Magnetic materials for nano-scale sensors

Bob O'Handley, M.I.T.

Objectives:

Low power consumption Smaller
Enhanced sensitivity lower noise, no domain walls
Enhanced functionality novel couplings

With strong reference to work by:
Caroline Ross (M.I.T.), Giesle Herzer (VAC/Morgan), Francesco Stellacci (M.I.T.), Mike McHenry (C.M.U.), Manfred Wuttig (U. Md), Moungi Bawendi (M.I.T.)

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Materials matrix suggested by Workshop

Outline

1) **Functionality:** beyond flux, Hall, MR...

2) **Materials** suggestions (beyond single-phase thin films):
- Not new compositions; new materials:
  Nano-structured magnetic materials,
  Immiscible materials
- Relevant length scales and
  implications for sensor materials

3) **Processing** opportunities
- From Top-down lithography
  of nano-magnetic structures
  to Bottom-up, Self assembled nano-magnetics,
  immiscible systems; metallic...polymeric
  Carbon-based (Fullerenes, nanotubes)

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1) Magnetic material functionality   2) Materials   3) Processing

The obvious:

Induction	*dB/dt* sensor
flux channel	Shield or focus *H*
Hall effect	*H* sensor
MR, GMR, tunnel MR	*H* sensor
Magneto-elastic	Accelerometer
Magneto-optic	Optical rotation (or inverse?)

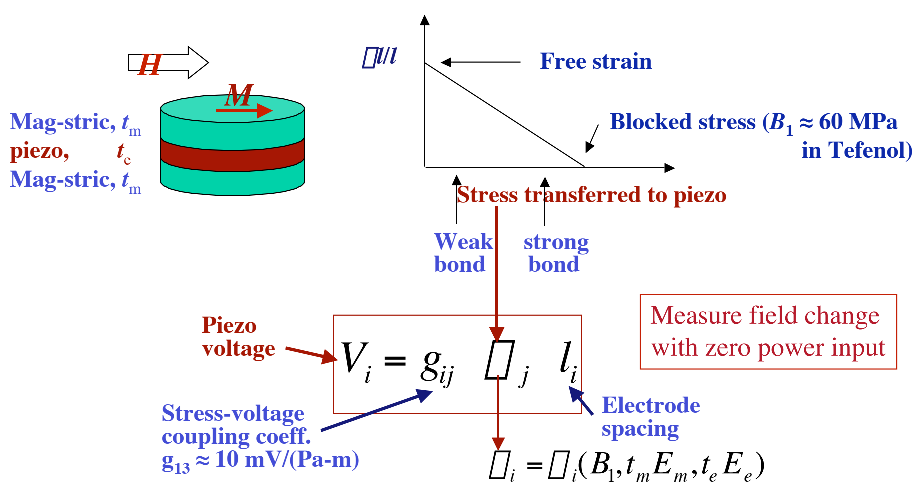
Perhaps less obvious:

Magneto caloric

Magneto-electric ← *H* sensor or accelerometer

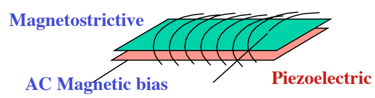
Spin-semiconductor hetero-effects

Magnetostrictive/electro-active sensors

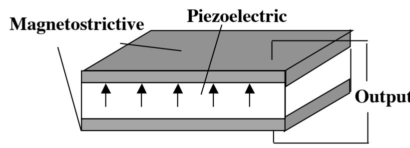


Prior art: magnetostrictive/electro-active field sensors

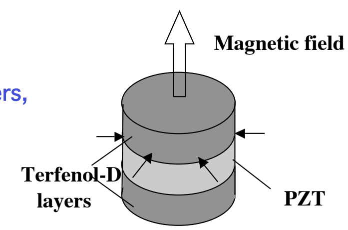
Marconi Research d_{31} sensor
Single magnetic layer,
AC bias field on magnetic layer,
Lynch and Gallantree. GEC Jrnl. Of Res. 8, (1990)



Spinix d_{31} sensor
Two or more magnetic layers,
Device is passive, no power needed,
Y-Q. Li and R. C. O'Handley,
J. Appl. Sens. Tech. 17, 10 (2000)



Penn State sensor
Two compressively prestressed Terfenol-D layers,
Device is passive, no power needed,
J. Ryu, A. V. Carazo, K. Uchino, and H. -E. Kim,
Jpn. J. Appl. Phys. 40, 4948 (2001)



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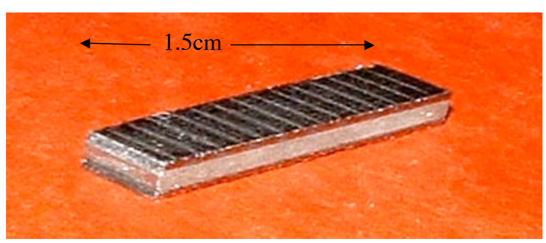
New magnetostrictive/electro-active field sensor



Ferro Solutions sensor
Two Terfenol-D layers, PZT
Device is passive, no power needed: sensitivity = 600 nV/nT

Can be AC biased: sensitivity = 6,000 nV/nT

J. K. Huang, R. C. O'Handley, Patent pending; SPIE Proc. March, 2003.

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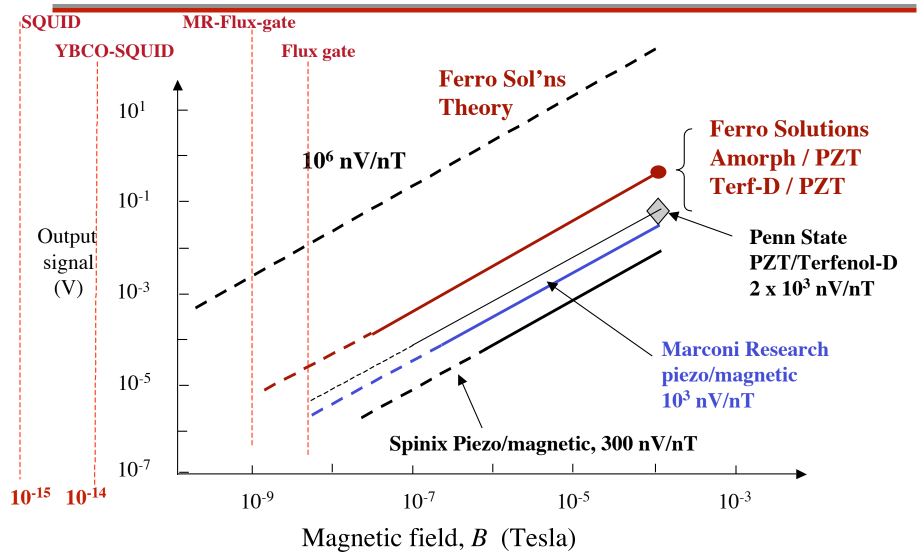
Comparison of magnetostrictive/electro-active sensors



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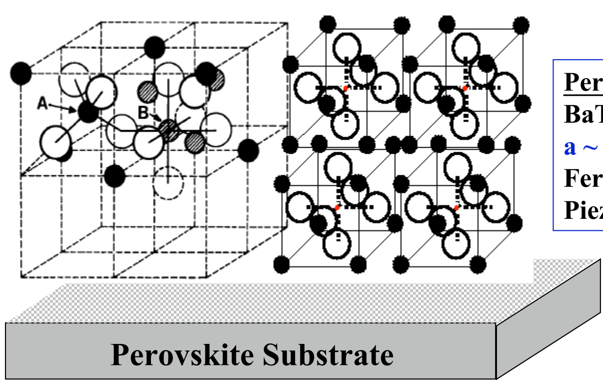
Doing same thin on a nanoscale

Manfred Wuttig, Dwight Viehland, Ichiro Takeuchi, U Md.

Magnetoelectric Epitaxial Nanocomposites

Spinel
$CoFe_2O_4$
a ~ 2·4 Å
Ferrimag.
□□ -10^{-4}



Perovskite
$BaTiO_3$
a ~ 4 Å
Ferroel.
Piezoel.

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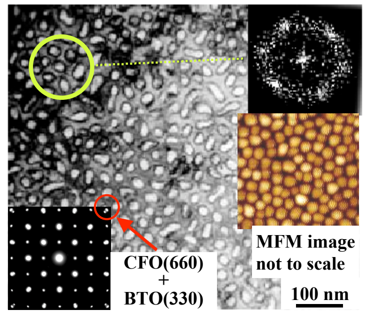
MULTIFERROICS FOR SMART STRUCTURES AND DEVICES

Manfred Wuttig, Dwight Viehland, Ichiro Takeuchi, U. Md

Promising Candidates

$CoFe_2O_4$-$BaTiO_3$
studied in bulk form 1976

Other systems:
$CoFe_2O_4$-$FeBiO_3$
$CoFe_2O_4$-$PbTiO_3$



Self-assembled $CoFe_2O_4$-$BaTiO_3$ hexagonal ME hetero-nano-structure

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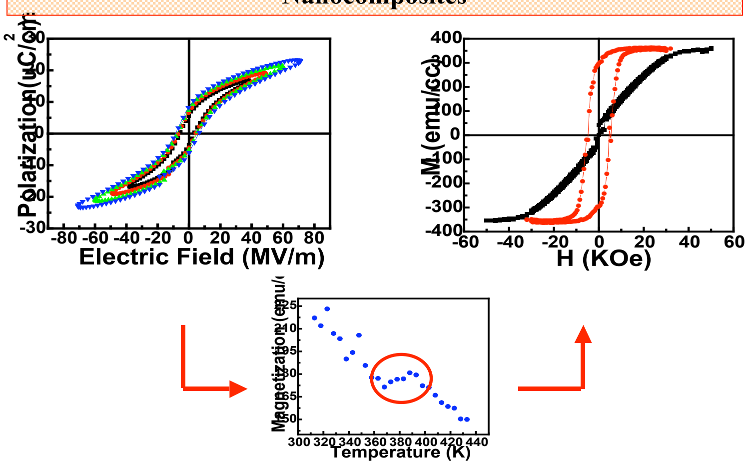
MULTIFERROICS FOR SMART STRUCTURES AND DEVICES

Manfred Wuttig, Dwight Viehland, Ichiro Takeuchi, U. Md

Magnetoelectricity of Epitaxial $CoFe_2O_4$-$BaTiO_3$ Nanocomposites



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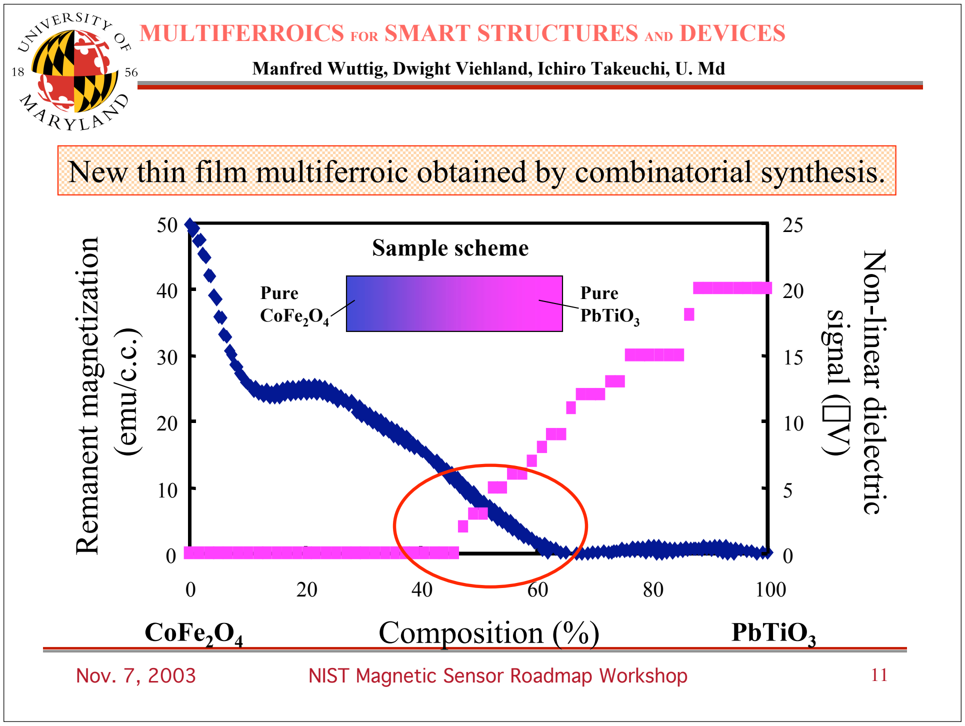
UNIVERSITY OF MARYLAND 18 56
MULTIFERROICS FOR SMART STRUCTURES AND DEVICES
Manfred Wuttig, Dwight Viehland, Ichiro Takeuchi, U. Md
New thin film multiferroic obtained by combinatorial synthesis.
Sample scheme
Pure $CoFe_2O_4$
Pure $PbTiO_3$
Remanent magnetization (emu/c.c.)
Non-linear dielectric signal (V)
50
40
30
20
10
0
25
20
15
10
5
0
0
20
40
60
80
100
$CoFe_2O_4$
Composition (%)
$PbTiO_3$
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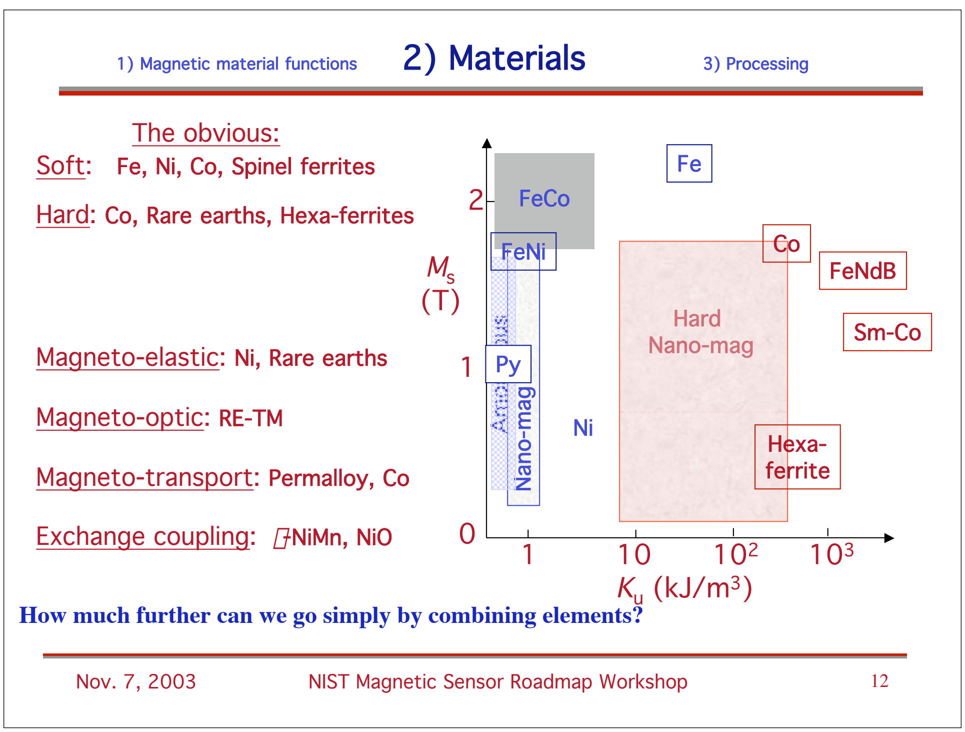
1) Magnetic material functions
2) Materials
3) Processing
The obvious:
Soft: Fe, Ni, Co, Spinel ferrites
Hard: Co, Rare earths, Hexa-ferrites
Magneto-elastic: Ni, Rare earths
Magneto-optic: RE-TM
Magneto-transport: Permalloy, Co
Exchange coupling: NiMn, NiO
M_s (T)
2
1
0
FeCo
FeNi
Py
Nano-mag
Ni
Fe
Co
FeNdB
Sm-Co
Hard Nano-mag
Hexa-ferrite
1
10
10^2
10^3
K_u (kJ/m^3)
How much further can we go simply by combining elements?
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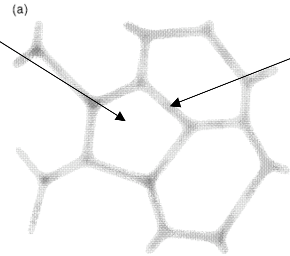
Magnetic nano-structured materials

Crystalline properties

Amorphous properties

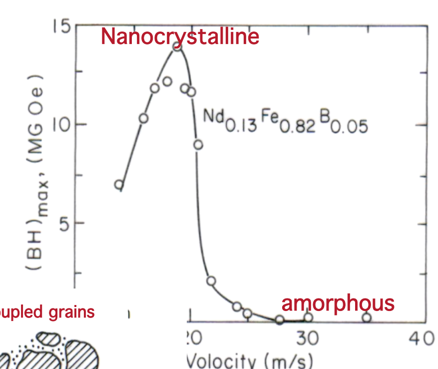


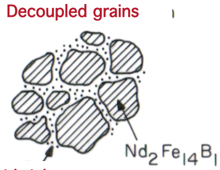
Nanostructured materials are MORE THAN JUST AVERAGE PROPERTIES of amorphous and crystalline materials; new property fields are accessible…

…and in nano-MAGNETIC materials,
several competing length scales in play
and can be exploited to advantage

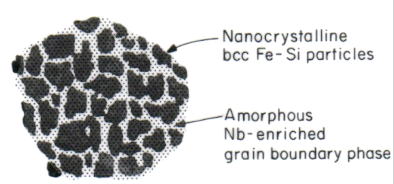
Nano-magnetic materials - first pass

Rapidly solidified Nd-Fe-B (Croat et al. '84)



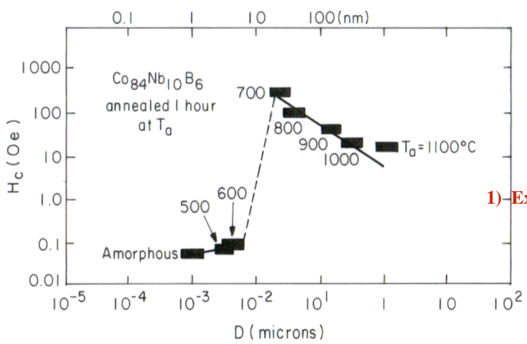


Amorphous $Fe_{74}Si_{15}B_7Cu_1Nb_3$
"Fe_3Si" nano-crystals in amorphous matrix (Yoshizawa, '88)



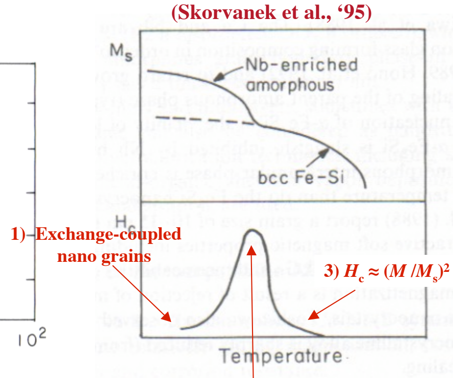
Nano-magnetic materials - first pass

Devitrified amorphous alloy (O'H et al., '89)



(Herzer, '90)

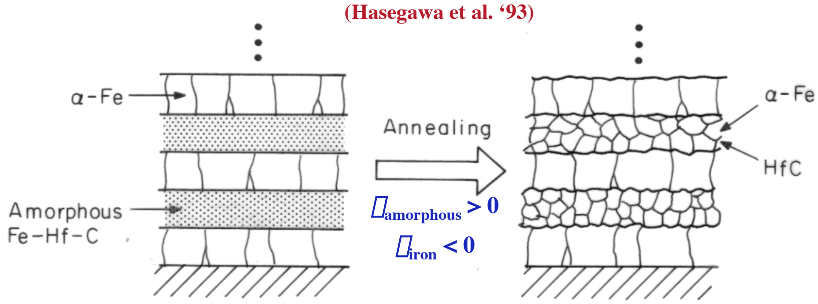
Devitrified amorphous alloy (Skorvanek et al., '95)



2) Exchange-coupling breaks down; array of single-domain particles

Nano-magnetic materials - first pass

Fe/Fe-Hf-C (Hasegawa et al. '93)



$B_s \approx 2$ T with good soft magnetic properties, low magnetostriction.

Nano-magnetic materials - first pass

Crystallizing to α-Fe rather than Fe_3Si (DO_3) increases B_s:

Amorphous $Fe_{88}Zr_7B_4Cu_1$
⇒ α-Fe nanocrystals
in amorphous matrix
(Suzuki et al., '91)

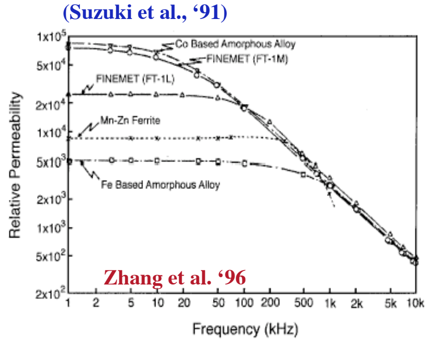
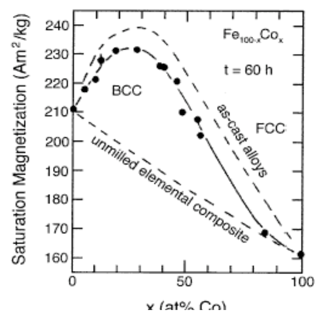


Fig. 67. Frequency dependence of the permeability for a FINEMET material as compared w based amorphous material and with Mn–Zn ferrites [290,291].

Amorphous $Fe_{44}Co_{44}Zr_7B_4Cu_1$
⇒ α-FeCo nanocrystals
in amorphous matrix (HITPERM)
(Willard et al., '98)



B_s > 2 T with permeability up to 4000
Now in thin film form: HITPERM/SiO_2
McHenry group, C.M.U.

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Nano-magnetic material properties - first pass

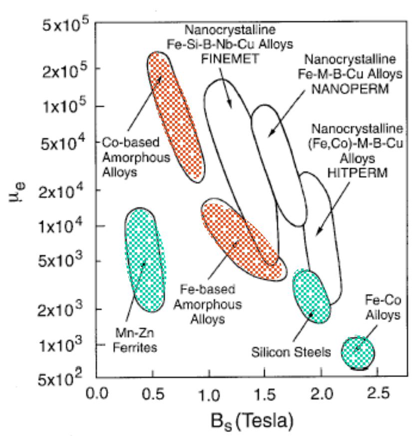

Fig. 1. Relationship between permeability, μ_e (at 1 kHz) and saturation polarization for soft magnetic materials (adapted from Ref. [193]).

(Machino et al, '95)

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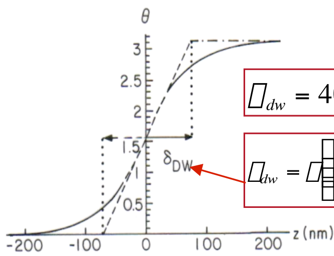
1) Magnetic material functions **2) length scales** 3) Processing

Prior nano-magnetic results due to
Changed *length scales* => Completely new properties

Bloch domain walls (180°) walls in materials



$$\gamma_{dw} = 4(AK_u)^{1/2}$$

$$\delta_{dw} = \pi\left(\frac{A}{K_u}\right)^{1/2}$$

	K_u (kJ/m^3)	δ_{dw} (nm)	γ_{dw} (mJ/m^2)
Ni	4.5	150	0.85
Fe	48	45	2.8
Co	410	15.5	8.1
$Fe_{14}Nd_2B$	5,000	4.4	28
Amorphous	1	1,000	0.1

Exchange lengths

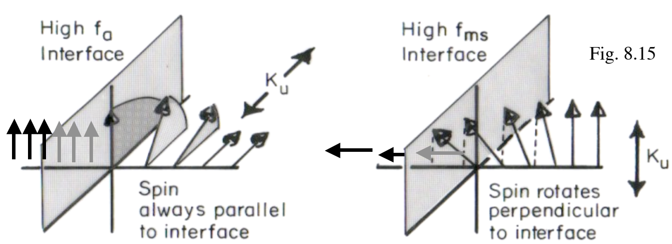


Fig. 8.15

M parallel to interface:

$$l_{ex}^{\parallel} = \left(\frac{A}{K_u}\right)^{1/2} = \frac{\delta_{dw}}{\pi}$$

M perpendicular to interface:

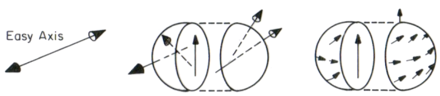
$$l_{ex}^{\perp} = \left(\frac{A}{K_u + 2\pi M_s^2}\right)^{1/2} \text{ can be} << \delta_{dw}$$

Energy pushing spins back to EA

Single-domain particles

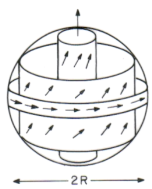
For what spherical radius is magnetostatic energy smaller than domain wall energy?

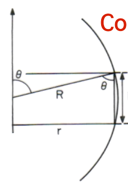
$$\underbrace{\approx \frac{1}{3}\mu_0 M_s^2 \cdot \frac{4}{3}\pi r^3 \qquad \approx \sigma_{dw} \cdot \pi r^2 = 4\pi r^2 \sqrt{AK_u}}$$



$$\boxed{r_c \approx 9\frac{(AK_u)^{1/2}}{\mu_0 M_s^2}} \qquad \text{(large } K_u\text{)}$$

r_c = 8 nm for Co, 31 nm for $Fe_{14}Nd_2B$





Compare exchange energy cost to magnetostatic energy

$$\boxed{r_c = \sqrt{\frac{9A}{\mu_0 M_s^2}\left[\ln\left(\frac{2r_c}{a}\right) - 1\right]}} \quad \text{(small } K_u\text{)}$$

r_c for Fe (small K) ≈25 nm
(instead of ≈5 nm)

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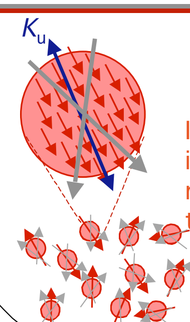
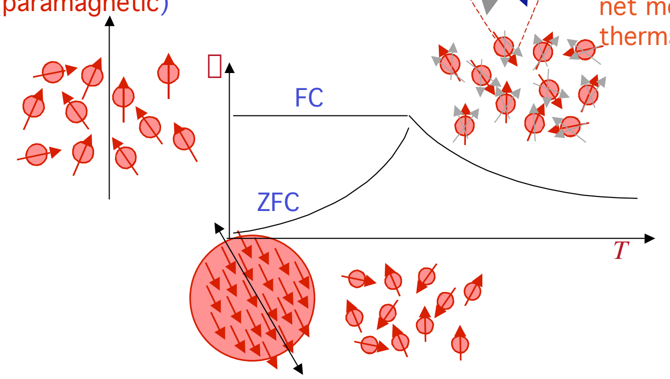
Superparamagnetism

Material is an assembly of super-large (super) magnetic moments, Nm_m , that are NON-interacting (paramagnetic)



Individual particle/region is ferromagnetic with net moment, Nm_m thermally freed from K_u



$$\boxed{r_0^{1s} \approx \left(\frac{6k_BT}{K_u}\right)^{1/3}}$$

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Random anisotropy

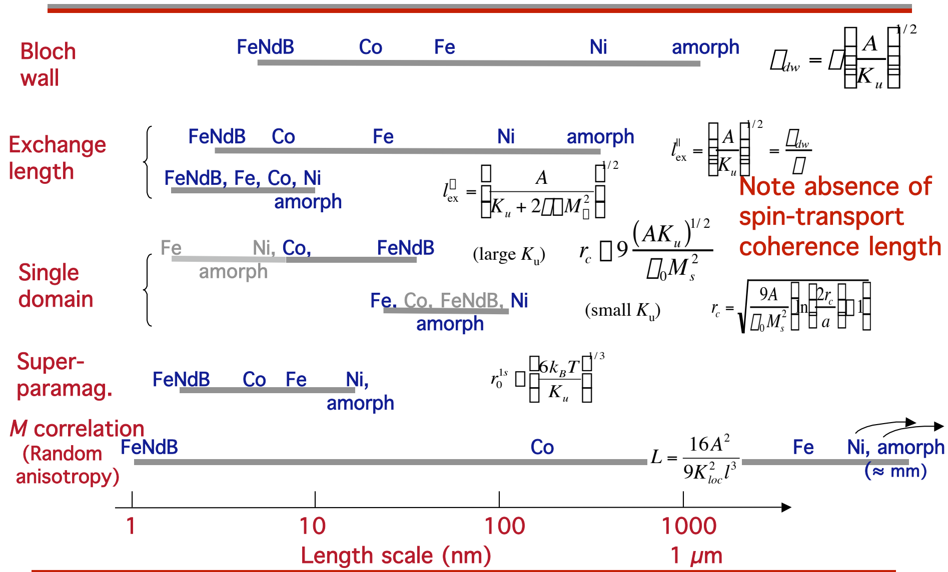
Local anisotropy correlation length: l

Magnetization correlation length:

$$\boxed{L = \frac{16A^2}{9K_{\text{loc}}^2 l^3}}$$

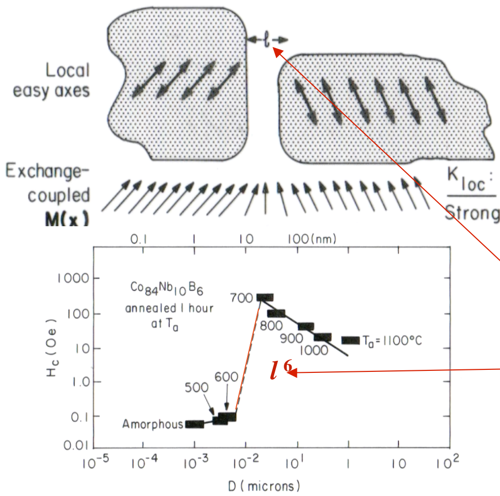
Imry&Ma, '75

Magnetic length scales



Random anisotropy in nanocrystalline materials

Nano-magnetics - second pass: combine lengths



Herzer added L_{ex} to Imry & Ma:

$$L = \frac{16A^2}{9K_{loc}^2 l^3} \qquad L_{exch} \approx \left(\frac{A}{\langle K\rangle}\right)^{1/2}$$

$$\langle K\rangle \approx 0.32\left(\frac{K_u^4}{A^3}\right) l^6$$

l^6

Length over which anisotropy direction changes

Random anisotropy in nanocrystalline materials

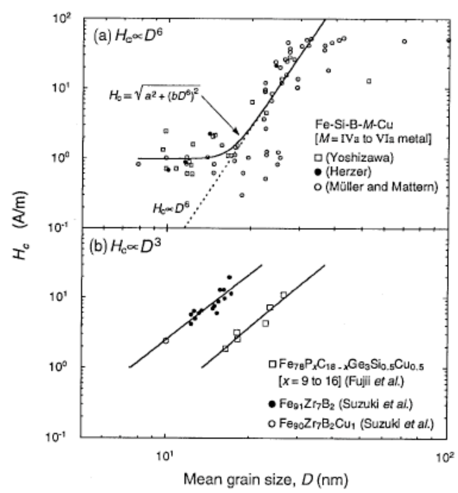
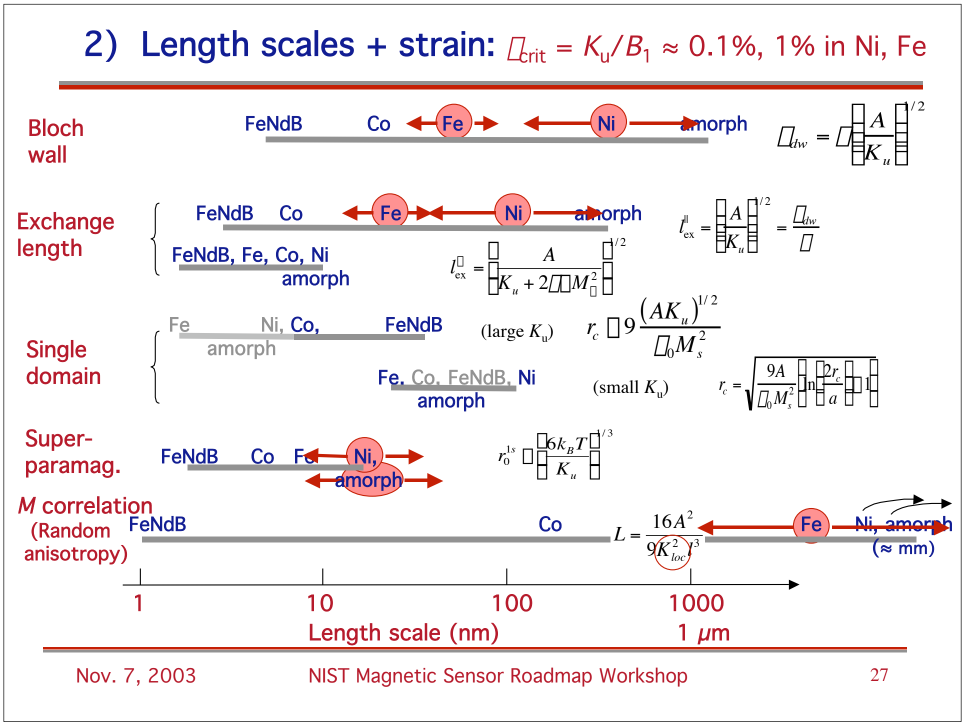


Fig. 58. Coercivity, H_c vs. grain size for (a) Fe–Si–B–TE–Cu (TE = early transition metal) (FINEMET) and (b) Fe–Zr–B–Cu (NANOPERM) and Fe–P–C–Ge–Si–Cu alloys [264–266].

Herzer. $H_c \propto D^6$

$H_c \propto D^3$ due to an additional, long-range, uniaxial anisotropy, possibly of magneto-elastic origin.

McHenry, Willard, Laughlin, Prog. Matrls Sci. 44, 291-433 (1999)


2) Length scales + strain: crit = K_u/B_1 ≈ 0.1%, 1% in Ni, Fe
Bloch wall
FeNdB Co Fe Ni amorph
Exchange length
FeNdB Co Fe Ni amorph
FeNdB, Fe, Co, Ni
amorph
Single domain
Fe Ni, Co, FeNdB
amorph
(large K_u)
Fe, Co, FeNdB, Ni
amorph
(small K_u)
Super-paramag.
FeNdB Co Fe Ni,
amorph
M correlation (Random anisotropy)
FeNdB
Co
Fe
Ni, amorph
(≈ mm)
1
10
100
1000
Length scale (nm)
1 μm
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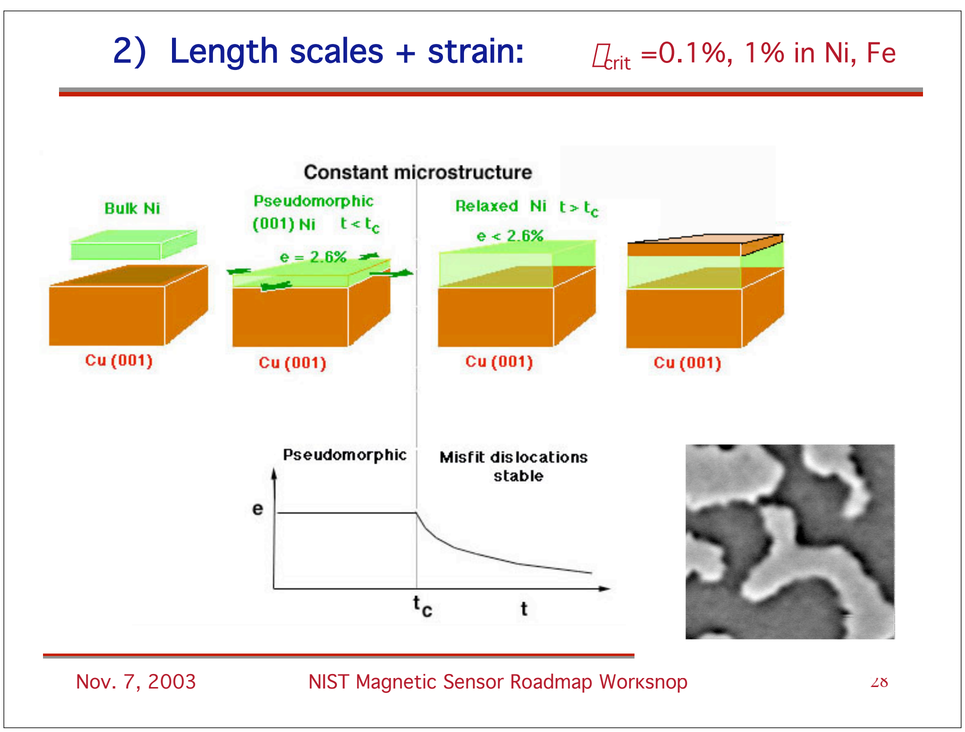
2) Length scales + strain: crit =0.1%, 1% in Ni, Fe
Constant microstructure
Bulk Ni
Pseudomorphic (001) Ni t < t_c
e = 2.6%
Relaxed Ni t > t_c
e < 2.6%
Cu (001)
Cu (001)
Cu (001)
Cu (001)
Pseudomorphic
Misfit dislocations stable
e
t_c
t
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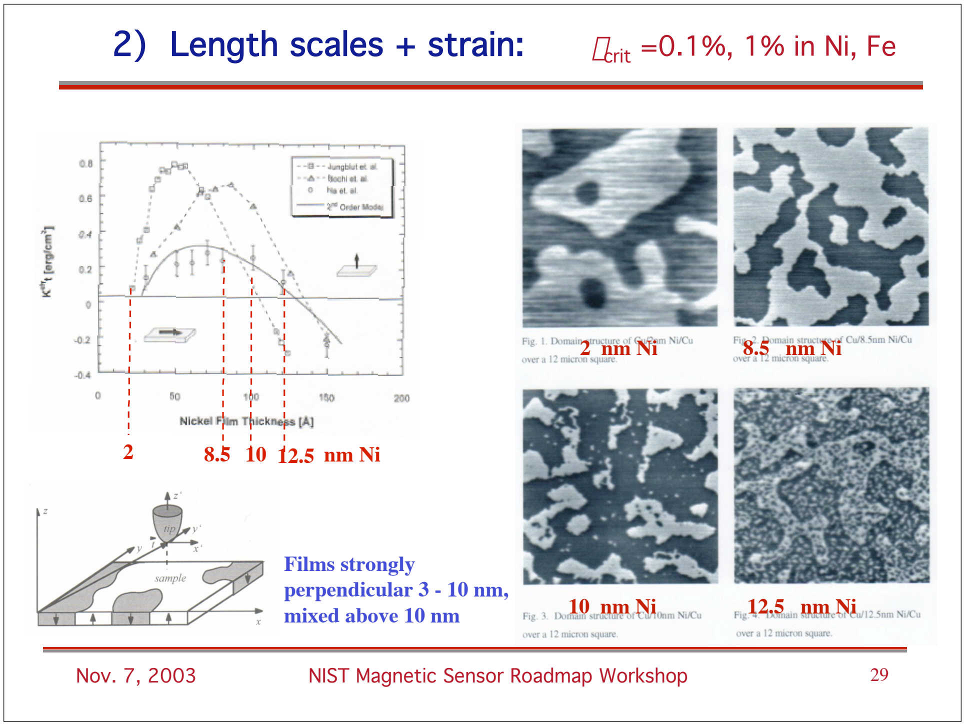

2) Length scales + strain:
crit =0.1%, 1% in Ni, Fe
Jungblut et. al.
Bochi et. al.
Ha et. al.
2nd Order Model
Nickel Film Thickness [Å]
2 8.5 10 12.5 nm Ni
Films strongly perpendicular 3 - 10 nm, mixed above 10 nm
2 nm Ni
8.5 nm Ni
10 nm Ni
12.5 nm Ni
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