Exchange Bias and Bi-stable Magneto-Resistance States in Amorphous TbFeCo and TbSmFeCo Thin Films

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Outline

• Background
  Why are we interested in Tb(Sm)FeCo thin films and exchange bias?

• Experimental Results
  Magnetic and structural properties of exchange biased Tb(Sm)FeCo

• Micromagnetic Simulations
  Two-sublattice, two-phase model
Background

Amorphous TbFeCo films

- Ferrimagnetic (FiM)
- Tb and FeCo sublattices
- Compensation Temperature ($T_{\text{comp}}$)
Background

Amorphous TbFeCo films

• Perpendicular magnetic anisotropy (PMA)
• Structural anisotropy gives rise to PMA in sputtered amorphous TbFe films

• Magnetic random access memory (MRAM)

• Ultrafast switching (picoseconds)
Background

Exchange bias

- Ferromagnetic (FM)/Antiferromagnetic (AFM) bilayer act as a pinned layer in spintronics devices

- Stabilize the magnetization in FM layer
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• Micromagnetic Simulations
  Interpenetrating two-phase, two-sublattice model
Experiment Methods

- Si/SiO$_2$ substrates
- Radio frequency (RF) magnetron sputtering at room temperature
- Magnetic Properties: Quantum Design Versa Lab system
- Thickness: Rigaku SmartLab system
Properties of Amorphous $\text{Tb}_{26}\text{Fe}_{64}\text{Co}_{10}$ Films

- 100 nm thick
- $T_{\text{comp}} \sim 250$K.
- PMA

![Graph](Li et al, Appl. Phys. Lett. 108, 012401 (2016))
Exchange Bias in Amorphous Tb\textsubscript{26}Fe\textsubscript{64}Co\textsubscript{10} Films

- Exchange bias effect is observed near $T_{\text{comp}}$
Exchange Bias in Amorphous Tb$_{26}$Fe$_{64}$Co$_{10}$ Films

- At 300K, both positive (P) and negative (N) exchange bias minor loops are observed, with different initialization procedures.

(N) Initialized at 355K and 30kOe

(P) Initialized at 175K and 30kOe

Out-of-plane Field (kOe)

Magnetization (emu/cc)
Origin of Exchange Bias in Tb$_{26}$Fe$_{64}$Co$_{10}$ Films

High-angle annular dark field imaging (STEM-HAADF)

- Non-uniform contrast indicates local compositional fluctuations

Energy-dispersive X-ray spectroscopy (STEM-EDS)

- Non-uniform distribution of all three elements.

- The regions marked with arrows indicate a local depletion in Tb, which directly coincides with an enrichment in Fe
Origin of Exchange Bias in $\text{Tb}_{26}\text{Fe}_{64}\text{Co}_{10}$ Films

Atomic probe tomography (APT)

- Tb (blue), Fe (green) and Co (red) distribution along a slice parallel to the film plane
- A network-like segregation of all three elements
- Existence of two compositional phases in amorphous $\text{Tb}_{26}\text{Fe}_{64}\text{Co}_{10}$ film
Origin of Exchange Bias in Tb$_{26}$Fe$_{64}$Co$_{10}$ Films

- Two nanoscale amorphous phases on the length scale of 2-5nm are revealed from STEM and APT.

- A Tb-enriched phase (Phase I) is nearly compensated and acts as a fixed layer

- A Tb-depleted phase (Phase II) is far away from compensation and acts as a free layer

- Exchange bias in Tb$_{26}$Fe$_{64}$Co$_{10}$ film originates from the exchange interaction between these two nanoscale amorphous phases
Origin of Exchange Bias in Tb$_{26}$Fe$_{64}$Co$_{10}$ Films

\[ M = \phi (M_{\downarrow Tb \uparrow I} + M_{\downarrow FeCo \uparrow I}) + (1-\phi)(M_{\downarrow Tb \uparrow II} + M_{\downarrow FeCo \uparrow II}) \]

\( \phi \) is the volume concentration of Phase I

Moment of Tb  
Moment of FeCo

\begin{align*}
\text{Magnetization (emu/cc)} \\
\text{Out-of-plane Field (kOe)}
\end{align*}

\begin{align*}
\text{Magnetization (emu/cc)} \\
\text{Out-of-plane Field (kOe)}
\end{align*}

Initialized at 355K and 30kOe

Initialized at 175K and 30kOe
Exchange Bias effect in magneto-transport measurements

Anomalous Hall Effect (AHE) and Magneto-resistance (MR) of \( \text{Tb}_{26}\text{Fe}_{64}\text{Co}_{10} \)

Current is injected through A and B

Voltage difference is measured between

EF for AHE

CD for MR
Exchange Bias effect in magneto-transport measurements

Anomalous Hall Effect (AHE) and Magneto-resistance (MR) of Tb$_{26}$Fe$_{64}$Co$_{10}$

\[ R_{\downarrow H} \propto C_{\uparrow I} (R_{\downarrow Tb\uparrow I} M_{\downarrow Tb\uparrow I} + R_{\downarrow FeCo\uparrow I} M_{\downarrow FeCo\uparrow I}) + C_{\uparrow I I} (R_{\downarrow Tb\uparrow I I} M_{\downarrow Tb\uparrow I I} + R_{\downarrow FeCo\uparrow I I} M_{\downarrow FeCo\uparrow I I}) \]

Bi-stable MR states are revealed at 300K, corresponds to the exchange bias observed in AHE loops.
Exchange Bias in Amorphous $\text{Tb}_{20}\text{Sm}_{15}\text{Fe}_{55}\text{Co}_{10}$ Films

- 100nm thick
- $T_{\text{comp}} \sim 250K$
- PMA

![Graph showing $M_s$ (emu/cc) and $H_c$ (kOe) vs Temperature (K)]
Exchange Bias in Amorphous Tb$_{20}$Sm$_{15}$Fe$_{55}$Co$_{10}$ Films

- Exchange bias at 275K
- Bistable MR states
Experimental Summary

• Exchange bias and bi-stable magneto-resistance states are uncovered in amorphous TbFeCo and TbSmFeCo films with perpendicular magnetic anisotropy.

• Structural analysis revealed two nanoscale amorphous phases with different Tb atomic percentages distributed within the films.

• Exchange anisotropy originates from the exchange interaction between the two amorphous phases.
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Magnetic and structural properties of exchange biased TbFeCo

• Micromagnetic Simulations
Two-sublattice, two-phase model.
Landau-Lifshitz-Gilbert Equation

Dynamic of Magnetization $\mathcal{M}$

Landau-Lifshitz-Gilbert (LLG) Equation

$$\frac{d\mathcal{M}}{dt} = -\gamma (\mathcal{M} \times H_{\text{eff}}) + \frac{\alpha}{\mathcal{M} \downarrow s} (\mathcal{M} \times \frac{d\mathcal{M}}{dt})$$

Where $\gamma$ is the gyromagnetic ratio, and $\alpha$ is the damping factor
Landau-Lifshitz-Gilbert Equation

The Effective Field

\[ H_{\text{eff}} = H_{\text{Ext}} + H_{\text{Demag}} + H_{\text{Ani}} + H_{\text{Exch}} \]

- External field
- Demagnetization field
- Anisotropy field
- Exchange field

Methods

- Atomistic model
- Micromagnetic model
The Micromagnetic Model

The Continuum Approximation

Multiple spins are grouped together to form a single cell of magnetization.
The Two-Sublattice Model

- Ferrimagnetic
- Tb and FeCo Sublattices
- Two LLG equations for each sublattice

\[
\begin{align*}
\frac{dM_{\downarrow Tb}}{dt} &= -\gamma (M_{\downarrow Tb} \times H_{\text{eff} \downarrow Tb}) + \frac{\alpha}{M_{\downarrow s \downarrow Tb}} (M_{\downarrow Tb} \times \frac{dM_{\downarrow Tb}}{dt}) \\
\frac{dM_{\downarrow Fe}}{dt} &= -\gamma (M_{\downarrow Fe} \times H_{\text{eff} \downarrow Fe}) + \frac{\alpha}{M_{\downarrow s \downarrow Fe}} (M_{\downarrow Fe} \times \frac{dM_{\downarrow Fe}}{dt})
\end{align*}
\]
The Two-Sublattice Model

The effective field due to the exchange interaction ($H_{\downarrow \text{exch} \uparrow}$)

\[
H_{\downarrow \text{exch} \downarrow \text{Tb}} = 2A_{\downarrow \text{Tb} \rightarrow \text{Tb}} / \mu_0 M_{\downarrow \text{Tb}} \ \nabla \uparrow 2 m_{\downarrow \text{Tb}} + 2A_{\downarrow \text{Tb} \rightarrow \text{Fe}} / \mu_0 M_{\downarrow \text{Tb}} \ \nabla \uparrow 2 m_{\downarrow \text{Fe}} + B_{\downarrow \text{Tb} \rightarrow \text{Fe}} / \mu_0 M_{\downarrow \text{Tb}} m_{\downarrow \text{Fe}} \\
H_{\downarrow \text{exch} \downarrow \text{Fe}} = 2A_{\downarrow \text{Fe} \rightarrow \text{Fe}} / \mu_0 M_{\downarrow \text{Fe}} \ \nabla \uparrow 2 m_{\downarrow \text{Fe}} + 2A_{\downarrow \text{Fe} \rightarrow \text{Tb}} / \mu_0 M_{\downarrow \text{Fe}} \ \nabla \uparrow 2 m_{\downarrow \text{Tb}} + B_{\downarrow \text{Fe} \rightarrow \text{Tb}} / \mu_0 M_{\downarrow \text{Fe}} m_{\downarrow \text{Tb}}
\]

- Neighbor cells from both sublattice
- Same cell from the other sublattice
The Two-Sublattice Model

The effective field due to the exchange interaction ($H\downarrow\text{exch}\uparrow$)

$$A\downarrow\text{Tb} - \text{Tb} = 1/4 \ J\downarrow\text{Tb} - \text{Tb} S\downarrow\text{Tb} S\downarrow\text{Tb}$$
$$r\downarrow\text{nn} \uparrow2 \ c\downarrow\text{Tb} / a\uparrow3$$

$$A\downarrow\text{Fe} - \text{Fe} = 1/4 \ J\downarrow\text{Fe} - \text{Fe} S\downarrow\text{Fe} S\downarrow\text{Fe} S\downarrow\text{Fe}$$
$$r\downarrow\text{nn} \uparrow2 \ c\downarrow\text{Fe} / a\uparrow3$$

$$A\downarrow\text{Tb} - \text{Fe} = 1/4 \ J\downarrow\text{Tb} - \text{Fe} S\downarrow\text{Tb} S\downarrow\text{Fe} S\downarrow\text{Fe}$$
$$r\downarrow\text{nn} \uparrow2 \ c\downarrow\text{Tb} / a\uparrow3$$

$$A\downarrow\text{Fe} - \text{Tb} = 1/4 \ J\downarrow\text{Fe} - \text{Tb} S\downarrow\text{Fe} S\downarrow\text{Fe}$$
$$r\downarrow\text{nn} \uparrow2 \ c\downarrow\text{Tb} / a\uparrow3$$

<table>
<thead>
<tr>
<th></th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K\downarrow\text{Tb}$ (J/m³)</td>
<td>3.4x10⁵</td>
<td>1.9x10⁵</td>
</tr>
<tr>
<td>$A\downarrow\text{Tb} - \text{Tb}$ (J/m)</td>
<td>1.90x10⁻¹²</td>
<td>1.21x10⁻¹²</td>
</tr>
<tr>
<td>$A\downarrow\text{Tb} - \text{Fe}$ (J/m)</td>
<td>-2.43x10⁻¹²</td>
<td>-1.87x10⁻¹²</td>
</tr>
<tr>
<td>$A\downarrow\text{Fe} - \text{Fe}$ (J/m)</td>
<td>1.40x10⁻¹¹</td>
<td>1.68x10⁻¹¹</td>
</tr>
<tr>
<td>$B\downarrow\text{Tb} - \text{Fe}$ (J/m³)</td>
<td>-1.43x10⁷</td>
<td>-1.09x10⁷</td>
</tr>
</tbody>
</table>
The Two-Phase Model

- Two interpenetrating phase
- Phase I (Red) and Phase II (Green) blocks
- 6x6x6 cells in each block
- Distributed throughout the modeling space
The Two-Phase Model

- Each cell is 0.5nm x 0.5nm x 0.5nm
- Each Phase I and Phase II block is 3nm x 3nm x 3nm
- Each block has 6x6x6 cells (Total 18x18x18 = 5832 cells)
- 27 blocks, 13 Phase I and 14 Phase II blocks

Finite distance methods based on OOMMF

Simulation Result of TbFeCo

- Positive and negative exchange bias minor loops near $T_{comp}$
- Positive shift in magnetization accompanied by negative exchange bias
- Negative shift in magnetization accompanied by positive exchange bias
Atomistic Simulations

Courtesy of Xiaopu Li

- Frustrated TbFe region
- Fe-Fe antiferromagnetic coupling
Simulations Summary

Micromagnetic model is employed to study exchange bias in a two-phase magnetic material with ferrimagnets.

Positive and negative exchange bias minor loops are obtained near $T_{\text{comp}}$.

This model provides a platform for developing exchange bias materials using ferrimagnets.
Exchange bias and bi-stable magneto-resistance states are revealed in two phase amorphous TbFeCo and TbSmFeCo thin films.

A two-phase, two-sublattice micromagnetic model is employed to simulate exchange bias effect in TbFeCo films.

Using this study, we can explore various FiM/FM and FiM/FM systems by tuning the composition of FiM phase, and develop desirable EB properties for applications at various temperatures.
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Supplementary

The HRTEM image of the amorphous Tb$_{26}$Fe$_{64}$Co$_{10}$ thin film by Titan 300 kV
Supplementary

Reduced FFT of the HRTEM
Derivation of effective field due to exchange interaction

\[ H_{\downarrow A} = -\frac{1}{2} \sum_{i,j} J_{\downarrow ij} S_{\downarrow i} \cdot S_{\downarrow j} = -\frac{1}{2} \sum_{Tb \downarrow i} \sum_{Tb \downarrow j} -\frac{1}{2} \sum_{Fe \downarrow i} \sum_{Fe \downarrow j} \]

We can rewrite Tb-Tb and Fe-Fe terms as follow

\[ H_{\downarrow Tb} = -\frac{1}{2} J_{\downarrow Tb} \sum_{Tb \downarrow i} \sum_{Tb \downarrow j} \]

Using the continuous assumption

\[ m_{\downarrow Tb} \approx m_{\downarrow Tb} + r_{ij} \cdot \nabla \]

\[ H_{\downarrow Tb} \approx 1/4 J_{\downarrow Tb} \sum_{Tb \downarrow i} \sum_{Tb \downarrow j} \]
Derivation of effective field due to exchange interaction

The ferrimagnetic (Tb-Fe) term

\[ H_{\downarrow Tb-Fe} = - \sum \langle Tb_{\downarrow i}, Fe_{\downarrow j} \rangle \uparrow \uparrow J_{\downarrow Tb-Fe} S_{\downarrow Tb_{\downarrow i}} \cdot S_{\downarrow Fe_{\downarrow j}} = \frac{1}{2} J_{\downarrow Tb-Fe} S_{\downarrow Tb} S_{\downarrow Fe} \]

\[ \sum \langle Tb_{\downarrow i}, Fe_{\downarrow j} \rangle \uparrow \uparrow (m_{\downarrow Tb_{\downarrow i}} - m_{\downarrow Fe_{\downarrow j}}) \uparrow 2 \]

Using the continuous assumption to expand \( m_{\downarrow Fe_{\downarrow j}} \)

\[ H_{\downarrow Tb-Fe} \approx \frac{1}{2} J_{\downarrow Tb-Fe} S_{\downarrow Tb} S_{\downarrow Fe} \sum \langle Tb_{\downarrow i}, Fe_{\downarrow j} \rangle \uparrow \uparrow (m_{\downarrow Tb_{\downarrow i}} - m_{\downarrow Fe_{\downarrow i}} - r_{\downarrow ij} \cdot \nabla m_{\downarrow Fe_{\downarrow i}} - \frac{1}{2} r_{\downarrow ij} \uparrow 2 \nabla \uparrow 2 m_{\downarrow Fe_{\downarrow i}}) \uparrow 2 \]

\[ \approx \frac{1}{2} J_{\downarrow Tb-Fe} S_{\downarrow Tb} S_{\downarrow Fe} \sum \langle Tb_{\downarrow i}, Fe_{\downarrow j} \rangle \uparrow \uparrow ((m_{\downarrow Tb_{\downarrow i}} - m_{\downarrow Fe_{\downarrow i}}) \uparrow 2 - 2(m_{\downarrow Tb_{\downarrow i}} - m_{\downarrow Fe_{\downarrow i}})(m_{\downarrow Tb_{\downarrow i}} - m_{\downarrow Fe_{\downarrow i}}) (m_{\downarrow Tb_{\downarrow i}} - m_{\downarrow Fe_{\downarrow i}}) \cdot (m_{\downarrow Tb_{\downarrow i}} - m_{\downarrow Fe_{\downarrow i}}) \cdot (m_{\downarrow Tb_{\downarrow i}} - m_{\downarrow Fe_{\downarrow i}})) \]
Derivation of effective field due to exchange interaction

\[ \mathcal{H}_{\downarrow A} = \int \nabla (A_{\downarrow Fe} - Fe \nabla m_{\downarrow Fe}) \nabla^2 + A_{\downarrow Tb} - Tb \nabla (m_{\downarrow Tb}) \nabla^2 - 2A_{\downarrow Tb} - Fe m_{\downarrow Tb} \cdot \nabla \nabla \]

\[ m_{\downarrow Fe} - B_{\downarrow Tb} - Fe (m_{\downarrow Tb} \cdot m_{\downarrow Fe}) d^3 x + 2 \]

\[ A_{\downarrow Tb} - Fe \oint m_{\downarrow Fe} \nabla m_{\downarrow Fe} \cdot n dS \]

The last term is integrated on the boundary, so the energy density is

\[ \mathcal{E}_{\downarrow A} = A_{\downarrow Fe} - Fe (\nabla m_{\downarrow Fe}) \nabla^2 + A_{\downarrow Tb} - Tb (\nabla m_{\downarrow Tb}) \nabla^2 - 2A_{\downarrow Tb} - Fe m_{\downarrow Tb} \nabla^2 m_{\downarrow Fe} - B_{\downarrow Tb} - Fe (m_{\downarrow Tb} \cdot m_{\downarrow Fe}) \]

The effective field due to exchange interaction

\[ H_{\downarrow eff, Tb} = - \frac{\delta \mathcal{E}_{\downarrow A}}{\mu_{\downarrow 0}} M_{\downarrow s}, Tb \delta m_{\downarrow Tb} \]

\[ = 2/\mu_{\downarrow 0} M_{\downarrow s}, Tb A_{\downarrow Tb} - Tb \nabla \nabla m_{\downarrow Tb} + 2/\mu_{\downarrow 0} \]