Time scales in magnetism

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

Electronic processes

Magneto-
ization
precession

Thermally activated magnetization dynamics

Overview timescales

Photoelectric interactions
Different time-related parameters or derivated parameters are used:

\[ \text{Frequency} = \frac{1}{\text{time}} \quad \text{1 nanosecond} \leftrightarrow \text{1 Gigahertz} \]
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\[ \text{Energy} = h \times \text{frequency} \quad \text{1GHz} \leftrightarrow 6.63 \times 10^{-25} \text{ J} = 4.14 \mu\text{eV} \]

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\[ \text{Energy} = k \times \text{temperature} \quad \text{1 meV} \leftrightarrow 11.6 \text{ K} \]

\[ k = 1.38 \times 10^{-23} \text{ J.K}^{-1} = 8.617 \times 10^{-5} \text{ eV.K}^{-1} \]
Small magnetic particle, with uniaxial magnetic anisotropy constant $K$ (two stable orientations)

Thermally activated magnetization dynamics

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

J. Vogel, Targoviste, 22/08/2011
Thermally activated magnetization dynamics

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

\[ \tau_N = \tau_0 e^{KV/kT} \]

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

\( 0.1 \times 0.1 \times 0.1 \mu\text{m}^3 : \tau_N \approx \infty \)
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10 x 10 x 10 nm\(^3\): \( \tau_N \approx 7 \times 10^{39} \text{ s} \) (1 year \( \approx 3 \times 10^7 \text{ s} \))
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- $6 \times 6 \times 6 \text{ nm}^3: \tau_N \approx 870 \text{ s}$
- $4 \times 4 \times 4 \text{ nm}^3: \tau_N \approx 9.6 \mu\text{s}$
Thermally activated magnetization dynamics

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

Same particle, decreasing temperature:

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

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

$T = 50 \text{ K} : \tau_N \approx 184 \text{ ns}$
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- \( T = 10 \text{ K} : \tau_N \approx 214 \text{ s} \)
- \( T = 5 \text{ K} : \tau_N \approx 4.6 \times 10^{13} \text{ s} \)

Particle is 'superparamagnetic' above a certain 'blocking temperature' that depends on the measuring time.
Materials with frustrated ferro/antiferromagnetic interactions, short and long range order: many different states with equivalent energies, separated by energy barriers. Relaxation over long timescales (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

\[ \frac{dM}{dt} = \gamma M \times H_{\text{eff}} + \frac{\alpha}{M_S} (M \times \frac{dM}{dt}) \]
Beyond thermal activation: Landau-Lifshitz-Gilbert equation: precession and damping

\[
d\mathbf{M}/dt = \gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} + \alpha/\mathbf{M}_S (\mathbf{M} \times d\mathbf{M}/dt)
\]

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

\[
\gamma = 176 \text{ GHz/T (for } g=2) \]

\[
f (1\text{T}) = 28 \text{ GHz} \quad \tau = 1/f = 36 \text{ ps}
\]

\( \gamma \): gyromagnetic ratio \quad g : \text{Landé factor}
Precession and damping: ferromagnetic resonance

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

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

Ph.D. thesis C. Bilzer

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

Ultrafast magnetization dynamics (femtomagnetism)

Beaurepaire et al.,
Ultrafast magnetization dynamics (femtomagnetism)


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

Ultrafast magnetization dynamics

Ultrafast magnetization dynamics

Magnetization reversal with one 40fs circularly polarized laser pulse


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 – $\infty$
Thermally activated 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

- Steels
- Ferrites
- Alnico
- Sm-Co
- Nd-Fe-B

Hand held tools, appliances...

↑(BH)\text{max} \rightarrow ↓ magnet volume

Courtesy: Nora Dempsey
Applications: permanent magnets

High performance permanent magnets need to operate at $T \leq 180^\circ C$

$H_c < H_A$ (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

Magnetic Recording Media

Commercial 2010
421 Gbit/in² (demo Seagate sept. 2006)
275 kti, 1530 kbi BAR 5.6 PMR

Demo 800 Gbit/in²
Applications: magnetic recording

\[ \tau_N = \tau_0 e^{KV/kT} \]

For data storage, \( \tau \) should be about 10 years, i.e. \( KV/kT > 60 \)

The higher \( K \), the higher the field needed to write a bit

<table>
<thead>
<tr>
<th></th>
<th>( K_1 ) (MJ/m(^3))</th>
<th>( \phi_{\text{min}} ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0.05</td>
<td>20</td>
</tr>
<tr>
<td>Co</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>( \text{Nd}<em>2\text{Fe}</em>{14}\text{B} )</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>SmCo(_5)</td>
<td>17</td>
<td>2</td>
</tr>
</tbody>
</table>
Applications: magnetic recording

Heat-assisted recording: local decrease of coercivity

Diagram showing the interaction of a heating laser, write current, head velocity, and near field light source in the context of magnetic recording.
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

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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

- 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

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Freescale Semiconductor Data Sheet

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

MR2A16A

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

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 (E), write enable (W), and output enable (G) 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 65°C) and Extended temperature range (-40°C to 105°C)
- Symmetrical high-speed read and write with fast access time (35 ns)

Figure 2: Single transistor flash memory cell

Courtesy: Laurent Ranno
Applications: domain wall memories

S.S.P. Parkin, IBM patent

Advantages: 3D storage?
No moving parts

Needed: DW speeds > 100 m/s
Current density < 1x10^{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)


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