Exchange Bias(EB): I.AFM Partial Wall Models

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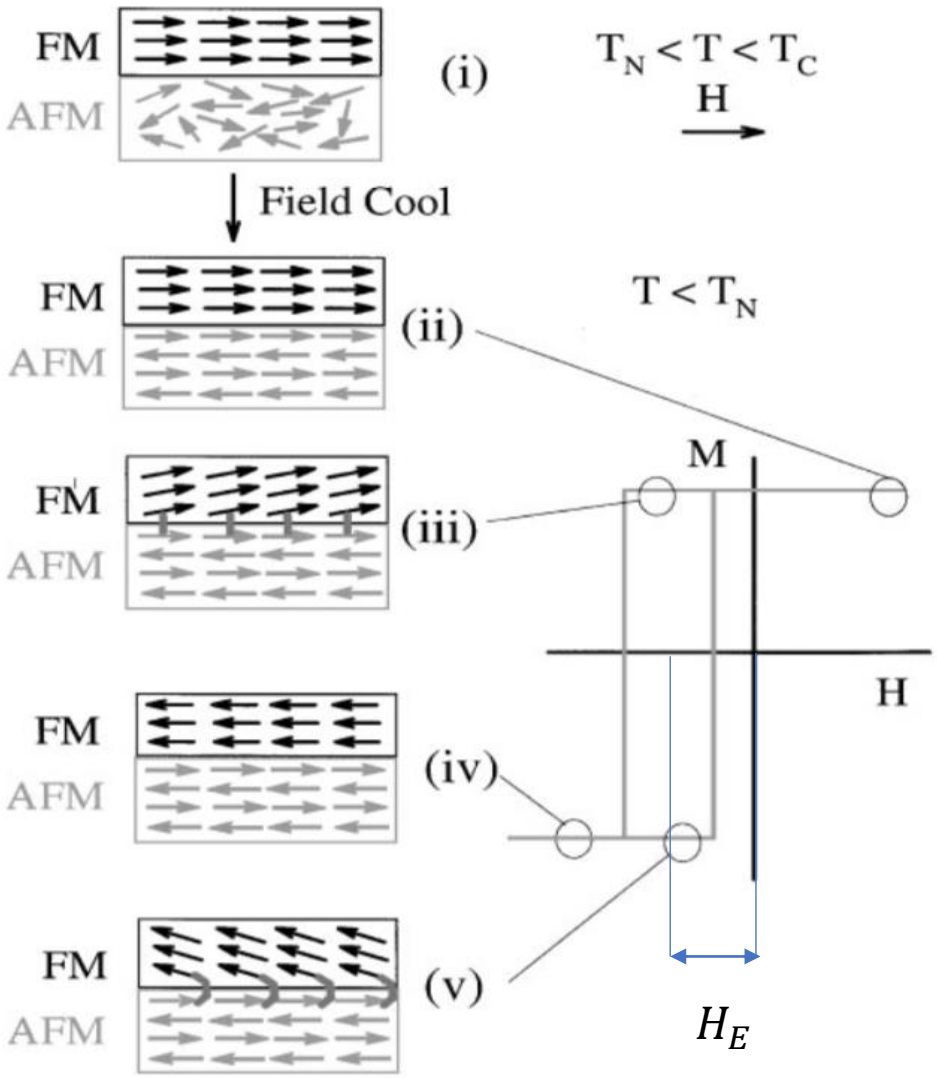
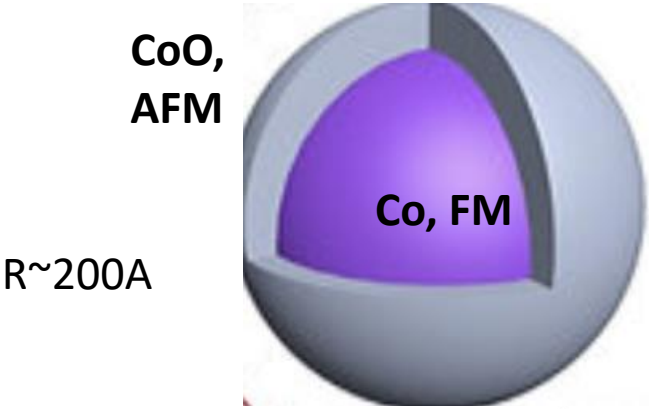
2019.08.02

What is EB?

W.P. Meiklejohn, C.P. Bean, Phys. Rev. 102 (1956) 1413





$T_C = 1388\ K$

$T_N = 293K$

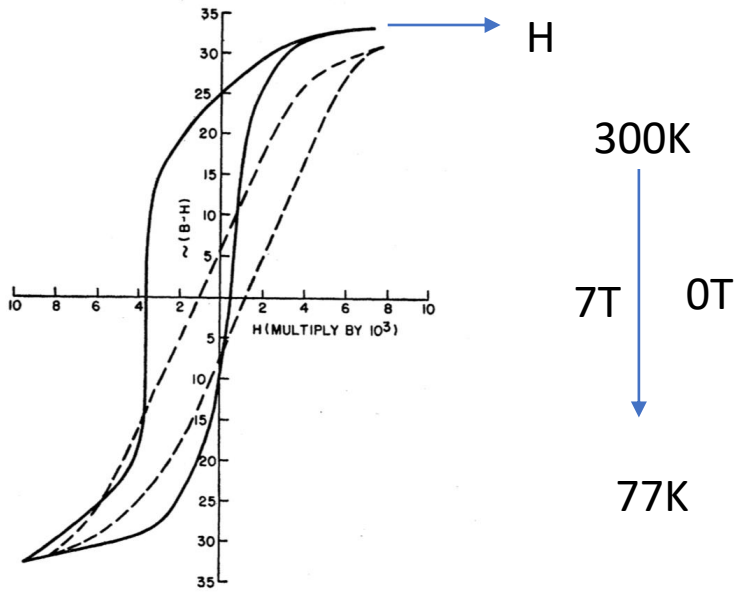


FIG. 3. Hysteresis loops of fine oxide-coated particles of cobalt taken at 77°K. The dashed lines show the hysteresis loop when the material is cooled in the absence of a magnetic field. The solid lines show the hysteresis loop when the material is cooled in a saturating magnetic field.

A Naïve Model: Rigid Antiferromagnet Model

Assumptions:

(0) Thin film system

(1) AFM remains rigidly aligned along its easy axis

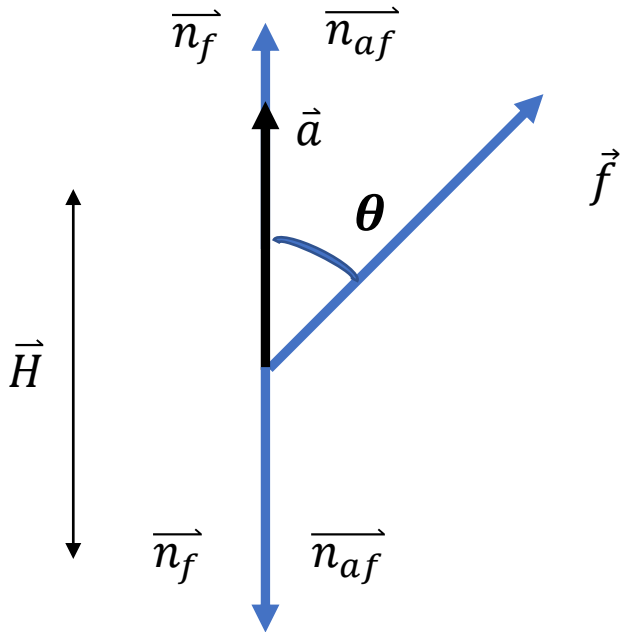
(2) Perfect interface

(3) uncompensated interface

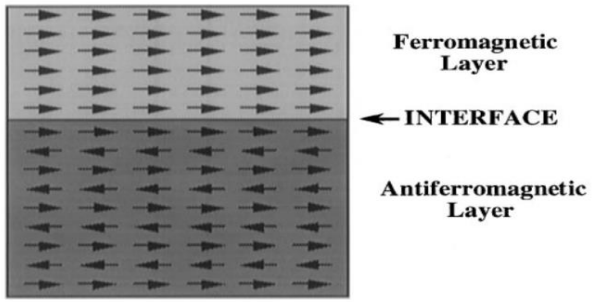
(4) Uniform magnetization

(5) Uniaxial FM anisotropy

W.P. Meiklejohn, J. Appl. Phys. 33 (1962) 1328.
R.L. Stamps, J. Phys. D: Appl. Phys. 33 (2000) R247



$$E = -HMt_f \cos\theta - J\cos\theta + K_f \sin^2\theta.$$



H: applied field; M: saturation magnetization of FM
J: FM-AFM interlayer exchange; t_f: the thickness of FM film
K_f: uniaxial anisotropy in FM

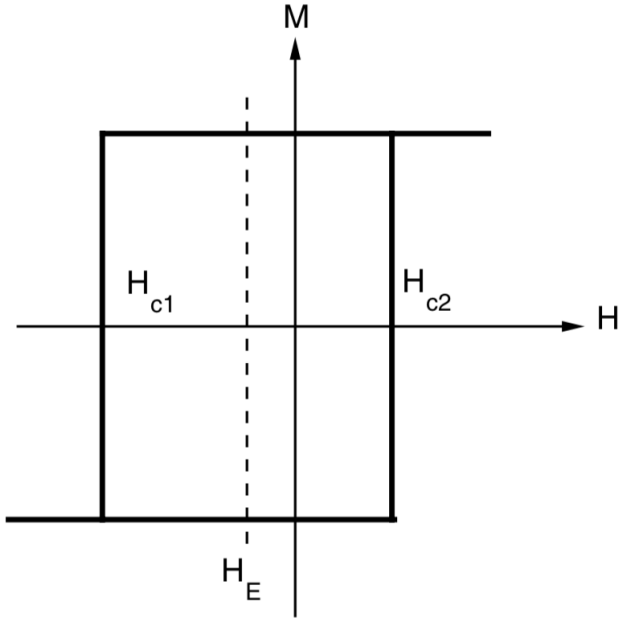
A Naïve Model: Rigid Antiferromagnet Model

$$E = -HMt_f \cos\theta - J\cos\theta + K_f \sin^2\theta.$$

$$\begin{cases} \dfrac{\partial E}{\partial \theta} = 0 \\ \dfrac{\partial^2 E}{\partial \theta^2} = 0 \end{cases} \Rightarrow \begin{cases} \theta = 0, \pi \\ H_{c2} < H \ or, H < H_{c1} \end{cases}$$

where $H_{c1} \equiv -\frac{2K_f + J}{Mt_f}, H_{c2} \equiv \frac{2K_f - J}{Mt_f}$

$$H_E = \frac{H_{c1} + H_{c2}}{2} = \frac{-J}{Mt_f}$$



Conclusions: (1) EB comes from exchange interaction between Interface AFM and FM spins

(2) Coercivity originates from FM anisotropy

(3) $H_E \propto \frac{1}{t_f}$

Failure of this Naïve Model

TABLE I. Experimental values for the $Ni_{80}Fe_{20}/Fe_{50}Mn_{50}$ system.

Preparation method	Substrate	$t_{Ni\text{-}Fe}$ (Å)	$H_{eb}t_{Ni\text{-}Fe}$ (kA/m Å)	$Fe_{100-x}Mn_x$ (at. %)
MBE[a]	Cu(111)	68	1000	57
MBE[a]	Cu(110)	70	620	59
MBE[a]	Cu(001)	70	690	47
HV evap.[b]	[f]	400	670	57
HV evap.[b]	[f]	400	1160	53
HV evap.[b]	[f]	400	1040	47
HV evap.[b]	[f]	400	1000	46
HV evap.[b]	[f]	400	920	44
Sputtered[c]	Si(001)/Ta/Ni-Fe/Cu	60	1320	50
Sputtered[d]	Si(111)	400	1280	50
Sputtered[e]	Glass	400	360–820	50

Implications:

(1) $H_E < 0$

(2) Uncompensated interfaces should display the largest magnitudes of $|H_E|$

(3) The roughness of a compensated interface should increase $|H_E|$

Experimental Results:

W.P. Meiklejohn, J. Appl. Phys. 33 (1962) 1328

(1) H_E is orders of magnitude larger than that of experimentally observed. $(H_E t_f)_{theory} = 1.6 \times 10^5 \frac{kA}{m}$ Å. $\gg$. $(H_E t_f)_{experiments} = 360\sim1000$

$Ni_{80}Fe_{20}/Fe_{50}Mn_{50}$

(2) Some crystal orientations exhibit larger loop shifts than uncompensated orientations of the same AFM materials

Fe/FeF_2

J. Nogues, T.J. Moran, D. Lederman, I.K. Schuller, K.V.Rao, Phys. Rev. B

(3) H_E can decrease with the increasing roughness for systems of compensated interface

Fe/FeF_2

TABLE III. Summary of exchange bias properties for FeF_2 films and single crystals.

	Spin direction	Compensated vs. uncompensated	H_E	Roughness dependence of $\|H_E\|$
[110]				
Films	0°	Compensated	Large	Decrease
Crystals	0°	Compensated	Small	Increase
[101]				
Films	55°	Compensated	Moderate	Decrease
Crystals				
[001]				
Films	90°	Uncompensated	Zero	Unchanged
Crystals	90°	Uncompensated	Zero	Unchanged
[100]				
Films				
Crystals	0°	Uncompensated	Zero	Unchanged

EB Models for thin film system

I. ***Partial Wall Models***: the reorientation of the ferromagnet through application of an applied magnetic field can require formation of magnetic domain wall structures on either side of the interface

Mauri D, Siegmann H C, Bagus P S and Kay E 1987 *J. Appl. Phys.* **62** 3047–9

Koon N C 1997 *Phys. Rev. Lett.* **78** 4865–8

Schulthess T C and Butler W H 1998 *Phys. Rev. Lett.* **81** 4516–9

Stiles M D and McMichael R D 1999a *Phys. Rev.* B **59** 3722–33

Camley R E, McGrath B V, Astalos R J, Stamps R L, Kim J-V and Wee L 1999 *J. Vac. Sci. Technol.* A **17** 1335–9

Kiwi M, Mej´ıa-Lopez J, Portugal R D and Ramırez R 1999b *Appl. Phys. Lett.* **75** 3995–7

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II. ***Domain Wall Models***: with considerations of domain formation and domain wall motion, pinning and de-pinning during reversal of the ferromagnet.

Meiklejohn 1962; Schlenker and Paccard 1967; Schlenker 1968a, 1968b; Neel 1988; Malozemoff 1987;Nemoto *et al* 1999; Nikitenko *et al* 2000; Kiwi *et al* 1999a; Li and Zhang 2000; Kiwi *et al* 1999a; Leighton *et al* 2000;

EB Models for thin film system

III. ***Random Interface Field Models*** : Random interface roughness gives rise to a random magnetic field that acts on the interface spins, yielding unidirectional anisotropy.

A.P. Malozemoff, Phys. Rev. B 35 (1987) 3679.

T.C. Schulthess, W.H. Butler, Phys. Rev. Lett. 81 (1998) 4516

T.C. Schulthess, W.H. Butler, J. Appl. Phys. 85 (1999) 5510

……

IV. ***Spin Wave Model***: The interface coupling is a consequence of the emission and reabsorption , by a frromagneitc spin, of virtual AF spin waves across the interface.

T.M. Hong, Phys. Rev. B 58 (1998) 97.

H. Suhl, I.K. Schuller, Phys. Rev. B 58 (1998) 258

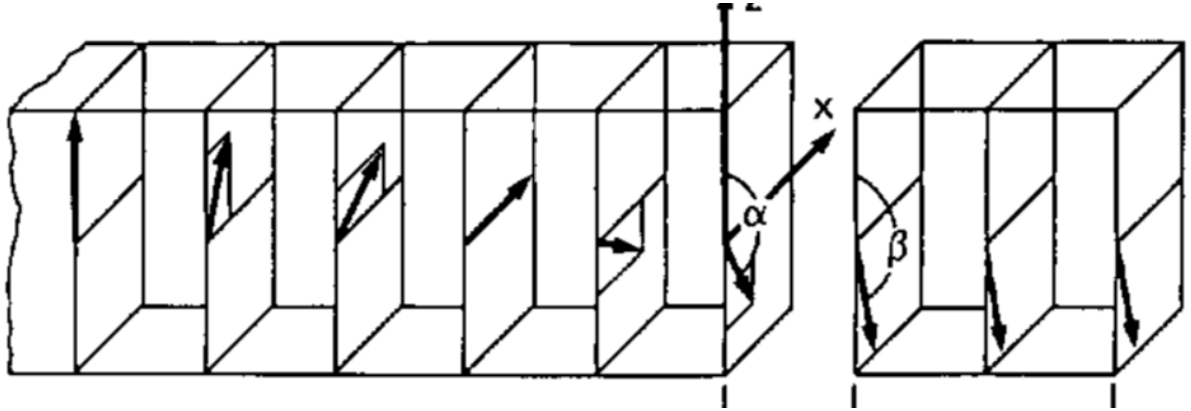
AFM Partial Wall Models: Uncompensated interfa

Assumptions:

(1) Uncompensated interface

(2) No FM anisotropy

(3) AFM partial wall



AFM

FM

$$E_{\mathrm{u}} = -\boldsymbol{H} M t_{\mathrm{f}} \cdot \boldsymbol{f} + J_1 \boldsymbol{f} \cdot \boldsymbol{a} + \sigma(1 - \boldsymbol{a} \cdot \boldsymbol{n}_{\mathrm{af}}).$$

$$H_{\mathrm{E}} = \frac{J_1}{M t_{\mathrm{f}} \sqrt{1 + \left(\frac{J_1}{2\sigma}\right)^2}}.$$

$$d_w \sim \frac{J_1}{\sigma}$$

$J_1 = \sigma$

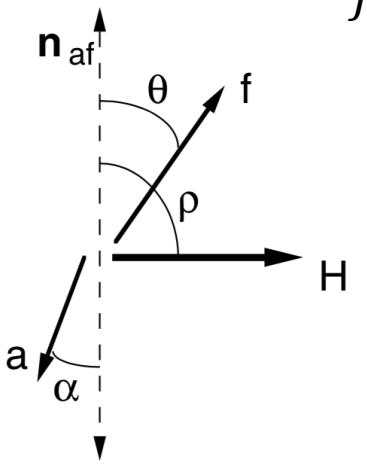


Figure 5. Angles for the applied field, ferromagnet, and antiferromagnet defined in reference to the antiferromagnet uniaxial anisotropy axis $\boldsymbol{n}_{\mathrm{af}}$.

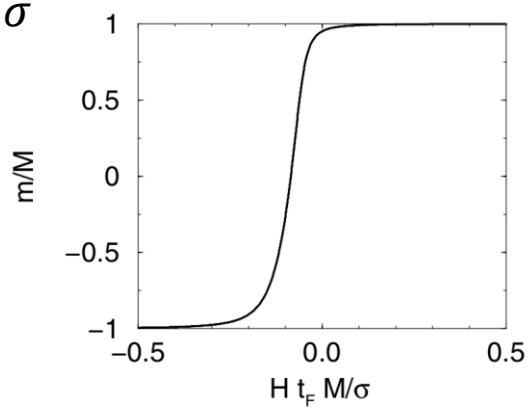


Figure 3. Magnetization along the direction of an applied magnetic field as a function of the field for an exchange biased structure. The interface has only one antiferromagnet sublattice present (uncompensated) and $J_1 = 1$. There is no anisotropy in the ferromagnet, and the bias involves a twist formed in the antiferromagnet. Note the asymptotic approach to saturation for negative field.

σ: the energy per unit surface of a 90° domain wall in AFM

Mauri D, Siegmann H C, Bagus P S and Kay E 1987 J. Appl. Phys. 62 3047–9

AFM Partial Wall Models: Compensated interface

Clue: exchange coupling to a FM at a compensated interface could automatically generate a small magnetic moment through a spontaneous canting of AFM spins; Spins in the interface region are frustrated by competing AFM exchange between the two sublattices and the FM

Koon N C 1997 *Phys. Rev. Lett.* **78** 4865–8

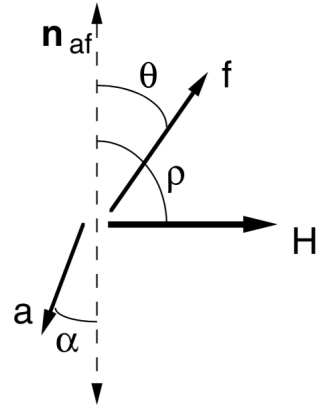


Figure 5. Angles for the applied field, ferromagnet, and antiferromagnet defined in reference to the antiferromagnet uniaxial anisotropy axis n_{af}.

Assumptions:

$$E_{\text{inter}} = -\boldsymbol{H} M t_{\text{f}} \cdot \boldsymbol{f} + J_1 \boldsymbol{f} \cdot \boldsymbol{a} + J_2 (\boldsymbol{f} \cdot \boldsymbol{a})^2 + \sigma (1 - \boldsymbol{a} \cdot \boldsymbol{n}_{\text{af}})$$

$$J_1 = 0 \quad \rho = \frac{\pi}{2} \qquad H_{\text{E}} = \frac{\sigma}{2 t_{\text{F}} M} \sqrt{1 - \left(\frac{\sigma}{4 J_2}\right)^2}.$$

$$J_2 > \sigma$$

Interface exchange larger than the energy required to form a wall in the antiferromagnet

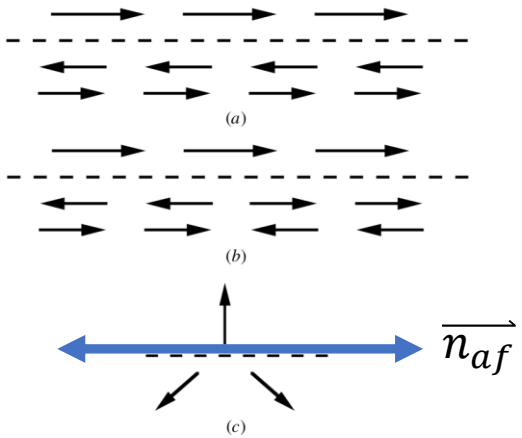


Figure 4. Schematic structure of a two sublattice antiferromagnet at (*a*) an uncompensated interface and (*b*) a fully compensated interface. Spin canting at a compensated interface is illustrated in (*c*).

J.C. Slonczewski, Phys. Rev. Lett. 67, 3172 (1991)

M. Riihrig, R. Schafer, A. Hubert, R. Mosler, J. A. Wolf, S. Demokritov, and P. Griinberg, Phys. Status Solidi (a) 125, 635 (1991)

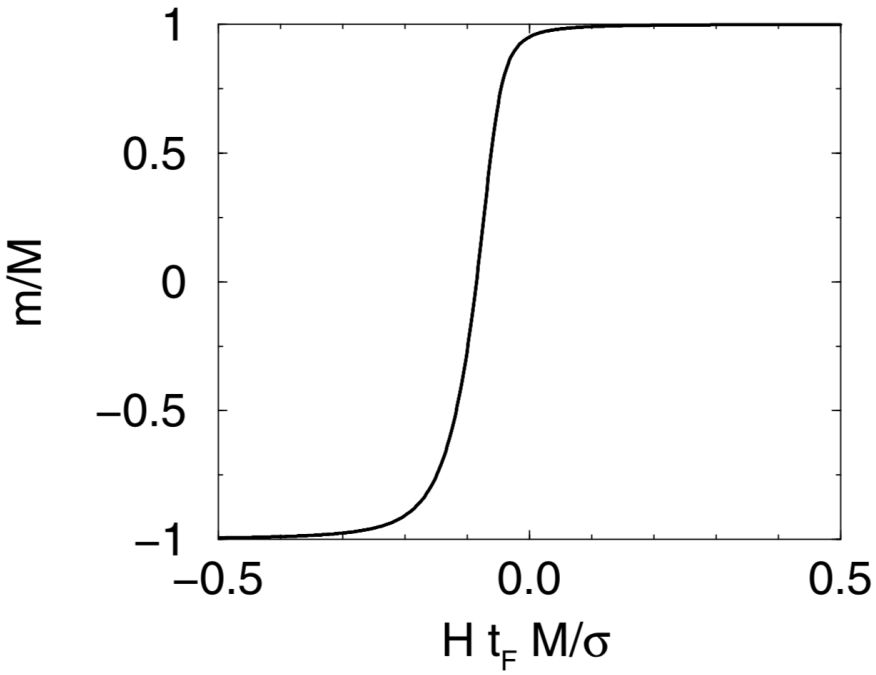
AFM Partial Wall Models: Stability Analysis

$$E_{\text{inter}} = -\boldsymbol{H} M t_{\text{f}} \cdot \boldsymbol{f} + J_1 \boldsymbol{f} \cdot \boldsymbol{a} + J_2 (\boldsymbol{f} \cdot \boldsymbol{a})^2 + \sigma (1 - \boldsymbol{a} \cdot \boldsymbol{n}_{\text{af}})$$

(1) **Uncompensated interface: $J_1 \gg J_2$**

(2) Compensated interface: $J_1 = 0$

(3) Mixed interface: $J_1 \sim J_2$



$J_1 = 0.1$ and $J_2 = 0.01$

$\rho = 0$

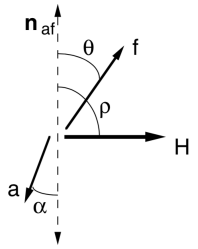
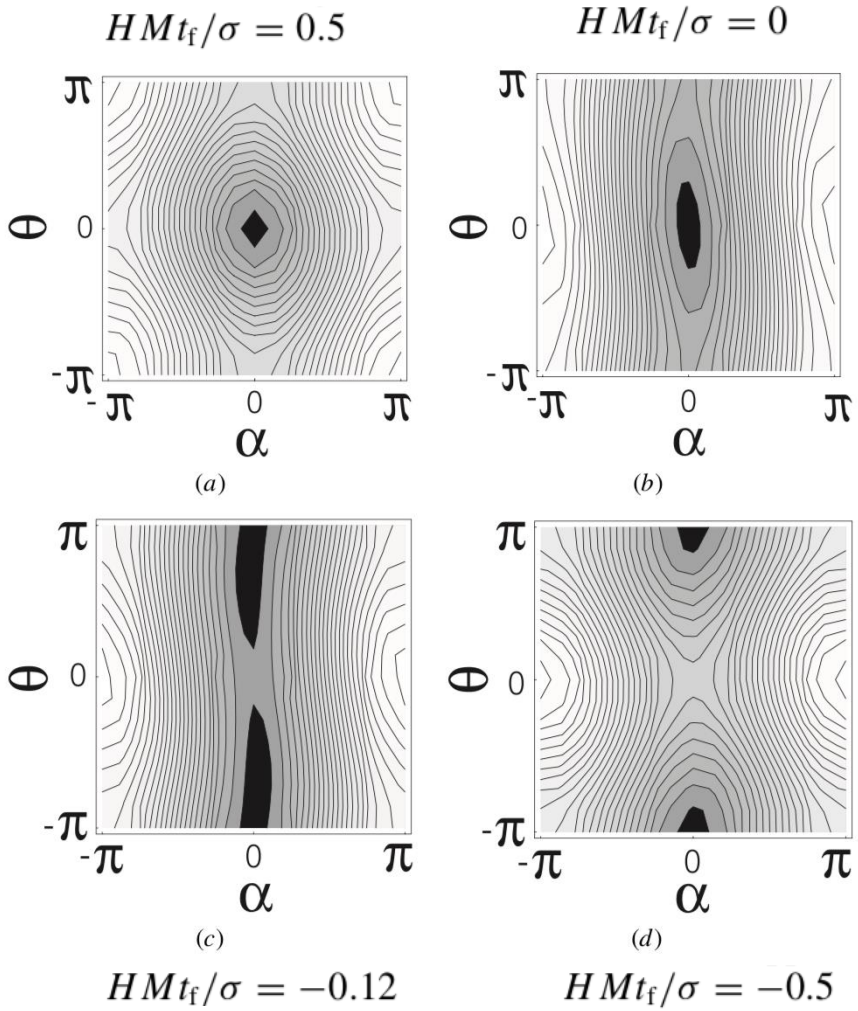
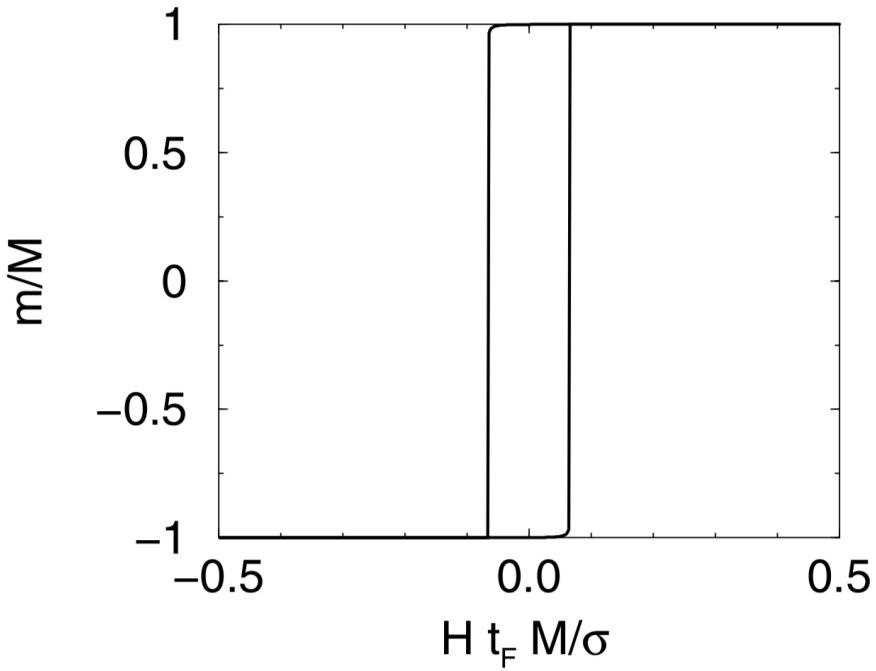


Figure 5. Angles for the applied field, ferromagnet, and antiferromagnet defined in reference to the antiferromagnet uniaxial anisotropy axis n_{af}.



Compensated interface: $J_1 = 0$

$$E_{\text{inter}} = -\boldsymbol{H} M t_{\text{f}} \cdot \boldsymbol{f} + J_1 \boldsymbol{f} \cdot \boldsymbol{a} + J_2 (\boldsymbol{f} \cdot \boldsymbol{a})^2 + \sigma (1 - \boldsymbol{a} \cdot \boldsymbol{n}_{\text{af}})$$



NO EB! Coercivity !

$J_2 = 0.04$

$J_1 = 0$

$\rho = \frac{\pi}{2}$

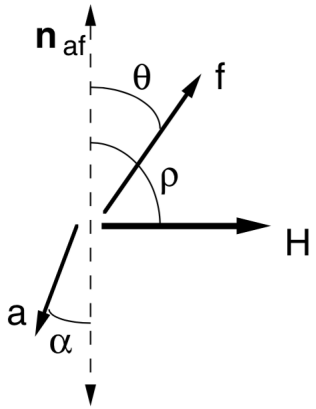
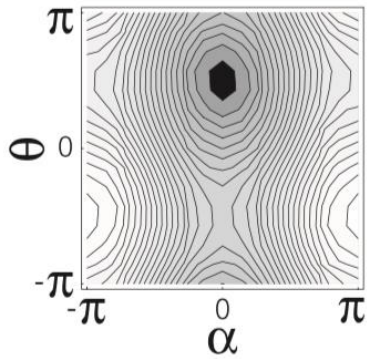


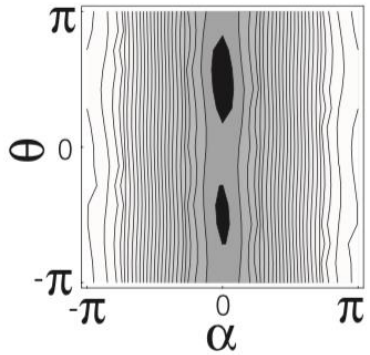
Figure 5. Angles for the applied field, ferromagnet, and antiferromagnet defined in reference to the antiferromagnet uniaxial anisotropy axis $\boldsymbol{n}_{\text{af}}$.

$HMt_{\text{f}}/\sigma = 0.5$



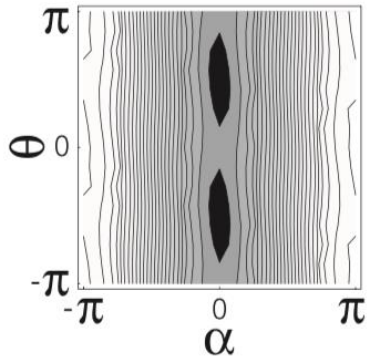
(a)

$HMt_{\text{f}}/\sigma = 0.01$



(b)

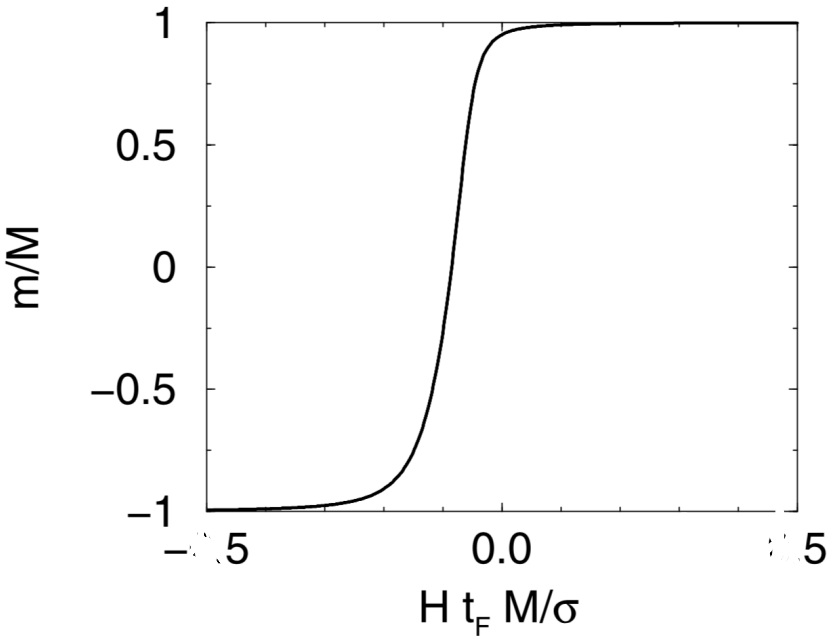
$HMt_{\text{f}}/\sigma = 0$



(c)

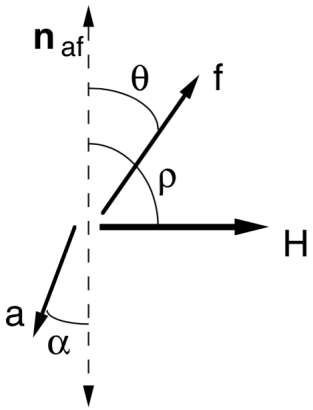
Compensated interface: $J_1 = 0$

$$E_{\text{inter}} = -\boldsymbol{H} M t_{\text{f}} \cdot \boldsymbol{f} + J_1 \boldsymbol{f} \cdot \boldsymbol{a} + J_2 (\boldsymbol{f} \cdot \boldsymbol{a})^2 + \sigma (1 - \boldsymbol{a} \cdot \boldsymbol{n}_{\text{af}})$$



$$J_2 = 1.5\,\sigma$$
$$\rho = \frac{\pi}{2}$$

No coercivity! EB!



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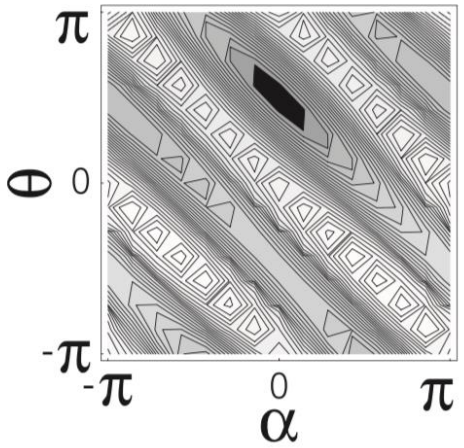
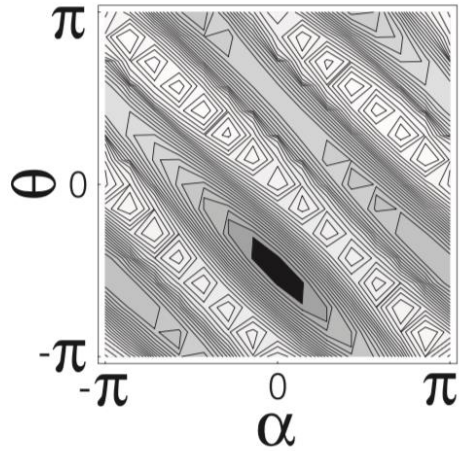


$HMt_{\text{f}}/\sigma = 2$

(a)

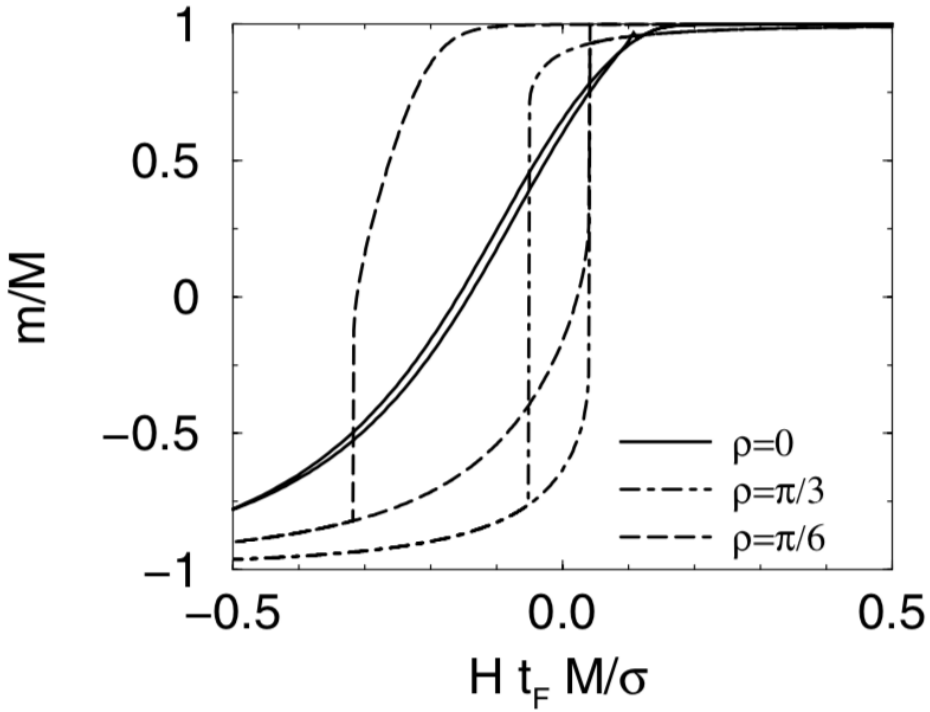


$HMt_{\text{f}}/\sigma = -2$

(b)

(3) Mixed interface: $J_1 \sim J_2$

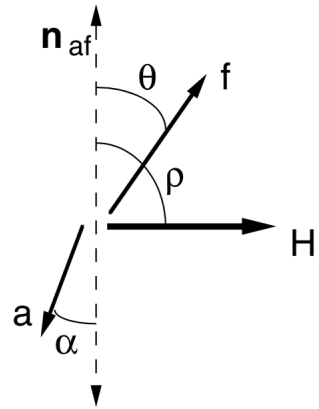
$$E_{\text{inter}} = -\boldsymbol{H} M t_{\text{f}} \cdot \boldsymbol{f} + J_1 \boldsymbol{f} \cdot \boldsymbol{a} + J_2 (\boldsymbol{f} \cdot \boldsymbol{a})^2 + \sigma (1 - \boldsymbol{a} \cdot \boldsymbol{n}_{\text{af}})$$



$J_1 = 0.2$

$J_2 = 0.16$

$\rho = \pi/6$



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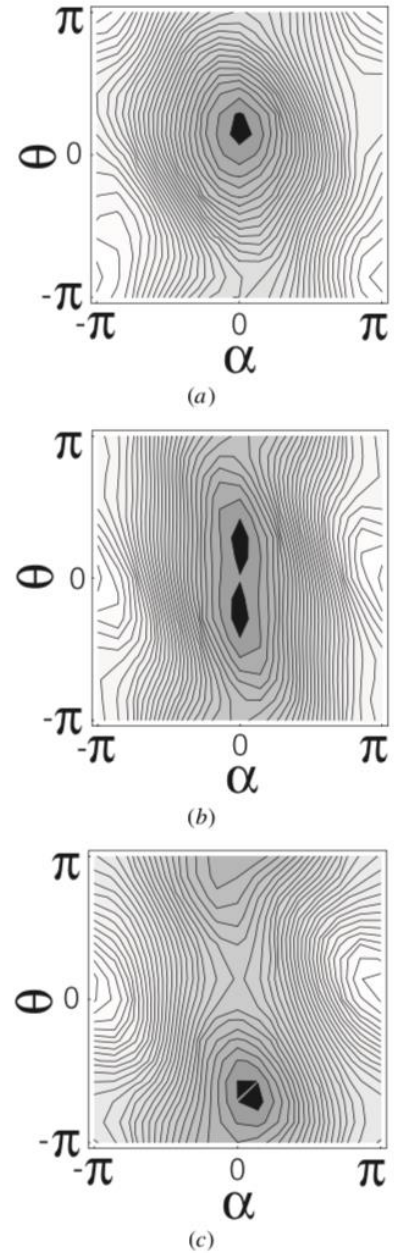

$H M t_{\text{f}}/\sigma = +0.5$

$H M t_{\text{f}}/\sigma = 0$

$H M t_{\text{f}}/\sigma = -0.5$