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.), Mike McHenry (C.M.U.),
Giesle Herzer (VAC/Morgan), Manfred Wuttig (U. Md),
Francesco Stellacci (M.I.T.), Moungi Bawendi (M.I.T.)

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)

1) Magnetic material functionality

2) Materials 3) Processing

The obvious:

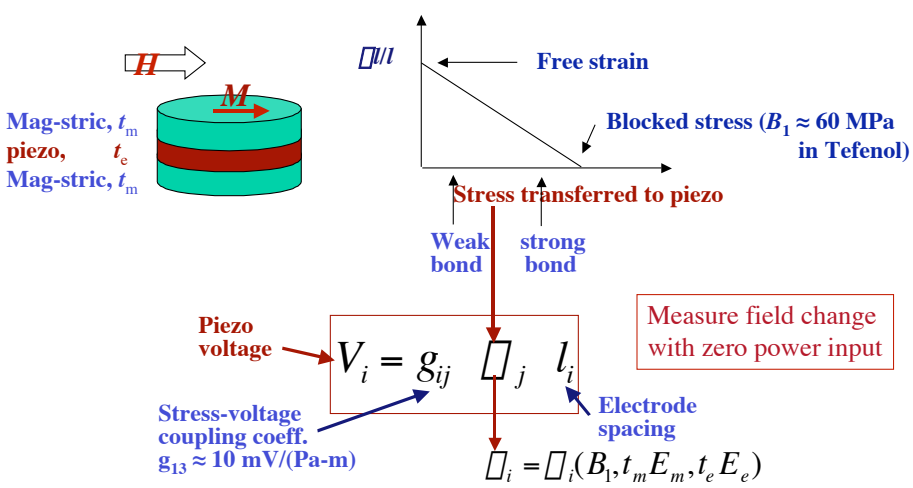
Induction	*dB/dt* sensor
flux channel	Shield or focus *H*
Hall effect	*H* sensor
MR, GMR, tunnel MR	*H* sensor
Magneto-elastic	Accelerometer
Magneto-optic	Optical rotation (or inverse?)

Perhaps less obvious:

Magneto caloric
Magneto-electric
Spin-semiconductor hetero-effects

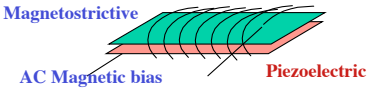
H sensor or accelerometer

Magnetostrictive/electro-active sensors

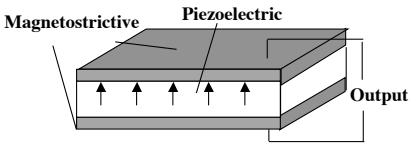


Prior art: magnetostrictive/electro-active field sensors

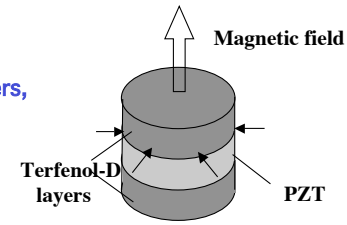
Marconi Research d_{31} sensor
Single magnetic layer,
AC bias field on magnetic layer,
Lynch and Gallantree. GEC Jrnl. Of Res. **8**, (1990)



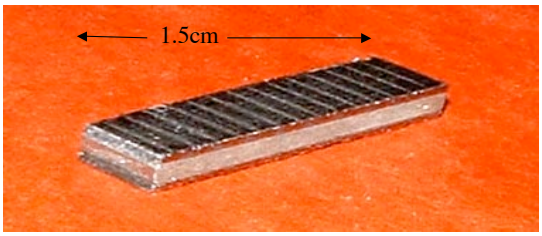
Spinix d_{31} sensor
Two or more magnetic layers,
Device is passive, no power needed,
Y-Q. Li and R. C. O'Handley,
J. Appl. Sens. Tech. **17**, 10 (2000)



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)



New magnetostrictive/electro-active field sensor

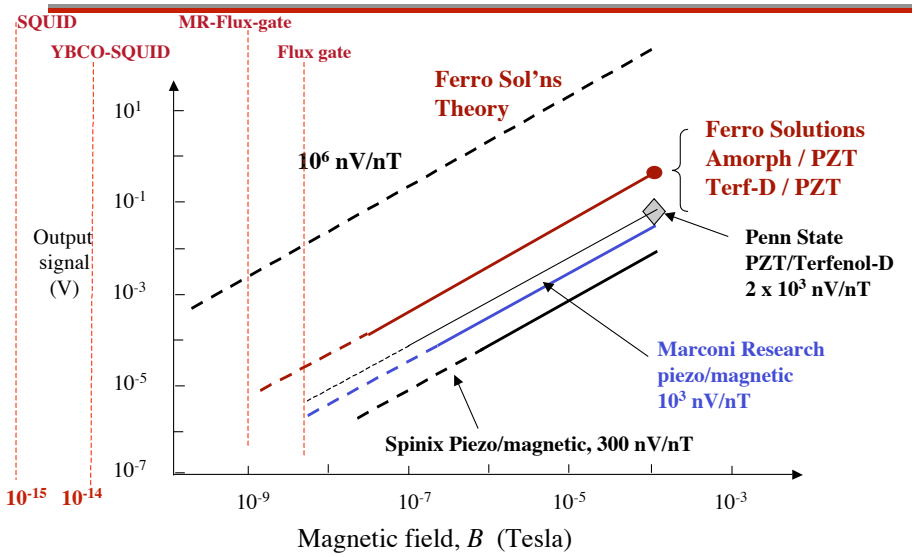


Ferro Solutions sensor
Two Terfenol-D layers, PZT
Device is passive, no power needed: sensitivity = 600 nV/nT

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

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

Comparison of magnetostrictive/electro-active sensors

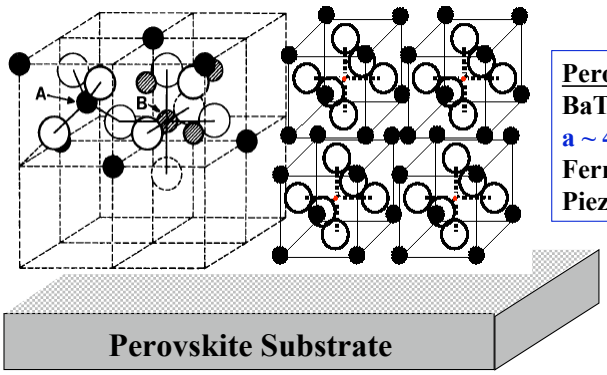


Doing same thin on a nanoscale

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.

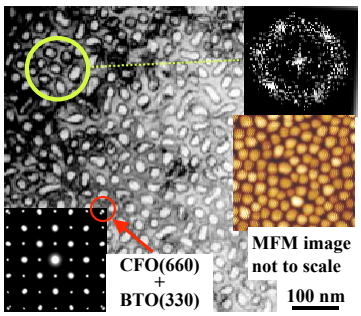
MULTIFERROICS FOR SMART STRUCTURES AND DEVICES

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

MULTIFERROICS FOR SMART STRUCTURES AND DEVICES

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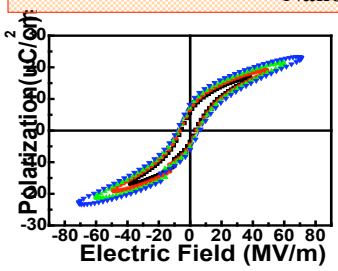
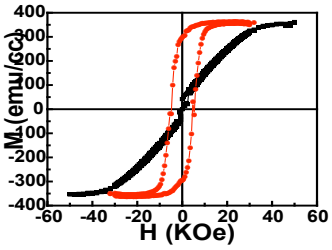
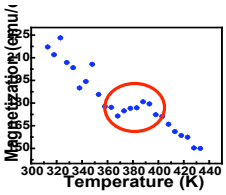
Magnetoelectricity of Epitaxial $CoFe_2O_4$-$BaTiO_3$ Nanocomposites



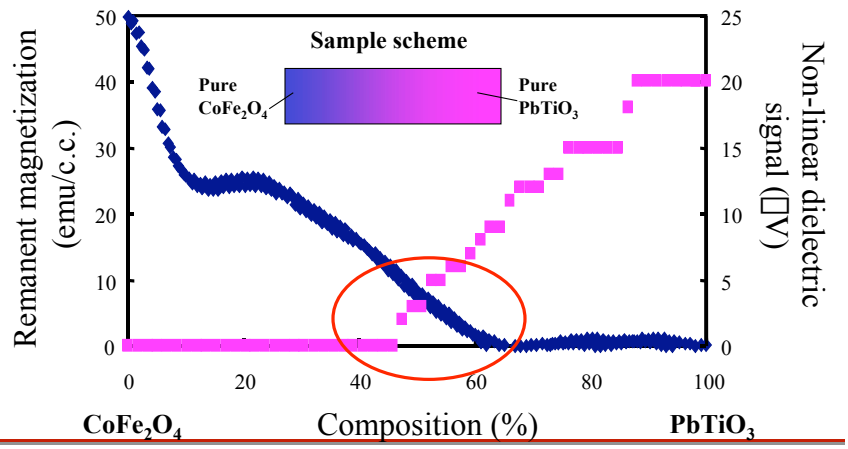




MULTIFERROICS FOR SMART STRUCTURES AND DEVICES

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

New thin film multiferroic obtained by combinatorial synthesis.



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1) Magnetic material functions **2) Materials** 3) Processing

The obvious:

Soft: Fe, Ni, Co, Spinel ferrites

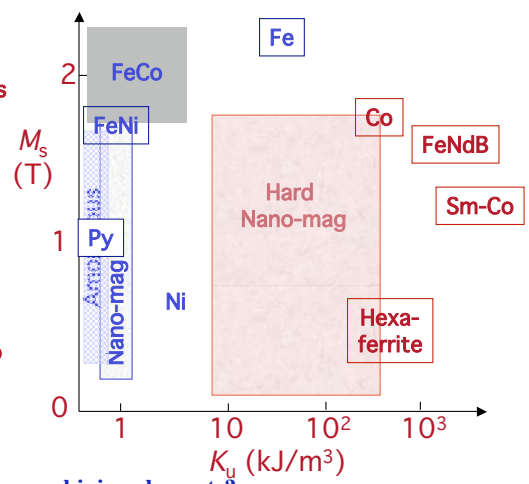
Hard: Co, Rare earths, Hexa-ferrites

Magneto-elastic: Ni, Rare earths

Magneto-optic: RE-TM

Magneto-transport: Permalloy, Co

Exchange coupling: □NiMn, NiO



How much further can we go simply by combining elements?

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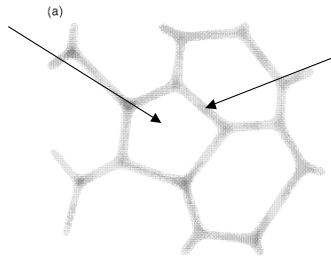
Magnetic nano-structured materials

Crystalline properties

Amorphous properties

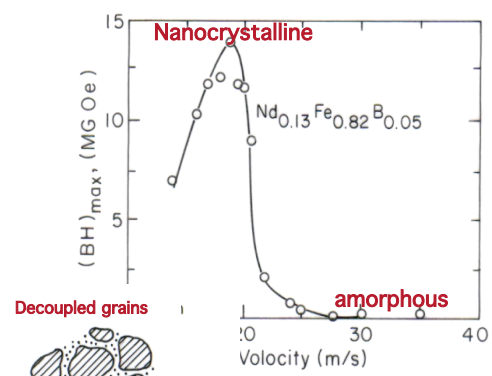


Nanostructured materials are MORE THAN JUST AVERAGE PROPERTIES of amorphous and crystalline materials; new property fields are accessible…

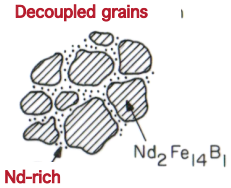
…and in nano-MAGNETIC materials, several competing length scales in play and can be exploited to advantage

Nano-magnetic materials - first pass

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

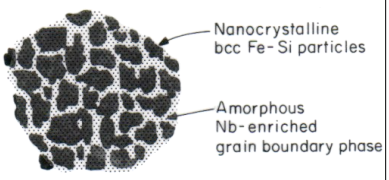


Decoupled grains



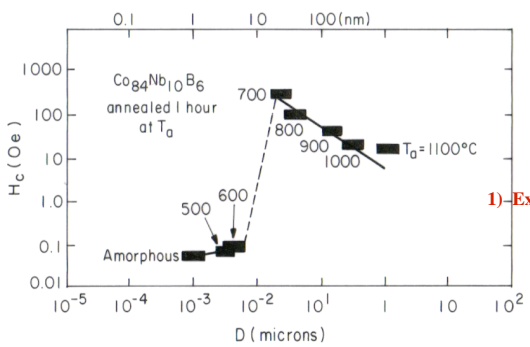
Nd-rich

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



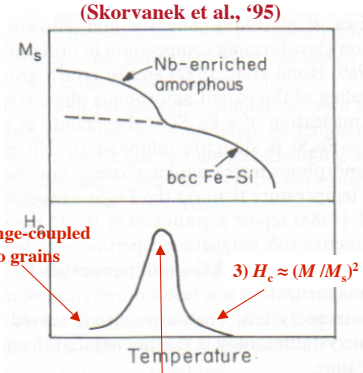
Nano-magnetic materials - first pass

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



(Herzer, '90)

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



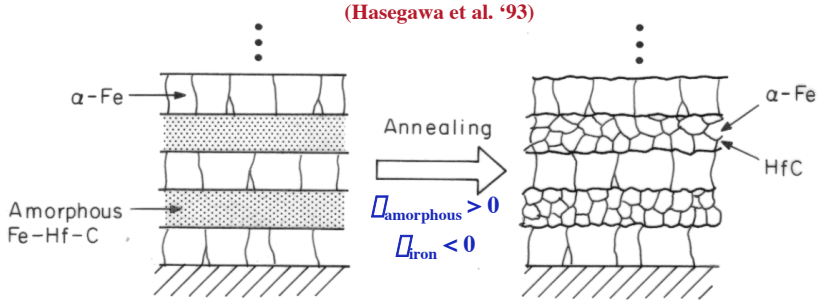
1) Exchange-coupled nano grains

3) $H_c \approx (M/M_s)^2$

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 α-Fe nanocrystals
in amorphous matrix
(Suzuki et al., '91)

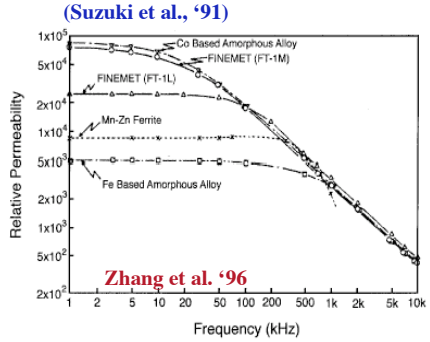
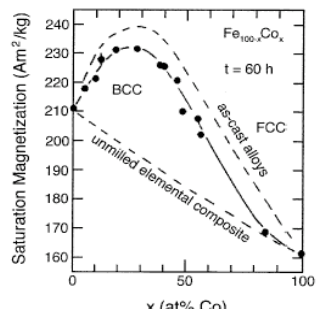


Fig. 67. Frequency dependence of the permeability for a FINEMET material as compared w based amorphous material and with Mn–Zn ferrites [290,291].

Amorphous $Fe_{44}Co_{44}Zr_7B_4Cu_1$
α 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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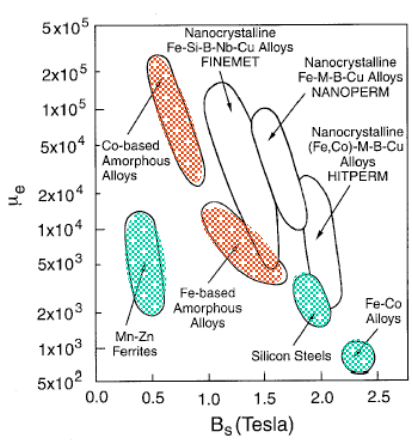
Nano-magnetic material properties - first pass



(Machino et al, '95)

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

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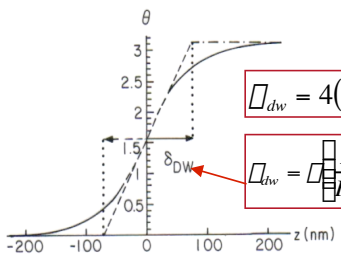
1) Magnetic material functions **2) length scales** 3) Processing

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

Bloch domain walls (180°) walls in materials



$$\delta_{dw} = 4\left(AK_u\right)^{1/2}$$

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

	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

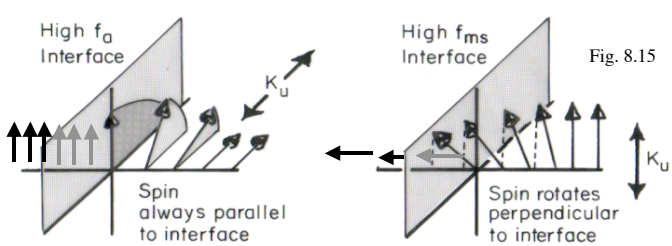


Fig. 8.15

M parallel to interface:

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

M perpendicular to interface:

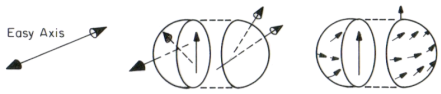
$$l_{ex}^{\perp} = \left(\frac{A}{K_u + 2\pi M_s^2}\right)^{1/2} \text{ can be } << \delta_{dw}$$

Energy pushing spins back to EA

Single-domain particles

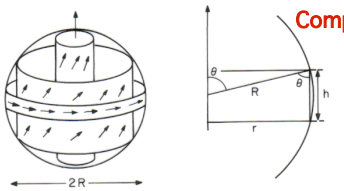
For what spherical radius is magnetostatic energy smaller than domain wall energy?

$$\frac{1}{3}\mu_0 M_s^2 \frac{4}{3}\pi r^3 \qquad \gamma_{dw}\pi r^2 = 4\pi r^2\sqrt{AK_u}$$



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

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



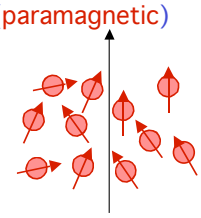
Compare exchange energy cost to magnetostatic energy

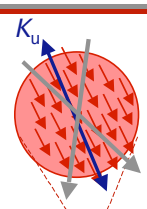
$$r_c = \sqrt{\frac{9A}{\mu_0 M_s^2}\left(\ln\left(\frac{2r_c}{a}\right)-1\right)} \qquad \text{(small } K_u\text{)}$$

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

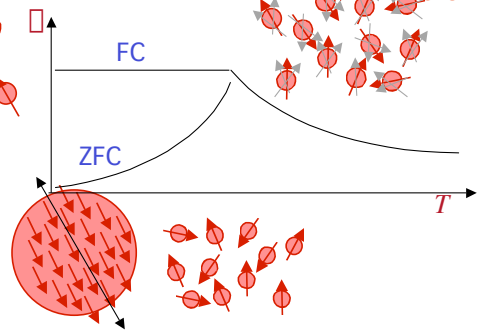
Superparamagnetism

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



$$r_0^{1s} = \left(\frac{6k_B T}{K_u}\right)^{1/3}$$

Random anisotropy

Local anisotropy correlation length: l

Magnetization correlation length:

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

Imry&Ma, '75

Magnetic length scales

Bloch wall — FeNdB, Co, Fe, Ni, amorph

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

Exchange length — FeNdB, Co, Fe, Ni, amorph; FeNdB, Fe, Co, Ni amorph

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

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

Note absence of spin-transport coherence length

Single domain — Fe, Ni, Co, FeNdB amorph (large K_u); Fe, Co, FeNdB, Ni amorph (small K_u)

$$r_c \approx 9\frac{(AK_u)^{1/2}}{\mu_0 M_s^2}$$

$$r_c = \sqrt{\frac{9A}{\mu_0 M_s^2}\ln\left(\frac{2r_c}{a}\right)}$$

Super-paramag. — FeNdB, Co, Fe, Ni, amorph

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

***M* correlation (Random anisotropy)** — FeNdB, Co, Fe, Ni, amorph (≈ mm)

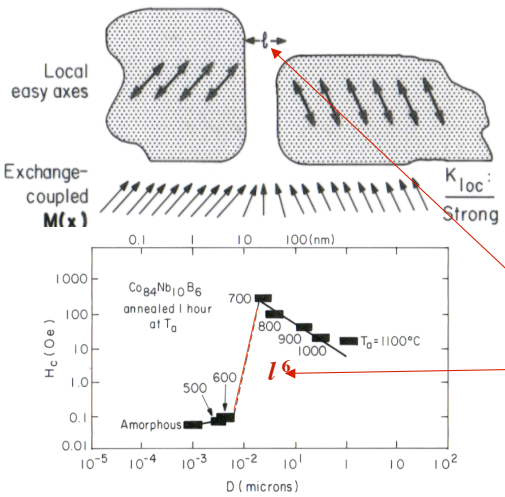
$$L = \frac{16A^2}{9K_{loc}^2 l^3}$$

1 — 10 — 100 — 1000

Length scale (nm) — 1 μm

Random anisotropy in nanocrystalline materials

Nano-magnetics - second pass: combine lengths



Herzer added L_{ex} to Imry & Ma:

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

$$\langle K \rangle \sim 0.32 \left(\frac{K_u^4}{A^3}\right)^{1/2} l^6$$

Length over which anisotropy direction changes

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Random anisotropy in nanocrystalline materials

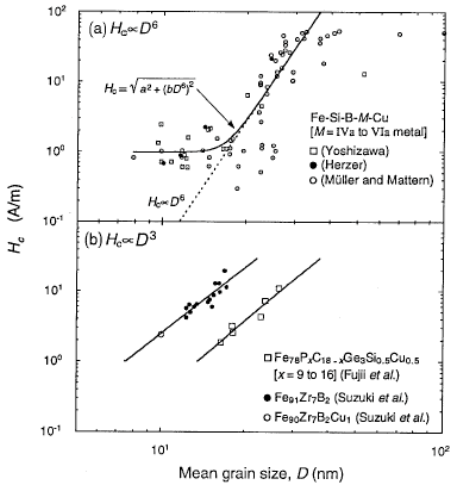

Fig. 58. Coercivity, H_c vs. grain size for (a) Fe–Si–B–TE–Cu (TE = early transition metal) (FINEMET) and (b) Fe–Zr–B–Cu (NANOPERM) and Fe–P–C–Ge–Si–Cu alloys [264–266].

Herzer. $H_c \mu D^6$

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

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

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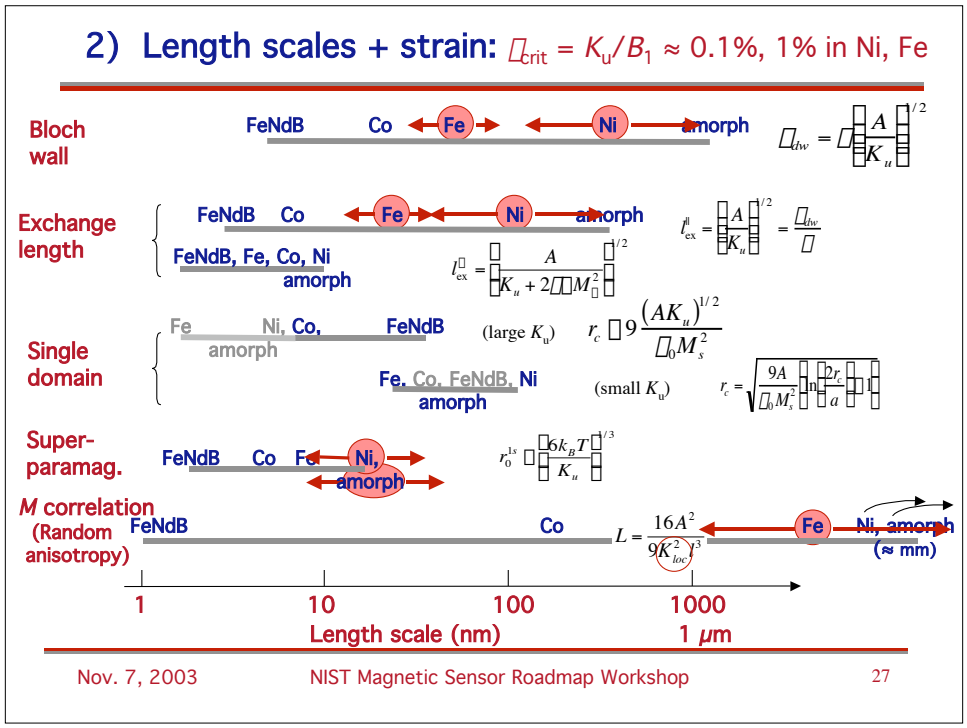
2) Length scales + strain: $\varepsilon_{crit} = K_u/B_1 \approx 0.1\%$, 1% in Ni, Fe
Bloch wall
FeNdB
Co
Fe
Ni
amorph
$\delta_{dw} = \pi\left(\frac{A}{K_u}\right)^{1/2}$
Exchange length
FeNdB Co
Fe
Ni
amorph
FeNdB, Fe, Co, Ni
amorph
$l^{\parallel}_{ex} = \left(\frac{A}{K_u}\right)^{1/2} = \frac{\delta_{dw}}{\pi}$
$l^{\perp}_{ex} = \left(\frac{A}{K_u + 2\pi M_s^2}\right)^{1/2}$
Single domain
Fe
Ni, Co,
FeNdB
amorph
(large K_u)
$r_c \approx 9\frac{(AK_u)^{1/2}}{\mu_0 M_s^2}$
Fe, Co, FeNdB, Ni
amorph
(small K_u)
$r_c = \sqrt{\frac{9A}{\mu_0 M_s^2}\ln\left(\frac{2r_c}{a}\right)}$
Super-paramag.
FeNdB
Co
Fe
Ni,
amorph
$r_0^{1s} \approx \left(\frac{6k_B T}{K_u}\right)^{1/3}$
M correlation
(Random anisotropy)
FeNdB
Co
$L = \frac{16A^2}{9K_{loc}^2}$
Fe
Ni, amorph
(≈ mm)
1
10
100
1000
Length scale (nm)
1 μm
Nov. 7, 2003
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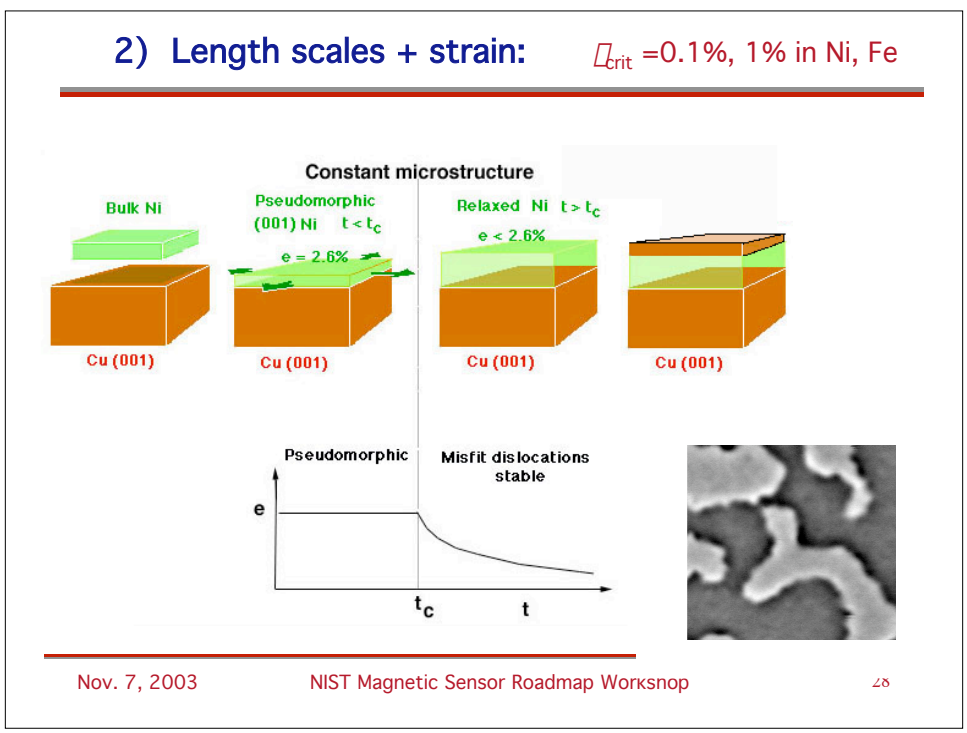
2) Length scales + strain: ε_{crit} =0.1%, 1% in Ni, Fe
Constant microstructure
Bulk Ni
Pseudomorphic (001) Ni t < t_c
e = 2.6%
Relaxed Ni t > t_c
e < 2.6%
Cu (001)
Cu (001)
Cu (001)
Cu (001)
Pseudomorphic
Misfit dislocations stable
e
t_c
t
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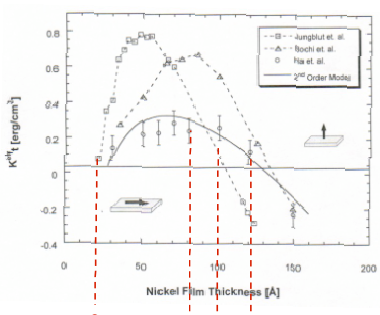
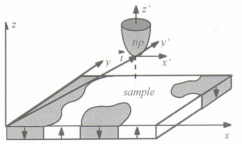
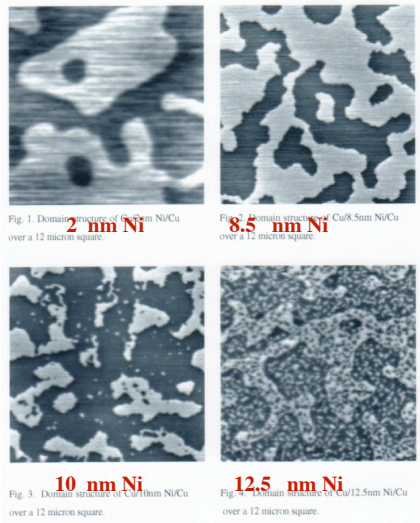
2) Length scales + strain: $\square_{crit}$ =0.1%, 1% in Ni, Fe



2 8.5 10 12.5 nm Ni



Films strongly perpendicular 3 - 10 nm, mixed above 10 nm



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