Spintronics and diluted magnetic semiconductors

DETI.2 workshop 2012

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HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Outline

1. **Principles of spintronics**
2. Paramagnetic DMS, giant Zeeman splitting and bound magnetic polarons
3. Magnetic coupling
4. Half metallic materials
5. Magnetism and Transport in GaMnAs
6. Oxide based DMS by ion implantation

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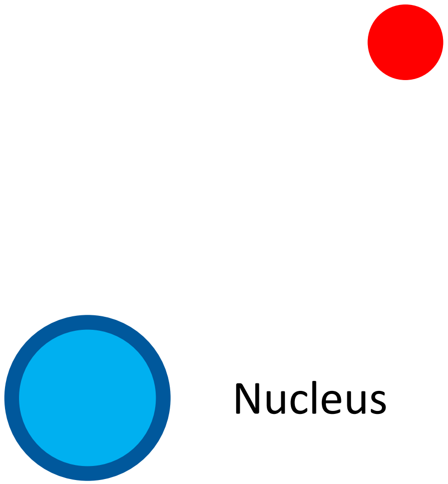
Origin of magnetism

Electron charge + movement
→ Magnetic moment



Nucleus

Dirac equation (Spin)

$$\left(c\vec{\gamma}\cdot\hat{p}+mc^2\right)\psi = i\hbar\gamma^0\frac{\partial}{\partial t}\psi$$

Orbital moment

$$\hat{L}^2 Y_l^{m_l} = \hbar^2 l(l+1) Y_l^{m_l}$$

$$\hat{L}_z Y_l^{m_l} = \hbar m_l Y_l^{m_l}$$

$$\hat{S}^2 Y_s^{m_s} = \hbar^2 s(s+1) Y_s^{m_s}$$

$$\hat{S}_z Y_s^{m_s} = \hbar m_s Y_s^{m_l}$$

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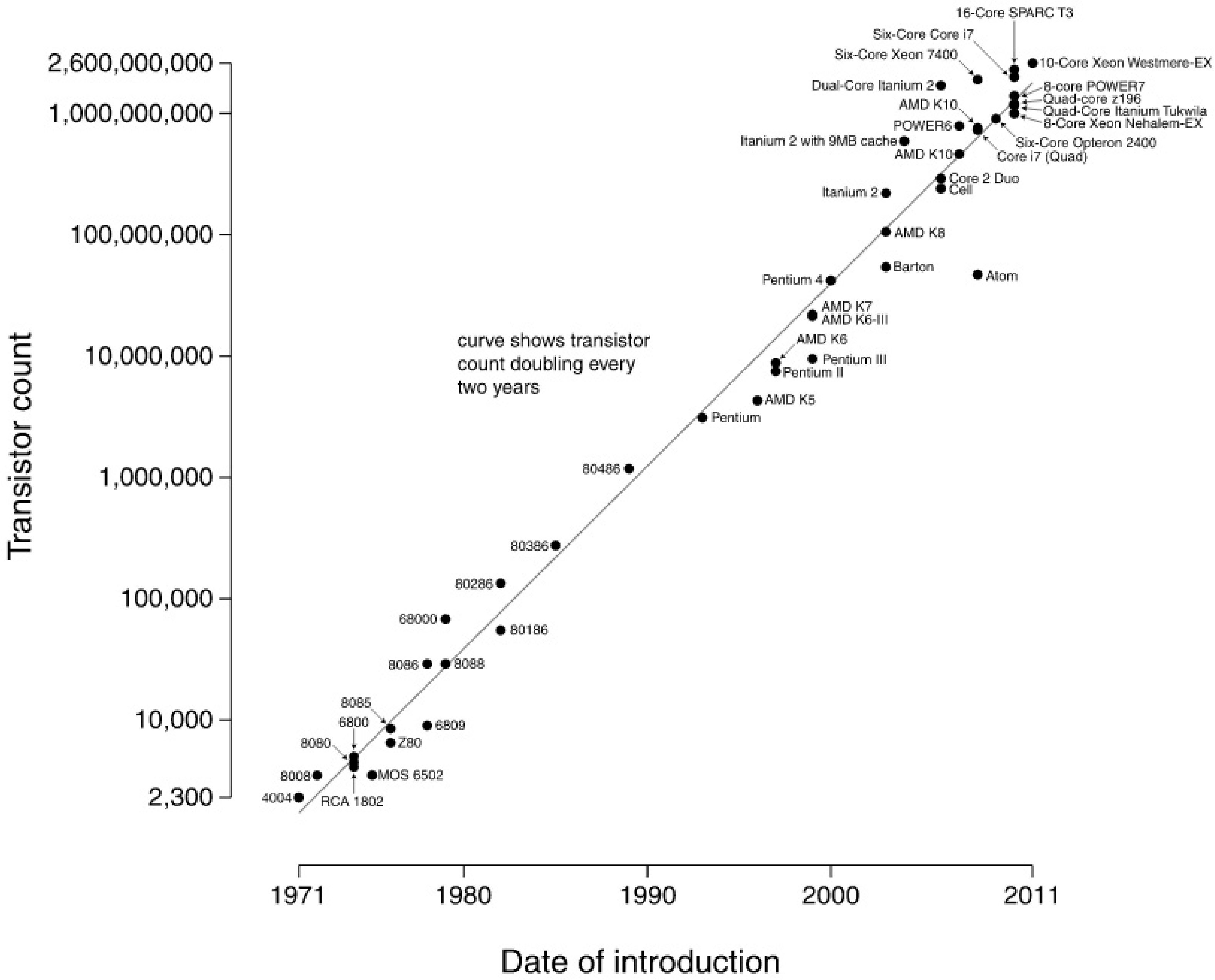
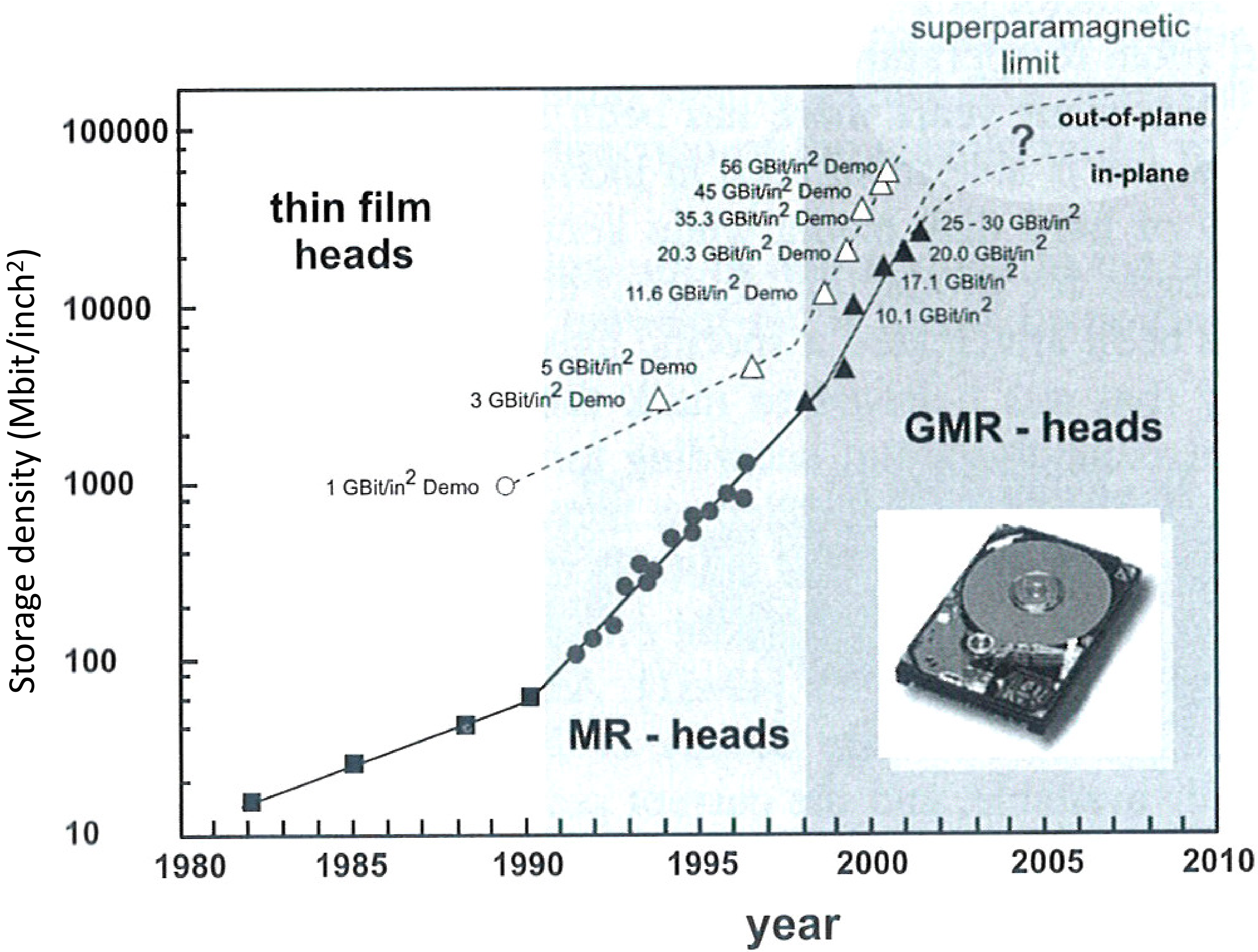
Microprocessor Transistor Counts 1971-2011 & Moore's Law



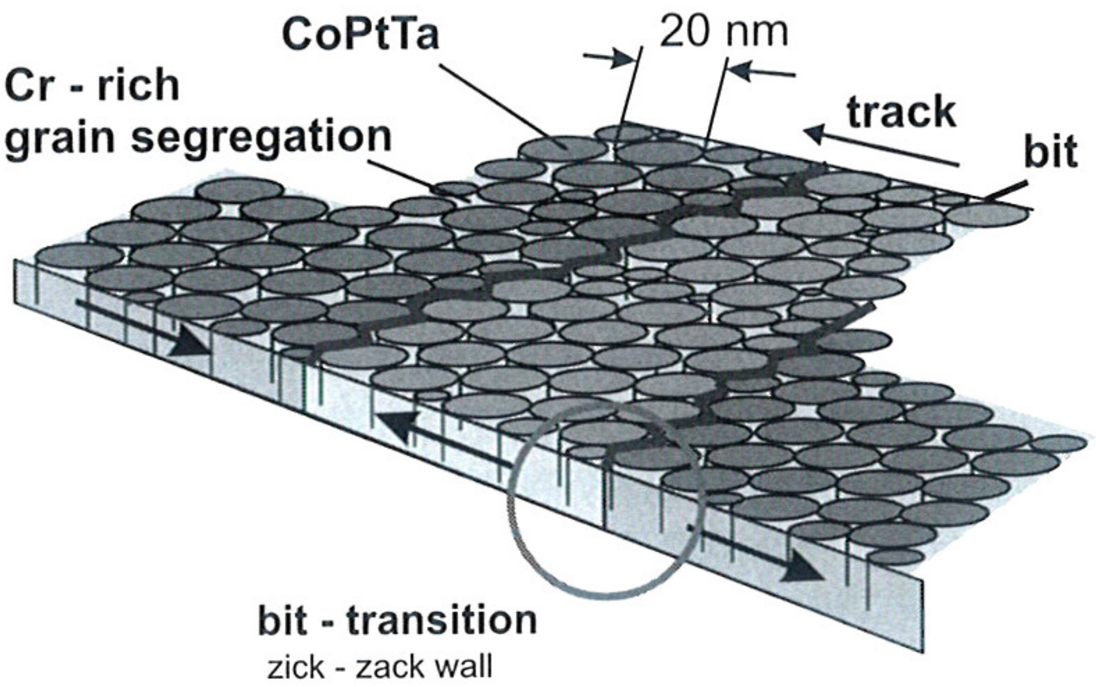
Moores law on data storage



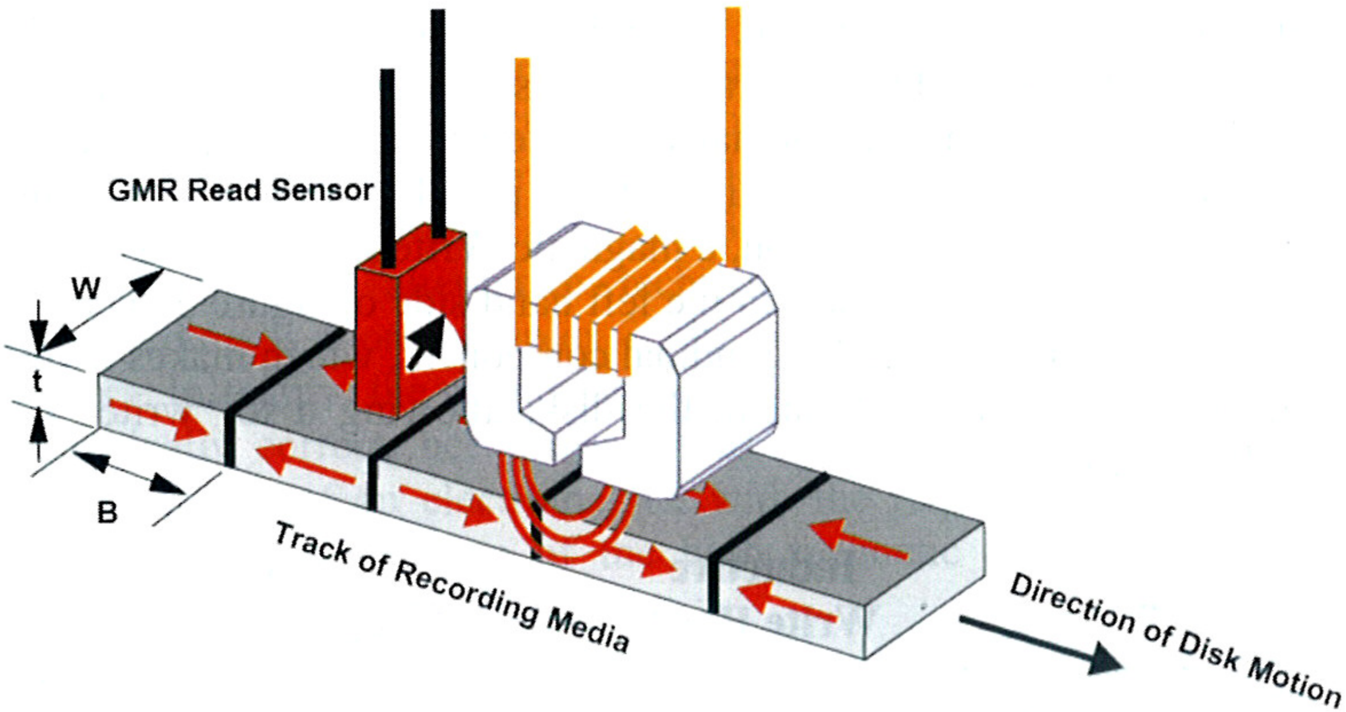
Traditional magnetic data storage

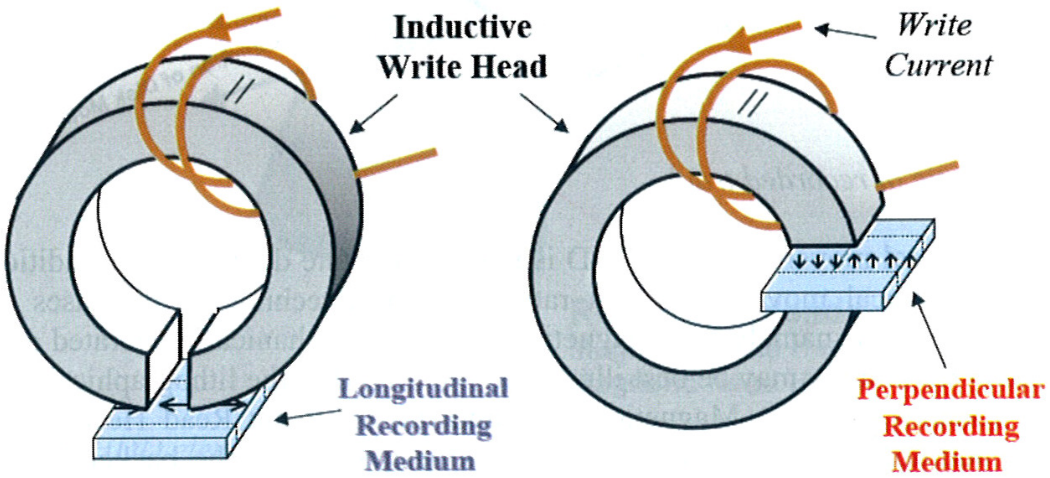
Technology NSIC:

1. Deposition of $Co_{70}Pt_8Cr_{22}$ + Ta on Cr/NiAl substrates
2. Annealing for phase separation between Cr-matrix and Co-Pt-Ta clusters
3. Result: Co-rich ferromagnetic clusters (10-15 nm) for data storage



Traditional magnetic data storage

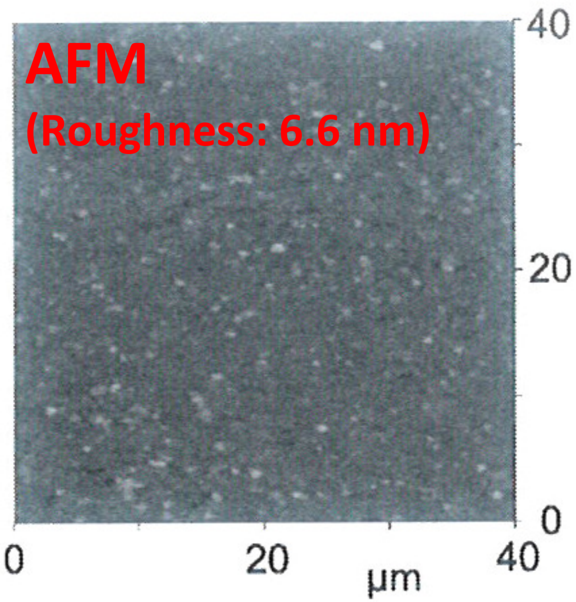


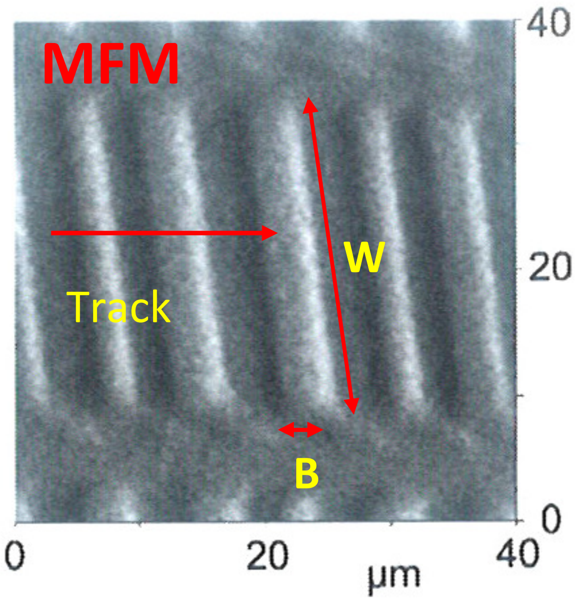


H. S. Nalwa, Magnetic Nanostructures

Stability

- Problems:
  - Intergranular Exchange interaction good for perfect common alignment, but no Sharp switching at the borders
  - No interaction → sharp switching
  - Smaller clusters → Instability with respect to stray field and thermal instability (Superparamagnetic effect)
    - Current criterion for stability: 10 years

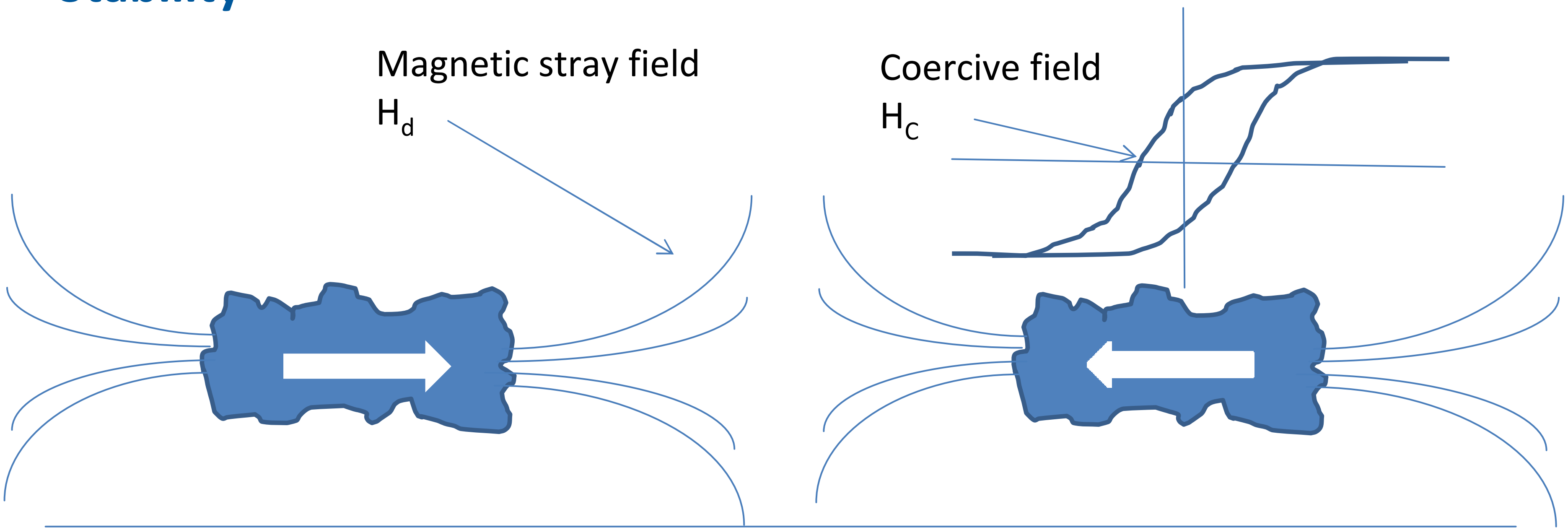


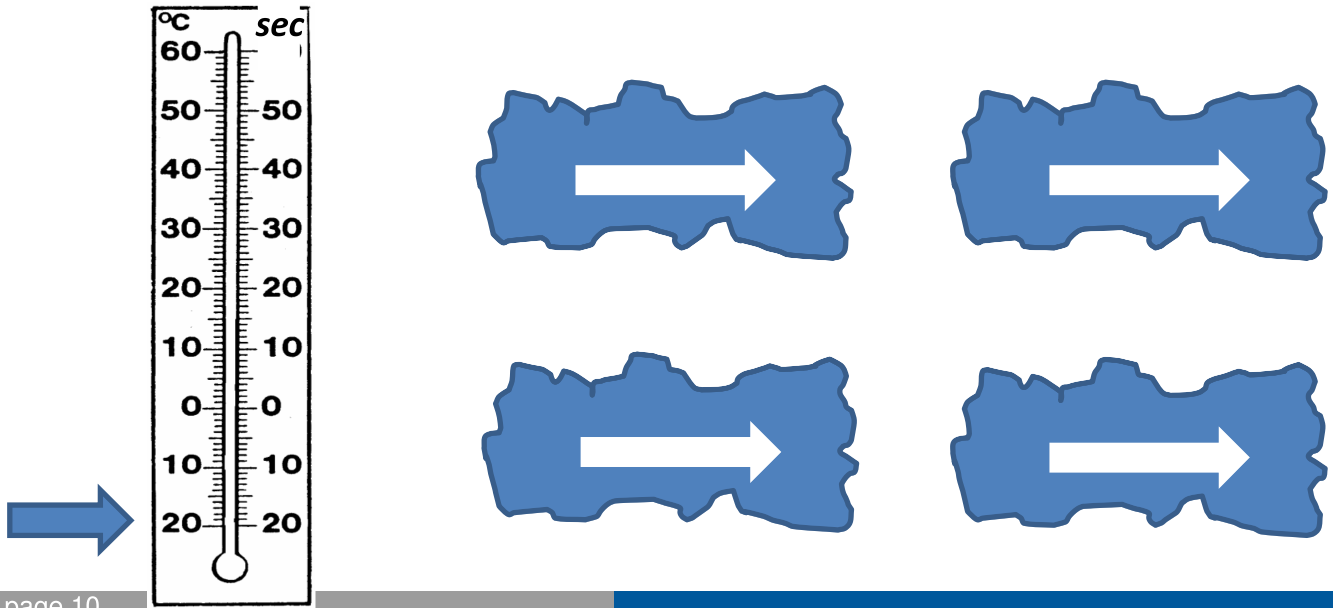


Ideal parameters for 20 Gbit/inch^2

- Bitsize: 40x500 nm
- Density: 490 kbpi
- Remanence x film thickness: $M_r t = 0.4$ memu/cm^2, t~12-15 nm

Stability


Magnetic stray field
H_d
Coercive field
H_C


°C
sec
60
50 50
40 40
30 30
20 20
10 10
0 0
10 10
20 20

Stability

- **Stray fields of neighbouring clusters**

Coercivity H_C vs. Demagnetisation field H_d

$$H_C > H_d = \frac{8M_r t}{W}\left[\sqrt{1+\left(\frac{2W}{B}\right)^2} - 1\right]$$

Problems:

- Reduction of H_d → Lowering of read signal
- Increase of H_C → Large stray field at read head necessary (max. 5 kOe)

- **Superparamagnetic effect**

Magnetocrystalline anisotropie k_1 (spherical cluster):

Frequency (f_0), Time (t)

$$k_1 V > \ln\left[\frac{f_0 t}{0.67}\right] \cdot k_B T$$

Parameters (300 K, 10 years):

- Minimum diameter for Co ($4.5 \times 10^5 J/m^2$) = 8 nm
- Min. diameter for CoPt ($5.3 \times 10^6 J/m^2$) = 3.5 nm

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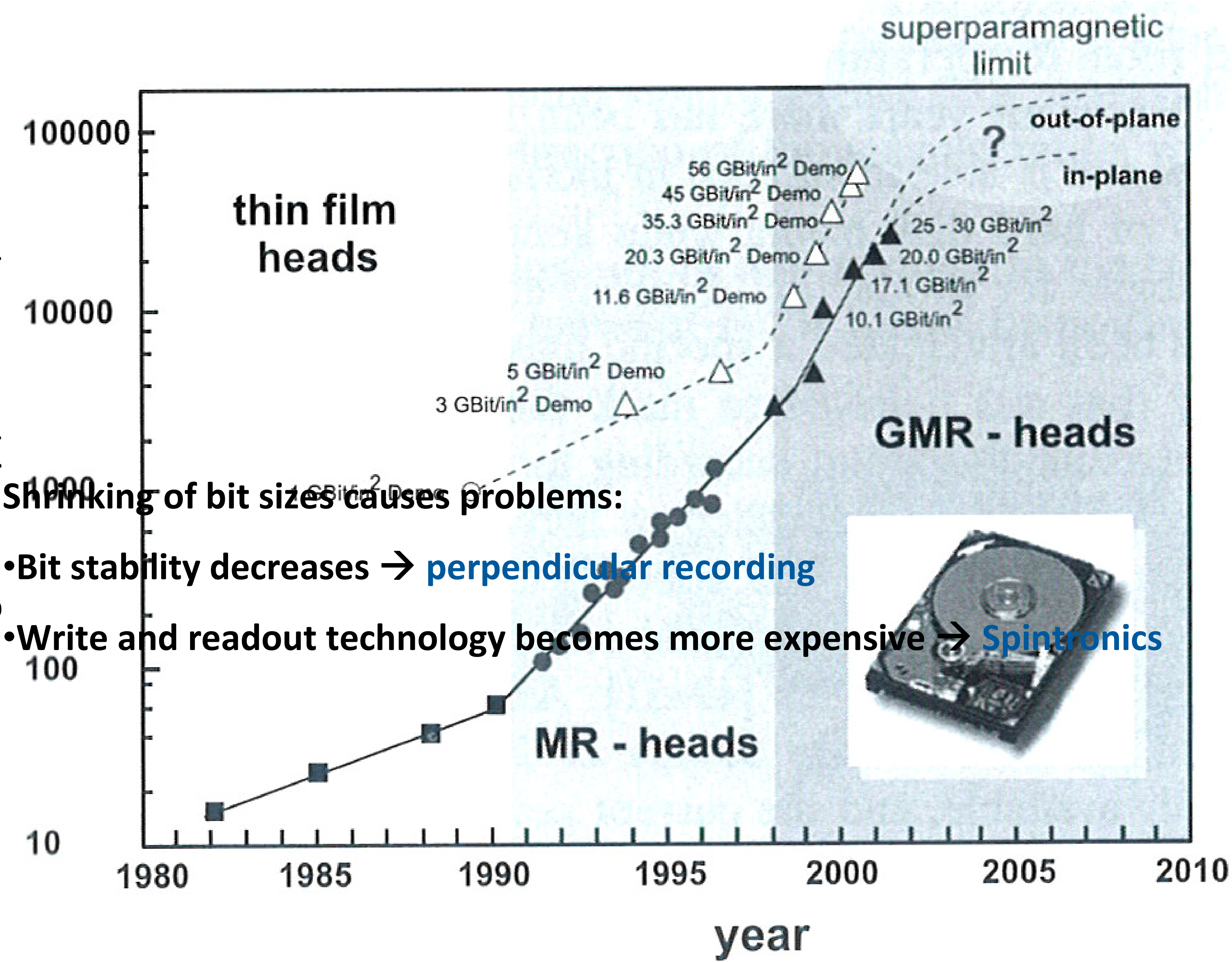
Moores law on data storage

Storage density (Mbit/inch²)



Shrinking of bit sizes causes problems:

- **Bit stability decreases → perpendicular recording**
- **Write and readout technology becomes more expensive → Spintronics**

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Spintronics= Data processing and data storage with electron spins!

Ferromagnet

•Magnetisation (attracts other magnets)

•Spin polarised electric current (Spintronics)

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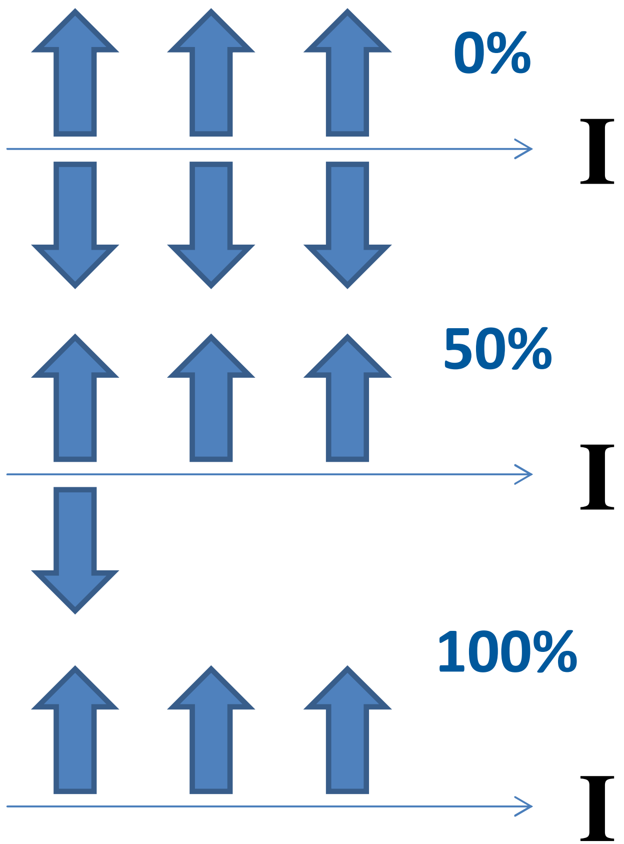
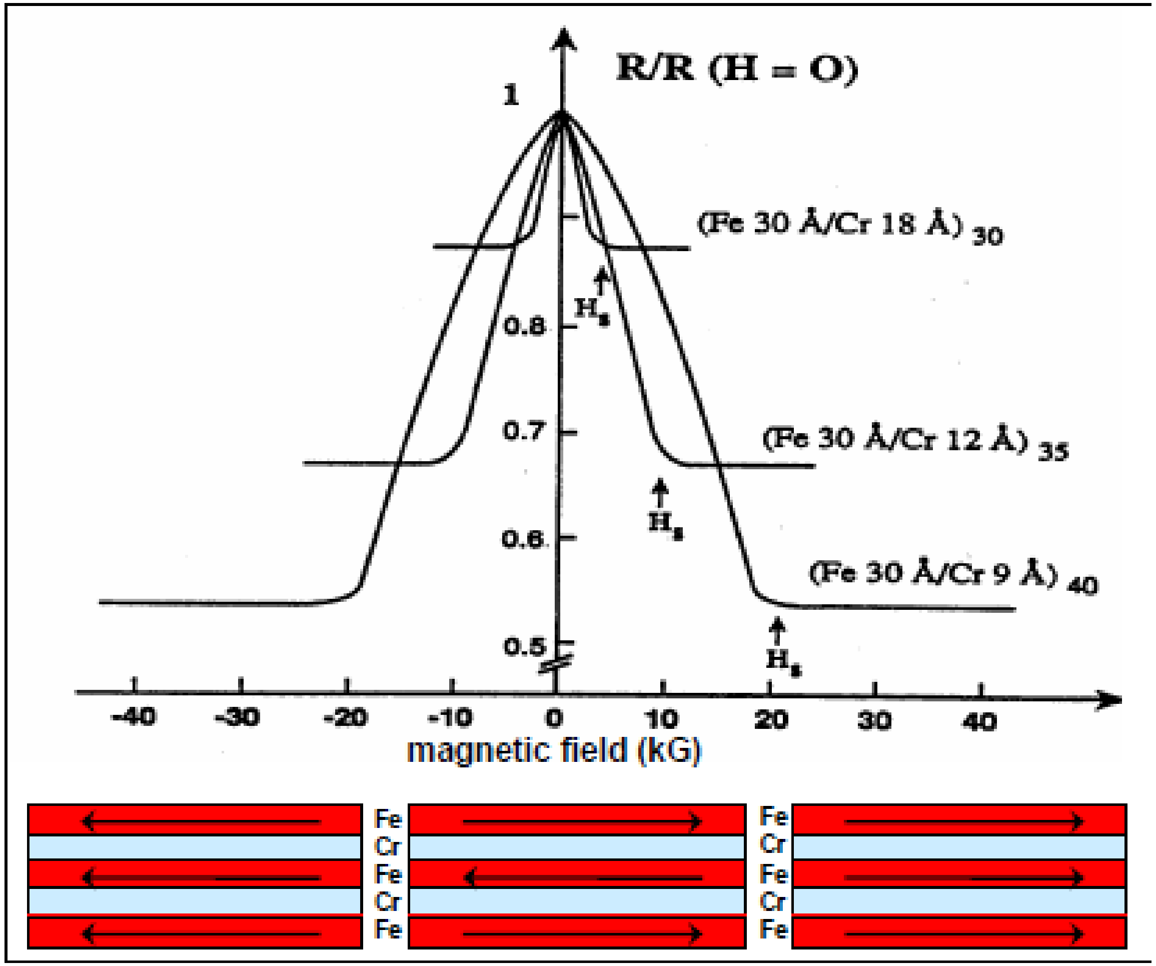
Spintronics
Requirement:
~ 100 % spin polarization of electric current



GMR effect (Noble price 2007)



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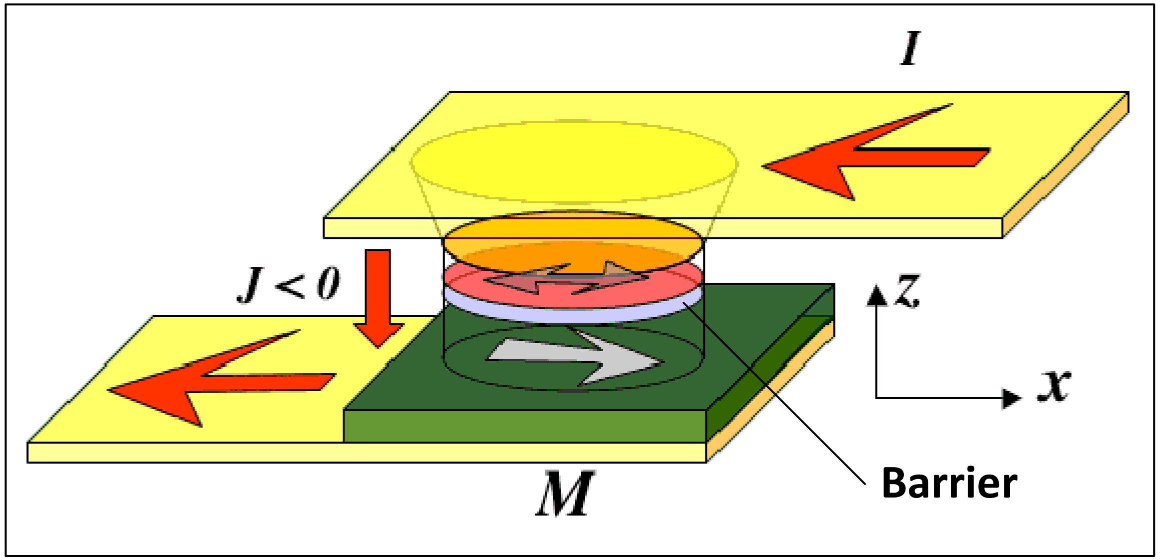
Spin transfer torque

Experiment: current through magnetic nanopillars

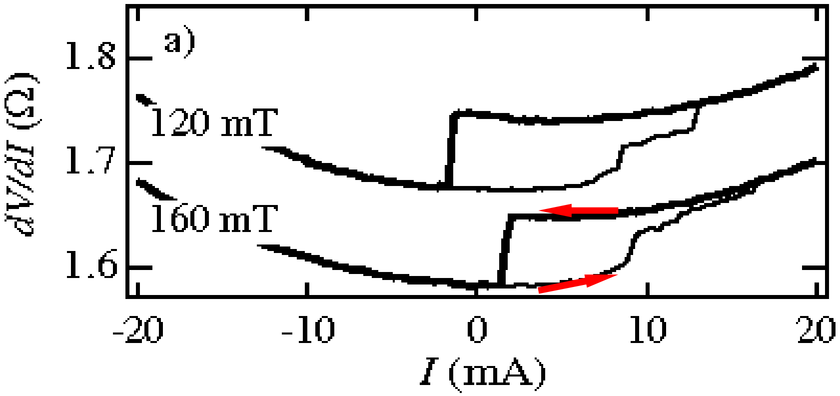
Figure: courtesy of J. Miltat



Katine et. al., *Phys. Rev. Lett.,* 84, 3149 (2000):

Main result: hysteresis observed for the differential resistance by the current sweep

Interpretation: magnetization switching caused by a spin-polarized current above a certain threshold



Spin transfer torque

Landau-Lifshitz-Gilbert-equation + STT

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times (\mathbf{H}_{\mathrm{eff}} + \mathbf{h}_{\mathrm{th}}) + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \frac{\gamma \hbar J \eta(\mathbf{m}, \mathbf{m}_{\mathrm{p}})}{2e M_{\mathrm{s}} t_{\mathrm{F}}} \mathbf{m} \times (\mathbf{m} \times \mathbf{m}_{\mathrm{p}})$$

Critical switching current:

Film thickness

$$J_{\mathrm{c}0} = \frac{2e\alpha M_{\mathrm{s}} t_{\mathrm{F}} (H_K \pm H_{\mathrm{ext}} + 2\pi M_{\mathrm{s}})}{\hbar \eta}$$

Spin-Transfer parameter

$$J_{\mathrm{c}} = J_{\mathrm{c}0}\left(1 - \frac{k_{\mathrm{B}} T}{K_{\mathrm{F}} V} \ln \frac{t_{\mathrm{p}}}{\tau_0}\right)$$

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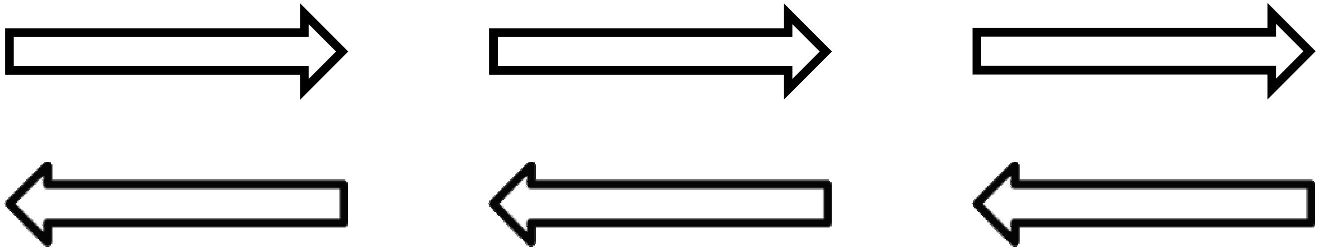
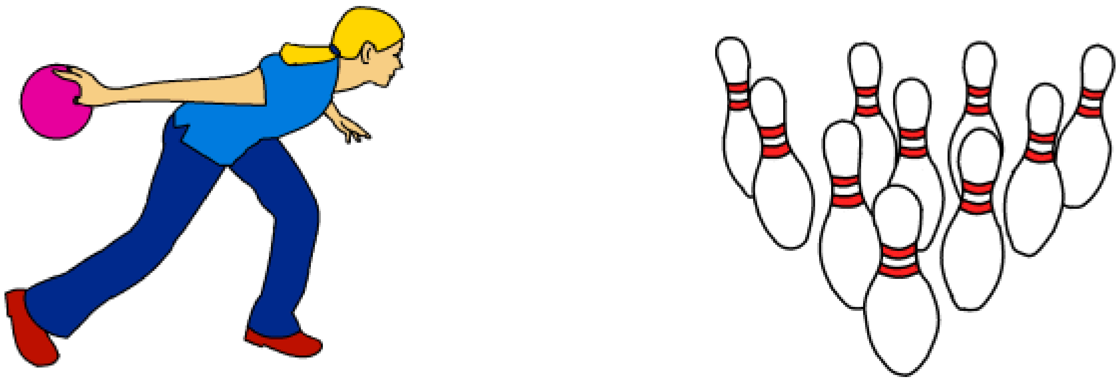
Spintronics

STT effect (Noble price ???)

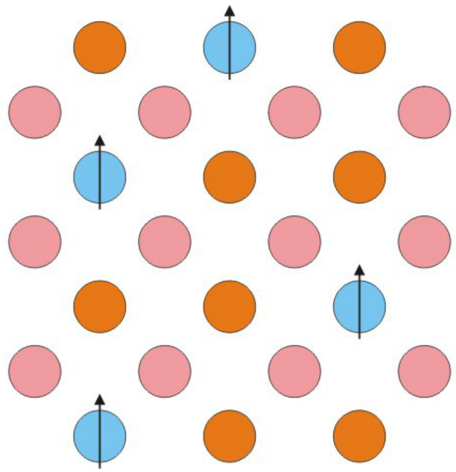




Diluted magnetic semiconductors (DMS)

Spintronics – Diluted Magnetic Semiconductors

DMS



Dispersed TM ions
(~ 5%) on
uniform lattice sites

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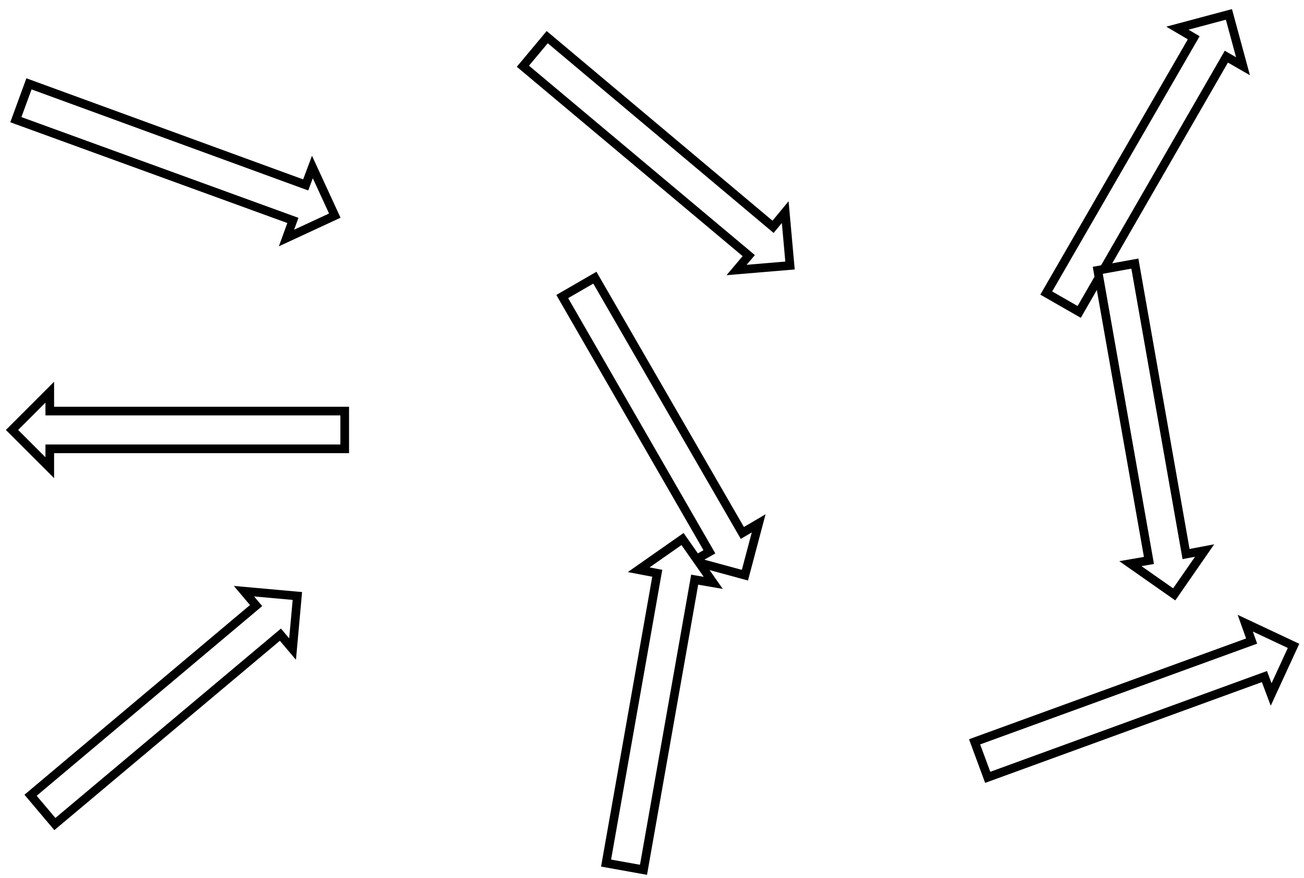
Magnetic moments in external fields

Magnetic field off

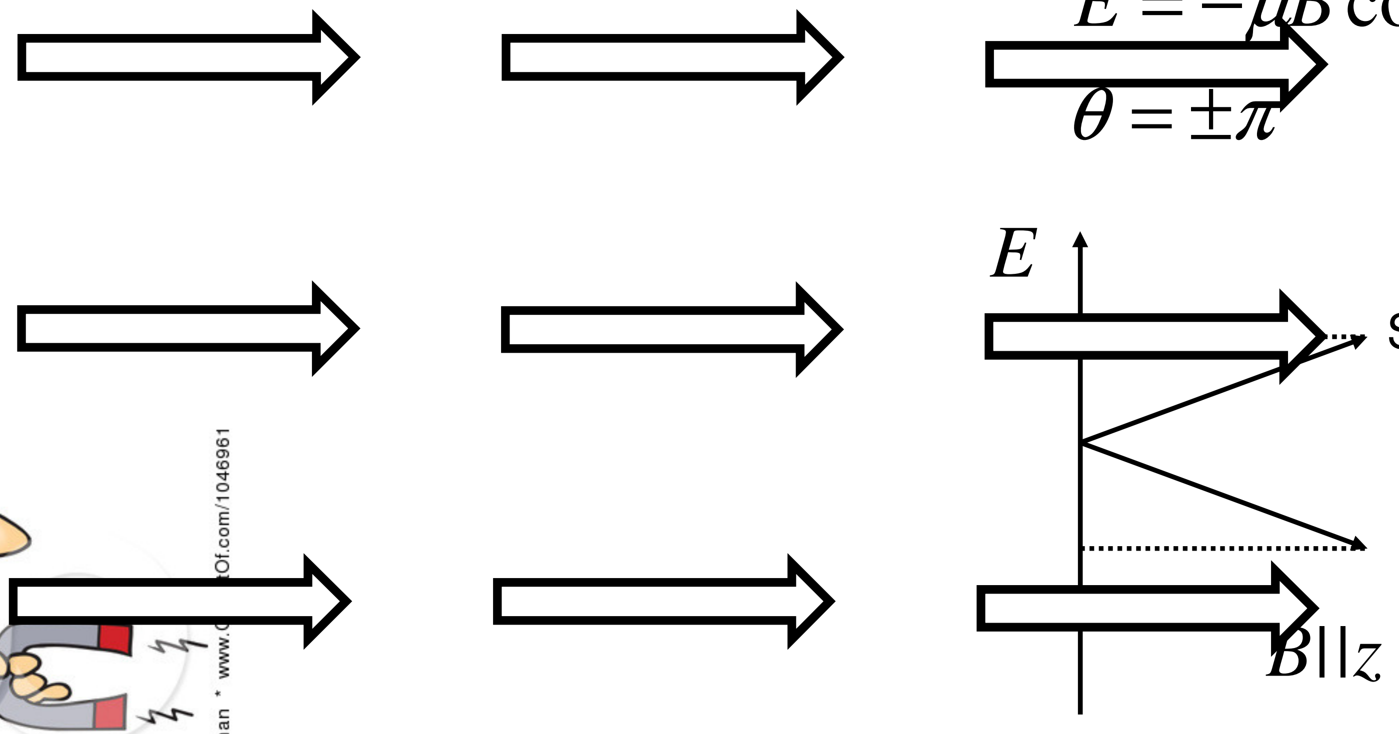


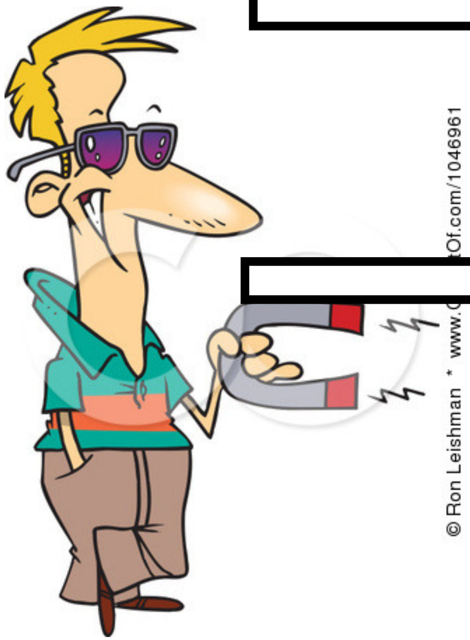
Magnetic moments in external fields

Magnetic field on

$$E = -\mu B \cos\theta$$

$$\theta = \pm\pi$$





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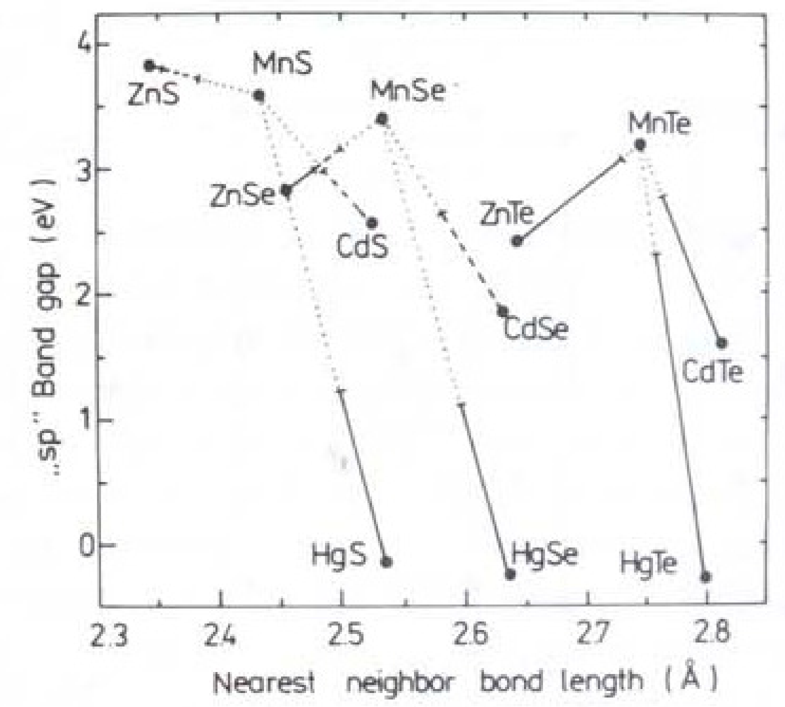
Paramagnetic DMS

J. K. Furdyna, JAP 64, 1988

- **Mainly II-VI doped with Mn - paramagnetic**
- **Giant Zeeman splitting of the conduction band**
- **Spin polarization of charge carriers**
- **Bound magnetic polaron at zero field**
- **Spin-glass freezing for high Mn concentration**



Classical DMS: Ideal spin aligner
but no ferromagnetic order at RT!

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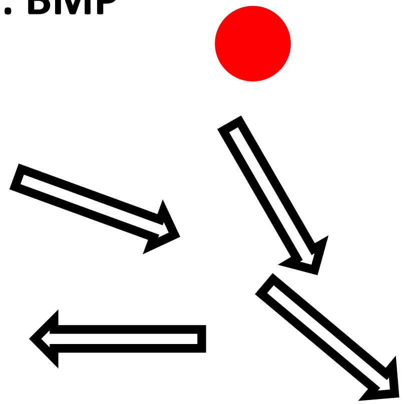
Paramagnetic DMS

Example: BMP



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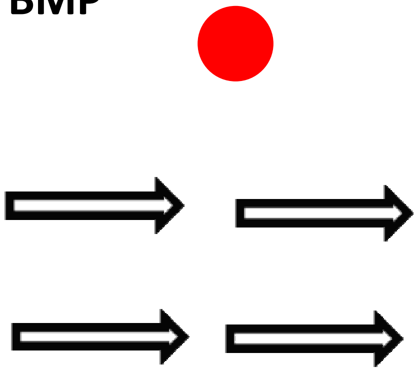
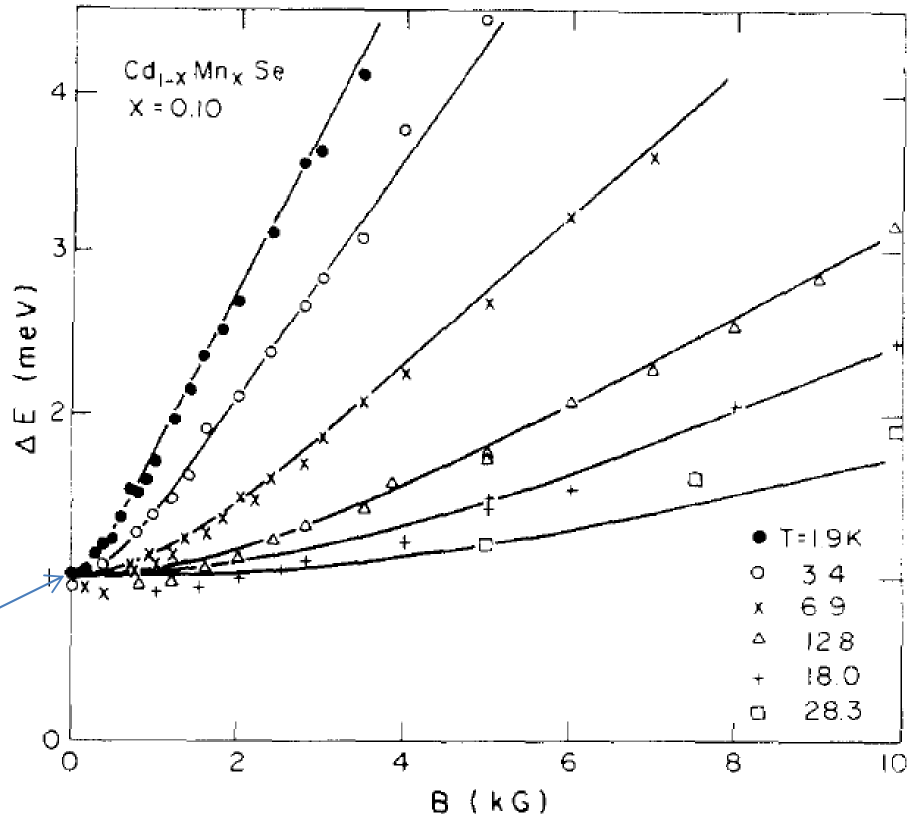
Paramagnetic DMS

Example: BMP



Spin-flip energies for CdMnSe at different temperatures:



Origin: *sp-d exchange interaction
Method: *Spin Flip Raman Scattering

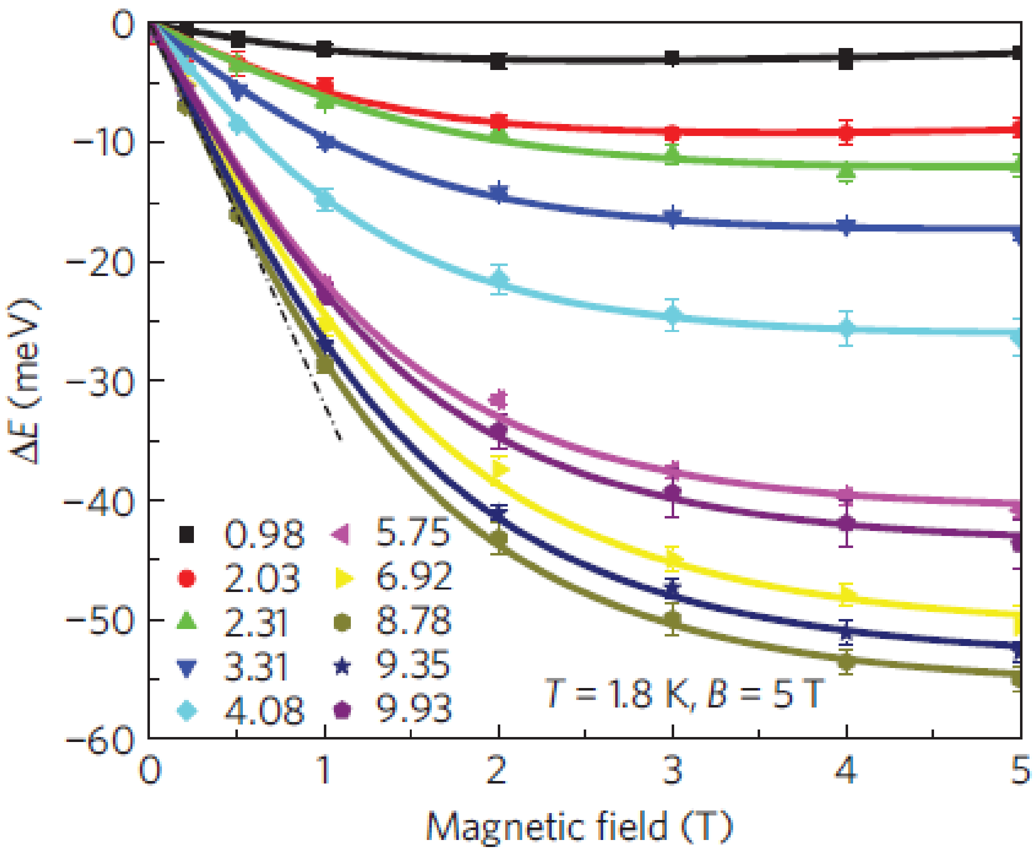
Zero field Spin flip energy = sign for BMP

P. A. Wolff and J. Warnock
J. Appl. Phys. 55, 2300 (1984);

Paramagnetic DMS

Example: Giant Zeeman splitting in $CdSe:Mn^{2+}$
(J. H. Yu et al., Nature Materials 2009)

Method: *MCD
Origin: *sp-d exchange interaction
***negative s-d interation due to quantum confinement**



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3. **Magnetic coupling**
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Magnetic coupling

How magnetic moments arrange themselves?

Finding the energy minimum:

- System gains energy from quantum mechanical exchange interaction (delocalization)
- System avoids too high Coulomb repulsion
- System avoids too large kinetic energies
- Pauli principle must be fulfilled
- Hunds rules must be fulfilled

$$\hat{H}_t = -t \sum_{\langle ij \rangle, \sigma} \left(c_{i\sigma}^{+} c_{j\sigma} + c_{j\sigma}^{+} c_{i\sigma} \right).$$

$$\hat{H}_U = U \sum_i n_{i\uparrow} n_{i\downarrow}$$

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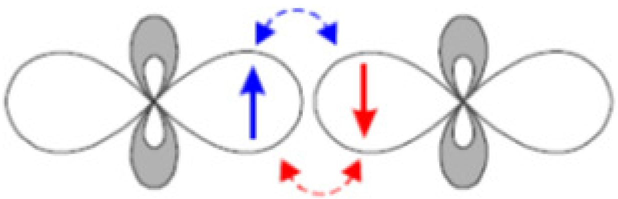
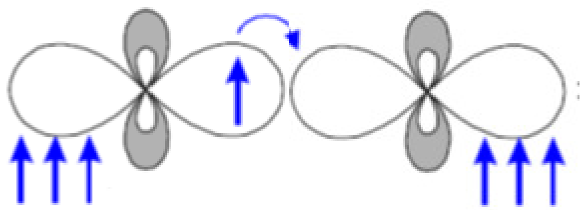
Magnetic coupling

Virtual hopping related



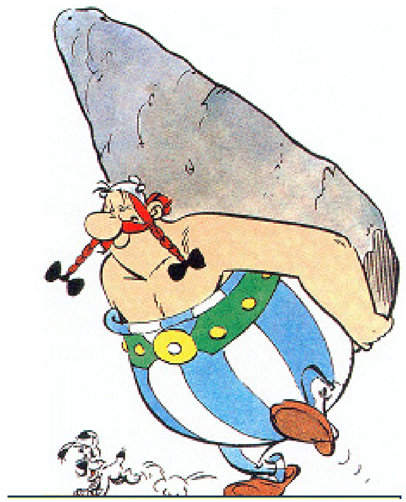
$$\Delta E = 2\sum_{i>j} \frac{2t^2}{U} S_i S_j$$

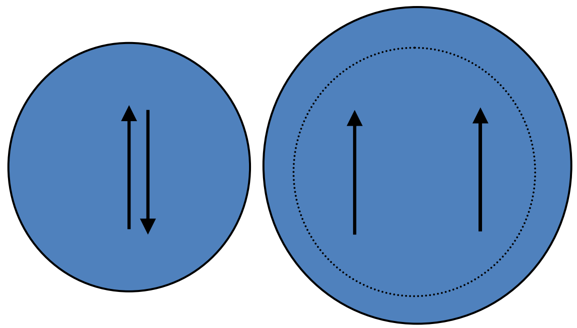
Electronic transport related



$$\Delta E \sim -zt\cos\frac{\theta}{2}$$

Itinerant



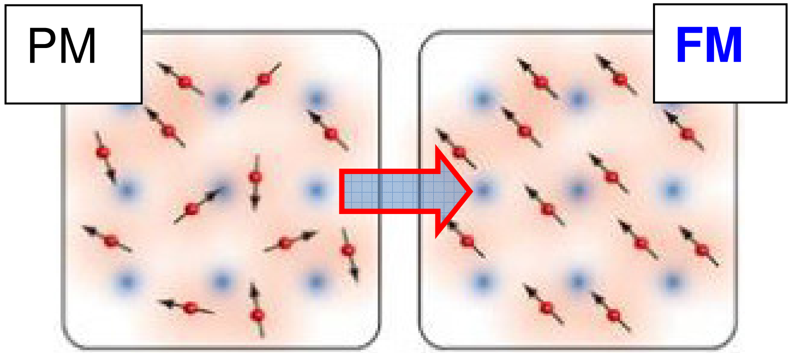


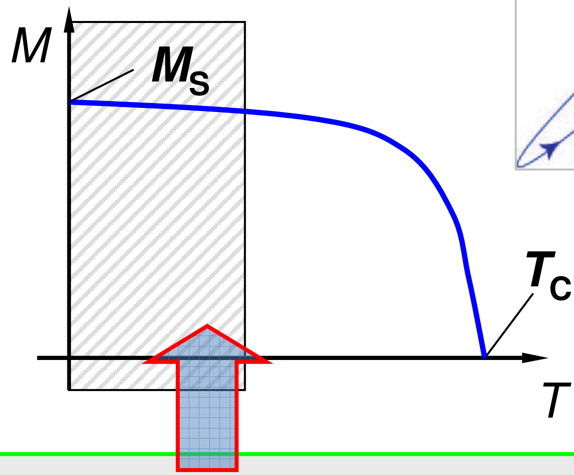
$$\Delta E \sim \left[1 - Ug(E_F)\right]$$

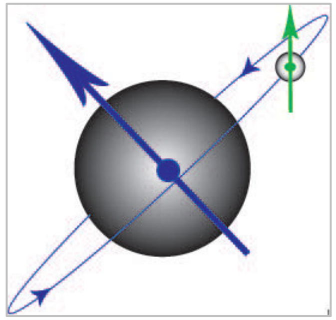
Magnetic coupling

D. Berkov, priv. Comm.

FM materials possess a **spontaneous magnetization** (magnetization without an external field) due to the **very strong exchange interaction** between atomic magnetic moments (which are due to the own angular moments of electrons called spins)







$$|\mathbf{M}| = Const = M_S$$

$$\mathbf{m} = \mathbf{M} / M_S$$

Unit vector field **m**(**r**) and the **saturation magnetization** M_S completely characterize the magnetization state of a FM body well below $\boldsymbol{T_C}$

$$E_{FM} = F(\{\mathbf{m}(\mathbf{r})\}, M_S)$$

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Spintronics – Diluted Magnetic Semiconductors

Magnetic coupling: Lets drive the mobility screw!

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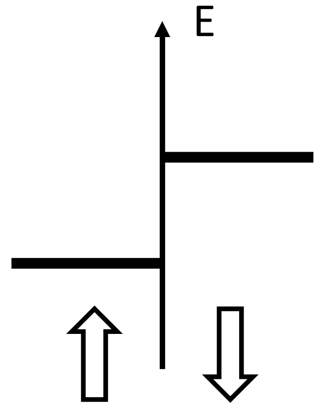
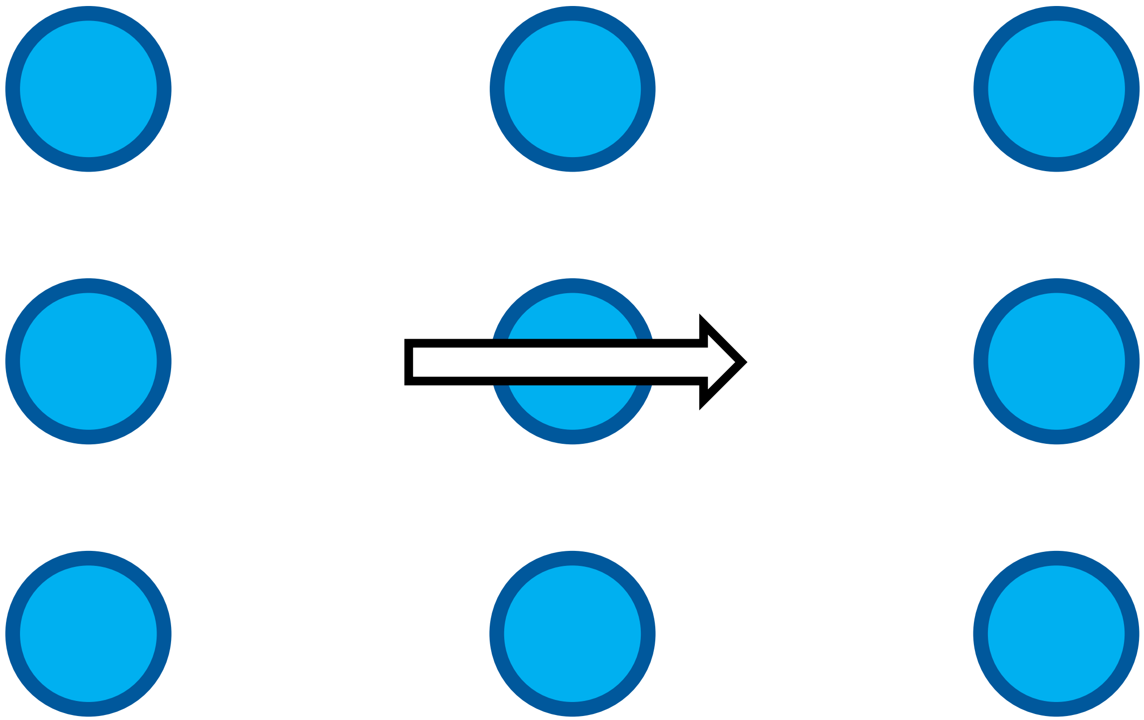
Spintronics – Diluted Magnetic Semiconductors



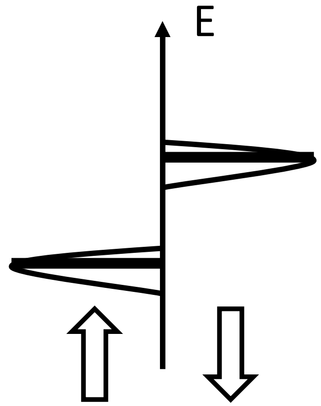
Driving the screw

- Paramagnet



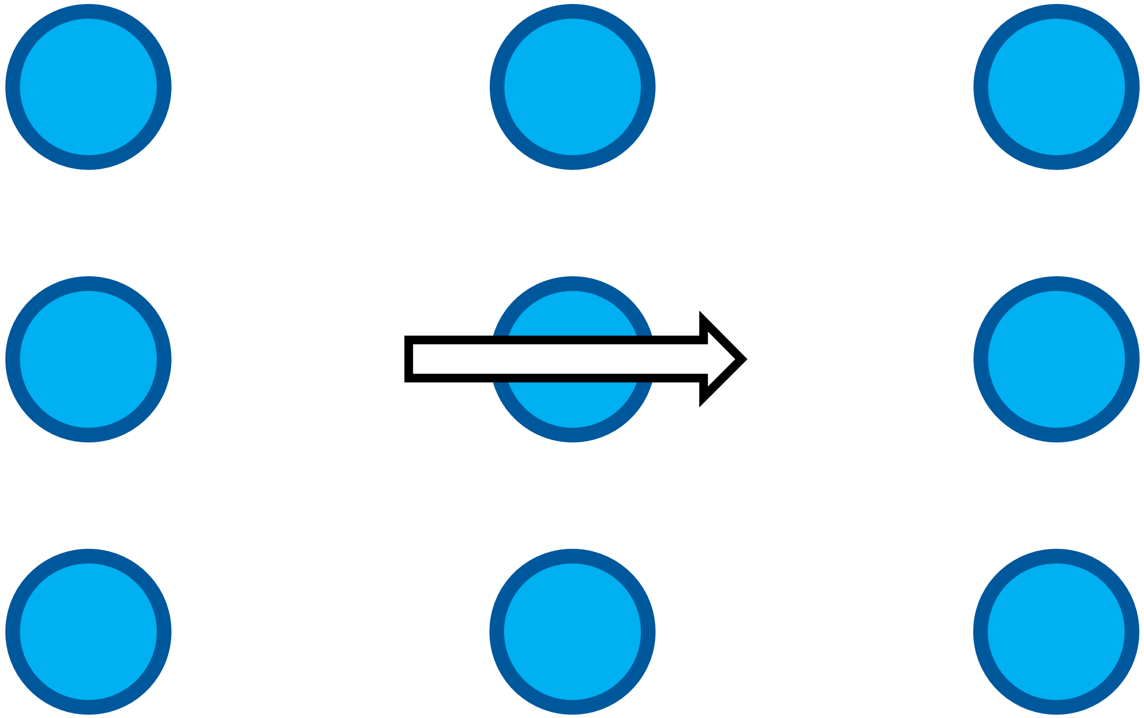
Local picture

Spintronics – Diluted Magnetic Semiconductors



Driving the screw

- Paramagnet



Local picture

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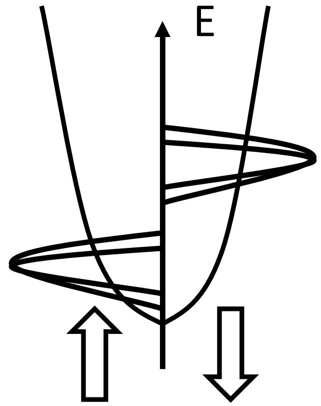
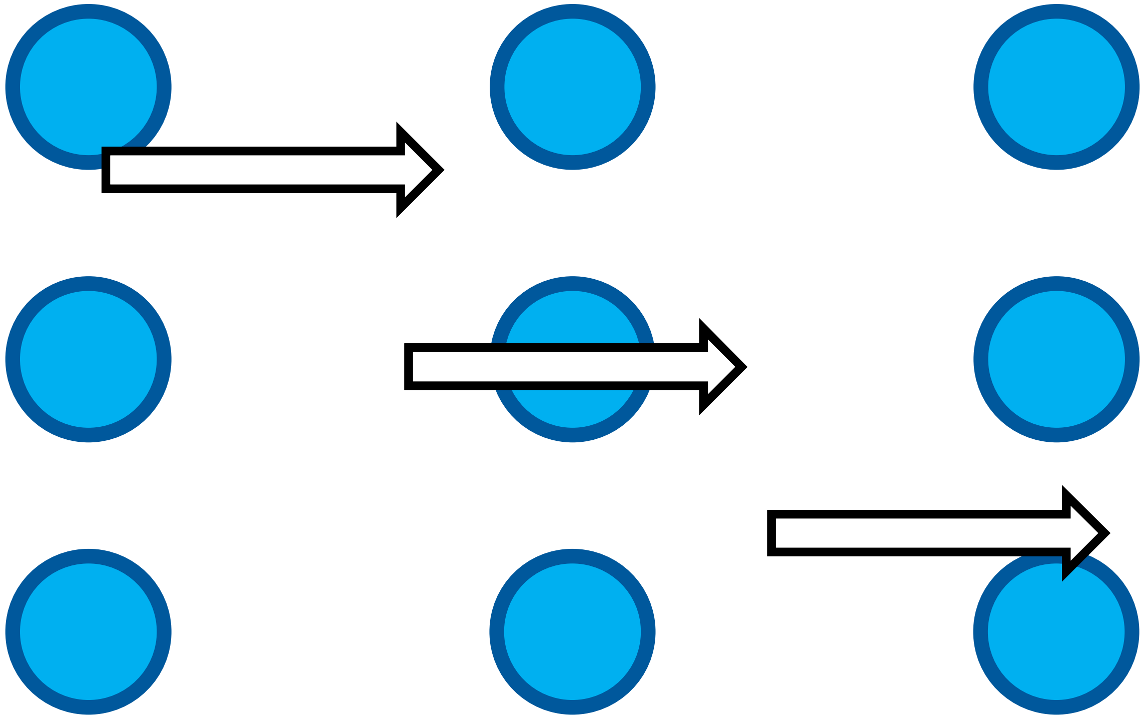
Spintronics – Diluted Magnetic Semiconductors

Driving the screw

- Paramagnet
- Diamagnet





Local picture
Global picture

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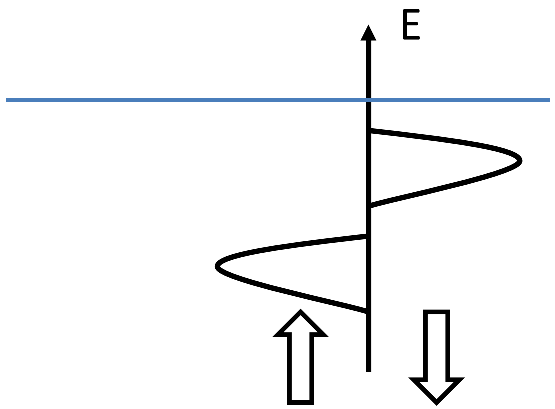
Spintronics – Diluted Magnetic Semiconductors

- Ferromagnet

The half-metallic state:

- Magnetic metal
- Magnetic semiconductor
- 100 % Spinpolarization



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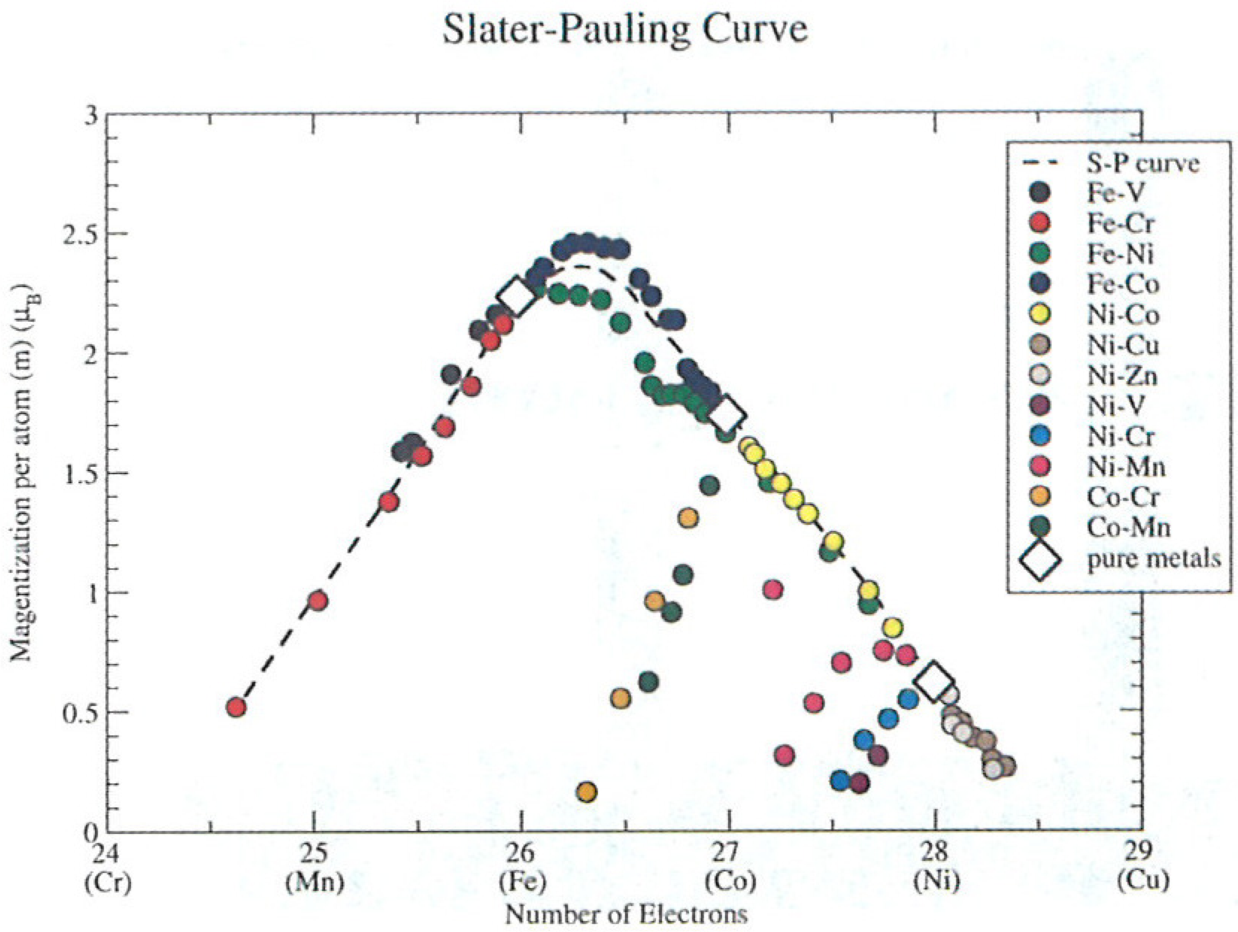
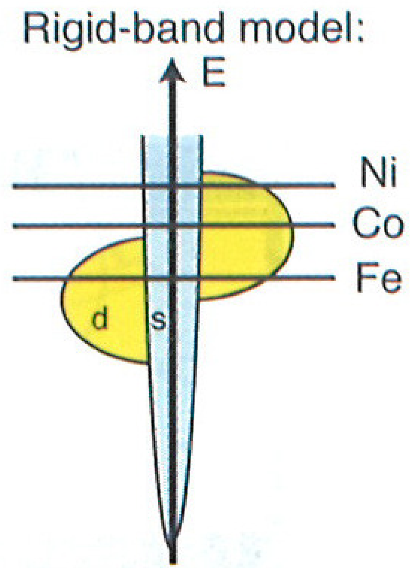
Metallic ferromagnets



data taken from Bozorth, PR 79, 887 (1950)



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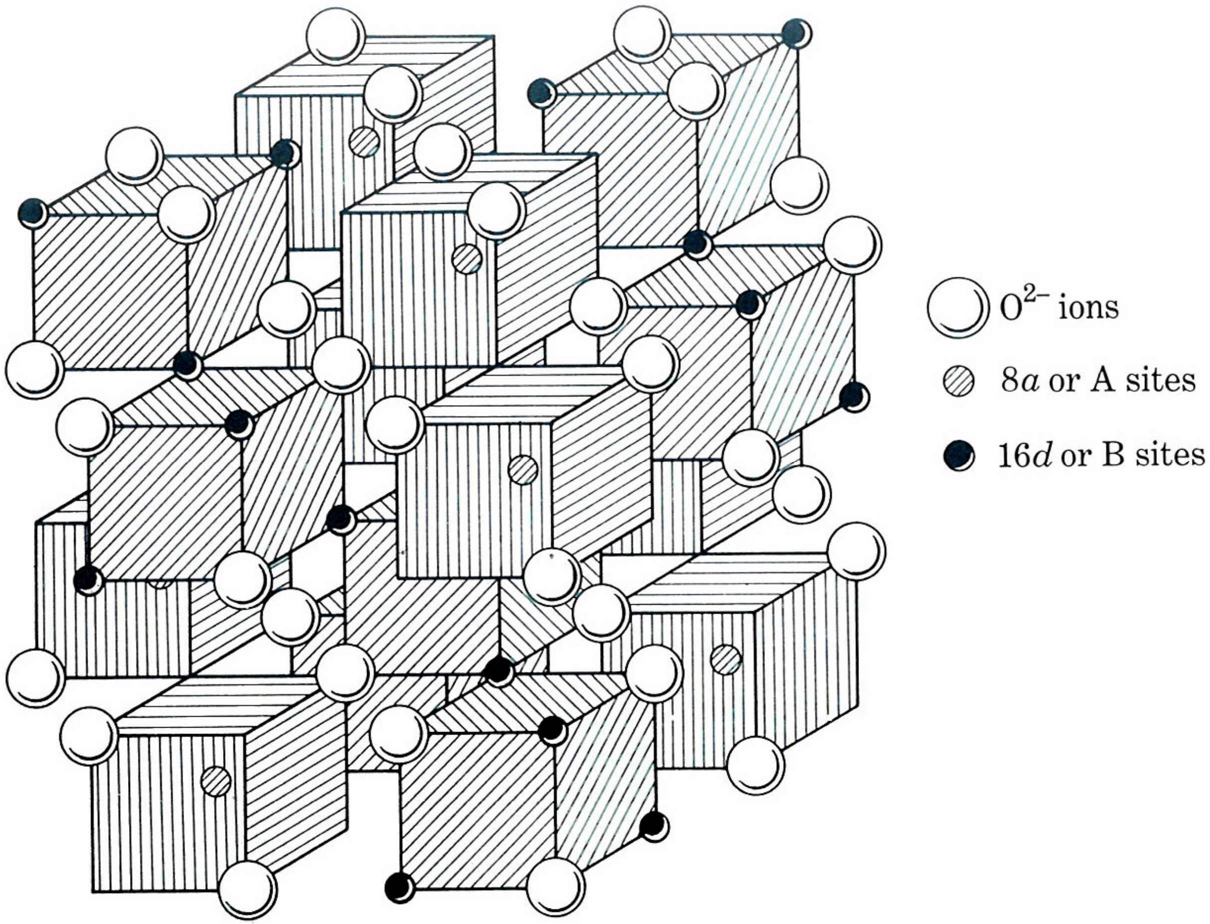
Ferrimagnetic spinels

Normal spinel structure

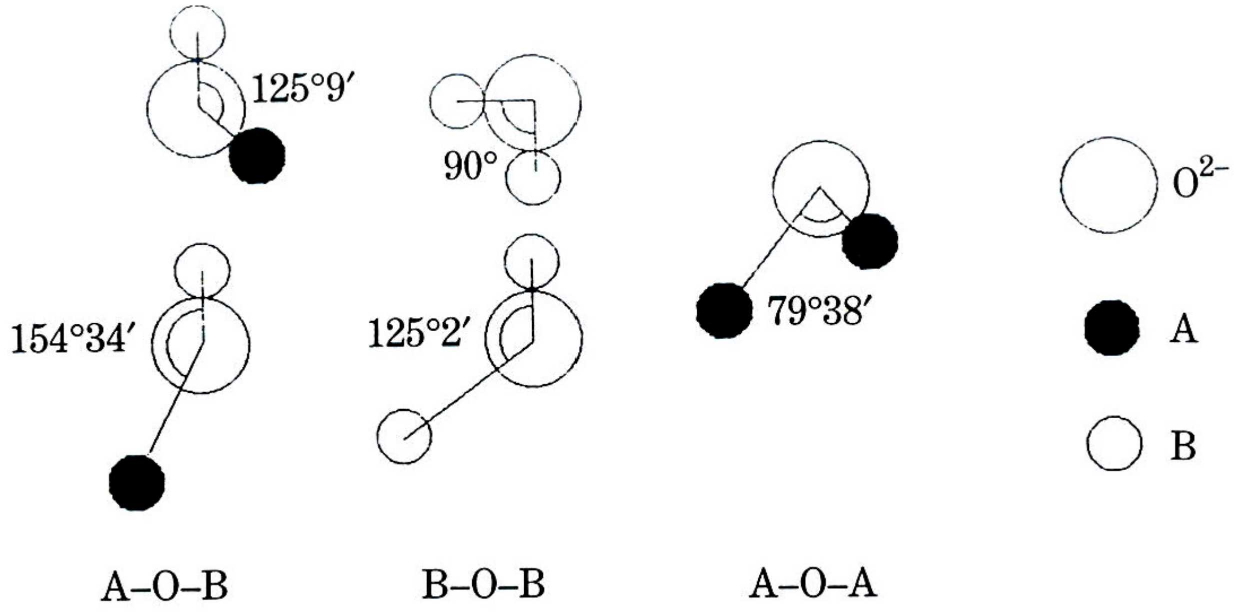


Chikazumi

Ferrimagnetic spinels

Magnetic Structure:

A-O-B: Antiferro
A-O-A: Ferro
B-O-B: Ferro



A ***B***

General Spinell: $$\left(Me_{\delta}Fe_{1-\delta}\right)\left(Me_{1-\delta}Fe_{1+\delta}\right)O_4$$

Zn: δ=1
Mn: δ=0.8
Fe: δ=0

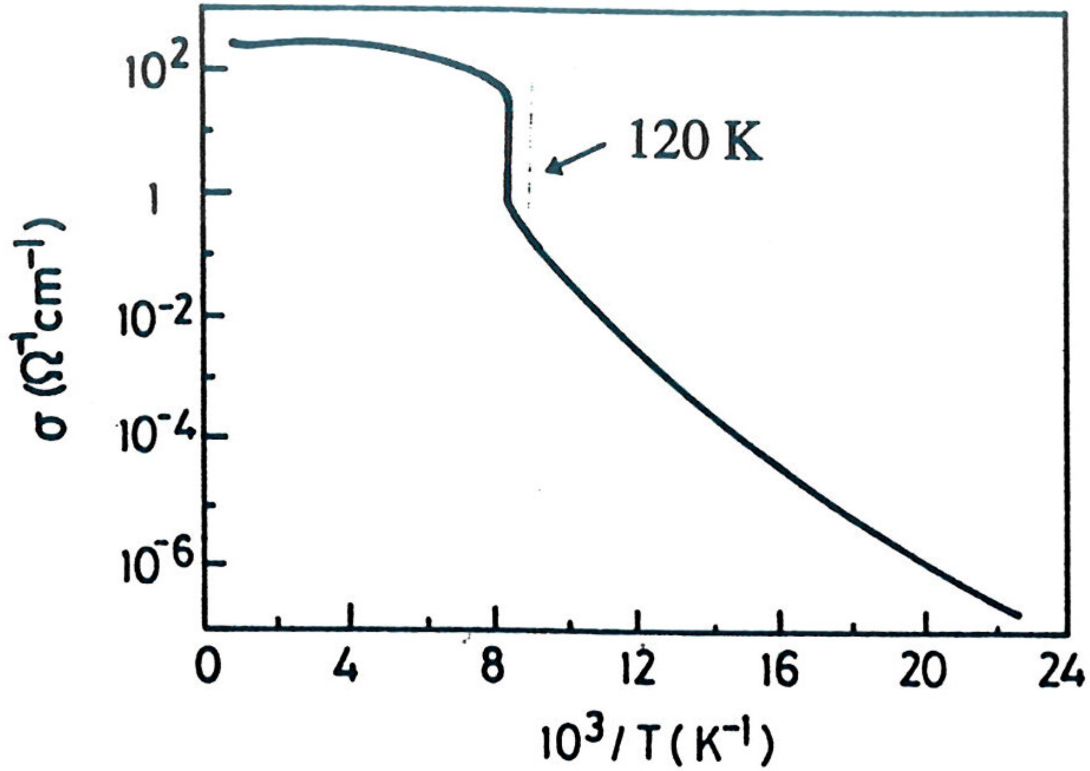
Normal Spinell (δ=1): $$\left(\overleftarrow{Me}^{2+}\right)O\cdot\left(\vec{Fe}^{3+}\vec{Fe}^{3+}\right)O_3$$

Inverse Spinell (δ=0): $$\left(\vec{Fe}^{3+}\right)O\cdot\left(\overleftarrow{Me}^{2+}\overleftarrow{Fe}^{3+}\right)O_3$$

Ferrimagnetic spinels: Magnetite

A B

$$\left(\vec{F}e^{3+}\right)O\cdot\left(\overleftarrow{F}e^{2+}\overleftarrow{F}e^{3+}\right)O_3$$



Fe^{3+} and Fe^{2+} coexist on B-sites → e⁻hopping is possible
→ High conductivity and spin polarized electrons

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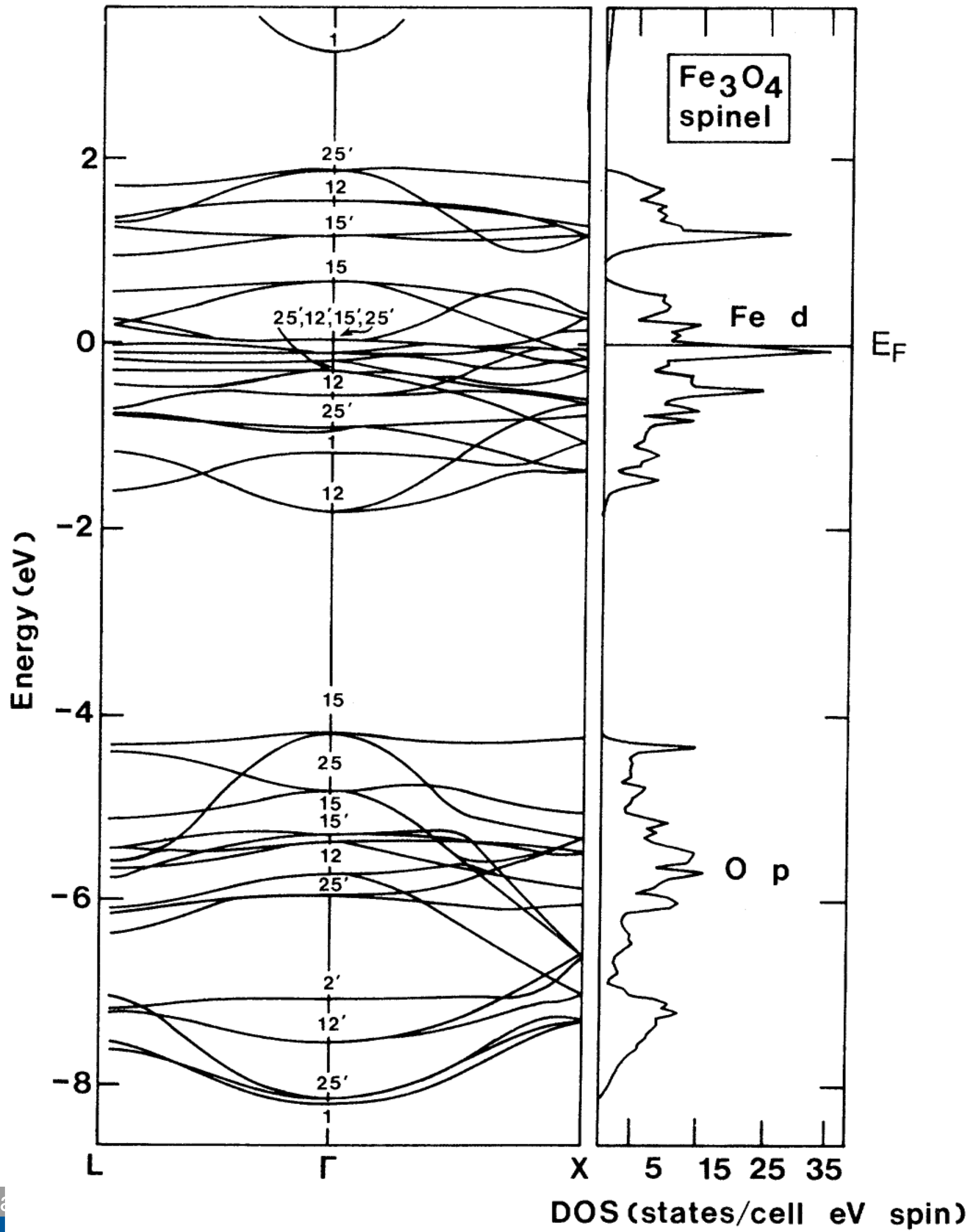
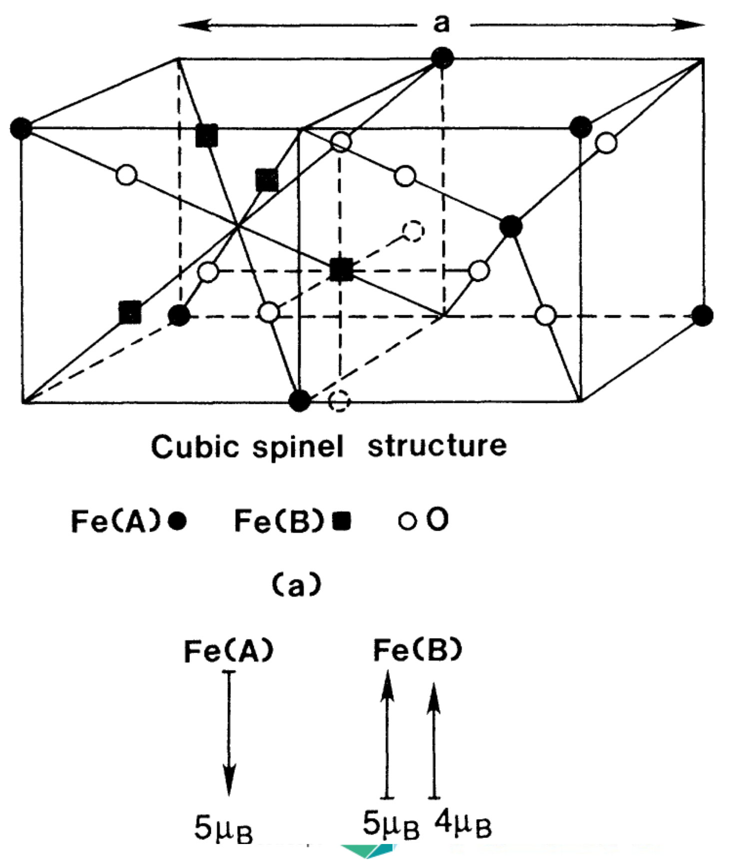
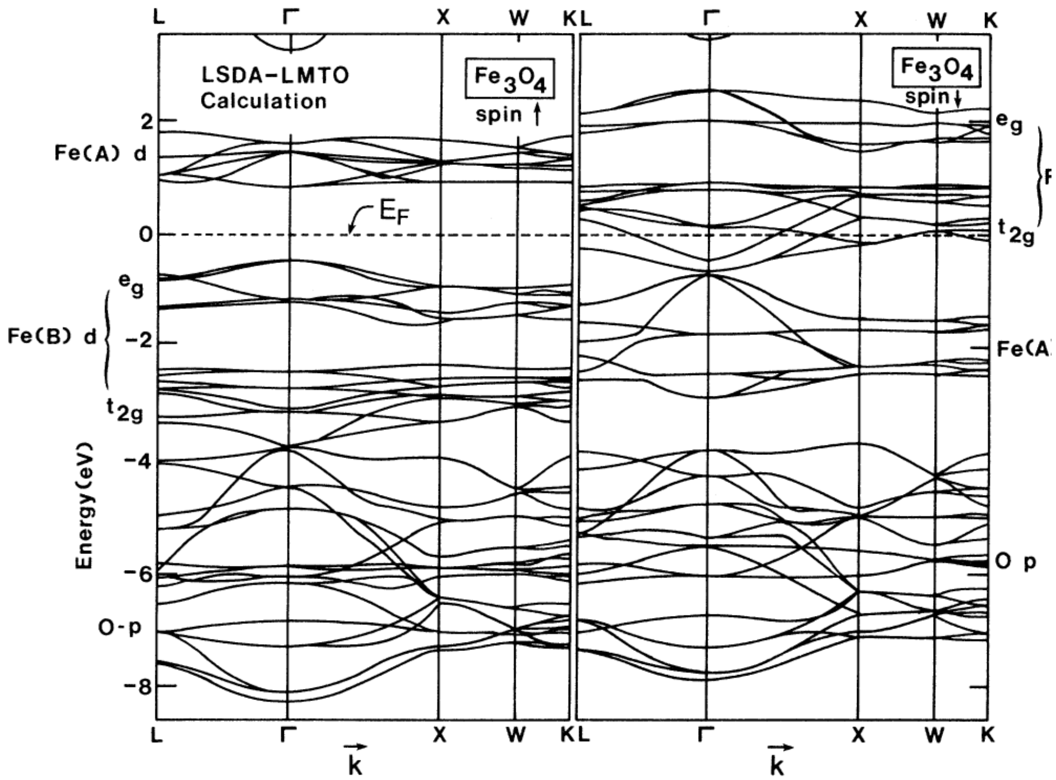
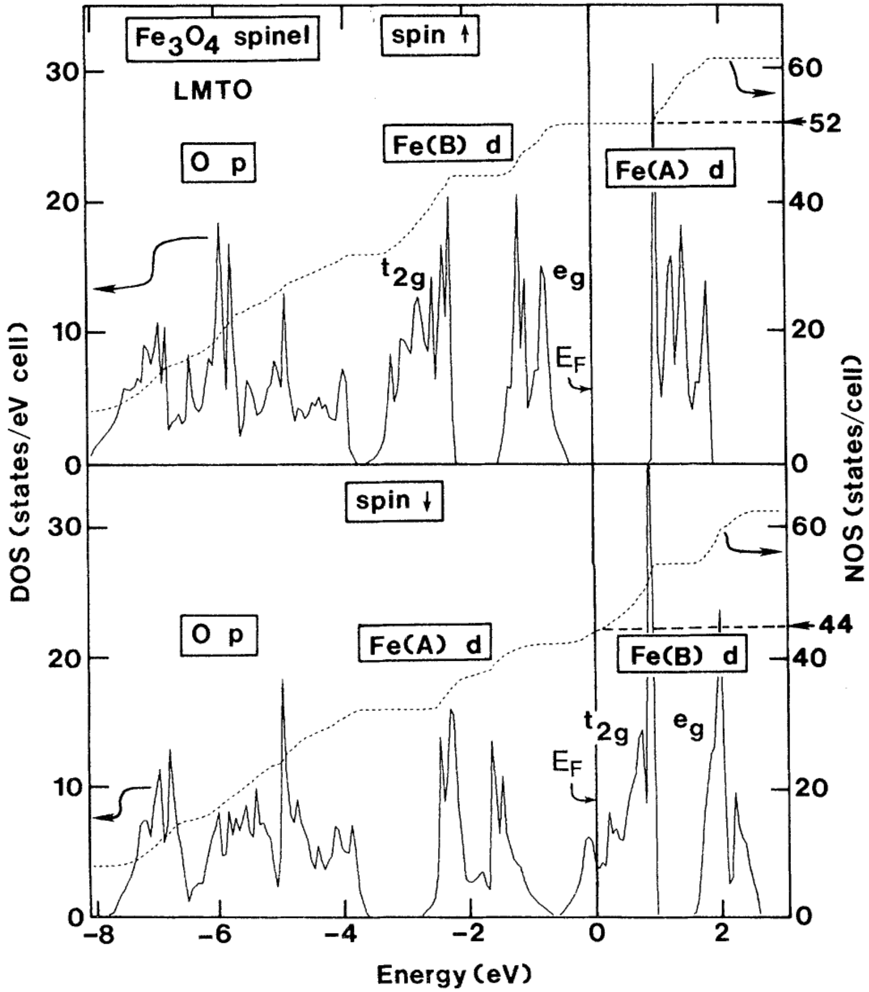
Ferrimagnetic spinels: Magnetite





Ferrimagnetic spinels: Magnetite





- Mixed valency $Fe^{2+/3+}$
- Moment = $4\mu_B$ per Fe_3O_4 formula unit
- ↑ semiconducting, E_g~1.5 eV

Ze Zhang, PRB 1991

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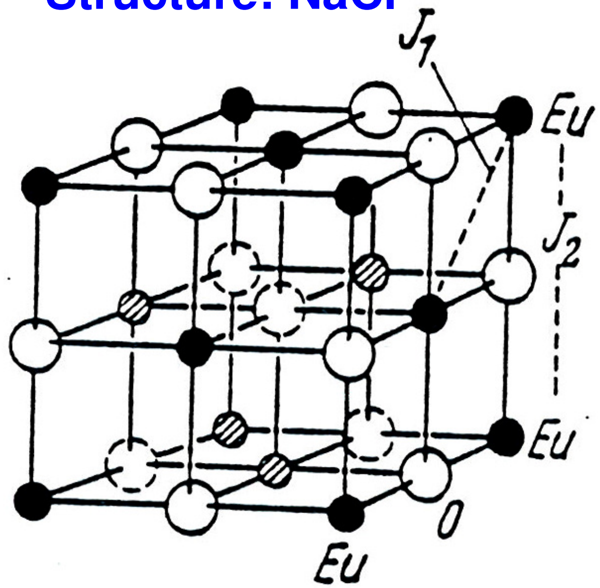
Magnetic semiconductors: Eu chalcogenides

Structure: NaCl



EuO: T_C=69.33 K ΔE=1.12 eV a=5.141 A
EuS: T_C=16.57 K ΔE=1.65 eV a=5.986 A
EuSe: T_M=4.6 K ΔE=1.8 eV a=6.195 A
EuTe: T_N= 9.58 K ΔE=2.0 eV a=6.598 A

Heisenberg-exchange

Ineraction between nearest (nN) and Next nearest neighbors (nnN):

$$\hat{H} = -\sum_{ij} \tilde{J}_{ij} \vec{S}_i \vec{S}_j$$

$$\hat{H} = -\tilde{J}_1 \sum_{nN} \vec{S}_0 \vec{S}_{nN} - \tilde{J}_2 \sum_{nnN} \vec{S}_0 \vec{S}_{ünN}$$

$J_1>0$, 4f-5d-4f-exchange (5d=empty orbital) - FM
$J_2<0$, 4f-2p-4f-Superexchange (180°) - AFM

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Magnetic semiconductors: Eu chalcogenides

IFF Ferienkurs Jülich 1998

$$\hat{H} = -\tilde{J}_1 \sum_{nN} \vec{S}_0 \vec{S}_{nN} - \tilde{J}_2 \sum_{nnN} \vec{S}_0 \vec{S}_{nnN}$$

Molekular field approximation:

nN (12)

$$T_C = \frac{2}{3} S(S+1)(z_1 \tilde{J}_1 + z_2 \tilde{J}_2)$$

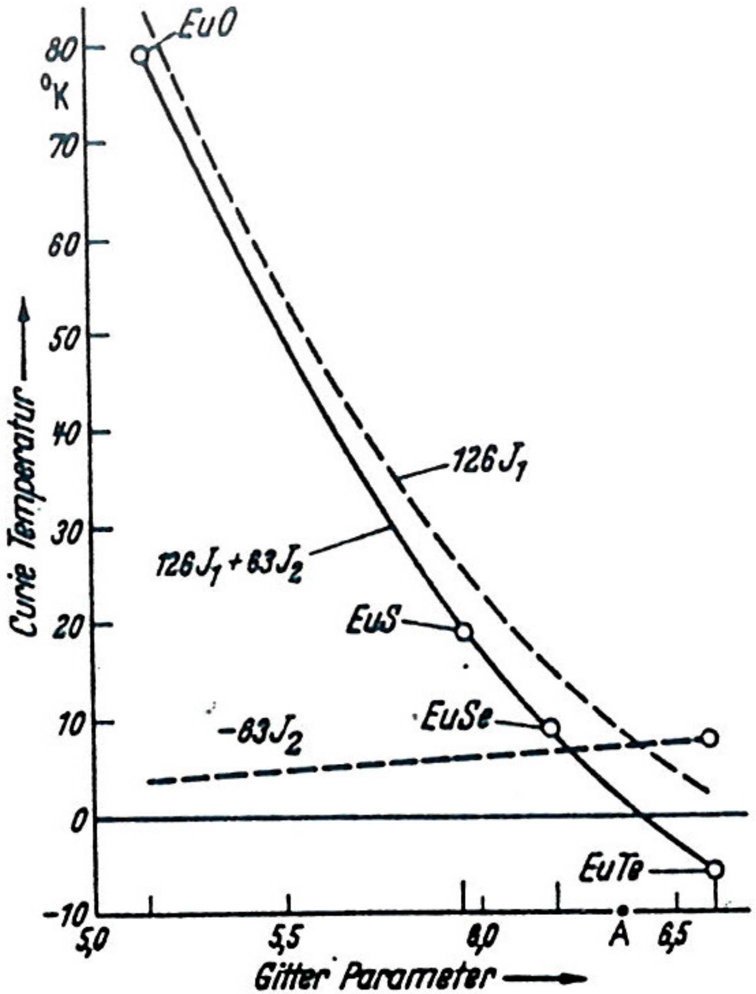
nnN (6)

$$T_N = \frac{2}{3} S(S+1)(-z_2 \tilde{J}_2)$$

Changes with lattice constant

$$T_C = 126 J_1 + 63 J_2$$

$$T_N = -63 J_2$$



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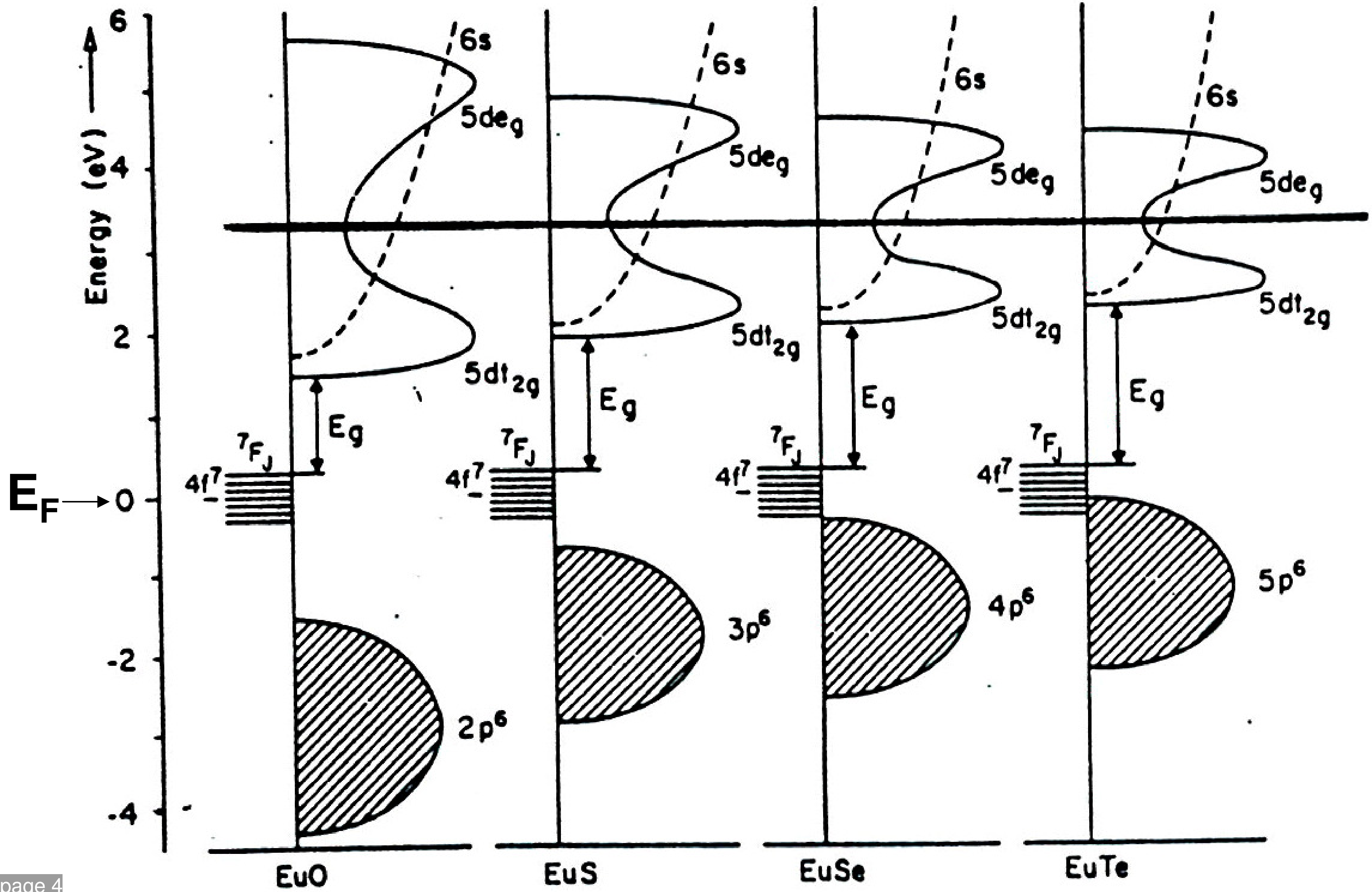
Magnetic semiconductors: Eu chalcogenides

Paramagnetic DOS

$4f^7Eu$



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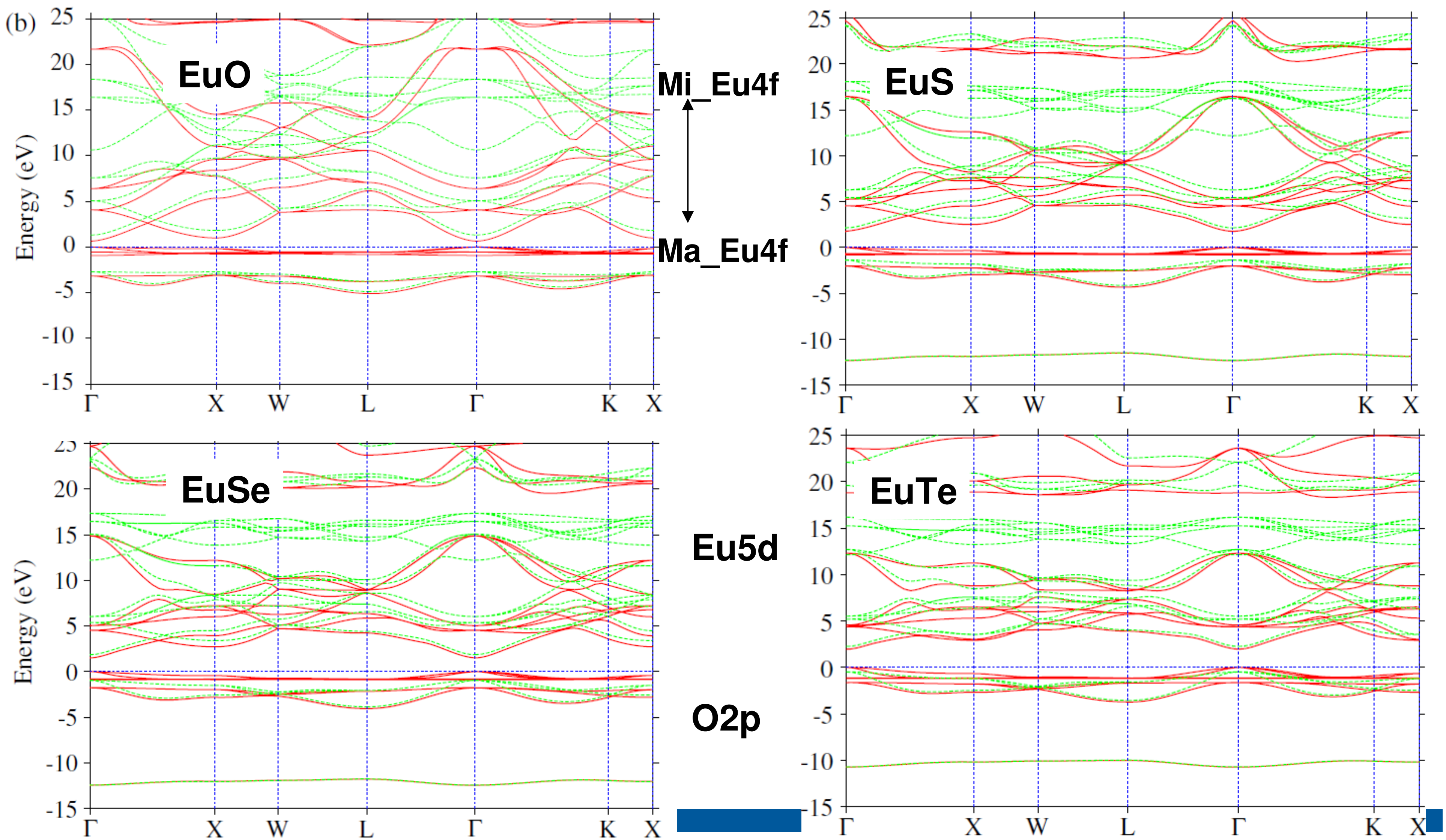
P. Larson, L.E. Lambrecht 2006

Magnetic semiconductors: Eu chalcogenides

DOS for Eu-Chalkogenides (FM)

Red=Majority (Ma)
Green=Minority (Mi)



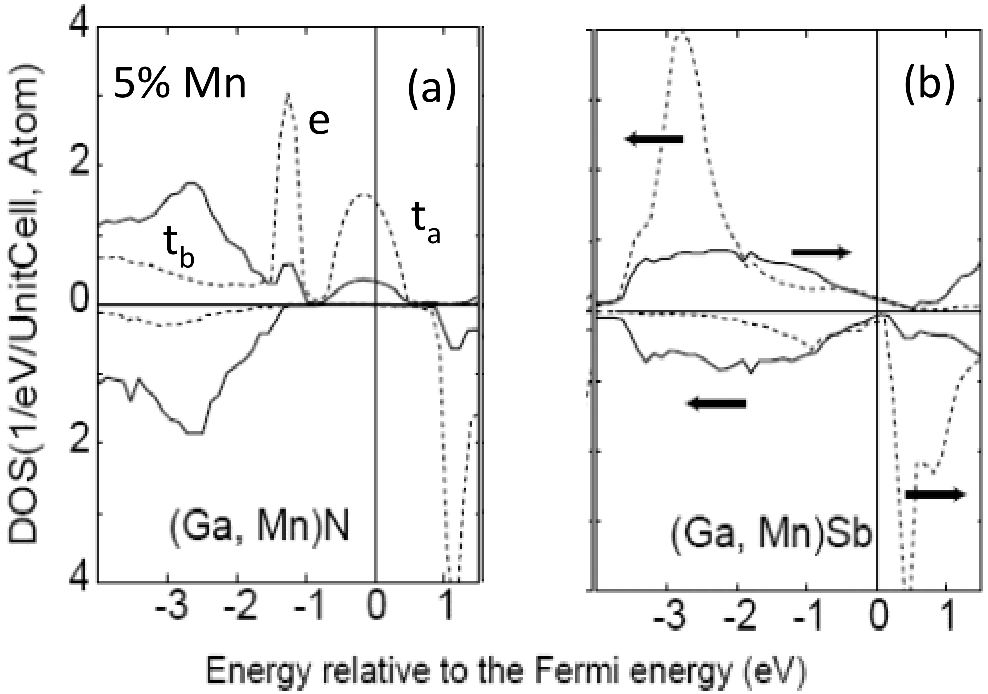
Outline

1. Principles of spintronics
2. Paramagnetic DMS, giant Zeeman splitting and bound magnetic polarons
3. Magnetic coupling
4. Half metallic materials
5. **Magnetism and Transport in GaMnAs**
6. Oxide based DMS by ion implantation

Spintronics – Diluted Magnetic Semiconductors

Theory

P. H. Dederichs, IFF Ferienkurs Jülich, 2005



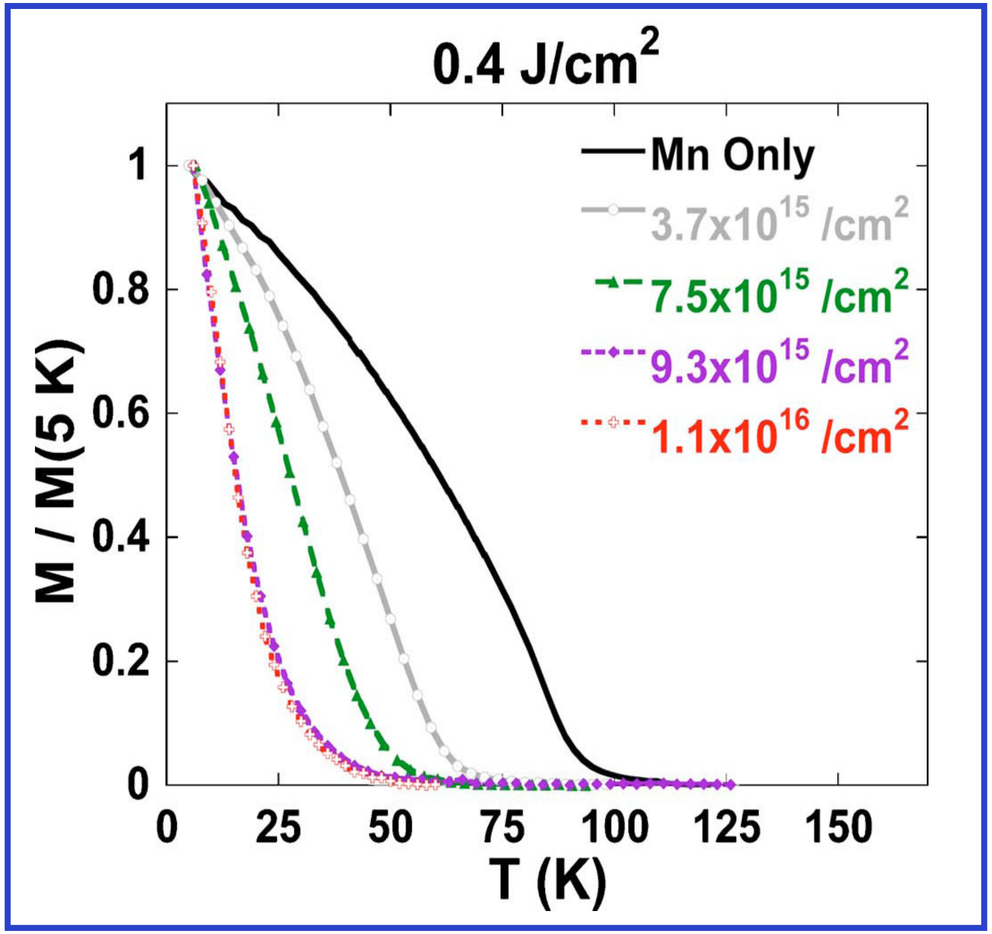
(a) – d-d Zener exchange - $T_C \sim \sqrt{c}$

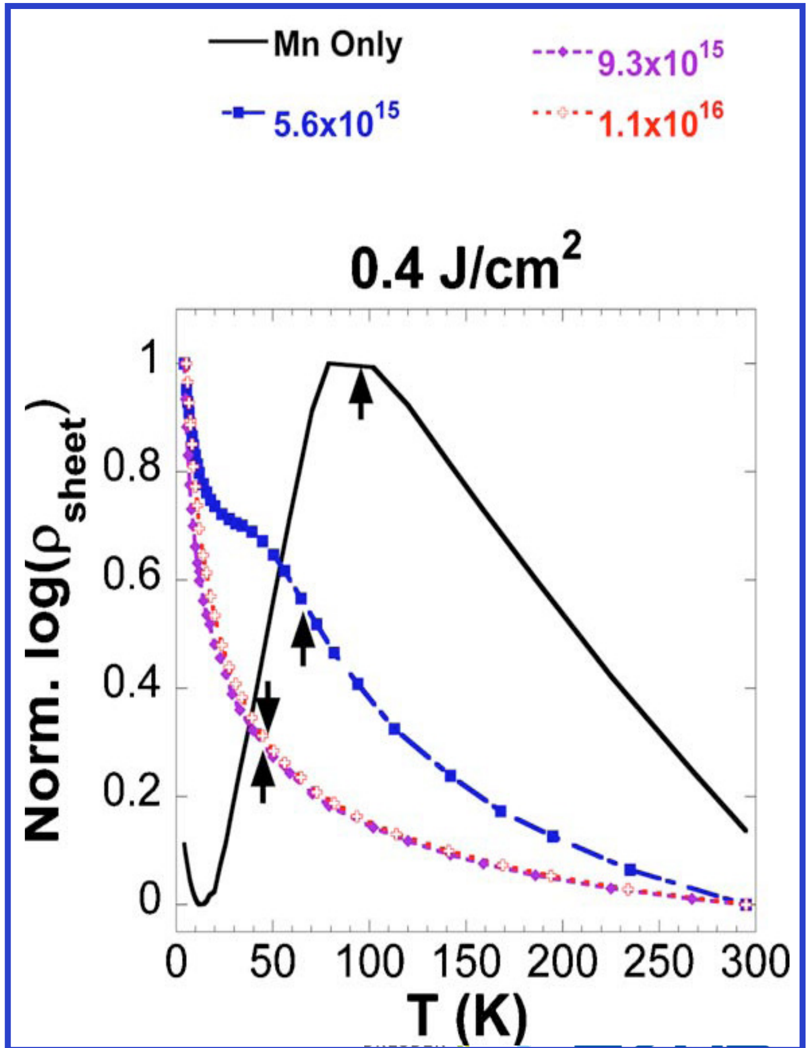
(b) – p-d Zener exchange - $T_C \sim c$

Spintronics – Diluted Magnetic Semiconductors

GaAs + Mn + Te Implantation + laser-melting:

FM for metallic and localized case





Scarpulla et al. JAP 103, 123906, (2008)

Spintronics – Diluted Magnetic Semiconductors

- **Reproducible ferromagnetic DMS: GaMnAs** (T. Dietl, Science, 2000)
- **Curie temperature record (2011) = -88 ℃**

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Outline

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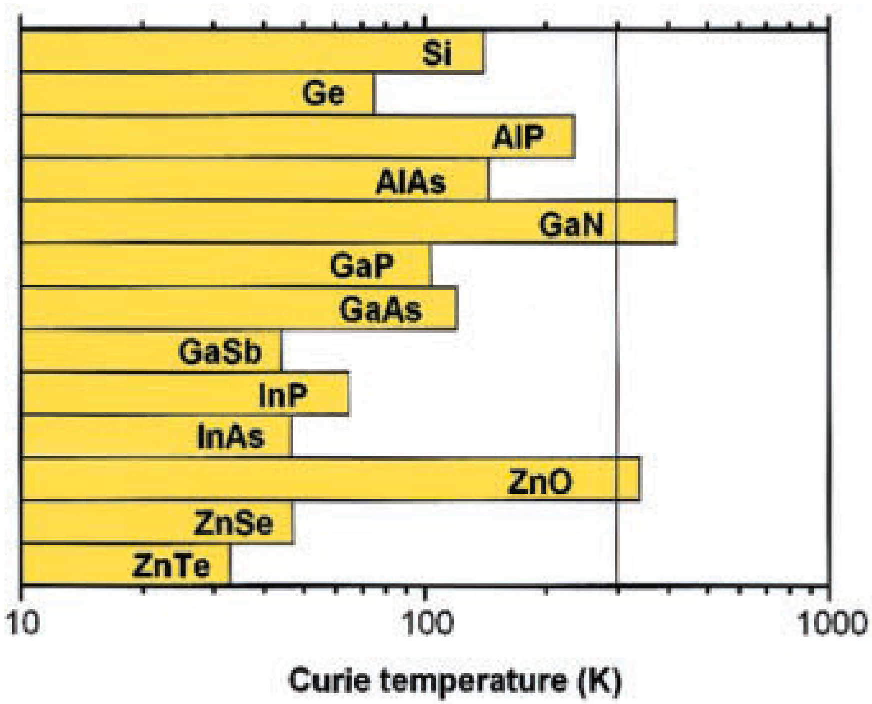
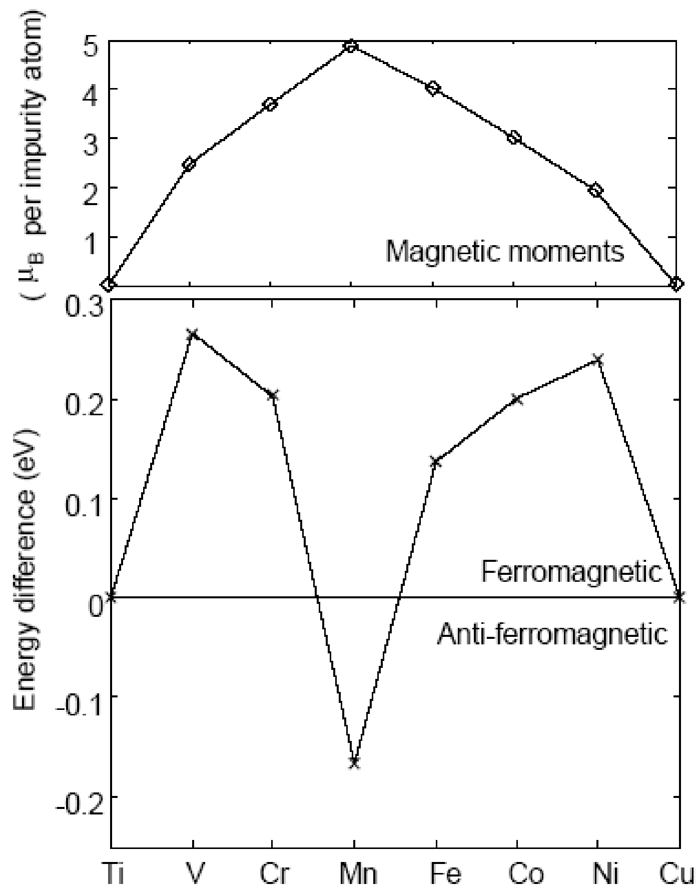
Magnetic doping of oxides

TM doped semiconductors and oxides



5% Mn and p-carriers
$3.5 \times 10^{20}/cm^3$

T. Dietl, Science, 287 (2000) 1091



25% TM in ZnO, without any additional carrier doping

K. Sato, JJAP, 39 L555

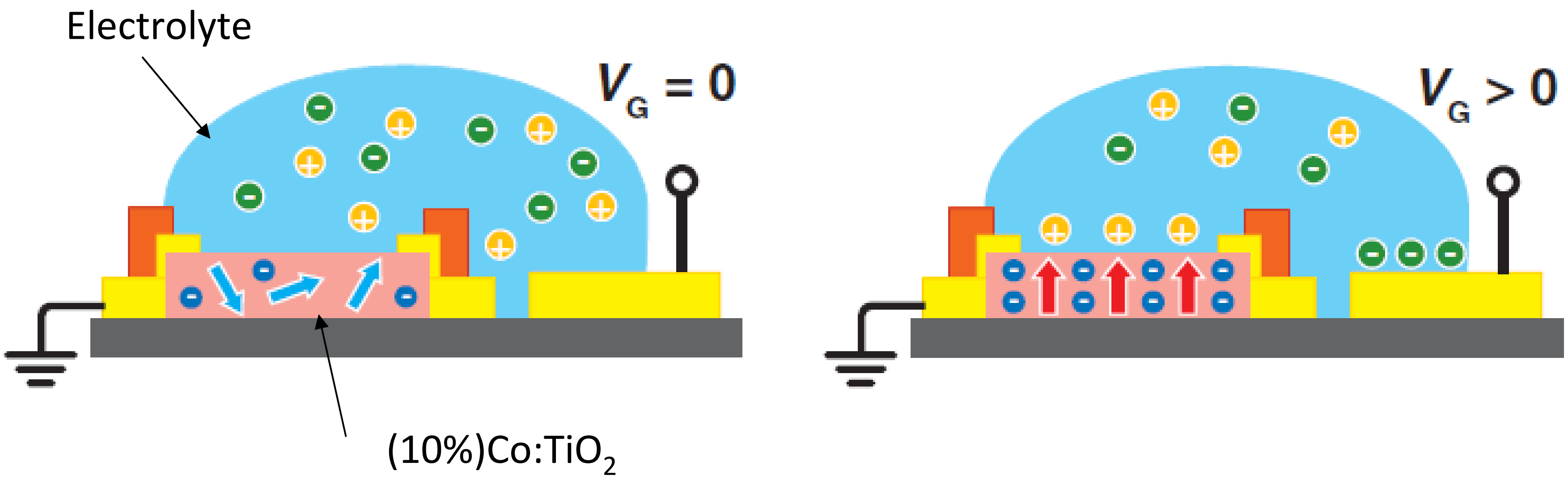
Magnetic doping of oxides

Co or V ions

Oxide (here TiO_2)

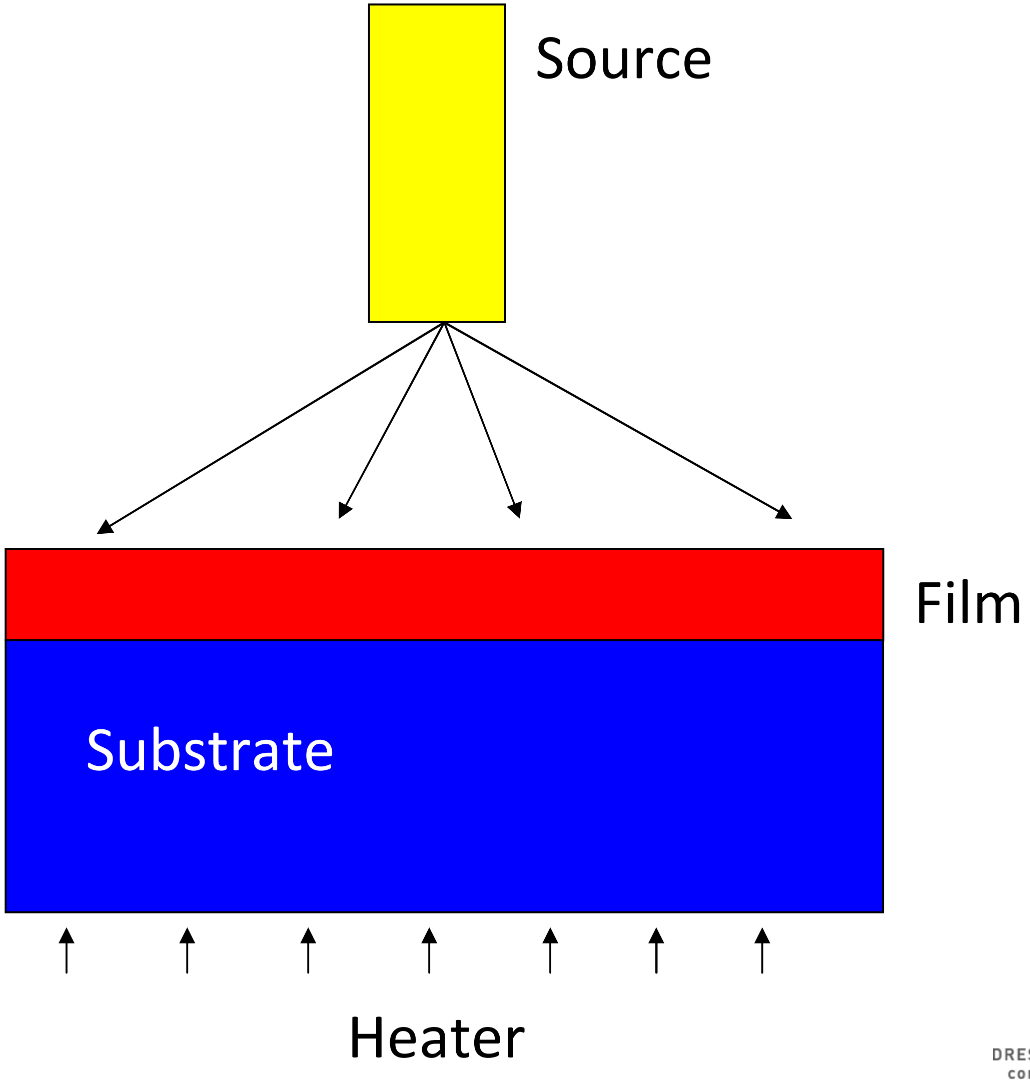
Candidate with electrically induced magnetization switching:

- TiO_2 doped with Cobalt (e.g., Y. Yamada, Science 2011)



Deposition methods

- Physical vapor deposition



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Thin film growth

Physisorption/Chemisorption: Weak/Strong interaction between substrate and deposited film

Physisorption

Van der Waals between the atoms of
The film and their image charge:
Lenard-Jones-Potential

$$U(r) = -\frac{\alpha}{r^6} + \frac{\beta}{r^{12}}$$

Flat potential minimum of 10-100 meV
at 0.3-1 nm aboe the surface

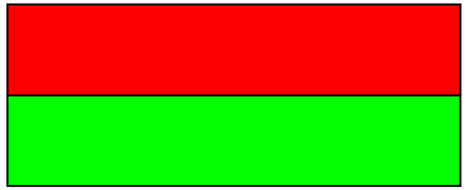
Chemisorption

Change of the electronic structure
Of the surface. Described by Morse
Potentials:

Deep potential minimum ~eV
at 0.1-0.3 nm above the surface

Thermodynamic considerations

Assumption of a thermodynamic equilibrium:
Surface diffusion must be faster than particle flux.



Energies for dominating surfave energies γ:

$$\gamma_{Substr} < \gamma_{Adsorbat} + \gamma_{Interface}$$

→Island growth (Old surface+ droplets preferred)

$$\gamma_{Substr} \geq \gamma_{Adsorbat} + \gamma_{Interface}$$

→Layer growth (Formation of new surface preferred)

$$\gamma_{Interface} = 0$$

→Homoepitaxie

Deviation of the interface energy from that
Of two substrate layers

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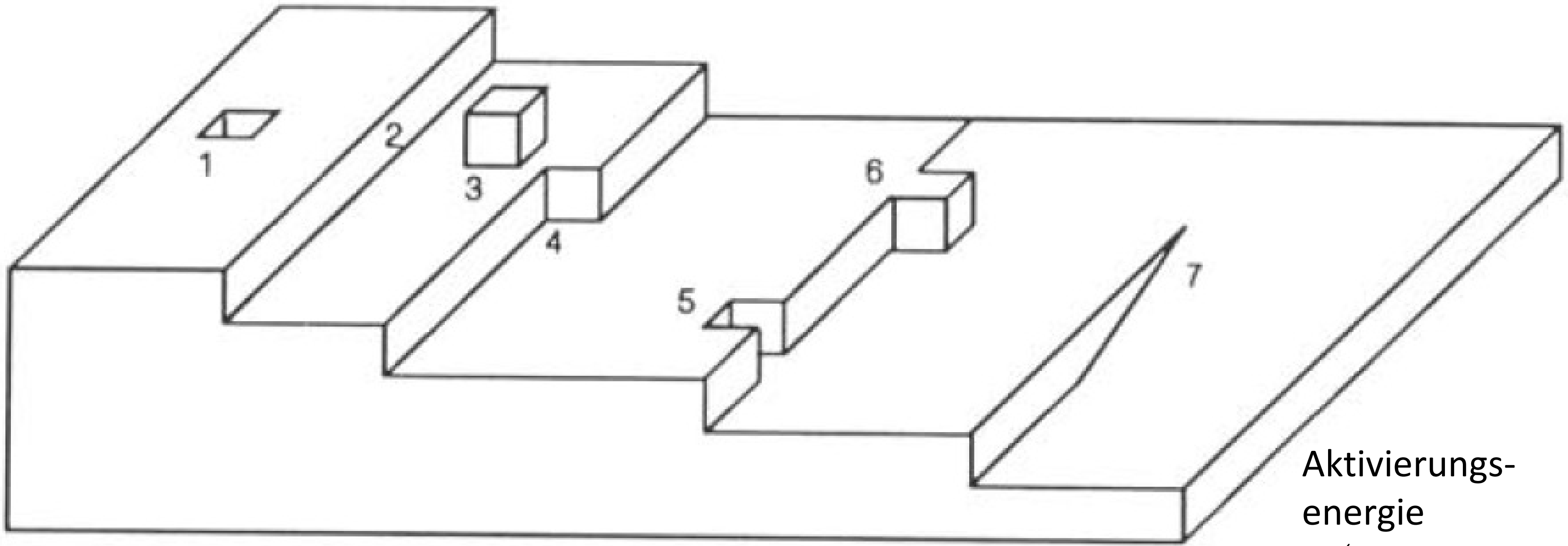
Kinetic/microscopic model

Diss. Mitte Halle 2001



Aktivierungs-energie

(1) Vacancy
(2) At step
(3) Adsorbate (singe atom)
(4) Kink
(5) In step
(6) Adsorbate at step
(7) Screw dislocation

Duration of stay: $\tau = \frac{1}{\nu} e^{\frac{E_{desorption,diffusion}}{k_B T}}$

•Surface defects are preferential sites for nucleation

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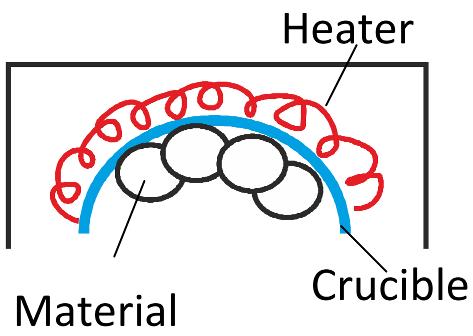
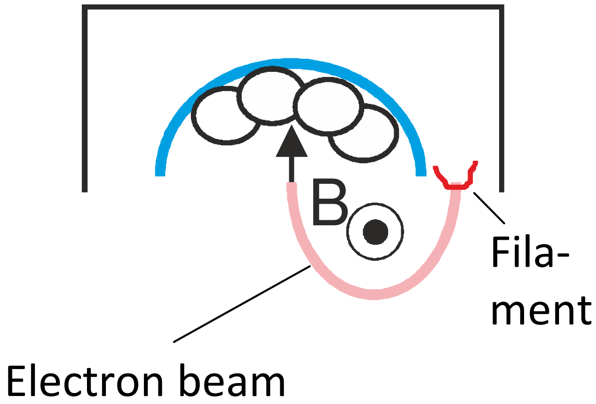
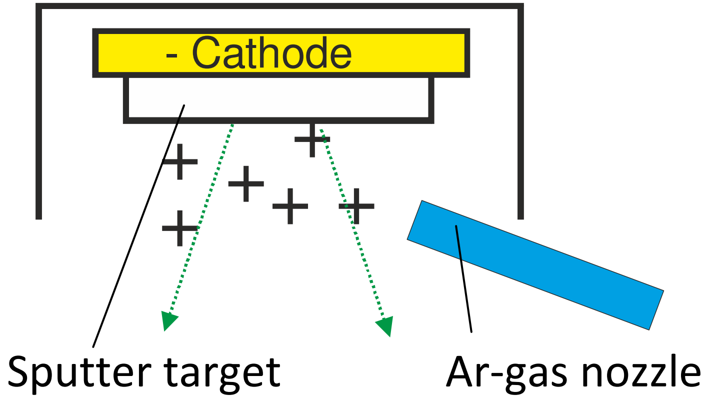
Methods for deposition

Molecular beam epitaxy (MBE)

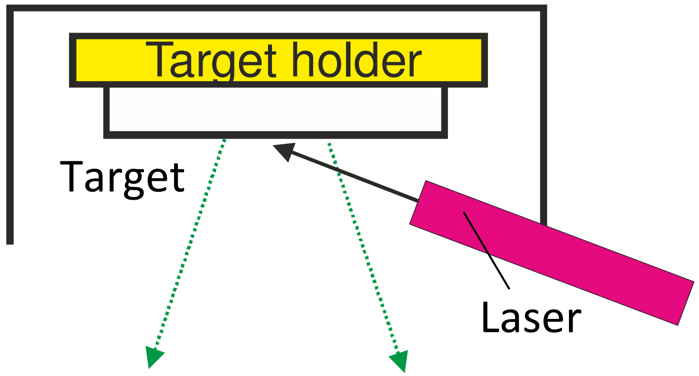




Sputter deposition



Pulsed laser deposition (PLD)



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Methods for deposition

	Physical Vapor Deposition Evaporation	 Sputtering	 PLD
Mechanism of production of depositing species	Thermal energy	Momentum transfer	Thermal energy
Deposition rate	High Up to 750,000 Å/min	Low, except for pure metals (Cu:10000 Å/min)	Moderate
Deposition species	Atoms and ions	Atoms and ions	Atoms, ions and clusters
Throwing power for a) Complex shaped Object b) Into blind hole	Poor, line of Sight Coverage Poor	Nonuniform thickness Poor	Poor Poor
Metal deposition Alloy deposition Refractory compound deposition	Yes Yes Yes	Yes Yes Yes	Yes Yes Yes
Energy of deposit-species	Low 0.1 to 0.5 eV	Can be high 1- 100 eV	Low to high
Substrate heating (external)	Normally yes	Not generally	Yes

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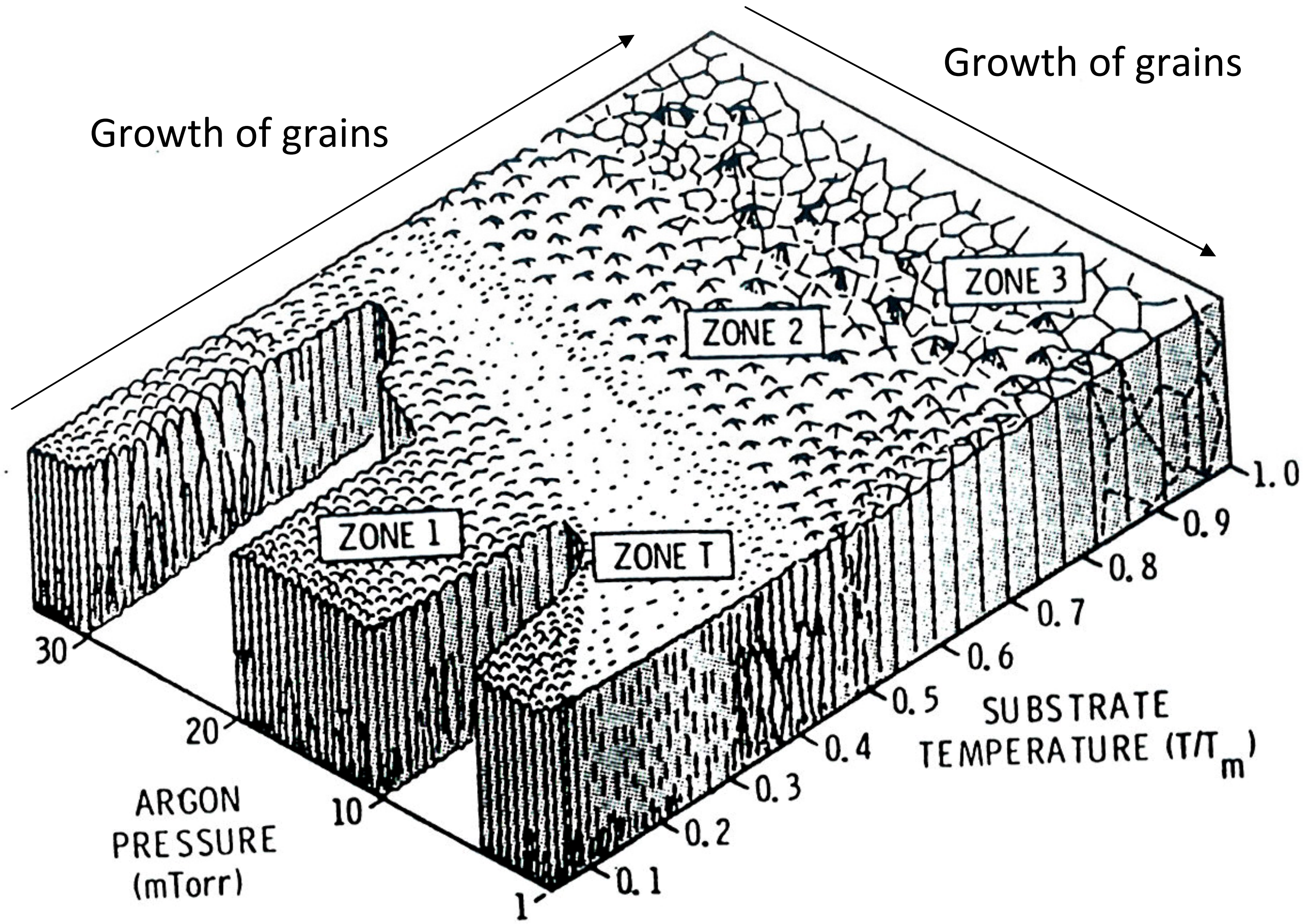
Thornton-Zone-Diagram

Morphology of the as grown film:



Vacuum generation

For low deposition rates, ultra high vacuum is required!

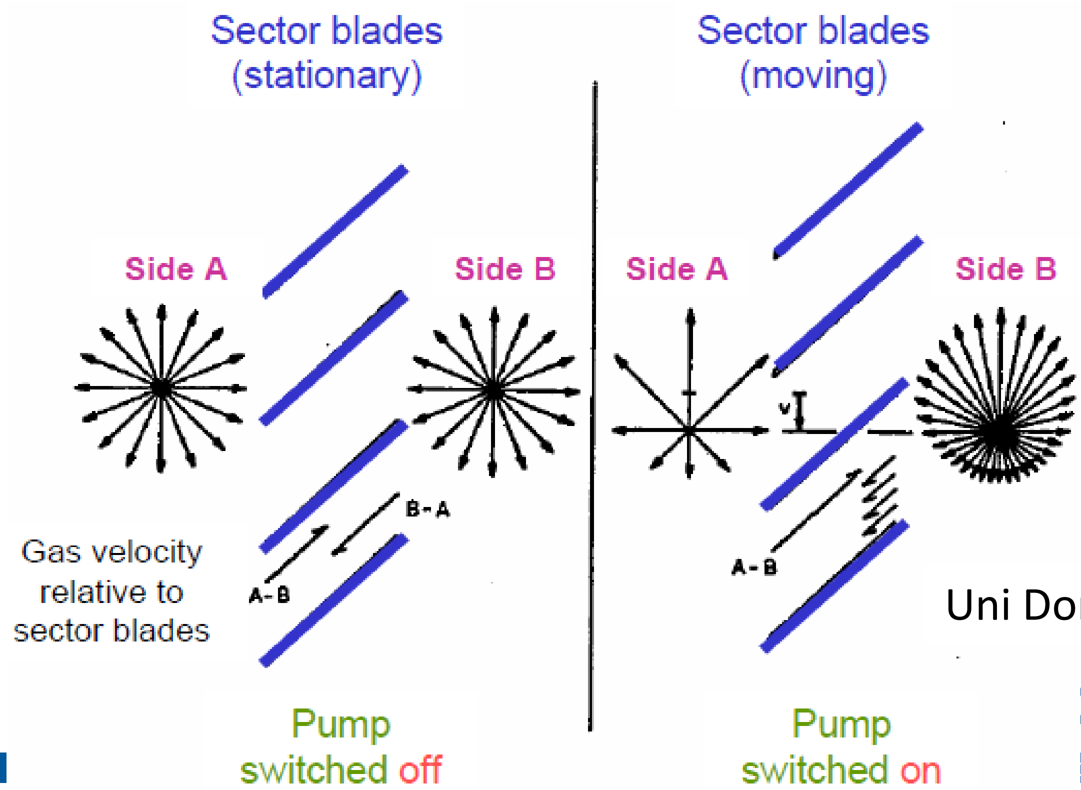
Pressure, Torr	Mean free path, cm (between collisions)	Collisions /sec (between molecules)	Molecules/(cm^2 sec) (striking surface)	Monolayers /sec *
10^{-3}	5.1	$9\ 10^{3}$	$3.8\ 10^{17}$	440
10^{-5}	510	90	$3.8\ 10^{15}$	4.4
10^{7}	$5.1\ 10^{4}$	0.9	$3.8\ 10^{13}$	$4.4\ 10^{-2}$
10^{-9}	$5.1\ 10^{6}$	0.009	$3.8\ 10^{11}$	$4.4\ 10^{-4}$

* Assuming the condensation coefficient is unity

Fore-pumps:

- Roughing-
- Membrane-
- Scroll-

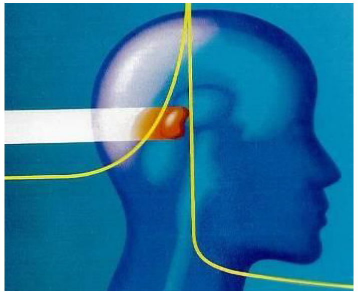
- **High vacuum pumps**
- Turbomolecular-
- Ion getter-
- Titanium evaporator-
- Kryo-



Uni Dortmund

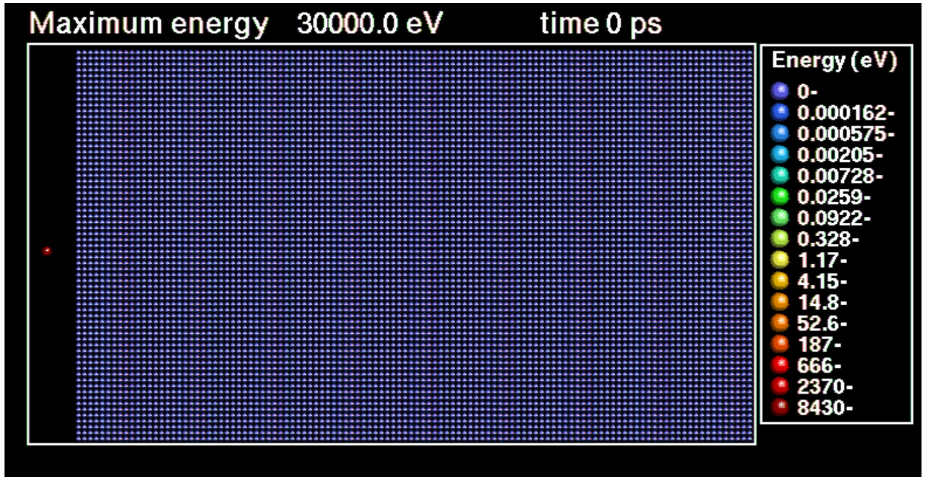
Ion implantation

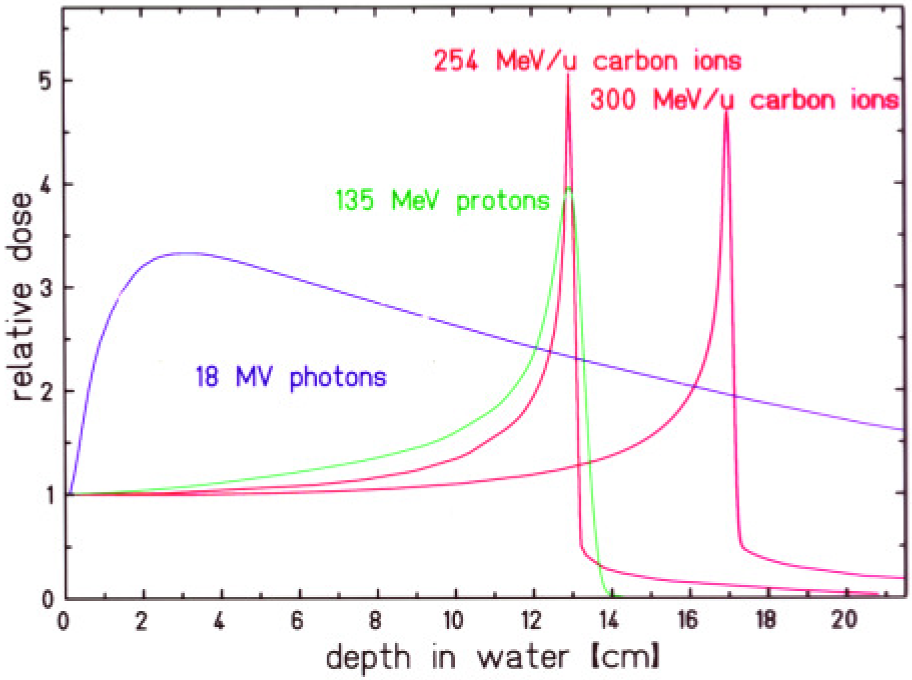
- Doping (e.g. semiconductors)
- Synthesis of nanoparticles and buried layers
- Defect generation, amorphization and interface mixing
- Sputtering and nano-patterning
- Phase transformation and annealing
- Bio application (destruction of tumors)



Courtesy: GSI

30 keV Xe in Au (courtesy K. Nordlund)





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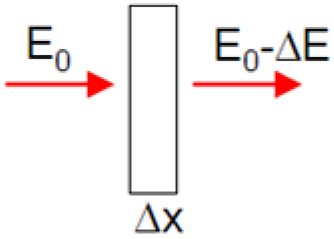
Ion-solid- interaction

Loss of energy per unit length

Stopping power:

$$B(E) = \left(\frac{dE}{dx}\right) \qquad \left[\frac{eV}{nm}\right]$$



$$E_0 = \sum \Delta E = \sum \left(\frac{dE}{dx}\right)\Delta x$$

Stopping cross section: $S(E) = \frac{1}{n}\left(\frac{dE}{dx}\right) \qquad \left[eV \cdot nm^2\right]$

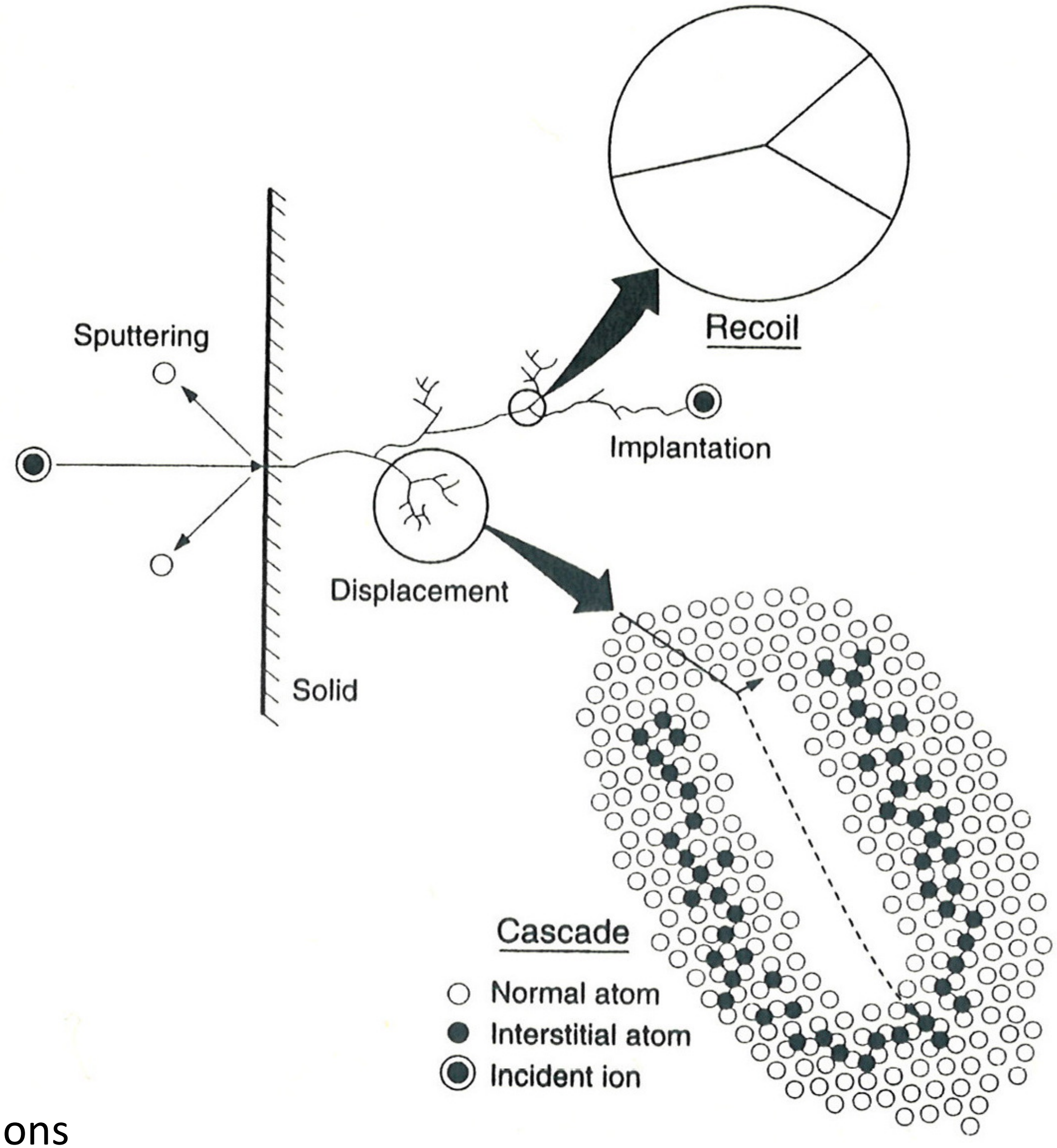
Nuclear (low energies, high ion mass):

- Massive collisions
- High energy loss and angular deviation per collision
- Lattice damage (Vacancy, Interstitial)

Electronic (high energies, low ion mass):

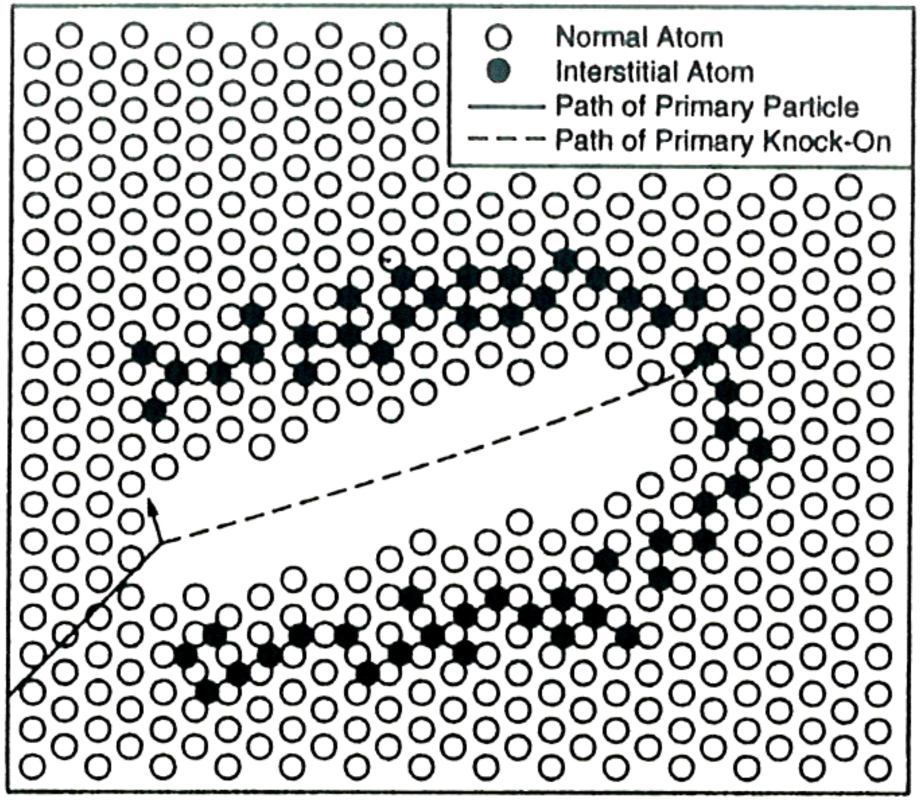
- Negligable collision
- Low energy loss and angular deviation per collision
- Low lattice damage
- Ionisation

Ion-solid- interaction



M. Nastasi
Ion-Solid Interactions
2004

Spikes



Displacement-Spike

High density cascade of moving atoms
Inside a certain volume

Spikes: Mean free path l_d between the collisions
Reaches the lattice constant

Thermal Spike

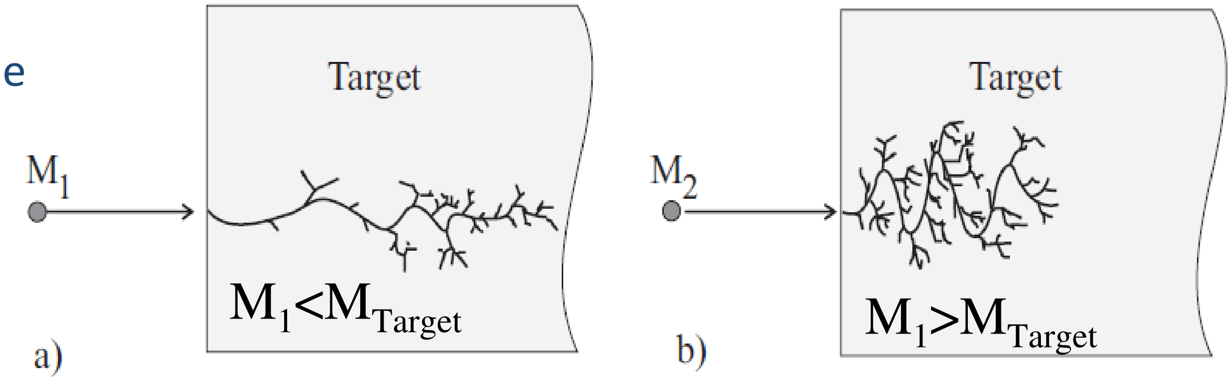
At the end of the displacement spike → Atoms have too low energy to generate Displacements and dissipate the residual energy via phonons (heat). $t_{thermal}$~10^{-12} s

M. Nastasi, Ion-Solid Interactions, 2004

Defects

(aus Diss. S. Eichler, Halle 1997)

Displacement cascade



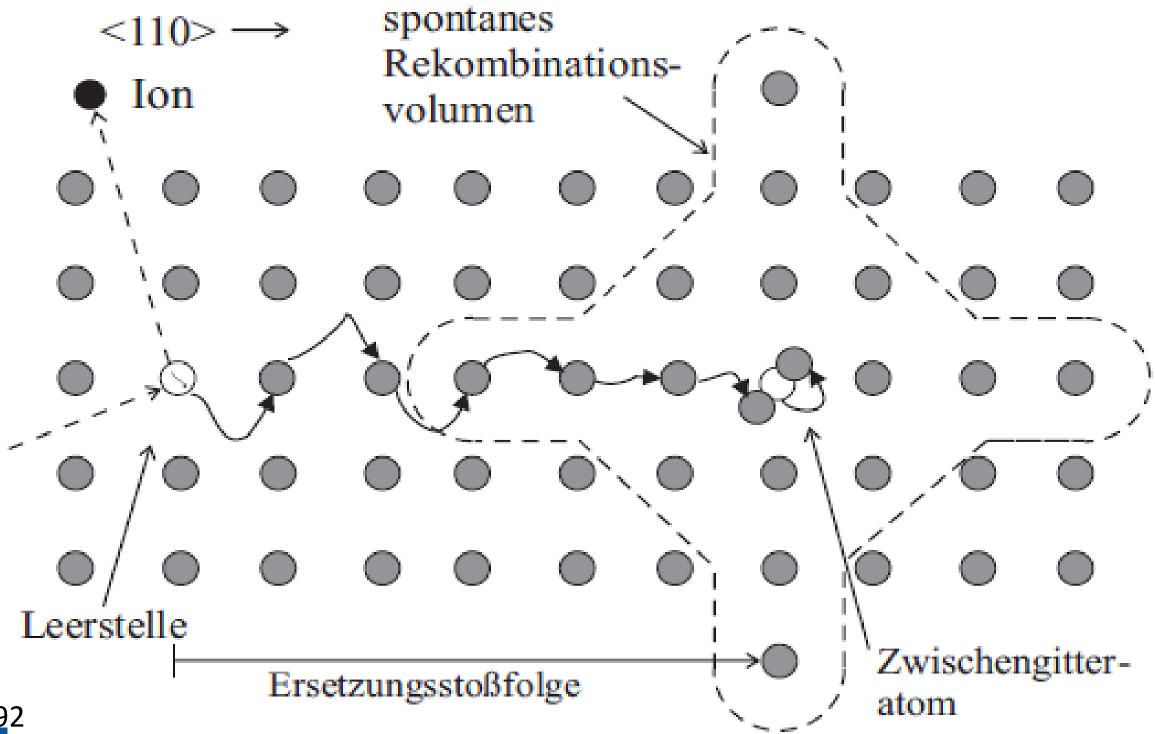
H. Ryssel, 1978

Pointdefects

- Vakancies
- Interstitial atoms

=Frenkel-Pairs

Can be energetically Instable and transform into defect complexes



Bergmann/Schäfer 1992

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Defects

Defect complex

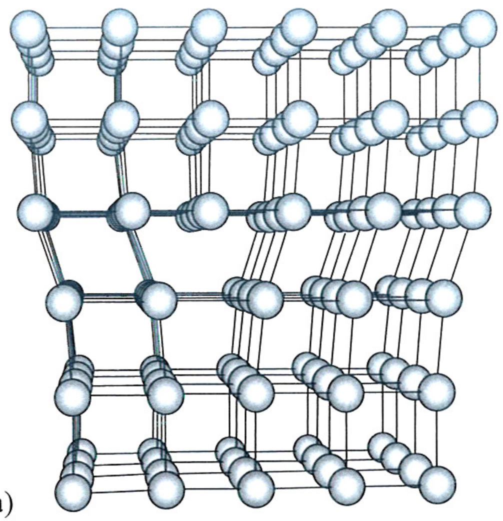
- Point defect+Point defect
- Point defect+Target atom

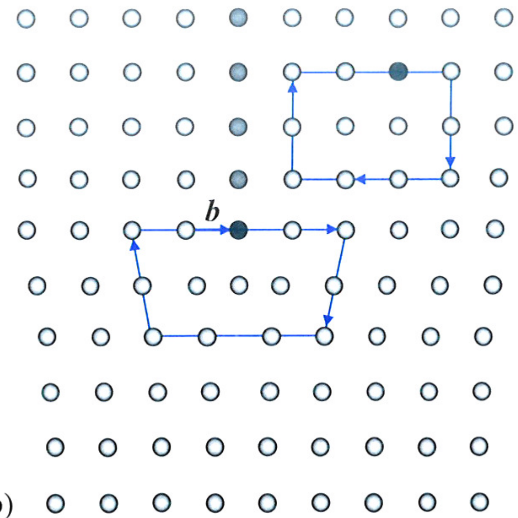
Example: Oxygen in Si →

Defekt	Ausheiltemperatur (isochron)
VO	570-670 K
VO_2	770 K
V_2O	620 K
V_3O	670 K
V_2O_2	670 K
V_3O_3	870 K

Extended defects

- Dislocations
- Grain boundaries


a)



(b)

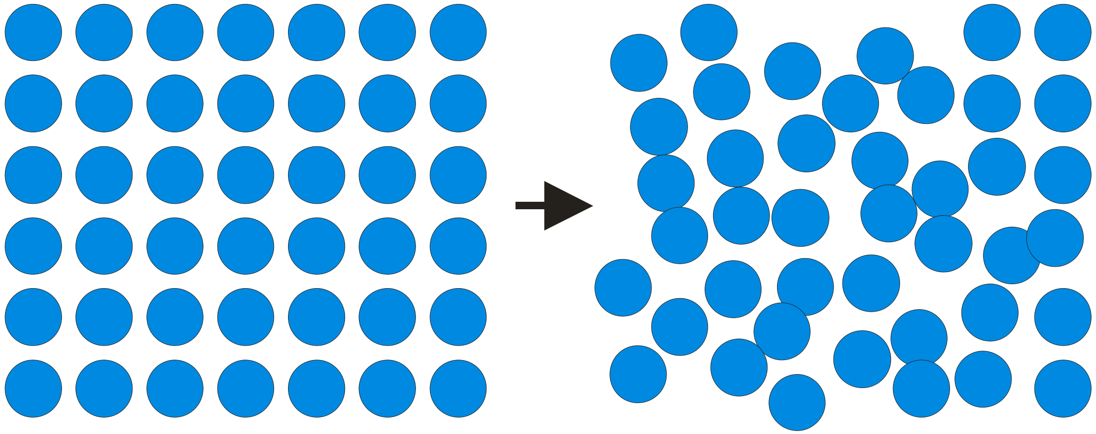
e.g. added lattice plane
b=Burgers-vector

S. Hunklinger, "Festkörperphysik", 2007

Defects

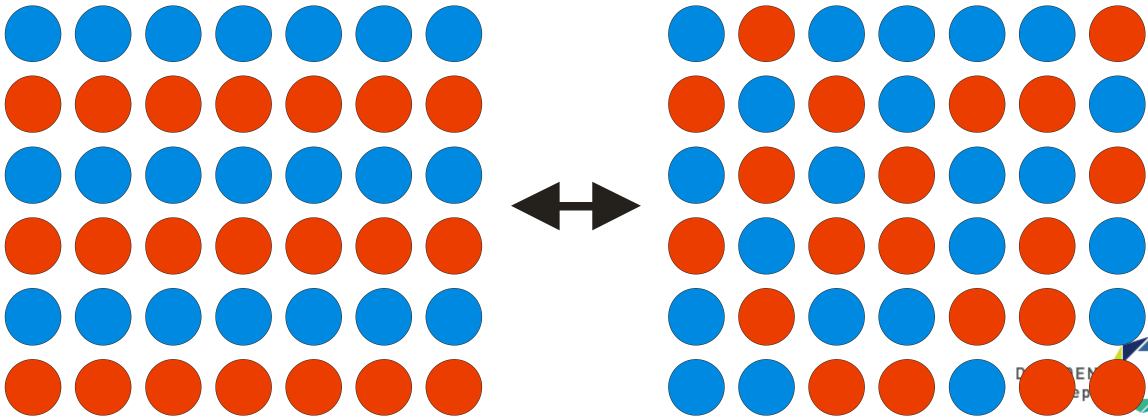
Amorphisation

Amorphous materials have dangling bonds
→ Passivation of Si with H



Chemical disorder
(Multi layers, alloys)

e.g. ferro/para FeAl, FeRh, fcc-fct FePt



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Doping by ion implantation

Implant doping (in semiconductor industries)

- **Step1: Implantation**
- **Step2: Annealing for defect removal**

Problems for DMS:

- **Cluster buildup due to supersaturation**
- **Defects might be helful for coupling**

Spintronics – Diluted Magnetic Semiconductors

Diluted magnetic semiconductors: Lets drive the DEFECT screw!

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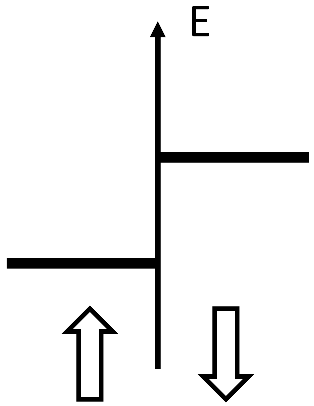
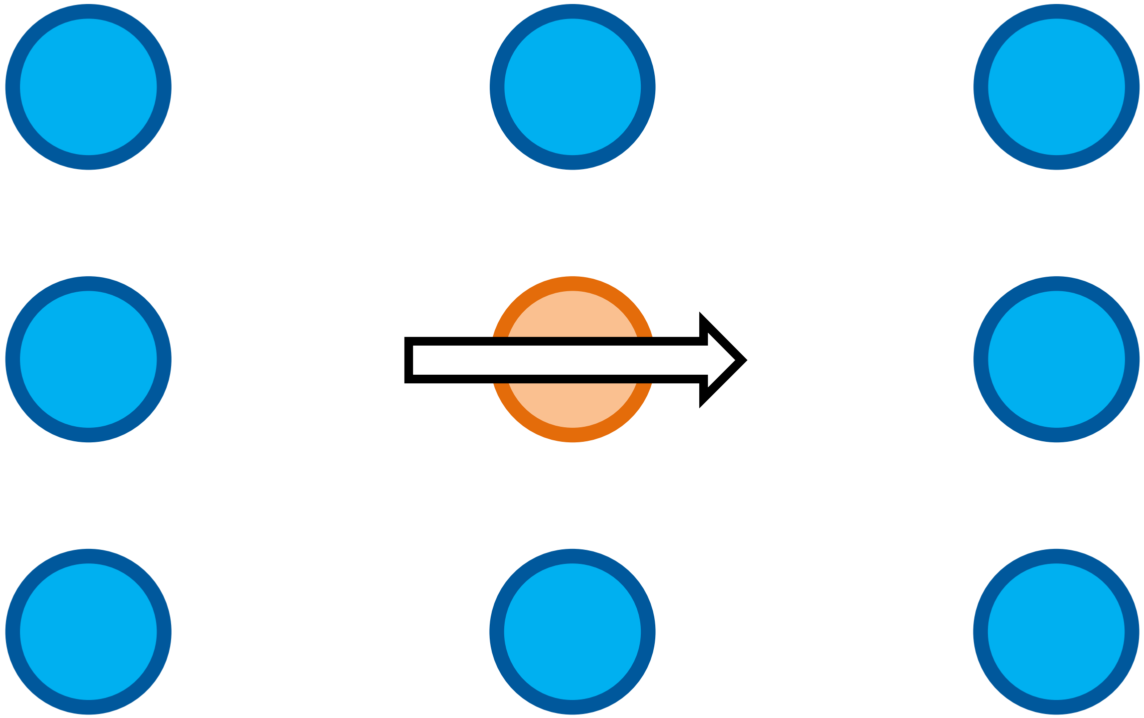
Driving the screw

- Paramagnet





Local picture

DRESDEN concept HZDR
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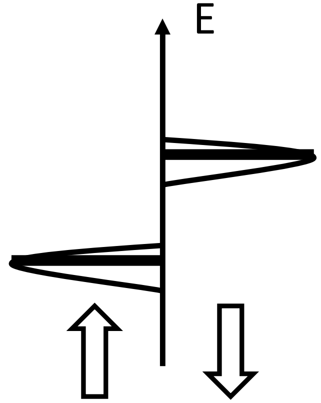
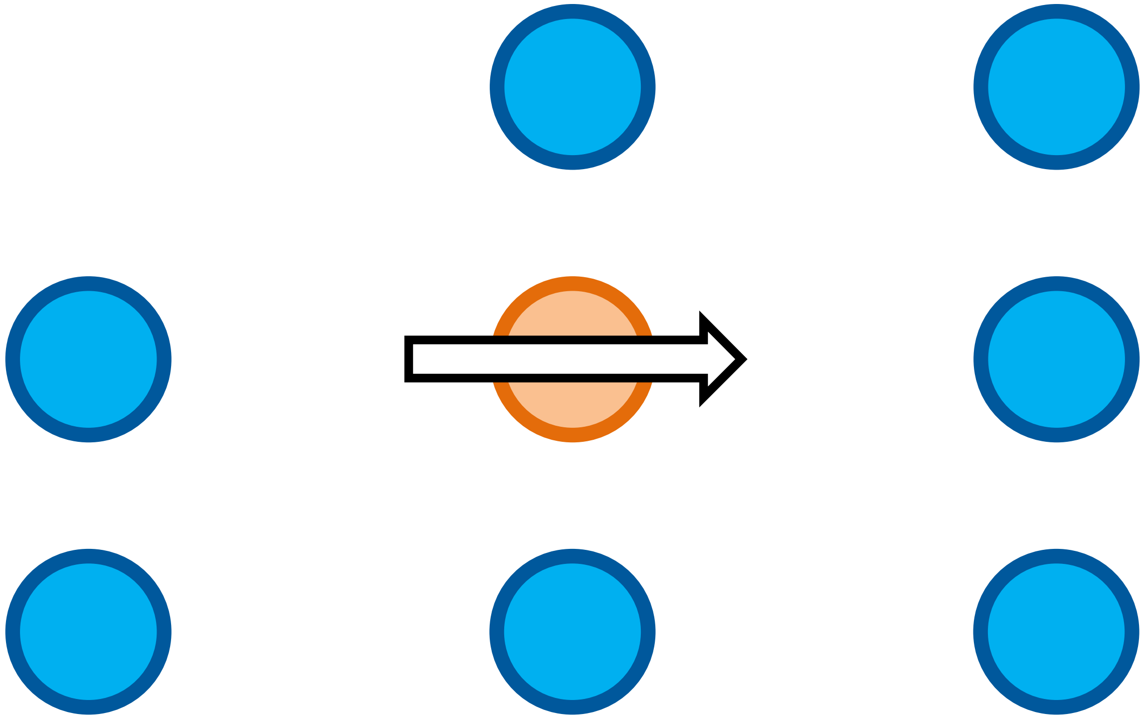
Spintronics – Diluted Magnetic Semiconductors



Driving the screw

- Paramagnet

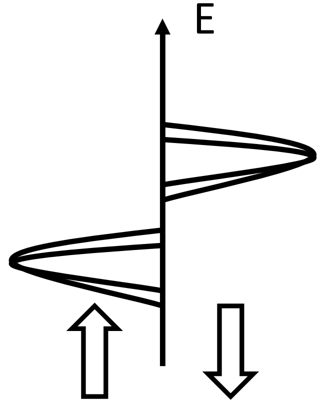


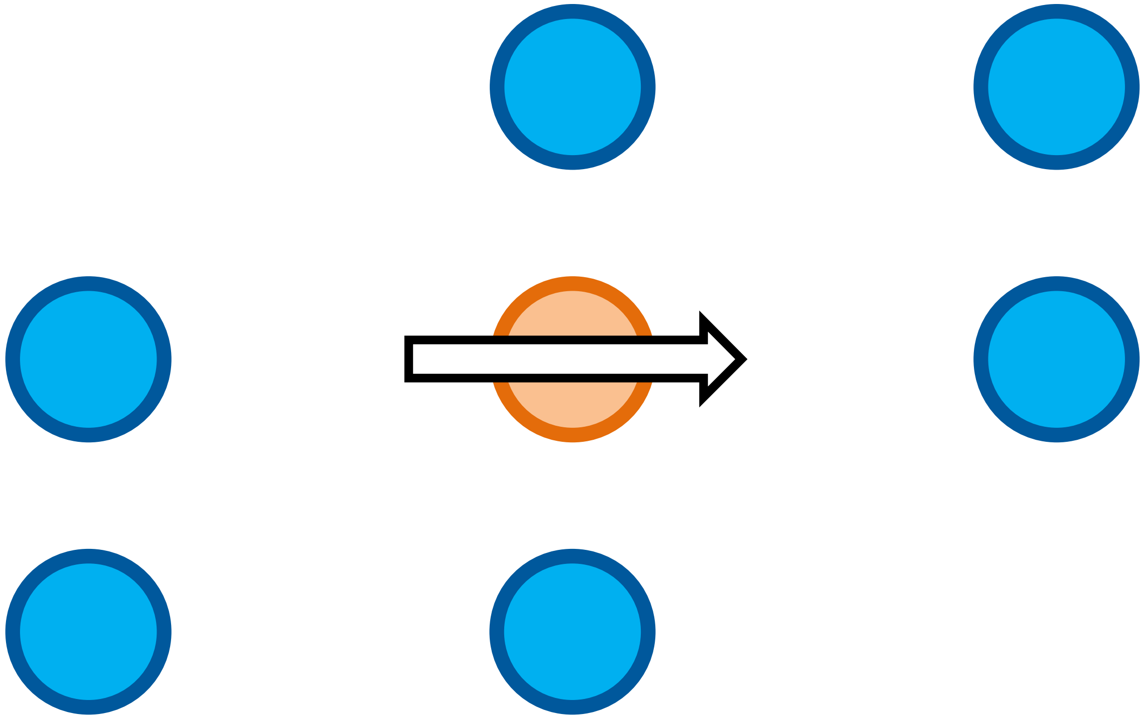
Local picture

Spintronics – Diluted Magnetic Semiconductors

Driving the screw

- Ferromagnet





Local picture
Global picture

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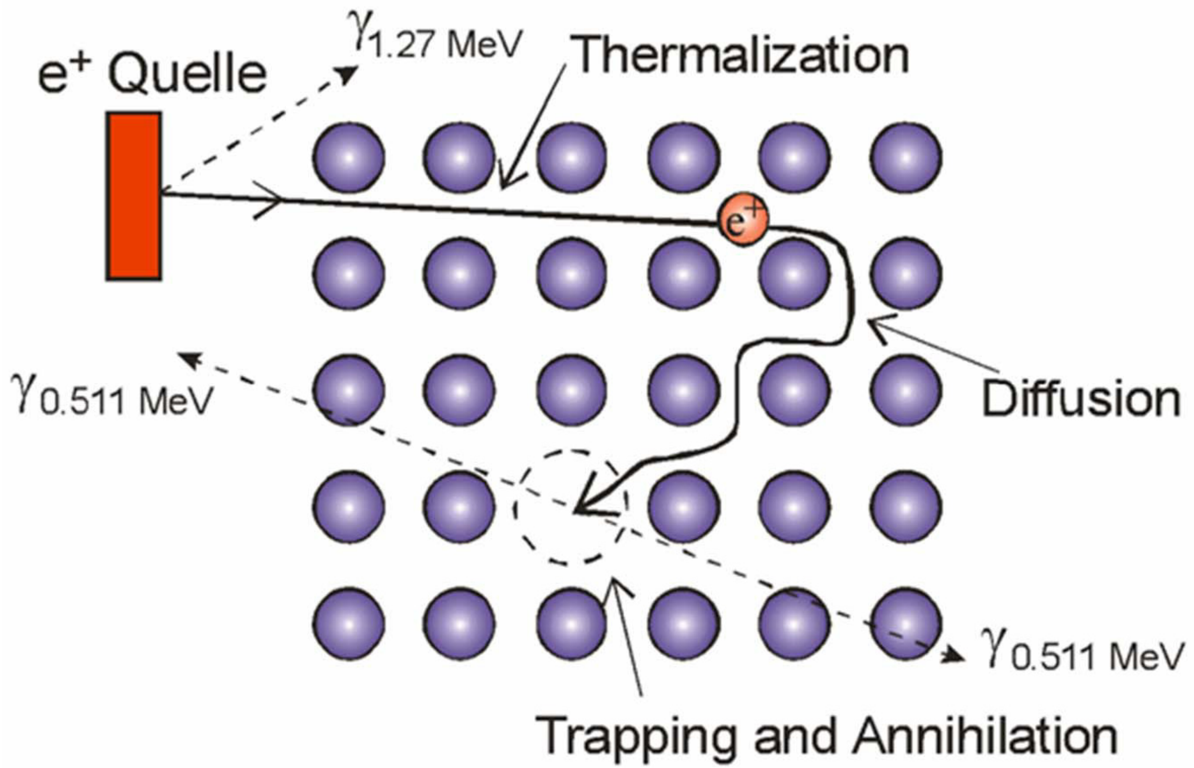
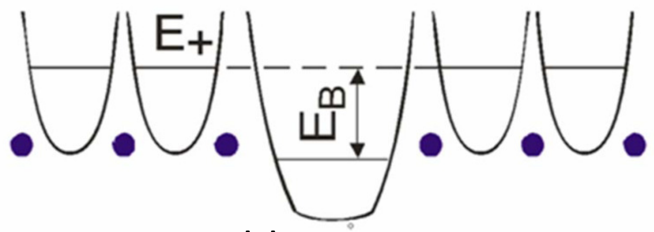
Defects in TiO_2

Why Positrons?





Courtesy R. Krause-Rehberg

- Positron @ the attractive defect potential

→positron lifetime increases in a vacancy

→Doppler broadening decreases in open volume defect

→Coincidence spectrum depends on local chemistry

→ **Defect identification and quantification possible**

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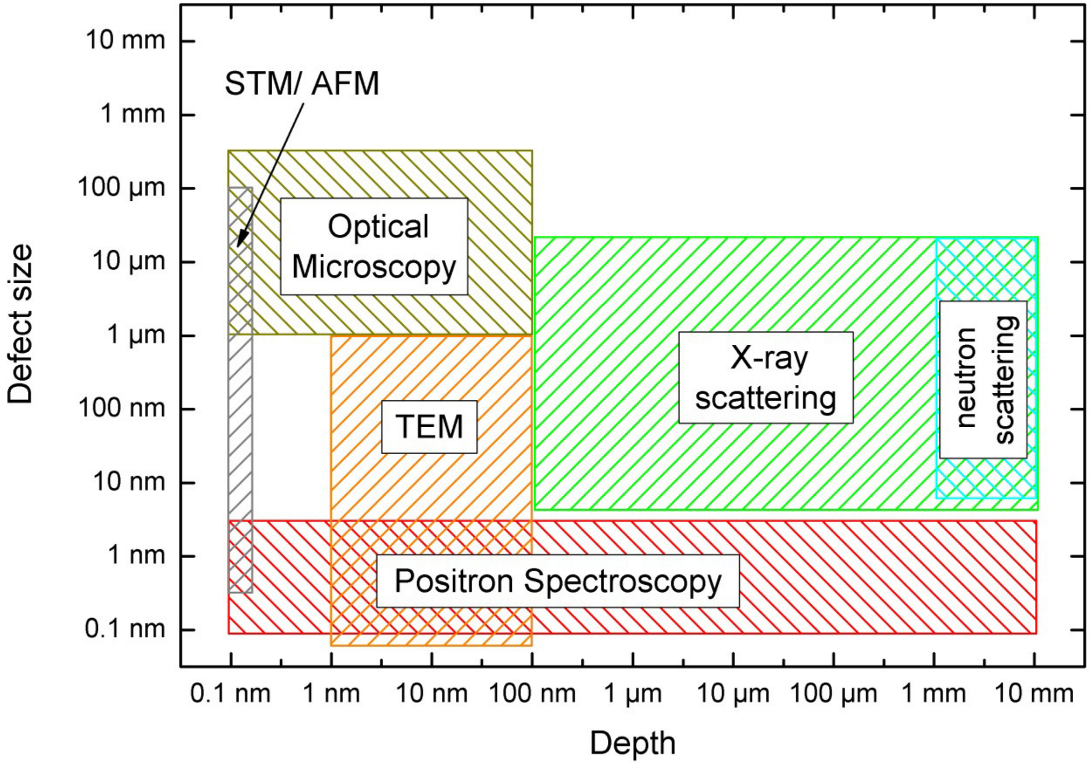


Positron Spectroscopy:

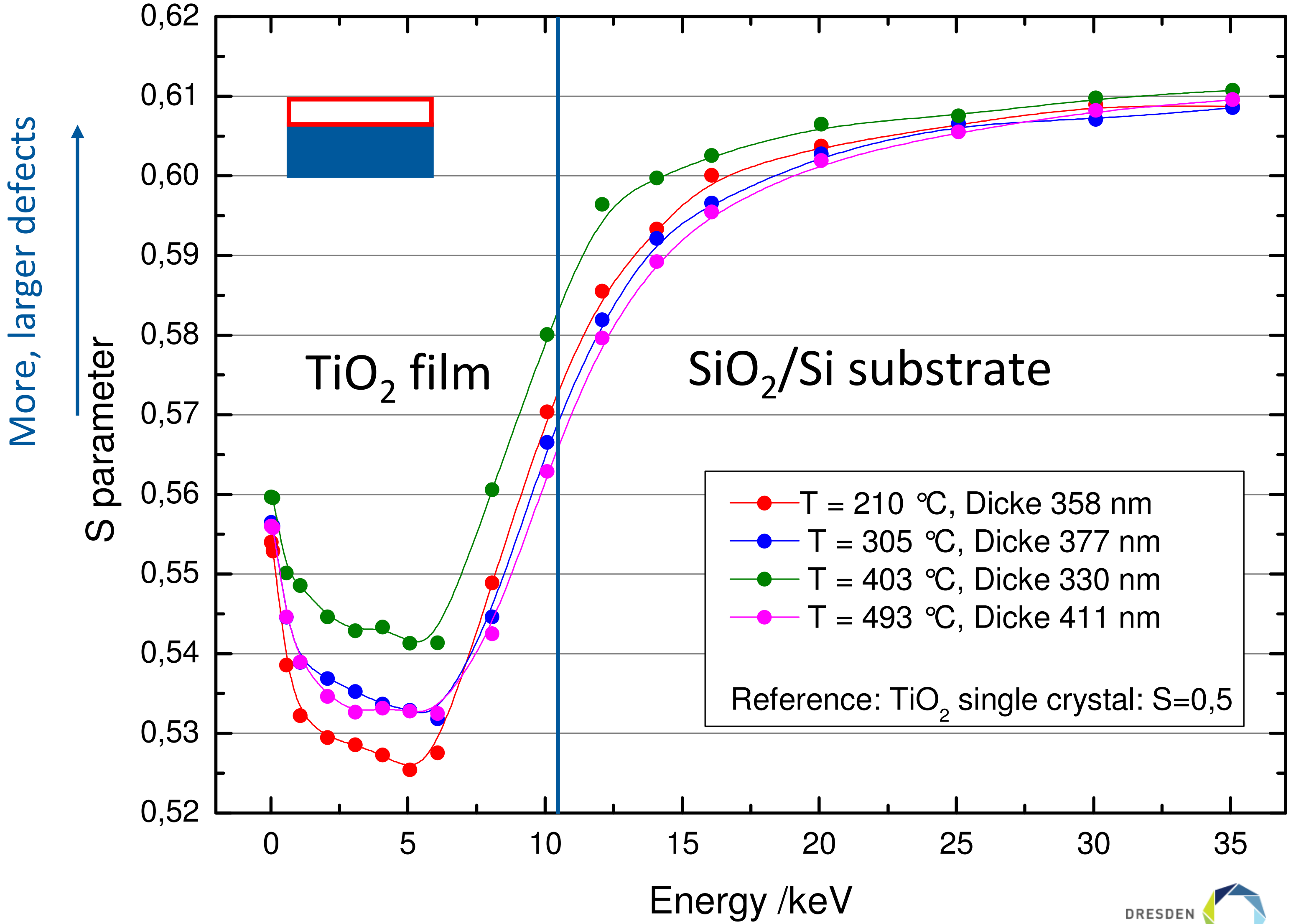
non-destructive method for material investigation and characterization of atomic defects

sensitivity is much higher for small defect sizes than standard techniques

STM … **S**canning **T**unneling **M**icroscope, **AFM** … **A**tomic **F**orce **M**icroscope, **TEM** … **T**ransmission **E**lectron **M**icroscope

Defects in TiO_2

Positron annihilation spectroscopy



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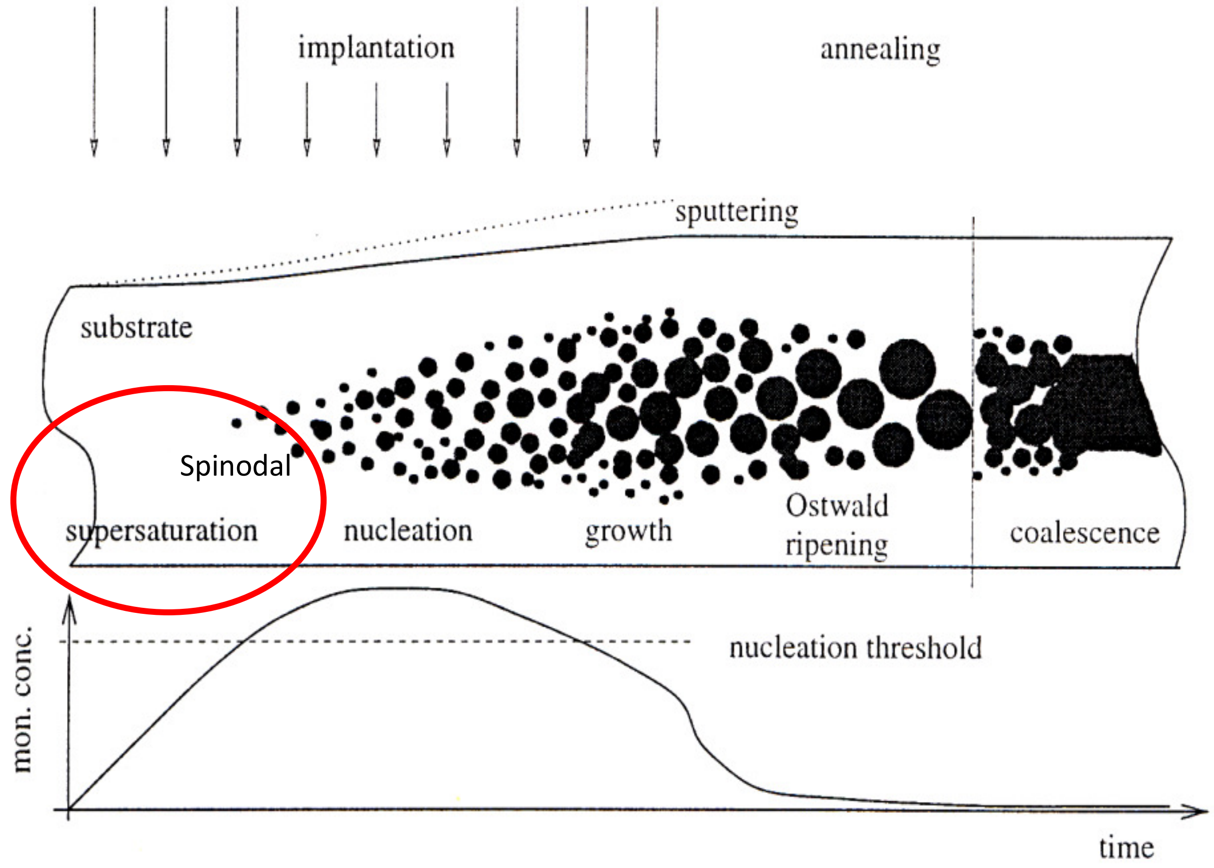
Example Supersaturation by Fe ion implantation

Problem: Cluster buildup due to ion implantation



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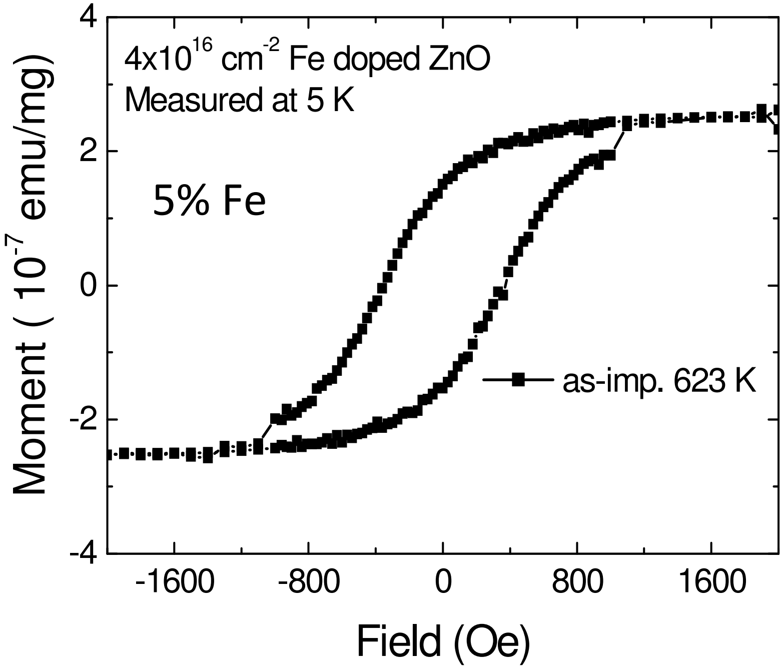
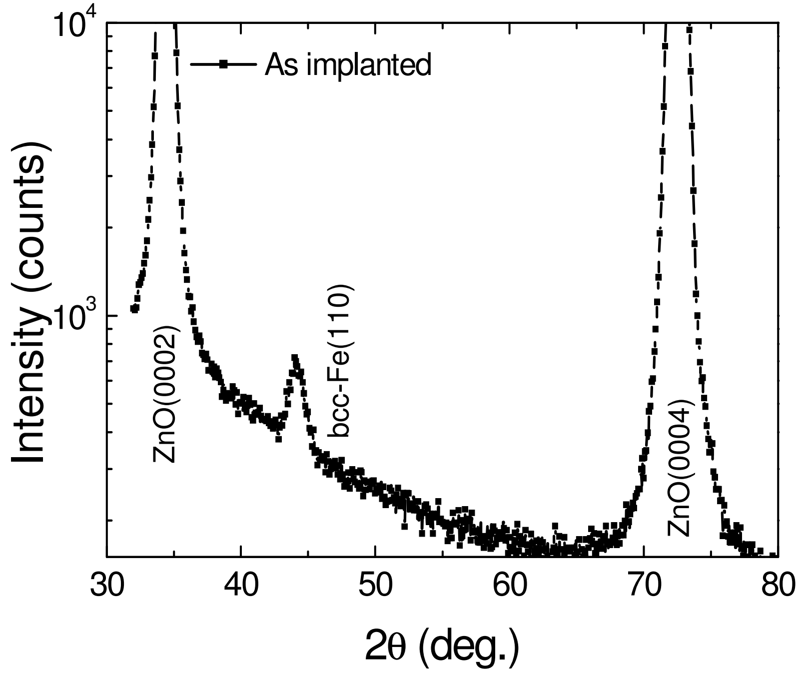
Cluster formation upon implantation

SQUID



Synchrotron-XRD (ROBL)



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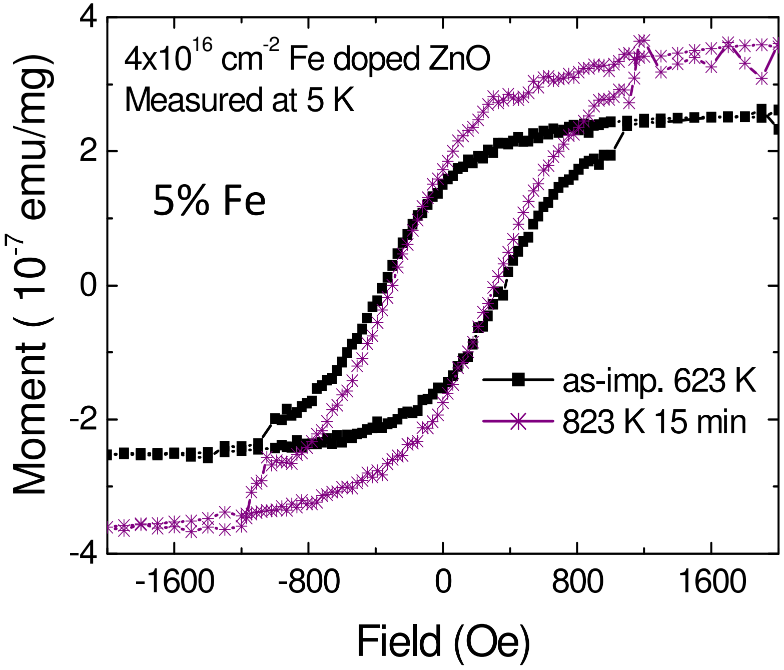
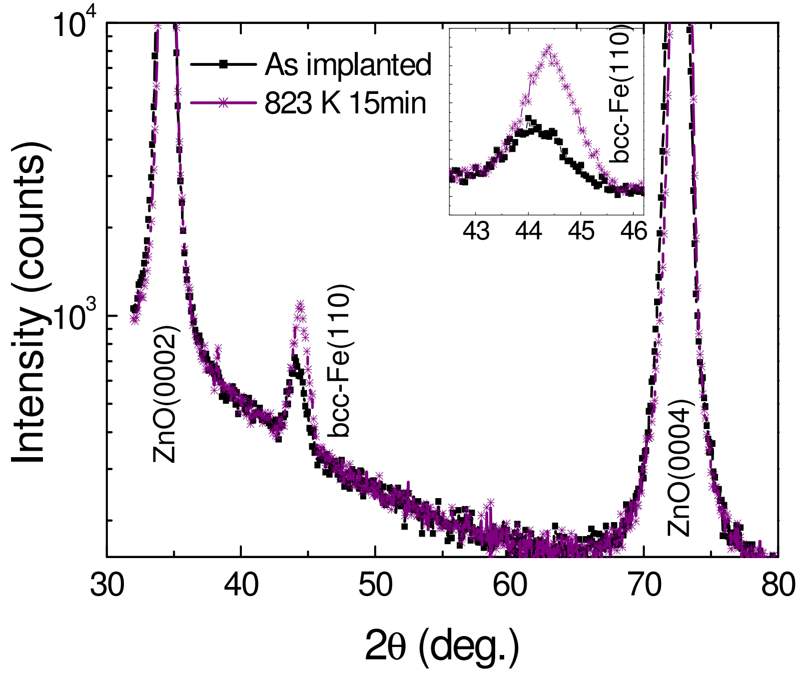
Cluster formation upon implantation





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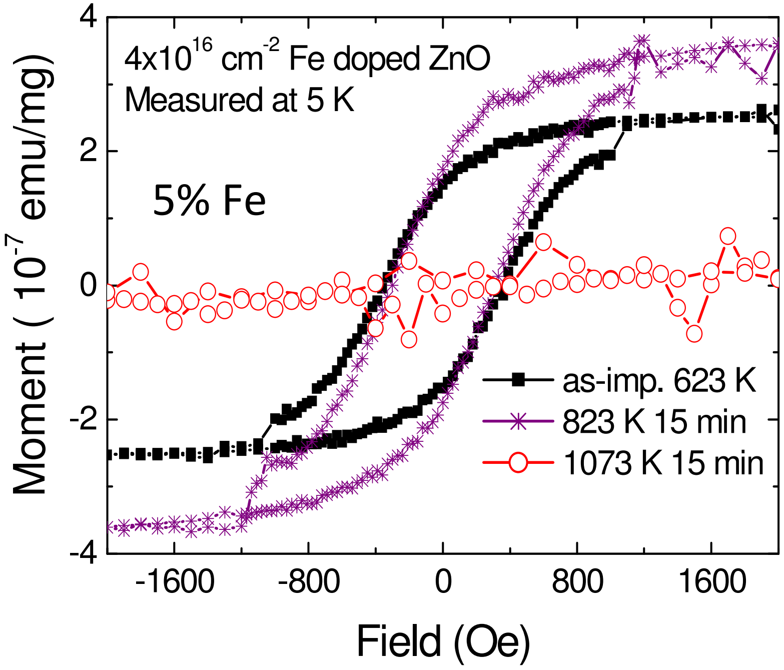
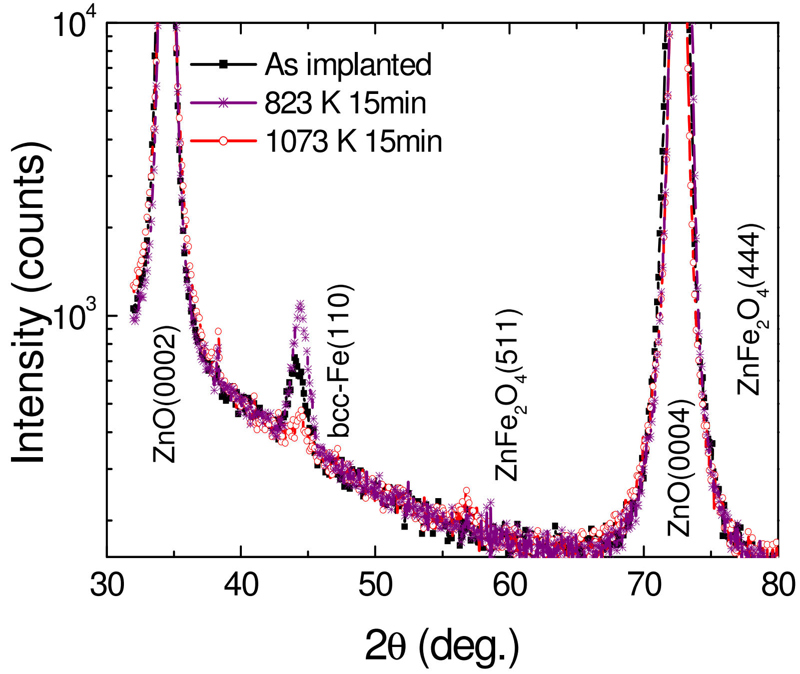
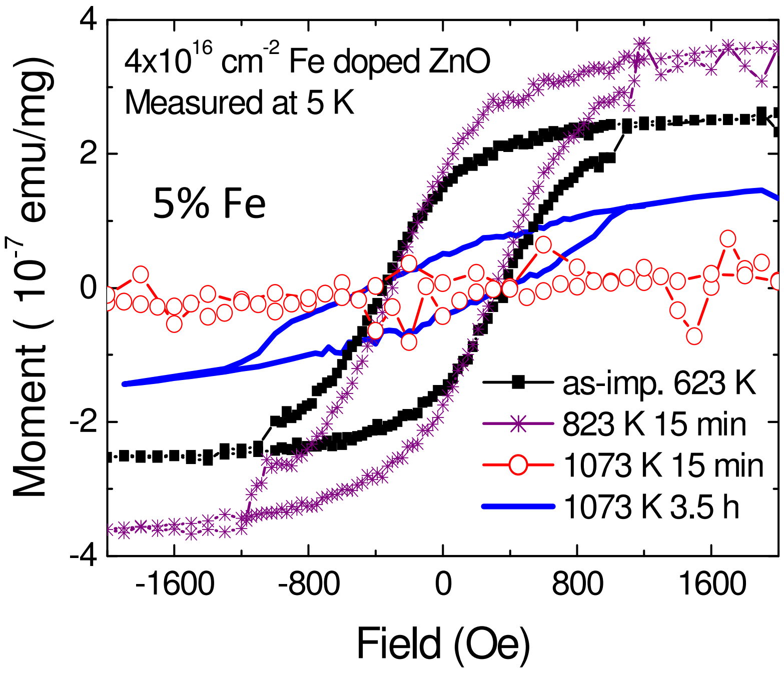
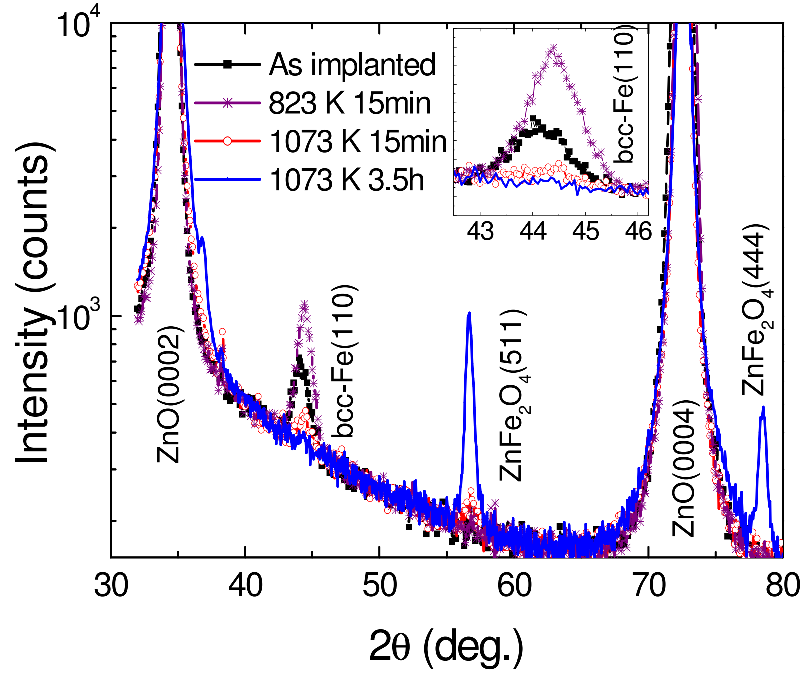
Cluster formation upon implantation





Cluster formation upon implantation





- Low annealing temperature T_A : bcc Fe
- **High T_A and short time : no crystalline secondary phases detected**
- High T_A and long time : $ZnFe_2O_4$

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The DETI.2 project

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Thank you!

Master students welcome!

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