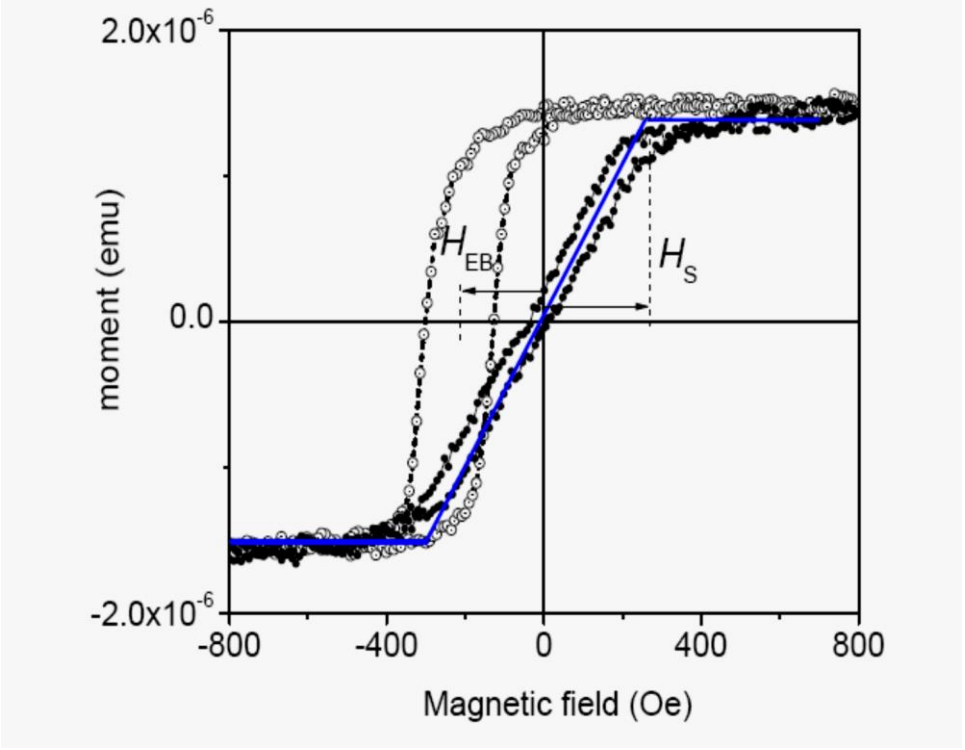
Micromagnetic approach to EB

SWISS CONTRIBUTION



NANOSPIN

I.Gościańska
K. Załęski
H. Głowiński…

Micromagnetic approach to EB

Typical length scales

Symbol	Length	Typical magnitude (nm)
a (ξ)	Interatomic distance	$2.5 – 3\ 10^{-1}$
d_{ex}	Range of exchange interactions	$\sim 10^{-1}$ - <1
l_{cor}	Correlation length	$\sim 10 - 10^{2}$
l_{ex}	**Exchange length**	**~1 - <10**

$$l_{cor} = \sqrt{(A/K)} \qquad l_{ex} = \sqrt{(A/2\pi M^2)}$$

M - magnetization K - anisotropy A – exchange stiffness

J. Dubowik , Institute of Molecular Physics, Poznań

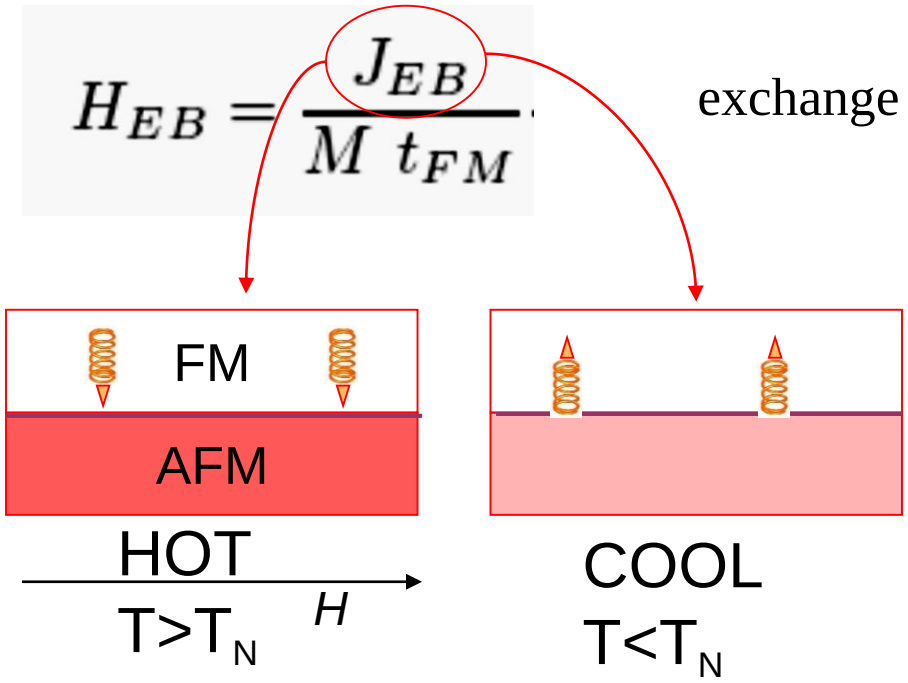
Important facts

(i)

master equation for EB:

$$H_{EB} = \frac{J_{EB}}{M\ t_{FM}}$$

exchange bias field

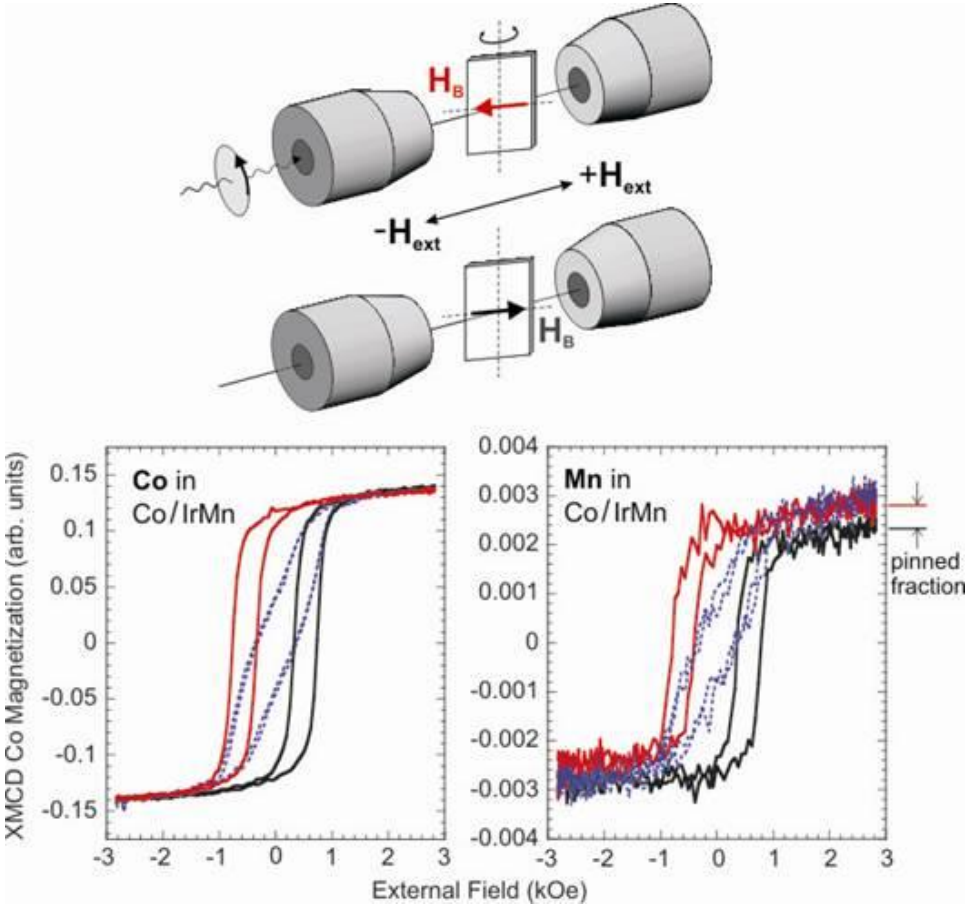


A 4 % breakthrough (XMCD)

(ii)

"Thus the tiny amount of only 4% of a monolayer of pinned Mn moments are responsible for the entire exchange bias effect! This illustrates why it took so long to unravel the puzzle.."

X-Rays Unravel the Puzzle of Exchange Bias



Slonczewski: field-induced anisotopy - 10^{-3}

H. Ohldag, A. Scholl, F. Nolting, E. Arenholz, S. Maat, A.T. Young,, M. Carey, J. Stöhr
Phys. Rev. Lett. **91**, 017203 (2003)

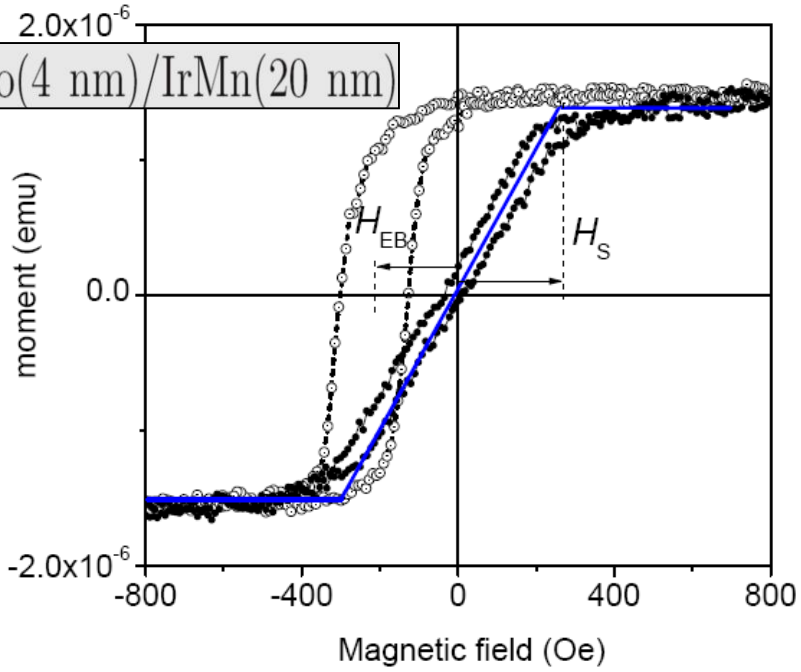
PM'14

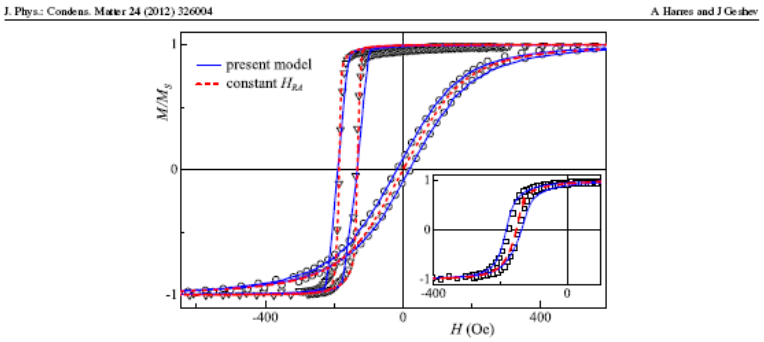
Hs vs. Hc

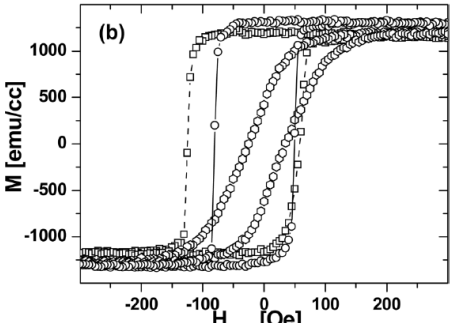
H_S !

(iii)

$$H_S = \frac{2\ \langle K \rangle}{M}$$



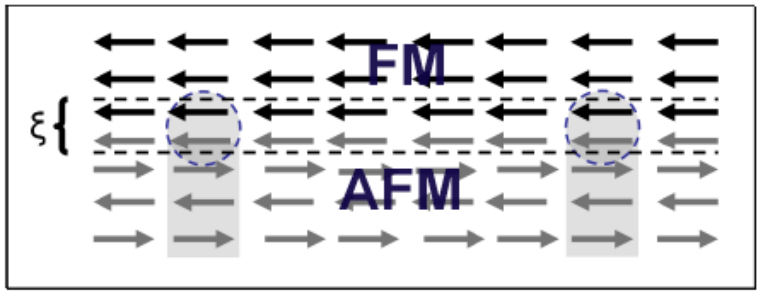




J. Appl. Phys. **109**, 083924 (2011)

Model

$$H_{EB} = \frac{J_{EB}}{M\ t_{FM}}$$



$$H_{EB} = \frac{2\langle A \rangle}{M\ \xi\, t_{FM}}$$

$$l_{ex} = \sqrt{(A/2\pi M^2)}$$

$$H_{EB} = 4\pi M\ \frac{\langle A \rangle}{2\pi\, M^2}\ \frac{1}{\xi\, t_{FM}} = 4\pi M\ \frac{\langle l_{ex} \rangle^2}{\xi\, t_{FM}}$$

$$\langle A \rangle \approx \frac{I\ \epsilon S_{FM}\ \epsilon S_{AFM}}{a} \approx \epsilon^2 A$$

$$\mathbf{Heb} := 4\cdot\pi\cdot\mathbf{M}\cdot\mathbf{lex}^2\cdot\frac{\boldsymbol{\varepsilon}^2}{\boldsymbol{\xi}}\cdot\frac{1}{\mathbf{tfm}}$$

mainly FM

mainly interface (AFM)

Typical values

$$Heb := 4 \cdot \pi \cdot M \cdot lex^2 \cdot \frac{\varepsilon^2}{\xi} \cdot \frac{1}{tfm}$$

Material	$4\pi M$ (kOe)	A (μerg/cm)	D (meV nm^2)	l_{ex} (nm)	$4\pi M\ l_{ex}^2$ (10^9Oe cm^2)
Fe	21.4[a]	2.0[b]	2.8	3.3	2.3
Co	18.1[a]	2.5[b]	4.5	4.4	3.5
Ni	6.1[a]	0.8[b]	4.5	7.6	3.5
$Ni_{80}Fe_{20}$	10.0[a]	1.0[b]	2.5	5.0	2.5
$Co_{47}Fe_{53}$	17.0[c]	5.9[c]	8.0	7.2	8.7
Co_2FeSi	14.1[d]	3.2[d]	7.0	6.4	5.7
Co_2MnSn	9.9 [e]	0.6[e]	2.0	3.9	1.5
Ni_2MnSn	5.1 [f]	0.1[f]	0.4	2.6	0.3
Fe_3O_4 [h]	5.9 [g]	0.7[g]	5.0	7.1	3.0

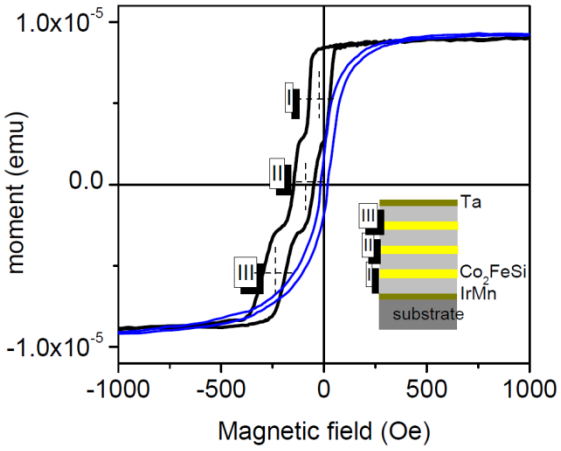
ε=1 (M-B) ξ=0.3 nm=3 10^{-8} cm t_{fm}=10 nm=10^{-6} cm $H_{eb}=10^5$ Oe

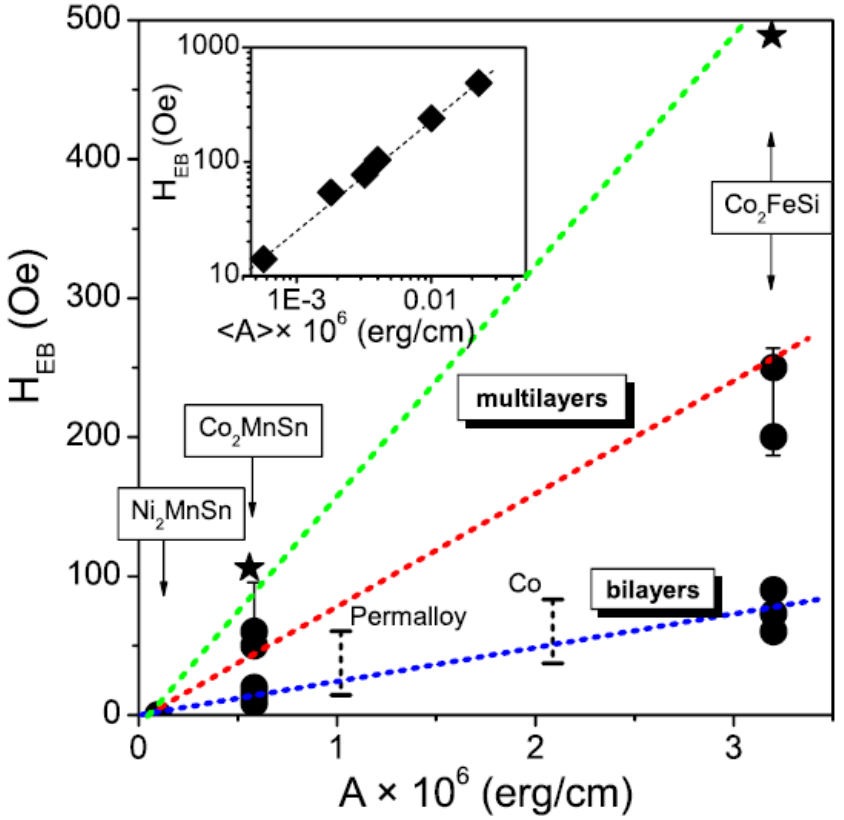
$\varepsilon=4\ 10^{-2}$ ξ=0.3 nm=3 10^{-8} cm t_{fm}=10 nm=10^{-6} cm $H_{eb}=10^2$ Oe

Heusler alloy films in contact with AFM

"Our results show that EB in HA/IrMn structures is proportional to *A* scaled by a reduction factor of ~0.001 - 0.01, which is ascribed to a small number of the pinned spins."

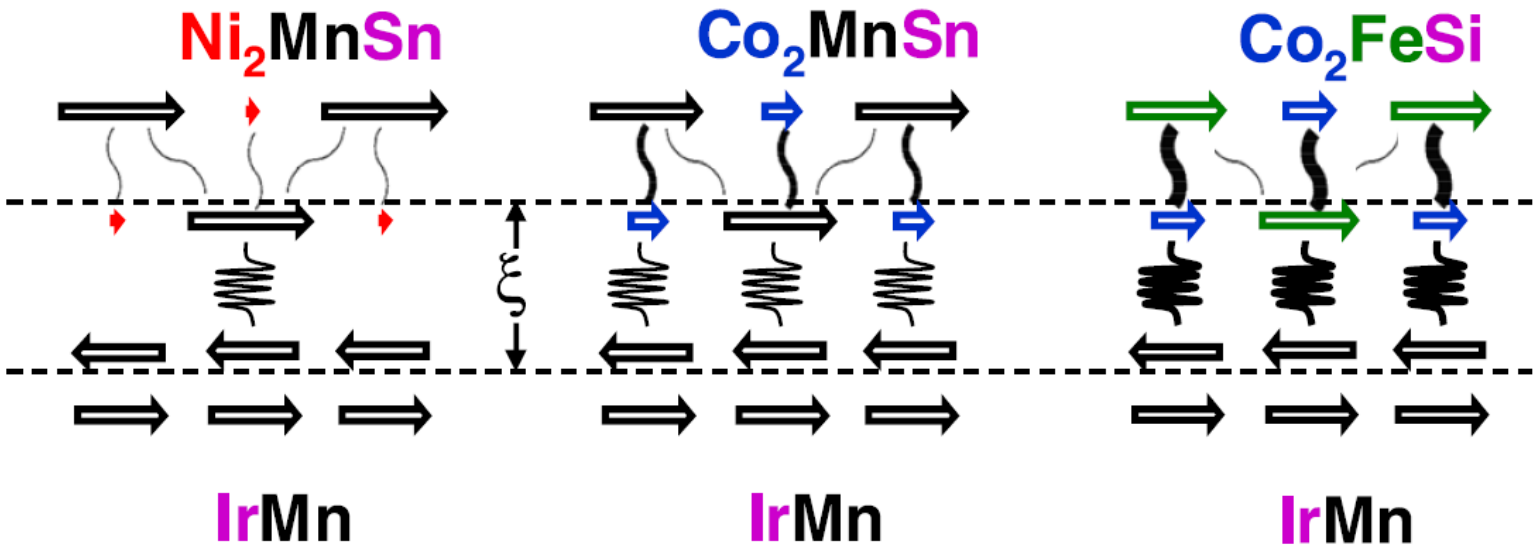
$H_{eb} \propto A$ (FM)





Dubowik *et al.* J. Appl. Phys. **113**, 193907 (2013)

Heusler alloy films in contact with AFM



Heusler alloy	m μ_B/f.u.	m_X μ_B	m_Y μ_B	J_{X-X}[a] mRy	J_{X-Y}[a] mRy	J_{Y-Y}[a] mRy	$A \times 10^6$ erg/cm
Ni_2MnSn	4.0 (Ref. 28)	0.14 (Ref. 28)	3.50 (Ref. 28)	≈0	0.2	0.2	0.1 (Ref. 9)
Co_2MnSn	5.0 (Ref. 21)	0.97 (Ref. 21)	3.23 (Ref. 21)	0.1	0.8	0.1	0.6 (Ref. 22)
Co_2FeSi	6.0 (Ref. 21)	1.40 (Ref. 21)	2.87 (Ref. 21)	0.4	1.5	0.05	3.2 (Ref. 22)
Permalloy	≈4 (Ref. 1)	…	…	…	0.3	…	1.0 (Ref. 1)

[a]The values of the exchange integrals are calculated by the EMTO package.[27]

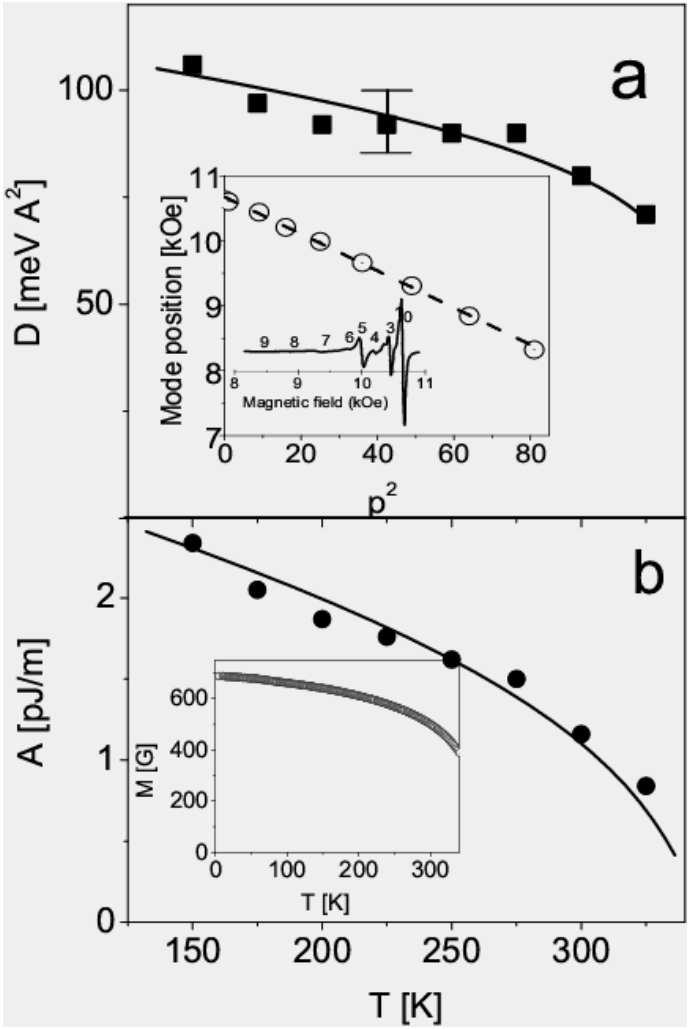
Dubowik *et al.* J. Appl. Phys. **113**, 193907 (2013)

A case of Ni_2MnSn HA films

Ni_2MnSn

Ni_2MnSn films :
films with a low Gilbert damping α=0.007
and with a
„soft" spin wave stiffness D

$$D=2Ag\mu_B/M$$



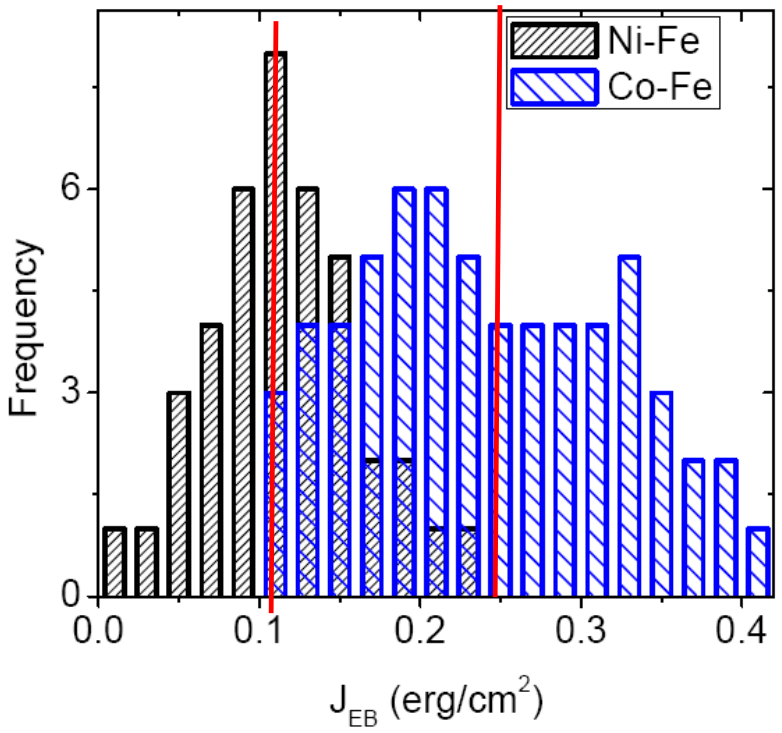
J. Dubowik et al. Acta Phys. Polon. A 121, 1121 (2012)

Some statistics for all-metalic EB bilayers

$$J_{EB} = 4\pi M^2 \left(\frac{l_{ex}^2 \epsilon^2}{\xi}\right)$$

$\varepsilon \cong 0.04$

$$J_{EB} = \{\ 0 \ - 1\ \text{erg/cm}^2\}$$



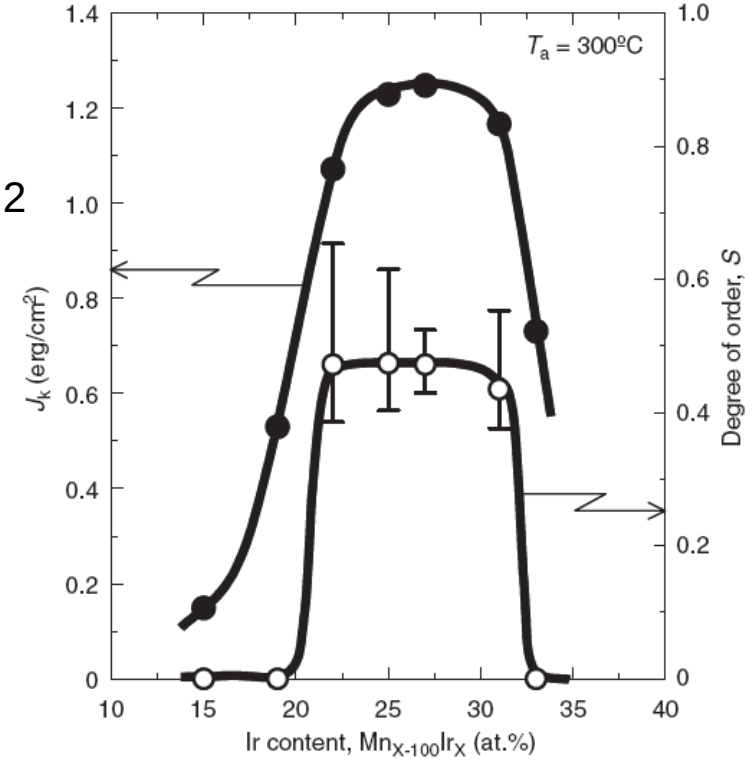
Conclusion: the assumed ratio of irreversible pinned spins of a few % seems to be typical of metallic FM/AFM

R. Coehoorn, "Lecture notes on novel magnetoelectronic materials and devices: exchange biased spinvalves, part 4."

The highest EB in all-metalic bilayers

$$J_{EB} = 4\pi M^2 \left(\frac{l_{ex}^2 \epsilon^2}{\xi}\right)$$ = 1.3 erg/cm^2

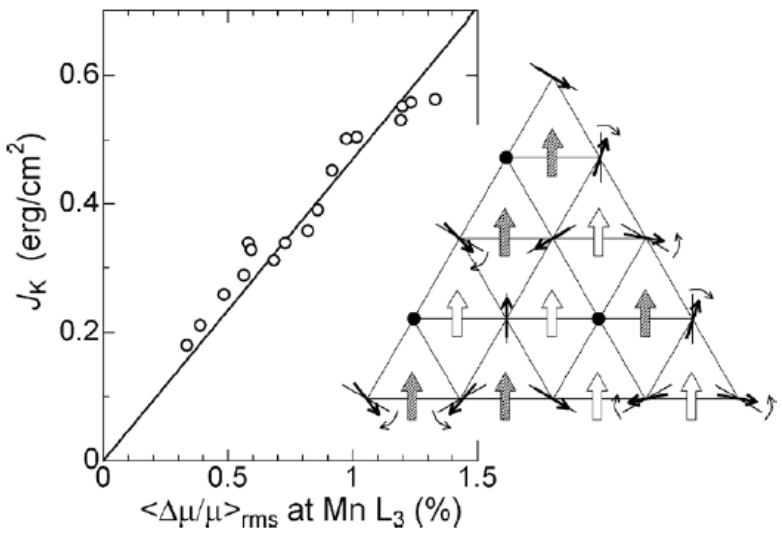
$\varepsilon \cong 0.08 - 0.09$



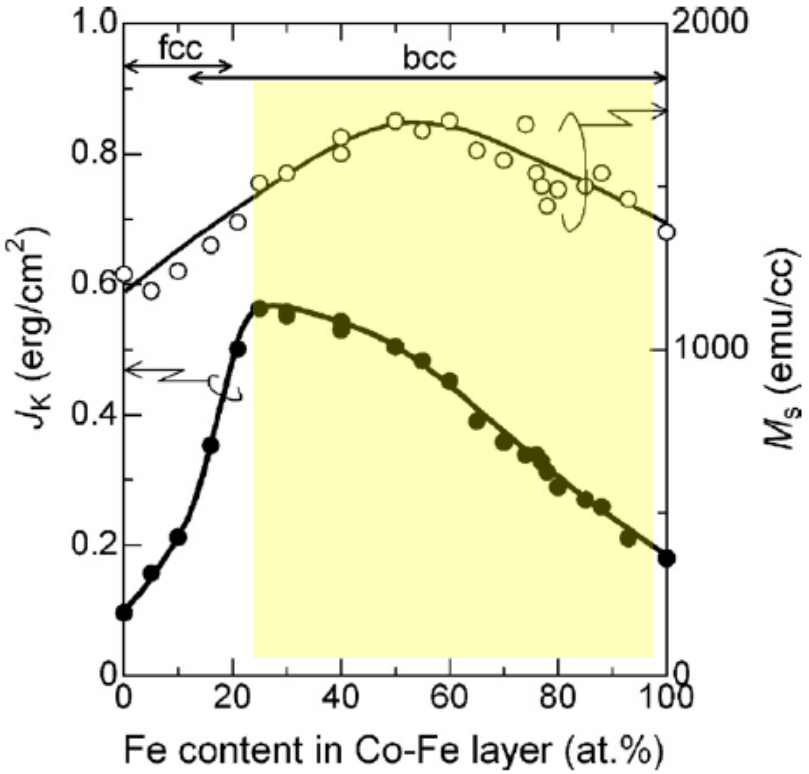
$Co_{70}Fe_{30}$ (4 nm)
in contact with $L1_2$ Mn_3Ir

M. Tsunoda et al. / Journal of Magnetism and Magnetic Materials 304 (2006) 55–59

EB vs. FM composition in all-metallic $Co_{1-x}Fe_x$/IrMn



uncompensated Mn spins

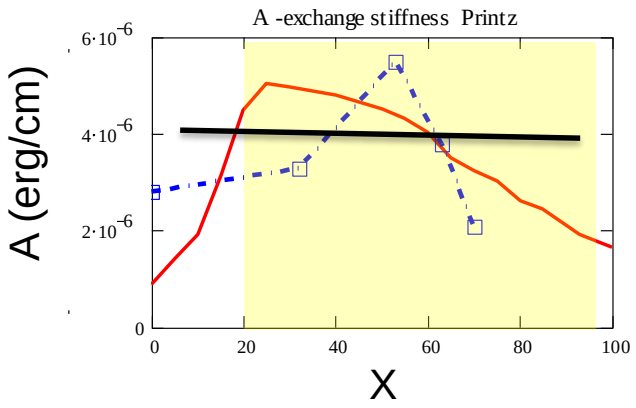


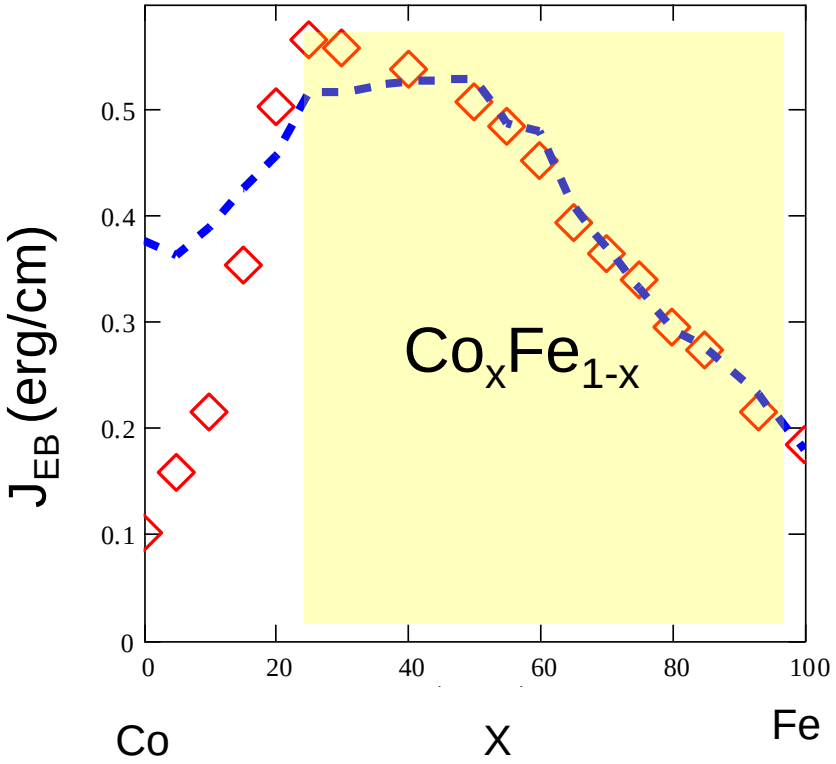
"It was suggested that the variation in the J_K with varying the FM layer composition is due to the change of the exchange coupling energy at the heterointerface."

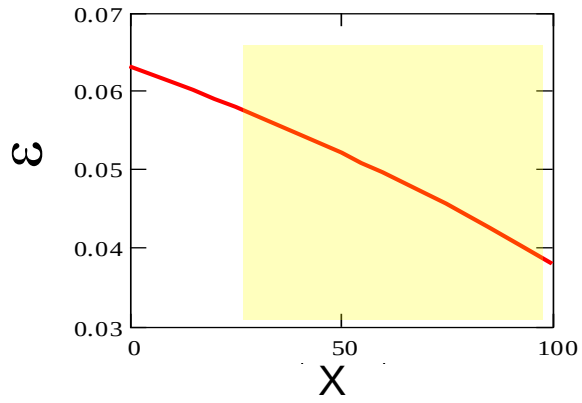
Tsunoda *et al.* Appl. Phys. Lett. **97**, 072501 (2010)

EB vs. FM composition in all-metalic bilayers

$$J_{EB} = 4\pi M^2 \left(\frac{l_{ex}^2 \epsilon^2}{\xi}\right)$$





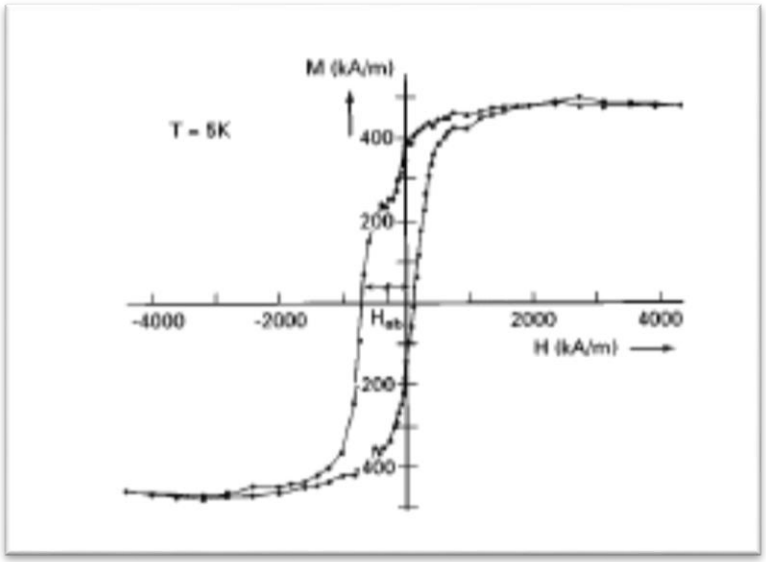


ε = { 6% to 4%}

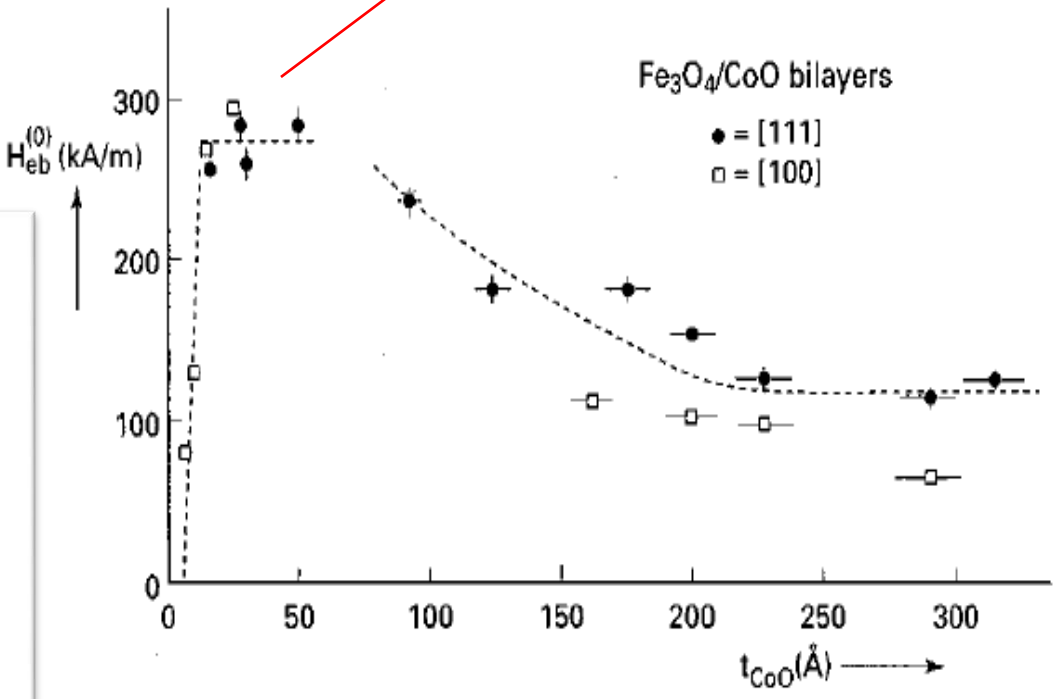
X. Liu, R. et al. J. Appl. Phys. 75, 7021 (1994);

Ideal (almost) EB: all-oxide bilayers

Fe_3O_4/CoO



H_{eb} ~ 3700 Oe



P. J. van der Zaag et al. in: Magnetic properties of AFM oxide materials

Ideal (almost) EB: all-oxide bilayers

F/AF system	Interface	$K_{eb}^{(0)}$ (mJ/m^2)	Δ
Fe_3O_4/CoO	(100)	2.11	8
Fe_3O_4/CoO	(111)	1.43	35
$Ni_{80}Fe_{20}$/FeMn	(111)	0.22	73

$$J_{EB} = 4\pi M^2 \left(\frac{l_{ex}^2 \epsilon^2}{\xi}\right)$$

$\Delta=\varepsilon^2=1/8 = 0.125$

J_{eb} (K_{eb}) extrapolated to 0 K is of 2.1 erg/cm^2, which is only a factor of 8 smaller than calculated on the basis of n-n exchange across a perfectly flat interface..

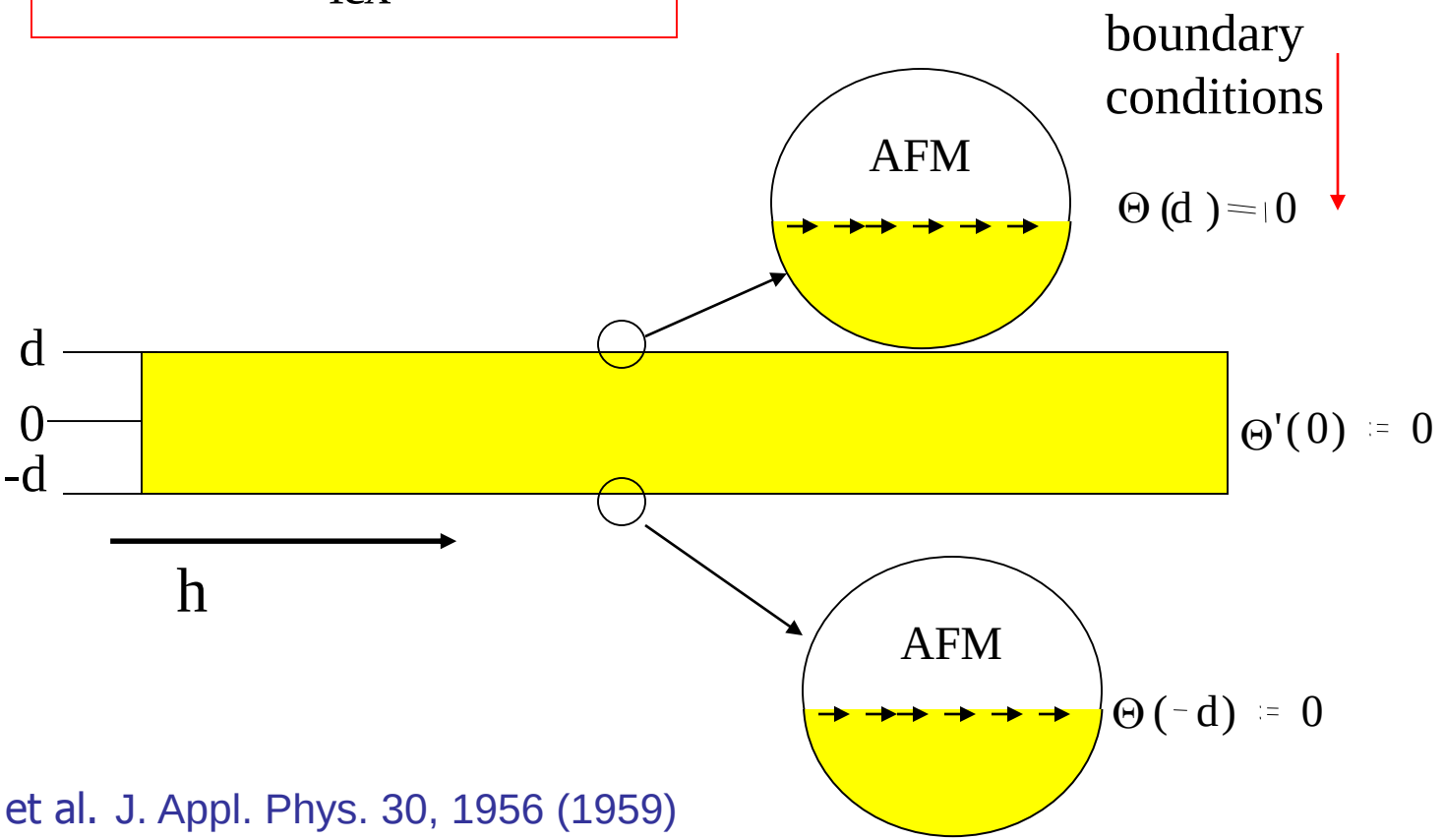
P. J. van der Zaag et al. in: Magnetic properties of AFM oxide materials

Micromagnetic approach: magnetization twisting

Euler eq.

$$\frac{d^2}{dt^2}\Theta - \frac{h}{lex^2}\cdot\sin\Theta := 0$$

t=x/d h=H/4πM



after Aharoni et al. J. Appl. Phys. 30, 1956 (1959)

Micromagnetic approach: magnetization twisting

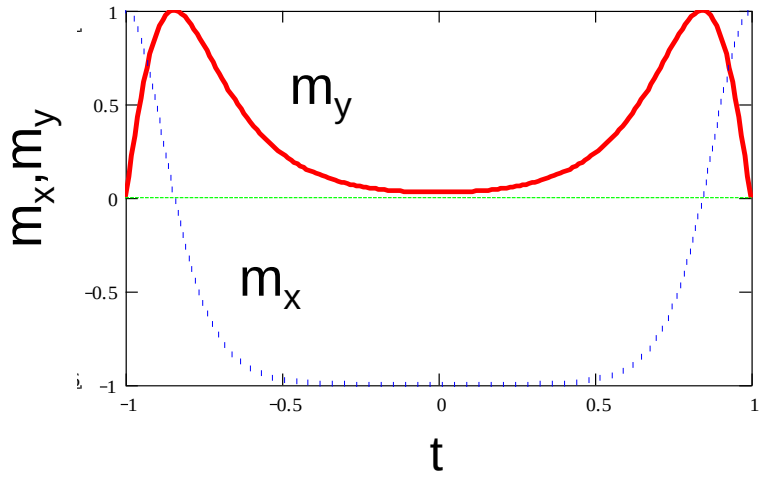
$$\frac{d^2}{dt^2}\Theta - \frac{h}{lex^2}\cdot\sin\Theta := 0$$

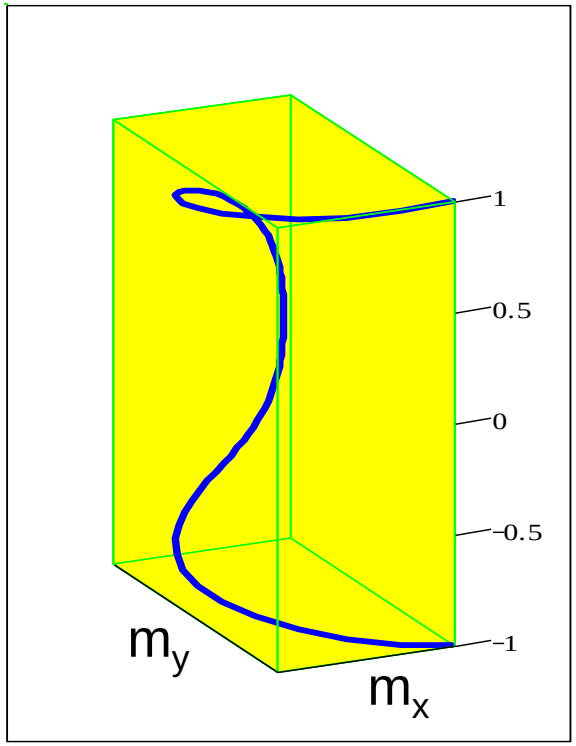
$$\Theta'(0) := 0$$

$$\Theta(-d) := 0 \qquad \Theta(d) := 0$$

Boundary conditions

$$\Theta(t) := 2\,\mathrm{asin}(k\cdot sn((1-t)\cdot \mathrm{LegendreKc}(k),k))$$

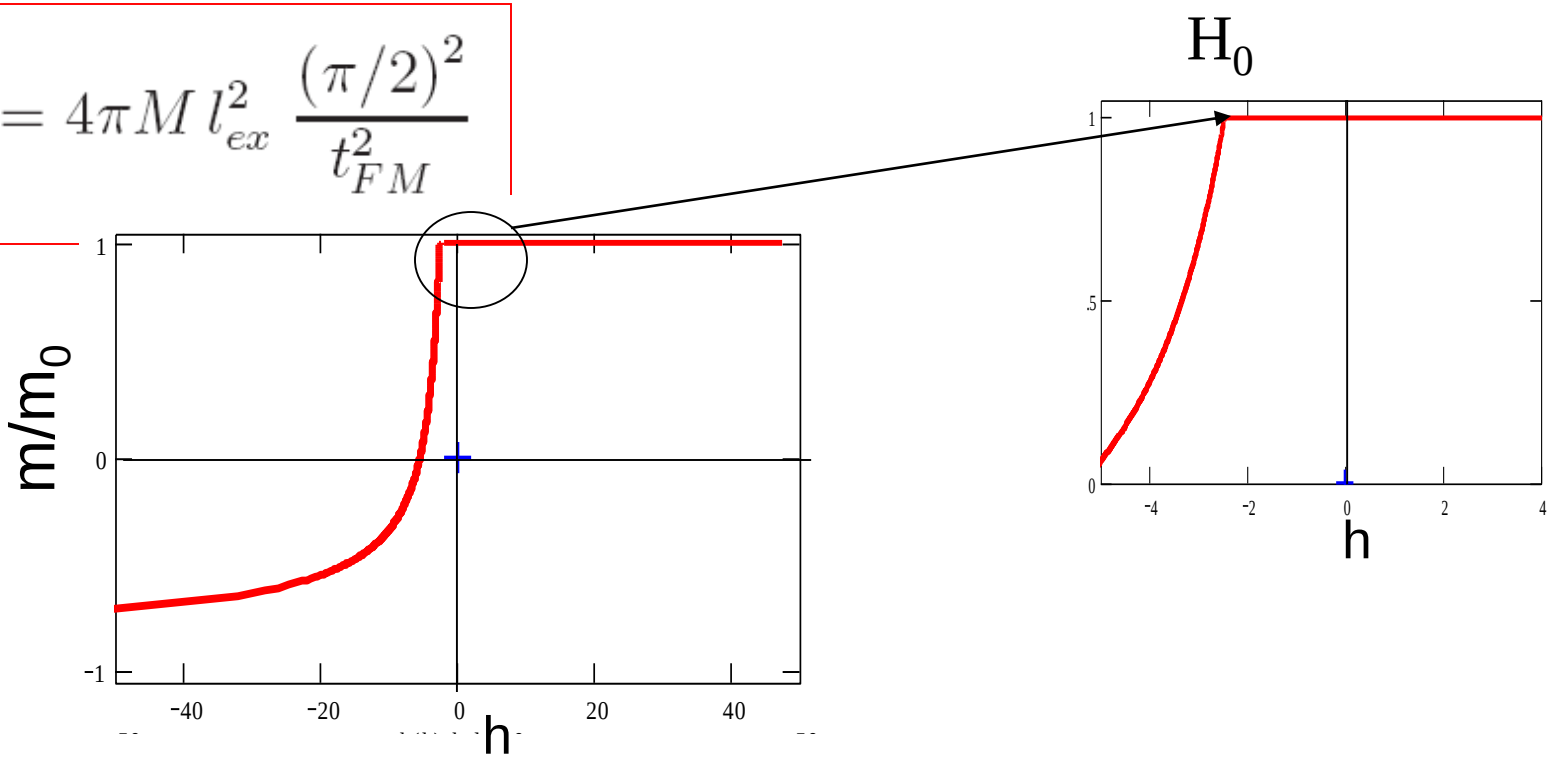




after Aharoni et al. J. Appl. Phys. 30, 1956 (1959)

Micromagnetic approach: magnetization twisting

$$H_0 = 4\pi M\, l_{ex}^2\, \frac{(\pi/2)^2}{t_{FM}^2}$$

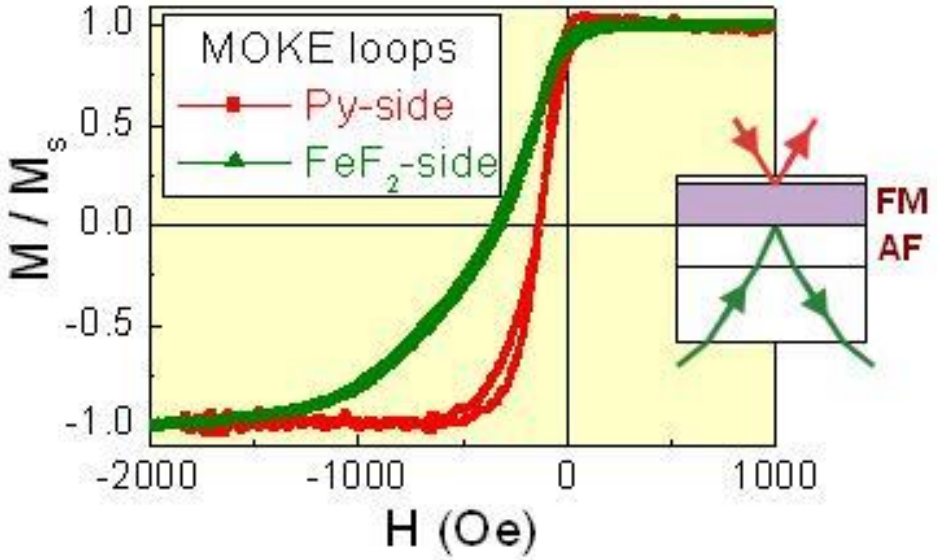


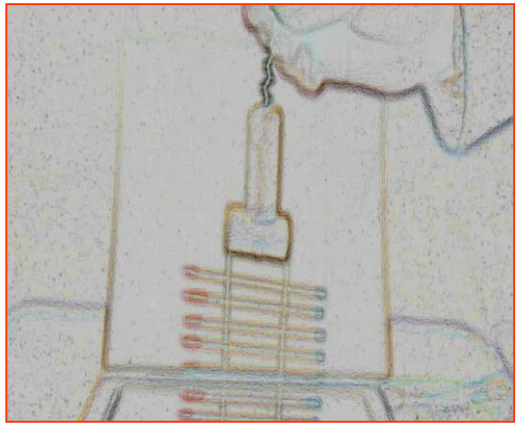
$$\epsilon_{max}^2 = (\pi/2)^2 \frac{\xi}{t_{FM}}$$ = 0.15 – 0.075 if $\xi \approx 0.3$ nm, $t_{FM} \approx l_{ex} \approx 5 - 10$

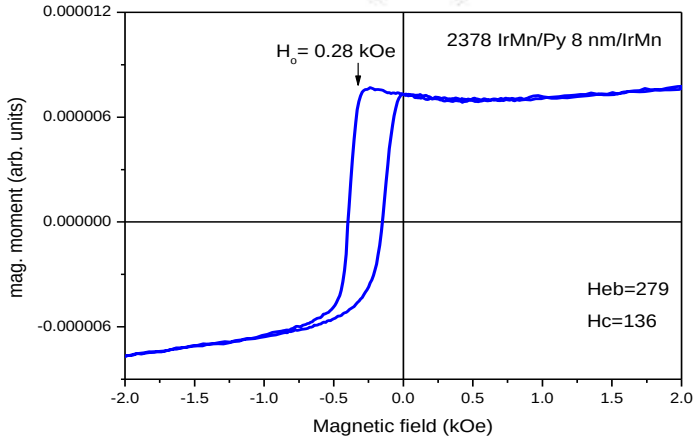
…the highest EB FM can “withstand” is of ~ 1/8 of M-B

after Aharoni et al. J. Appl. Phys. 30, 1956 (1959)

Magnetization twisting: experiment







Z-P. Li et al. Phys. Rev. Lett. 96, 217205 (2006)

SUMMARY

Interfacial interactions FM/AFM → geometrical problem

Heb : $4 \cdot \pi \cdot \mathbf{M} \cdot \mathbf{lex}^2$ FM ε^2 : AFM

Heb : model gives the values compatible with exp.
with ε of 4% for all-metallic FM/AFM structures

Heb^{max} : ~ 1/8 of that of M-B due to
winding of magnetization (eqiv. to ε of 35%)