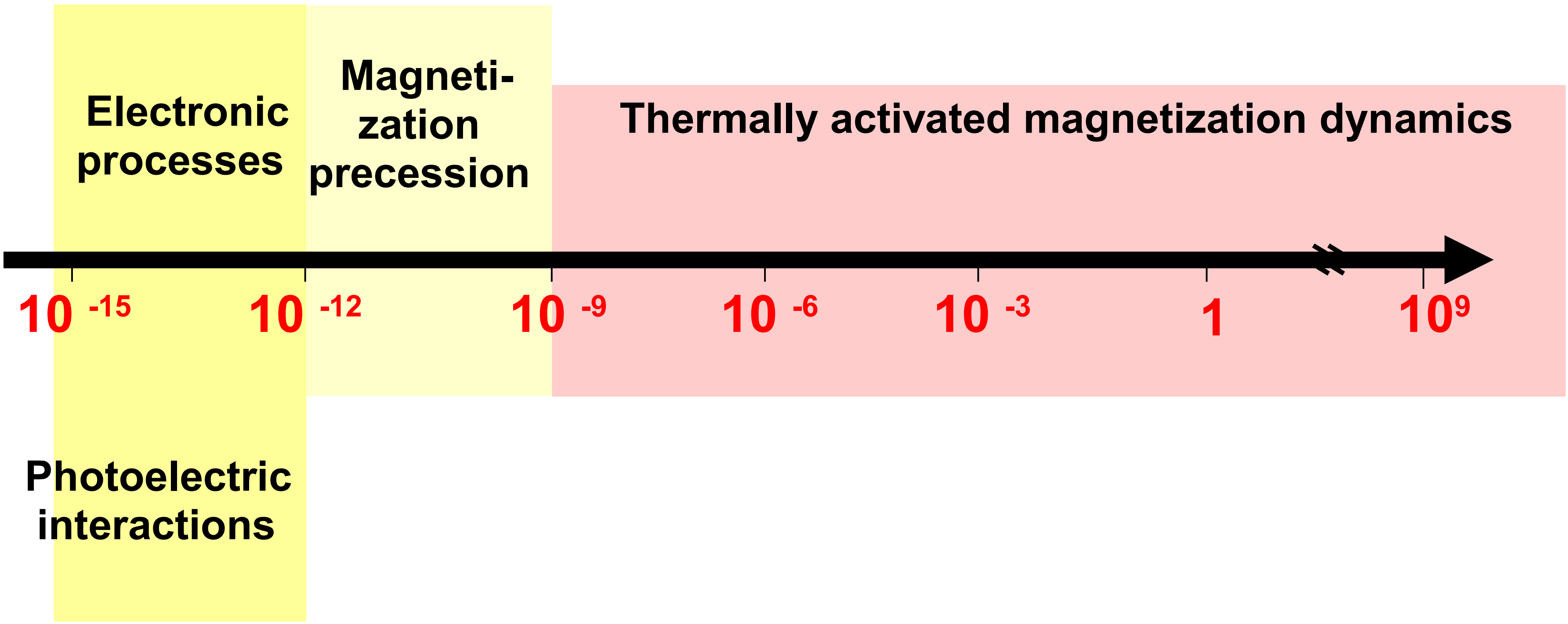
Time scales in magnetism

Jan Vogel
Institut Néel, CNRS and Université Joseph Fourier
Grenoble, France
http://neel.cnrs.fr

Overview timescales



Thermally activated magnetization dynamics

Different time-related parameters or derivated parameters are used :

Frequency = time $^{-1}$ *1 nanosecond ↔ 1 Gigahertz*

Thermally activated magnetization dynamics

Different time-related parameters or derivated parameters are used :

Frequency = time $^{-1}$ *1 nanosecond ↔ 1 Gigahertz*

*Energy = h * frequency* *1GHz ↔ 6.63 x 10* $^{-25}$ *J = 4.14 μeV*

h = 6.63 x 10 $^{-34}$ *J.s = 4.136 x 10* $^{-15}$ *eV.s*

Thermally activated magnetization dynamics

Different time-related parameters or derivated parameters are used :

Frequency = time $^{-1}$ *1 nanosecond ↔ 1 Gigahertz*

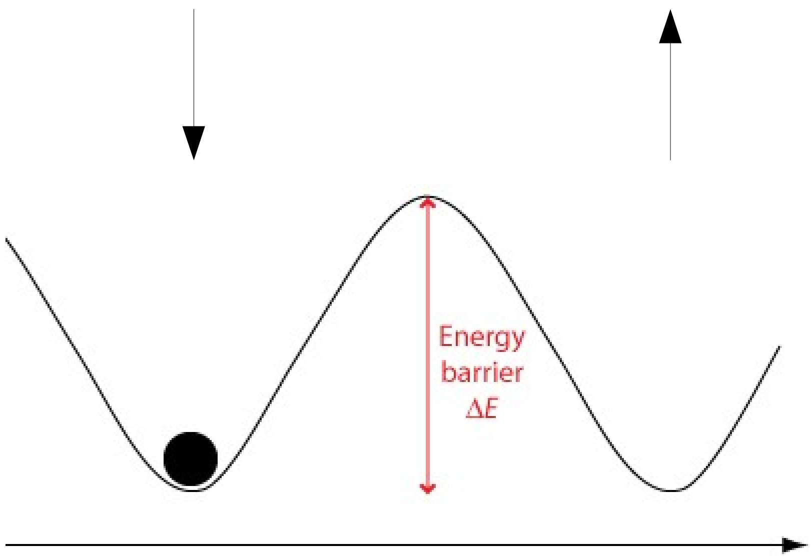
*Energy = h * frequency* *1GHz ↔ 6.63 x 10 $^{-25}$ J = 4.14 μeV*

h = 6.63 x 10 $^{-34}$ J.s = 4.136 x 10 $^{-15}$ eV.s

*Energy = k * temperature* *1 meV ↔ 11.6 K*

k = 1.38 x 10 $^{-23}$ J.K $^{-1}$ = 8.617 x 10 $^{-5}$ eV.K $^{-1}$

Thermally activated magnetization dynamics



Small magnetic particle, with uniaxial magnetic anisotropy constant K
(two stable orientations)

Stoner-Wohlfarth model :
macrospin, energy barrier $\Delta E = KV$ (V : volume of particle)

Thermally activated magnetization dynamics

Average time between two magnetization flips (Néel-Arrhenius law) :

$$\tau_N = \tau_0 \, e^{KV/kT}$$

Example : Co particle, $K = 45 \times 10^4$ J/m^3
Room temperature 293 K : $kT = 4 \times 10^{-21}$ J
$\tau_0 \approx 10^{-9}$ s

0.1 x 0.1 x 0.1 μm^3 : $\boldsymbol{\tau_N \approx \infty}$

Thermally activated magnetization dynamics

Average time between two magnetization flips (Néel-Arrhenius law) :

$$\tau_N = \tau_0 \, e^{KV/kT}$$

Example : Co particle, K = 45 x 10^4 J/m^3
Room temperature 293 K : kT = 4 x 10^{-21} J
$\tau_0 \approx 10^{-9}$ s

0.1 x 0.1 x 0.1 μm^3 : $\tau_N \approx \infty$

10 x 10 x 10 nm^3 : $\tau_N \approx 7 \times 10^{39}$ s (1 year ≈ 3 x 10^7 s)

Thermally activated magnetization dynamics

Average time between two magnetization flips (Néel-Arrhenius law) :

$$\tau_N = \tau_0 \, e^{KV/kT}$$

Example : Co particle, $K = 45 \times 10^4$ J/m^3
Room temperature 293 K : $kT = 4 \times 10^{-21}$ J
$\tau_0 \approx 10^{-9}$ s

0.1 x 0.1 x 0.1 μm^3 : $\tau_N \approx \infty$

10 x 10 x 10 nm^3 : $\tau_N \approx 7 \times 10^{39}$ s (1 year $\approx 3 \times 10^7$ s)

8 x 8 x 8 nm^3 : $\tau_N \approx 1 \times 10^{16}$ s

Thermally activated magnetization dynamics

Average time between two magnetization flips (Néel-Arrhenius law) :

$$\tau_N = \tau_0 \, e^{KV/kT}$$

Example : Co particle, K = 45 x 10^4 J/m^3
Room temperature 293 K : kT = 4 x 10^{-21} J
$\tau_0 \approx 10^{-9}$ s

0.1 x 0.1 x 0.1 μm^3 : $\tau_N \approx \infty$

10 x 10 x 10 nm^3 : $\tau_N \approx 7 \times 10^{39}$ s (1 year ≈ 3 x 10^7 s)

8 x 8 x 8 nm^3 : $\tau_N \approx 1 \times 10^{16}$ s

6 x 6 x 6 nm^3 : $\tau_N \approx 870$ s

Thermally activated magnetization dynamics

Average time between two magnetization flips (Néel-Arrhenius law) :

$$\tau_N = \tau_0 \, e^{KV/kT}$$

Example : Co particle, K = 45 x 10^4 J/m^3
Room temperature 293 K : kT = 4 x 10^{-21} J
$\tau_0 \approx 10^{-9}$ s

0.1 x 0.1 x 0.1 µm^3 : $\tau_N \approx \infty$

10 x 10 x 10 nm^3 : $\tau_N \approx 7 \times 10^{39}$ s (1 year $\approx 3 \times 10^7$ s)

8 x 8 x 8 nm^3 : $\tau_N \approx 1 \times 10^{16}$ s

6 x 6 x 6 nm^3 : $\tau_N \approx 870$ s

4 x 4 x 4 nm^3 : $\tau_N \approx 9.6$ µs

Thermally activated magnetization dynamics

$2 \times 2 \times 2\ nm^3 : \tau_N \approx 2.4$ ns

Same particle, decreasing temperature :

T = 150 K : $\tau_N \approx 5.7$ ns

T = 100 K : $\tau_N \approx 13.6$ ns

T = 50 K : $\tau_N \approx 184$ ns

Thermally activated magnetization dynamics

$2 \times 2 \times 2\ nm^3 : \tau_N \approx 2.4$ ns

Same particle, decreasing temperature :

$T = 150$ K : $\tau_N \approx 5.7$ ns

$T = 100$ K : $\tau_N \approx 13.6$ ns

$T = 50$ K : $\tau_N \approx 184$ ns

$T = 20$ K : $\tau_N \approx 462$ µs

Thermally activated magnetization dynamics

$2 \times 2 \times 2 \text{ nm}^3 : \tau_N \approx 2.4 \text{ ns}$

Same particle, decreasing temperature :

$T = 150 \text{ K} : \tau_N \approx 5.7 \text{ ns}$

$T = 100 \text{ K} : \tau_N \approx 13.6 \text{ ns}$

$T = 50 \text{ K} : \tau_N \approx 184 \text{ ns}$

$T = 20 \text{ K} : \tau_N \approx 462\ \mu\text{s}$

$T = 10 \text{ K} : \tau_N \approx 214 \text{ s}$

Thermally activated magnetization dynamics

$2 \times 2 \times 2\ \mathrm{nm}^3 : \tau_N \approx 2.4$ ns

Same particle, decreasing temperature :

$T = 150$ K : $\tau_N \approx 5.7$ ns

$T = 100$ K : $\tau_N \approx 13.6$ ns

$T = 50$ K : $\tau_N \approx 184$ ns

$T = 20$ K : $\tau_N \approx 462$ μs

$T = 10$ K : $\tau_N \approx 214$ s

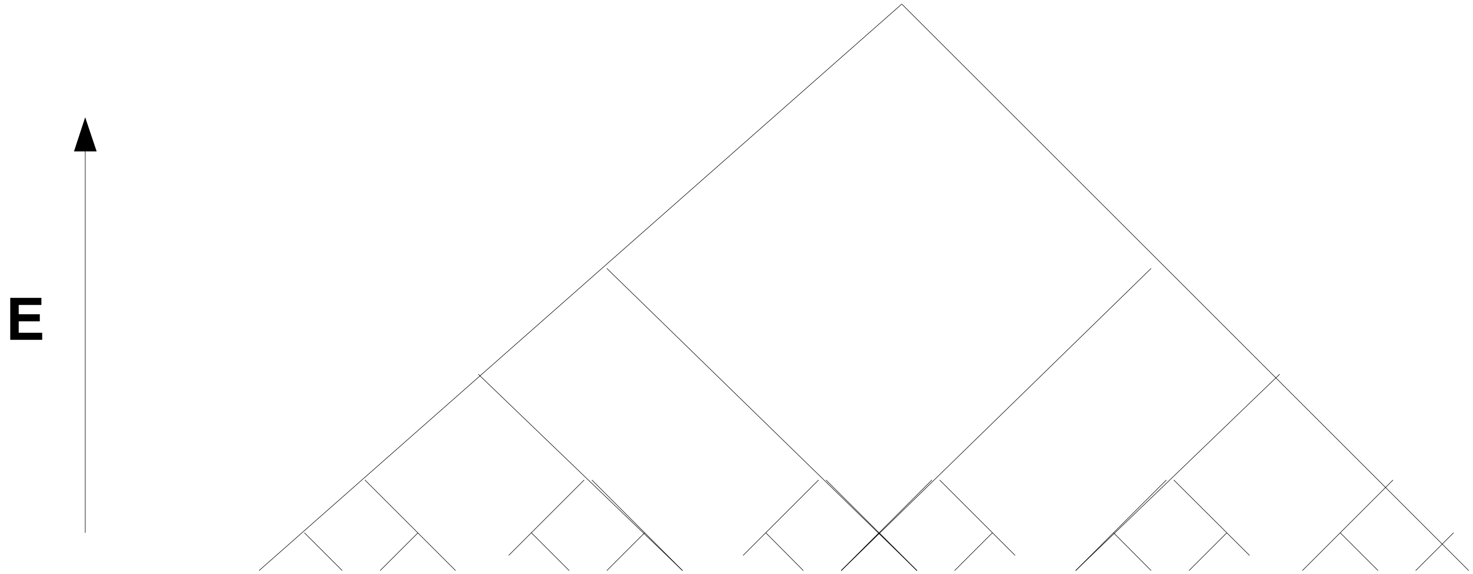
$T = 5$ K : $\tau_N \approx 4.6 \times 10^{13}$ s

Particle is 'superparamagnetic' above a certain 'blocking temperature' that depends on the measuring time

Thermally activated magnetization dynamics

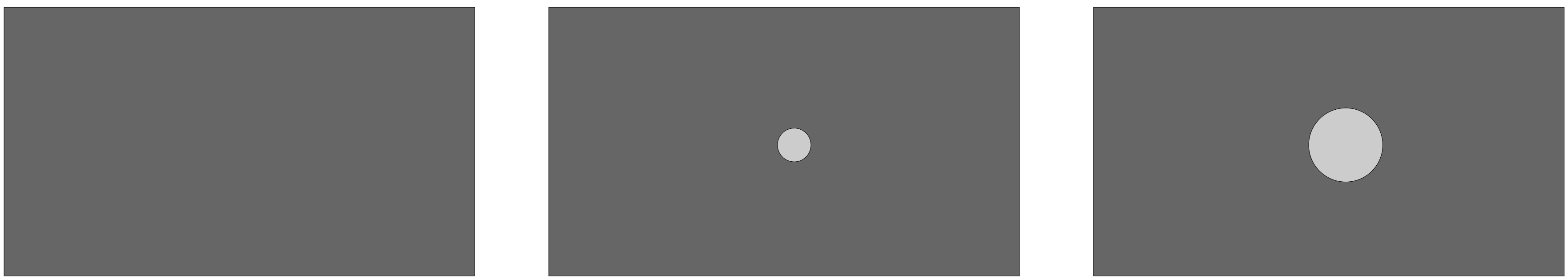
Slow dynamics : Spin glasses

Materials with frustrated ferro/antiferromagnetic interactions, short and long range order : many different states with equivalent energies, separated by energy barriers. Relaxation over long times scales (days or more)



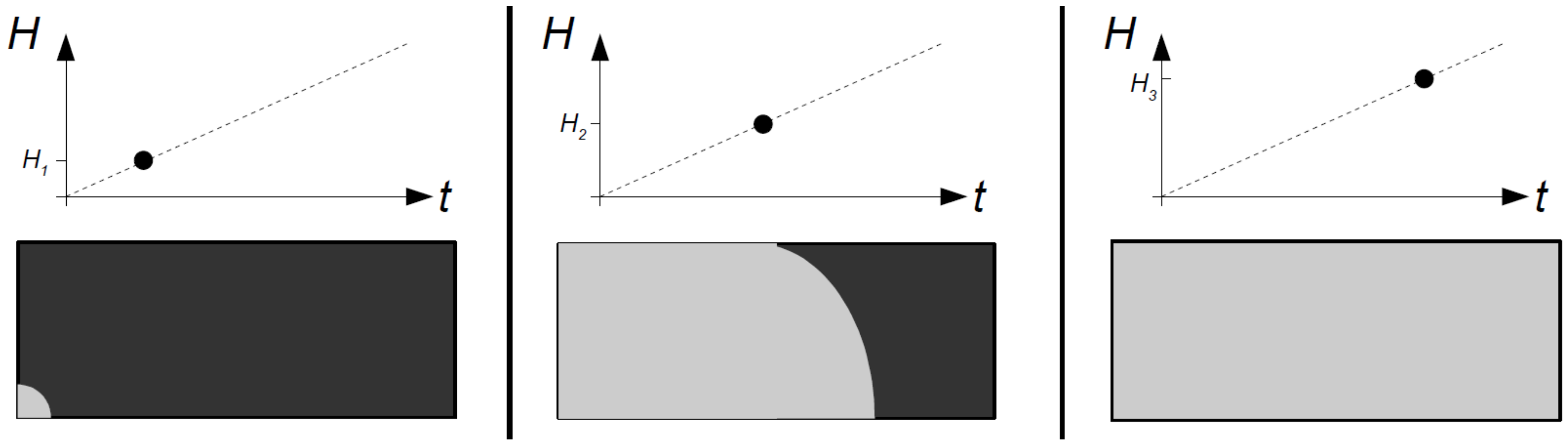
Thermally activated magnetization dynamics

Domain nucleation + domain wall propagation

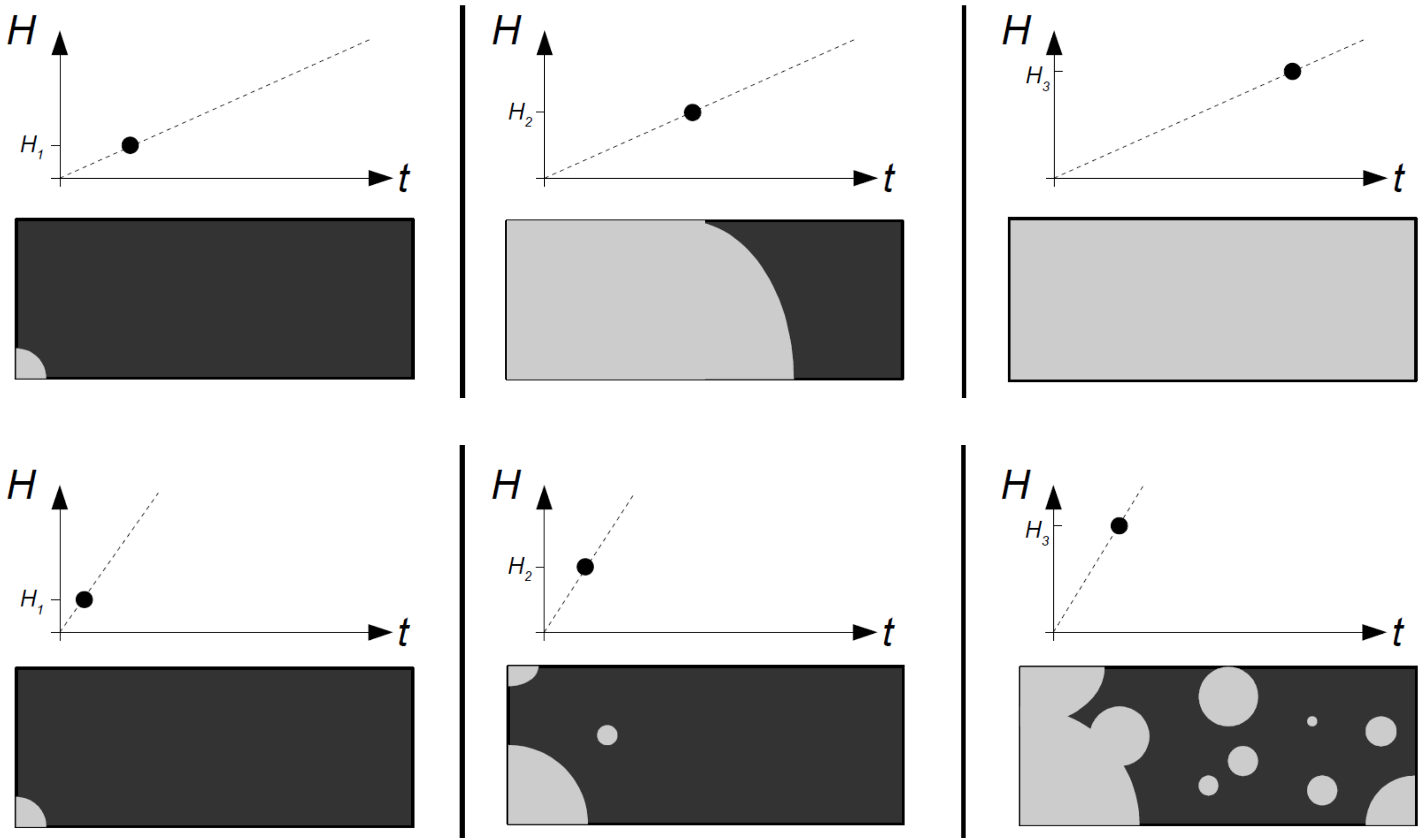


Thermally assisted reversal of nucleation volume (>1ns)
Propagation of domain walls over pinning barriers, maximum speeds ~1000 m/s

Thermally activated magnetization dynamics

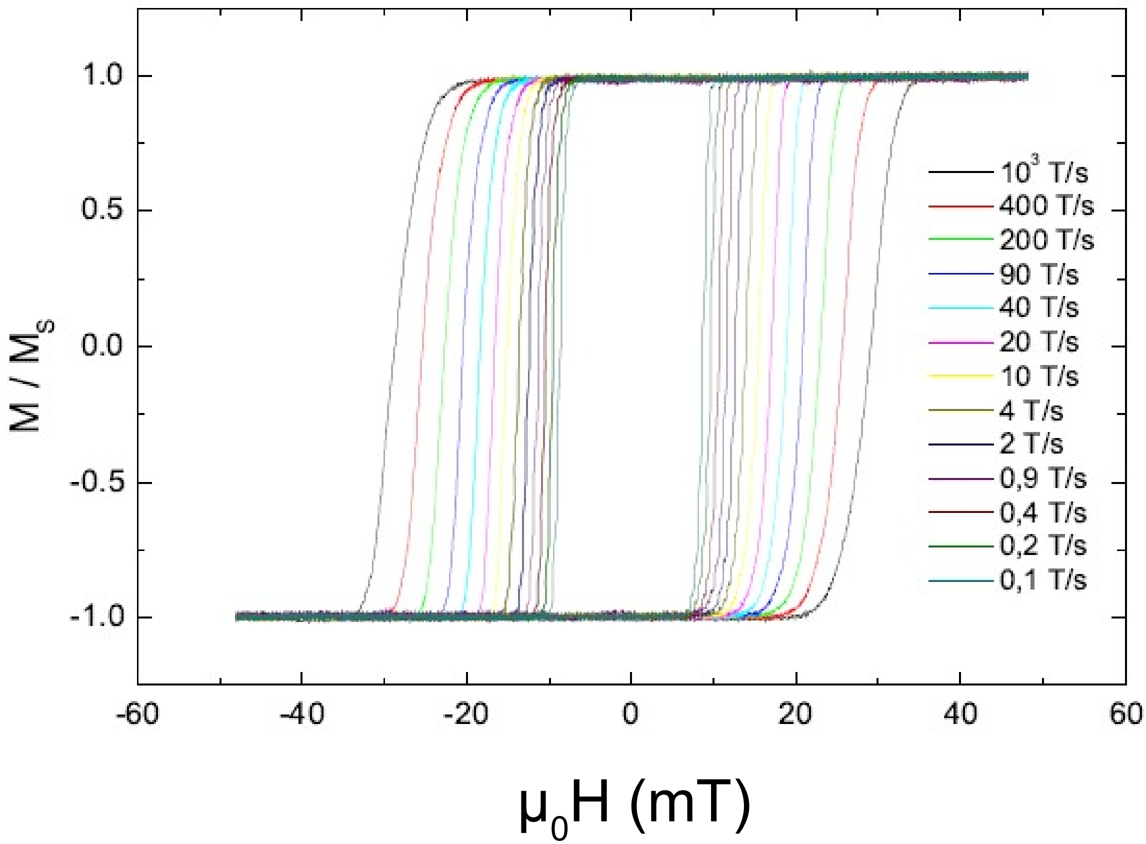


Thermally activated magnetization dynamics



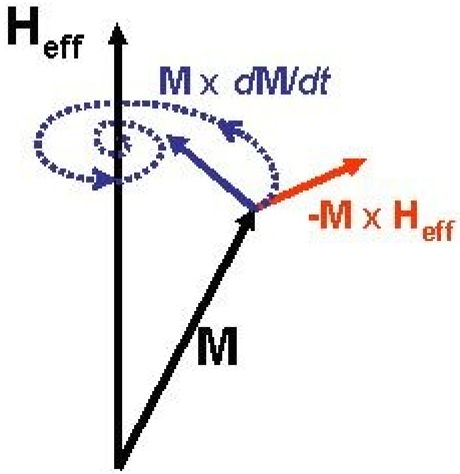
Thermally activated magnetization dynamics

Pt/Co multilayer



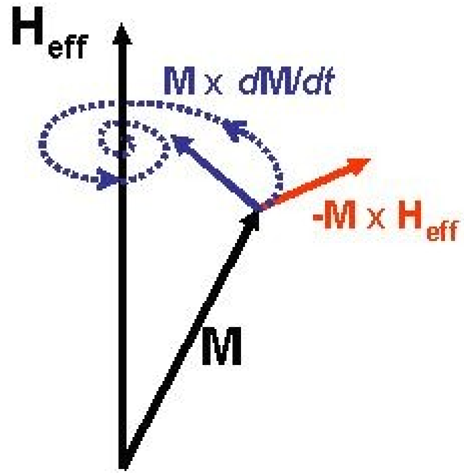
Reversal mode and coercivity are dynamical properties of a sample (depend on field sweep rate, temperature)

Beyond thermal activation : Landau-Lifshitz-Gilbert equation : precession and damping



$$d\mathbf{M}/dt = \gamma \mathbf{M} \times \mathbf{H}_{\mathbf{eff}} + \alpha / M_S (\mathbf{M} \times d\mathbf{M}/dt)$$

Beyond thermal activation : Landau-Lifshitz-Gilbert equation : precession and damping



$d\mathbf{M}/dt = \gamma \mathbf{M} \times \mathbf{H}_{eff} + \alpha/M_s\,(\mathbf{M} \times d\mathbf{M}/dt)$

Larmor precession frequency : $f = \gamma B/2\pi$

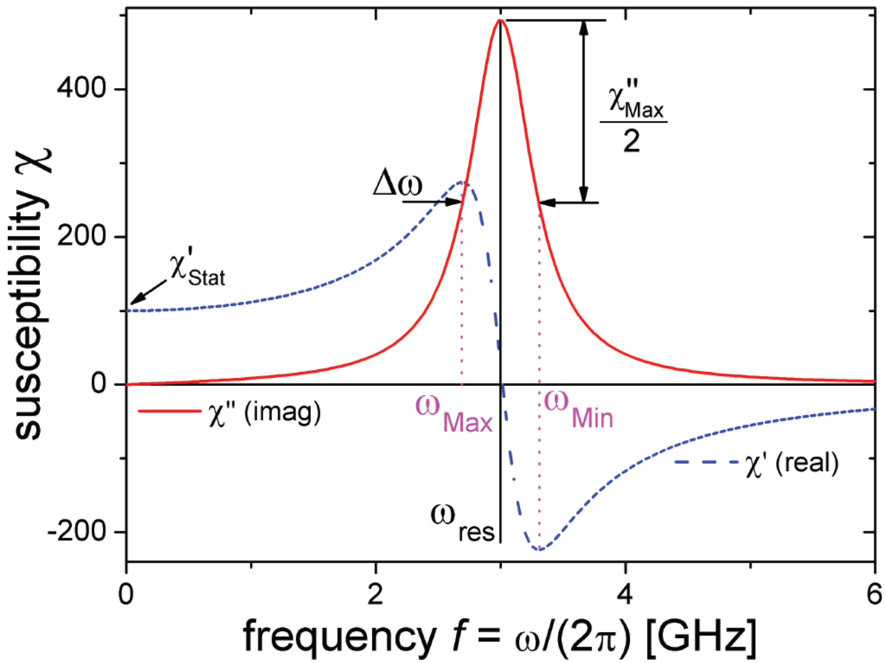
$\gamma = 176$ GHz/T (for g=2)

f (1T) = 28 GHz $\tau = 1/f = 36$ ps

γ : gyromagnetic ratio g : Landé factor

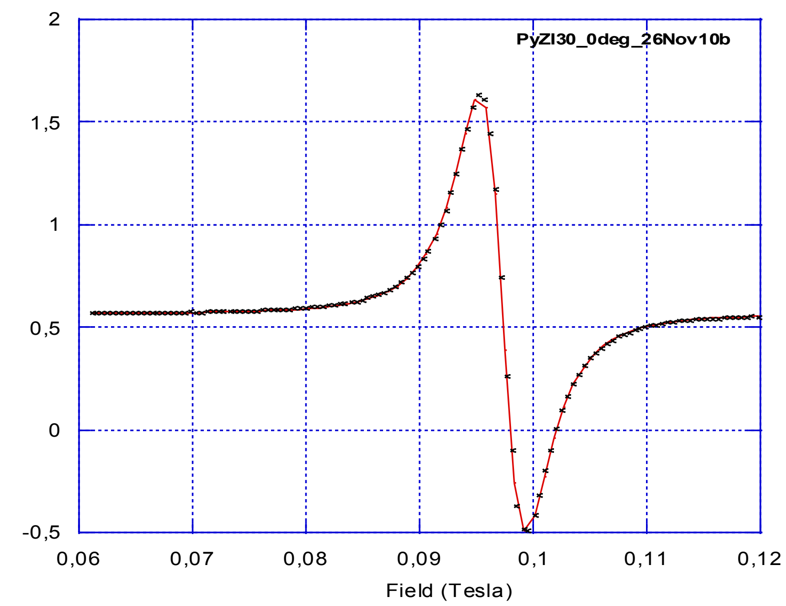
Precession and damping : ferromagnetic resonance

Calculation for
$\mu_0 M_S = 1T$; $\mu_0 H_{eff} = 0.01T$



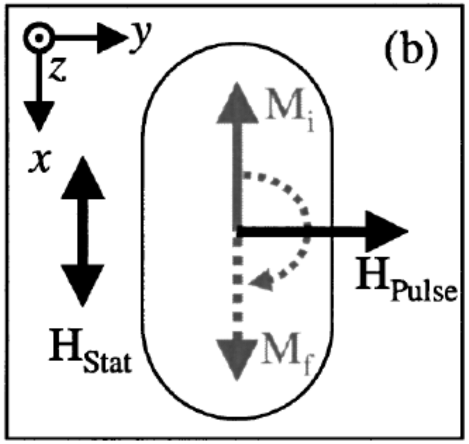
Ph.D. thesis C. Bilzer

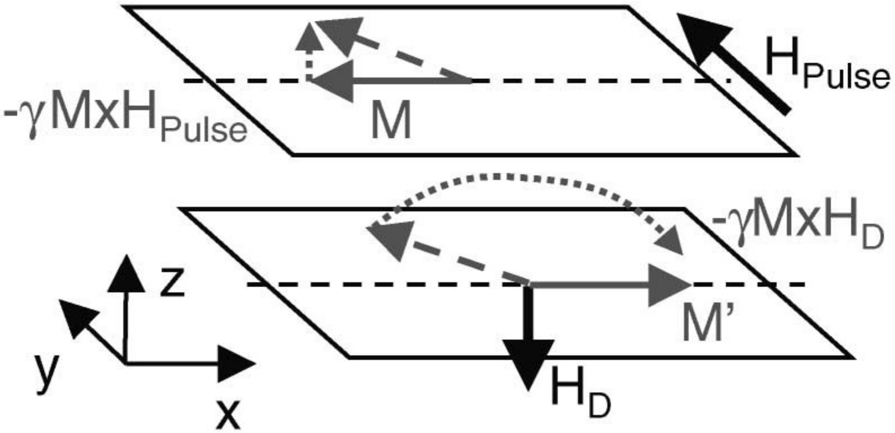
Ferromagnetic resonance (FMR) of
NiFe @ f = 9.77 Ghz

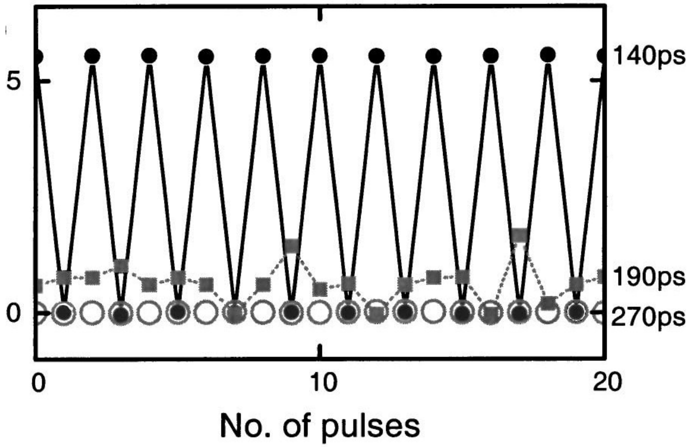


$\mu_0 \Delta H = 2(\alpha/\gamma)\omega_{res}$

Beyond thermal activation : precessional switching







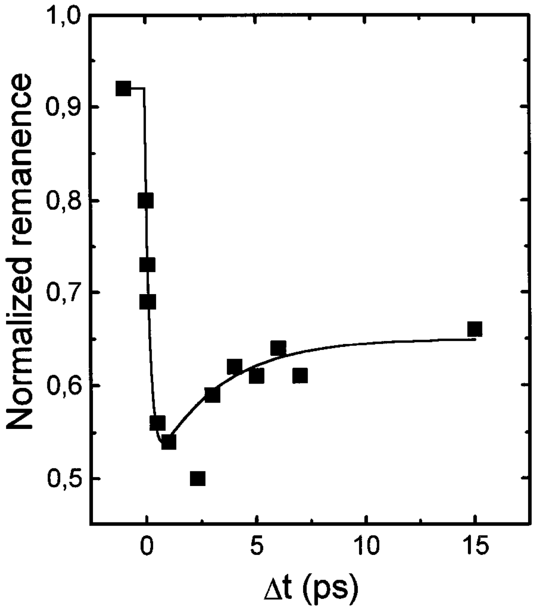
Precessional switching with **140 ps** pulses of $\mu_0 H$ = 15.5 mT pulses

$\tau = 1/f_L = 2.3$ ns ?

Switching by demagnetizing field

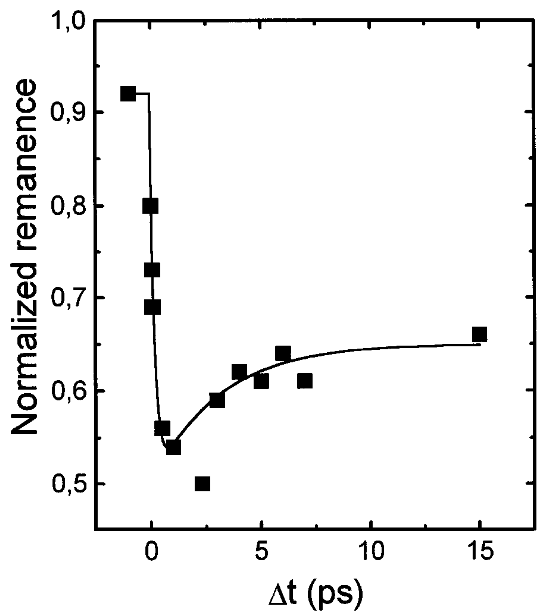
H.W. Schumacher et al., Phys. Rev. Lett. 90, 017201 (2003) ; 017204 (2003)

Ultrafast magnetization dynamics (femtomagnetism)

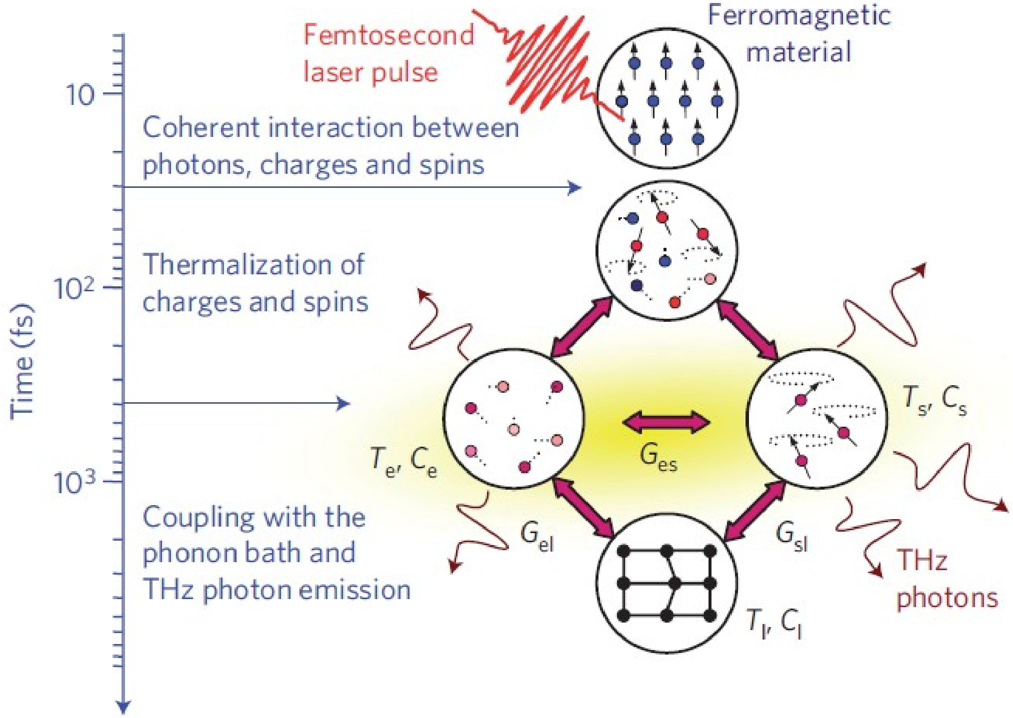


Beaurepaire et al.,
Phys. Rev. Lett. 76, 4250 (1996).

Ultrafast magnetization dynamics (femtomagnetism)

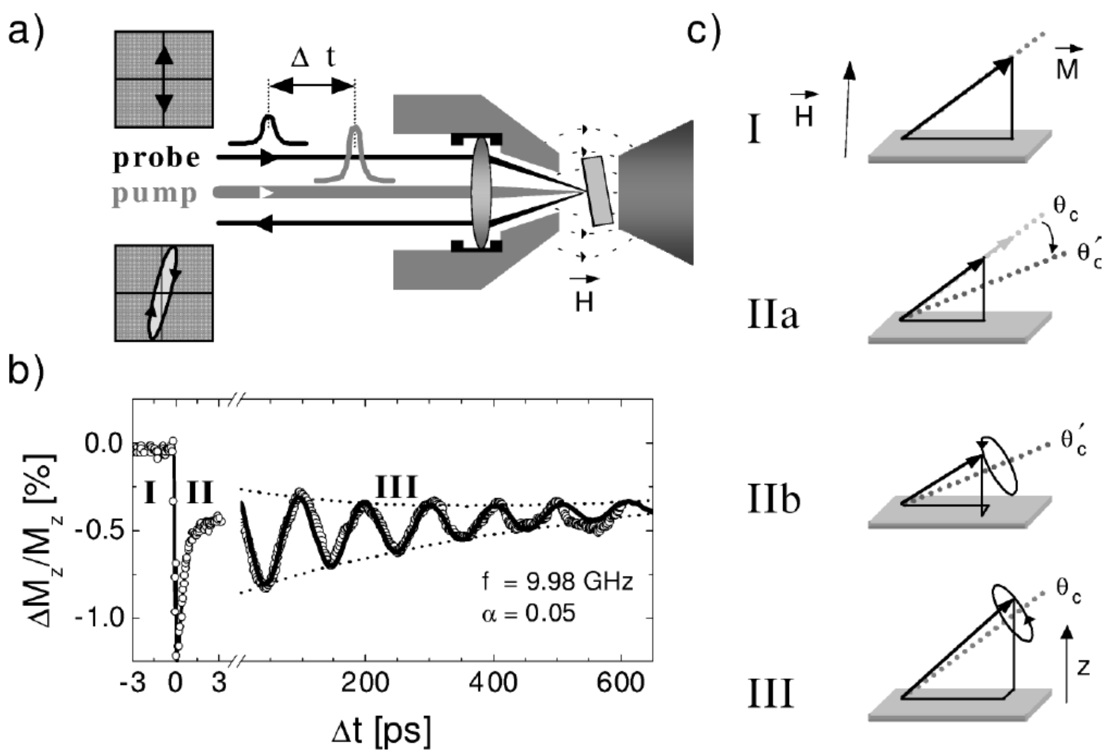


Beaurepaire et al.,
Phys. Rev. Lett. 76, 4250 (1996).



Bigot et al., Nature Phys. 5, 515 (2009)

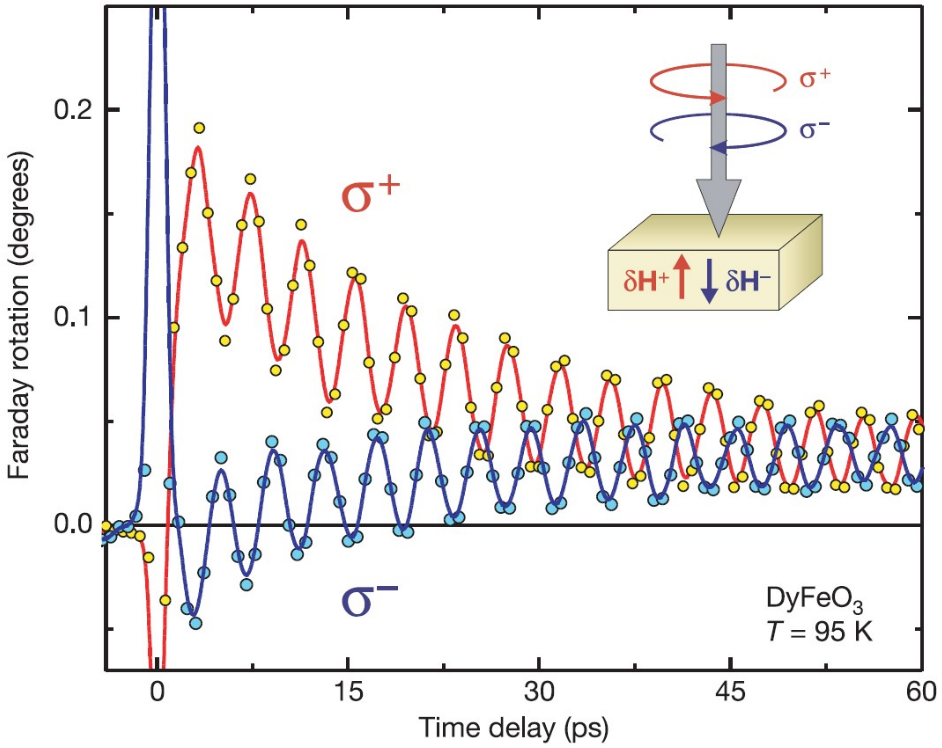
Ultrafast magnetization dynamics



I :	Initial equilibrium
II :	Fast demagnetization + thermalization, changing M and anisotropy
III :	Precession around new equilibrium

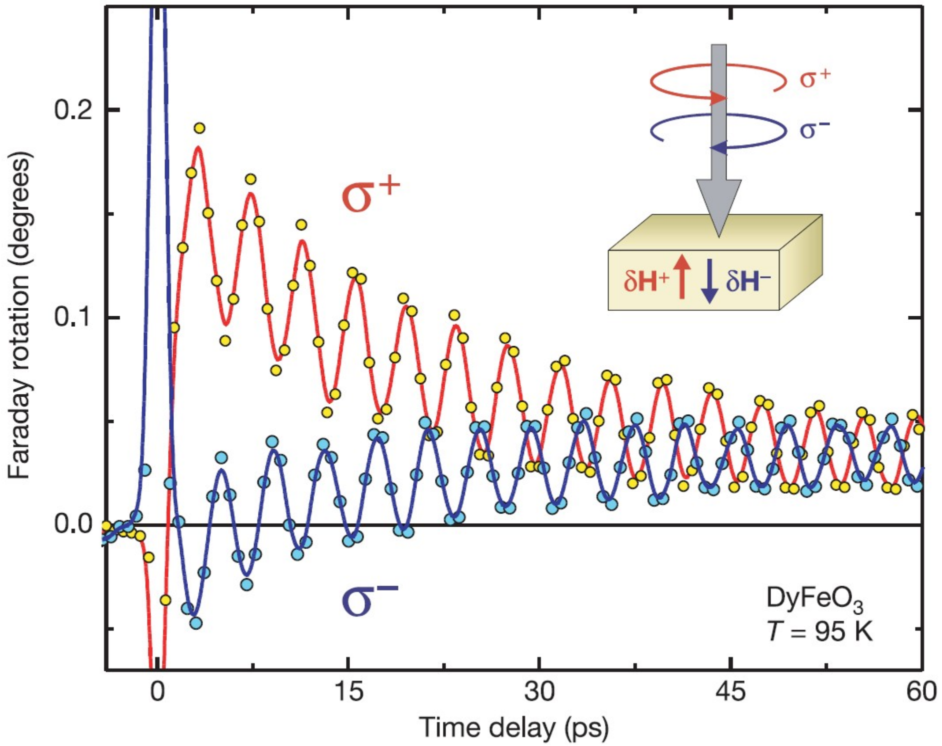
M. van Kampen et al. Phys. Rev. Lett. 88, 227201 (2002).

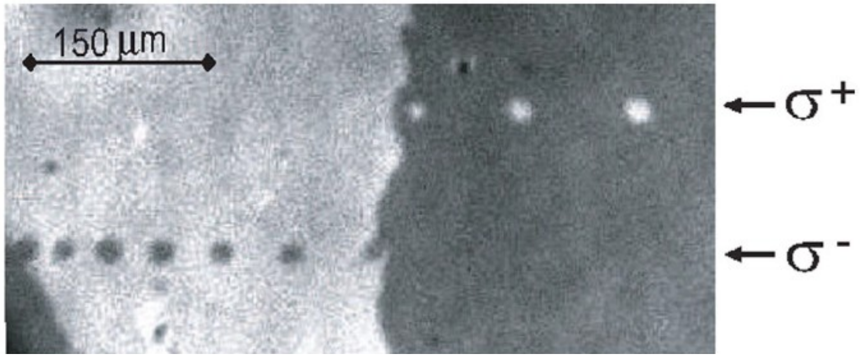
Ultrafast magnetization dynamics



A.V. Kimel et al., Nature 435, 655 (2005)

Ultrafast magnetization dynamics





Magnetization reversal with one 40fs circularly polarized laser pulse

A.V. Kimel et al., Nature 435, 655 (2005)

C.D. Stanciu, A. Kirilyuk, Th. Rasing et al., Phys. Rev. Lett. 99, 047601 (2007)

Summary time scales

10^{-15} – 10^{-12} s (femto- to picosecond)

Electronic processes : electron-photon interactions, exchange interaction, spin-orbit interaction, spin-flips, electron-phonon interactions

10^{-12} – 10^{-9} s (pico- to nanosecond)

Magnetization precession, ferromagnetic resonance, spin waves

10^{-9} s – ∞

Thermally acivated magnetization processes : relaxation, domain nucleation, domain wall propagation

Magnetization dynamics for applications

- Permanent magnets

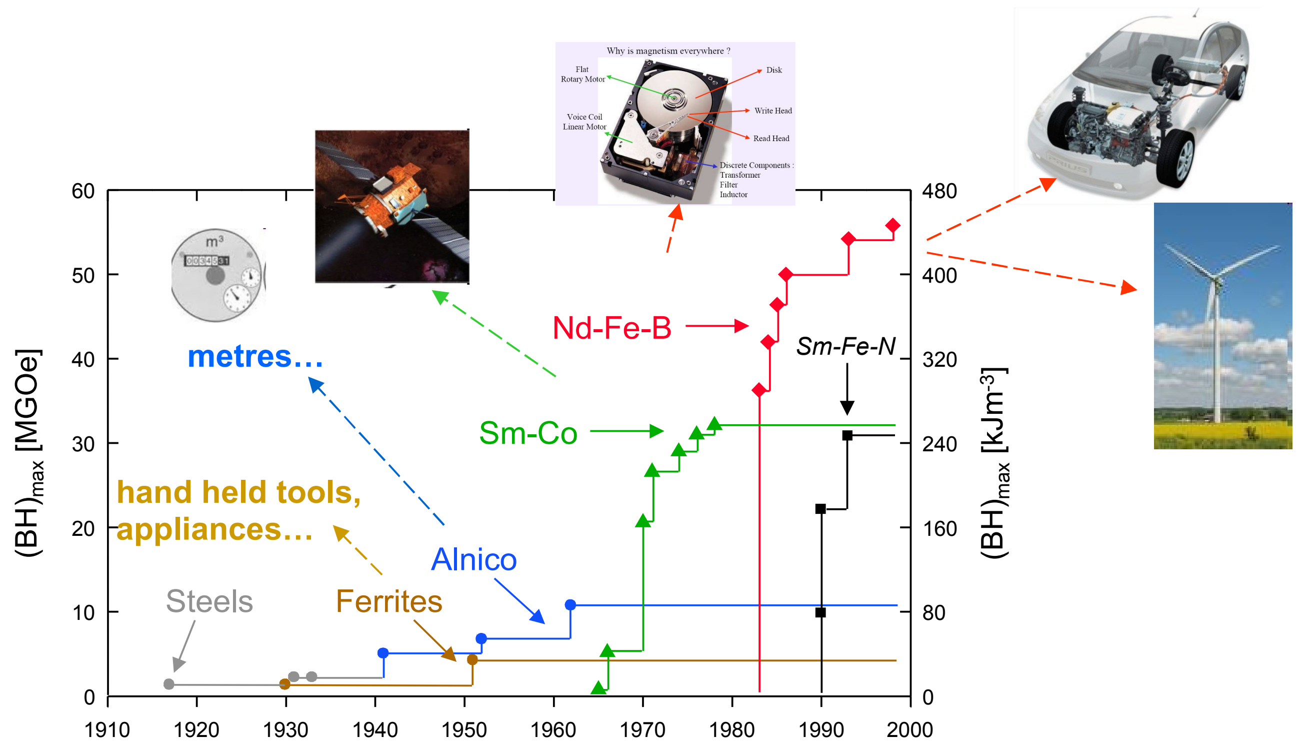
- Transformers

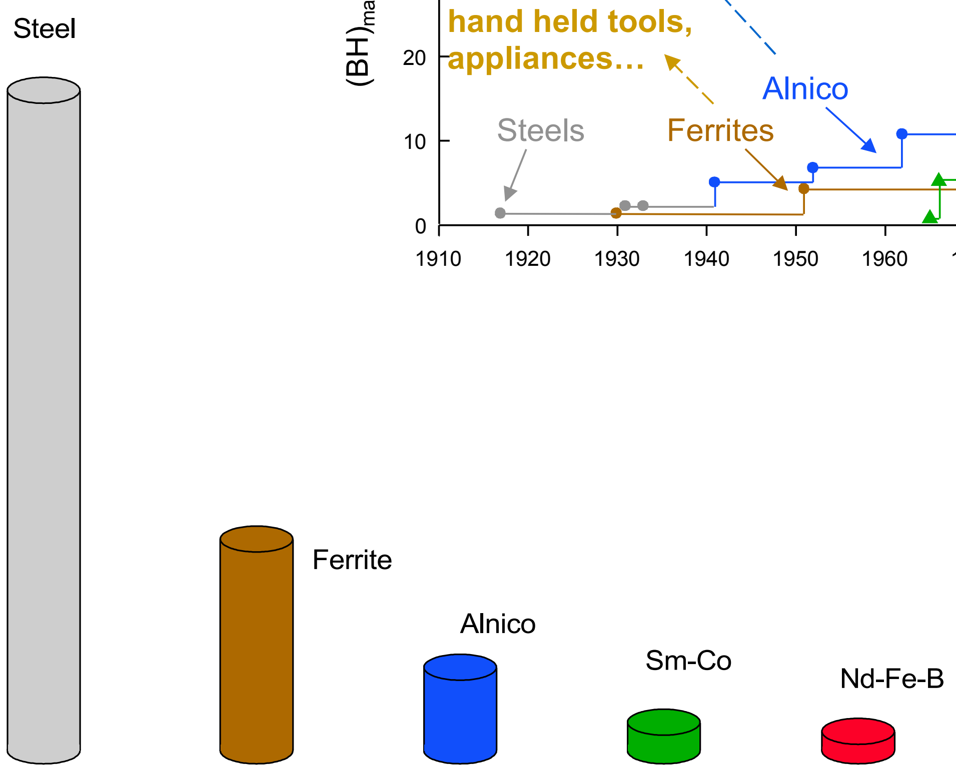
- Magnetic recording

- Magnetic Random Access Memories

- Oscillators

Applications : permanent magnets



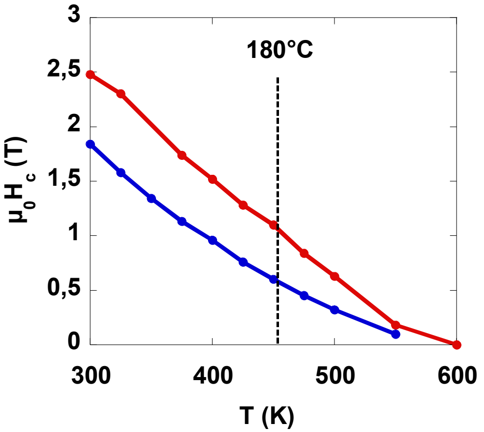


↑$(BH)_{max}$ → ↓ magnet volume

Courtesy : Nora Dempsey

Applications : permanent magnets

High performance permanent magnets need to operate at T ≤ 180°C



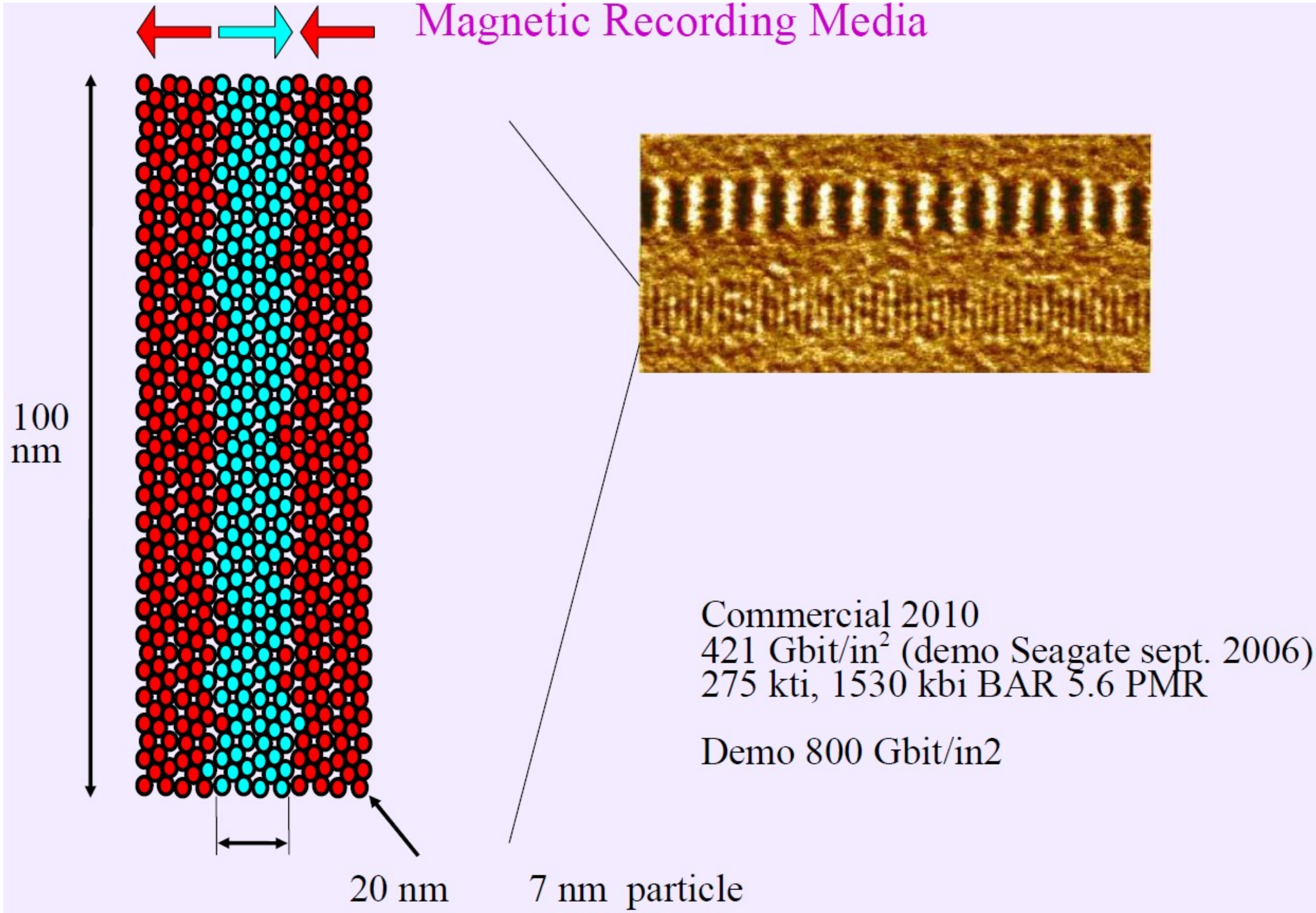
$H_C < H_A$ (anisotropy field) : improve microstructure

Better understanding of coercivity--> modelling

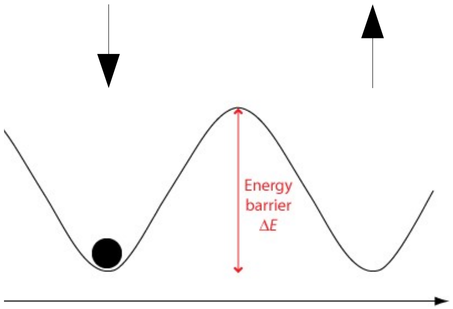
5 µm thick NdFeB films ($\mu_0 H_c$= 2.6 T) as model systems for coercivity analysis

(Institut Néel, IFW Dresden, NIMS, U. Sheffield, Toyota Motor Corporation)

Applications : magnetic recording



Applications : magnetic recording



$$\tau_N = \tau_0 \, e^{KV/kT}$$

For data storage, τ should be about 10 years, i.e. KV/kT > 60

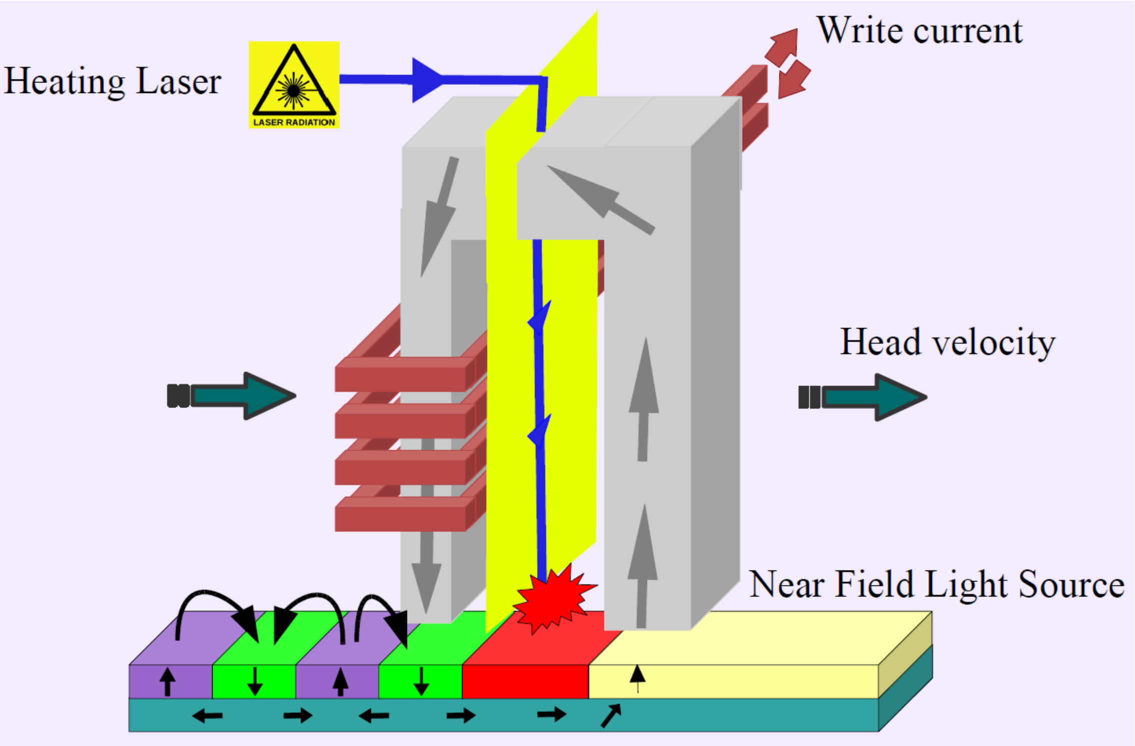
at 300 K

	K_1 (MJ/m³)	ϕ_{min} (nm)
Fe	0.05	20
Co	0.5	8
$Nd_2Fe_{14}B$	5	4
$SmCo_5$	17	2

The higher K, the higher the field needed to write a bit

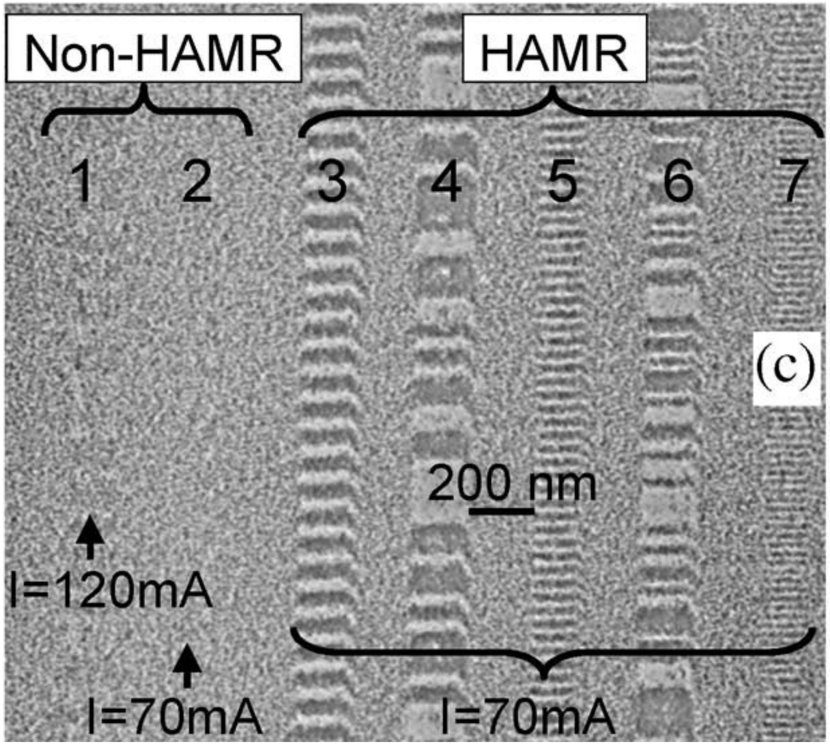
Applications : magnetic recording

Heat-assisted recording : local decrease of coercivity



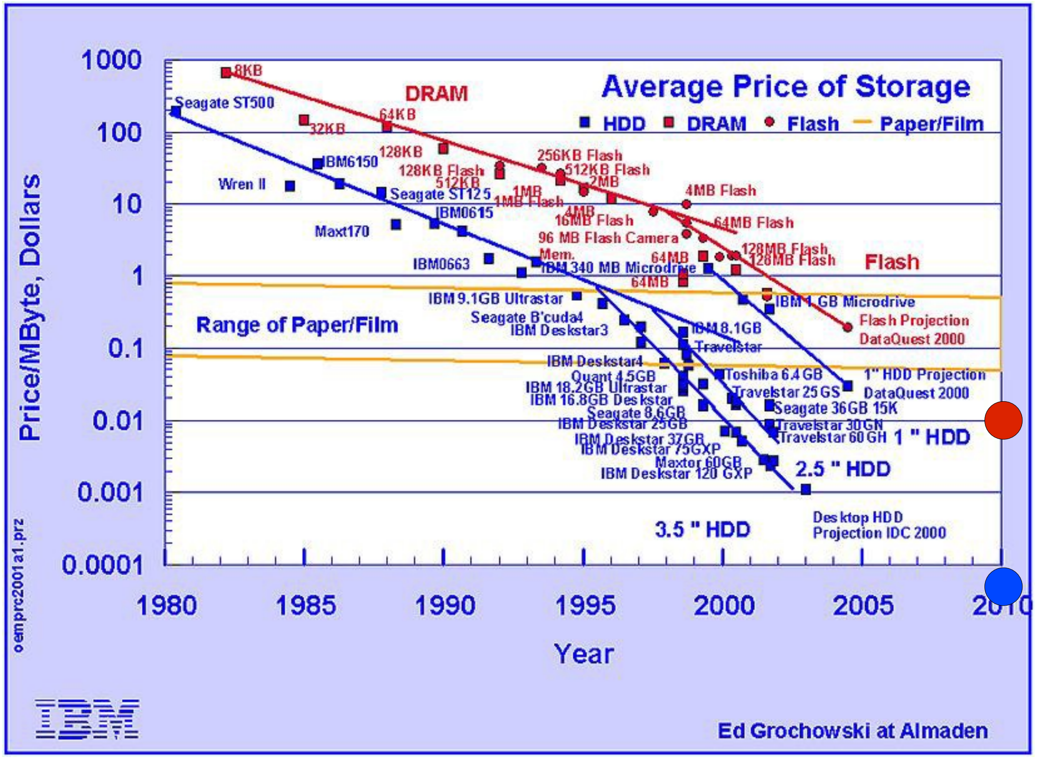
Applications : magnetic recording

Heat-assisted recording : local decrease of coercivity



Michael A. Seigler et al., IEEE TRANSACTIONS ON MAGNETICS 44, 119 (2008)
Seagate Technology

Applications : magnetic recording



Magnetic storage on hard disk drives still competitive (storage density, cost, durability, speed) with other techniques

Applications : magnetic recording

Read- and write times are below 1ns per bit

Is it possible to go faster ?

Yes : precessional switching (100ps, laser induced switching some ps)

Applications : magnetic recording

Read- and write times are below 1ns per bit

Is it possible to go faster ?

Yes : precessional switching (100ps, laser induced switching some ps)

Is it necessary to go faster ?

1 ns/bit → 8 s/Gb

Test on my computer : writing 4 Mb in 2 s → 60 ns/bit

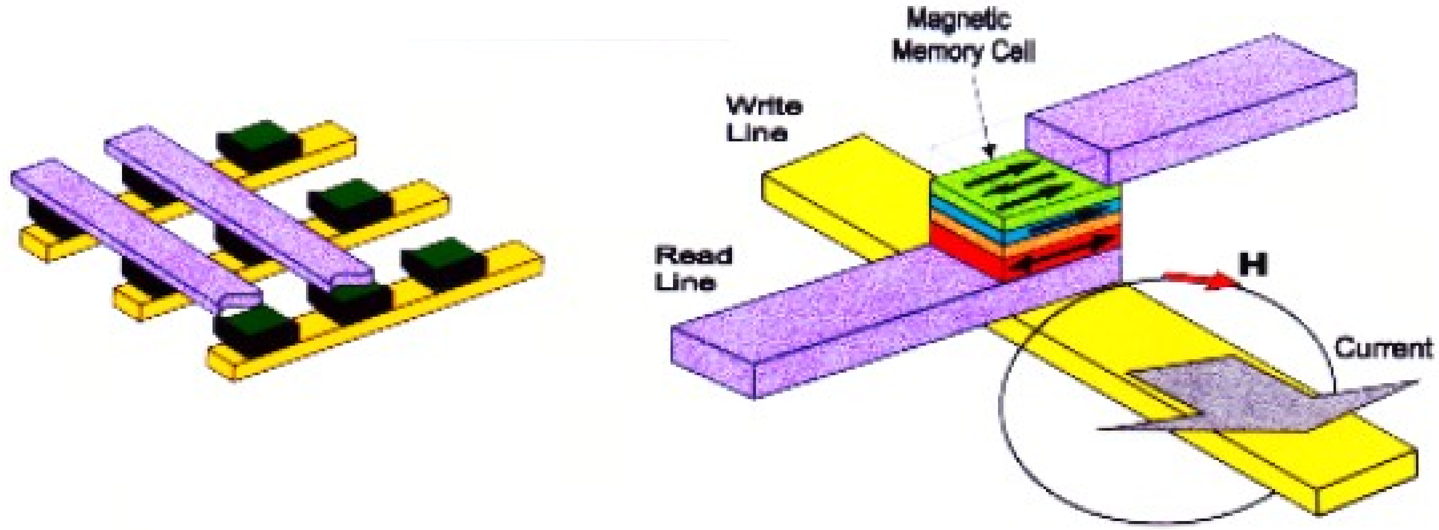
reading (opening file) much longer

Discrepancy ?

Before reading/writing a bit, you have to find it !

Bits scattered over HDD, 'seek time' ~ 3 ms, depends on rotational speed disk (~7000 rpm), etc.

Applications : magnetic random access memories



Non volatile
Fast < 50 ns read and write cycle time
infinite cyclability

Semiconductor Dynamic RAM (DRAM) : each bit stored in separate capacitor, refreshed every 64 ms (leakage currents) → volatile, energy consumption

Main problems for MRAM 'breakthrough' : cost, storage density,
compatibility with semiconductor industry

Applications : magnetic random access memories

Flash memory

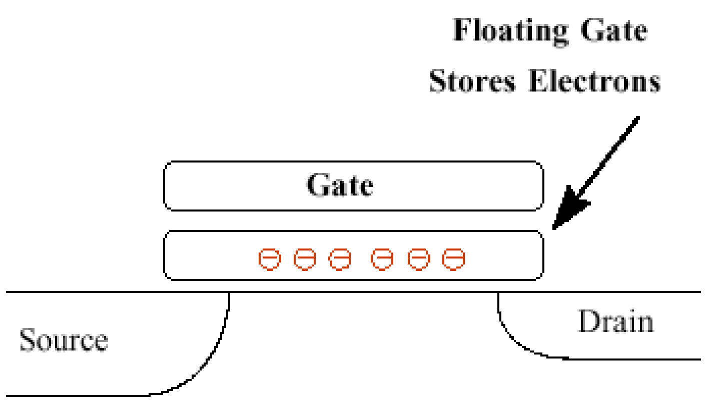


Figure 2: Single transistor flash memory cell

- Characteristic charging time given by RC of the circuit
  - large RC, less volatile storage, less rapid
    - Write endurance 10^5 cycles
      - Transfer rates ~ 15 MB/s
        - Access time ~ 100ns

Applications : magnetic random access memories

Flash memory

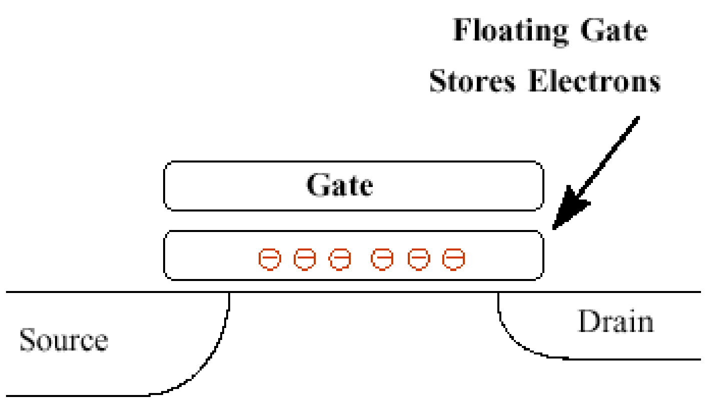
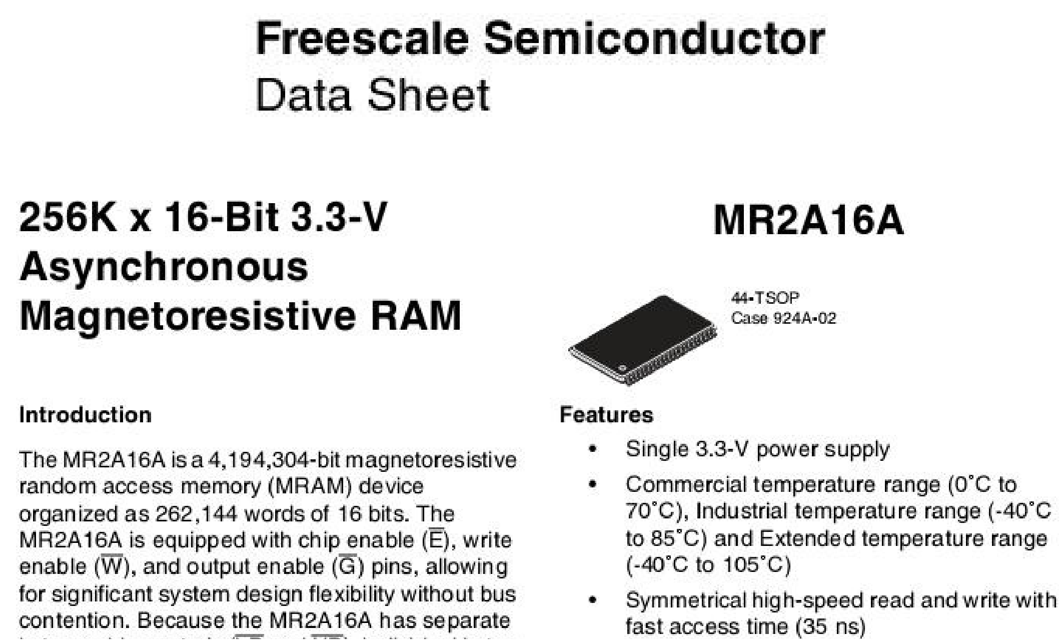


Figure 2: Single transistor flash memory cell

- Characteristic charging time given by RC of the circuit
- large RC, less volatile storage, less rapid
- Write endurance 10^5 cycles
- Transfer rates ~ 15 MB/s
- Access time ~ 100ns



Freescale Semiconductor
Data Sheet

256K x 16-Bit 3.3-V Asynchronous Magnetoresistive RAM

MR2A16A

44-TSOP
Case 924A-02

Introduction

The MR2A16A is a 4,194,304-bit magnetoresistive random access memory (MRAM) device organized as 262,144 words of 16 bits. The MR2A16A is equipped with chip enable (Ē), write enable (W̄), and output enable (Ḡ) pins, allowing for significant system design flexibility without bus contention. Because the MR2A16A has separate

Features

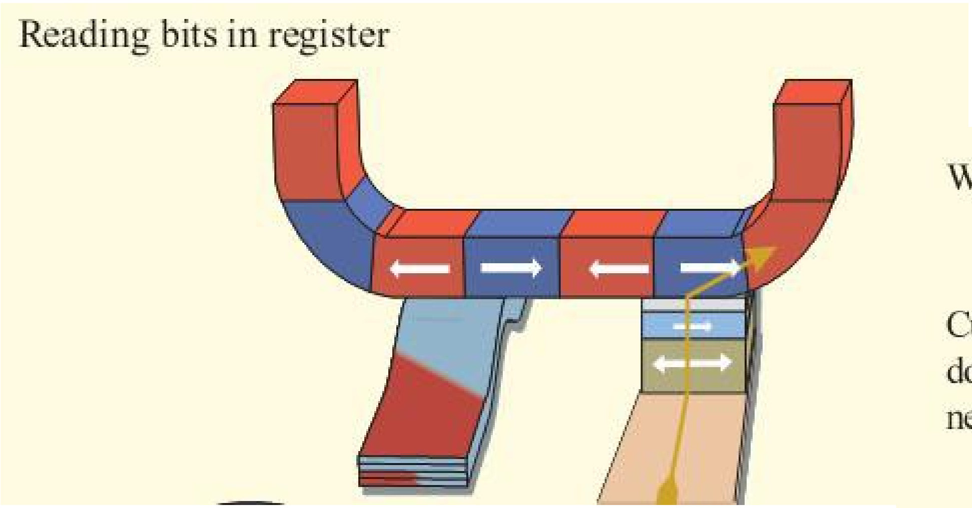
- Single 3.3-V power supply
- Commercial temperature range (0˚C to 70˚C), Industrial temperature range (-40˚C to 85˚C) and Extended temperature range (-40˚C to 105˚C)
- Symmetrical high-speed read and write with fast access time (35 ns)

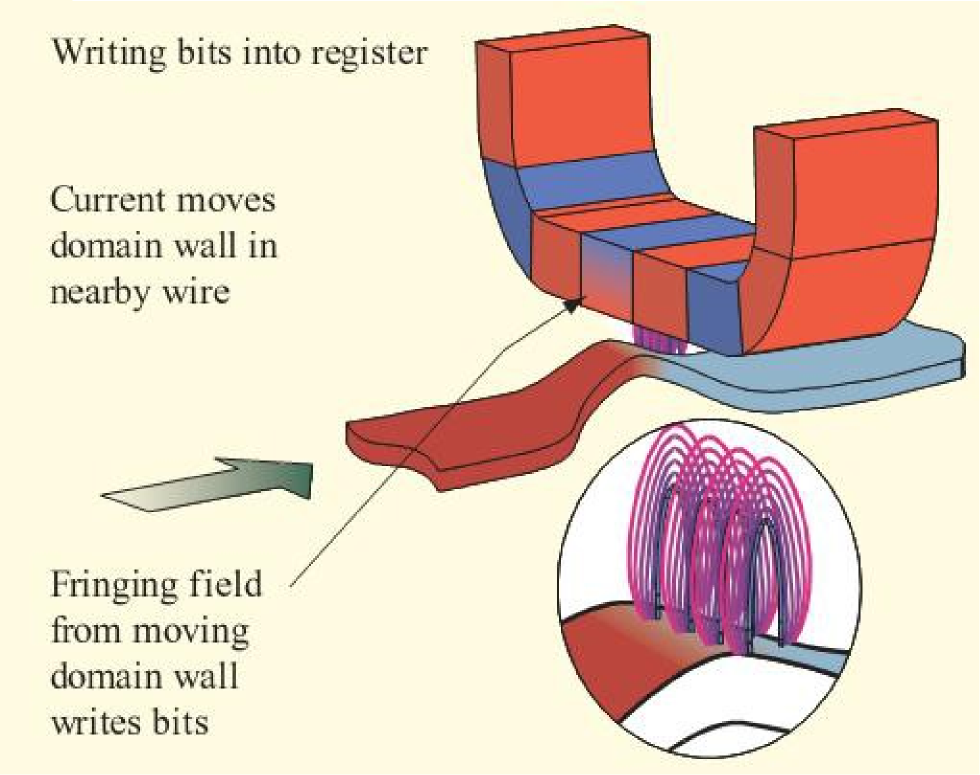
- First commercial MRAM : 4MB
- Access time : 35 ns
- Write endurance ~ infinite

Courtesy : Laurent Ranno

Applications : domain wall memories

S.S.P. Parkin, IBM patent



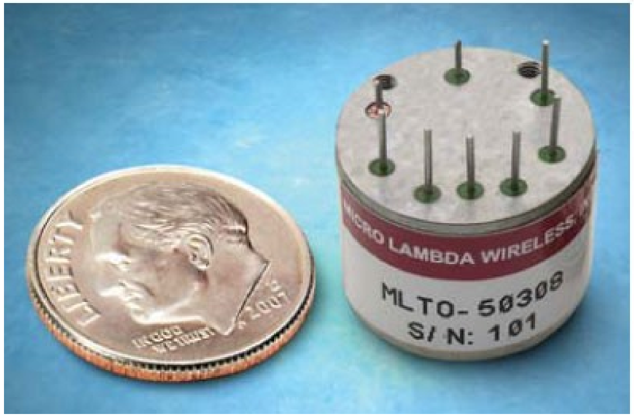


Advantages : 3 D storage ?
No moving parts

Needed : DW speeds > 100 m/s
Current density < 1×10^{11} A/m^2

Applications : oscillators

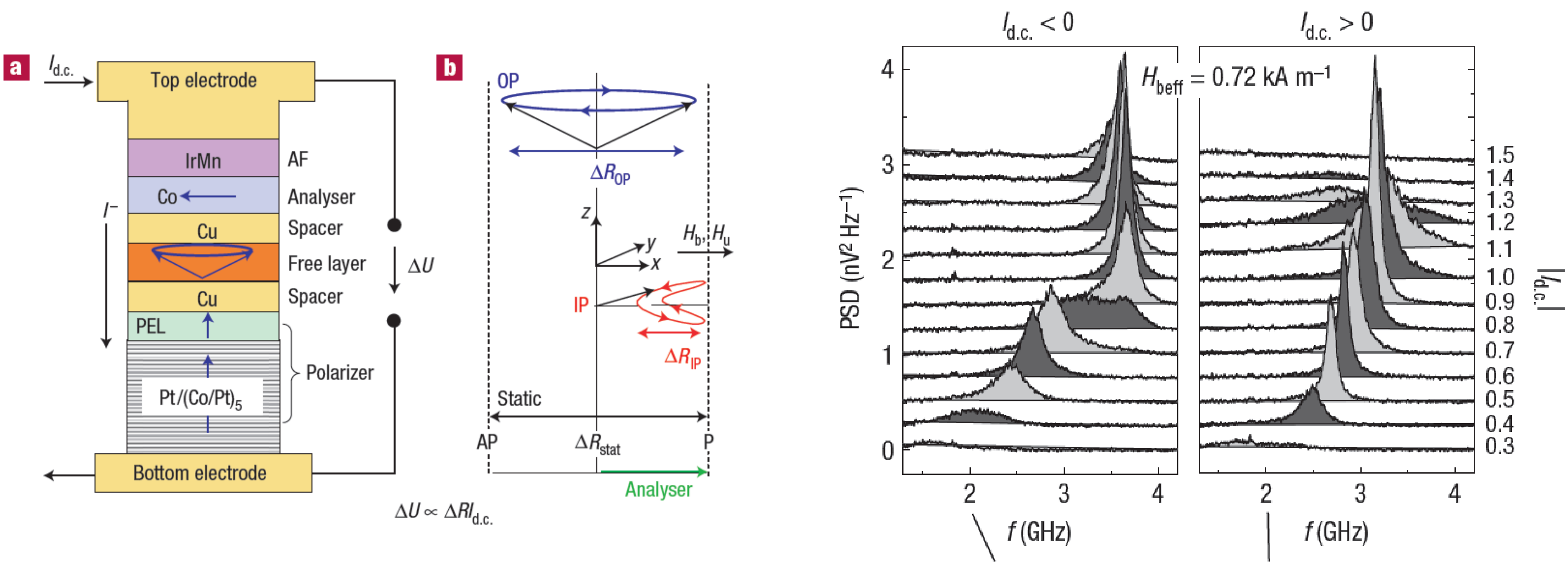
Telecommunication (cell phones, radio emitter, satellites)



Yttrium Iron Garnets (YIG) : YFeO
Tunable 2-40 GHz with magnetic field
High output power
High quality factor

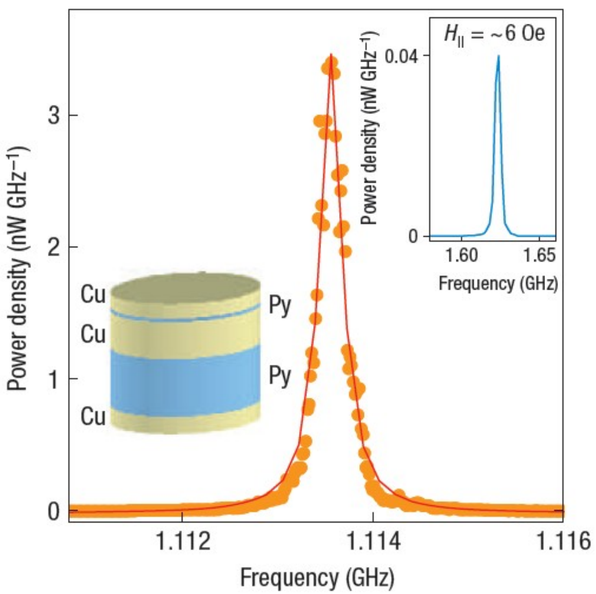
Applications : oscillators

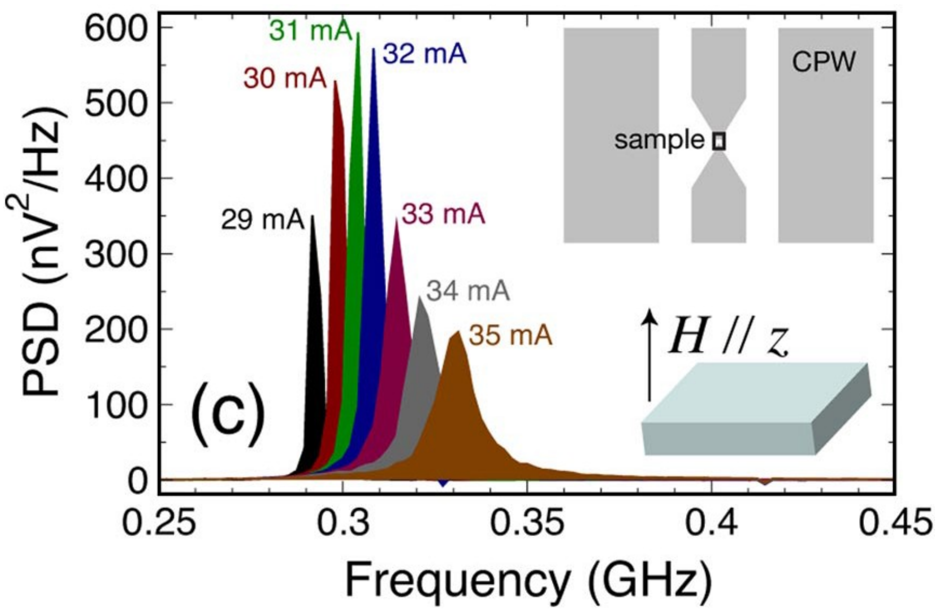
Oscillators using spin-transfer torque, frequency tunable with DC current



D. Houssameddine et al., Nature Mater. 6, 447 (2007)

Applications : spin-torque oscillators (vortex)





Pribiag et al., Nature Phys. 3, 498 (2007)

Mistral et al., Phys. Rev. Lett. 100, 257201 (2008)

Improvements spin-torque oscillators : emitted power, Q-factor

Summary + conclusions

- Magnetization dynamics take place over timescales from the femtoseconds to many gigaseconds !

- Many different physical processes take place, and many techniques are used to detect magnetization dynamics --> 10 days of lectures !!

- Applications : except for hard magnetic materials, alternatives to magnetic devices exist --> need to be better, smaller, faster !

Practicals

Schedule for the practicals

Analytical

Computer

		Wednesday 24	Saturday 27	Monday 29	Thursday 01
Monte Carlo	Z. Neda				
Dynamical spin susceptibility	S. Raymond	A	B		
Spin waves	S. Petit				
Analytical micromagnetism	S. Rohart			A	B
Precessional dynamics	U. Ebels			A	B
Read a publication	O. Fruchart				
Write a publication	O. Fruchart				

Please follow these rules when expressing your wishes to attend the tutorials :

1. Grade the tutorials 1, 2, 3 … you wish to attend. '1' of highest priority, 2 lower, 3 even lower etc.
2. Although two tutorials may be attended by each person, express at least three choices to accomodate for the global balance

Z. Neda : magnetic interactions in two dimensions (Ising 2D)
S. Raymond : dynamic spin susceptibility
S. Rohart : determination of domain wall profiles and domain wall pinning (quasi-static)
U. Ebels : calculate magnetization trajectories, frequencies for different parameters of field, anisotropy

Inscription on paperboard (left going out of the conference room)