Domain Wall Switched Media: Overcoming the Superparamagnetic Limit

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Outline

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Magnetic recording

Bilayers
Switching Times
Influence of $J_s$

Multilayers
Basic Concept

Graded Media
Optimal variation of $K_1$
Granular Exchange Coupling
Basic Concept
Basic Concept

Composite Media (ECC) [1]

- weak coupling
- $J_s$ homogenous within hard and soft layer

Exchange Spring Media [2]

- strong coupling
- formation of domain wall

Composite Media/Exchange Spring

$K_{\text{hard}} = 0.5 \times 10^6 \text{J/m}^3$

$K_{\text{soft}} = 0$

to vary interface coupling

$10 \text{ nm}$
Domain wall width

$\delta_s$ decreases with larger external fields
Required Soft Layer Thickness

• Domain wall width \([1,2,3]\):

\[
\delta_s = \pi \sqrt{\frac{A}{K_{\text{eff}}}}
\]

\[
K_{\text{eff}} = J_s H_{\text{ext}} + K_s
\]

• Maximum external field if \(H_{\text{ext}} = \) pinning field

\[
H_{\text{ext}} = \frac{1}{4} \times \frac{2(K_H - K_S)}{J_s}
\]

• Minimum pinning field if:

\[
K_S = \frac{1}{5} K_H
\]

Influence of anisotropy of hard layer on $H_c$

Limit $K_s=0$
Required soft layer thickness is:

$$\delta_s \approx \pi \sqrt{2A_{soft} / K_H}$$

- $K_{hard} = 4.0 \times 10^6 \text{J/m}^3$
- $K_{hard} = 1.0 \times 10^6 \text{J/m}^3$
- $K_{hard} = 0.25 \times 10^6 \text{J/m}^3$
Influence of different $J_s$ in hard/soft layer.

Demagnetizing fields are different in both layer.

- $J_s = 2\, \text{T}$
- $J_s = 0\, \text{T}$

$H_d$

$-0.18 \rightarrow 1.8$
Influence of different $J_s$ in hard/soft layer

Magnetization $J_s$ is varied in hard and soft layer

$$J_{\text{aver}} = \frac{J_s + J_H}{2} = 0.5T$$

$$H_c = \frac{2K_H - 2K_S}{\left(\sqrt{J_s} + \sqrt{J_H}\right)^2}$$

Saturation field has a minimum if $J_s = J_H$
Different $J_s$ on energy barrier

\[ J_{\text{aver}} = \frac{J_s + J_H}{2} = 0.5T \]

\[ J_H \approx J_S \]
Switching Times

Single Phase Media:

Exchange Spring Media:

Exchange Spring Media

\[ H_c = \frac{2K_{\text{hard}}}{J_{\text{hard}}} \frac{1 - \varepsilon_K \varepsilon_A}{(1 + \sqrt{\varepsilon_J \varepsilon_A})^2} \]

\[ \varepsilon_K = \frac{K_s}{K_H} \quad \varepsilon_A = \frac{A_s}{A_H} \quad \varepsilon_J = \frac{J_s}{J_H} \]

\[ J_s = J_H \]
\[ A_s = A_H \]

\[ H_c = \frac{1}{4} \times \frac{2(K_{\text{hard}} - K_{\text{soft}})}{J_{\text{hard}}} \]

For specific cases:

- \( K_s = 0 \):
  \[ H_c = \frac{1}{4} \times \frac{2K_{\text{hard}}}{J_{\text{hard}}} \]

- \( K_s = \frac{K_H}{5} \):
  \[ H_c = \frac{1}{5} \times \frac{2K_{\text{hard}}}{J_{\text{hard}}} \]

$K_1 = K_H$

$K_2 = K_H / 2$

$K_3 = 0$

$$H_c = \frac{1}{4} \times \frac{2(K_2 - K_3)}{J_{\text{hard}}} = \frac{1}{8} \times \frac{2K_H}{J_{\text{hard}}}$$
Trilayer

\[ K_1 = K_H \]

\[ K_2 = \frac{K_H}{2} \]

\[ K_3 = 0 \]

\[ H_c = \frac{1}{4} \times \frac{2(K_1 - K_2)}{J_{hard}} \]

\[ = \frac{1}{8} \times \frac{2K_H}{J_{hard}} \]
\[ H_c = \frac{1}{4} \times \frac{2(K_2 - K_3)}{J_{\text{hard}}} \]

\[ = \frac{1}{4(N-1)} \times \frac{2K_H}{J_{\text{hard}}} \]

<table>
<thead>
<tr>
<th>structure</th>
<th>reduction ( H_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>single</td>
<td>1</td>
</tr>
<tr>
<td>bilayer</td>
<td>1/4</td>
</tr>
<tr>
<td>trilayer</td>
<td>1/8</td>
</tr>
<tr>
<td>4 layers</td>
<td>1/12</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>N layers</td>
<td>( \frac{1}{4(N-1)} )</td>
</tr>
</tbody>
</table>

\[ K_m = mK_H / (N-1) \]

\[ K_{m+1} = (m+1)K_H / (N-1) \]
Hysteresis of different Media

\[ K_1 = 2 \times 10^6 \text{ J/m}^3 \]
\[ K_1 = 1.11 \times 10^6 \text{ J/m}^3 \]
\[ K_1 = 2.2 \times 10^5 \text{ J/m}^3 \]

25 nm
Energy Barrier Comparison

Trilayer has same energy barrier as single layer of same thickness
Graded Media

- What is the optimal dependence of $K_1(z)$?
- In order to keep DE constant we assume a thick graded anistropy layer (g-layer) thickness is varied.

layer with constant $K_1$ (20 nm)
What is the optimal shape to move a ball up a ramp with minimum force?

- force is small
- force is the same everywhere
- at some points large force required
Magnetic Problem

• Pinning field should be the same everywhere!

\[ H_{pinning} = \frac{1}{2J_s} \frac{\partial E(x)}{\partial x} \]

\[ E(x) = 4\sqrt{A \cdot K(x)} \]

• Pinning field is constant if

\[ E(x) = \beta x \quad \rightarrow \quad K(x) = \alpha x^2 \]

\[ K(x) = \left( \frac{K_{hard}}{t_G^2} \right) x^2 \]

\[ H_{pinning} = \frac{2}{t_G J_s} \sqrt{AK_{hard}} = \frac{E}{F t_G J_s 2} \]

D. Suess, APL 89, 113105 (2006)
Comparision with simulation

- g-layer discretized in 50 layer
- $K(x)$ proportional $x^2$

For thick g-layers very good agreement with analytic data.
\[ \Delta E_B = 4r^2 \pi L K \]
\[ \Delta E_B = 4r^2 \pi \sqrt{AK} \]

\[ l_{\text{max}} = 4\sqrt{A/K} \]
\[ \Delta E_{\text{max}} = 4r^2 \pi \sqrt{AK} \]

Energy barrier

extent transition is one task of ESM
Comparissson with Single Phase Media

Keeping coercive field constant: \( \mu_0 H_c = 1.7T \)
\[ d = 2r = 4\text{nm} \]

Graded Media:
\[ \Delta E_B = 2r^2 \pi J_s t_g H_c \]
\[ K(x) = \alpha x^2 \]
\[ \text{gain} \to \infty \]

Single Phase Media:
\[ \Delta E_B = 4r^2 \pi \sqrt{AK} \]
\[ K = 0.33\text{MJ/m}^3 \]
Comparisson with Single Phase Media

Keeping energy barrier constant:

\[ \Delta E = 54k_B T_{300} \]

\[ d = 2r = 4\text{nm} \]

analytic formula not valid

Single Phase Media:

Graded Media:

\( K = 2 \text{ MJ/m}^3 \)

\( K > > 2 \text{ MJ/m}^3 \)

coherent \( t_g \) (nm) incoherent
Global Optimization Algorithm

Film thickness 25 nm

\[
\mu_0 H_{\text{ext}} = 1.5 T
\]

- quadratic dependence very close to optimal structure
Magnetization Dynamics

Reversal as function of the field rise time
\( \alpha = 0.02 \)
Optimal Intergrain Exchange

$H_{ex, mean} = 0.3T$

1.5% of full exchange
Strong Lateral Coupling

Spins aligned almost parallel

Reduction of energy barrier due to exchange

\[ A_{\text{int}} = 12 \times 10^{-14} \text{ J/m} \]

Energy barrier vs. coordinate along MEP (a.u.)
• The particle needs the **same thermal activation** to overcome the energy well
• **The force** to push the particle from one minimum to the other depends on the slope of the energy landscape
• The microstructure allows to change the energy landscape
Summary

Optimal bilayer structure consists of a hard layer and a super hard layer.

With graded media in principle every hard magnetic material can be written with a limited external field (e.g. H=1.5 T).

The gain in energy barrier of an exchange spring media compared to a single phase media for the same magnetization, film thickness and coercive field increases unbounded with the film thickness.

The optimal (lateral) exchange field should be about 0.3T.
Sharrock’s Law

• How to measure the energy barrier ???

• For single phase media using Sharrocks law

\[ H_c = H_0 \left( 1 - \left( \frac{k_B T}{\Delta E_0} \ln\left( -\frac{\tau}{\ln(1/2)\tau_0} \right) \right)^{1/n} \right) \]

• Assumption the energy barrier can be described by

\[ \Delta E(H) = \Delta E \left( 1 - \frac{H}{H_c(\theta)} \right)^n \]
Sharrock’s Law

\[
\Delta E(H) = \Delta E \left(1 - \frac{H}{H_c(\theta)}\right)^n
\]

- fit n locally

\[
\theta = \text{soft layer thickness}
\]

\[
\Delta = \Delta - \text{single phase}
\]

Sharrock's Law

- fit n locally

\[
\Delta E(H) = \Delta E \left(1 - \frac{H}{H_c(\theta)}\right)^n
\]

- fit n locally

\[
\theta = \text{soft layer thickness}
\]
Local fit of $n$

- $t_{\text{hard}} = 18 \text{ nm}$
- Field $0.5^\circ$ off the easy axis

For single phase media see:

\[ \Delta E(H) = \Delta E \left( 1 - \frac{H}{H_c(\theta)} \right)^n \]
Extrapolation

• 36 nm thick soft layer (infinite thick soft layer) = worst case

Error 40% !!!!
Varied soft layer thickness from 0 nm to 36 nm

\( n = 1.5 \)

hard layer thickness 18 nm

<table>
<thead>
<tr>
<th>soft layer thickness</th>
<th>Error in Energy Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_s = 0 )</td>
<td>Underestimation of 18 %</td>
</tr>
<tr>
<td>( t_s = 7 )</td>
<td>Overestimation of 8 %</td>
</tr>
<tr>
<td>( t_s = 36 )</td>
<td>Underestimation of 40%</td>
</tr>
</tbody>
</table>

Standard deviation +/- 10%

- Fit cannot be improved by using \( n \) as an additional fit parameter
Extrapolation - Field Applied at 45°

H_{ext} at 0.5°

H_{ext} at 45°

\( n \text{ almost constant} \)
Extrapolation - Comparison

- $n$ can be determined from fit
- Excellent fits can be obtained for the whole field range

\[ \Delta E(H) = \Delta E \left( 1 - \frac{H}{H_c(\theta)} \right)^n \]

Standard deviation of error of barrier

<table>
<thead>
<tr>
<th>$H_{\text{ext}}$ at 0.5°</th>
<th>$H_{\text{ext}}$ at 45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>3%</td>
</tr>
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</table>
Theoretical Limits: New point of view of writeability problem

In principle every hard magnetic material can be written with a limited external field (e.g. $H=1.5$ T)

$H_c$ not proportional to $\Delta E_0$

finite thickness: trilayer (hard layer=FePt) with total thickness 25 nm

decreases $H_c$ by factor of 7

no reduction of energy barrier

Experimental measurement of energy barriers with Sharrock's law:

more accurate for a field angle of 45°.
Neuronal Network - Optimization

Use the trained network for simulated annealing

New optimal design variables (approximation)

Perform FE Sim. with new set of design variables to calculate $\Delta E$

Train neuronal Network with new set of design variables and $\Delta E$
Summary

**Theoretical Limits:** New point of view of writeability problem

In principle every hard magnetic material can be written with a limited external field (e.g. H=1.5 T)

**finite thickness:** trilayer (hard layer=FePt) with total thickness 25 nm

decreases $H_c$ by factor of 8

no reduction of energy barrier