Manipulation of the magnetization of Perpendicular magnetized Rare-earth-transition metal alloys using polarized light

S. Mangin
7th Framework Program for Research

IEF: Intra-European Fellowships
IOF: International Outgoing Fellowships
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Optical Probe and Manipulation of Magnetization at the nanometer scale

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Nancy (France)
Institut Jean Lamour

- Born from 5 laboratories merging: 400 peoples
  - Nano-science
  - Surface science
  - Nuclear Fusion
  - Metallurgy

Jan 2015: New common building

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Nanomagnetism / Spintronic

2 technicians, 2 CNRS researcher, 7 faculty members, 6 Ph.D & Post-Doc

http://www.lpm.u-nancy.fr/nanomag/

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Outlines

- Introduction
  - All optical switching
  - Our goals

- All optical switching for TbCo
  - Influence of composition
  - Influence of thickness

- Devices
  - How to record magnetization switching in TbCo
All optical switching

40 fs pulses, 1 kHz repetition

20 nm thick Gd$_{22}$Fe$_{74.6}$Co$_{3.4}$

All-optical switching with circularly polarized light

Stanciu et al., PRL 99, 047601 (2007)

- All-optical writing works without any applied external magnetic field
- All-optical writing event depends on combination magnetization and laser helicity
- All-optical switching only works above a certain fluence threshold
What is (are) the mechanism(s) ?

- **Magnetic field** created by a laser beam

  **Inverse Faraday effect**

  \[
  \vec{H}_{\text{eff}} = \frac{\varepsilon_0}{\mu_0} \alpha \left[ \vec{E}(\omega) \times \vec{E}^*(\omega) \right]
  \]

  _circular polarization_

- **Heat** transfer by the laser

- **Angular momentum** transfer by the laser

Still under discussion

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Magnetic field

Inverse Faraday effect

\[ \tilde{H}_{\text{eff}} = \frac{\varepsilon_0}{\mu_0} \alpha \left[ \tilde{E}(\omega) \times \tilde{E}^*(\omega) \right] \]

- circular polarization

- Could reach several Tesla?
- Sign depends on polarization
- Short field pulse

From LLG equation 100 ps field pulse is needed

LLB?

\[ H_{\text{IFE}} \sim 0.52 \text{kOe} \]

Heat

Ferrimagnetic material is needed

Doesn’t depends on polarization

Will depend on pulse length

Radu et al., Nature 472, 205 (2011)
Angular Momentum transfer

Sign depends on polarization

Light transfers little angular momentum

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What are the Interactions / Time scales

- Field switching: Slow
- Spin Transfer: Fast

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What are the important parameters?

20 nm thick Gd$_{22}$Fe$_{74.6}$Co$_{3.4}$
40 fs pulse 1 kHz repetition

Polarization?
Pulse length?
Fluence?
Repetition?
Thickness?
Rare earth – Transition metal?
Ferrimagnetic?
Composition?
Why RE-TM alloys?

ferrimagnetic RE-TM alloy

rare earth (Gd, Tb)

transition metal (Fe, Co, Ni)

alloy (GdFeCo)
The materials: Ferrimagnetic alloys

\[ \text{M} = g_{\text{RE}} (\gamma) A_{\text{RE}} \]

\[ \text{M}_{\text{TM}} = g_{\text{TM}} (\gamma) A_{\text{TM}} \]

\[ g_{\text{RE}} \neq g_{\text{TM}} \]

Angular Momentum Compensation at \( T_A \)
Magnetization Compensation at \( T_M \)

\[ T_C \sim 500 \text{ K} \]
Can we use it?

Magnetic data storage, Magnetic Memories, Magnetic Logic?

**Low energy** 10 fJ to switch 20 nm x 20 nm

**Fast** Magnetizations reversal in 100 fs

*Phys Rev B 86, 140404(R) (2012)*

**High density**?

High Perpendicular Magnetic anisotropy

**Detectable**?

Can a current “read” Magnetization orientation

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Our Goal

- Demonstrate AOS for other materials
  - Better understanding
  - Find material compatible with application requirement

- Tune parameters
  - Magnetization
  - Thickness

- Build devices
All-optical switching in TbCo

AG Aeschlimann: circular polarized LASER beam, spot size: 20 μm
### AOS – TbCo vs GdCo

<table>
<thead>
<tr>
<th></th>
<th>Tb$<em>{0.26}$Co$</em>{0.74}$</th>
<th>≠</th>
<th>Gd$<em>{22}$Fe$</em>{74.6}$Co$_{3.4}$</th>
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<tr>
<td>Ferrimagnetic</td>
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<td>Ferrimagnetic</td>
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<td>$H_C = 6\ 000\ \text{Oe}$</td>
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<td>$H_C = 400\ \text{Oe}$</td>
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<td>$H_K = 6\ \text{T}$</td>
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<td>Low $H_K$</td>
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<td>Close to</td>
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<td>$t= 20\ \text{nm}$</td>
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<td>$t= 20\ \text{nm}$</td>
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<tr>
<td>400 fs and 10ps</td>
<td>≠</td>
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<td>50 fs</td>
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All-optical switching for a high anisotropy material ($\sim 4\times10^6\ \text{ergs/cm}^3$)

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Amorphous structure of $\text{Co}_{1-x}\text{Tb}_x$ alloys

Cu(2nm) /Pt(2nm) capping

$\text{Co}_{1-x}\text{Tb}_x$ (t nm)

substrate + Ta(5nm) buffer

Transmission electron microscopy:

$\text{Co}_{74}\text{Tb}_{26}$

$\text{Au}$

$\rightarrow$ $\text{Co}_{1-x}\text{Tb}_x$ amorphous for $12\% \leq x \leq 26\%$

$\text{d}_{\text{Tb-Tb}} = 3.52 \text{ Å}$

$\text{d}_{\text{Co-Co}} = 2.50 \text{ Å}$

$\text{d}_{\text{C-C}} = 1.54 \text{ Å}$
Perpendicular anisotropy

Co$_{1-x}$Tb$_x$ has PMA for $8\% \leq x \leq 34\%$
Tunable magnetization

\[ |m| = |m_{Tb} - m_{Co}| \]

\[ 0 \leq M(x, T) \leq 600 \text{ kA/m} \]

Tunable Perpendicular Magnetic Anisotropy

- Origin of PMA unclear
- $50 \text{ kJ/m}^3 \leq K(x, T) \leq 1600 \text{ kJ/m}^3$

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Composition influence on AOS

Conclusion

- AOS observed close to compensation
- AOS observed above compensation

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Understanding

At $T_A$ any torque is very efficient

- **Magnetic field** created by a laser beam

- **Heat** transfer by the laser

- **Angular momentum** transfer by the laser

Bring the sample to $T_A$

Switching at $T_A$


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Influence of concentration and pulse duration


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Thickness dependence

Competition between:

- Heat transfer
- Angular momentum transfer
Model

- **Magnetic field** created by a laser beam
- **Heat** transfer by the laser
- **Angular momentum** transfer by the laser
Applications

Data Storage
Memories
Logic

Read Data

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Transport measurements to Read

Anisotropic Magnetoresistance (AMR)

Extraordinary Hall Effect (EHE)

Giant Magnetoresistance (GMR)

\[ \Delta R(M) = (R \parallel - R \perp) \cos^2(\theta) \]

\[ \Rightarrow M \parallel I \]

\[ \Delta R(M) = R_{EHE} \cdot \frac{(\vec{I} \times \vec{M}) \cdot \hat{e}_z}{|\vec{M}| \cdot |\vec{I}|} \]

\[ \Rightarrow M \perp \text{plane} \]

\[ \Delta R(M) = GMR \cdot \left( \frac{\vec{M}_1 \cdot \vec{M}_2}{|\vec{M}_1| \cdot |\vec{M}_2|} \right)^2 \]

\[ \Rightarrow \theta(M_1, M_2) \]
Transport properties of CoTb alloys

MgO/Co$_{88}$Tb$_{12}$/MgO

$\Delta R/R \left[ 10^{-3} \right]$ vs $\mu_0 H$ [T]

$\rho_H/\rho$ [%]

Complementary tools to observe magnetization reversal
Spin valves

- Decoupled soft & hard layer
- EHE Sign positive for Co sublattices
- GMR sign: Co sublattices
- Small GMR (low polarization, short electron mean-free path?)

Conclusion

- Demonstration of AOS for TbCo
- Composition and thickness dependence
- Model based on Heat + Angular momentum transfer
- TbCo reversal may be probed using transport measurements


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Toward Low Power Spintronic Devices

July 8th - 12th, 2013 La Jolla, California

http://nanomag.ucsd.edu/iwst/

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Abstracts (see template online) must be submitted before March 1, 2013. Posters and oral presentations will be selected by the scientific committee and authors will be informed of the selection by April 1st.
Registration will be accepted until June 1st