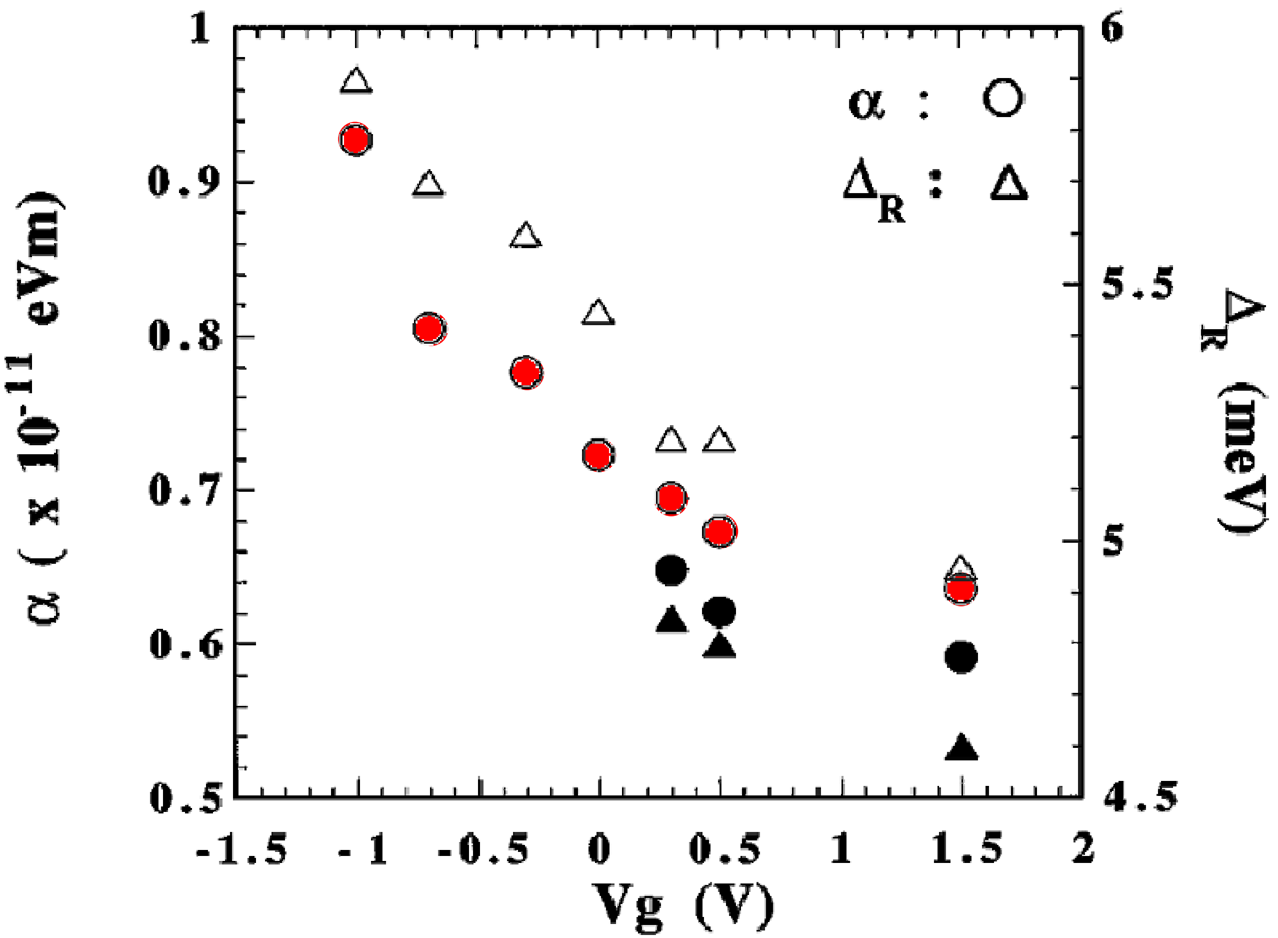




Nitta et al., Phys. Rev. Lett **78**, 1335 (1997)

Tuning of Rashba coefficient a by gate voltage V_g

Corresponds to tuning of spin orbit field, i.e., $\vec{B}_{eff} = \alpha \begin{pmatrix} k_y \\ -k_x \end{pmatrix}$



Nitta et al., Phys. Rev. Lett **78**, 1335 (1997)

Magnetism and Spin-Orbit Interaction:

Magnetism

Basic concepts

magnetic moments, susceptibility, paramagnetism, ferromagnetism
exchange interaction, domains, magnetic anisotropy,

Examples:

detection of (nanoscale) magnetization structure
using Hall-magnetometry, Lorentz microscopy and MFM

Spin-Orbit interaction

Some basics

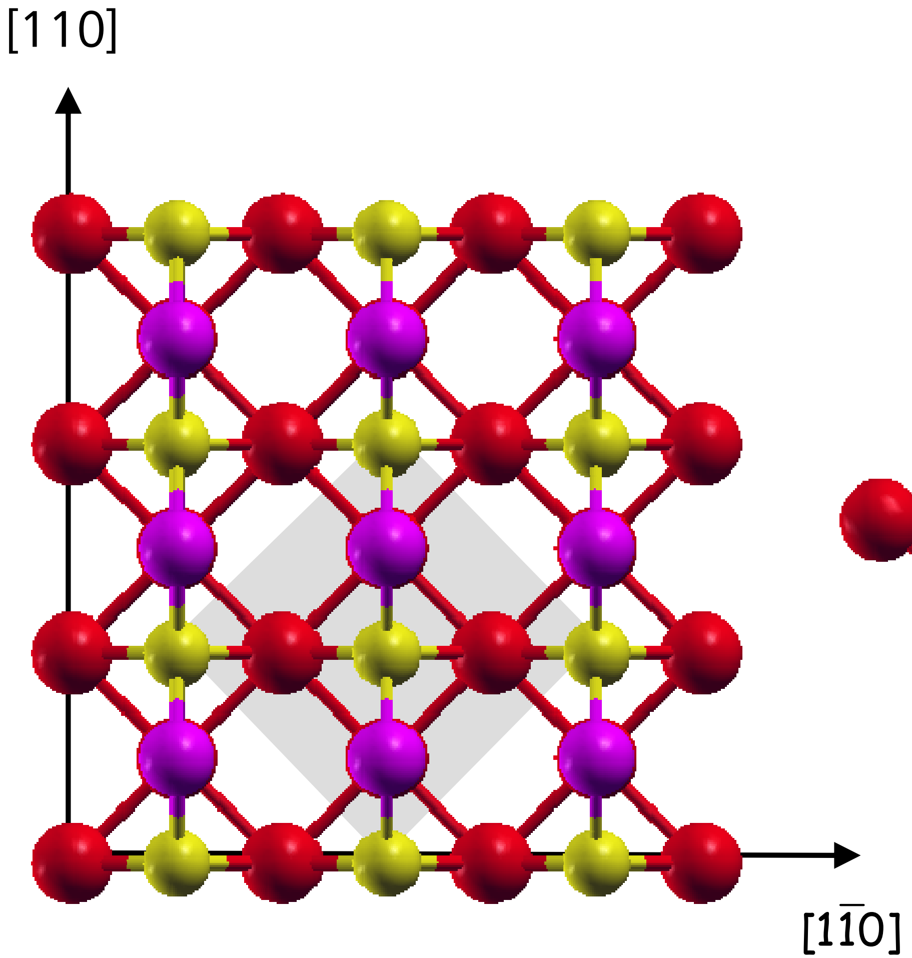
Rashba- and Dresselhaus contribution, SO-interaction and effective magnetic field

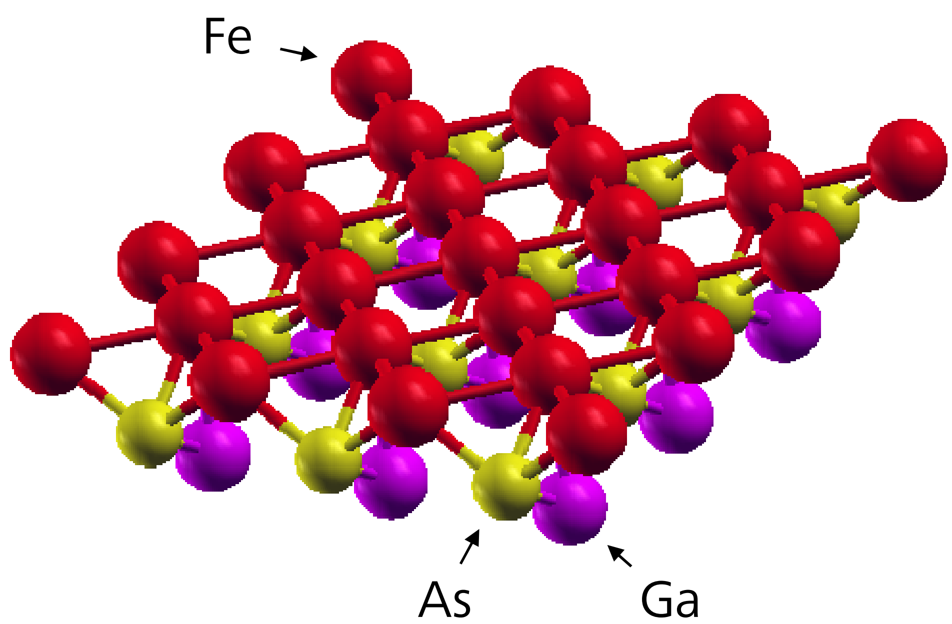
Example:

Ferromagnet-Semiconductor Hybrids: TAMR involving epitaxial Fe/GaAs interfaces

Spin-orbit interaction plays also role in tunneling

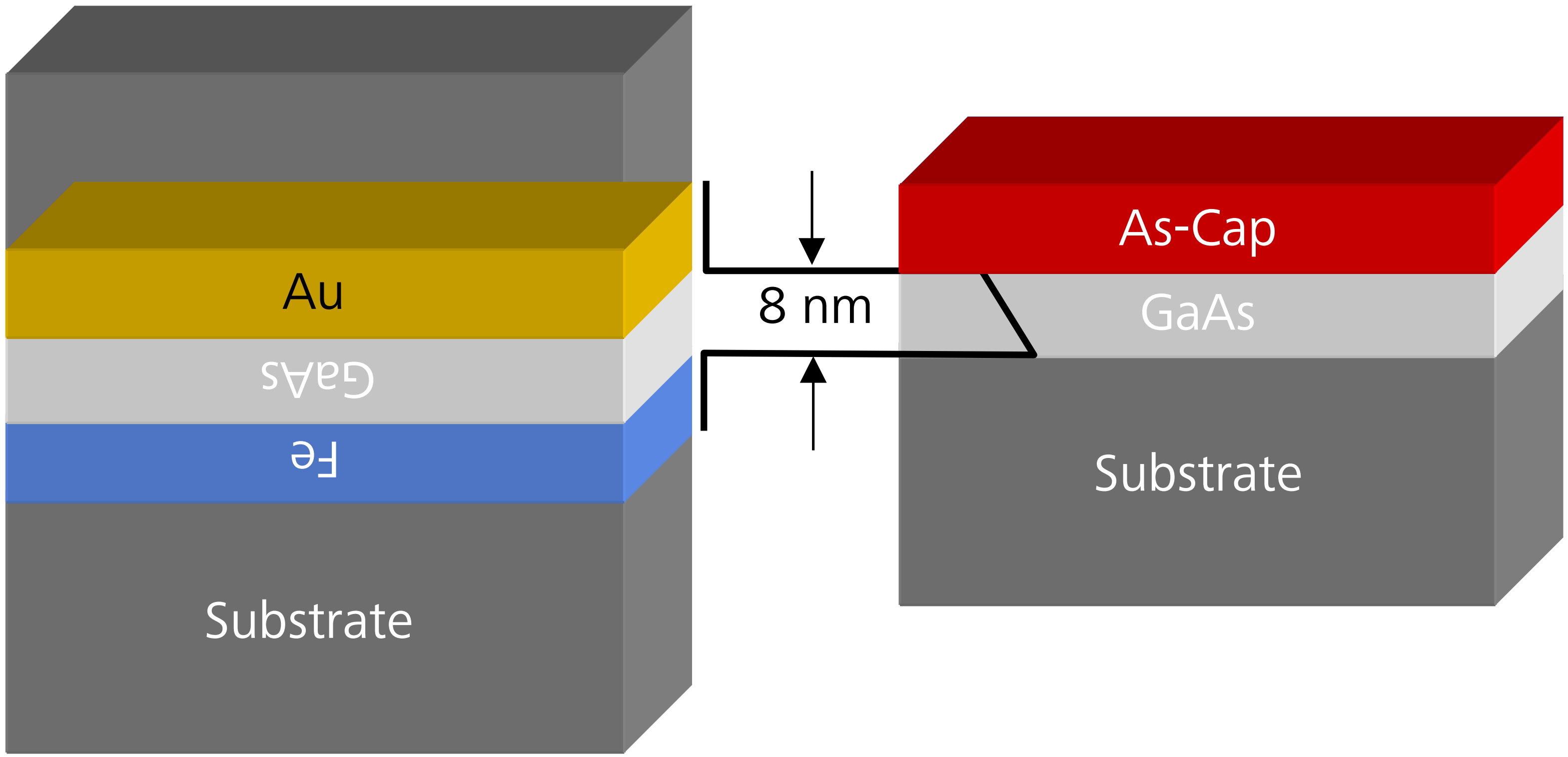
Epitaxial Fe-GaAs interface



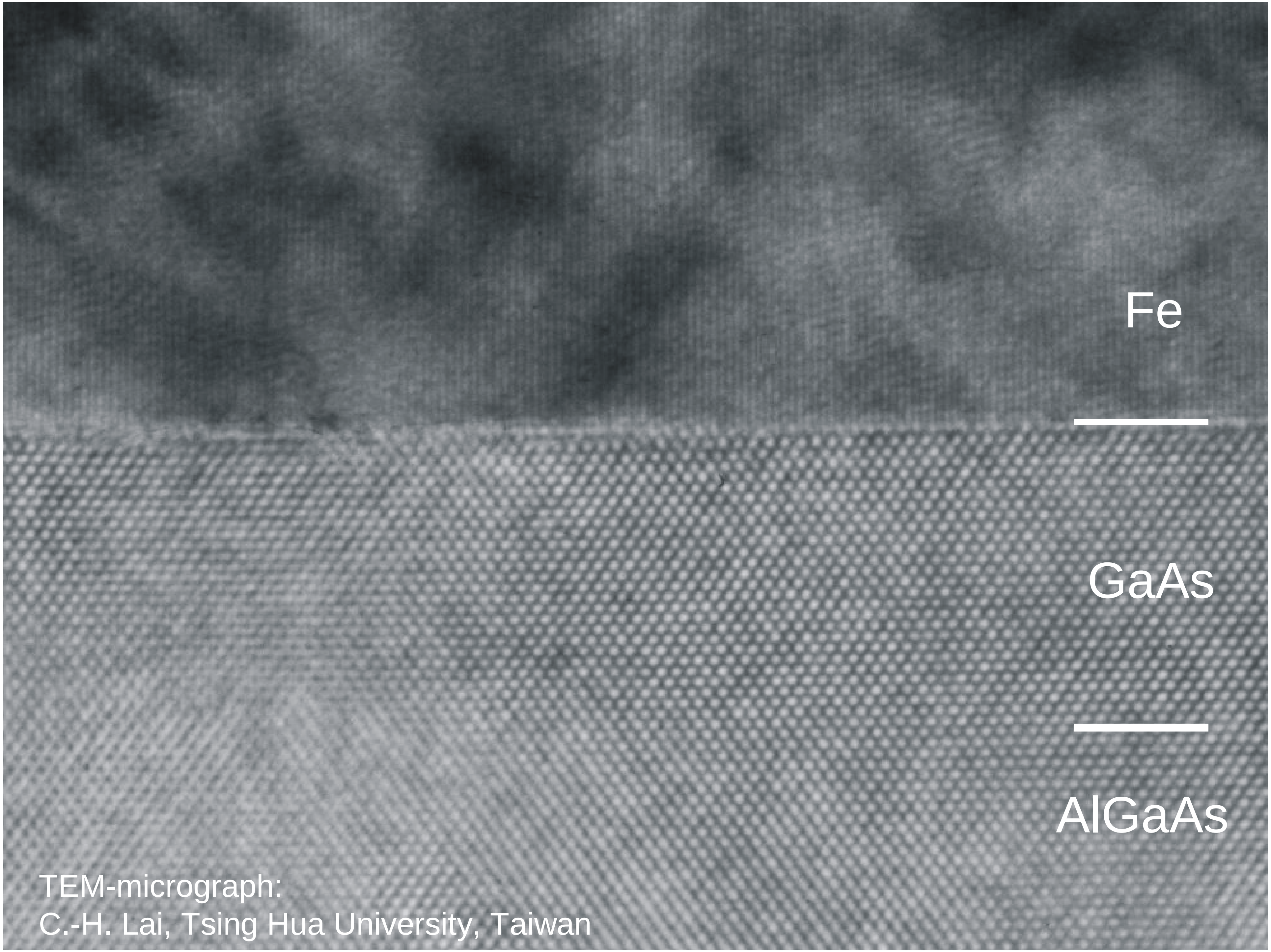


a_{GaAs}=5.653 Å a_{Fe}=2.867 Å

Device fabrication



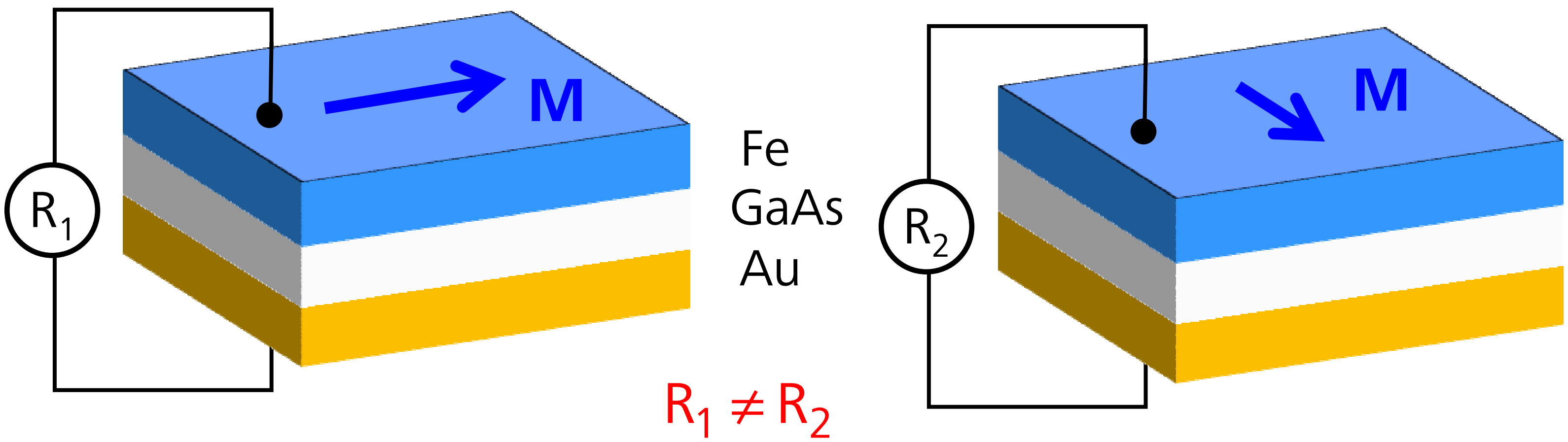
J. Moser et al. Appl. Phys. Lett. **89**, 162106 (2006)


Fe
GaAs
AlGaAs
TEM-micrograph:
C.-H. Lai, Tsing Hua University, Taiwan

TAMR: Tunneling Anisotropic Magnetoresistance

Are always two ferromagnetic layers necessary to see a magnetization dependent resistance?

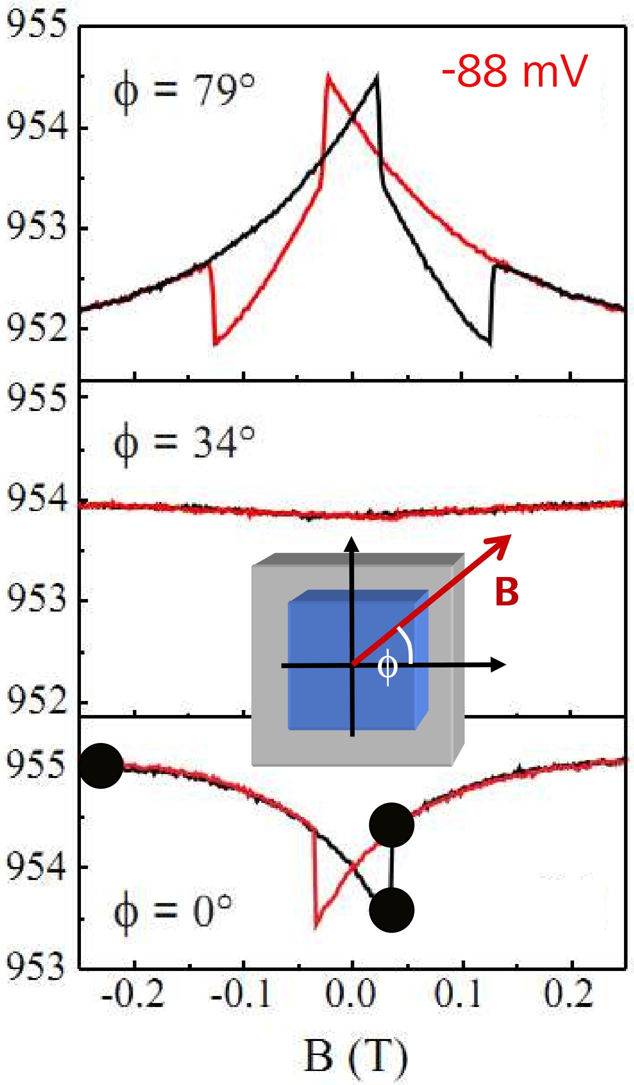
Our model system: Fe/GaAs/Au with epitaxial Fe/GaAs interface



See also:
Gould et al. PRL **93**, 117203 (2004)
$(Ga,Mn)As/Al_2O_3/Au$

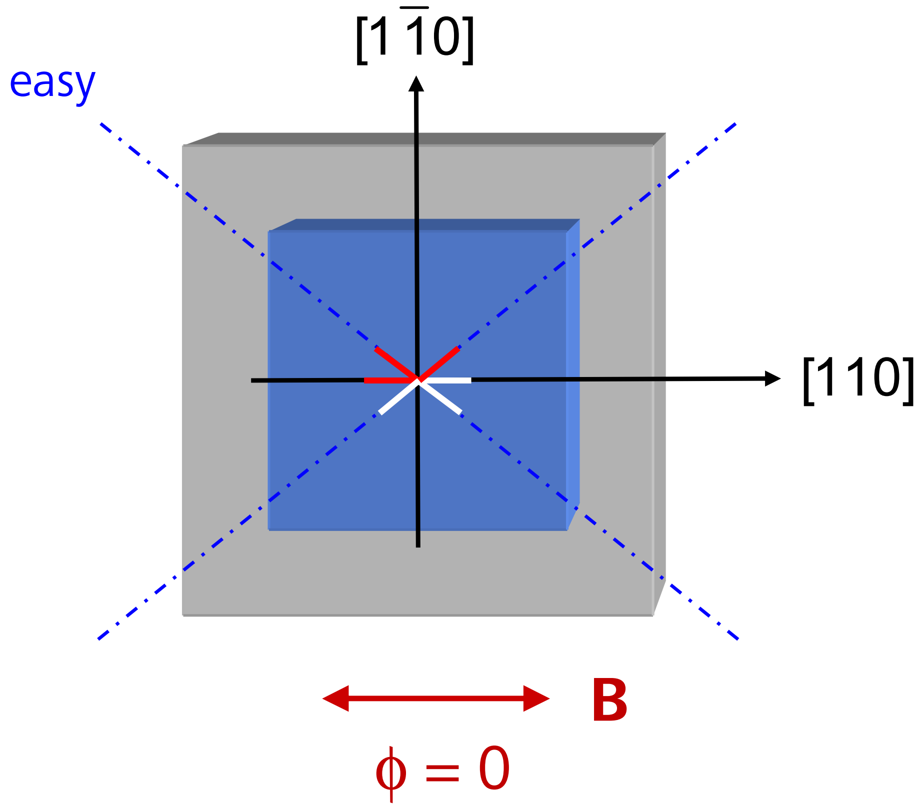
Tunneling magnetoresistance: **B** dependence

Spin-valve like signal



Double step/single step switching due to magnetic anisotropy

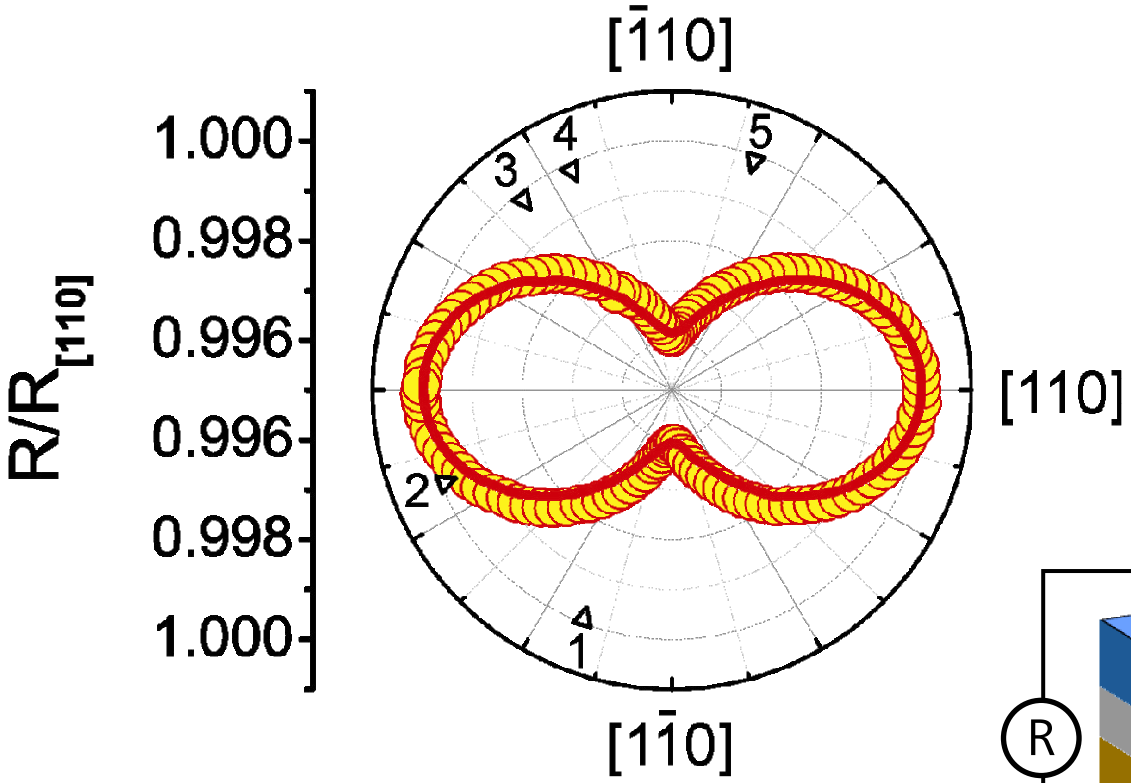
Fe on GaAs: Cubic + uniaxial anisotropy



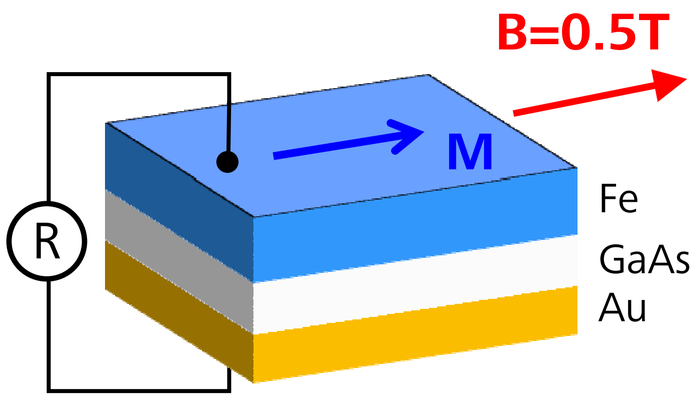
Moser et al., Phys. Rev. Lett. **99**, 056601, 2007

Angular dependence of TAMR: negative bias

Co/Fe(epi)/GaAs(8nm)/Au



measured at
T = 4.2 K and -90 mV



J. Moser et al., Phys. Rev. Lett. **99**, 056601, 2007

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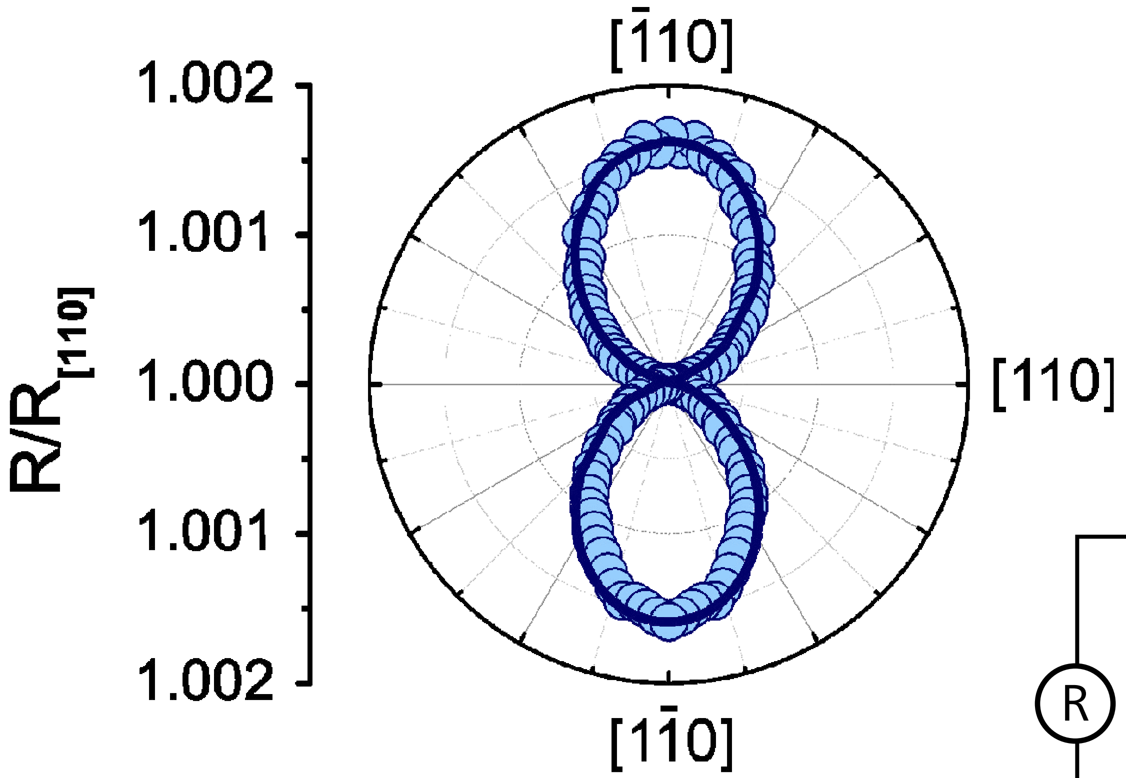
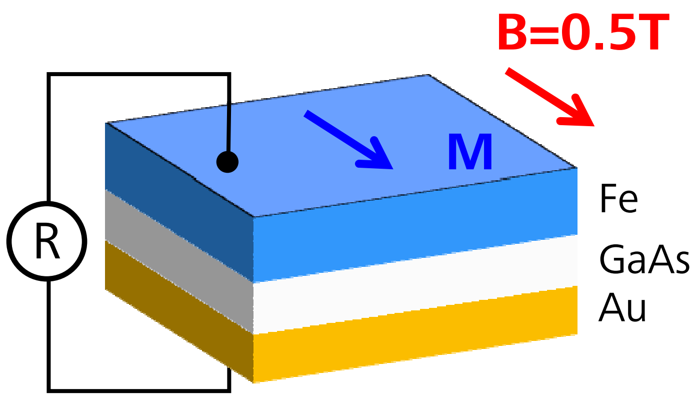


measured at
T = 4.2 K and +90 mV



J. Moser et al., Phys. Rev. Lett. **99**, 056601, 2007

Modelling

A. Matos-Abiague & J. Fabian, PRB **79**, 155303 (2009)

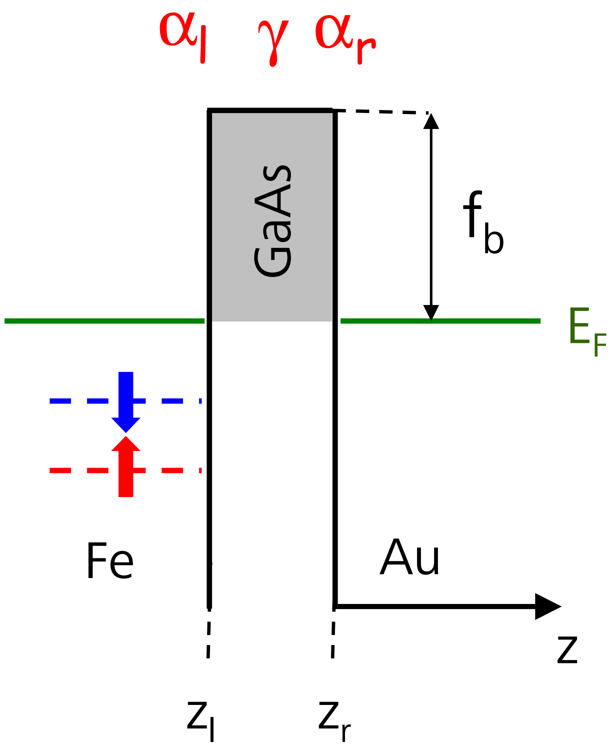
$$H = H_0 + H_z + H_{BR} + H_D$$

$$H_0 = -\frac{\hbar^2}{2}\nabla\left[\frac{1}{m(z)}\nabla\right] + V(z)$$

$$H_{BR} = \frac{1}{\hbar}\sum_{i=l,r}\alpha_i(\sigma_x p_y - \sigma_y p_x)\delta(z - z_i)$$

$$H_z = -\frac{\Delta(z)}{2}\mathbf{n}\cdot\boldsymbol{\sigma}$$

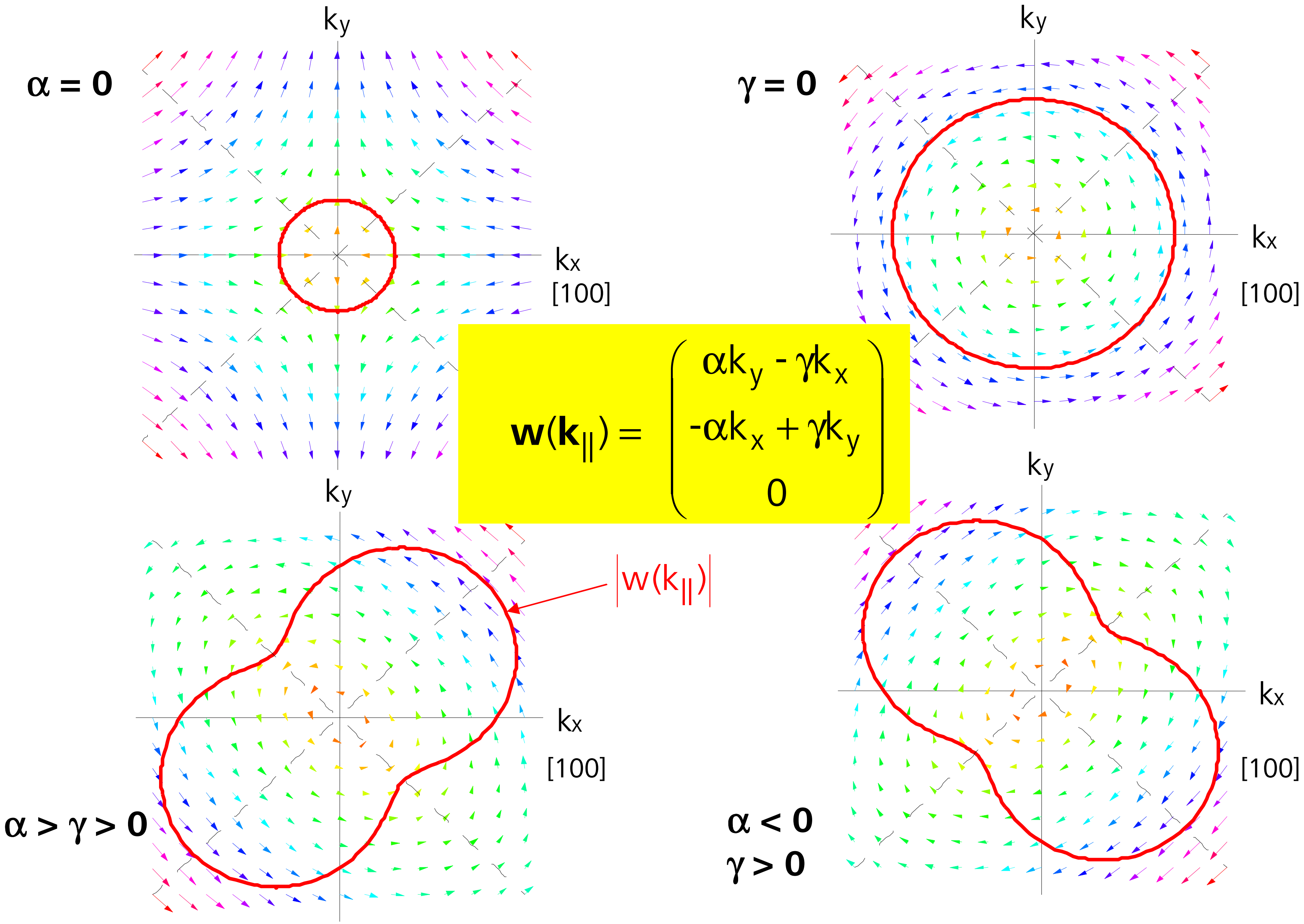
$$H_D = \frac{1}{\hbar}(\sigma_x p_x - \sigma_y p_y)\frac{\partial}{\partial z}\left(\gamma(z)\frac{\partial}{\partial z}\right)$$



$$I = \frac{e}{(2\pi)^3\hbar}\sum_{\sigma=-1,1}\int dE d^2k_{\|} T_\sigma(E,k_{\|})[f_l(E) - f_r(E)]$$

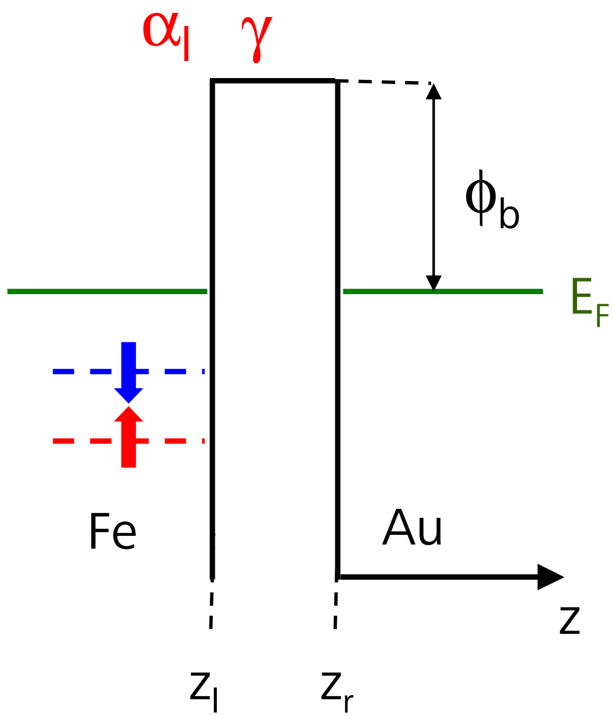
particle transmissivity

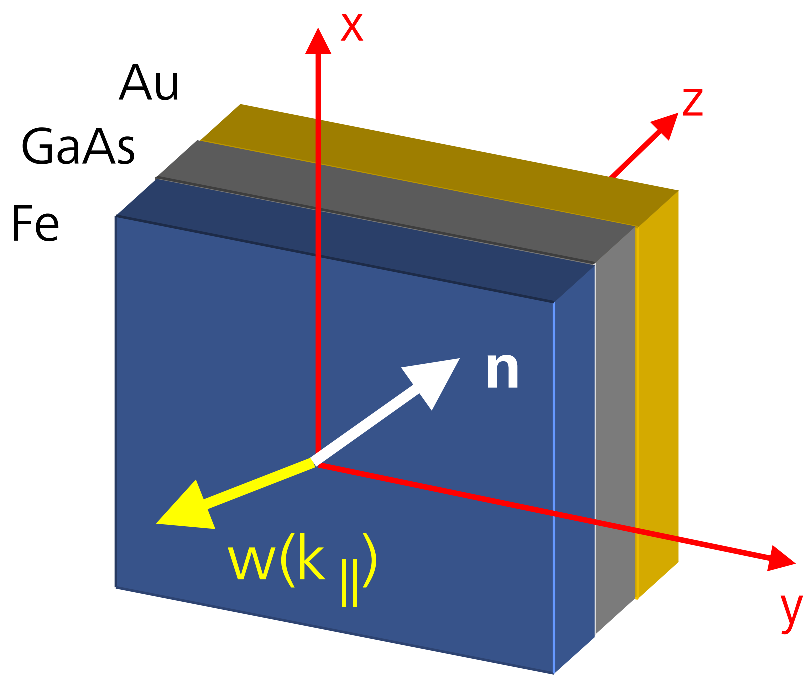
Spin-orbit field **w**(**k**)



$$\mathbf{w}(\mathbf{k}_{\|}) = \begin{pmatrix} \alpha k_y - \gamma k_x \\ -\alpha k_x + \gamma k_y \\ 0 \end{pmatrix}$$

Origin of anisotropic resistance: superposition of Rashba & Dresselhaus SO-contribution





Anisotropy determined by

$$T(\mathbf{k}_{||}) \approx f([\mathbf{n}\cdot\mathbf{w}(\mathbf{k}_{||})]^2) \rightarrow R / R_{[110]} - 1 \sim \alpha\gamma(\cos 2\phi - 1)$$

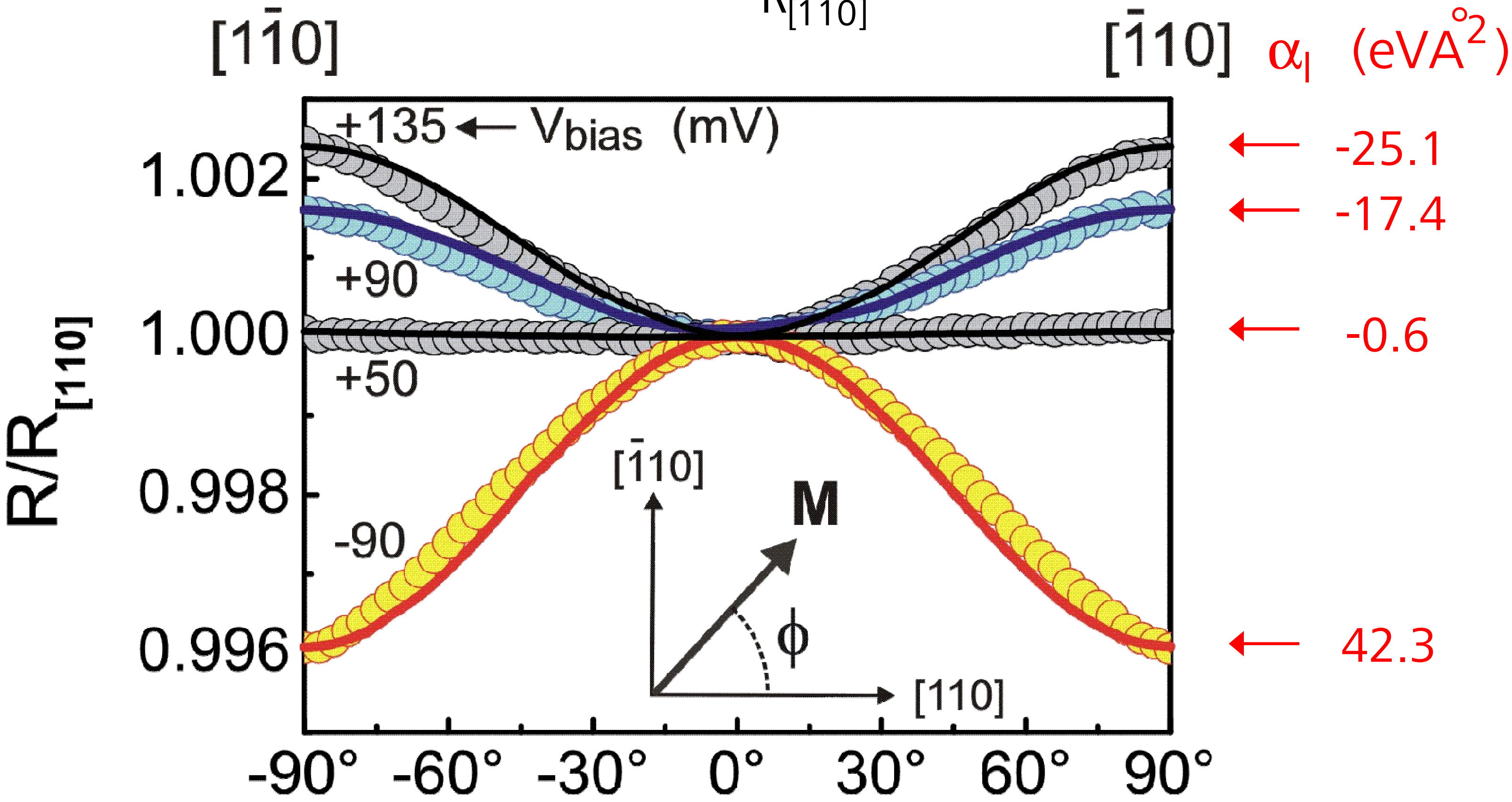
$$\mathbf{w}(\mathbf{k}_{||}) = \begin{pmatrix} \alpha k_y - \gamma k_x \\ -\alpha k_x + \gamma k_y \\ 0 \end{pmatrix}$$

Anisotropy vanishes for $\alpha\gamma \rightarrow 0$

J. Moser et al., Phys. Rev. Lett. **99**, 056601, 2007

Angular dependence of TAMR: bias dependence

$$\mathrm{TAMR} = \frac{R(\phi) - R_{[110]}}{R_{[110]}}$$



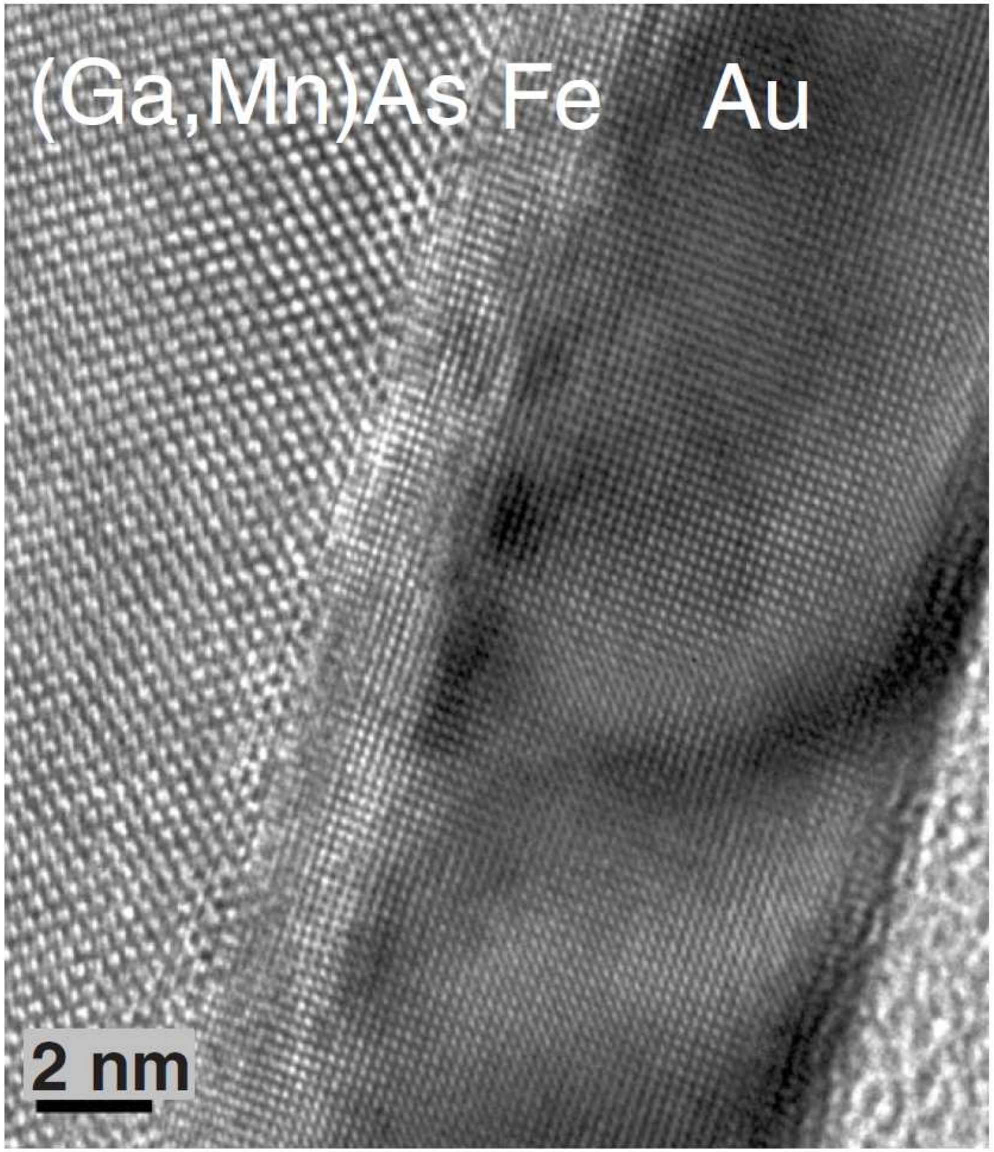
γ in GaAs: 24 eVÅ^3

J. Moser et al., Phys. Rev. Lett. **99**, 056601, 2007
See also:T. Uemura, Appl. Phys. Lett. **98**,102503 (2011)

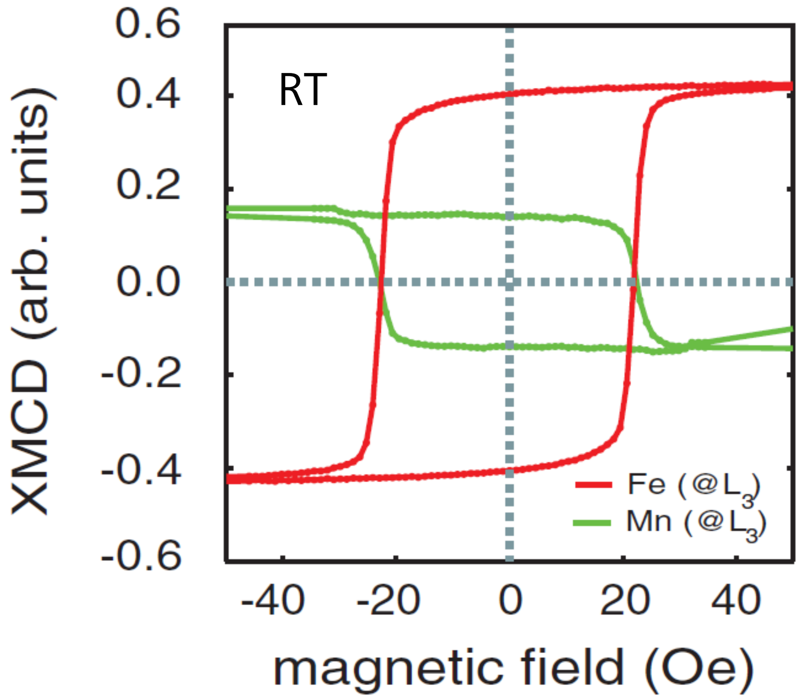
Fe on (Ga,Mn)As

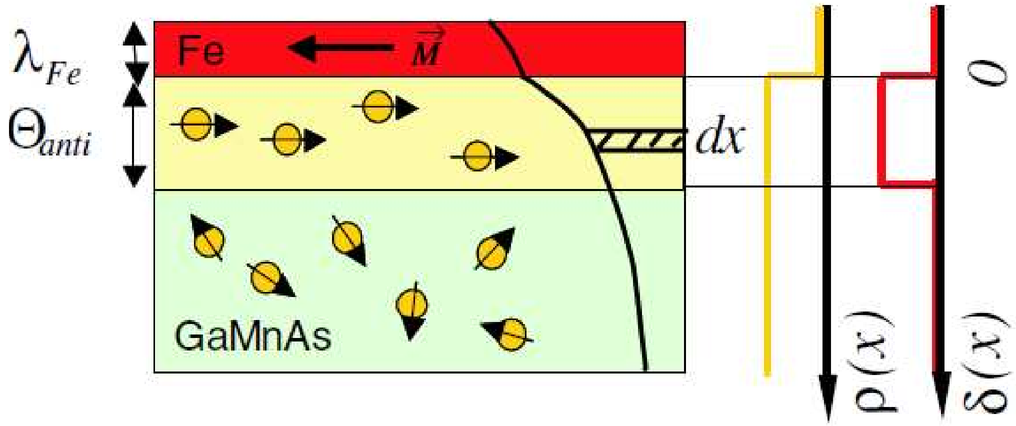
F. Maccherozzi et al.
PRL **101**, 267201 (2008)

M. Sperl et al.,
Phys. Rev B **81**, 035211 (2010)



XMCD: antiferromagnetic coupling





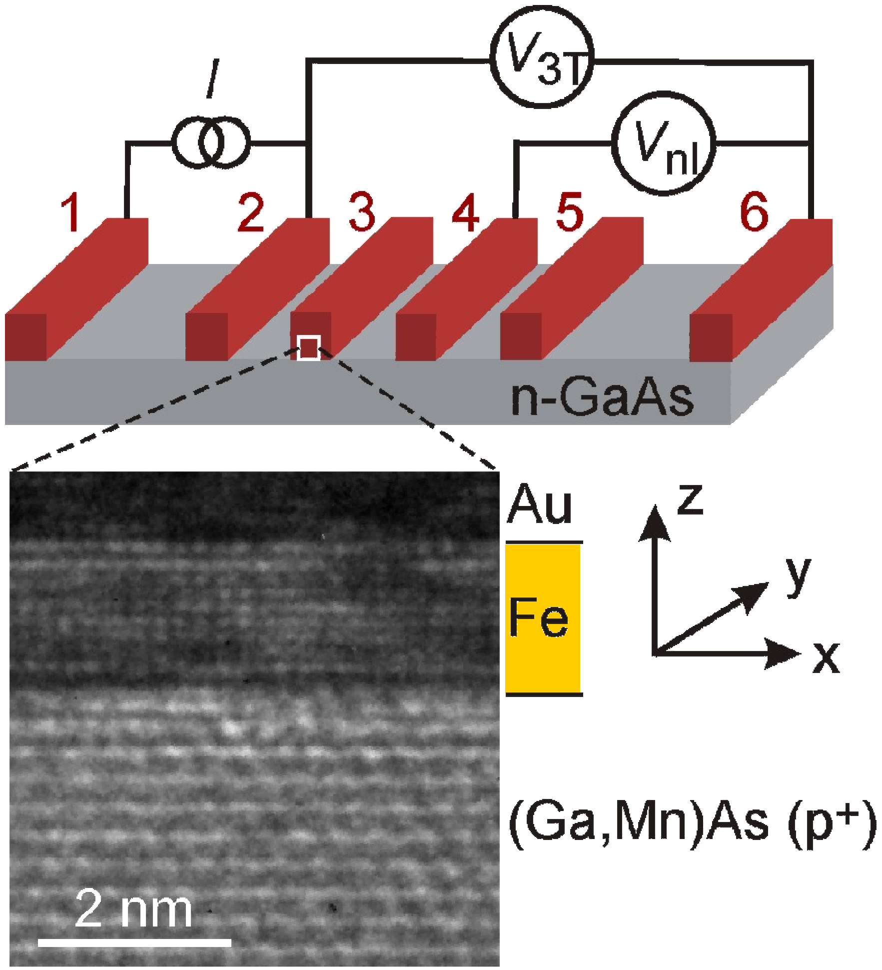
US pat 61/133,344

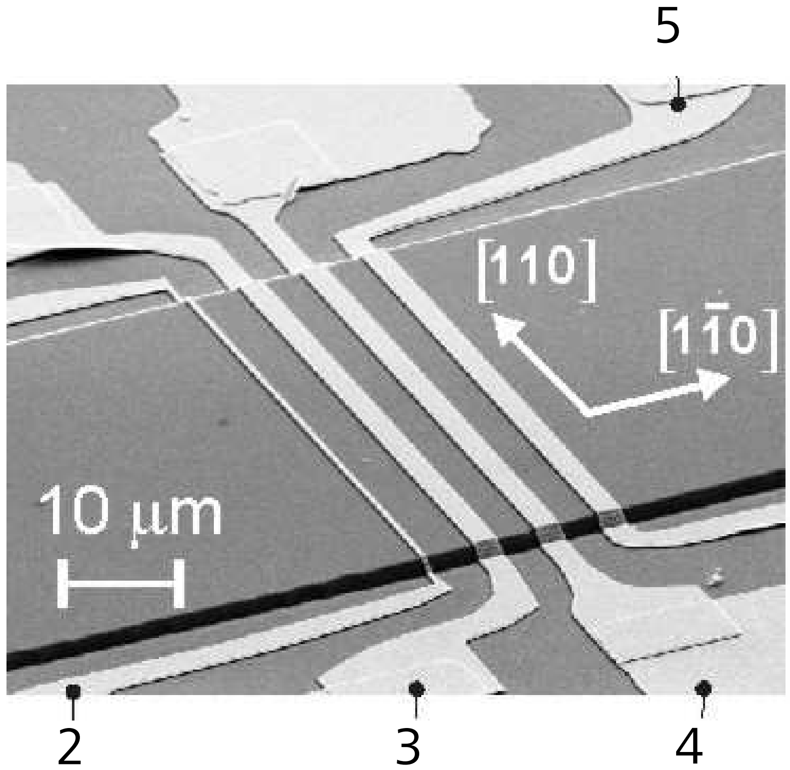
Thin ferromagnetic iron film induces antiferromagnetic coupling in (Ga,Mn)As at room temperature. Minimum thickness of the coupled (Ga,Mn)As layer is at least 1 nm

F. Maccherozzi et al. PRL **101**, 267201 (2008)
M. Sperl et al., Phys. Rev B **81**, 035211 (2010)

Spin injection: Proximity effect enhances T_c

Proximity effect: exchange coupling between
Fe and Mn at Fe/(Ga,Mn)As interface





FP-34 C. Song et al.
WP-30 M. Ciorga et al.
WP-105 J. Shiogai et al.

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The End