e-ESM, an online higher-education Magnetism event

MAGNETIZATION PROCESSES
I. SPATIAL SCALES

GROUND STATE AND COERCIVITY MECHANISMS IN FERROMAGNETS

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CSIC, SPAIN

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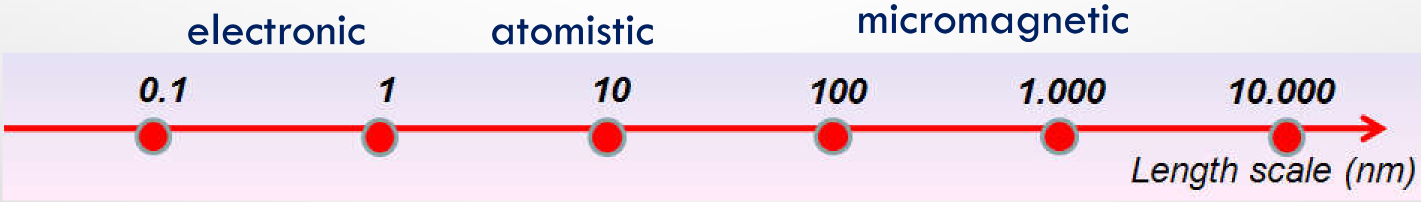
SCALES IN MAGNETISM



Magnetism processes at different scales

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Quantum

Single-domain

Multi-domain

1nm

100nm

1000nm

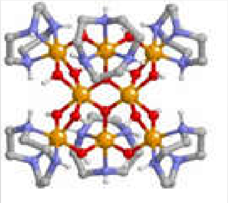
exchange energy

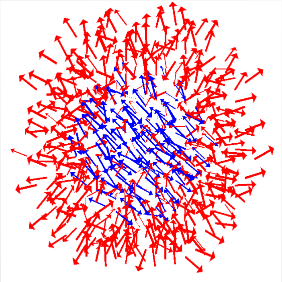
magnetostatic energy

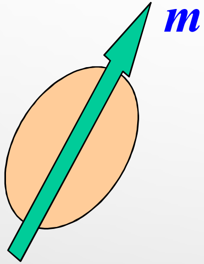
Surface dominating Core dominating

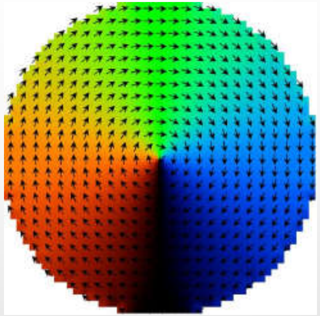
Vortex state

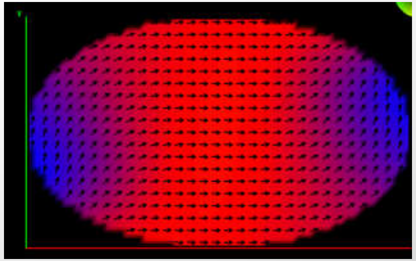
Inhomogeneous state



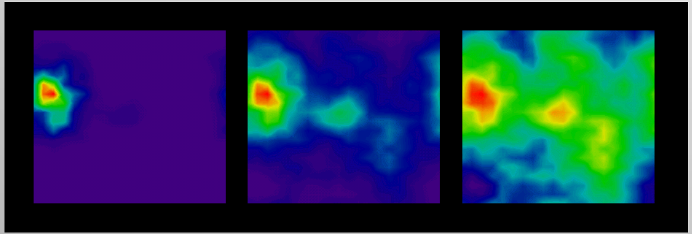




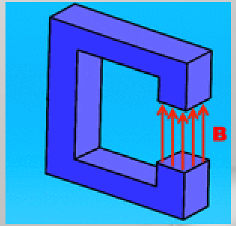




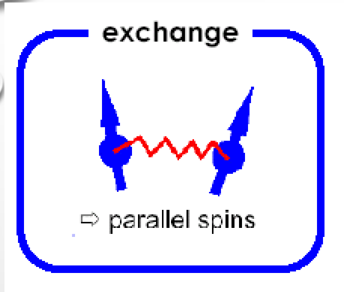
The sequence of nucleation-propagation-pinning-depinning
is governed by atomistic defects: inclusions, grain boundaries, interfaces etc.

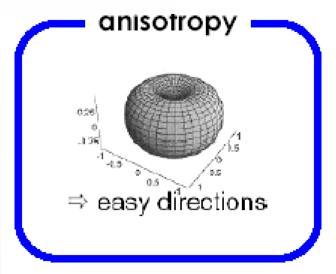


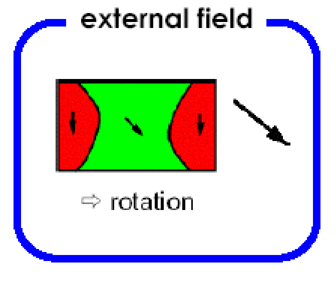
Magnets design

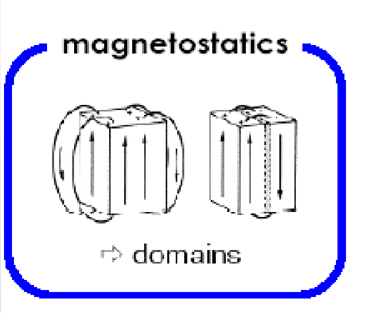


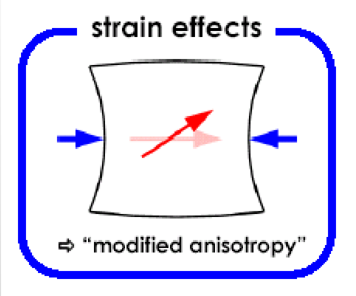
MAGNETIC ENERGIES

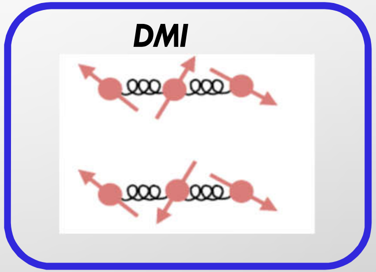


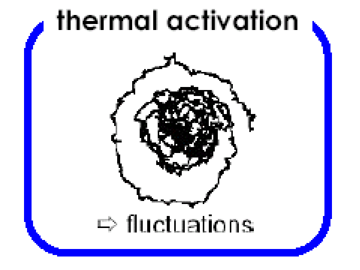








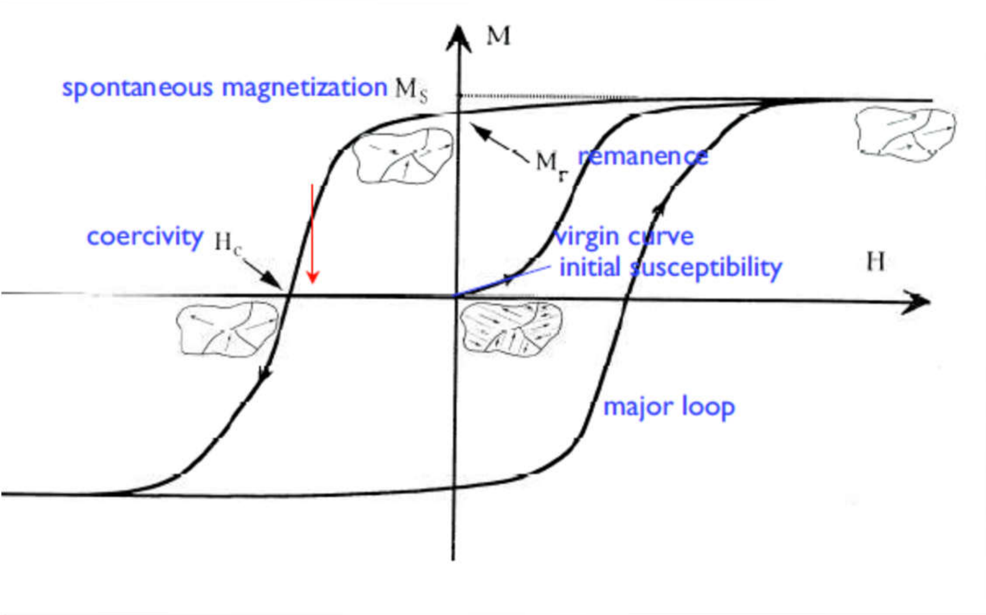


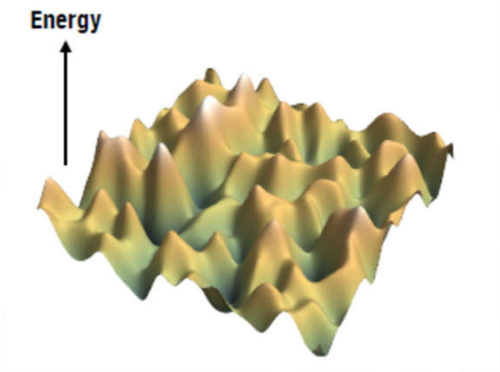


The relevance of different energies depend on the system dimensions

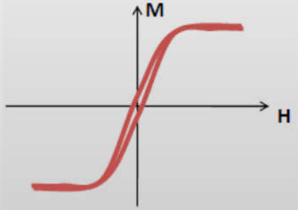
Novel torques and fields

MAGNETIC HYSTERESIS



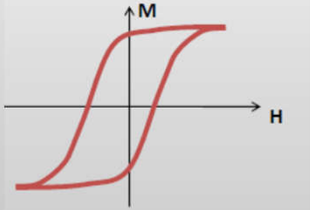


Soft materials
(sensors etc.)



Small Hc

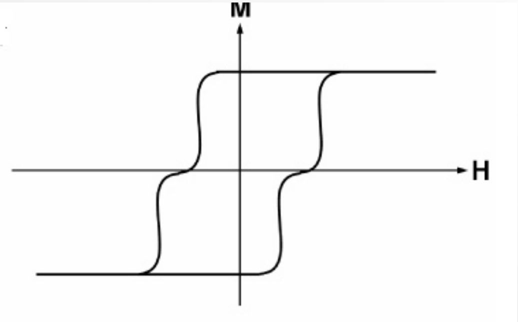
Hard materials
(permanent magnets etc.)



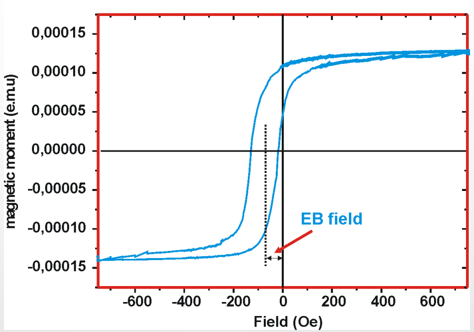
Large Hc

DIFFERENT HYSTERESIS HYSTERESIS LOOPS

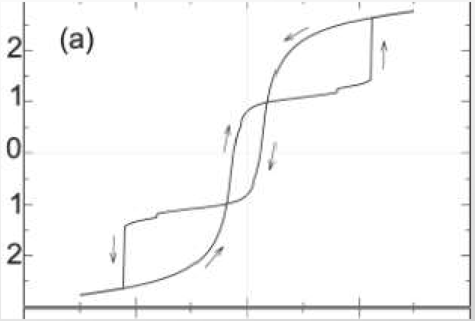
Composite materials: soft FM+hard FM



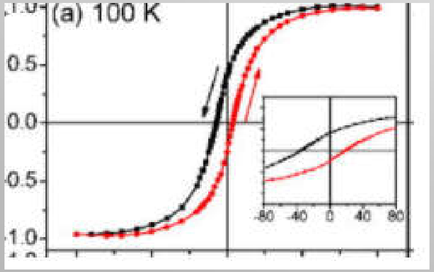
Exchange bias (FM coupled to AFM)



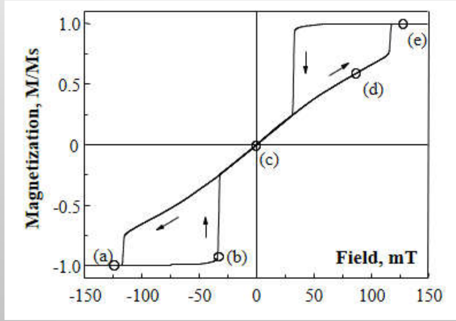
Spin-flop transition (AFM)



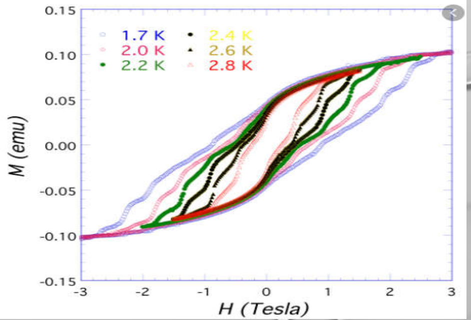
Inverted hysteresis loop
(influence of interactions)



Magnetic vortex in dots



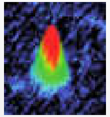
Quantum hysteresis (molecular magnets)



Very small scale: Quantum nanomagnets:

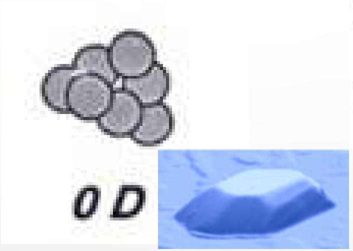
Magnetism of Individual atoms on surfaces:

H,M



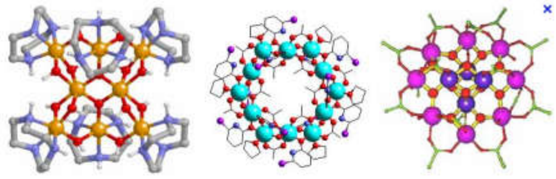
SP-STM: Co on Pt

Clusters and islands



Fe/Mo(110)

Magnetic molecules



Fe8 Ni12 Mn12

Quantum mechanics phenomenon:

•Quantum tunneling

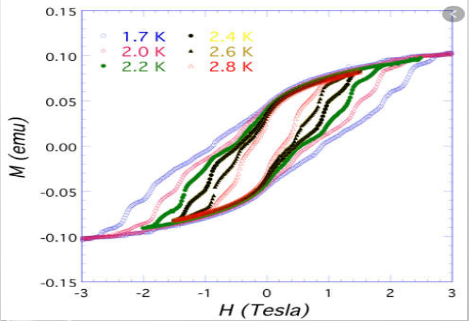
•Quantum oscillations, quantum interference, quantum

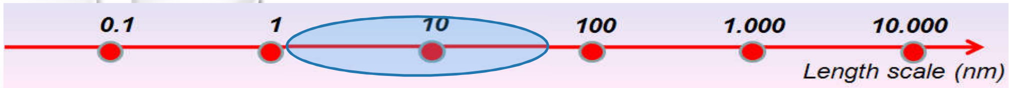
•coherence

• Relatively non-small values of the anisotropy barriers

•Small interactions between objects

•Normally paramagnetic at room T





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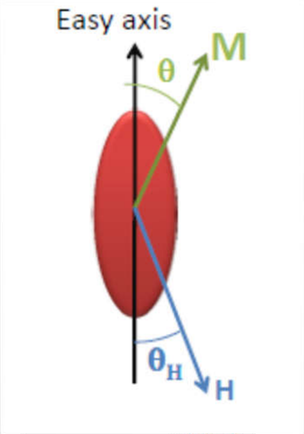
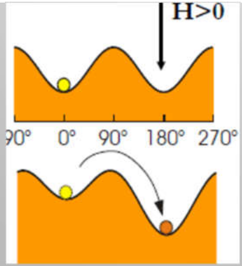
NANOPARTICLES: THE STONER-WOLFARTH MODEL FOR COHERENT REVERSAL

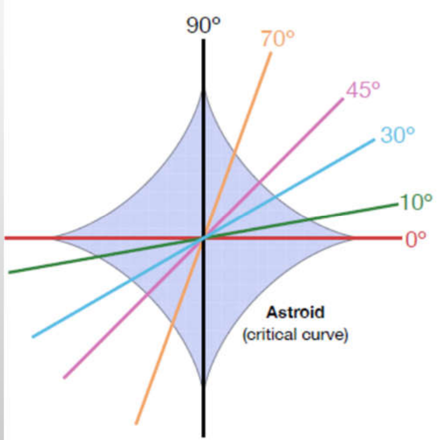
The maximum coercive field is equal to the anisotropy field

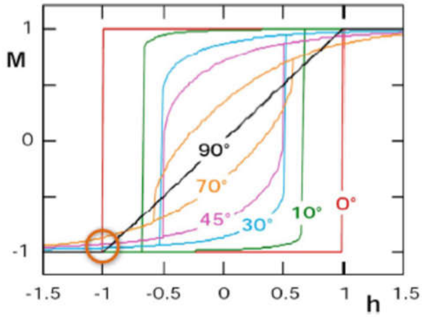




$$E = K_{eff} \sin^2\theta - \mu_0 M_S H \cos(\theta + \theta_H)$$

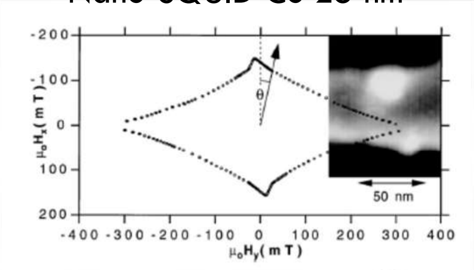
$$H_K(H_A) = \frac{2K}{M_s}$$ Anisotropy field





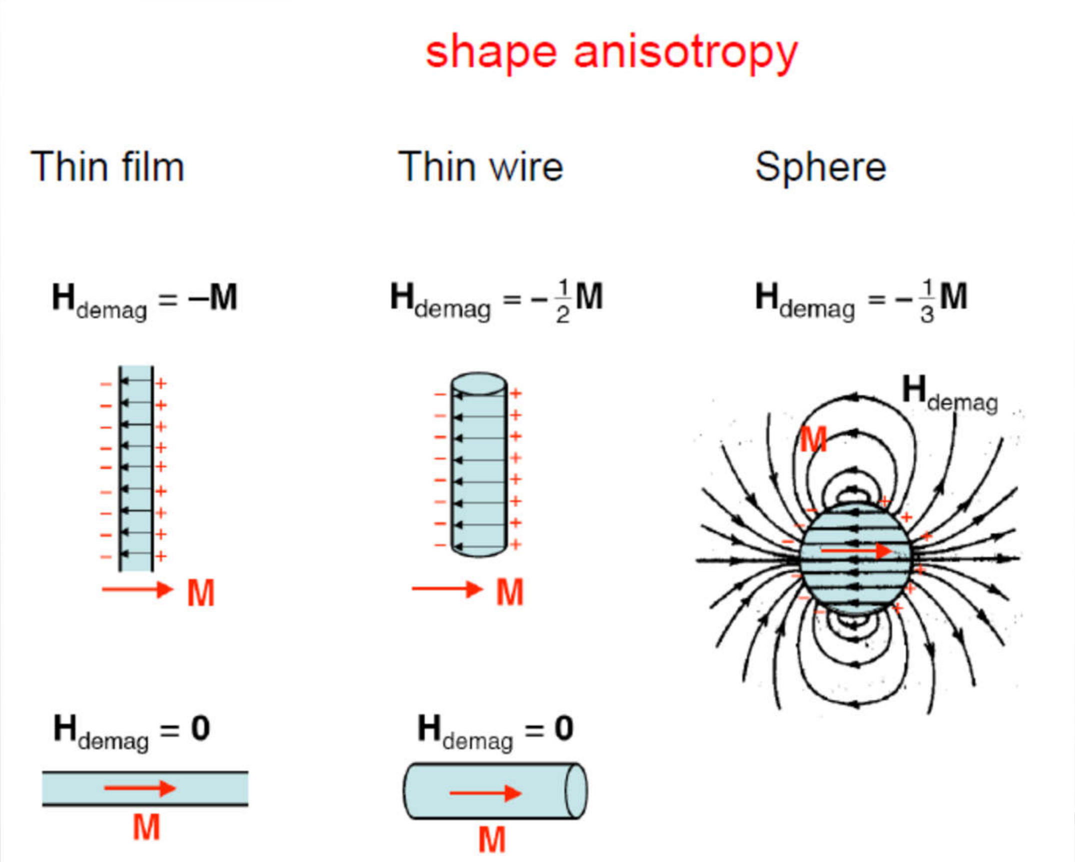
$$\frac{H_{sw}}{H_K} = \left[\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right]^{-3/2}$$

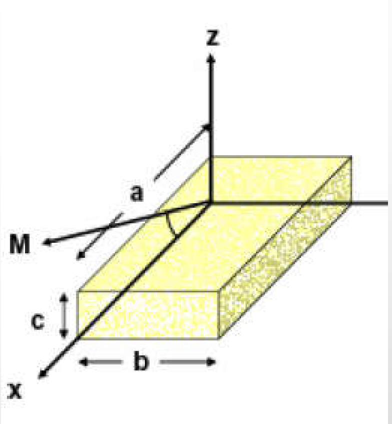
Real measurement
Nano-SQUID Co 25 nm



Wernsdorfer et al
PRL 78 (1997)

THE CONCEPT OF SHAPE SHAPE ANISOTROPY

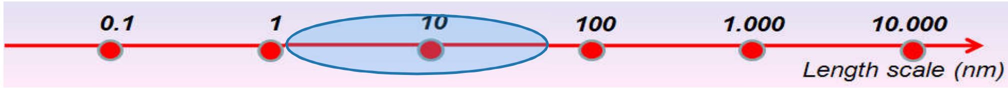




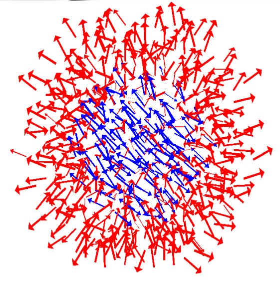
$$E_{magn} = \frac{1}{2}\mu_0 (N_c - N_a) M_s^2 \sin^2(\theta)$$

Shape anisotropy acts similar to magnetocrystalline anisotropy

But the concept is valid for saturated objects only



Surface dominating

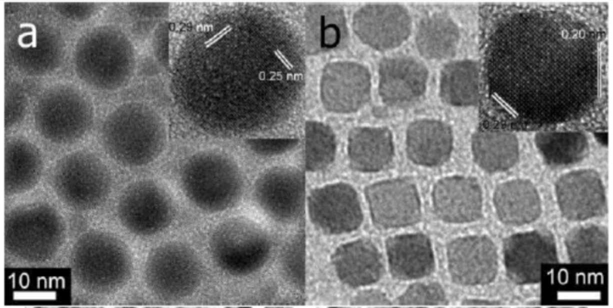


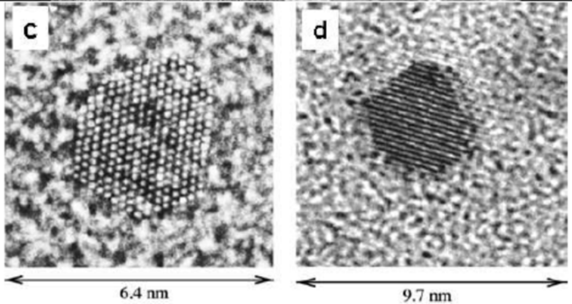
NANOPARTICLES: SURFACE EFFECT

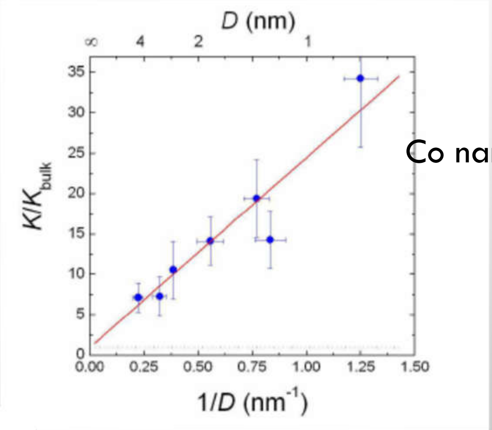
Also in thin films

$$K_{eff} = K_V + \frac{K_s S}{V}$$

Shape
Surface reconstruction
Lattice relaxation
Oxidation & capping
Charge transfer
Variation of magnetic moment,
Lost of exchange
Surface anisotropy

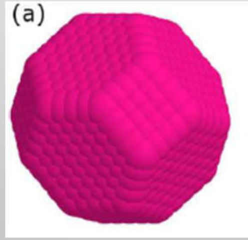


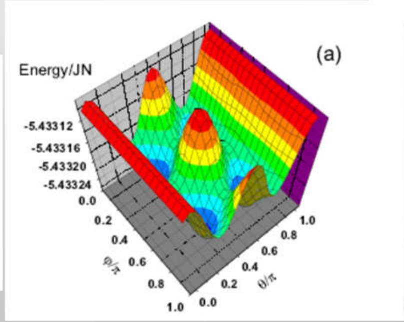




Co nanopart.

F.Luis et al PRB 65 (2002)

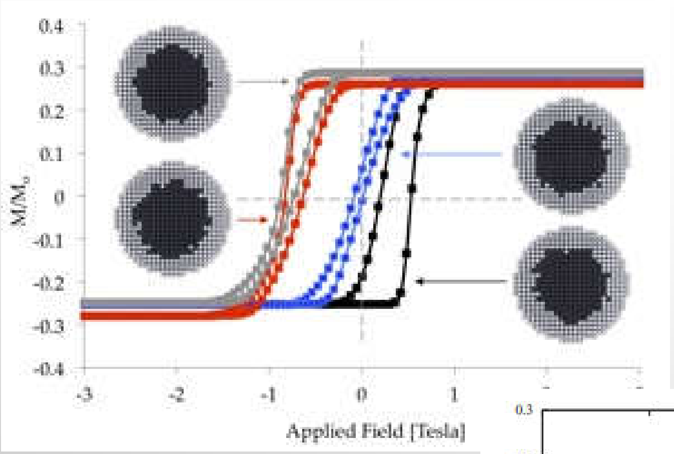


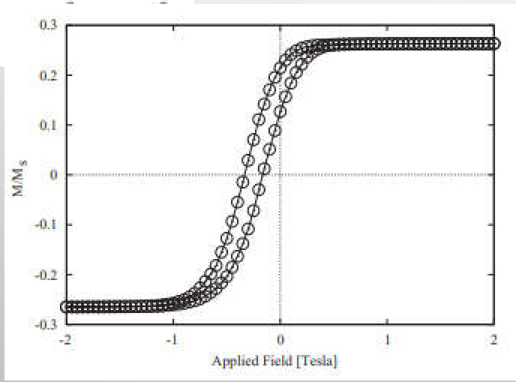


R.Yanes et al PRB 40 (2007)

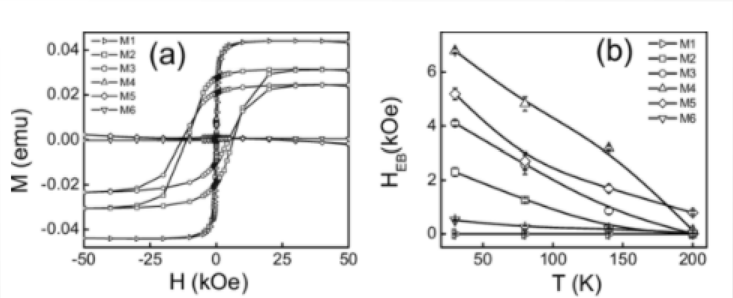
NANOPARTICLES: EXCHANGE BIAS

Co/CoO





R.Evans et al PRB 84 (2011)



M.Feygenson et a PRB 81 (2010l

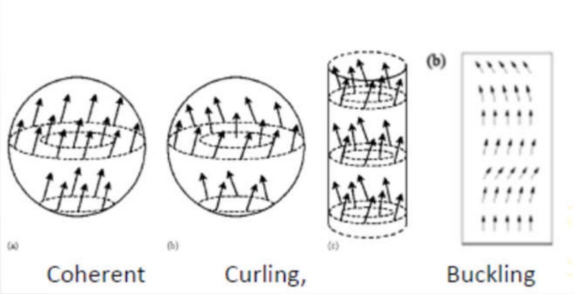
Also in thin films

BROWN'S PARADOX

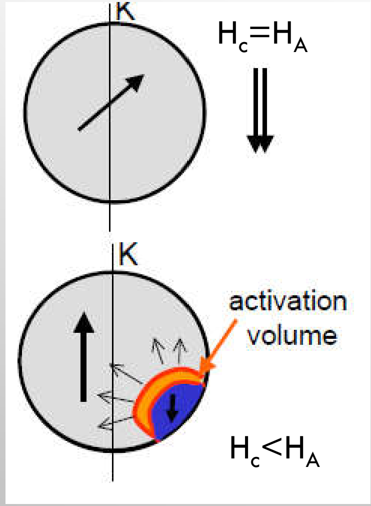
Brown's paradox

In most systems $H_c \prec\prec \frac{2K}{\mu_0 M_s}$

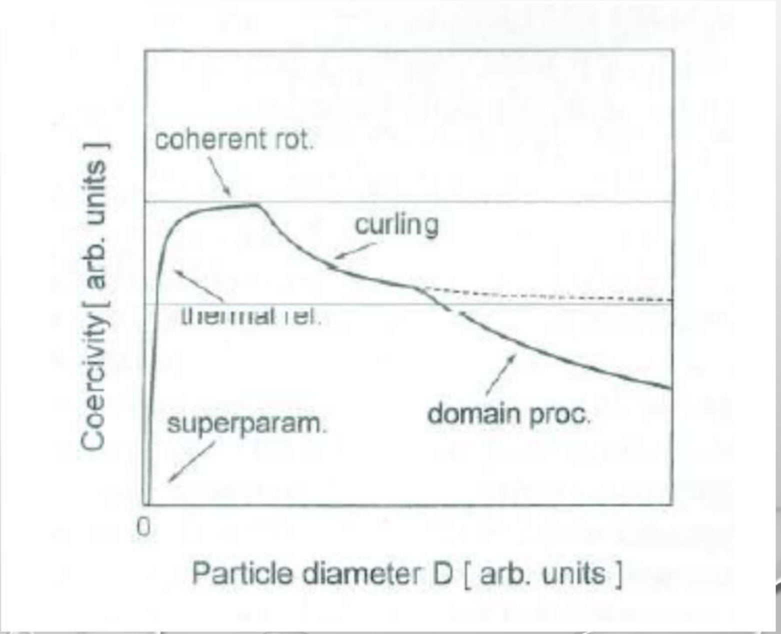
For nanomagnets: Non-uniform reversal modes

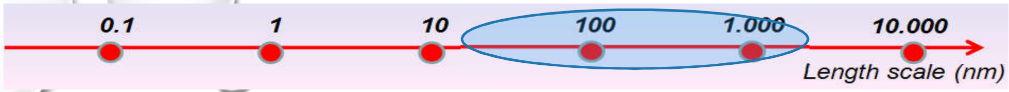


For larger systems: Nucleation (on defects and thermal nucleation)



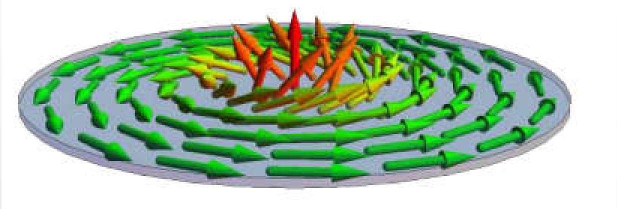
Pinning an depinning of structures.

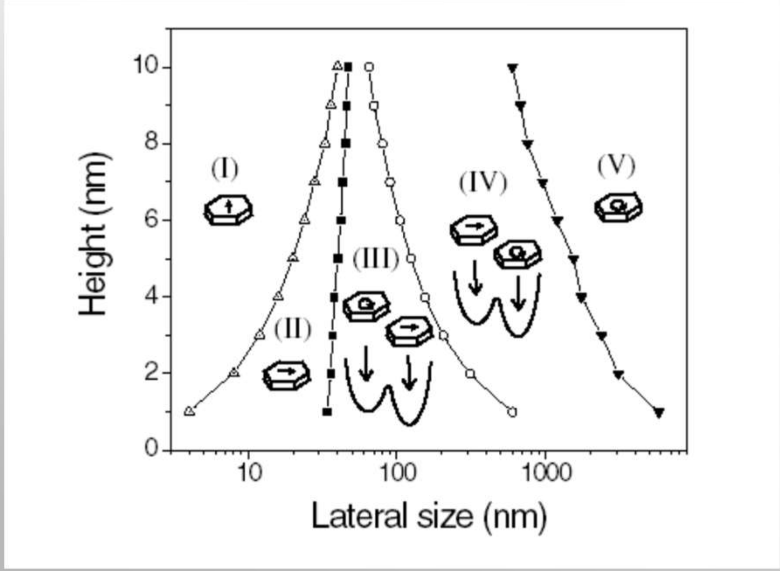




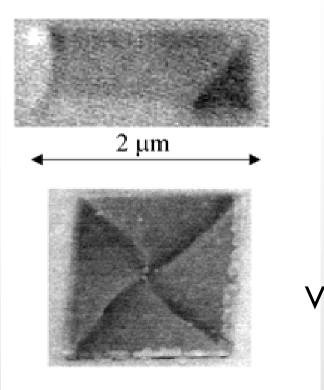
NANOMAGNETS GROUND STATES

Magnetic vortex



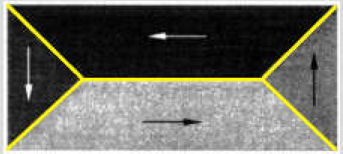


C-state

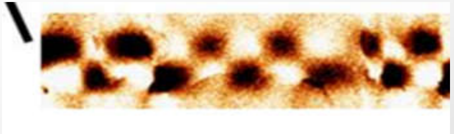


Vortex

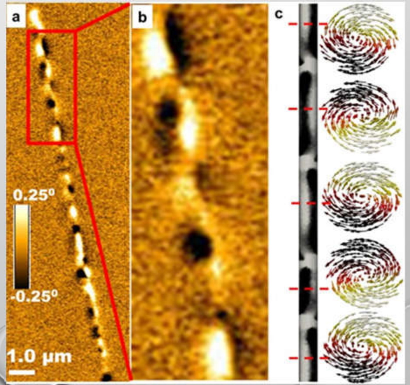
Landau pattern

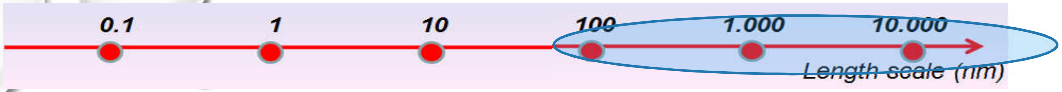


Co stripe with perpendicular anisotropy: perp domains



Co cylindrical nanowire with perpendicular anisotropy: vortex domains





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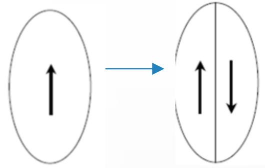
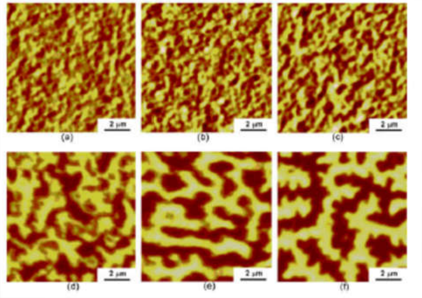
DOMAINS

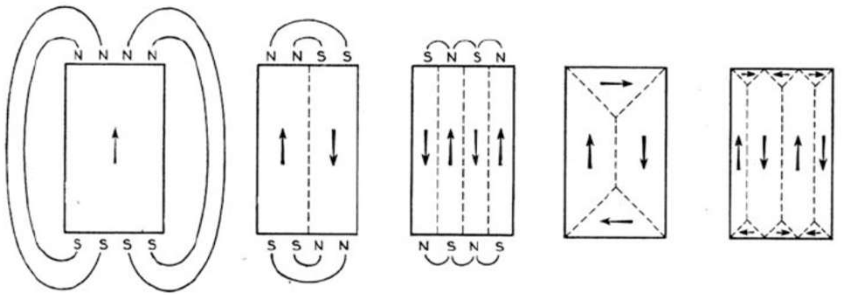


$$2\pi R^2\sqrt{AK} = \frac{1}{2}NM_s^2$$

$$R_{sd} = \sqrt{AK} / \mu_0 M_s^2$$

Criterium for single domain particle



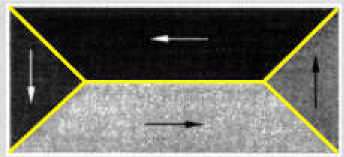


domains form to minimize the magnetic energy

$$\nabla \cdot \mathbf{M} = 0$$

$$\hat{\mathbf{n}} \cdot \mathbf{M}|_{\text{surface}} = 0$$

Glosure domains



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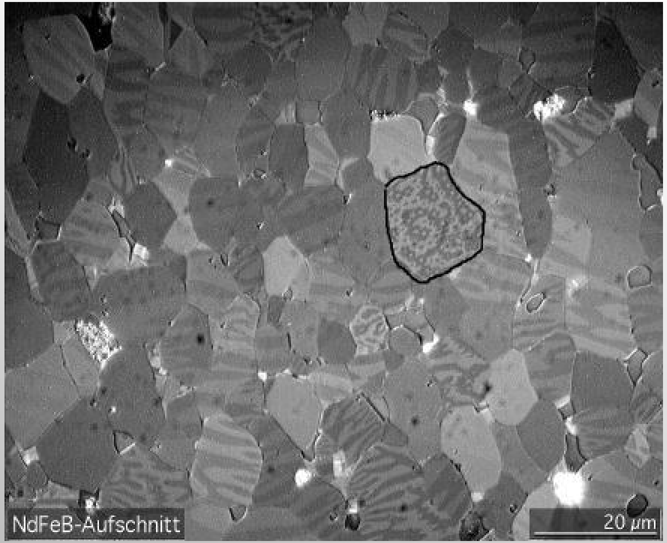
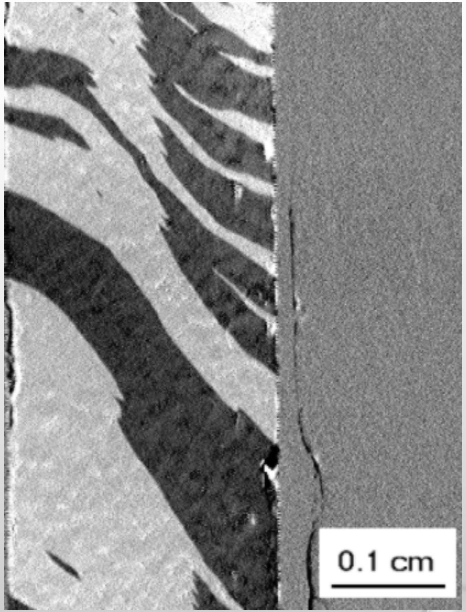
DOMAINS

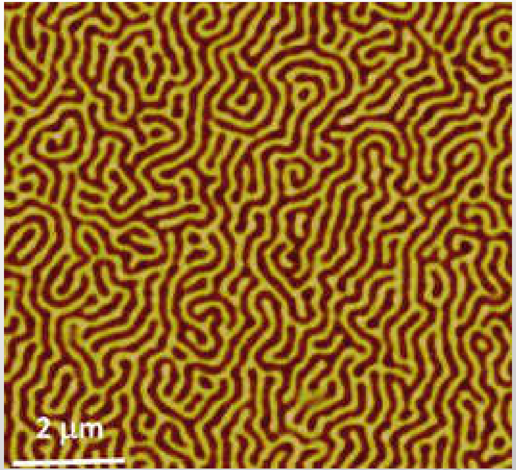
Hard magnet: NiFeB



Soft magnetic material: finemet (FeSiB)

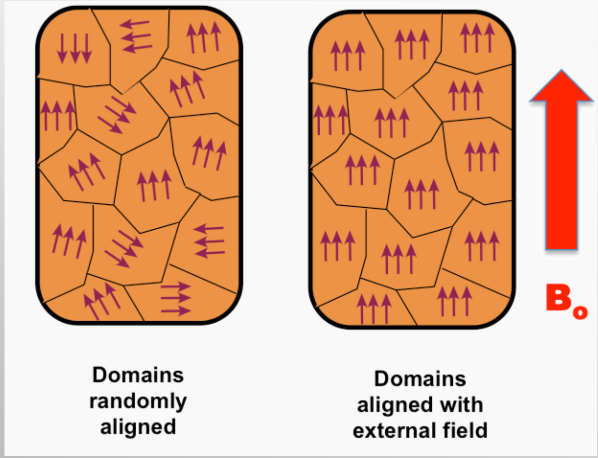


Systems with PMA: stripe domains

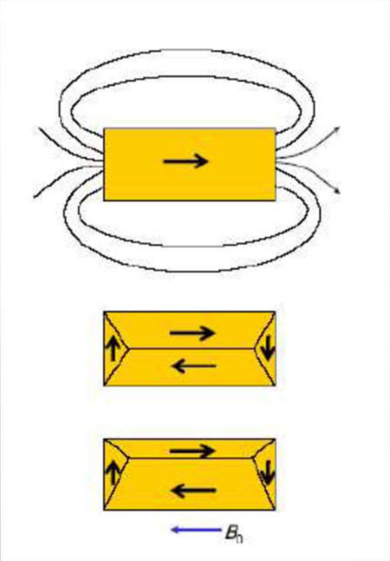


GROWTH OF DOMAINS UNDER MAGNETIC FIELD

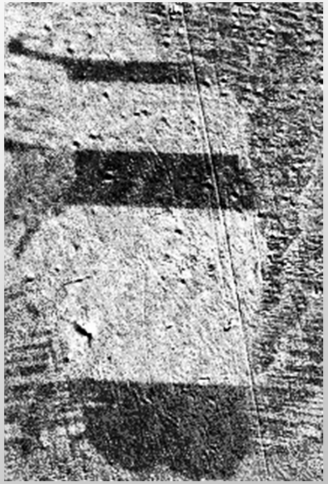
Rotation

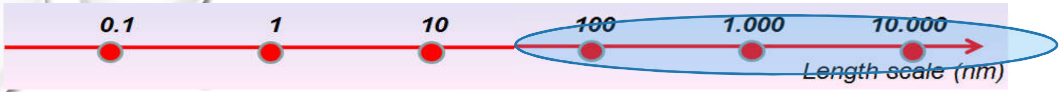


Domain wall propagation



Steel





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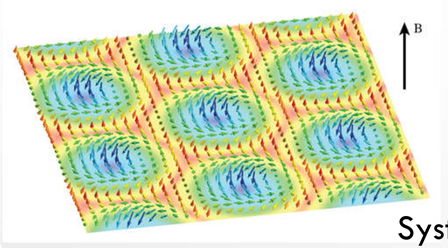
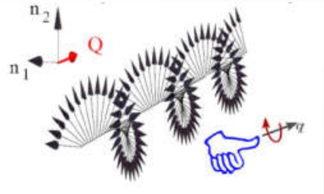
SYSTEMS WITH DMI: SKYRMIONS AND CHIRAL DOMAIN WALLS

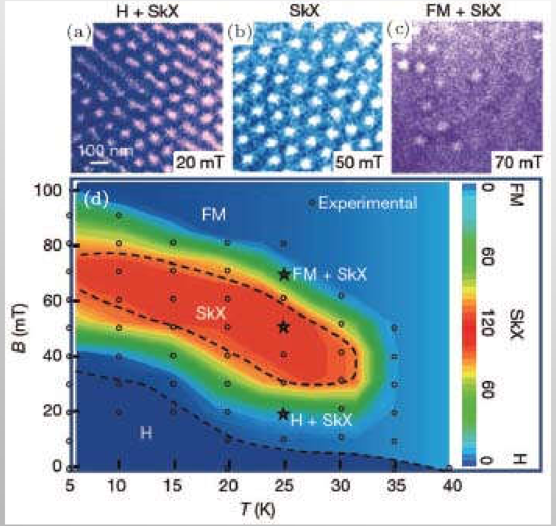


Systems with SO-coupling and broken symmetry



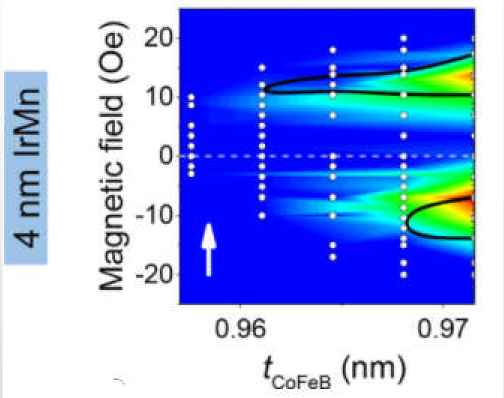
Systems with intrinsic DMI

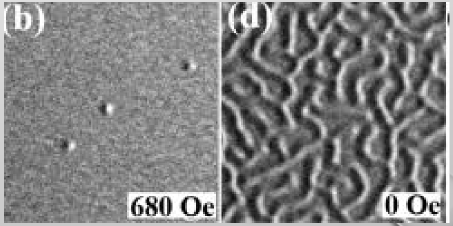
MnSi Ye-Hua et al



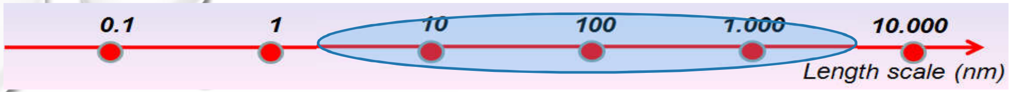
Ultra thin multilayers: TM + strong SO coupling materials

Hao Wu et al

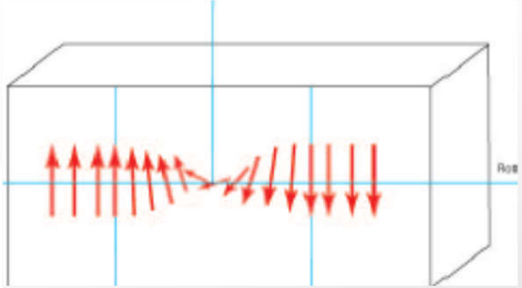




Pt/Co/Ta
He at al APL 2017



DOMAIN WALL



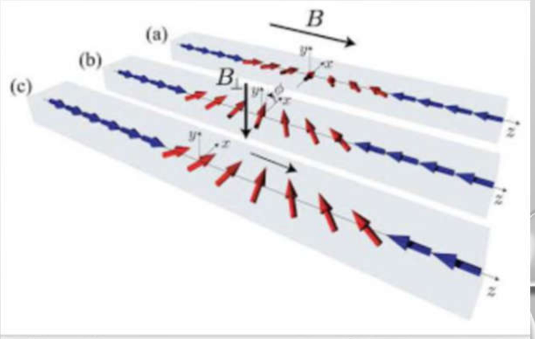
$$\mathcal{E} = \int dx \left[A \left(\frac{\partial \theta}{\partial x} \right)^2 + K_u \sin^2 \theta \right] \longrightarrow 2A \frac{\partial^2 \theta}{\partial x^2} - K_u \sin 2\theta = 0$$

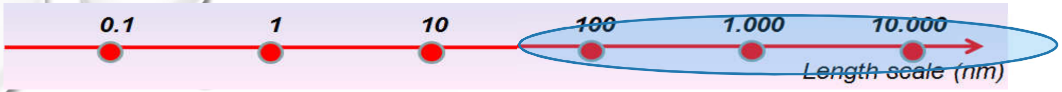
$$\theta(x) = 2 \tan^{-1} \left[\exp \left(x/\Delta \right) \right]$$

$$\Delta = \sqrt{A/K_u}$$

DOMAIN WALL WIDTH

Δ=2 nm (very hard materials) ---- more than 100 nm (very soft materials)





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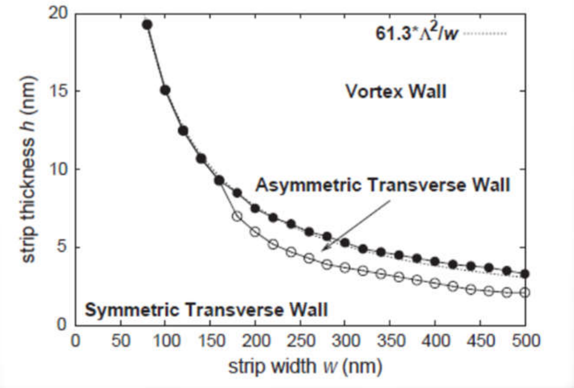
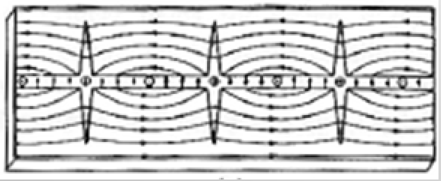
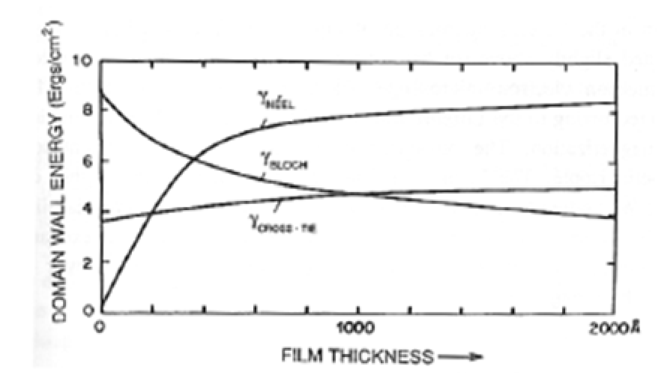
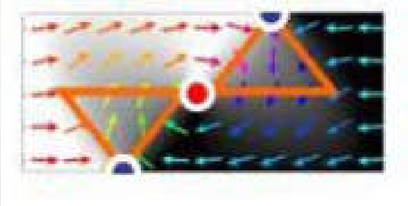
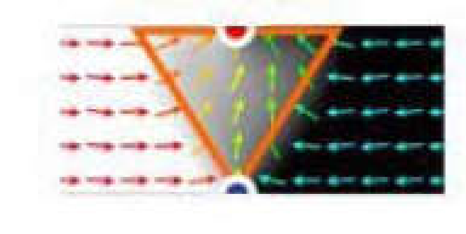
DOMAIN WALLS

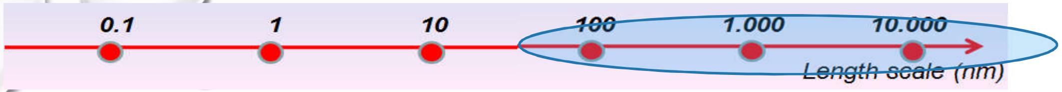






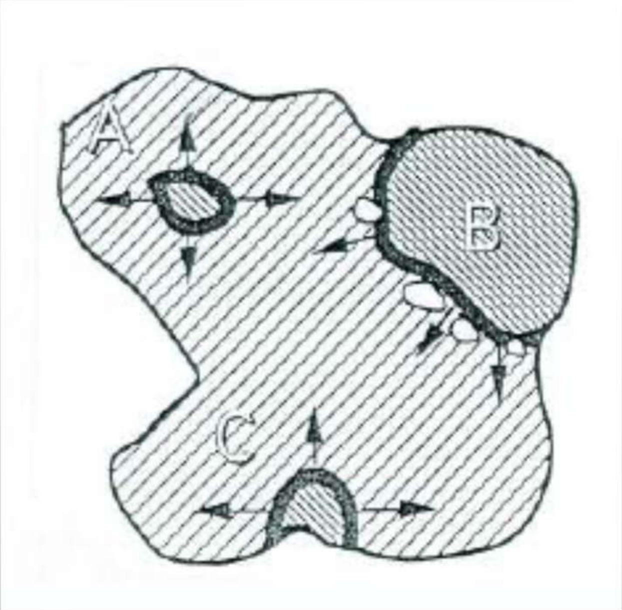






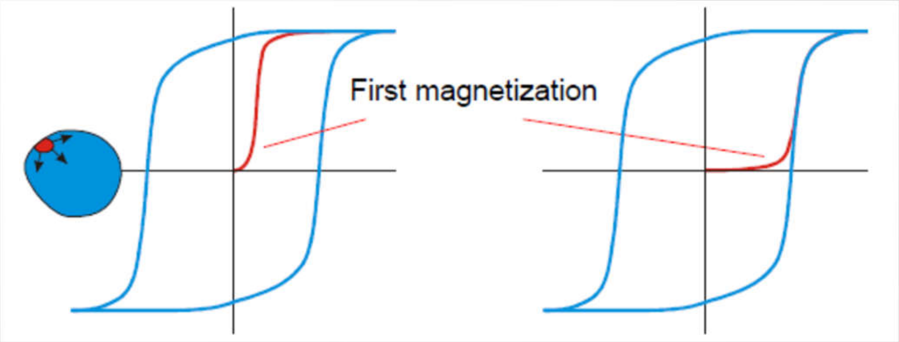
COERCIVITY TYPE MECHANISMS

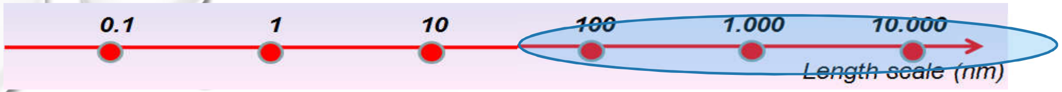
Rotation, nucleation, DW propagation, pinning, depinning



Nucleation-type coercivity

Pinning-type coercivity





e-ESM, an online higher-education Magnetism event

NUCLEATION AND DOMAIN WALL PROPAGATION THEORIES

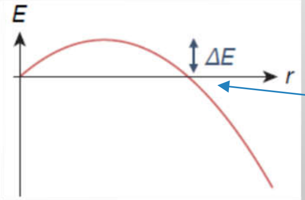
Nucleation mechanism

The concept of nucleation volume

$$E(r) = (2\pi r d)\sigma - (\pi r^2 d)(2\mu_0 M_s H_0)$$

Wall energy — Zeeman energy

$$\sigma = 4\sqrt{AK_u}$$



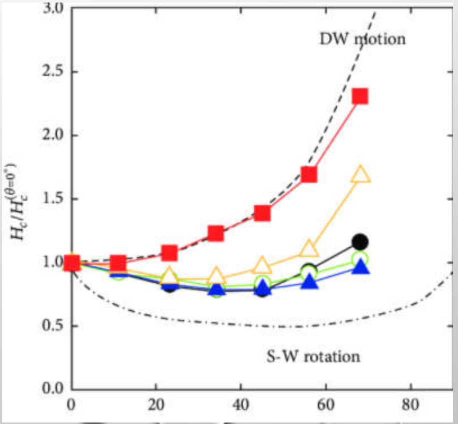
Nucleation size

DW nucleation + propagation

$$H_c(\theta_H) = \frac{H_c(0)}{\cos(\theta)}$$

Angular dependence of coercivity

DW energy > thermal energy



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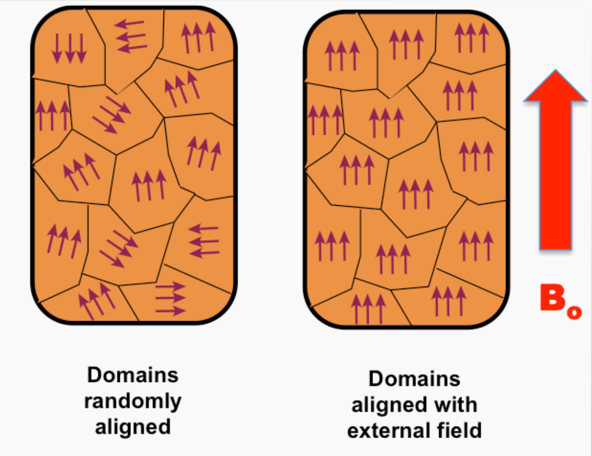
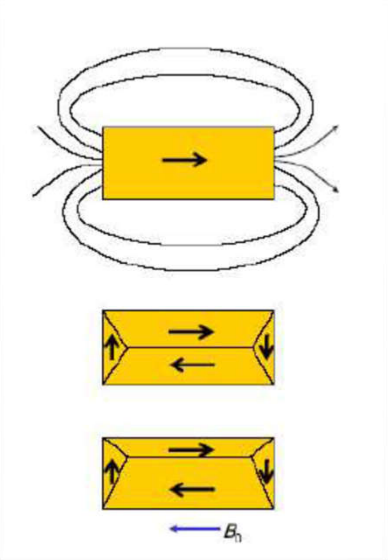
GROWTH OF DOMAINS UNDER MAGNETIC FIELD

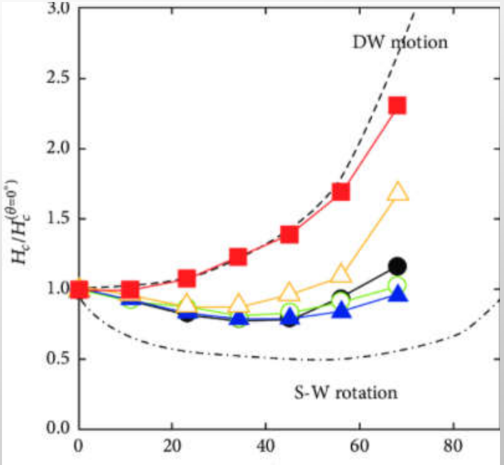
Rotation



Domain wall propagation



Angular dependence of coercivity



COERCIVITY IN SOFT MATERIALS: RANDOM ANISOTROPY MODEL

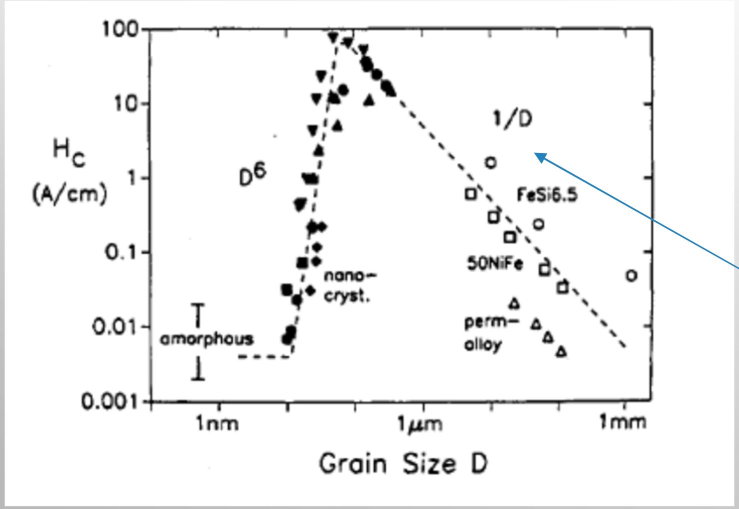
Exchange correlation length is much larger than the grain size

Mostly demagnetize by domain wall propagation

$$< K > = \frac{K}{\sqrt{N}}, \quad N = \frac{L^3_{ex}}{D^3}$$

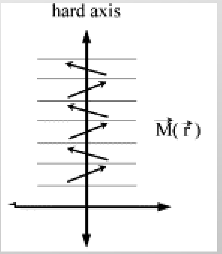
Number of grains within exchange correlation length

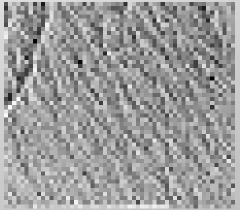
$$< K > \propto K_1 D^6$$



Nucleation model

Magnetisation ripple

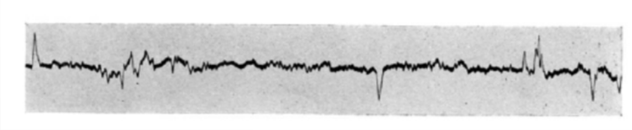




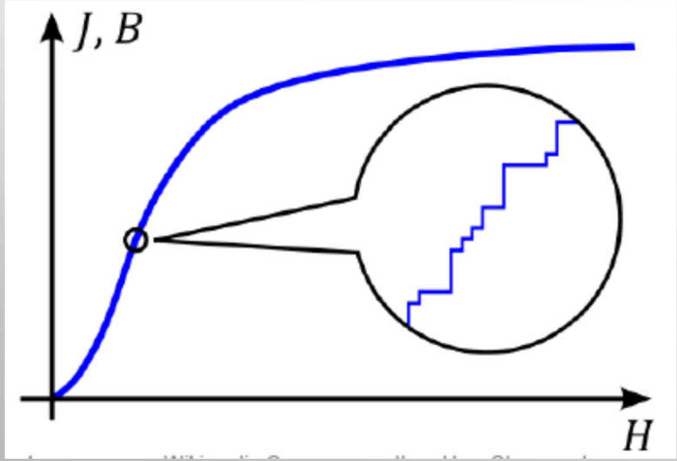
TEM image: NiFe
L.Heyderman et al JMMM

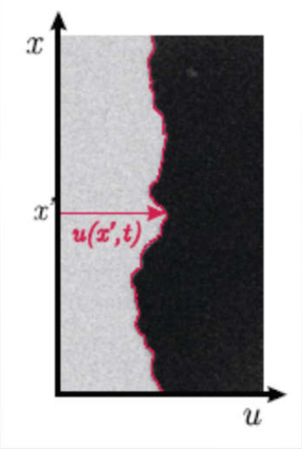
e-ESM, an online higher-education Magnetism event

BARKHAUSEN EFFECT

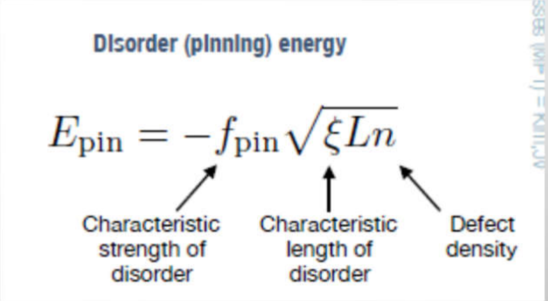


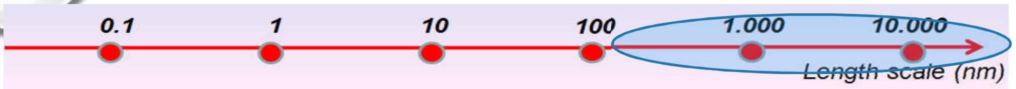
R.M.Bozorth PRB 34 (1929)





Domain wall as an elastic band in a Random potential : creep motion





e-ESM, an online higher-education Magnetism event

COERCIVITY IN HARD MAGNETIC MATERIALS:

Exchange correlation length is smaller or comparable with grain size

Mostly demagnetize via multiple nucleation and pinning sequence at grain boundary

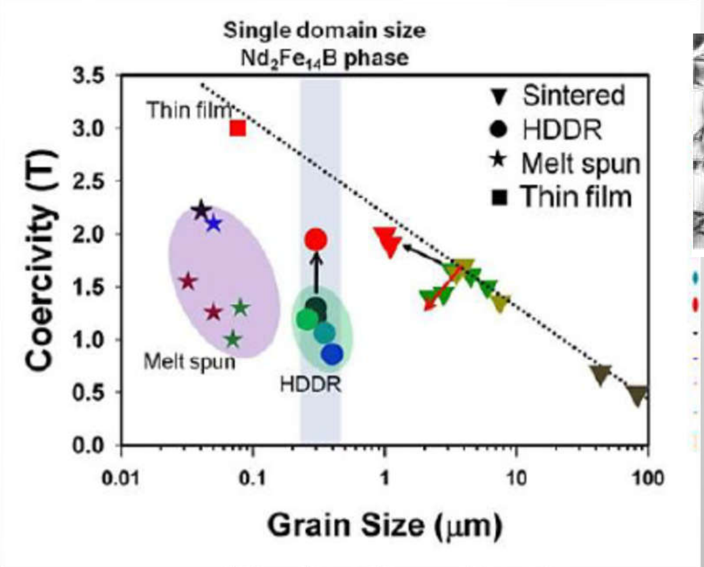
Kronmuller Equation

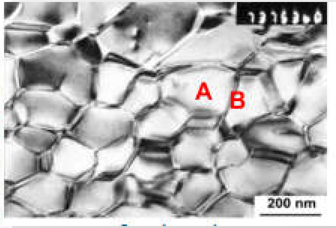
$$H_c = \alpha_K(2K_1/\mu_0 M_s) - N_{eff} M_s$$

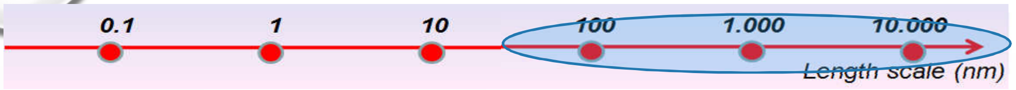
Pinning strength

Grain shape factor

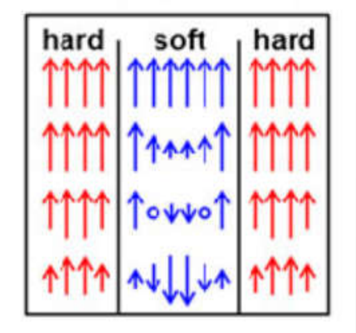
- ✓ Grain size reduction
- ✓ Exchange decoupling





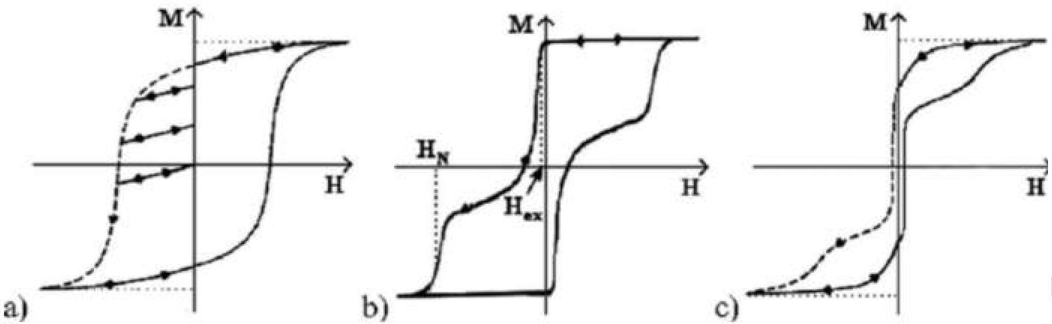


COMPOSITE MATERIALS: THE CONCEPT OF "EXCHANGE SPRING"

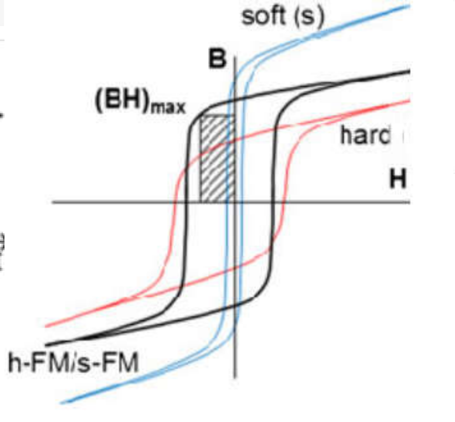


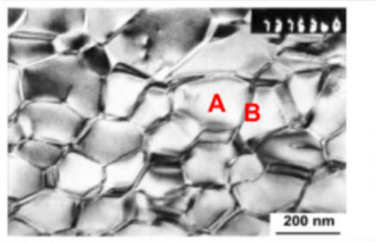
Soft phase: nucleation-type coercivity, also provides high M e.g. Sm_2Co_{17}

Hard phase: pinning type coercivity, e.g. $SmCo_5$



Typical hysteresis loops for the three types of magnets: (a) rigid nanocomposite, (b) exchange-spring nanocomposite, (c) two uncoupled phases.





MESSAGES

- MAGNETISATION PROCESSES DEPEND STRONGLY ON SPATIAL DIMENSIONS. MAGNETIC STATES CANNOT BE RESCALED
- NANOPARTICLES: SURFACE EFFECTS ARE IMPORTANT
- LARGER NANOSTRUCTURES: SHAPE IS VERY IMPORTANT, NEW NONHOMOGENEOUS
- THIN FILMS, BULK MATERIALS: NUCLEATION, PROPAGATION, PINNING OF DOMAIN WALLS

MAGNETIZATION PROCESSES II
TEMPORAL SCALES
(MAGNETIZATION DYNAMICS AND TEMPERATURE EFFECTS)

O.CHUBYKALO-FESENKO

INSTITUTO DE CIENCIA DE MATERIALES DE MADRID,

CSIC, SPAIN

TIME SCALES IN MAGNETISM

10^{-17}s as

10^{-14}s fs

10^{-11}s ps

10^{-9}s ns

10^{-6}s µs

10^{-3}s ms

10^{-0}s s

10^{3}s hs

10^{6}s month

10^{9}s years

Light-induced coherent processes.

Electron-spin relaxation processes.
Spin-orbit coupling

Magnetisation precession.

Hysteresis measurements.

Magnetic viscosity experiments.

Long-time thermal stability for magnetic recording.

Atto-second Laser pulses

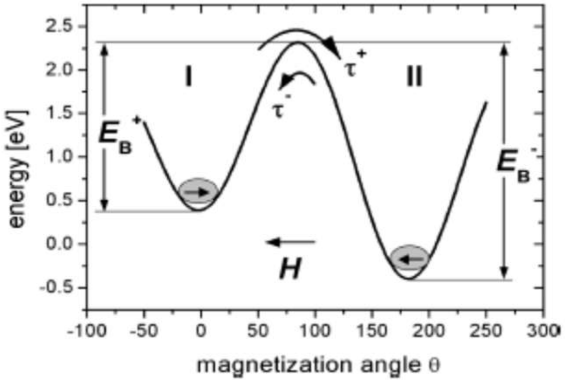
All-optical laser-pulsed experiments

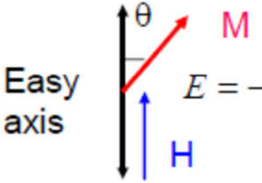
Fast-Kerr measurements, FMR, Domain Wall motion

Conventional magnetometers (VSM, SQUID)

LONG-TIME DYNAMICS: TEMPERATURE EFFECTS

The Stoner-Wolfarth particle





$$E = -KV\cos^2\theta - MH\cos\theta$$

Energy barrier:

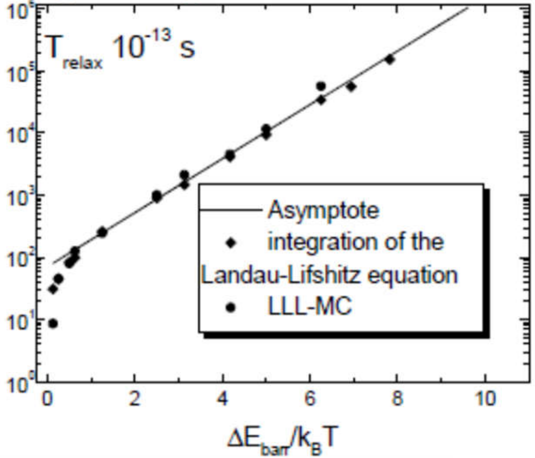
$$\Delta E = KV\left[1 - \frac{H}{H_K}\right]^2, \quad H_K = 2K/M_s$$

The Arrhenius-Neél law

$$\tau_{\pm}^{-1} = f_0 \exp(-\Delta E_{\pm}/kT) = f_{1,2}$$

$$dm_1/dt = -f_1 m_1 + f_2 m_2 \quad \text{- Master equation}$$

$$f_2 << f_1 \quad m(t) \propto \exp(-t/\tau)$$



Relaxation in complex systems

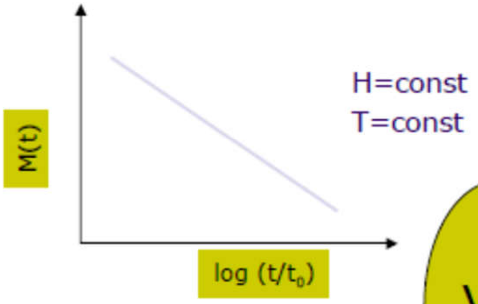
$$\tau_{\pm}^{-1} = f_0 \exp(-\Delta E_{\pm} / kT) \qquad m(t) \propto \int \exp[--t / \tau(\Delta E)] \rho(\Delta E) d\Delta E$$

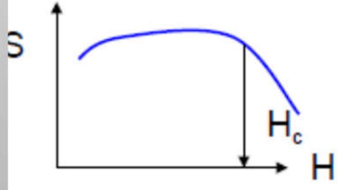
If in some interval $[\Delta E, \Delta E + \delta\Delta E]$ $\qquad \rho(\Delta E) \approx const$

$m(t) \propto \Delta E \propto M_0 - S \log(t)$ -widely observed behavior

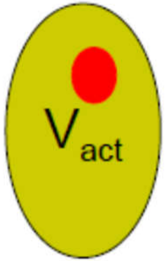
•Based on the assumption of
Homogeneous energy barrier distribution
which is constant in time

$S = dM / d(\log t)$ -magnetic viscosity

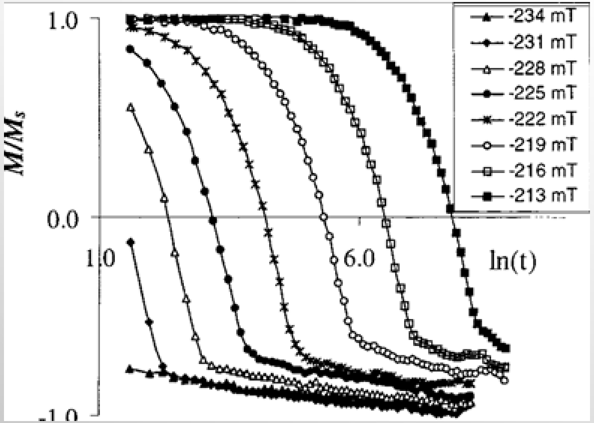




$V_{act} = k_B T / (\mu_0 H M_s)$ Activation volume



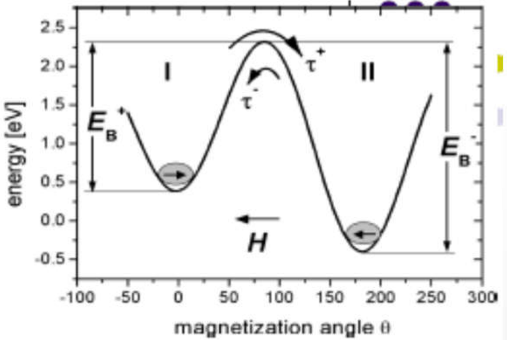
MAGNETIC VISCOSITY



Co/Pt multilayer film

Bennet et al J modern Phys. 2014

Superparamagnetism



- The relaxation time of a grain is given by the Arrhenius-Neel law

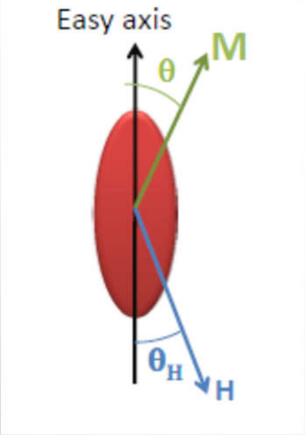
$$\tau_{\pm}^{-1} = f_0 \exp(-\Delta E_{\pm} / kT)$$

- where $f_0 = 10^9 s^{-1}$. and ΔE is the energy barrier
- This leads to a critical energy barrier for superparamagnetic (SPM) behaviour $\Delta E_c = KV_c = k_B T ln(t_m f_0)$

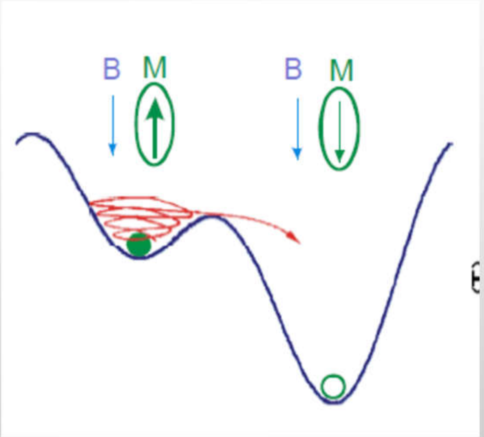
- where t_m is the 'measurement time'
  - Nanoparticles with $\Delta E < \Delta E_c$ exhibit thermal equilibrium (SPM) behaviour - no hysteresis

$KV>25k_BT$ – for stability at room temperature, $KV>60k_BT$ – for magnetic recording

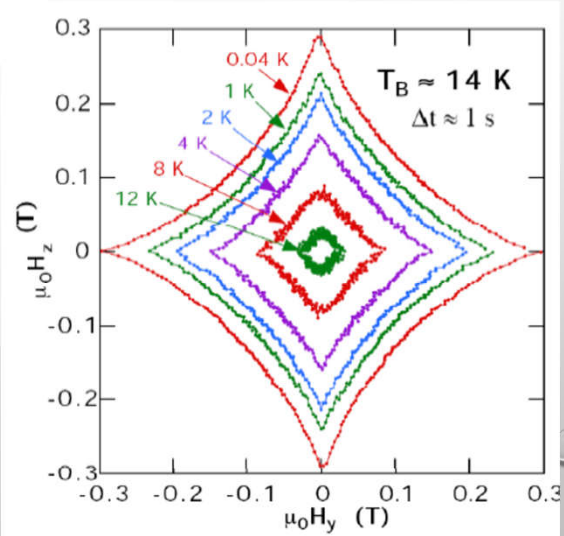
NANOPARTICLES: THE STONER-WOLFARTH MODEL FOR COHERENT REVERSAL (NOW WITH TEMPERATURE)



$$E = K_{eff} \sin^2\theta - \mu_0 M_S H \cos(\theta + \theta_H)$$

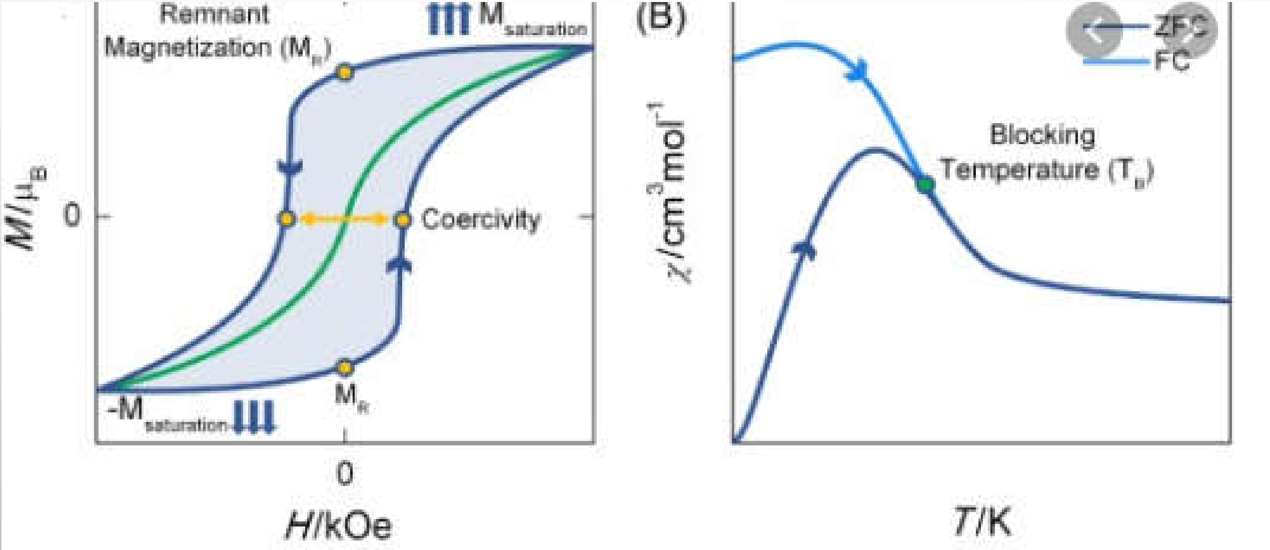


$$\Delta E = KV\left(1 - \frac{H}{H_{sw}(0)}\right)^2$$



3 nm Co Cluster, Micro-SQUID Experiment
Wernsdofer et al. PRL 2002 36

DYNAMIC COERCIVITY AND BLOCKING TEMPERATURE



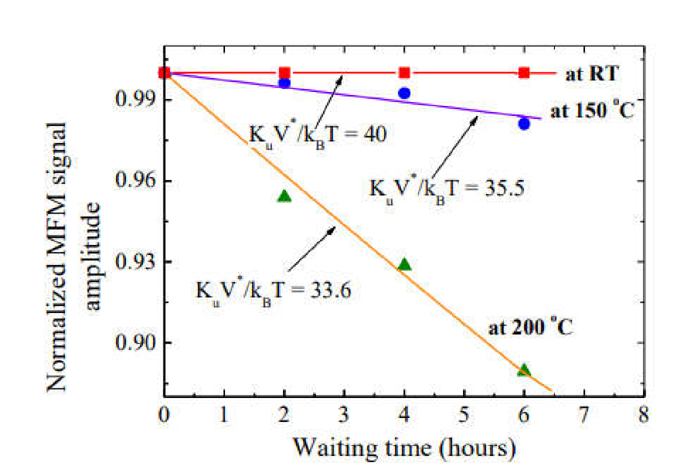
MAGNETIC RECORDING: SHARROCK'S LAW

$$\Delta E = KV(1-\frac{H}{H_{sw}(0)})^n$$

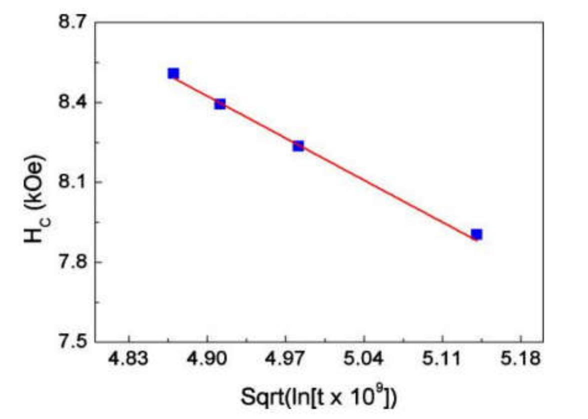
n=2 for the simplest case
(field parallel to anisotropy)

$$\Delta E > 50k_BT$$

$$\frac{H_c(t,T)}{H_0} = 1-[\frac{k_BT}{KV}\ln\frac{f_0t}{0.69}]^{1/n}$$



Z-Zhang etal JMMM (2005)



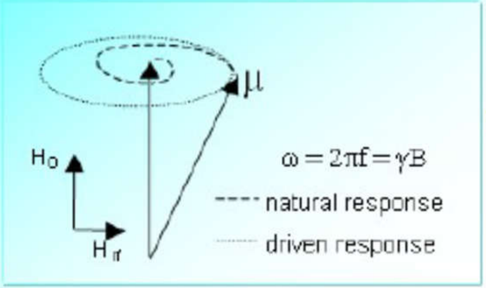
A.Perumal et al JAP (2010)

Ferromagnetic resonance(FMR): (Arkadiev, 1911; Kittel, 1947)

A ferromagnetic body under applied field has a maximum absorption in frequencies:

$$\omega = \gamma\sqrt{\left[H + (N_x - N_z)M\right]\left[H + (N_y - N_z)M\right]}$$

The absorption peak contains information about anisotropy field.

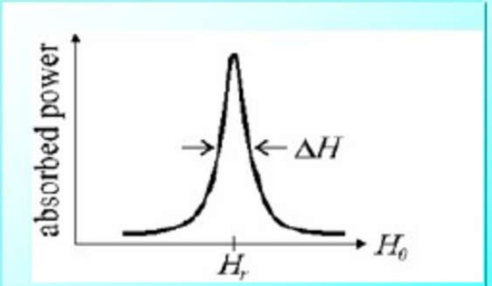


Precession and relaxation of **M** in response to an applied field **H**.

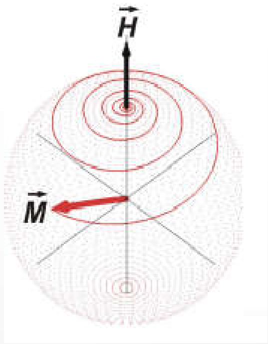
Torque on magnetisation

$$\frac{1}{\gamma}\frac{\partial M}{\partial t} = -\left[M \times H_0\right]$$

Lorentzian absorption line typical of FMR showing microwave power absorption as a function of swept bias field.



The absorption line width contains Information on damping processes



The Landau-Lifshitz (LL) and the Landau-Lifshitz-Gilbert (LLG) equations of motion

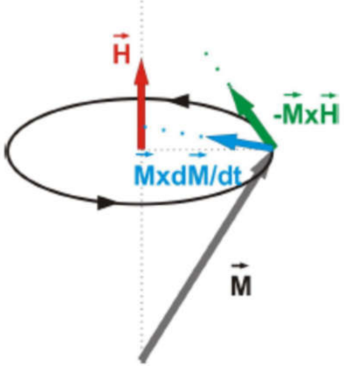
(for magnetization vector):

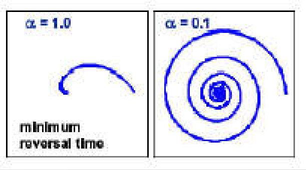
LL equation — Landau-Lifshitz damping, 1935

$$\frac{d\vec{M}}{dt} = -\gamma'_0\left[\vec{M}\times\vec{H}\right] - \frac{\alpha_{LL}\gamma_0}{M_s}\left[\vec{M}\times\left[\vec{M}\times\vec{H}\right]\right]$$

Gilbert equation
(physically more reasonable for large damping) — Gilbert damping, 1955

$$\frac{d\vec{M}}{dt} = -\gamma_0\left[\vec{M}\times\vec{H}\right] + \frac{\alpha_G}{M_s}\left[\vec{M}\times\frac{d\vec{M}}{dt}\right]$$

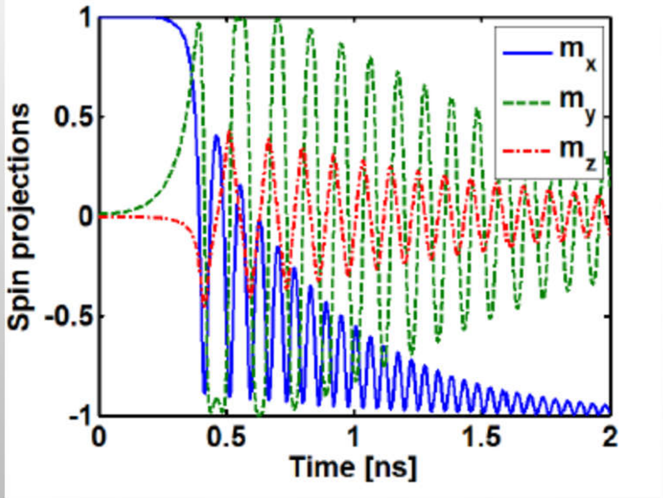


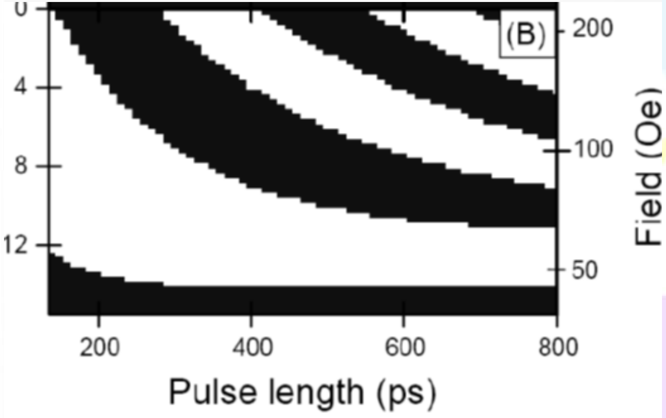


Damping form is phenomenological
The value includes many intrinsic and extrinsic contributions

PRECESSIONAL SWITCHING

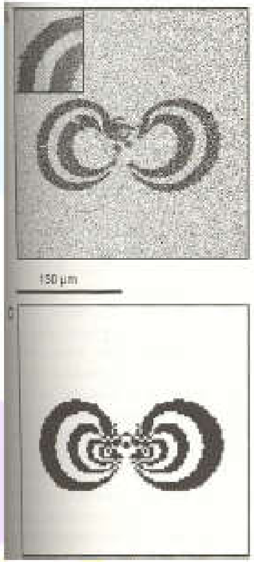
Perpendicular to M field





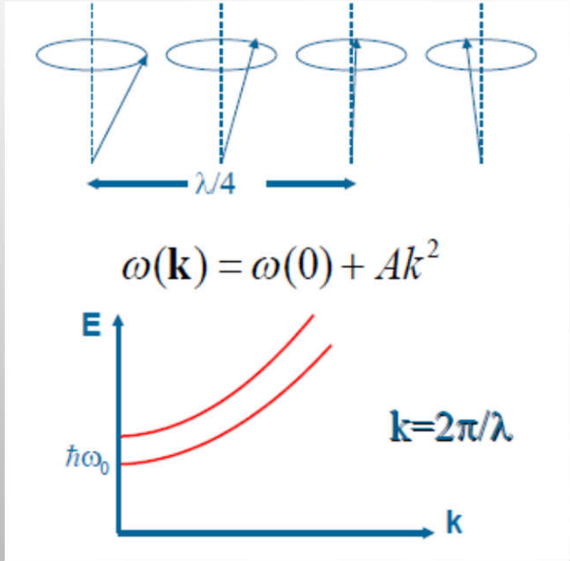
Experiment with ps field pulses perpendicular to the magnetisatrion (C.Back et al, Science, 1999)

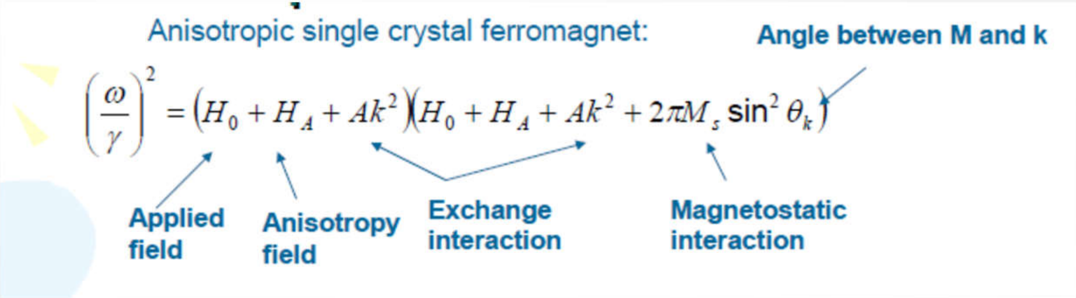
Fe/GaAs



SPIN WAVES

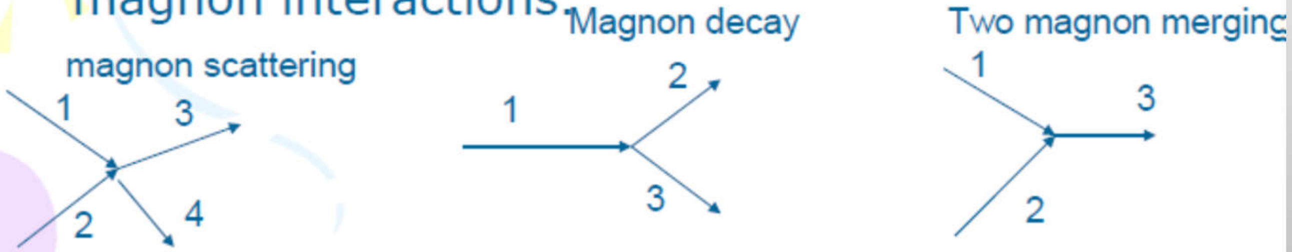
Kittel formula





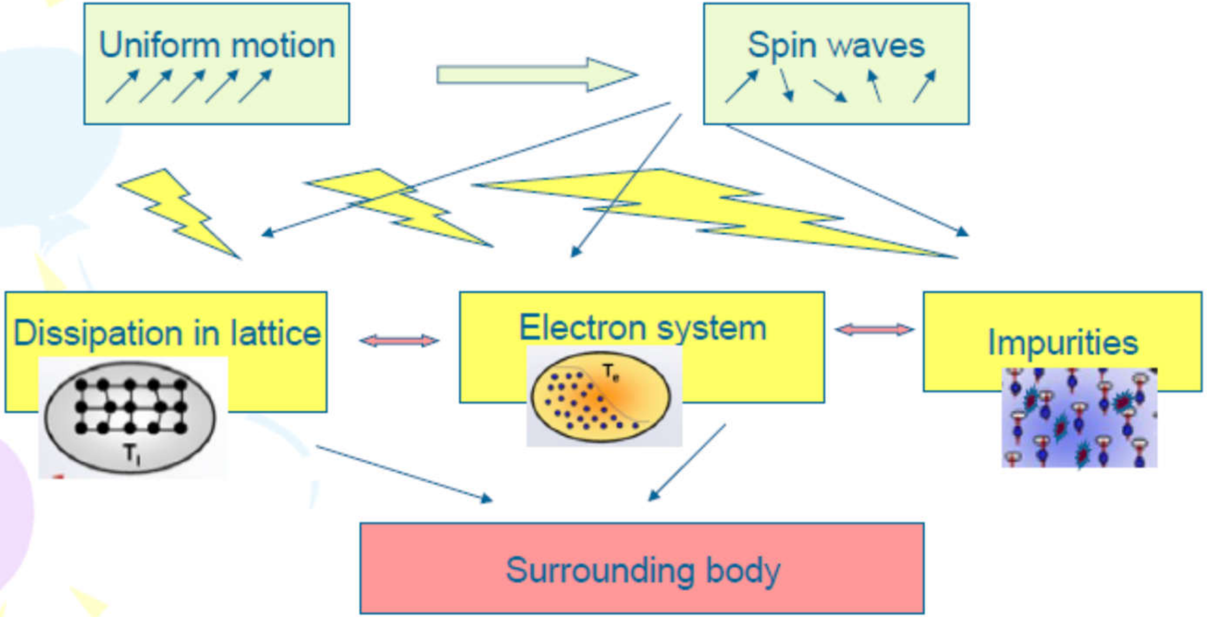
Magnons and their interactions:

- Classical spinwaves correspond to quasiparticles called magnons.
- Homogeneous magnetisation (FMR mode) corresponds to magnon with k=0.
- Linear normal modes (magnons) do not interact. Nonlinear processes correspond to magnon-magnon interactions.



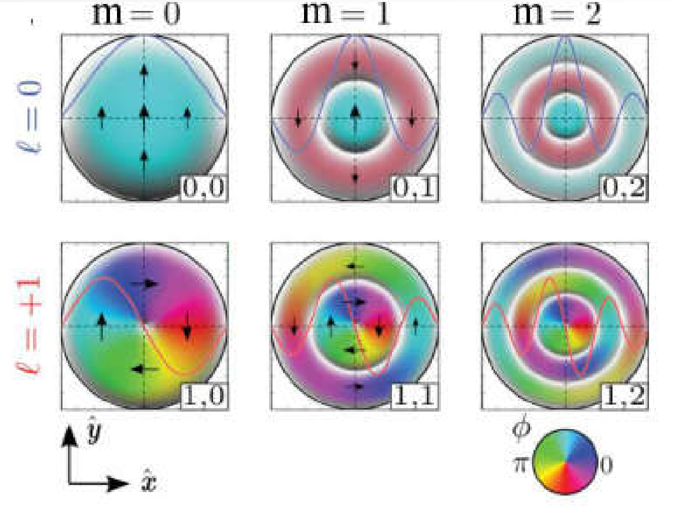
These interactions define kinetic effects (e.x. heat conductivity) and width and shape of the FMR line and magnon lifetime

Theory of magnetic damping constant (α):



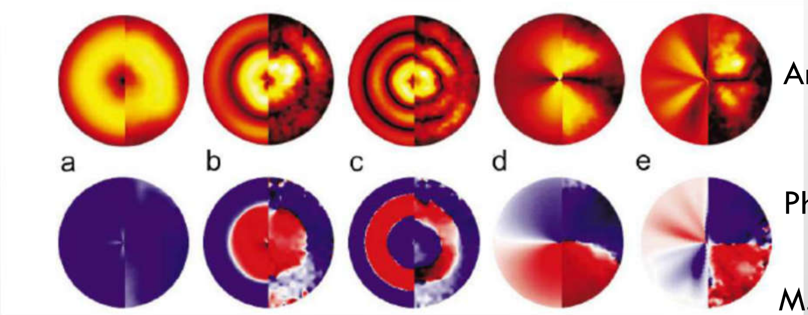
EXCITATION MODES IN NANOMAGNETS

Uniform magnetization in Py disc



B.Pegeau PhD

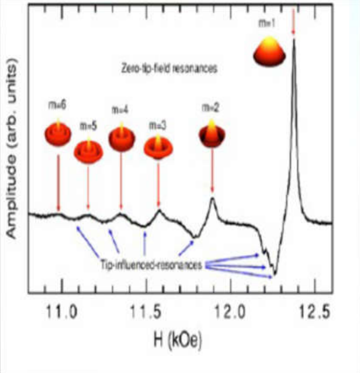
Vortex state in Py disc



Amplitude

Phase

M.Bues PRL (2004)



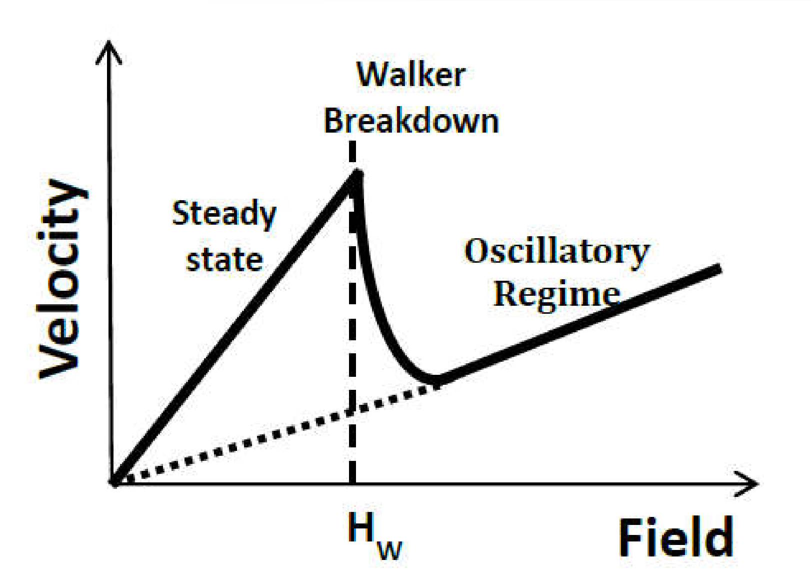
G.Kakazei et al

DOMAIN WALL DYNAMICS: WALKER BREAKDOWN

$$\frac{1}{w_{ex}}\dot{X} - \alpha\dot{\phi} = k_p \sin(2\phi)$$

$$\dot{\phi} + \frac{\alpha}{w_{ex}}\dot{X} = \gamma H$$

DW angle DW position



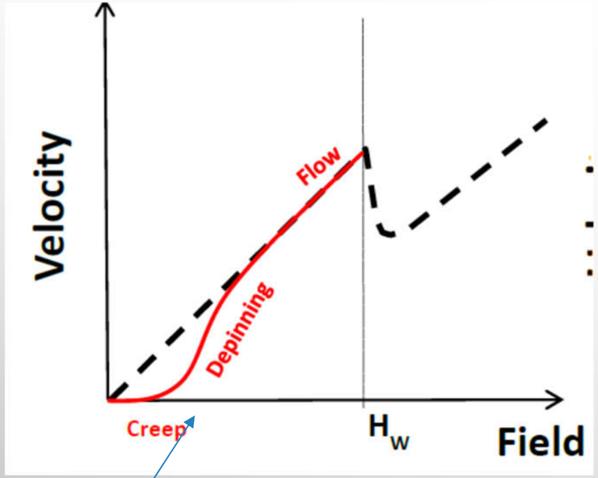
Linear regime

$$\ddot{X} + 2\alpha k_p \dot{X} = 2\gamma k_p w_{ex} H$$

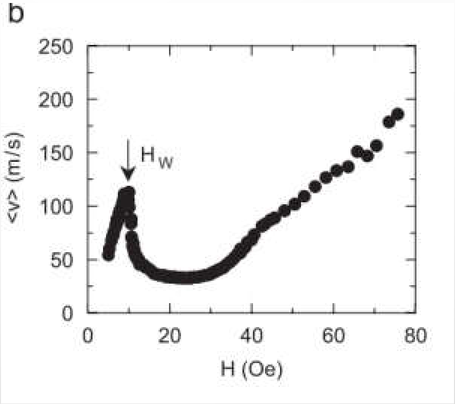
+ pinning potential

Newtonian particle

DOMAIN WALL DYNAMICS

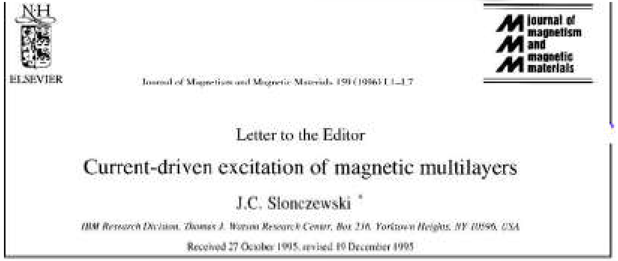


$$v_{DW} = d_0 f_0 \exp\left(-\frac{E}{K_B T}\left(H_z^{-1/4} - H_c^{-1/4}\right)\right)$$



G.Beach et al JMMM 320 (2008)

SPIN-TRANSFER TORQUE


NH ELSEVIER
Journal of Magnetism and Magnetic Materials 159 (1996) L1–L7
journal of magnetism and magnetic materials

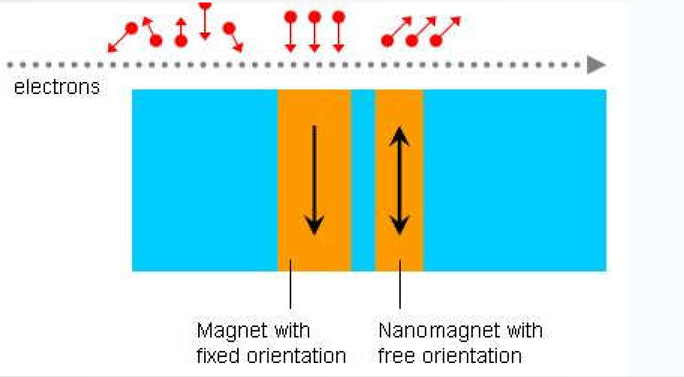
Letter to the Editor

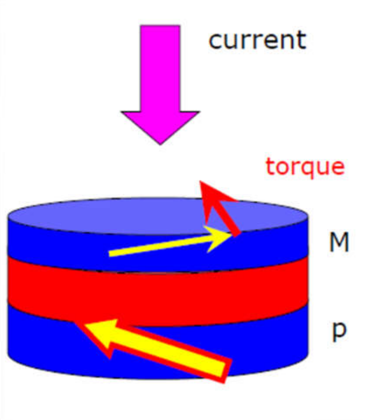
Current-driven excitation of magnetic multilayers

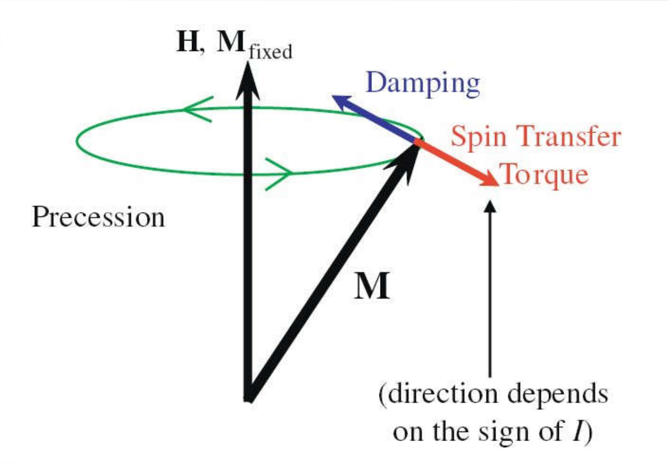
J.C. Slonczewski *
IBM Research Division, Thomas J. Watson Research Center, Box 218, Yorktown Heights, NY 10598, USA

Received 27 October 1995; revised 10 December 1995

- Electrons in magnetic material are spin polarised
- When electrons move through another thin magnetic layer with different M, they transfer their angular momentum exerting torque on magnetisation
- This can lead to magnetisation precession or switching







Magnetic random Access memories
Spin-torque nano-oscialltors

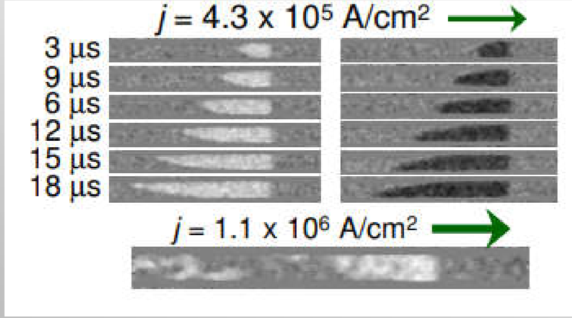
effective field damping spin transfer

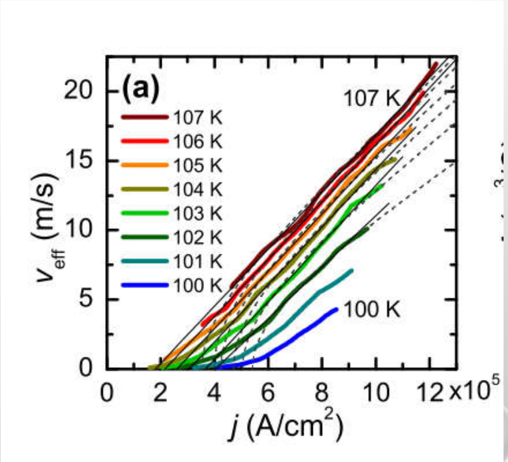
$$\frac{d\mathbf{M}}{dt} = -\gamma\left[\mathbf{M}\times\mathbf{B}_{eff}\right] + \frac{\alpha}{M_s}\left[\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right] - \frac{\Gamma}{g(\theta)}\left[\mathbf{M}\times\left[\mathbf{M}\times\mathbf{p}\right]\right]$$

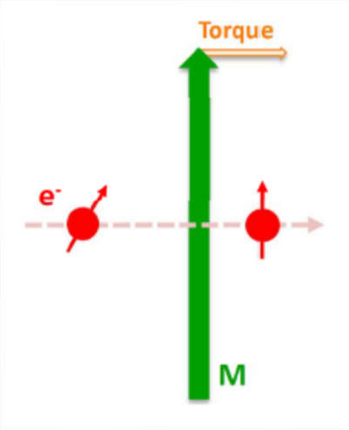
SPIN-TRANSFER TORQUE: ZHANG AND LI MODEL

Action of conduction electrons on the local magnetisation

$$\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{M} \times H_{eff} + \alpha \vec{M} \times \frac{\partial \vec{M}}{\partial t} + -u\frac{\partial \vec{M}}{\partial x} + \beta u\, \vec{M} \times \frac{\partial \vec{M}}{\partial x}$$



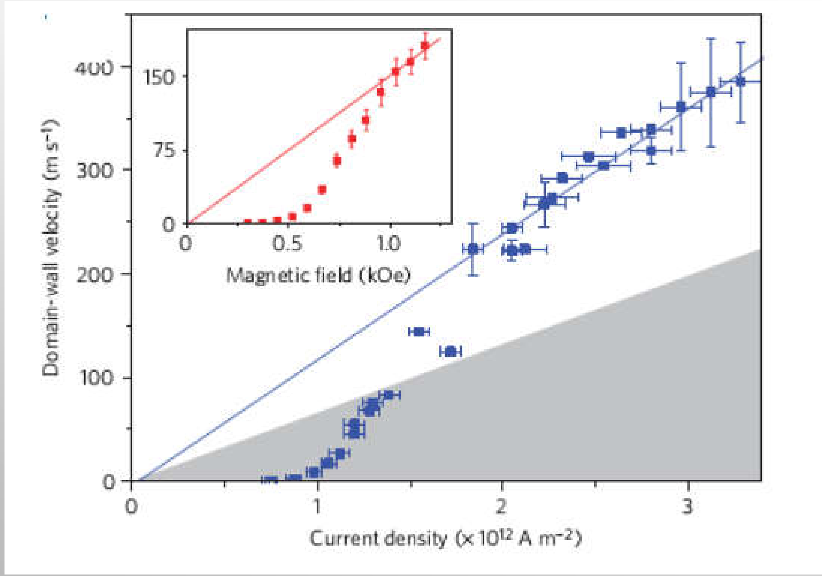


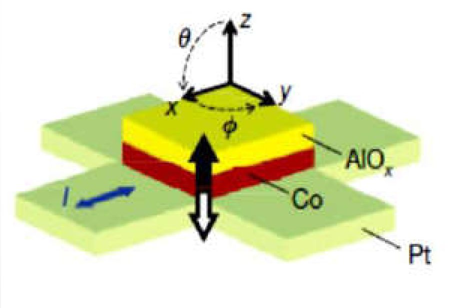


Yamanouchi et al PRL (2006)

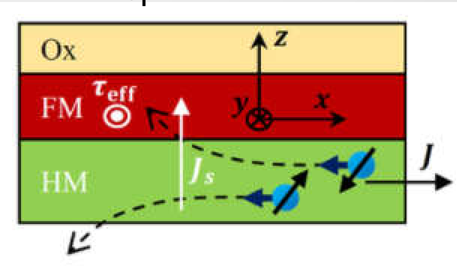
SPIN-ORBIT TORQUE

Pt/Co/AlO multilayers with spin-orbit field-like torque

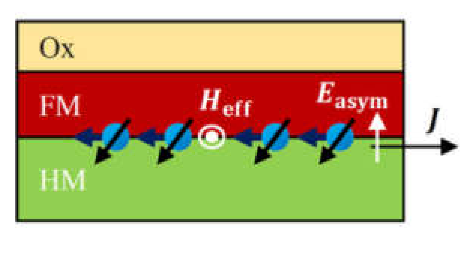




Spin-Hall effect



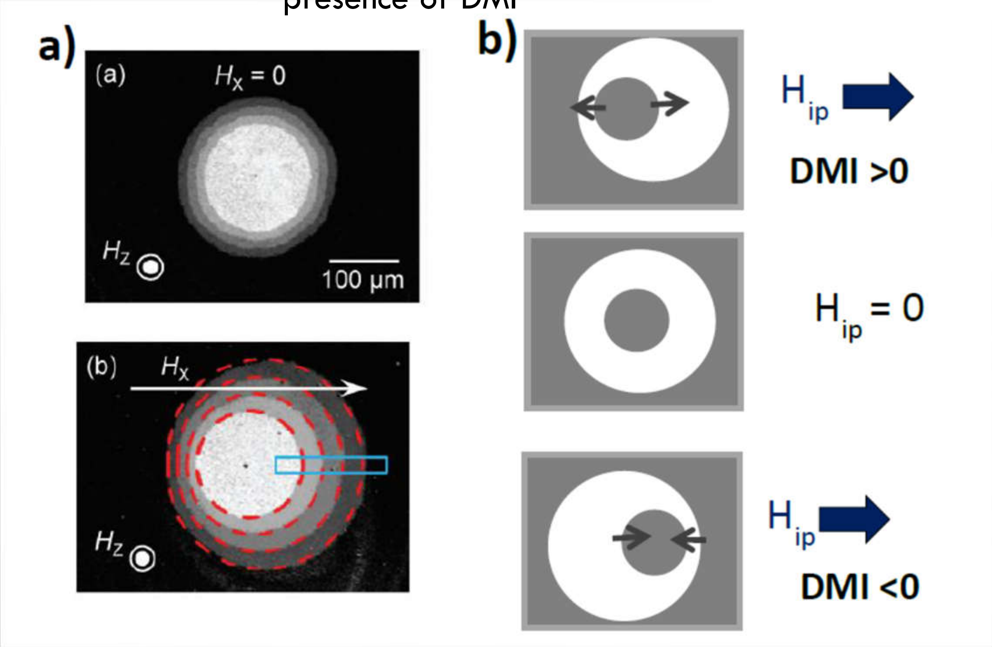
Rashba field



I.Miron Nature 2011

DW MOTION IN THE PRESENCE OF DMI

Asymmetric bubble expansion in the presence of DMI

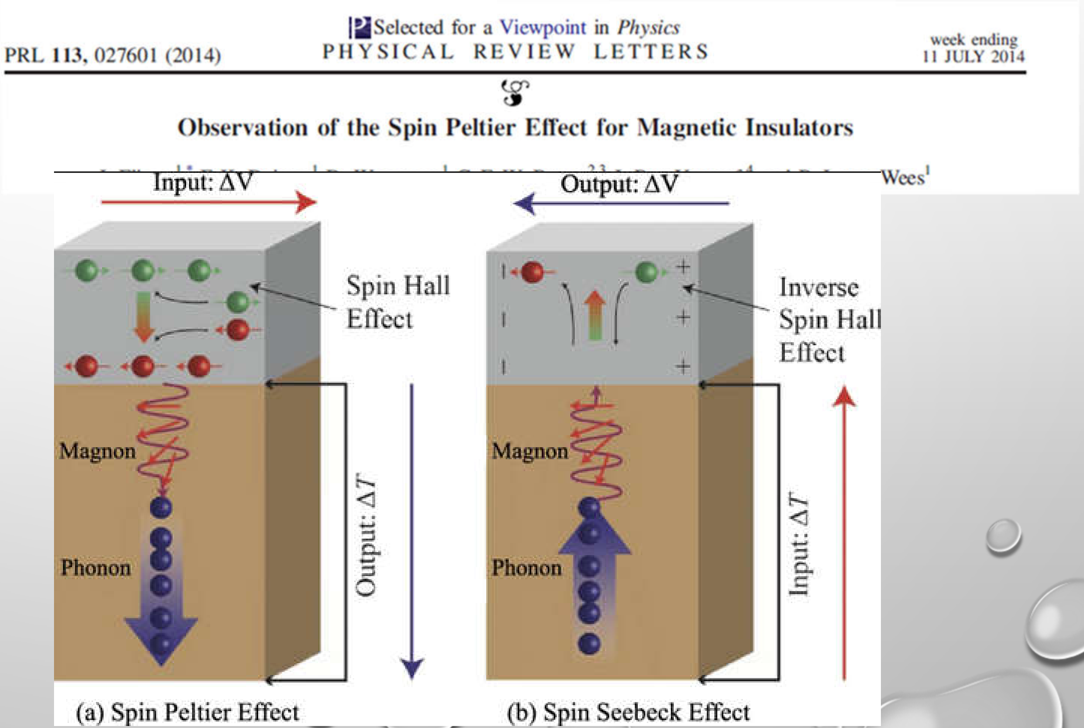


S.Je et al (2013)

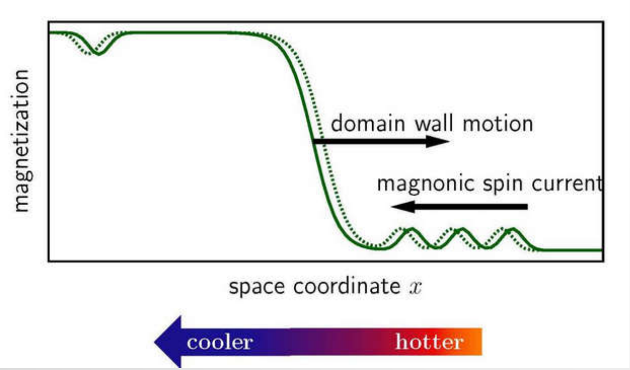
THERMAL GRADIENTS

Spin Seebeck: create ΔT -> measure spin current

Spin Peltier: create spin current ->measure ΔT

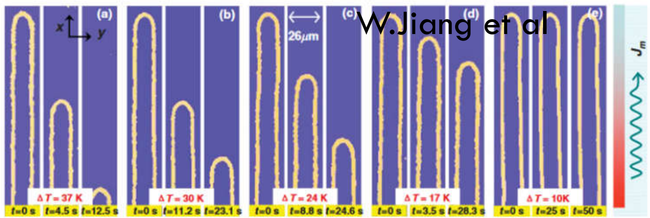


DOMAIN WALL MOTION BY SPIN-SEEBECK EFFECT



D. Hinzke and U. Nowak

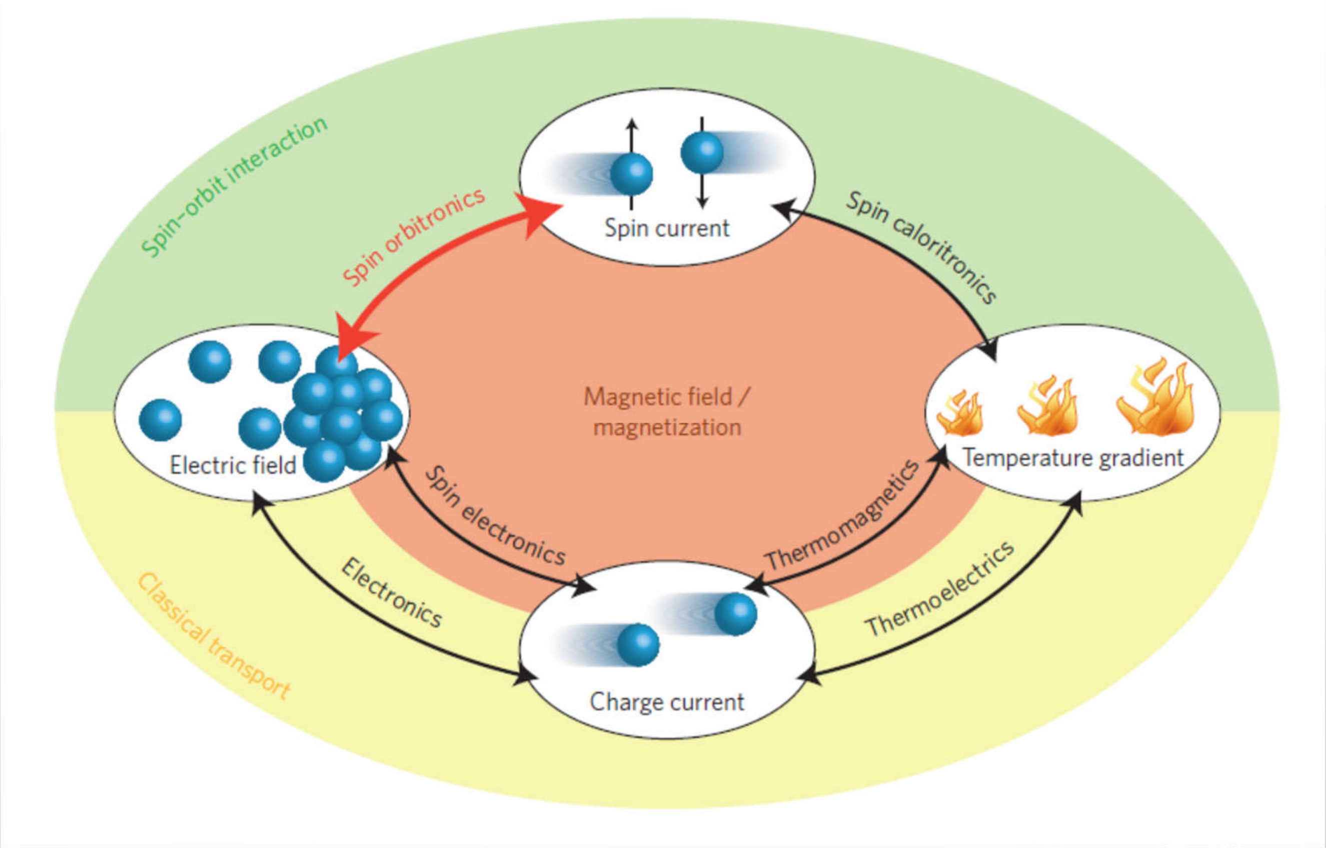
Phys. Rev. Lett. 107, 027205 (2011)



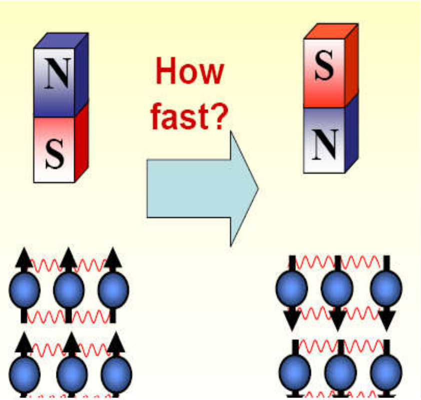
PRL 110, 177202 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

FIG. 4 (color online). Evolutionary demonstration of DW motion under varying temperature gradients. In the presence of the progressively decreasing temperature gradient, one clearly sees that the overall DW displacements decrease and the time intervals spent in traveling increase. These images together yield the decreasing average DW velocity. Here the corresponding temperature gradients for each measurement are (a) $\nabla T = 18.5$, (b) $\nabla T = 15$, (c) $\nabla T = 11.5$, (d) $\nabla T = 8.5$, and (e) $\nabla T = 5$ K/mm.

NEW TYPES OF DYNAMICS



"SPIN-FLIP" AS A FUNDAMENTAL PROBLEM



Applied physics

Speed limit ahead

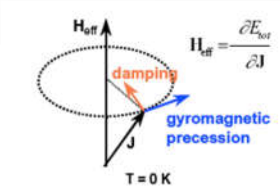
C. H. Back and D. Pescia

Are there any limits to what science and technology can achieve? When it comes to recording data in magnetic media, the answer is yes: there is a natural limit to the speed at which data can be encoded.

Via field pulses:

The ultimate speed of magnetic switching in granular recording media

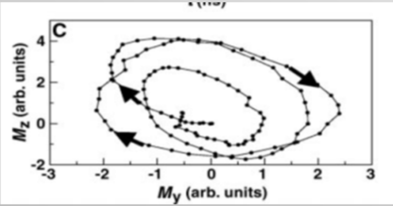
I. Tudosa[1], C. Stamm[1], A. B. Kashuba[2], F. King[3], H. C. Siegmann[1], J. Stöhr[1], G. Ju[4], B. Lu[4] & D. Weller[4]



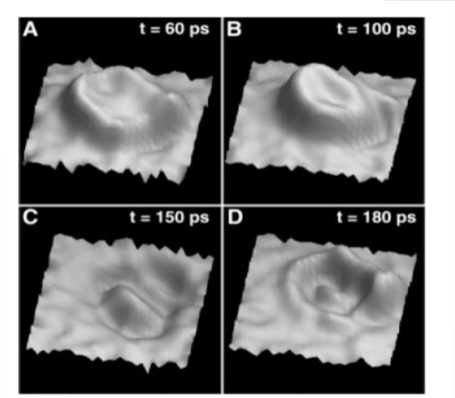
Imaging Precessional Motion of the Magnetization Vector

Y. Acremann,[1] C. H. Back,[1*] M. Buess,[1] O. Portmann,[1] A. Vaterlaus,[1] D. Pescia,[1] H. Melchior[2]

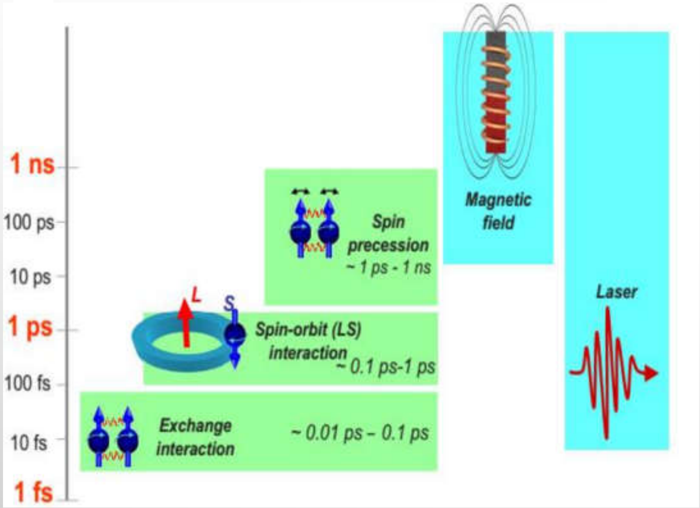
2000



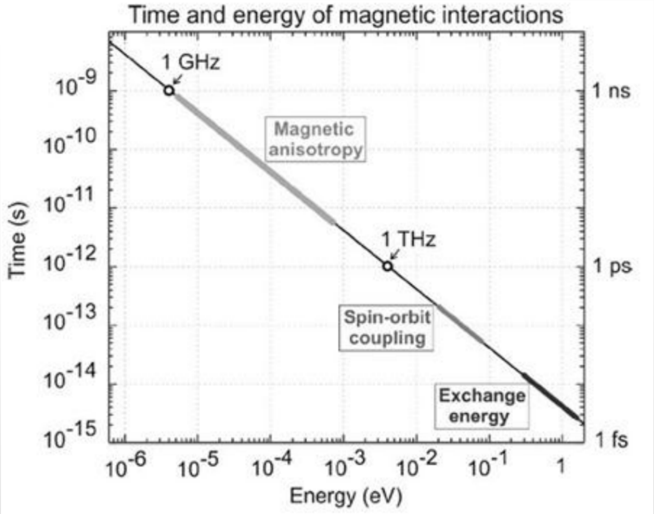
The precessional switching is limited to 100ps



RELEVANT TIME SCALE OF INTERACTIONS



Kirilyuk *et al* Rev. Mod. Phys. **82,** 2731 (2010)



Stöhr *et al* Magnetism Springer-Verlag. (2006)

Laser pulse duration (τ_p)

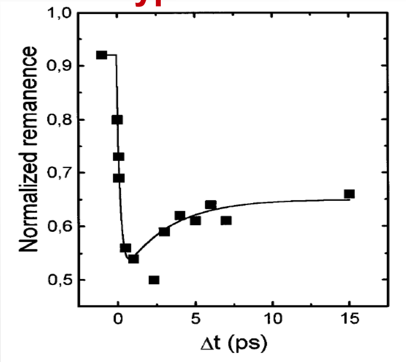
$$\Delta t \Delta E \geq \hbar/2$$

Corresponding energy

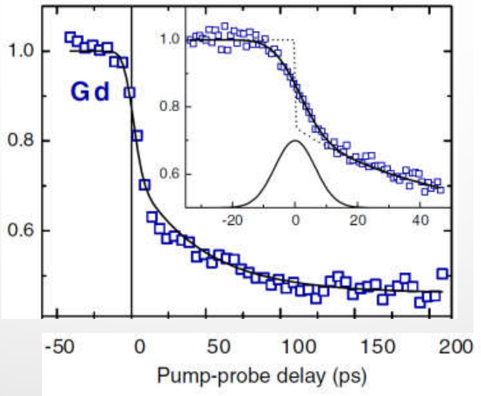
$$50\ fs \longrightarrow E \approx 10^{-21} J \approx 6meV$$

FEMTOSECOND DYNAMICS

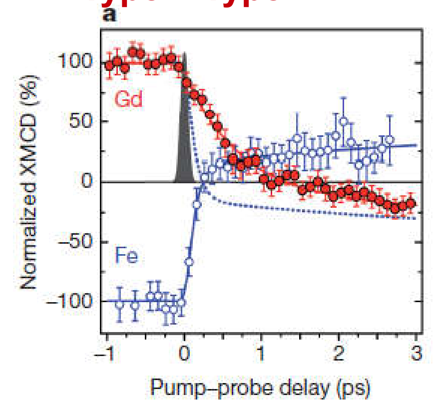
Nickel
Type I



Gadolinium
Type II



GdCoFe alloys
Type I+Type II



Nickel: Magnetisation breaks down in sub-ps time scale and recovers in ps.

Beaurepaire, Merle, Daunois, Bigot, Phys. Rev. Lett. **76**, 4250 (1996)

Gadolinium: Magnetisation decay in two 10/100ps timescales .

Wietstruk *et al.* Phys. Rev. Lett. **106**, 127401 (2011)

GdCoFe alloys: All-optical magnetisation switching in GdCoFe alloys.

(recently TbCo, TbFe)

Kimel *et al*. Phys. Rev. Lett. **99,** 047601 (2007), Nature **435,** 655 (2005)

TWO TYPES OF AOS MECHANISMS

First mechanism

(HD-AOS)

Helicity dependent all optical switching

- Helicity dependent
- Typically requires multiple laser shots
- Found in several materials FePt
- CoPt multilayers, ferrimagnets

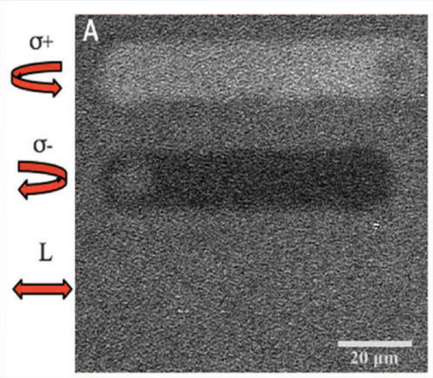
Second mechanism

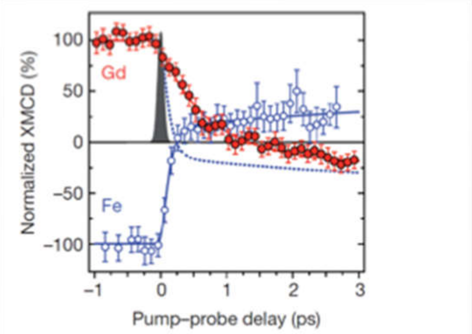
(TIMS)

Thermally induced magnetisation switching

- Helicity independent
- Only requires one laser shot
- Found only in GdFeCo (Other ferrimagnets?)

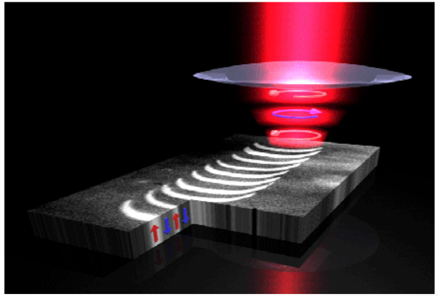
El Hadri *et al*, Phys. Rev. B , 94, 064412 (2016)



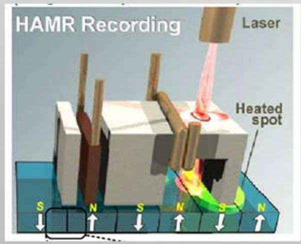


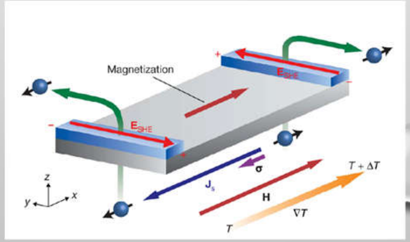
Radu *et al*., Nature, 472, 205-208 (2011).

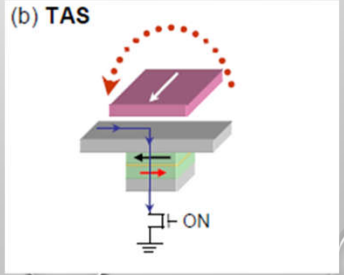
ALL OPTICAL DYNAMICS SWITCHING (AOS)



1. It is possible to reverse the magnetisation (write a bit) using only laser pulses.
   (No need for writing head).
2. The time needed to switch the magnetisation is few picoseconds.
3. Energy saving
4. Possibility of all-optical MRAMs







ATTOSECOND DYNAMICS?

LETTER

https://doi.org/10.1038/s41586-019-1333-x

Light-wave dynamic control of magnetism

Florian Siegrist[1,2], Julia A. Gessner[1,2], Marcus Ossiander[1], Christian Denker[3], Yi-Ping Chang[1], Malte C. Schröder[1], Alexander Guggenmos[1,2], Yang Cui[2], Jakob Walowski[3], Ulrike Martens[3], J. K. Dewhurst[4], Ulf Kleineberg[1,2], Markus Münzenberg[3], Sangeeta Sharma[5] & Martin Schultze[1,6]*

Initial non-dissipative processes

Optically-induced spin and orbital momentum transfer due to charge reallocation leads to the decrease of magnetic moment