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

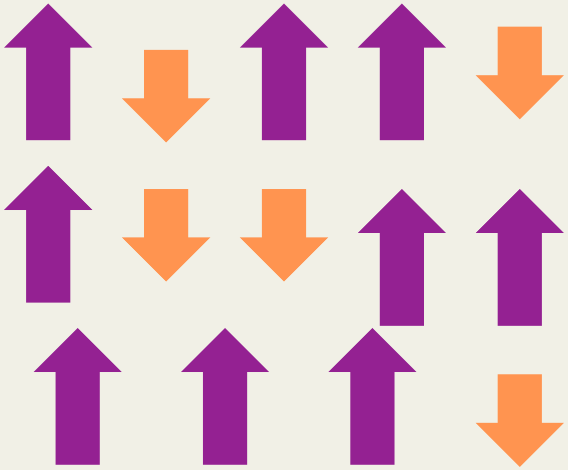
- Micromagnetic Simulations

  Two-sublattice, two-phase model

Background

Amorphous TbFeCo films

- Ferrimagnetic (FiM)
- Tb and FeCo sublattices
- Compensation Temperature (T_{comp})



Background

Amorphous TbFeCo films

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

  Harris, V. G., et al. Phys, Rev. Lett. **69**.13 (1992): 1939.

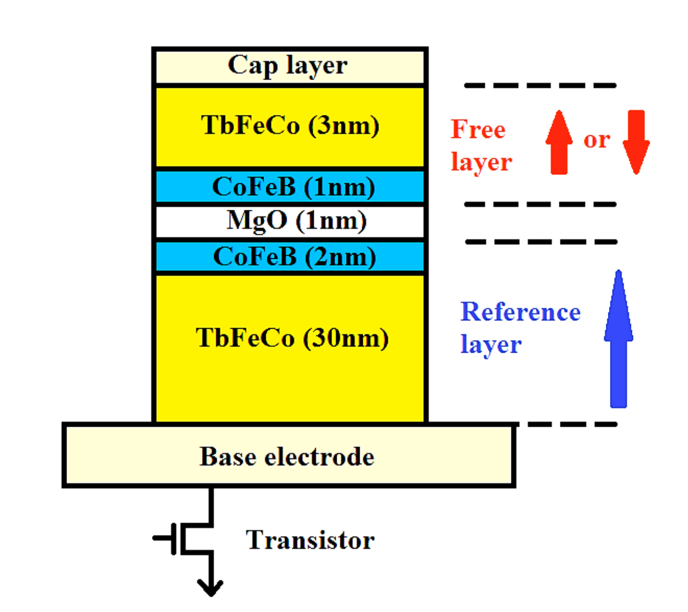
  Yan, X., et al, Phys. Rev. B **43**.11 (1991): 9300

- Magnetic random access memory (MRAM)

  Nakayama et al, J. Appl. Phys. **103**, 07A710 (2008).

- Ultrafast switching (picoseconds)

  Hassdenteufel et al, Adv. Mater. **25**, 3122 (2013)

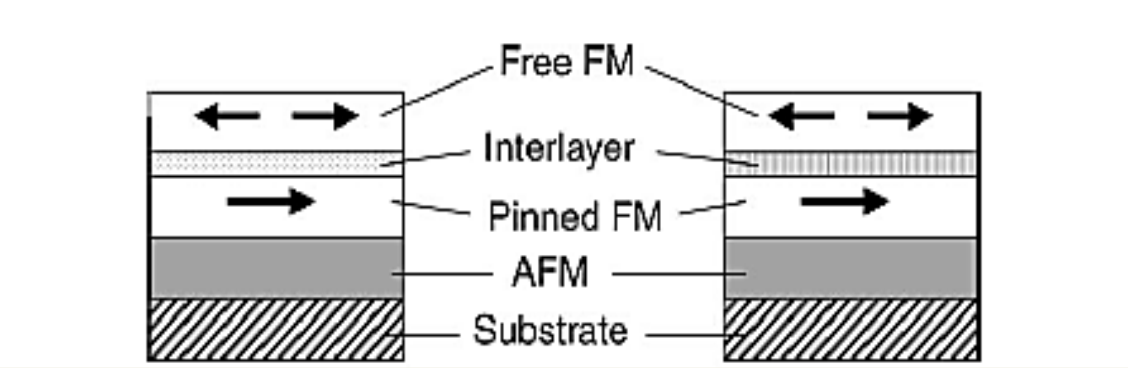


Background

Exchange bias

- Ferromagnetic(FM)/Antiferromagnetic(AFM) bilayer act as a pinned layer in spintronics devices
  Nogués et al. / Phys. Rep. **422** (2005) 65 –117

- Stabilize the magnetization in FM layer
  Liu et al. Appl. Phys. Lett. **81**, 4434 (2002)



Outline

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

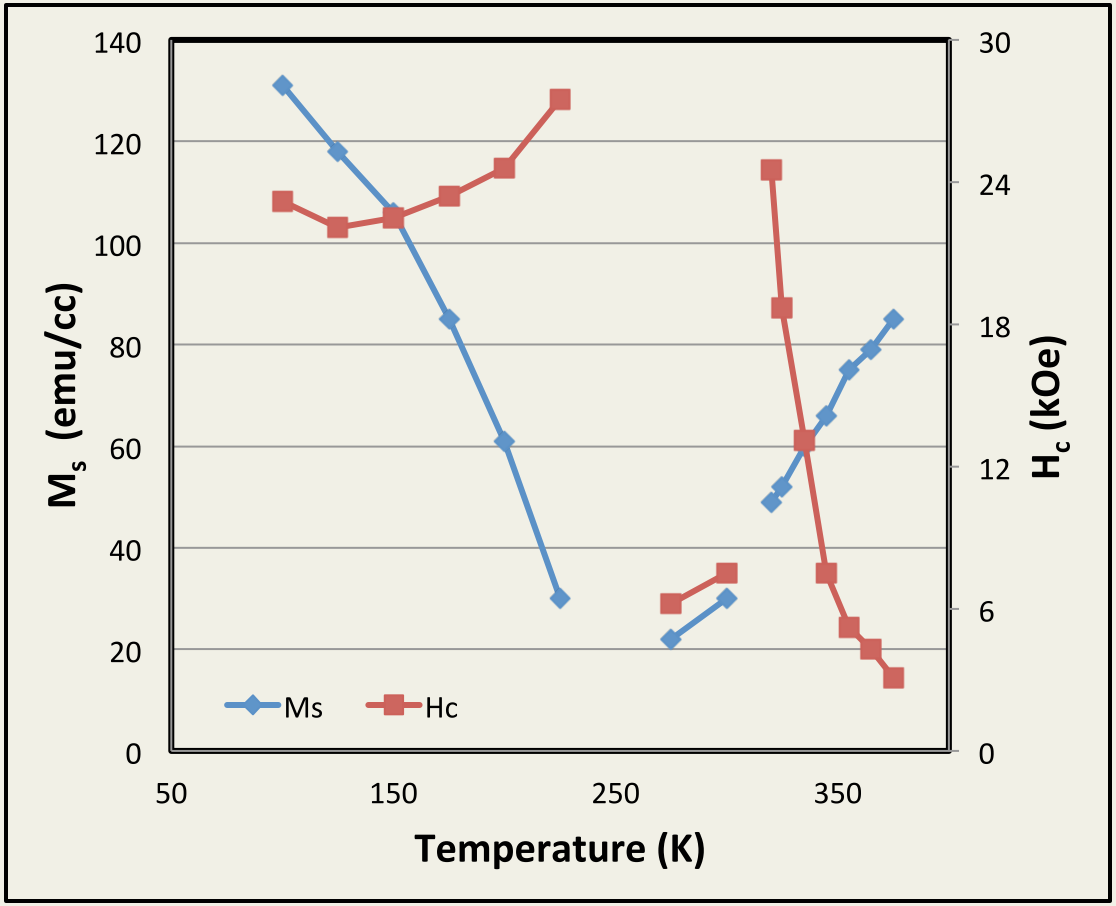
- Micromagnetic Simulations
  Interpenetrating two-phase, two-sublattice model

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 $Tb_{26}Fe_{64}Co_{10}$ Films

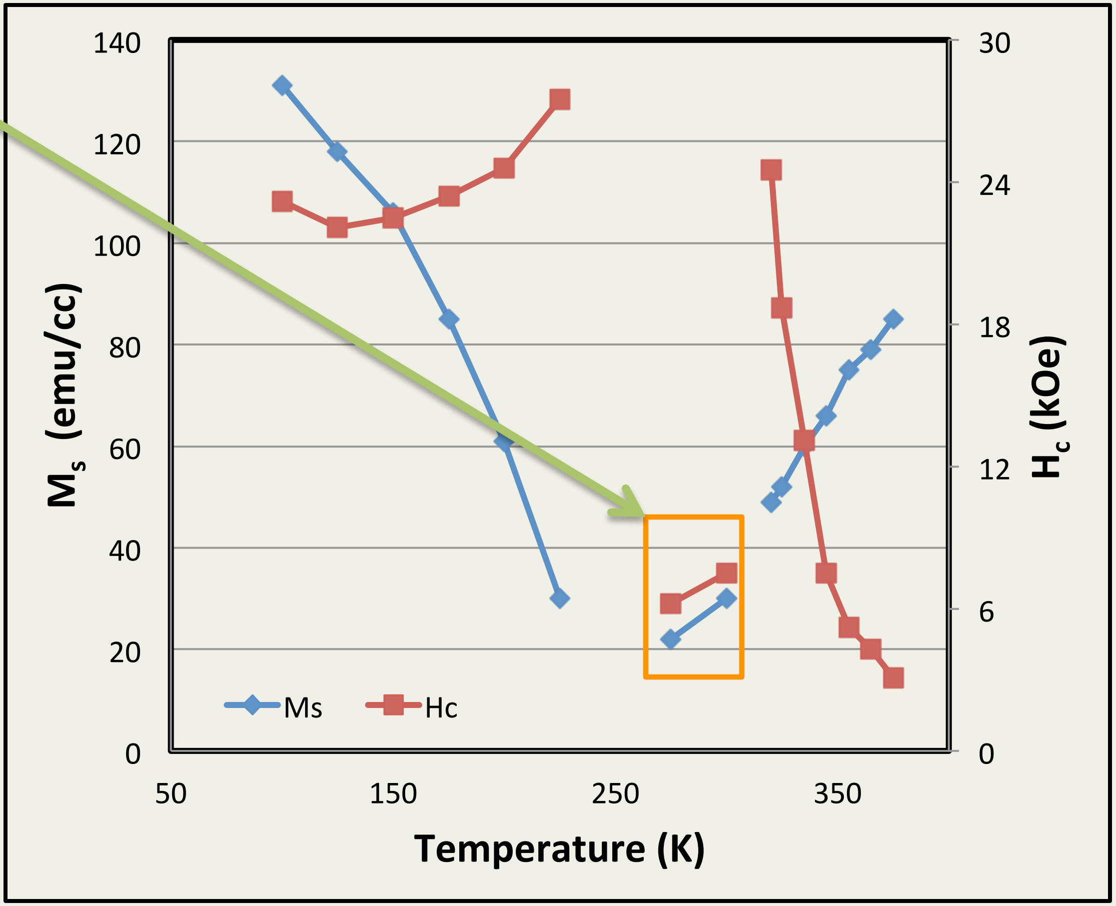
- 100 nm thick
- T_{comp} ~ 250K.
- PMA



Li et al, Appl. Phys. Lett. **108**, 012401 (2016)

Exchange Bias in Amorphous $Tb_{26}Fe_{64}Co_{10}$ Films

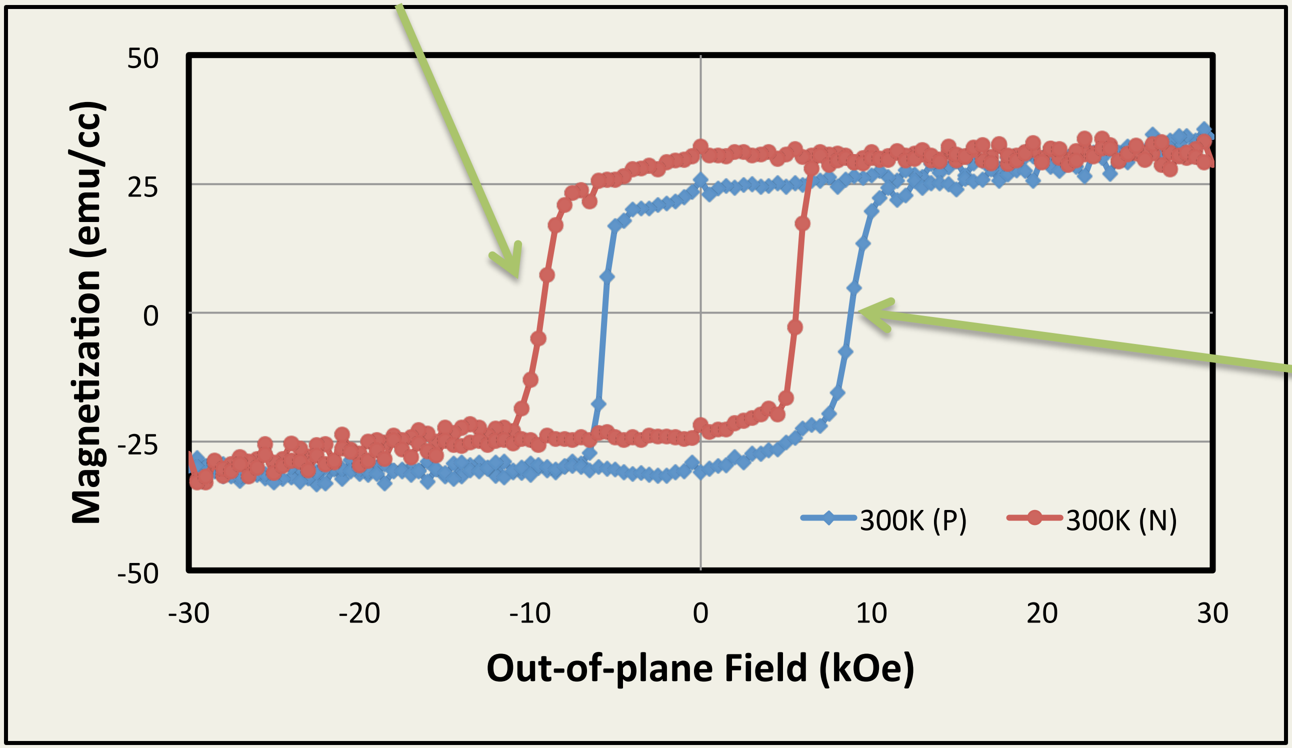
- Exchange bias effect is observed near T_{comp}



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

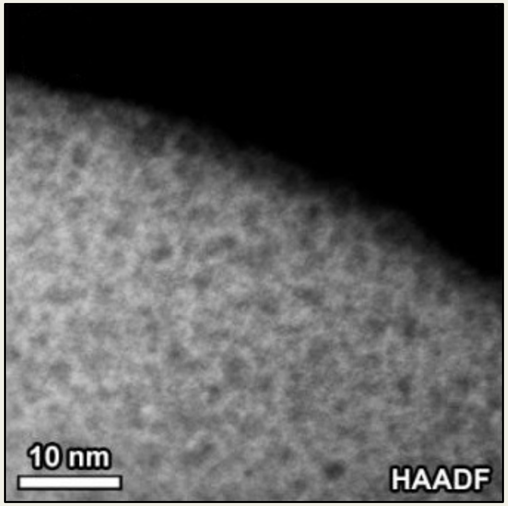
(N) Initialized at 355K and 30kOe



(P) Initialized at 175K and 30kOe

Origin of Exchange Bias in $Tb_{26}Fe_{64}Co_{10}$ Films

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

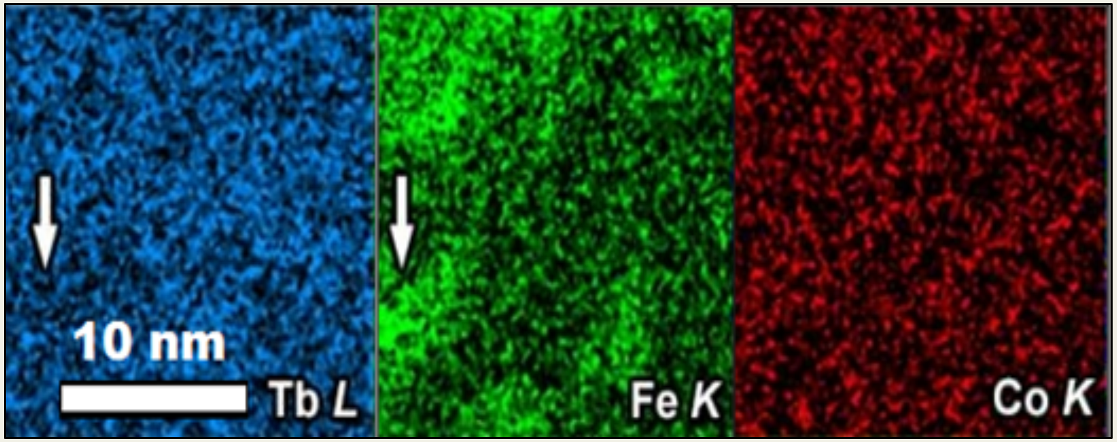


- Non-uniform contrast indicates local compositional fluctuations

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

- Non-uniform distribution of all three elements.

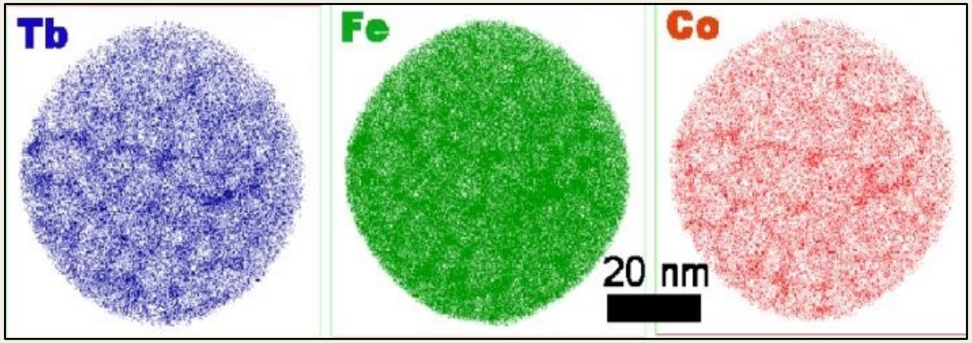
- The regions marked with arrows indicate a local depletion in Tb, which directly coincides with an enrichment in Fe



Origin of Exchange Bias in $Tb_{26}Fe_{64}Co_{10}$ Films

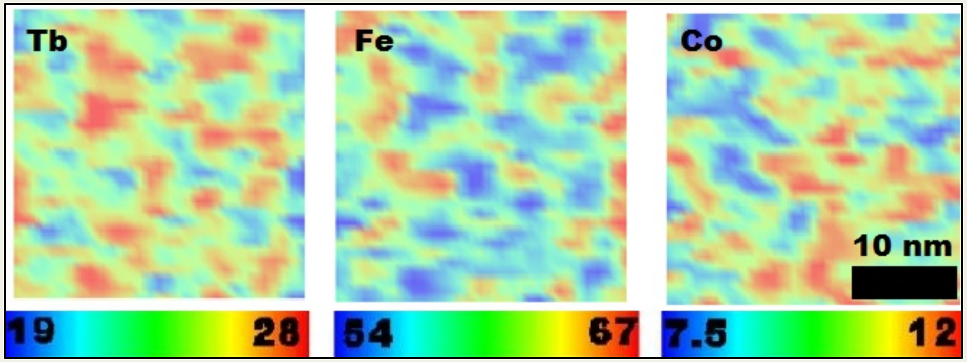
Atomic probe tomography (APT)

- 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 $Tb_{26}Fe_{64}Co_{10}$ 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

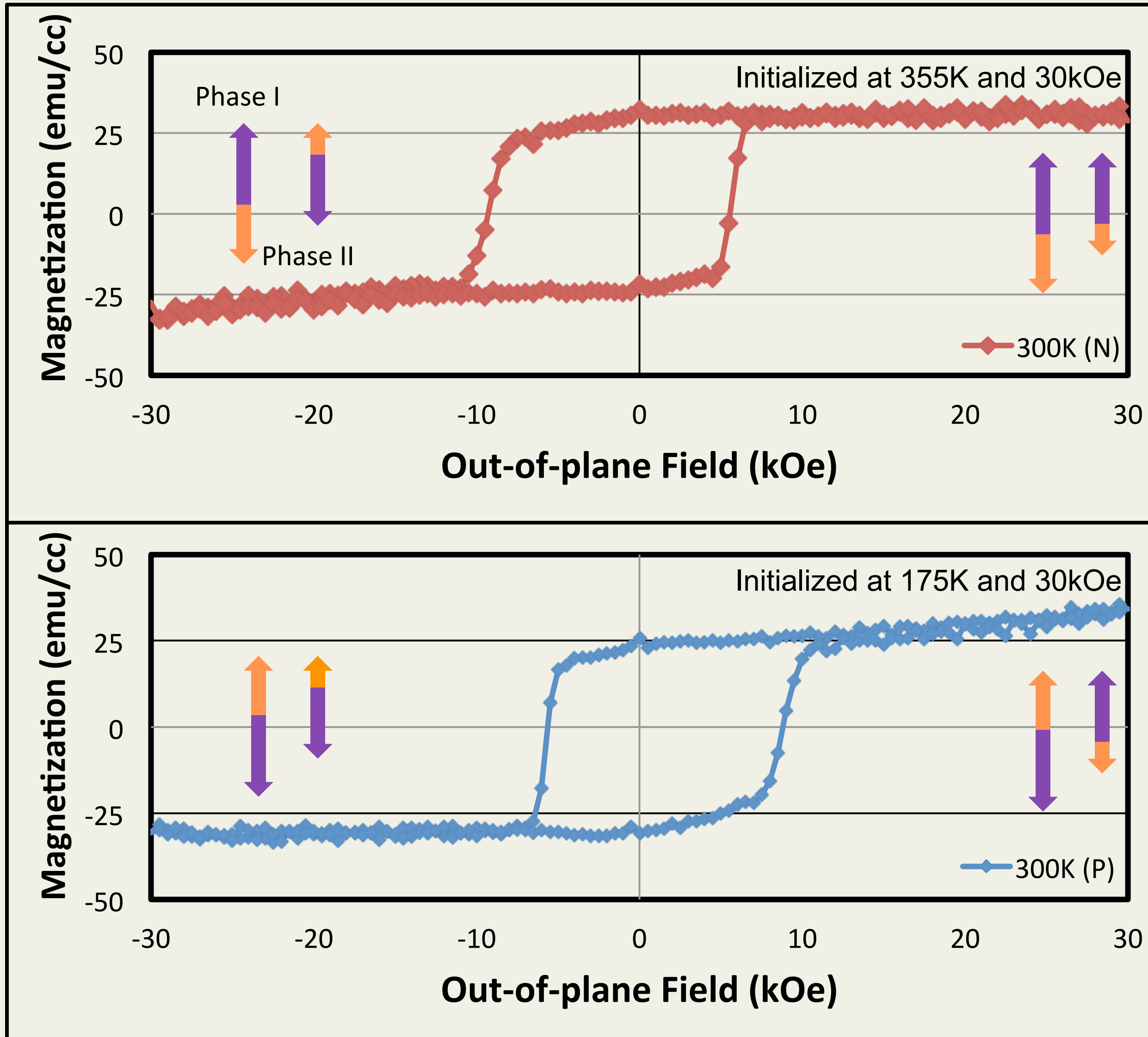
Moment of Tb

H

Moment of FeCo

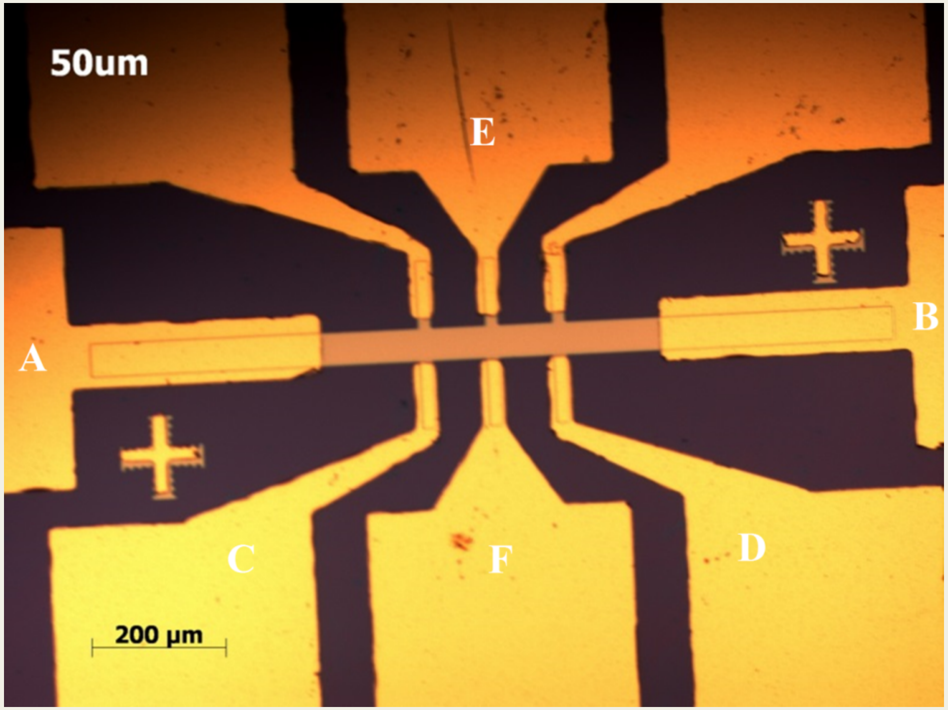
$$M = \phi(M_{Tb}^{I} + M_{FeCo}^{I}) + (1-\phi)(M_{Tb}^{II} + M_{FeCo}^{II})$$

ϕ is the volume concentration of Phase I



Exchange Bias effect in magneto-transport measurements

Anomalous Hall Effect (AHE) and Magneto-resistance (MR) of $Tb_{26}Fe_{64}Co_{10}$



Current is injected through A and B

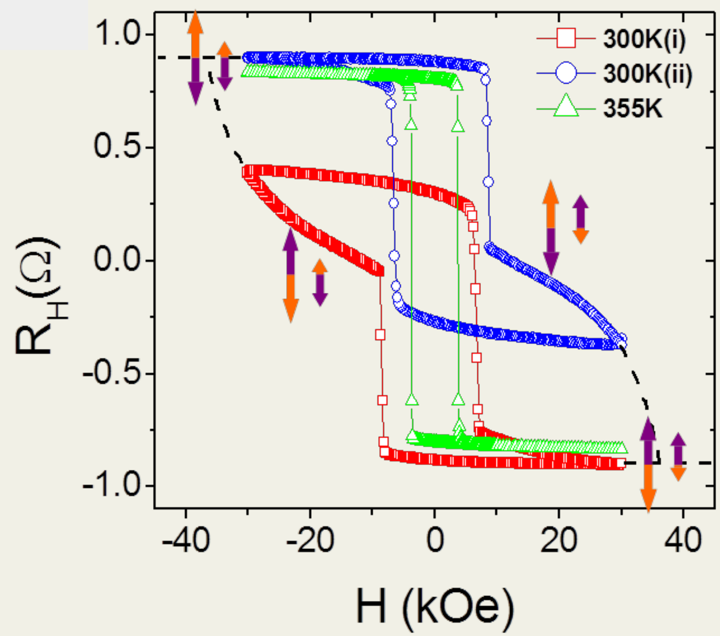
Voltage difference is measured between

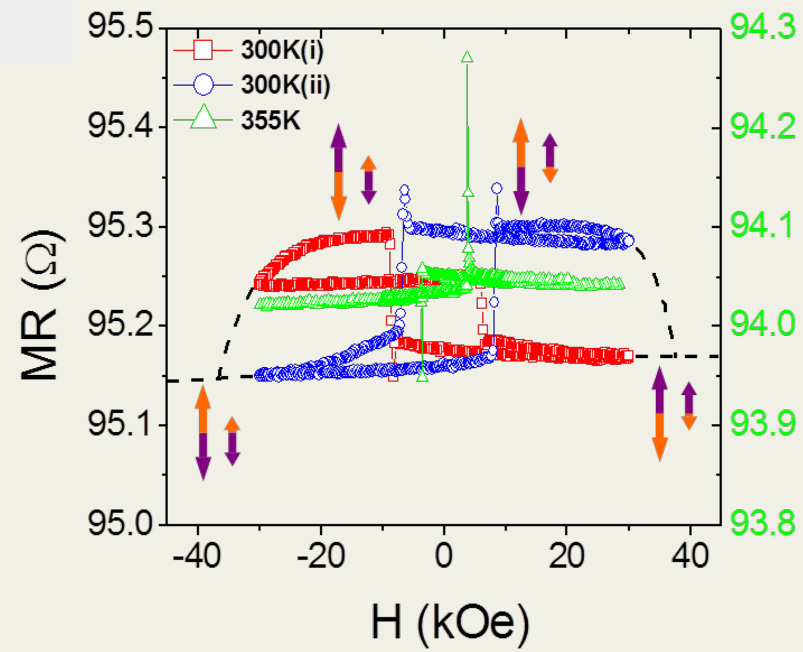
EF for AHE

CD for MR

Exchange Bias effect in magneto-transport measurements

Anomalous Hall Effect (AHE) and Magneto-resistance (MR) of $Tb_{26}Fe_{64}Co_{10}$



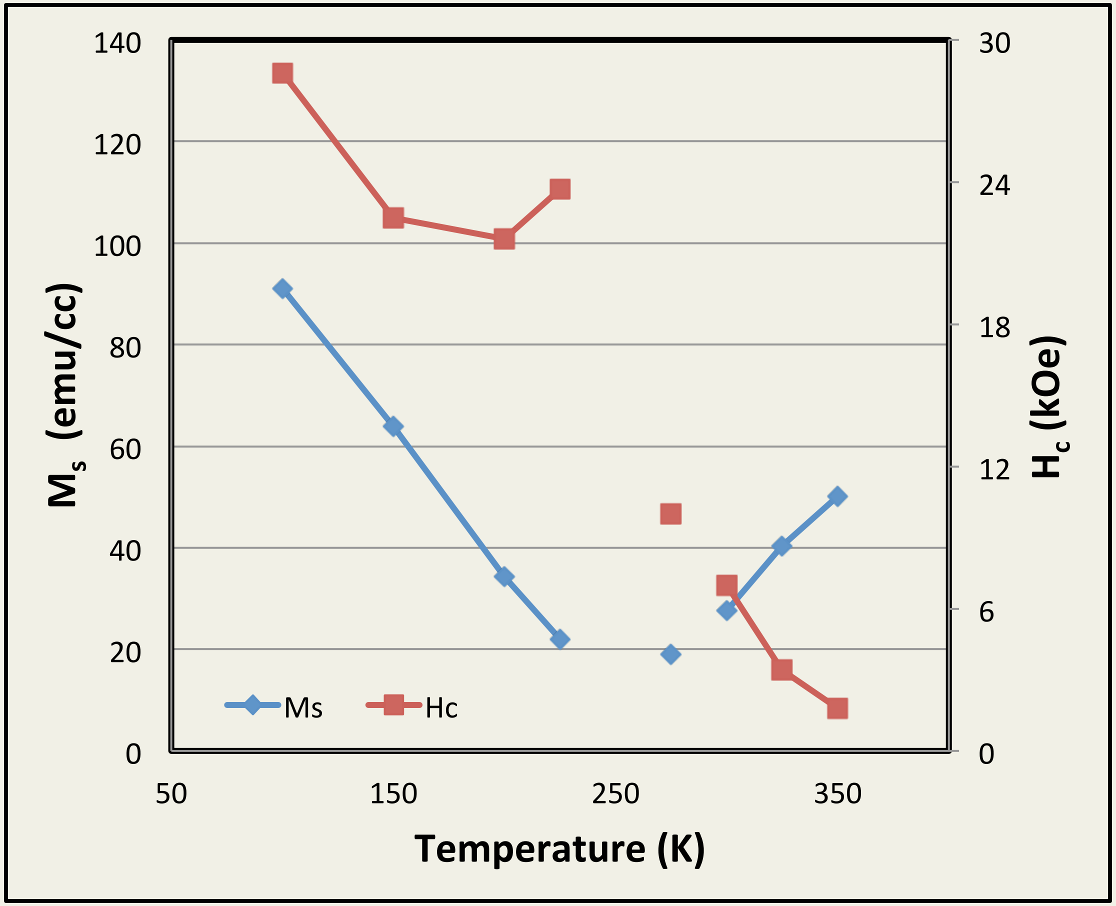


$$R_H \propto C^{I} (R_{Tb}^{I} M_{Tb}^{I} + R_{FeCo}^{I} M_{FeCo}^{I}) + C^{II} (R_{Tb}^{II} M_{Tb}^{II} + R_{FeCo}^{II} M_{FeCo}^{II})$$

Bi-stable MR states are revealed at 300K, corresponds to the exchange bias observed in AHE loops.

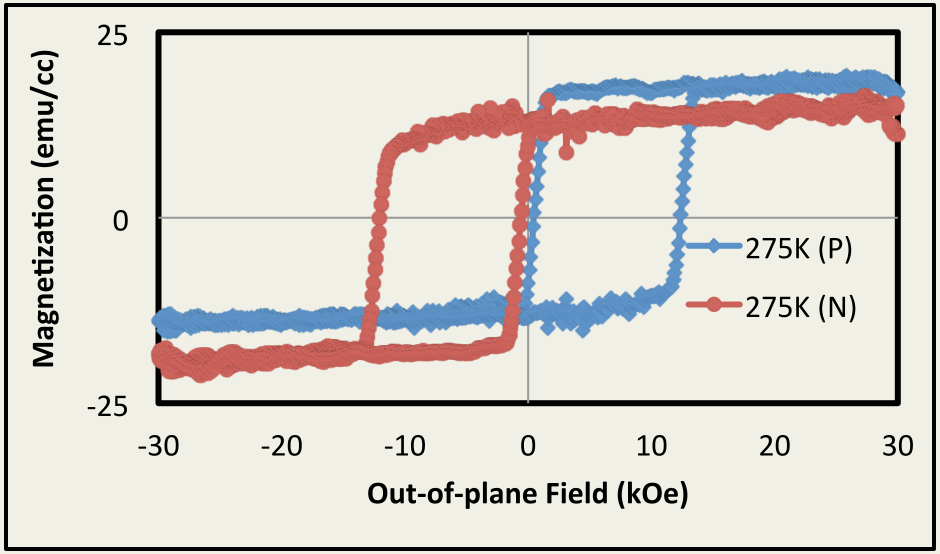
Exchange Bias in Amorphous $Tb_{20}Sm_{15}Fe_{55}Co_{10}$ Films

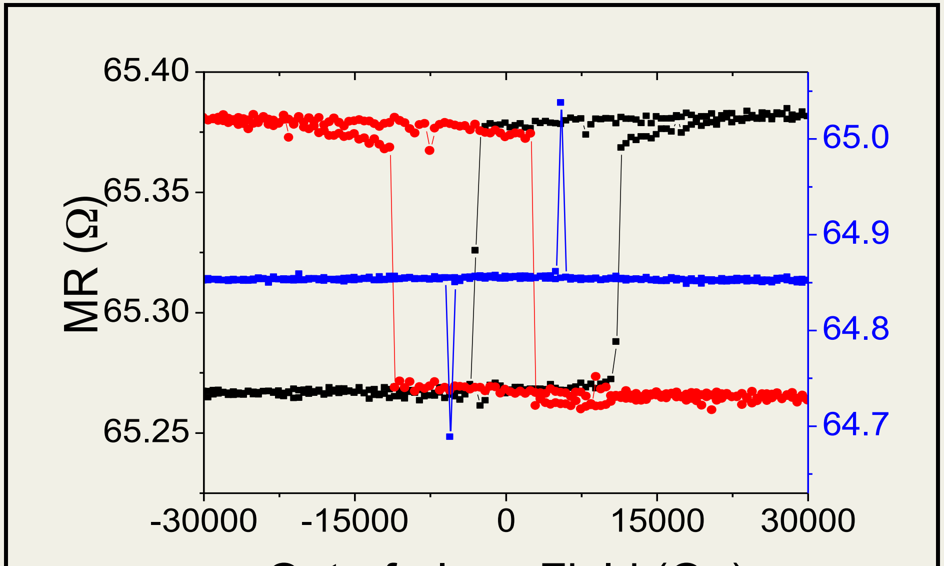
- 100nm thick
- T_{comp} ~ 250K
- PMA



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 M

Landau-Lifshitz-Gilbert (LLG) Equation

$$dM/dt = -\gamma(M \times H_{eff}) + \alpha/M_s \, (M \times dM/dt)$$

Where γ is the gyromagnetic ratio, and α is the damping factor

Landau-Lifshitz-Gilbert Equation

The Effective Field

$$H_{eff} = H_{Ext} + H_{Demag} + H_{Ani} + H_{Exch}$$

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

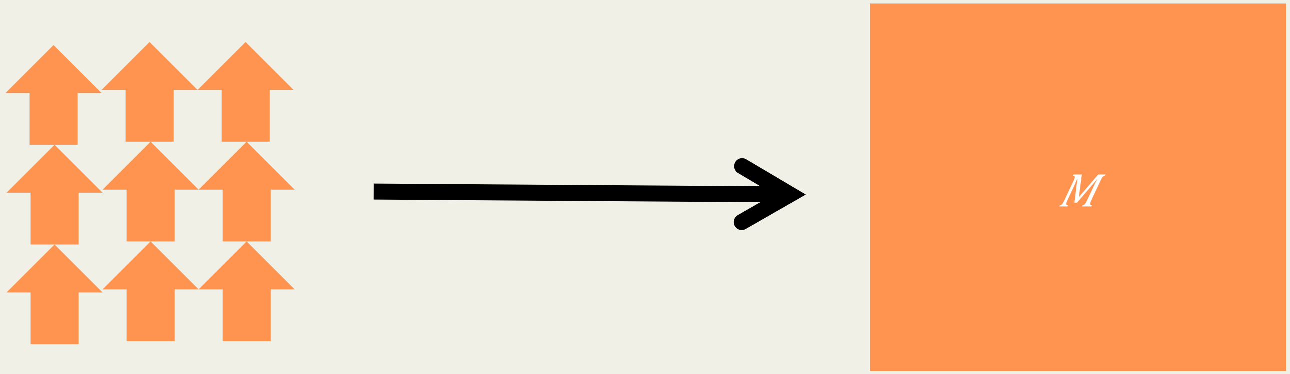
Methods

- 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

$$\frac{dM_{Tb}}{dt} = -\gamma\left(M_{Tb} \times H_{eff_{Tb}}\right) + \frac{\alpha}{M_{s_{Tb}}}\left(M_{Tb} \times \frac{dM_{Tb}}{dt}\right)$$

$$\frac{dM_{Fe}}{dt} = -\gamma\left(M_{Fe} \times H_{eff_{Fe}}\right) + \frac{\alpha}{M_{s_{Fe}}}\left(M_{Fe} \times \frac{dM_{Fe}}{dt}\right)$$

The Two-Sublattice Model

The effective field due to the exchange interaction (H_{exch})

$$\boldsymbol{H}_{\mathrm{exch}}^{\mathrm{Tb}} = 2A_{\mathrm{Tb-Tb}}/\mu_0 M_{\mathrm{Tb}} \nabla^2 \boldsymbol{m}_{\mathrm{Tb}} + 2A_{\mathrm{Tb-Fe}}/\mu_0 M_{\mathrm{Tb}} \nabla^2 \boldsymbol{m}_{\mathrm{Fe}} + B_{\mathrm{Tb-Fe}}/\mu_0 M_{\mathrm{Tb}} \boldsymbol{m}_{\mathrm{Fe}}$$

$$\boldsymbol{H}_{\mathrm{exch}}^{\mathrm{Fe}} = 2A_{\mathrm{Fe-Fe}}/\mu_0 M_{\mathrm{Fe}} \nabla^2 \boldsymbol{m}_{\mathrm{Fe}} + 2A_{\mathrm{Fe-Tb}}/\mu_0 M_{\mathrm{Fe}} \nabla^2 \boldsymbol{m}_{\mathrm{Tb}} + B_{\mathrm{Fe-Tb}}/\mu_0 M_{\mathrm{Fe}} \boldsymbol{m}_{\mathrm{Tb}}$$

- Neighbor cells from both sublattice
- Same cell from the other sublattice

The Two-Sublattice Model

The effective field due to the exchange interaction (H_{exch})

	Phase I	Phase II
K_{Tb} (J/m^3)	3.4×10^{5}	1.9×10^{5}
A_{Tb-Tb} (J/m)	1.90×10^{-12}	1.21×10^{-12}
A_{Tb-Fe} (J/m)	-2.43×10^{-12}	-1.87×10^{-12}
A_{Fe-Fe} (J/m)	1.40×10^{-11}	1.68×10^{-11}
B_{Tb-Fe} (J/m^3)	-1.43×10^{7}	-1.09×10^{7}

$$A_{Tb-Tb} = 1/4\, J_{Tb-Tb}\, S \ldots r_{nn}^2\, c_{Tb} / a^3$$

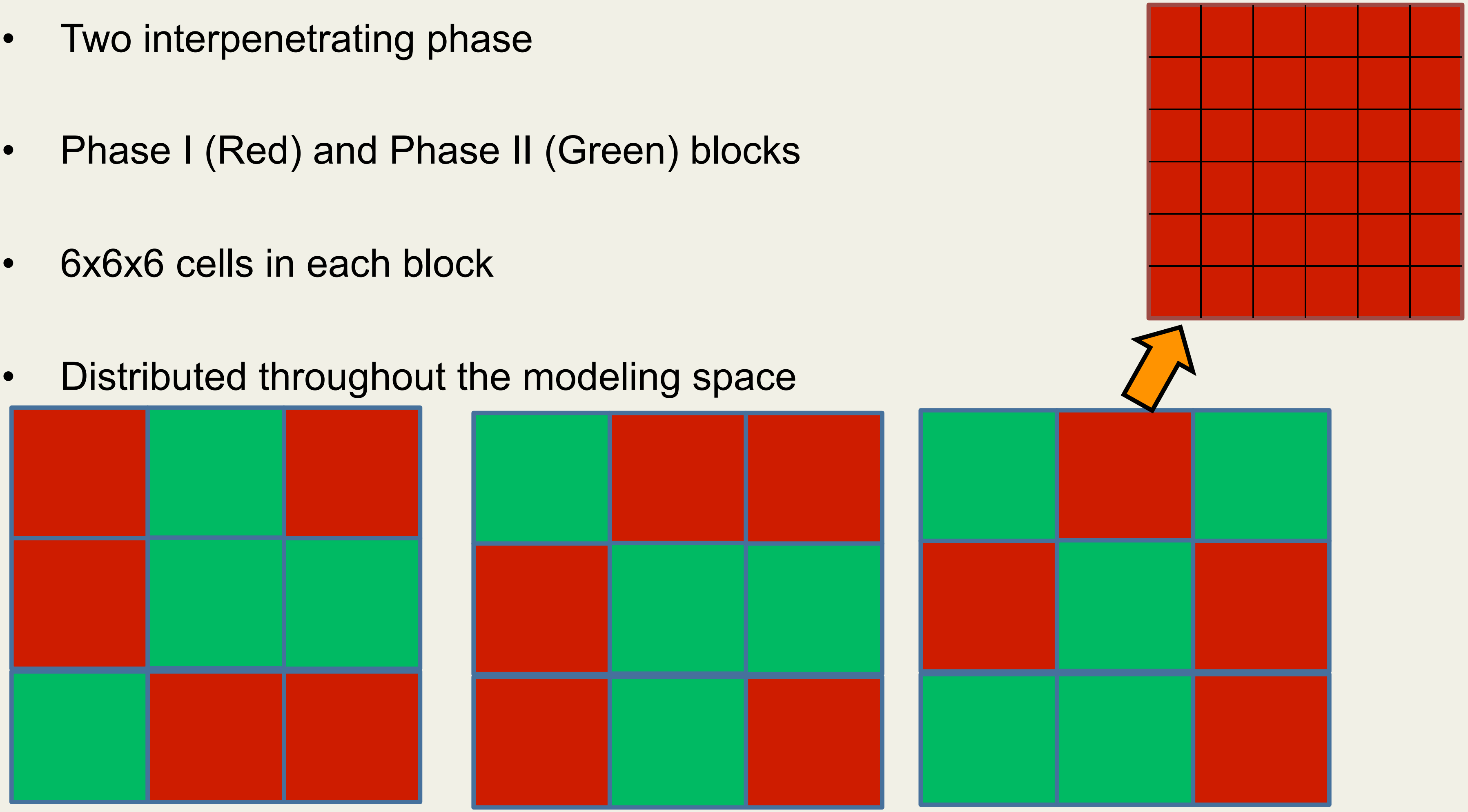
$$A_{Fe-Fe} = 1/4\, J_{Fe-Fe}\, S \ldots r_{nn}^2\, c_{Fe} / a^3$$

$$A_{Tb-Fe} = 1/4\, J_{Tb-Fe}\, S_{Tb}\, S_{Fe}\, z_{Tb-Fe}\, r_{nn}^2\, c_{Tb} / a^3$$

$$A_{Fe-Tb} = 1/4\, J_{Tb-Fe}\, S_{Tb}\, S_{Fe}\, z_{Fe-Tb} \ldots$$

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



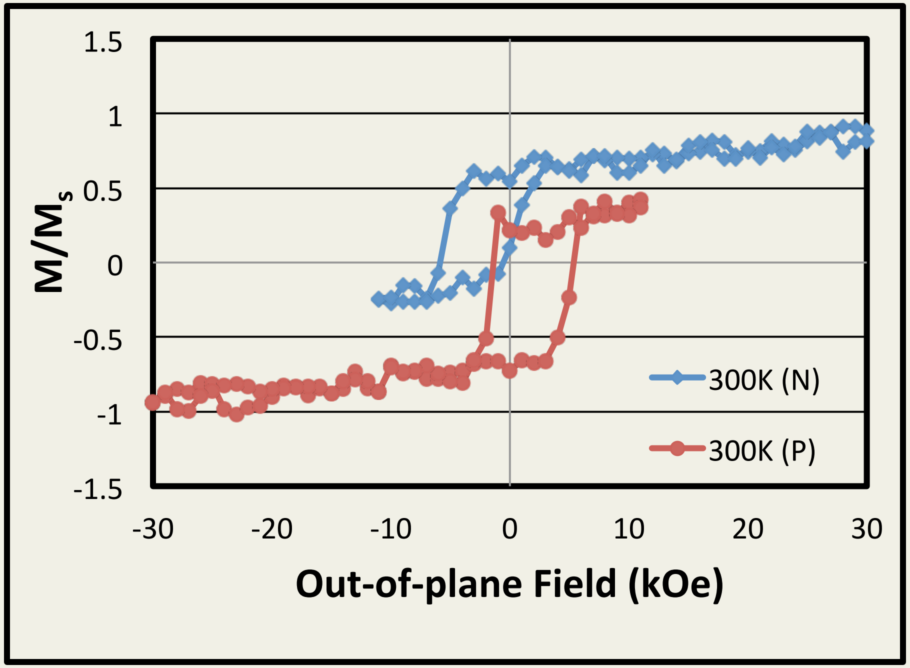
The Two-Phase Model

- 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

M. J. Donahue and D. G. Porter, **OOMMF User's Guide, version 1.0**, Interagency Report No. **NISTIR 6376**, National Institute of Standards and Technology, Gaithersburg, MD, 1999 (http://math.nist.gov/oommf/).

Simulation Result of TbFeCo

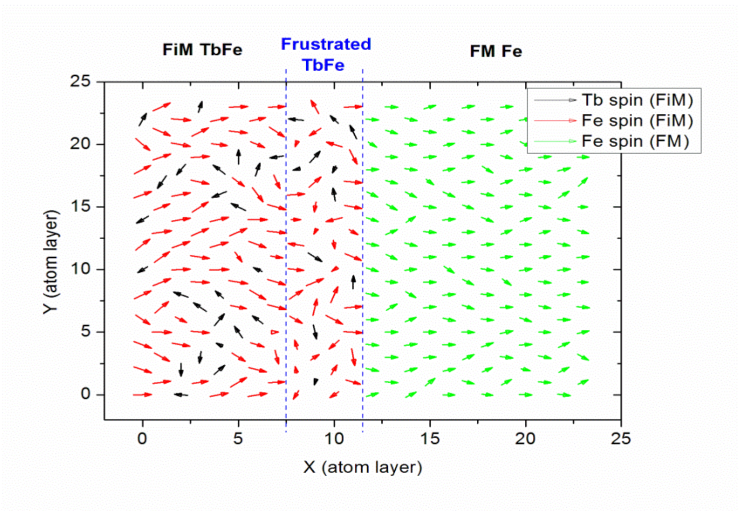
- Positive and negative exchange bias minor loops near T_{comp}
- Positive shift in magnetization accompanied by negative exchange bias
- Negative shift in magnetization accompanied by positive exchange bias

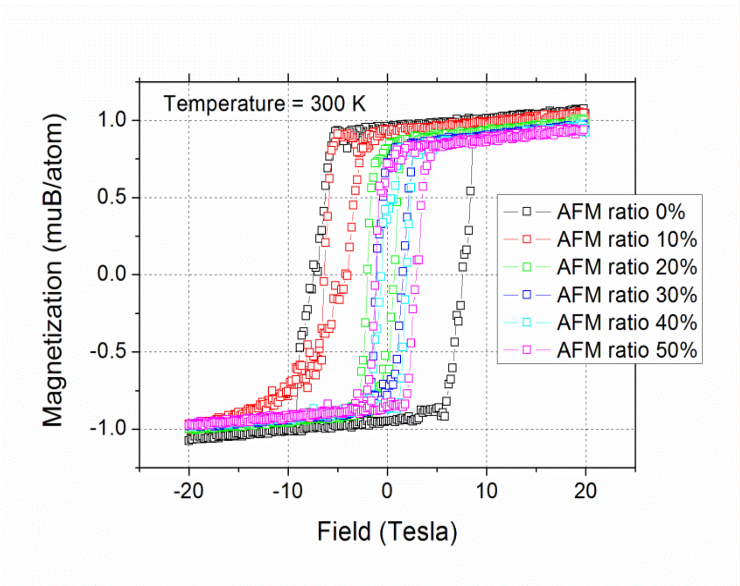


Atomistic Simulations

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_{comp}

This model provides a platform for developing exchange bias materials using ferrimagnets

Summary

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 temperature

Acknowledgement

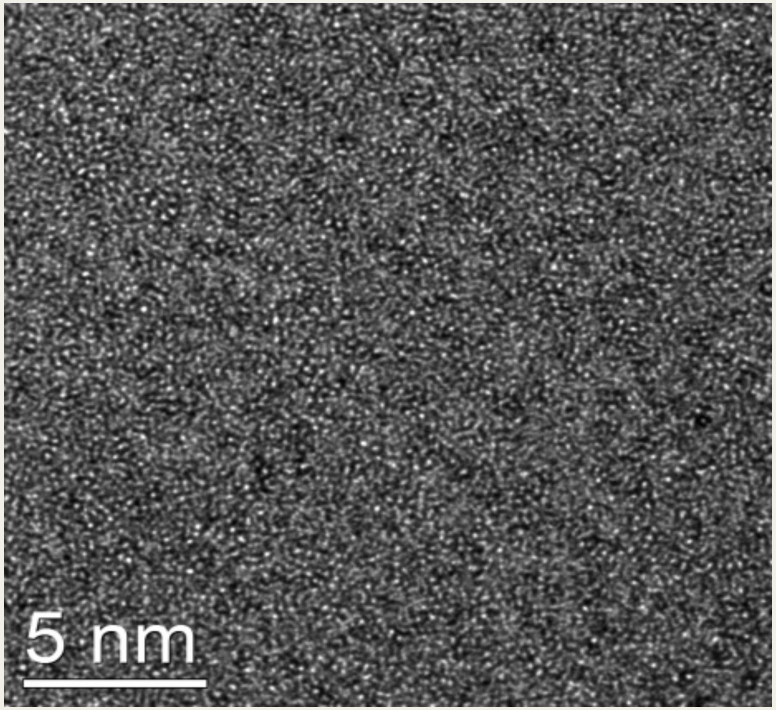
University of Virginia
Professor Jiwei Lu
Professor S. Joseph Poon
Xiaopu Li
Chung Ting (Marco) Ma

Pacific Northwest National Laboratory
Dr. Ryan Comes
Dr. Arun Devaraj
Dr. Steven Spurgeon

Acknowledgement

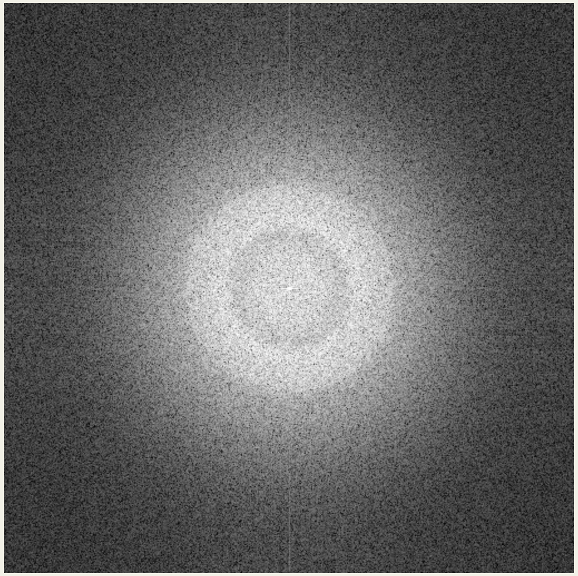
This work was supported by the Defense Threat Reduction Agency (DTRA) grant and the U.S. Department of Energy (DOE).

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

$$\mathcal{H}_A = -\frac{1}{2}\sum_{<i,j>} J_{ij}\,\mathbf{S}_i\cdot\mathbf{S}_j = -\frac{1}{2}\sum_{<Tb_i, Tb_j>} J_{Tb-Tb}\,\mathbf{S}_{Tb_i}\cdot\mathbf{S}_{Tb_j} - \frac{1}{2}\sum_{<Fe_i, Fe_j>} J_{Fe-Fe}\,\mathbf{S}_{Fe_i}\cdot\mathbf{S}_{Fe_i} - \sum_{<Tb_i, Fe_j>} J_{Tb-Fe}\,\mathbf{S}_{Tb_i}\cdot\mathbf{S}_{Fe_j}$$

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

$$\mathcal{H}_{Tb-Tb} = -\frac{1}{2} J_{Tb-Tb} S_{Tb}^2 \sum_{<Tb_i, Tb_j>} \mathbf{m}_{Tb_i}\cdot\mathbf{m}_{Tb_j}$$

$$= const. + \frac{1}{4} J_{Tb-Tb} S_{Tb}^2 \sum_{<Tb_i, Tb_j>} \left(\mathbf{m}_{Tb_i} - \mathbf{m}_{Tb_j}\right)^2$$

Using the continuous assumption

$$\mathbf{m}_{Tb_j} \approx \mathbf{m}_{Tb_i} + \mathbf{r}_{ij}\cdot\nabla\mathbf{m}_{Tb_i}$$

$$\mathcal{H}_{Tb-Tb} \approx \frac{1}{4} J_{Tb-Tb} S_{Tb}^2 z_{Tb-Tb} r_{nn}^2 \sum_{Tb_i} \left(\nabla\mathbf{m}_{Tb_i}\right)^2 = A_{Tb-Tb} \int \left(\nabla\mathbf{m}_{Tb}\right)^2$$

Derivation of effective field due to exchange interaction

The ferrimagnetic (Tb-Fe) term

$$\mathcal{H}_{Tb-Fe} = -\sum_{<Tb_i, Fe_j>} J_{Tb-Fe}\, \mathbf{S}_{Tb_i} \cdot \mathbf{S}_{Fe_j} = \frac{1}{2} J_{Tb-Fe} S_{Tb} S_{Fe} \sum_{<Tb_i, Fe_j>} (\mathbf{m}_{Tb_i} - \mathbf{m}_{Fe_j})^2$$

Using the continuous assumption to expand $\mathbf{m}_{Fe_j}$

$$\mathcal{H}_{Tb-Fe} \approx \frac{1}{2} J_{Tb-Fe} S_{Tb} S_{Fe} \sum_{<Tb_i, Fe_j>} (\mathbf{m}_{Tb_i} - \mathbf{m}_{Fe_i} - \mathbf{r}_{ij} \cdot \nabla \mathbf{m}_{Fe_i} - \frac{1}{2} \mathbf{r}_{ij}^2 \nabla^2 \mathbf{m}_{Fe_i})^2$$

$$\approx \frac{1}{2} J_{Tb-Fe} S_{Tb} S_{Fe} \sum_{<Tb_i, Fe_j>} ((\mathbf{m}_{Tb_i} - \mathbf{m}_{Fe_i})^2 - 2(\mathbf{m}_{Tb_i} -$$

Derivation of effective field due to exchange interaction

$$\mathcal{H}_A = \int (A_{Fe-Fe}(\nabla \mathbf{m}_{Fe})^2 + A_{Tb-Tb}(\nabla \mathbf{m}_{Tb})^2 - 2A_{Tb-Fe}\,\mathbf{m}_{Tb}\cdot\nabla^2 \mathbf{m}_{Fe} - B_{Tb-Fe}(\mathbf{m}_{Tb}\cdot\mathbf{m}_{Fe}))\,d^3x + 2A_{Tb-Fe}\oint \mathbf{m}_{Fe}\nabla\mathbf{m}_{Fe}\cdot\mathbf{n}\,dS$$

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

$$\mathcal{E}_A = A_{Fe-Fe}(\nabla \mathbf{m}_{Fe})^2 + A_{Tb-Tb}(\nabla \mathbf{m}_{Tb})^2 - 2A_{Tb-Fe}\,\mathbf{m}_{Tb}\nabla^2 \mathbf{m}_{Fe} - B_{Tb-Fe}(\mathbf{m}_{Tb}\cdot\mathbf{m}_{Fe})$$

The effective field due to exchange interaction

$$\mathbf{H}_{eff,Tb} = -\frac{\delta\mathcal{E}_A}{\mu_0 M_{s,Tb}\,\delta\mathbf{m}_{Tb}} = \frac{2}{\mu_0 M_{s,Tb}} A_{Tb-Tb}\nabla^2 \mathbf{m}_{Tb} + \frac{2}{\mu_0}$$