Exchange bias and coercivity of ferromagnetic/antiferromagnetic multilayers

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Contents:

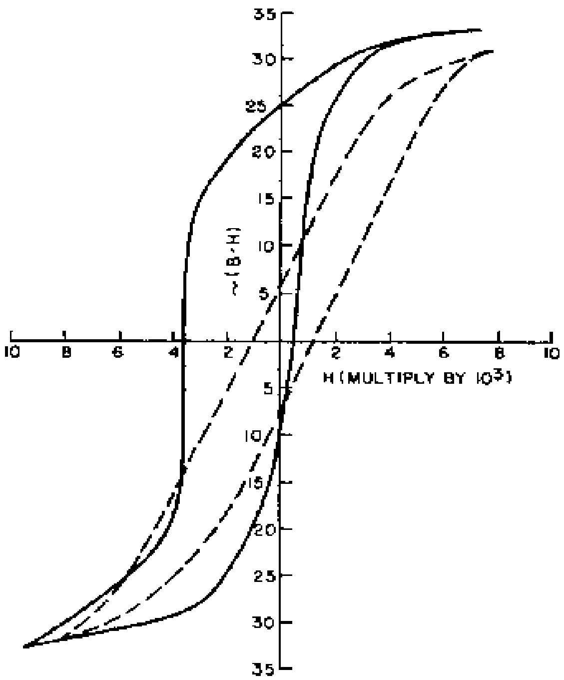
- exchange bias: introduction
- domain state model: results from MC simulations
- mean field approach for Ising AFM: coercivity and exchange bias
- generalisation to local vector spin models: dynamical consequences
- conclusions

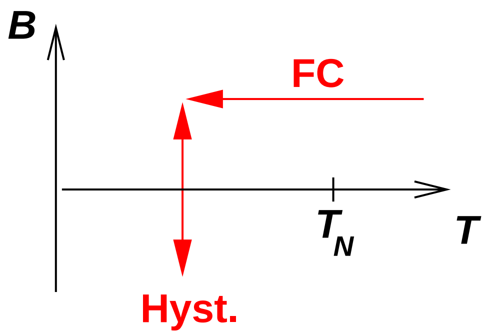
Coworkers:

- *U. Nowak, A. Misra, B. Beckmann, R. Stamps*

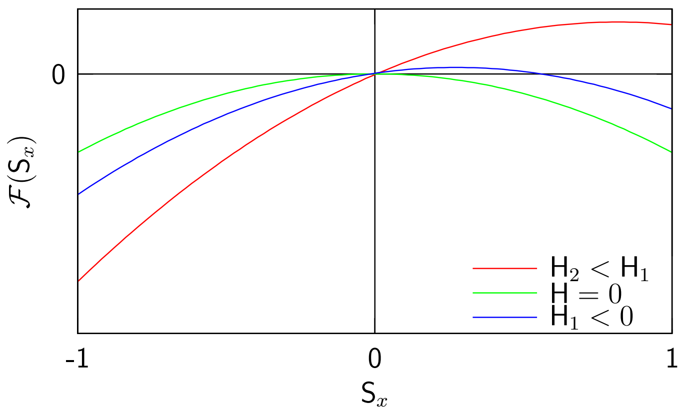
Exchange bias

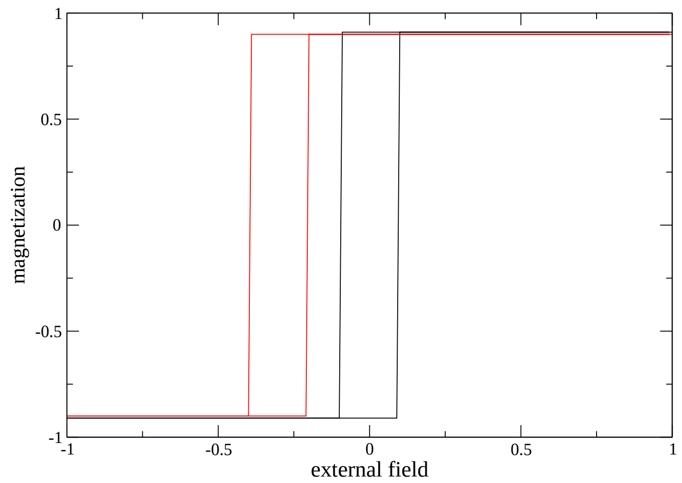
- exchange bias (EB) = shifted hysteresis loop
- first observation in Co/CoO particles (*Meiklejohn and Bean, Phys. Rev.* **102**,*1413 (1956)*)
- typical for FM/AFM compounds like multilayers, nanoparticles
- initial procedure: cooling the system in an external field from above to below Neel temperature of the AFM
- loop is shifted upwards and asymmetric; enhancement of the coercivity





Applications: sensors





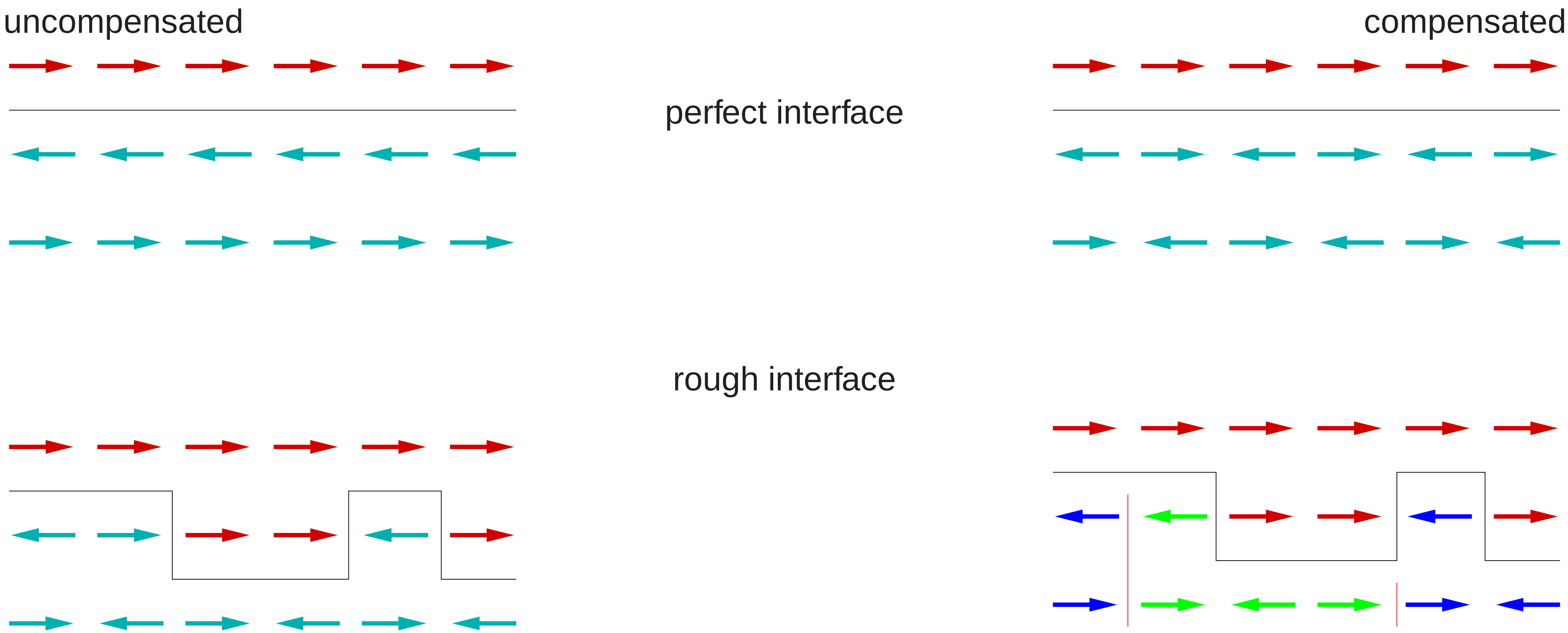
$$\mathcal{F}(S_x) \quad = \quad -DS_x^2 - BS_x$$

The fields B_- and B_+ at which the magnetization of the FM switches are obtained from $\mathcal{F}' = 0$ at $S_x = 1$ and $S_x = -1$, respectively:

$$B_- \quad = \quad -2D,$$
$$B_+ \quad = \quad 2D.$$

Understanding EB: problems

- external field and exchange field of the FM interface layer polarizes the AFM interface layer
- why is the polarisation stable during a hysteresis cycle? why is the symmetry broken?

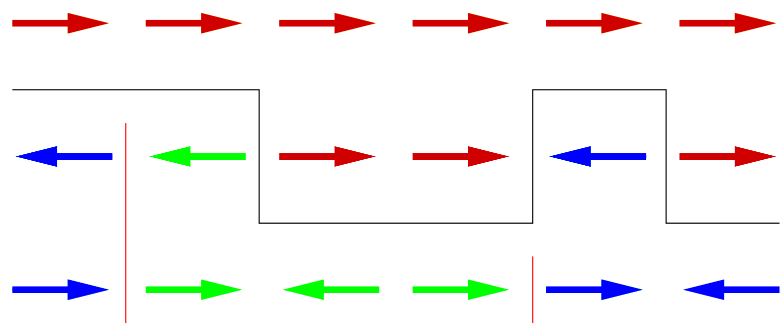


Domain wall formation

Solution: domain walls in the AFM

- breaking the symmetry necessary for EB by introducing frozen domains
- perpendicular domain walls in the AFM due to interface roughness

  (Malozemoff, Phys. Rev. B **35***, 3679 (1987))*

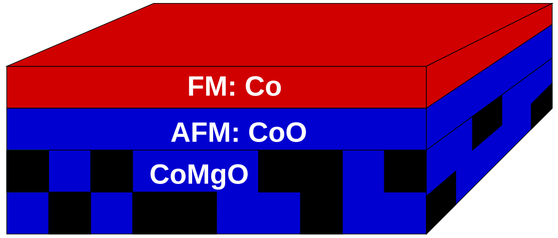


- but: domain wall formation unlikely for large AFM thicknesses
- **idea: introducing defects in the AFM to stabilize domains: domain state model**

  (Miltenyi, Gierlings, Keller, Beschoten, Güntherodt, Nowak, and Usadel, PRL **84***, 4224 (2000))*

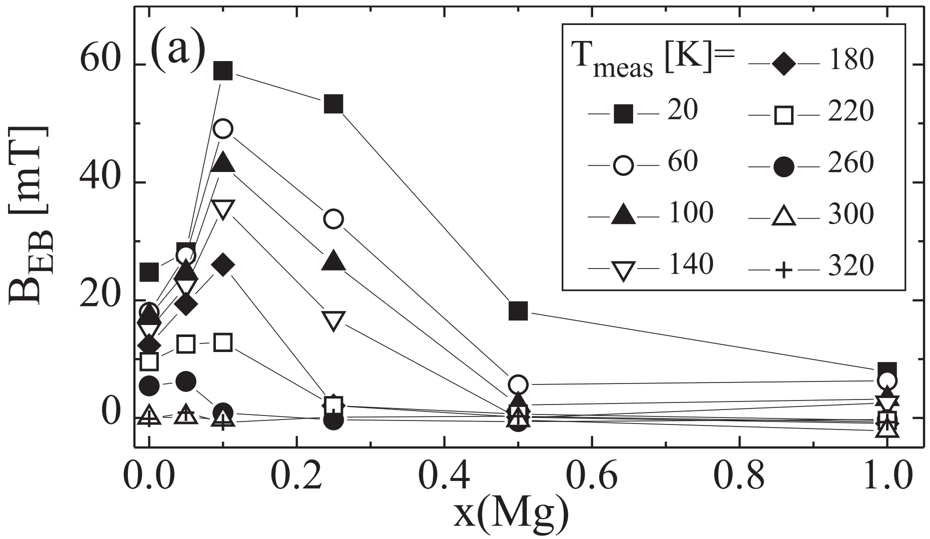
Experiments with diluted AFM

- Idea: generate defects in AFM:
  - CoO $\longrightarrow$ $Co_{1-x}Mg_xO$
  - interface layer without defects
  - vary bulk dilution



$\Rightarrow$ bulk dilution enhances exchange bias(EB)

$\Rightarrow$ associated with EB is an enhancement of the coercivity



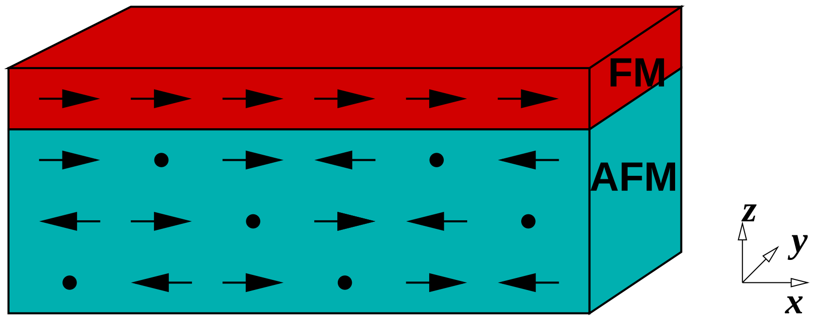
Miltenyi, Gierlings, Keller, Beschoten, Güntherodt, Nowak, Usadel, PRL ***84****, 4224 (2000)*

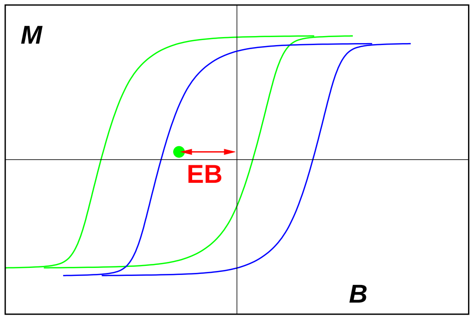
- see also:

  Mewes et al., APL ***76****, 1057 (2000)*

  Shi et al., JAP ***91****, 7763 (2002)*

Local spin model





$$\mathcal{H} = \mathcal{H}_{\rm F} + \mathcal{H}_{\rm AF} + \mathcal{H}_{\rm int}$$

$$\mathcal{H}_{\rm F} = -J_{\rm F} \sum_{\langle i,j \rangle} \vec{S_i} \cdot \vec{S_j} - \sum_i \left(D S_{ix}^2 + S_{ix} B \right)$$

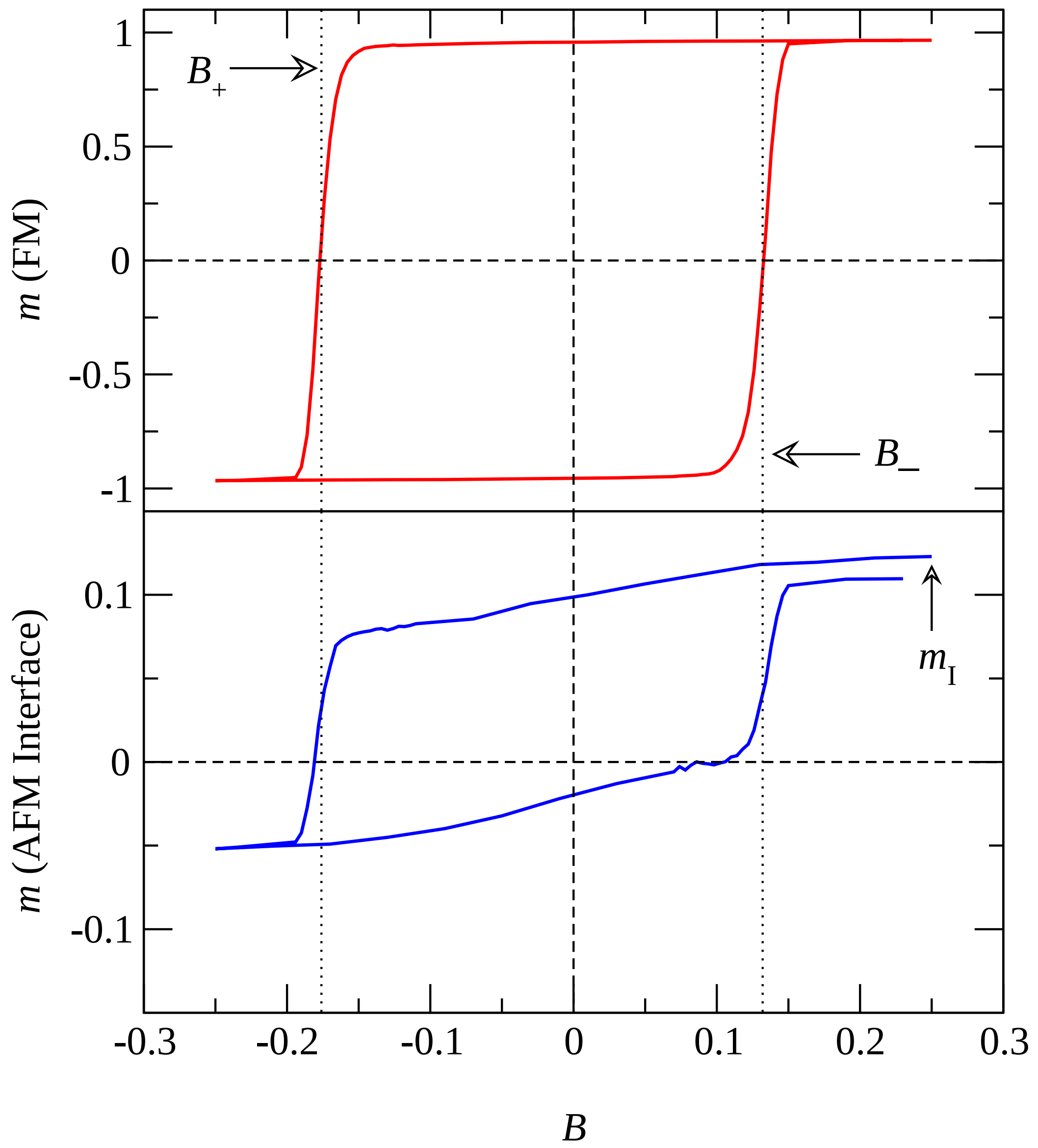
$$\mathcal{H}_{\rm AF} = J_{\rm AF} \sum_{\langle i,j \rangle} \epsilon_i \epsilon_j \sigma_i \sigma_j - \sum_i \epsilon_i \sigma_i B$$

$$\mathcal{H}_{\rm int} = -J_{\rm int} \sum_{i \in ({\rm int})} \epsilon_i S_{ix} \sigma_i ,$$

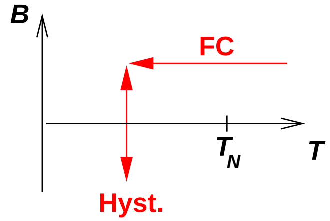
- $D > 0; \quad J_{\rm AF} = -J_{\rm F}/2;$ $J_{\rm int} = +/-J_{\rm AF};$
- Monte Carlo simulation, system size up to 128 $\times$ 128 $\times$ (9 + 1) up to 136000 MCS per hysteresis, average over up to 10 runs
- **local mean field theory**

Hysteresis of FM and AFM interface: MC simulations

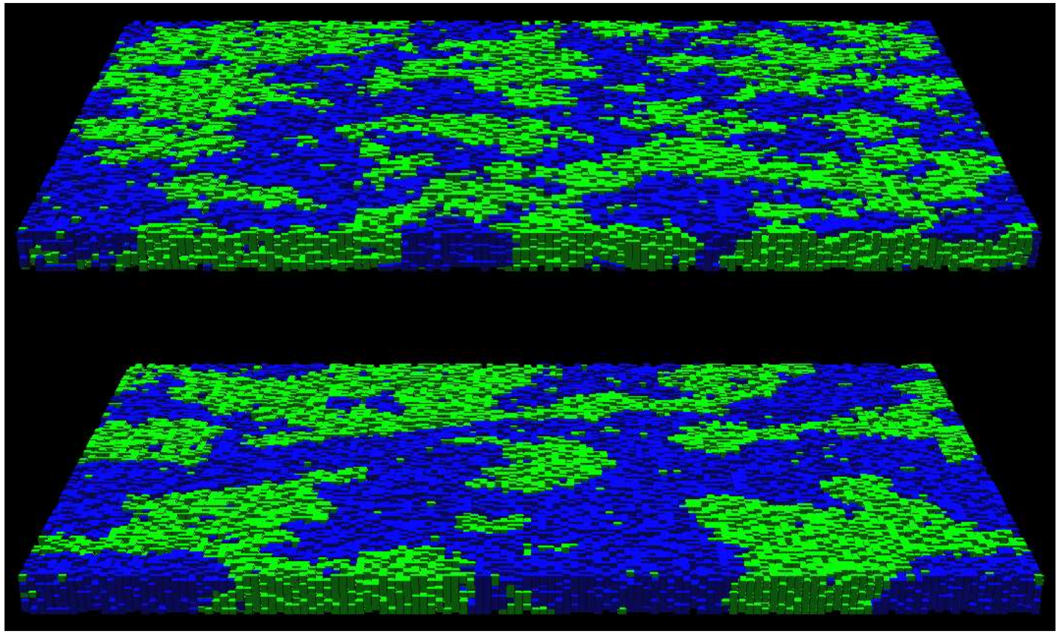
- system cooled in a field $B_c = 0.25 J_\mathrm{F}$ down to $k_\mathrm{B}T = 0.1 J_\mathrm{F}$
- AFM frozen in a domain state with interface magnetization
- its irreversible part leads to exchange bias
- $B_\mathrm{EB} \approx 0.03 J_\mathrm{int}$
- $D = 0.1 J_\mathrm{F}$



Structure of the AFM domains

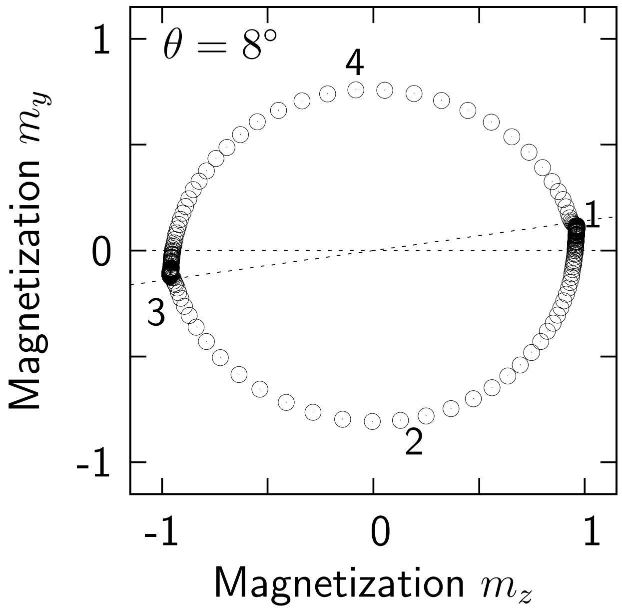


Staggered AFM magnetization after field cooling



above: large dilution, $p = 0.5$, small domains, below: small dilution, $p = 0.3$, larger domains.

Magnetization reversal of the FM layer



- **coherent rotation of the FM magnetization**
- no asymmetry for $\theta \to 0$
- local FM spins $\vec{S}_i = \vec{S}$ replaced by a **macro spin**

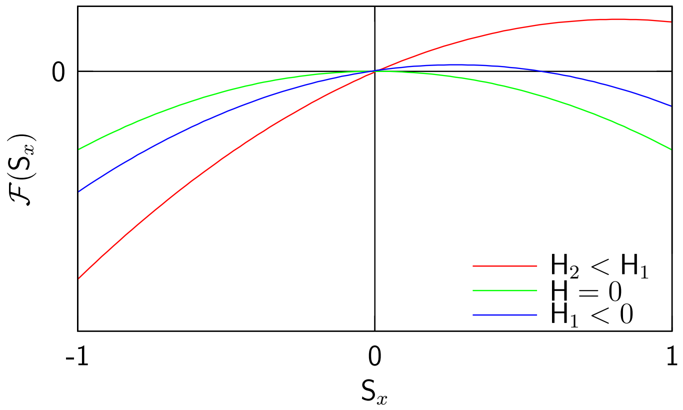
$$\mathcal{F}(S_x) = -NlDS_x^2 - NlBS_x - k_{\mathrm{B}}T\,\mathbf{Tr}\,e^{-\beta(\mathcal{H}_{\mathrm{AF}}+\mathcal{H}_{\mathrm{int}})}$$

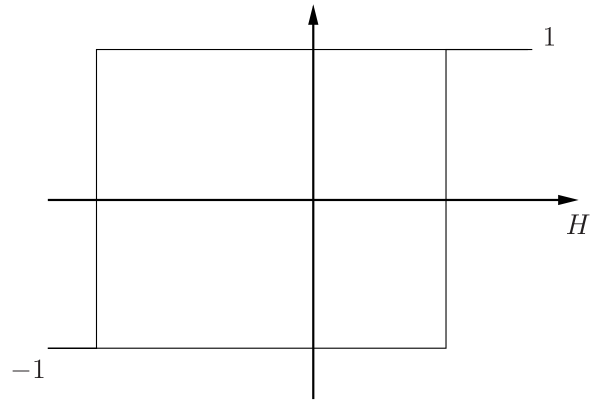
$$\mathcal{F}'(S_x) = -2NlDS_x - NlB - J_{\mathrm{int}} \sum_{i\in\mathrm{int}} \langle\sigma_i\rangle$$

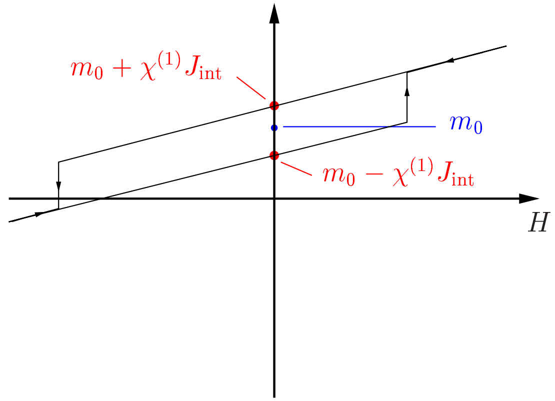
$$\mathcal{F}''(S_x) = -2NlD - \beta J_{\mathrm{int}}^2 \left\langle \Big(\sum_{i\in\mathrm{int}} (\sigma_i - \langle\sigma_i\rangle) \Big)^2 \right\rangle$$

- $m_{\mathrm{int}} = \sum_{i\in\mathrm{int}} \langle\sigma_i\rangle$
- l number of FM monolayers
- N spins per FM monolayer

Switching fields







$$\mathcal{F}'(S_x) = -2NlDS_x - NlB - J_{\rm int} m_{\rm int}$$

Fields B_- and B_+ for magnetization switching from $\mathcal{F}' = 0$ at $S_x = 1$ and $S_x = -1$, respectively:

$$B_- = -2D - J_{\rm int} m_{\rm int} \big(B_-, S_x = 1\big)/l,$$

$$B_+ = 2D - J_{\rm int} m_{\rm int} \big(B_+, S_x = -1\big)/l,$$

$$m_{\rm int} = m_0 + m_{\rm rev}$$

$$m_{\rm rev} = \chi^{(1)}_{\rm AF} J_{\rm int} S_x + \chi^{(2)}_{\rm AF} B$$

Hysteresis of FM and AFM interface: MC simulations

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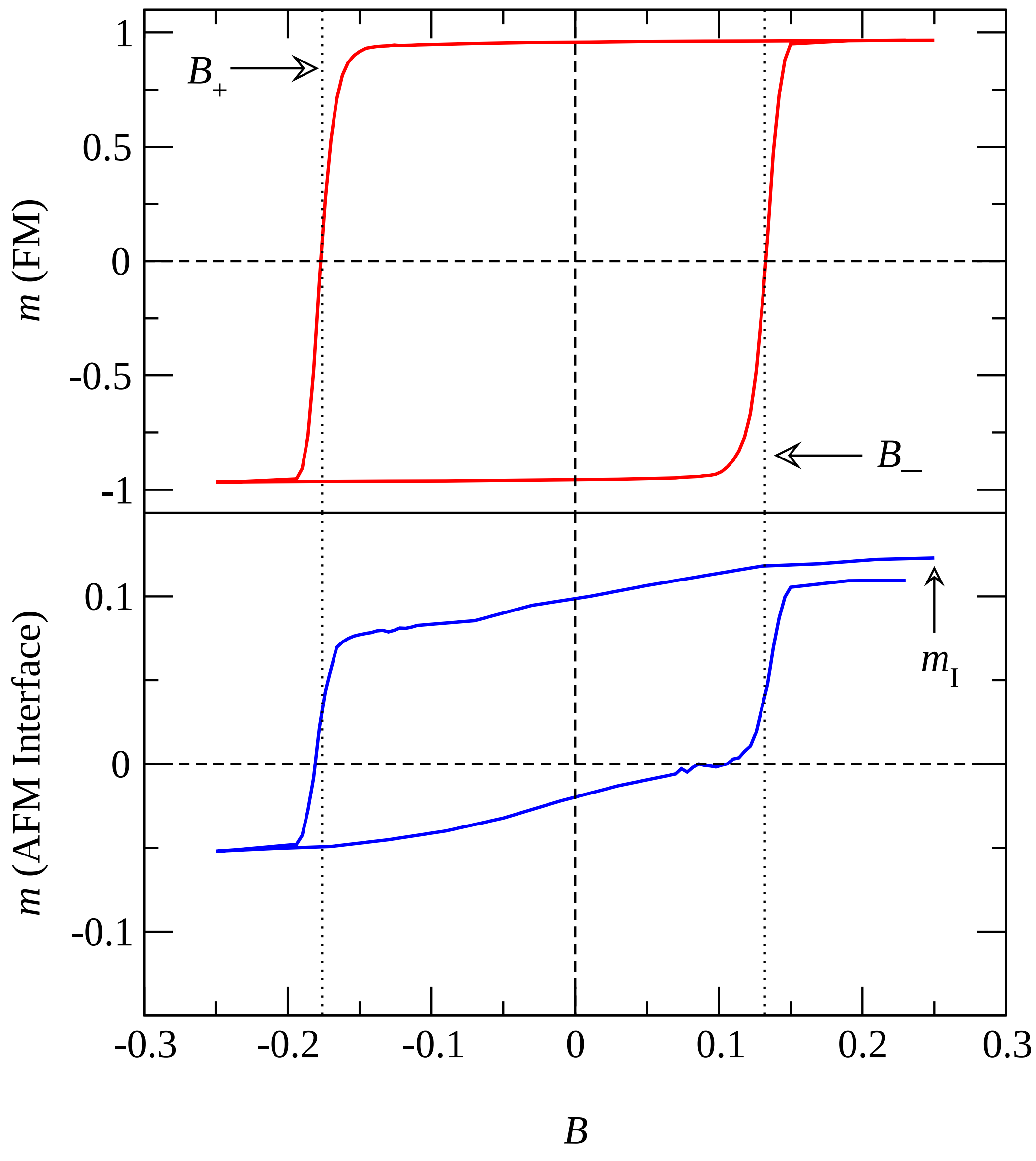


Linear approximation

$m_{int}(B, S_x = \pm 1)$: AFM interface magnetization determines coercivity and EB

$$B_\pm = \pm 2D - J_{\rm int} m_{\rm int}(B_\pm, S_x = \mp 1)/l$$

$$m_{\rm int} = m_0 + m_{\rm rev}$$

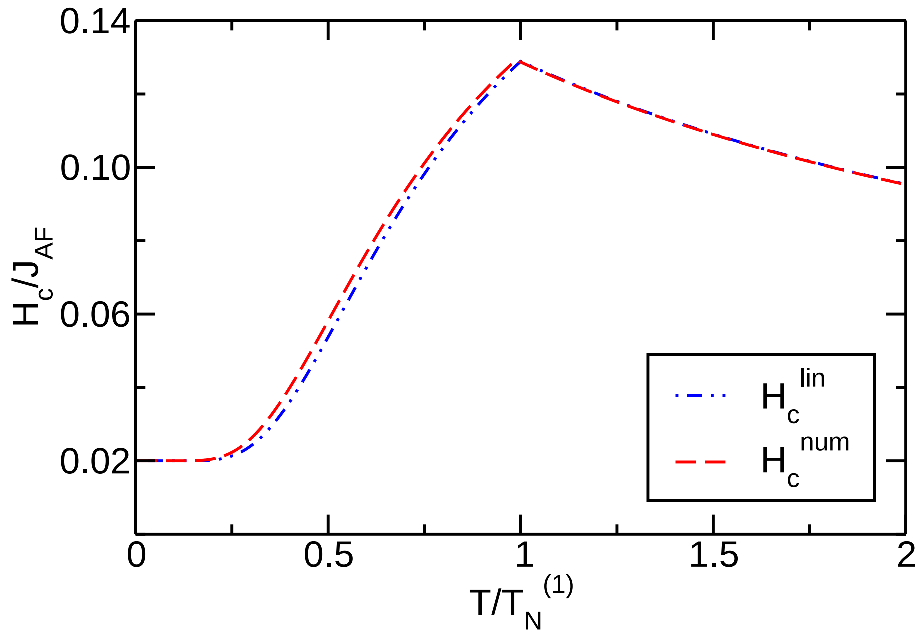
$$m_{\rm rev} = \chi^{(1)}_{\rm AF} J_{\rm int} S_x + \chi^{(2)}_{\rm AF} B$$

$$B_\pm = \frac{\pm 2D - J_{\rm int} m_0/l \pm J^2_{\rm int}\chi^{(1)}_{\rm AF}/l}{1 + J_{\rm int}\chi^{(2)}_{\rm AF}/l}$$

$$B_{\rm eb} = \frac{1}{2}(B_+ + B_-) = \frac{-J_{\rm int} m_0/l}{1 + J_{\rm int}\chi^{(2)}_{\rm AF}/l}$$

$$B_c = \frac{1}{2}(B_+ - B_-) = \frac{2D + J^2_{\rm int}\chi^{(1)}_{\rm AF}/l}{1 + J_{\rm int}\chi^{(2)}_{\rm AF}/l}$$

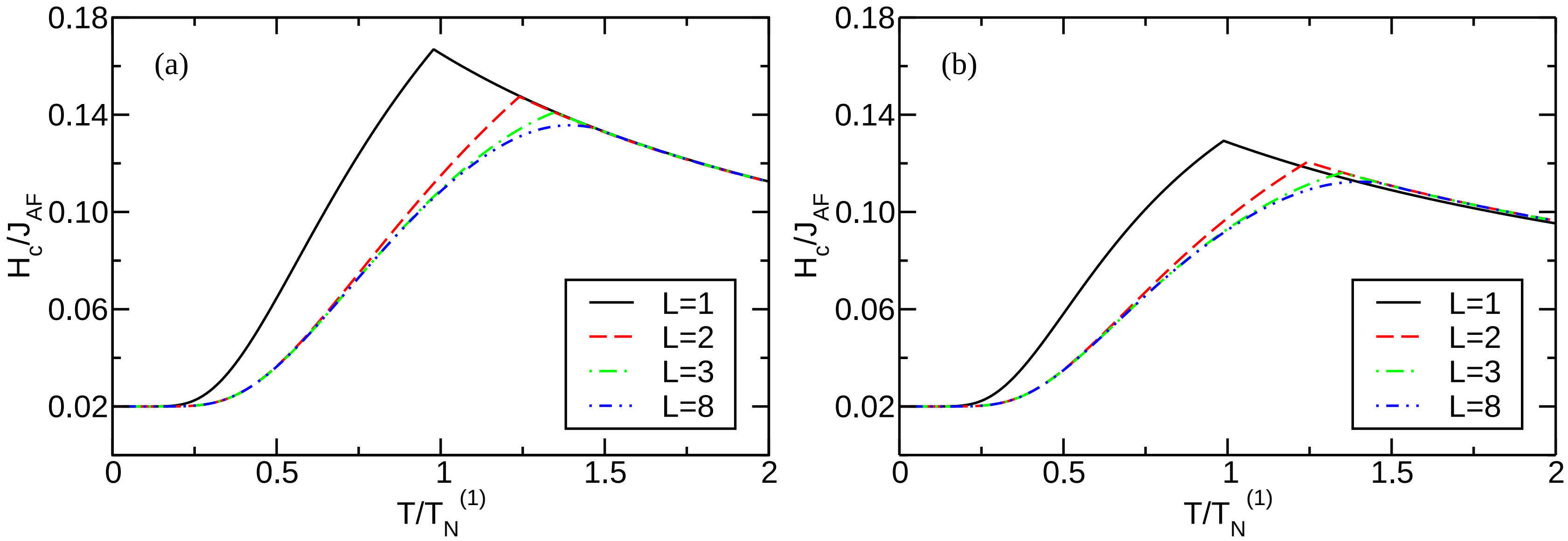
$\Rightarrow$ dependence on the sign of $J_{\rm INT}$



mean field approach

MF approximation; no dilution

$$\langle\sigma_i\rangle = m_i = \tanh\left(\beta\left(-J_{\mathrm{AF}}\sum_j m_j + J_{\mathrm{int}}S_x + B\right)\right)$$



Coercive field as function of reduced temperature for different AFM layer thicknesses l.

left: $J_{\mathrm{int}} = -J_{\mathrm{AF}}$ right: $J_{\mathrm{int}} = J_{\mathrm{AF}}$ $D/J_{\mathrm{F}} = 0.005$

$\Rightarrow$ **large increase of the coercivity in the vicinity of the Neel temperature T_N**

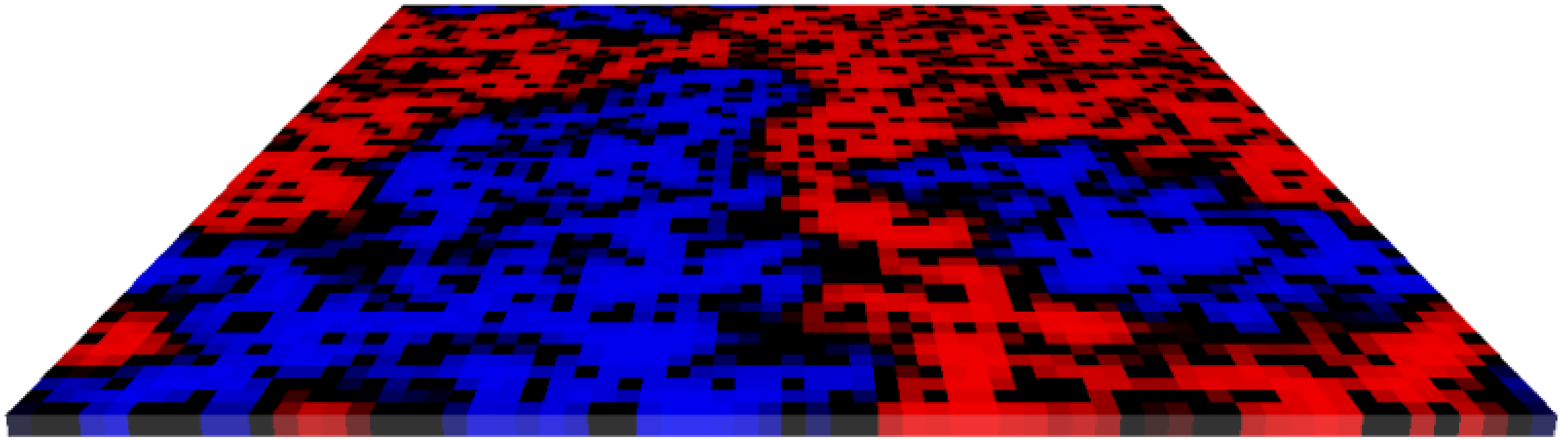
(*Scholten, Usadel, Nowak, Phys. Rev. B* **71**, *64413 (2005)*)

Diluted systems

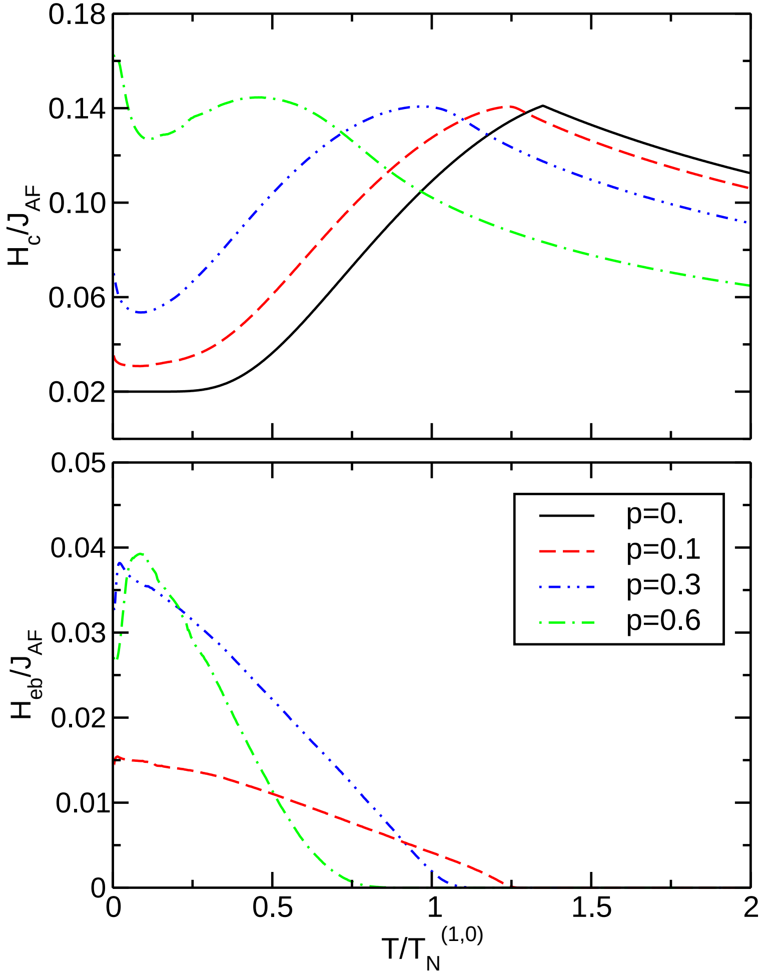
Local mean field equations:

$$m_i \quad = \quad \epsilon_i \tanh\Big(\beta\big(-J_{\mathrm{AF}}\sum_j \epsilon_j m_j + J_{\mathrm{int}} S_x + B\big)\Big)$$

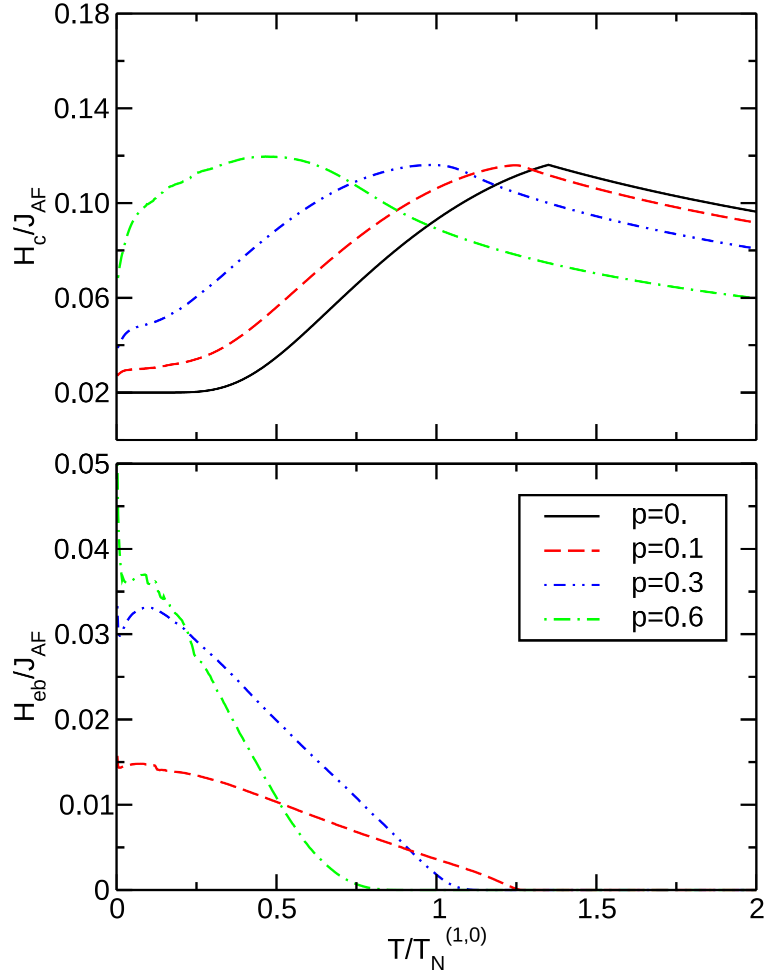
Cooling: Iteration at a fixed temperature until a (metastable) self-consistent solution is obtained, then reducing temperature in small steps.



Coercivity and bias fields: different AFM dilution p



$l = 3$ and $J_{\text{int}} = -J_{\text{AF}}$



$l = 3$ and $J_{\text{Int}} = J_{\text{AF}}$

- maximum of the coercivity independent of dilution: $\chi_{max} = x/T_N(x)$; x concentration of magnetic sites

Generalization to AFM vector spins

$$\mathcal{H}_o = -\sum_i B S_x(i) - D\sum_i S_x(i)^2 + \mathcal{H}_{ex}$$

$$\begin{aligned} h_\alpha(i) &= -\frac{\partial}{\partial S_\alpha(i)}\mathcal{H}_o + J_{\rm int}\sigma_\alpha(i) \\ \tilde{h}_\alpha(i) &= -\frac{\partial}{\partial S_\alpha(i)}\mathcal{H}_o + J_{\rm int} m_\alpha(i) \\ m_\alpha(i) &= \chi^{(1)}_{\alpha\beta}B_\beta + J_{\rm int}\chi^{(2)}_{\alpha\beta}S_\beta(i) + m_{0,\alpha}(i) \end{aligned}$$

- separation of time scales and/or slow variation in space: thermal average restricted to the AFM
- AFM eqilibrium susceptibilities $\chi^{(1)}_{\alpha\beta}$ and $\chi^{(2)}_{\alpha\beta}$ as response to external field and exchange field

- Effective (free) energy of the FM layer:

$$F = \mathcal{H}_o - J_{\rm int}\sum_i S_\alpha(i)\chi^{(1)}_{\alpha\beta}B_\beta - \frac{1}{2}J^2_{\rm int}\sum_i S_\alpha(i)\chi^{(2)}_{\alpha\beta}S_\beta(i) - \sum_i S_\alpha(i)m_{0,\alpha}(i)$$

- **enhanced moment; enhanced anisotropy**

$$F = \mathcal{H}_o - J_{\rm int} \sum_i S_\alpha(i)\chi^{(1)}_{\alpha\beta} B_\beta - \frac{1}{2} J^2_{\rm int} \sum_i S_\alpha(i)\chi^{(2)}_{\alpha\beta} S_\beta(i) - \sum_i S_\alpha(i) m_{0,\alpha}(i)$$

$\Rightarrow$ maximum lowering of symmetry occurs when only one component of the susceptibility tensor, $\chi_{x,x}$, is nonzero: Ising antiferromagnet

$$\tilde{\mathcal{H}}_o = -\sum_i \tilde{B} S_x(i) - \sum_i \tilde{D} S^2_x(i) + \mathcal{H}_{ex} - \sum_i S_\alpha(i) m_{0,\alpha}(i)$$

- $\tilde{B} = B[1 + (J_{\rm int}/l)\chi]$
- $\tilde{D} = D + [J^2_{\rm int}/(2l)]\chi = \tilde{B}_c/2$
- **strong dependence on temperature**
- relatively weak anisotropy in the ferromagnet: maximum value of $h_c/J_{\rm int} \sim 0.1$ for $2D/J_{\rm int} = 0.02$. This corresponds to $(\tilde{B}/B)_{max} \approx 1.1$ and $(\tilde{D}/D)_{max} \approx 5$.

Dynamical consequences:

$\Rightarrow$ domain wall width Δ and domain wall energy E_{DW}:

$(\tilde{\Delta})_{max} \approx \sqrt{J/\tilde{D}}$;

$(\tilde{E}_{DW})_{max} \approx \sqrt{J\tilde{D}}$

wall velocity v_{DW}: $\tilde{v}_{DW} \sim \tilde{B}\tilde{\Delta}$.

Stamps, Usadel,Europhys. Lett., **74**, *512 (2006)*

Conclusions

- Domain state model **explains** exchange bias and many effects associated with it without explicitely assuming some net AFM interface magnetization
- frozen AFM interface magnetization leads to EB
- reversible part of the AFM interface magnetization leads to enhanced coercivity providing the AFM is anisotropic
- for slow FM dynamics and slow spatial variation of its magnetization an effective FM energy can be obtained after integrating out the AFM degrees of freedom