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

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

CoO, AFM

Co, FM

$T_C = 1388 \, K$

$T_N = 293 \, K$

R ~ 200A

Fig. 3. Hysteresis loop of fine oxide-coated particles of cobalt taken at 77K. 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:**

1. Thin film system
2. AFM remains rigidly aligned along its easy axis
3. Perfect interface
4. Uncompensated interface
5. Uniform magnetization
6. Uniaxial FM anisotropy

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

- \( H \): 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

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![Diagram of a Naive Model: Rigid Antiferromagnet Model](image)
A Naïve Model: Rigid Antiferromagnet Model

\[ E = -H M t_f \cos \theta - J \cos \theta + K_f \sin^2 \theta. \]

\[
\frac{\partial E}{\partial \theta} = 0 \\
\frac{\partial^2 E}{\partial \theta^2} = 0
\]

\[
\begin{cases} 
\theta = 0, \pi \\
H_{c2} < H \text{ or } H < H_{c1}
\end{cases}
\]

\[
H_E = \frac{H_{c1} + H_{c2}}{2} = \frac{-J}{M t_f}
\]

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

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:

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

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

\[ \text{Fe/FeF}_2 \]


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

\[ \text{Fe/FeF}_2 \]
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


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

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.


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

AFM Partial Wall Models: Uncompensated interface

Assumptions:

1. Uncompensated interface
2. No FM anisotropy
3. AFM partial wall

\[ E_u = -HMm_f \cdot f + J_1 f \cdot a + \sigma (1 - a \cdot n_{af}) \]

\[ H_E = \frac{J_1}{M t_f \sqrt{1 + \left( \frac{J_1}{2\sigma} \right)^2}}. \quad d_w \sim \frac{J_1}{\sigma} \]

\( \sigma \): the energy per unit surface of a 90° domain wall in AFM

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

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.

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

**Assumptions:**

\[ E_{\text{inter}} = -HMf \cdot f + J_1 f \cdot a + J_2 (f \cdot a)^2 + \sigma (1 - a \cdot n_{af}) \]

\[ J_1 = 0 \quad \rho = \frac{\pi}{2} \quad H_E = \frac{\sigma}{2t_FM} \sqrt{1 - \left( \frac{\sigma}{4J_2} \right)^2} \]

\[ J_2 > \sigma \]

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

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**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).

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


AFM Partial Wall Models: Stability Analysis

1. Uncompensated interface: $J_1 \gg J_2$
2. Compensated interface: $J_1 = 0$
3. Mixed interface: $J_1 \sim J_2$

\[ E_{inter} = -HM_t f + J_1 f \cdot a + J_2 (f \cdot a)^2 + \sigma (1 - a \cdot n_{af}) \]

- $J_1 = 0.1$ and $J_2 = 0.01$
- $\rho = 0$

Figure 6: Angles for the applied field, magnetostatic, and anisotropy energies defined in reference to the easy axis [$\alpha$] and surface normal [$n_{af}$]

- $HM_t/\sigma = 0.5$
- $HM_t/\sigma = 0$
- $HM_t/\sigma = 0.12$
- $HM_t/\sigma = -0.5$
Compensated interface: $J_1 = 0$

\[ E_{\text{inter}} = -HM t_f \cdot f + J_1 f \cdot a + J_2 (f \cdot a)^2 + \sigma (1 - a \cdot n_{\text{af}}) \]

\[ J_2 = 0.04 \]

\[ J_1 = 0 \]

\[ \rho = \frac{\pi}{2} \]

\[ HM t_f / \sigma = 0.5 \]

\[ HM t_f / \sigma = 0.01 \]

\[ HM t_f / \sigma = 0 \]

**Figure 5.** Angles for the applied field, ferromagnet, and antiferromagnet defined in reference to the antiferromagnet uniaxial anisotropy axis $n_{\text{af}}$. NO EB! Coercivity!
Compensated interface: \( J_1 = 0 \)

\[
E_{\text{inter}} = -HM\mathbf{f} \cdot \mathbf{f} + J_1 \mathbf{f} \cdot \mathbf{a} + J_2 (\mathbf{f} \cdot \mathbf{a})^2 + \sigma (1 - \mathbf{a} \cdot \mathbf{n}_{af})
\]

\[
J_2 = 1.5 \sigma
\]

\[
\rho = \frac{\pi}{2}
\]

No coercivity! EB!

Figure 5. Angles for the applied field, ferromagnet, and antiferromagnet defined in reference to the antiferromagnet uniaxial anisotropy axis \( n_{af} \).
(3) Mixed interface: $J_1 \sim J_2$

$$E_{\text{inter}} = -HM t_f \cdot f + J_1 f \cdot a + J_2 (f \cdot a)^2 + \sigma (1 - a \cdot n_{af})$$

$$J_1 = 0.2$$
$$J_2 = 0.16$$
$$\rho = \pi/6$$

$HM t_f / \sigma = +0.5$
$HM t_f / \sigma = 0$
$HM t_f / \sigma = -0.5$

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