Fabricated Magnetic Structures

YURI SUZUKI

LECTURE 2
Magnetic Behavior in Small Magnetic Structures

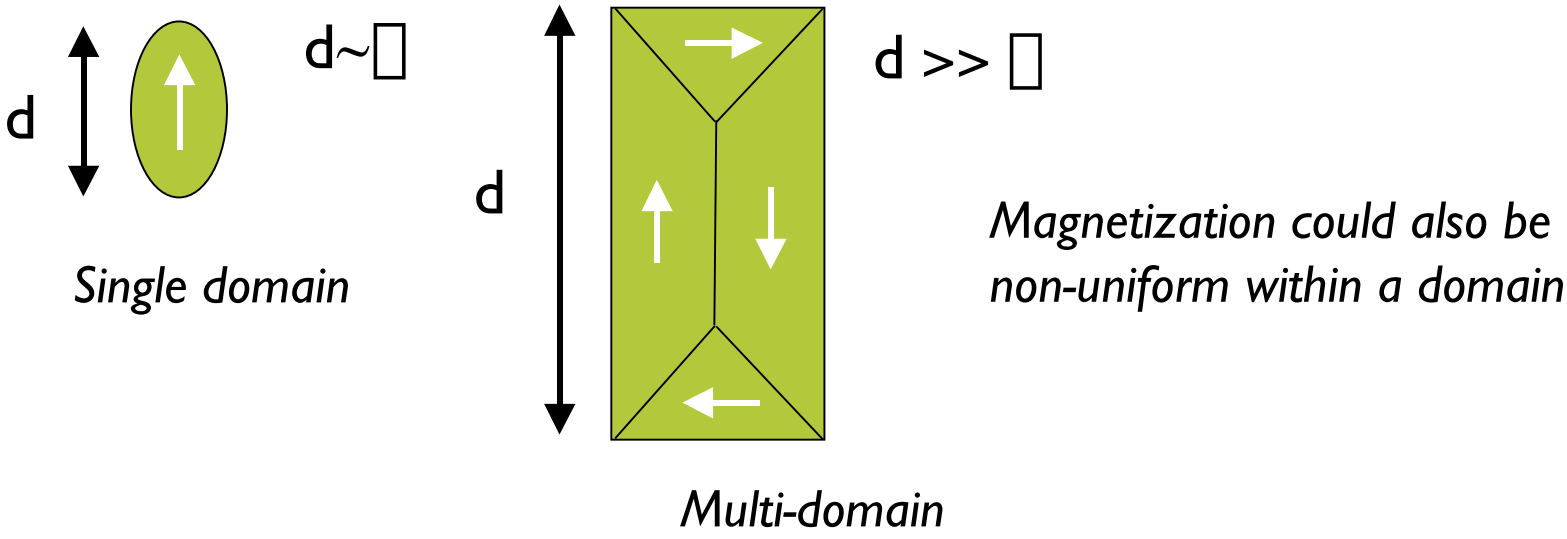
BOULDER SUMMER SCHOOL

Lectures on Fabricated Magnetic Structures

- Synthesis and fabrication techniques for magnetic structures
- Magnetic behavior in small magnetic structures
  - Review of fundamentals: energies, interactions
  - Magnetization process
  - Examples from the literature
- Magnetic Junction Devices

How small is small?

- What determines whether a magnetic structure is made of up a single domain or many domains?



- Characteristic length scales
  - *Exchange length*- over which magnetic moments are parallel
    □ = $\sqrt{A}$ /M_s where A= exchange constant, M_s= saturation magnetization
  - *Domain wall width*-
    □ = π $\sqrt{(A/K)}$ where K= anisotropy constant

Review of Fundamentals: Energies

- **Magnetostatic**
  - *associated with magnetization in its own self-field*

    potential energy/volume of magnetization M in an external field B: $u = -M \cdot B$

    potential energy/volume of magnetization M in its own self field H_d: $u = -(\mu_o/2)M \cdot H_d = (\mu_o/2)NM^2$
- **Exchange**
  - *associated with QM interactions (Pauli's exclusion principle) among atomic moments*
- **Anisotropy**
  - *associated with tendency for the magnetic moments to align in certain directions due to crystal symmetry, stress, etc.*

Magnetostatic Energy

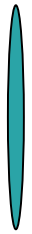
a.k.a. demagnetization or dipolar energy

- Potential energy

$$-\frac{\mu_0}{2}\int_V M.H_d\,dV = -\frac{\mu_0}{2}\int_V M^2 N_d\,dV$$

$N_d = 1/3$

- Minimizing magnetostatic energy by forming domains



M ↑ $N_d \sim 0$

M → $N_d \sim 1$

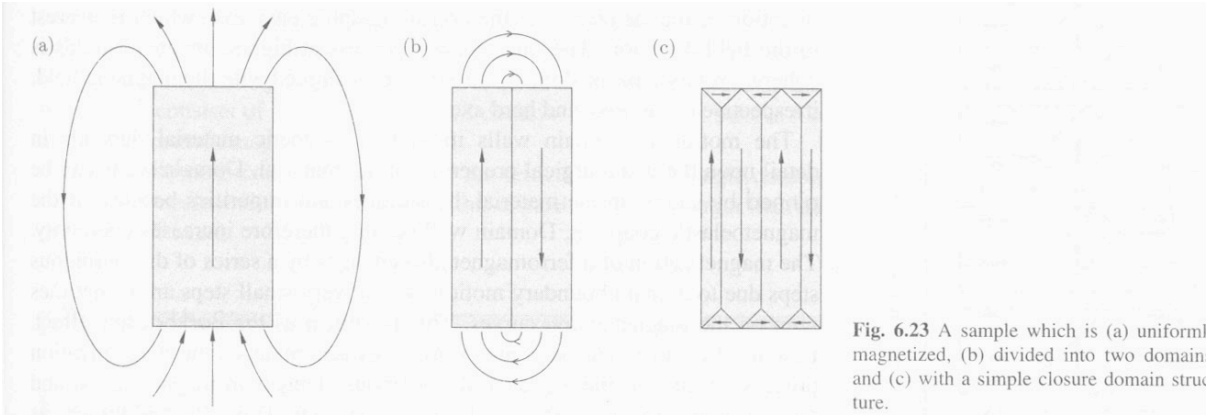


Fig. 6.23 A sample which is (a) uniformly magnetized, (b) divided into two domains and (c) with a simple closure domain structure.

Exchange Energy

- Exchange interactions are electrostatic interactions
- For a two electron system, the exchange constant or integral J is defined as

$$J = (E_T - E_S)/2 = \int \mathbf{dr}_1 \int \mathbf{dr}_2 \, \phi_a^*(\mathbf{r}_1)\, \phi_b^*(\mathbf{r}_2)\, \{e^2/4\pi\varepsilon_0 |\mathbf{r}_1 - \mathbf{r}_2|\}\, \phi_a(\mathbf{r}_2)\, \phi_b(\mathbf{r}_1)$$

where E_T and E_S are energies associated with the singlet and triplet states

(1) triplet and singlet states have *different Coulomb energy*
(due to different spatial distributions of electrons)

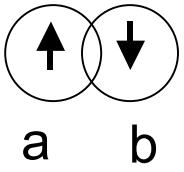
(2) J = 0 unless product $\phi_a(\mathbf{r}_2)\, \phi_b(\mathbf{r}_1) \neq 0$
(i.e. requires direct *overlap* of orbitals)

(3) if $J > 0 \rightarrow E_{singlet} > E_{triplet} \rightarrow$ triplet state favored (spins line up)
if $J < 0 \rightarrow E_{triplet} > E_{singlet} \rightarrow$ singlet state favored (S=0)

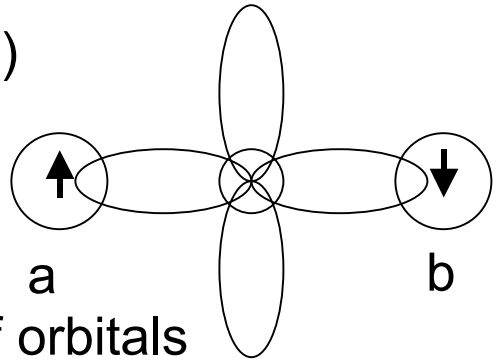
i.e. the relative orientation of spins is determined by Pauli & Coulomb
(exchange is sometimes referred to as a 'correction' to Coulomb…)

Exchange Energy

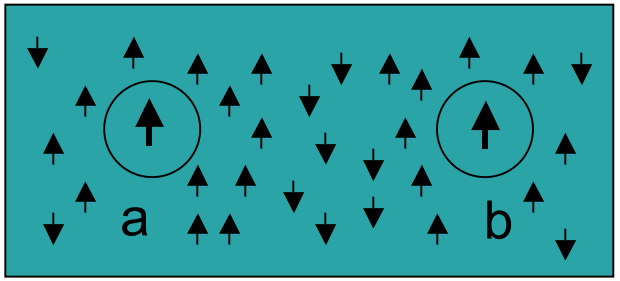
- Direct exchange
  real overlap of orbitals of atoms a and b
  usually not applicable (eg 4f)
  (even for 3d, for which itinerant nature more important)



- Indirect "super exchange" via non-magnetic atom
  dominant exchange for many insulators (MnF_2)
  exchange mediated by non-magnetic atom
  calculate energy for different possible combinations of orbitals
  (similar idea to model calc^n but much more complex)
  J can be + or – depending on orbital overlap



- Indirect "RKKY exchange"
  magnetic atom polarizes conduction electrons
  $J_{RKKY} \sim \{\cos(2k_F r)\} / r^3$
  oscillatory (period depends on k_F)
  → J can be + or – depending on distance between magnetic atoms

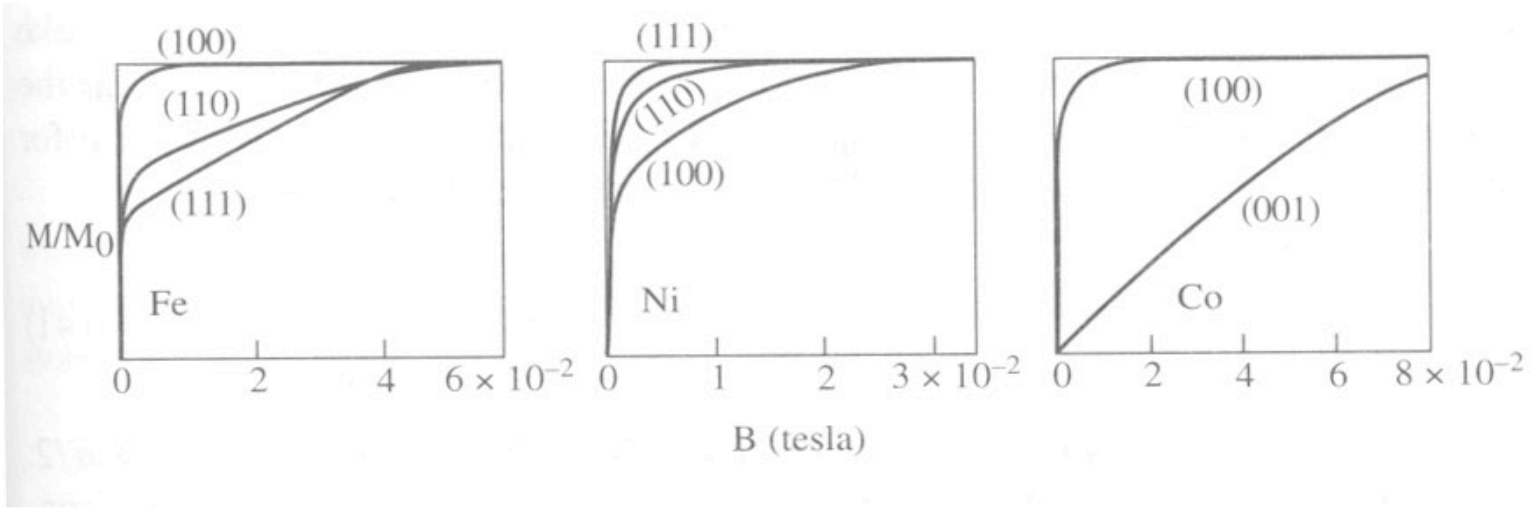


Anisotropy Energy

- Energy associated with rotating magnetic moment in the desired direction
- Possible origins of anisotropy
  - *shape (demagnetization energy)*
  - *crystal structure-> crystal field effects, spin-orbit coupling*
  - *strain -> spin-orbit coupling*

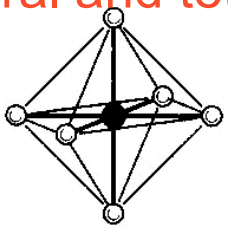
Magnetocrystalline Anisotropy

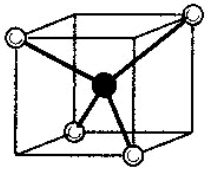
- Only magnetocrystalline anisotropy is intrinsic
- Origin: *spin orbit coupling* (related to the coupling of the spin part of the magnetic moment to the electronic orbital shape and orientation) and *crystalline electric field* (related to the filling of the orbital and point symmetry around the ion)
- $E_{anis}=K_o + K_1(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) + ..$ where α_i are directional cosines of Ms with the crystal axes and K_i are anisotropy constants
- Iron: K_1=4.8 ergs/cm^3, K_2=0.5 ergs/cm^3
- Nickel: K_1=-0.5 ergs/cm^3, K_2=-0.2 ergs/cm^3
- Cobalt: K_1=45 ergs/cm^3, K_2=15 ergs/cm^3

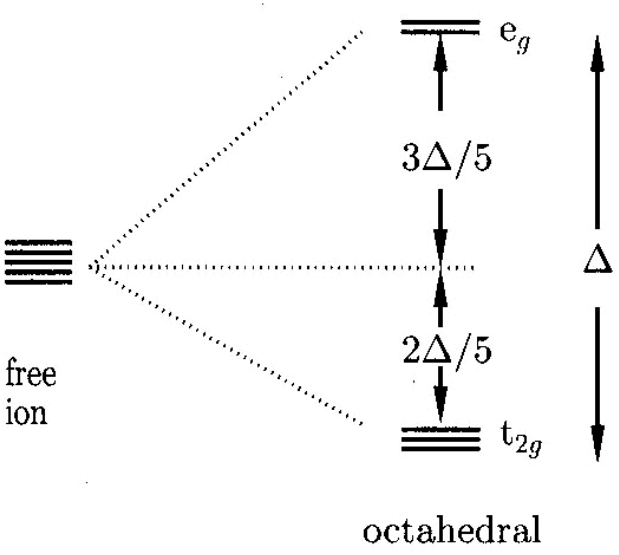


CEF splitting for d-electrons

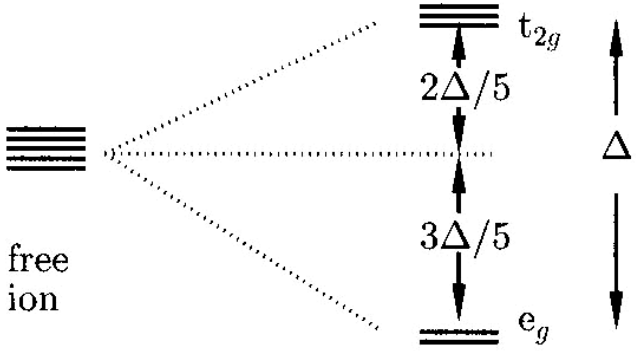
- 2 of the most common co-ordinations in transition metal oxides are octahedral and tetrahedral…







octahedral



tetrahedral

t_{2g} orbitals avoid ligands best

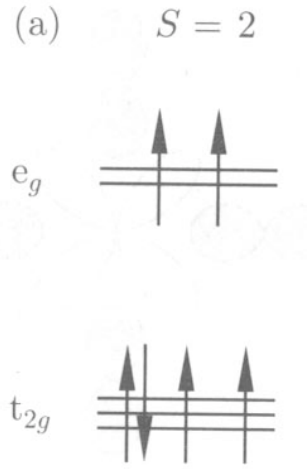
e_g orbitals avoid ligands best

- But how many electrons are we to put into each level for each element?
- Useful concept for electron counting: oxidation state…

"High spin" vs. "low spin"

- Filling of 3d orbitals is a balance of CEF and mutual electrostatic repulsion
  CEF weaker than Coulomb repulsion → "high-spin" (Hund's rule applies)
  (note: by this definition, rare earth moments are all "high spin")
  CEF stronger than Coulomb → "low spin"

- eg: Fe^{2+} ($3d^6$) in octahedral coordination…



high spin
minimizes # electrons in same orbitals

low spin
CEF stronger than Coulomb

Strain Anisotropy

- Anisotropic magneto-elastic coupling between the magnetization direction and mechanical strains affect the magnetic anisotropy
- Origin: *spin orbit coupling* (related to the coupling of the spin part of the magnetic moment to the electronic orbital shape and orientation) *under mechanical strain*
- $E_{me} = B_1(\alpha_1^2\varepsilon_{xx} + \alpha_2^2\varepsilon_{yy} + \alpha_3^2\varepsilon_{zz}) + B_2(\alpha_1\alpha_2\varepsilon_{xy} + \alpha_2\alpha_3\varepsilon_{yz} + \alpha_3\alpha_1\varepsilon_{zx}) + (c_{11}/2)(\varepsilon_{xx}^2 + \varepsilon_{yy}^2 + \varepsilon_{zz}^2) + c_{12}(\varepsilon_{xx}\varepsilon_{yy} + \varepsilon_{yy}\varepsilon_{zz} + \varepsilon_{zz}\varepsilon_{xx}) + (c_{44}/2)(\varepsilon_{xy}^2 + \varepsilon_{yz}^2 + \varepsilon_{zx}^2) + ..$

Chikazumi, Chap.14

For a cubic crystal,

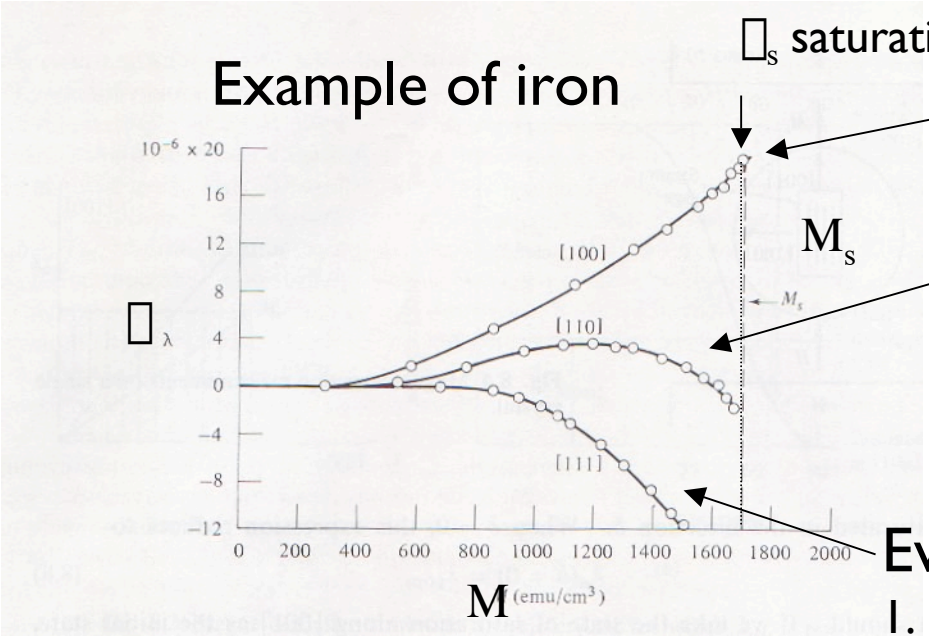
$E_{me} = -(3\lambda_{100}/2)(\alpha_1^2\gamma_1^2 + \alpha_2^2\gamma_2^2 + \alpha_3^2\gamma_3^2) - (3\lambda_{111}/2)(\alpha_1\alpha_2\gamma_1\gamma_2 + \alpha_2\alpha_3\gamma_2\gamma_3 + \alpha_3\alpha_1\gamma_3\gamma_1)$

where α_i and γ_i are directional cosines of M_s with the crystal axes and stress axes respectively, ε_j are the strain tensor components and λ's are magnetostriction constants

Magnetostriction

• Magnetostriction constants describe the fractional change in dimension under the application of an applied magnetic field.

• *Important because thin film samples are often under strains due to interactions with the substrate.*



Simple expansion

More complex

1. Wall motion until [001],[101], [001 with no dimensional change
2. Rotation toward [111] with contractio along [111]

Even more complex

1. 180° and 90°wall motion until two sets of domains closest to the applied field direction
2. Rotation of moments from crystal axes to [110]

Domain Walls

- 2 possible 180º domain walls: determined by anisotropies of your material

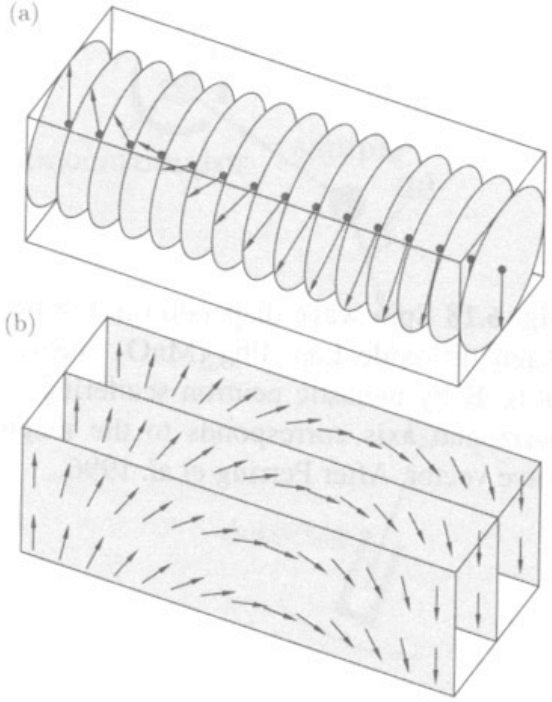


Fig. 6.20 (a) A Bloch wall. (b) A Néel wall.

- Energy cost of misaligning 2 spins:
  2 spins at an angle θ have an energy
  $-2J\mathbf{S}_1.\mathbf{S}_2 = -2JS^2\cos\theta$
  i.e. energy cost ~ $JS^2\theta^2$ for small θ
  (since $\cos\theta \sim 1 - \theta^2/2$)

- Energy cost of forming a Bloch wall:
  N sites along wall → $N\theta = \pi$
  i.e. N contributions of $JS^2\theta^2$
  → energy per unit area of wall is
  $\sigma_{BW} = JS^2\theta^2/Na^2$
  where a = x-area of one unit cell

- note:
  favors large N… i.e. minimize energy cost of misaligning spins

In absence of demagnetization, why doesn't domain wall "uncoil"?
Answer: there is another energy scale causing it to "coil up"…

Total Domain Wall Energy

- Contribution from magnetocrystalline anisotropy (or other types of anisotropy):

$$E = K N a$$

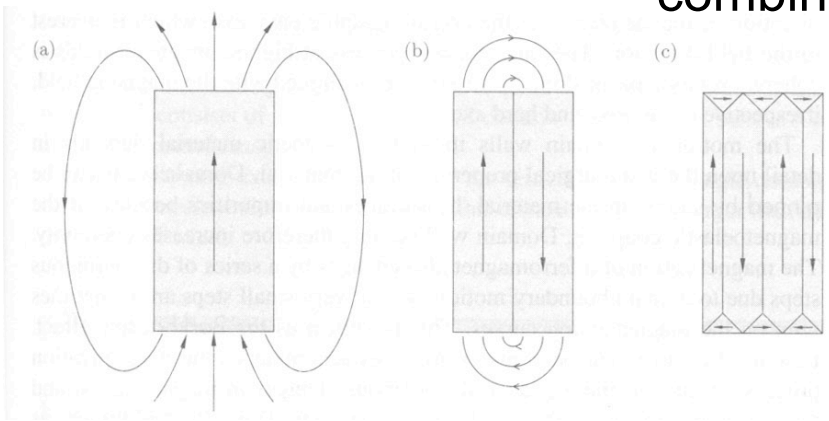
$$\frac{\pi}{N}$$

i.e. favors a small number of spins in the wall to minimize anisotropy energy (causes wall to "coil up")
note: this is energy density → contribution per unit area of wall = NKa/2

- Total energy per unit area of Bloch wall:

$$\gamma_{BW} = \frac{JS^2\pi^2}{Na^2} + K N a$$

- i.e. balance of exchange trying to maximize width of wall, and anisotropy trying to minimize it.
- Minimize expression to find width N for a specific combination of J and K



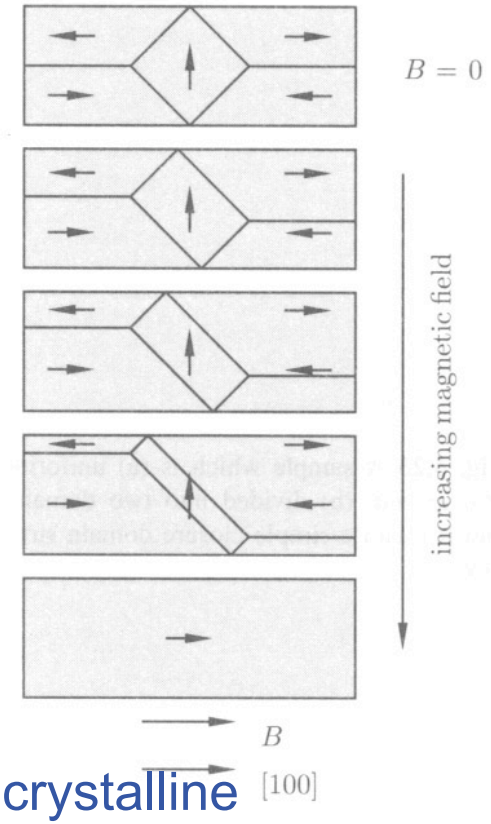
$$\pi = Na = \pi\sqrt{A/K}$$

where the exchange constant $A=Js^2\pi^2/a$

Magnetization Process

(1) domain wall motion

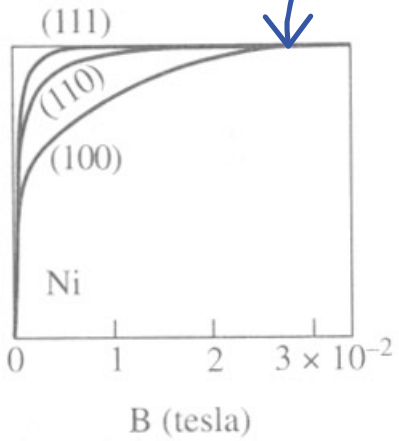
for a "soft" material, takes relatively little energy but moments stay pointing in easy directions (defined by whatever anisotropy there is in the material)



(2) coherent rotation of moments

field overcomes anisotropy

all moment slowly turn together away from their easy direction towards the applied field direction

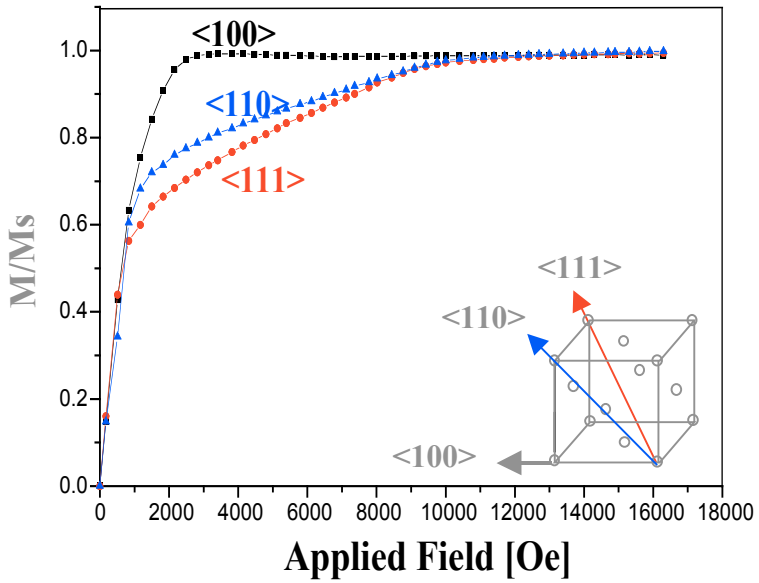


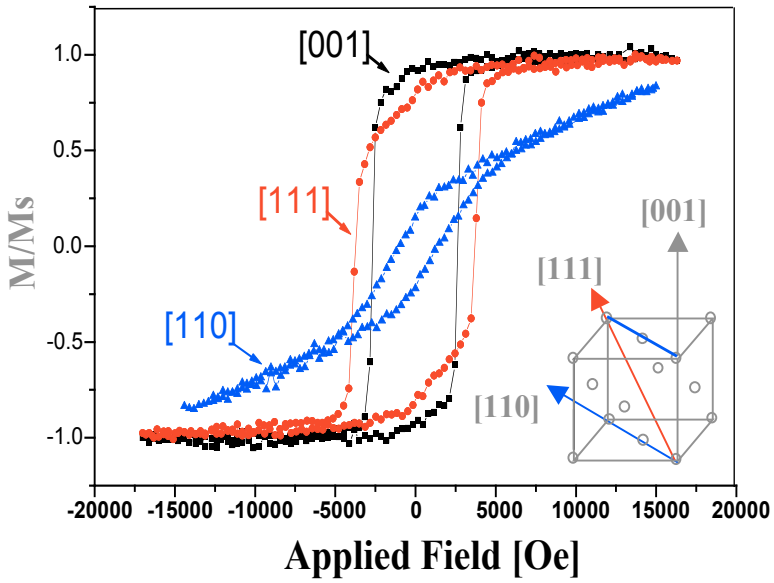
note 1: saturation field H_a depends on strength of magnetocrystalline anisotropy

note 2: makes more sense to think of reducing H from saturated state i.e. follow main curve of hysteresis loop rather than "virgin" curve from an ill-defined starting point

Stress Effects in Thin Film Samples

$CoFe_2O_4$





For bulk sample

Both <110> and <111>directions have been saturated at 1.2T (~$2K_1$/Ms)

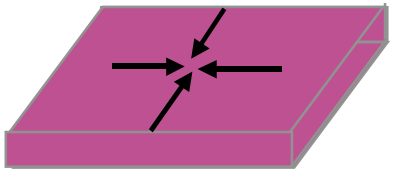
For thin film sample

[111] direction saturated at ~ 2T;
[110] direction saturated at ~ 4T.

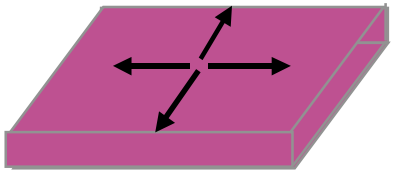
Hard and medium directions switch in the thin film samples

Hu et al. PRB 62 779 (00)

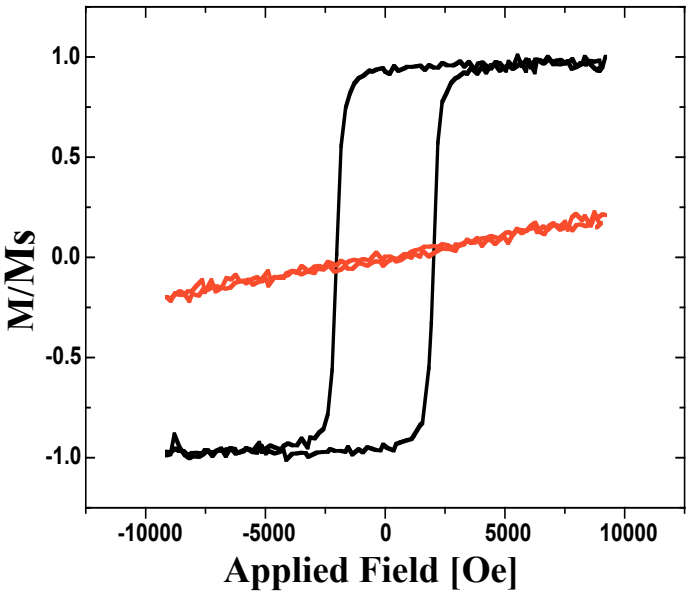
Stress Effects from Different Substrates

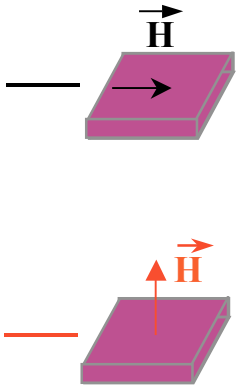


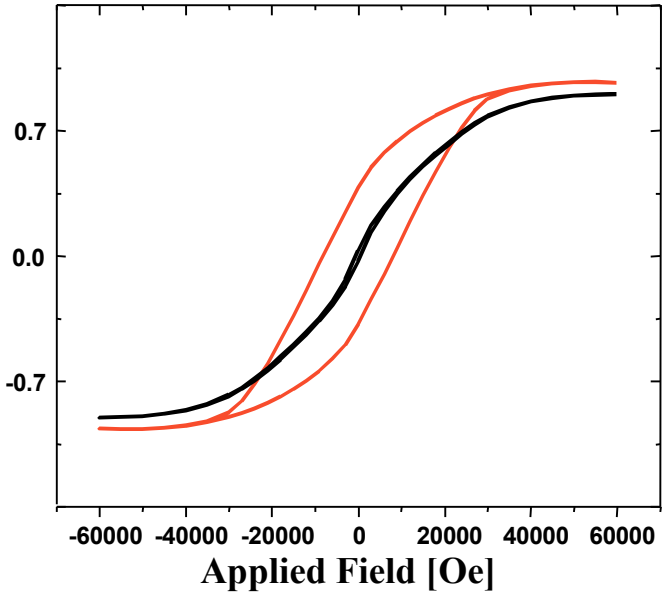
Film grown under compression on CCO buffered (100) MAO has an easy plane and a hard film normal.



Film grown under tension on (100) MgO has an easy film normal and a hard plane.

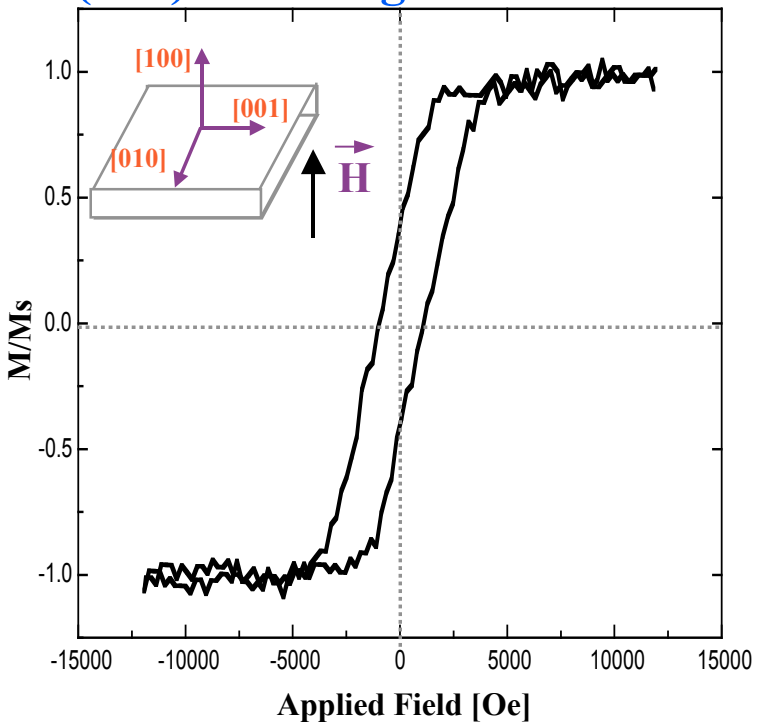




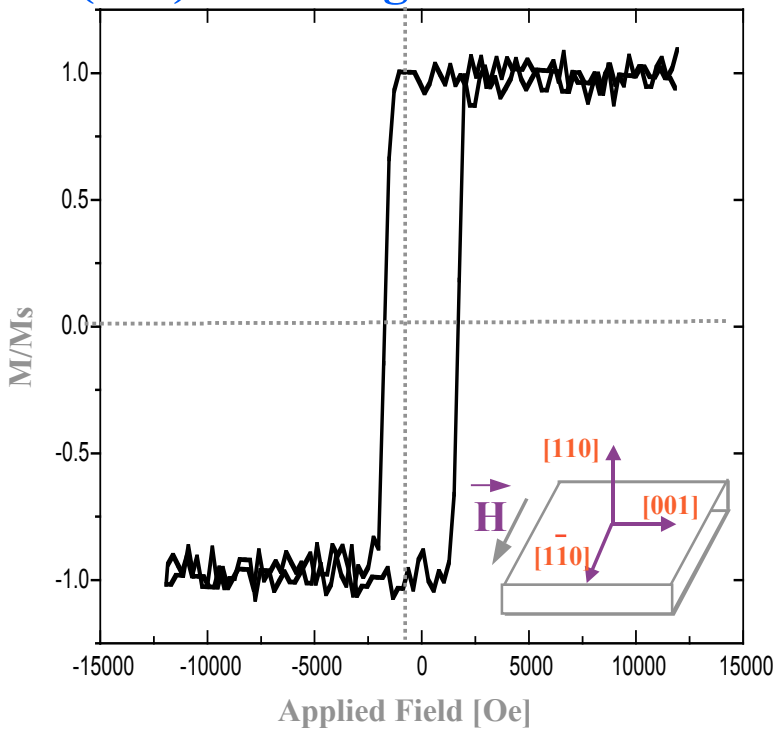


Stress Effects in Films with Different Orientation

(100) CFO/MgO



(110) CFO/MgO



Magnetically easy directions of films are only determined by stress anisotropy, which overcomes the crystalline anisotropy and the demagnetized effect .

Evaluation of Anisotropy Energy

- *Calculation of magnetoelastic energy*

$$E_{m.e.} = -\frac{3}{2}\lambda_{100}(\alpha_1^2\beta_1^2 + \alpha_2^2\beta_2^2 + \alpha_3^2\beta_3^2) - 3\lambda_{111}(\alpha_1\alpha_2\beta_1\beta_2 + \alpha_2\alpha_3\beta_2\beta_3 + \alpha_1\alpha_3\beta_1\beta_3)$$

For (100) oriented film

$E_{m.e.}^{[100]} = 0$ $\qquad$ $E_{m.e.}^{\text{in-plane}} = -3/2\lambda_{100}\lambda_{001}$

For (110) oriented film

$E_{m.e.}^{[110]} = 0$ $\qquad$ $E_{m.e.}^{[001]} = -3/2\lambda_{100}\lambda_{001}$

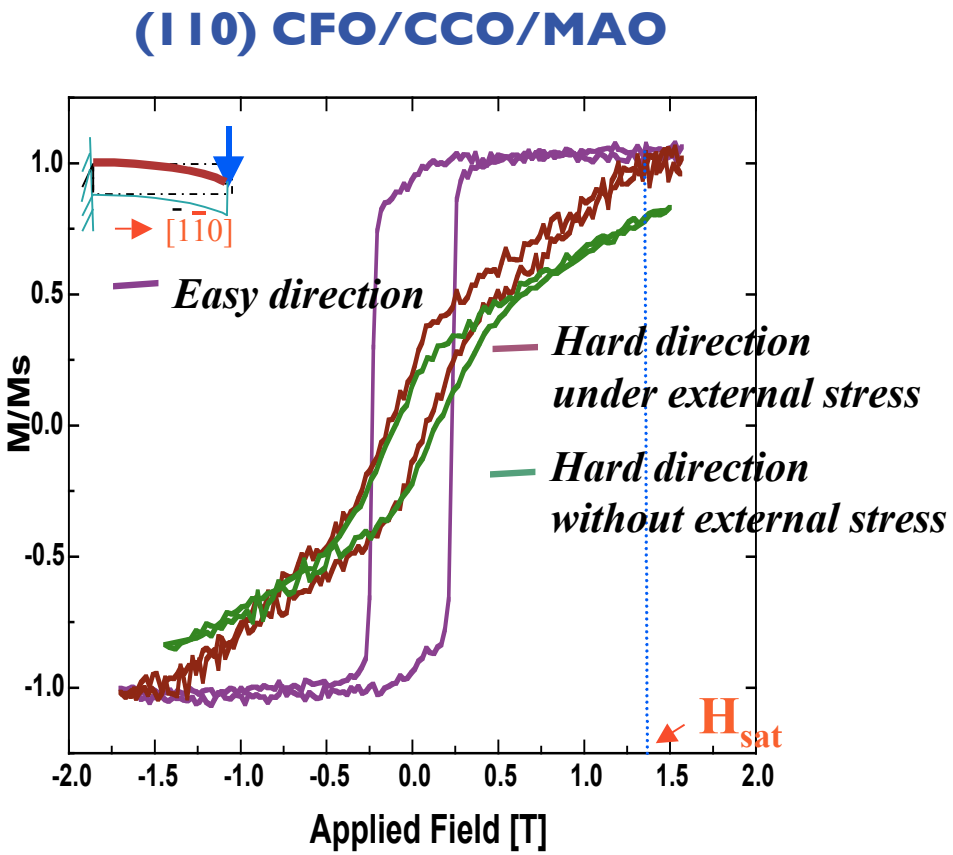
$E_{m.e.}^{[110]} = -3/4\lambda_{100}\lambda_{110} - 3/4\lambda_{111}\lambda_{110}$

$E_{m.e.}^{[111]} = -1/2\lambda_{100}\lambda_{110} - 1/2\lambda_{111}\lambda_{110} - 1/2\lambda_{100}\lambda_{001}$

$$E_{tot} = E_{m.c.} + E_{m.e.} + E_{m.s.}$$

Stress anisotropy dominates the magnetic behavior of all films, despite the different substrates and different orientations.

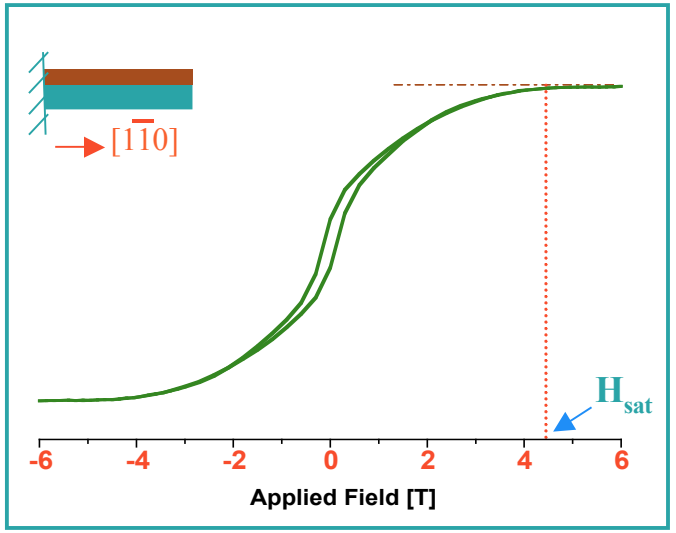
Effects of external stress



$$\Delta E_{m.e.} = -\int H \cdot dM$$

$$= -\frac{3}{4}(\lambda_{100} + \lambda_{111}) \cdot A \cdot \gamma \cdot \varepsilon_f \cdot dx$$

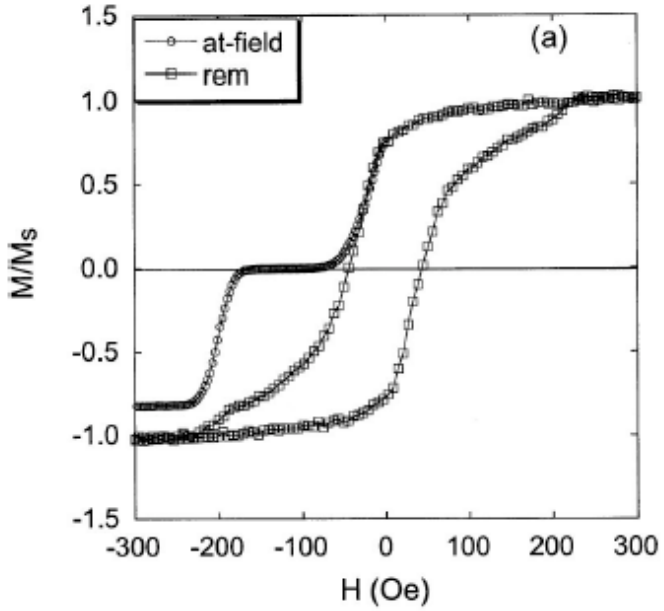
$$\lambda_{100} + \lambda_{111} = -120 \times 10^{-6}$$

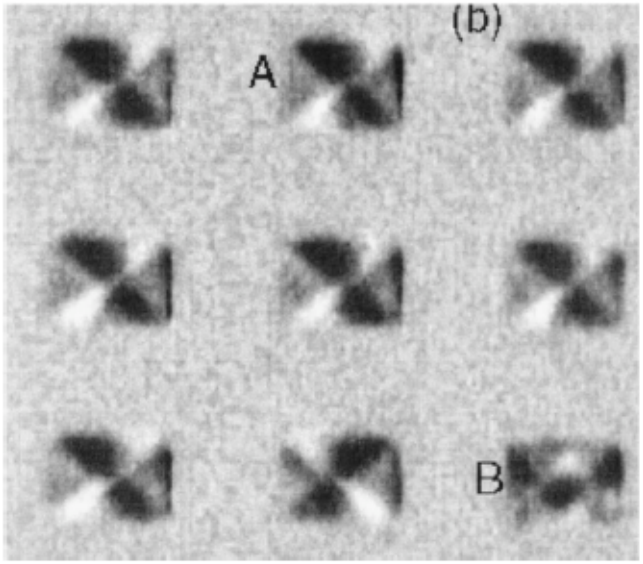


The external stress shifted the H_{sat} from 4.3T to 1.4T.

Shape Effects in Submicron Islands

- NiFe has negligible magnetocrystalline anisotropy with exchange length □~10nm.
- When dimension d of the patterned element is larger than □, magnetization vortices can develop in the reversal process
- Vortices play a more important role in small aspect ratio elements



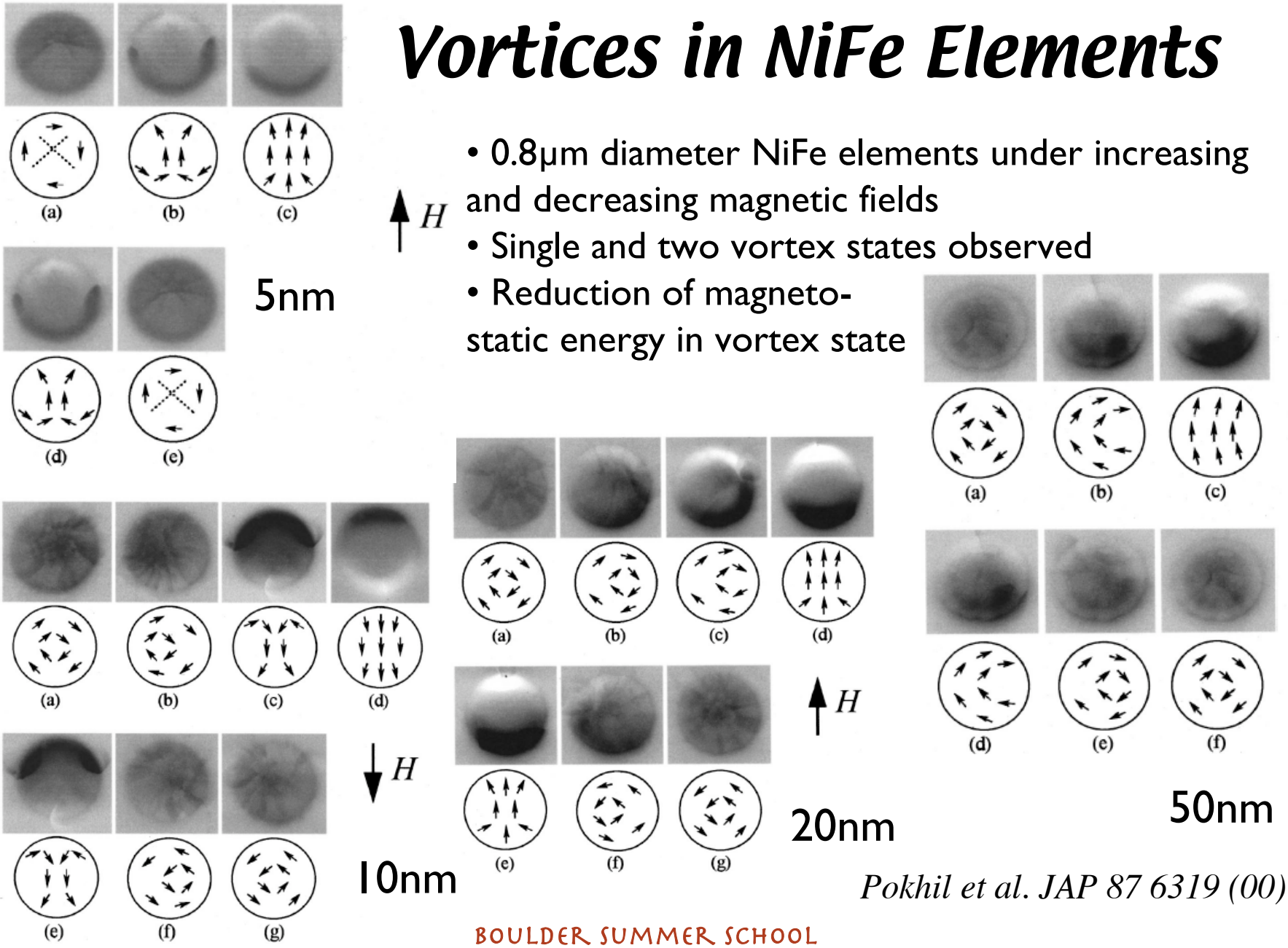


MFM of 200Å NiFe 0.9μmx1.2μm patterned arrays at remanence show single and multi-vortex states

Shi et al. APL 76 2588 (00)

Vortices in NiFe Elements

- 0.8μm diameter NiFe elements under increasing and decreasing magnetic fields
- Single and two vortex states observed
- Reduction of magneto-static energy in vortex state

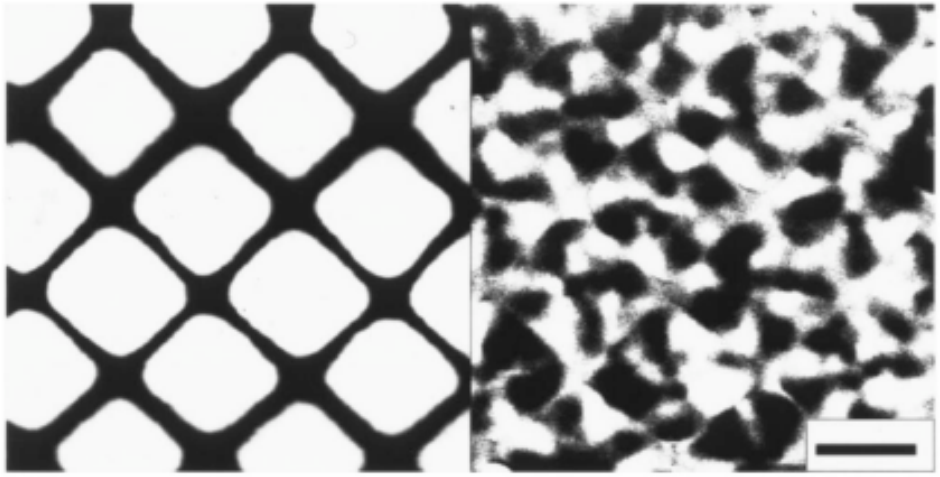


Pokhil et al. JAP 87 6319 (00)

Magnetic Islands on Templates

- Vortex state with 90° Neel walls with in-plane domains

  No in-plane anisotropy for FeCo



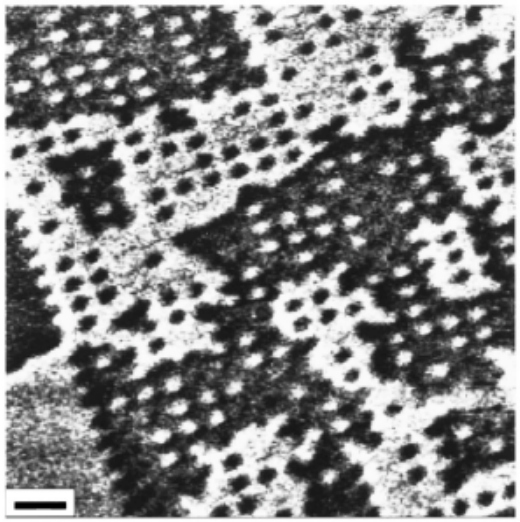
0.4μm

AFM and MFM of FeCo on 400nm square dots

No direct exchange effect due to sidewall deposits

- Perpendicular single domains

  Perp anisotropy for Co/Pt multilayers



0.8μm

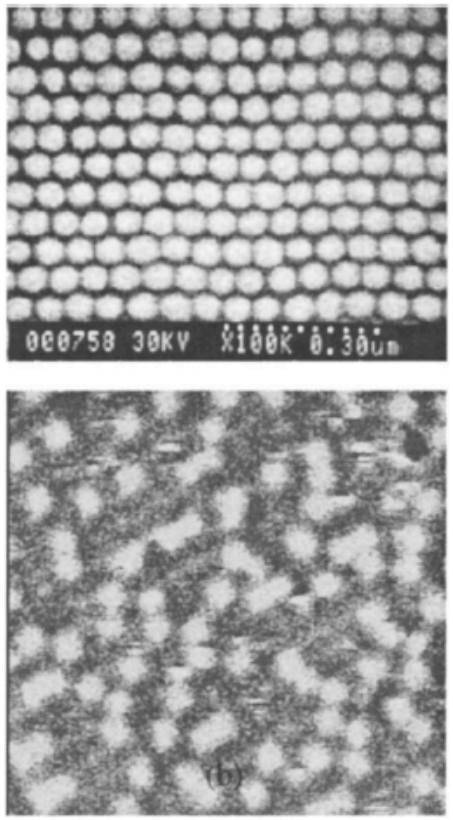
MFM of Co/Pt multilayers on 200nm square dots (200nm apart and 47 nm high)

Magnetic Dots on Nanoimprinted Structures

- Feature sizes from 30 to 400nm and periodicities from 60 to 500nm (d is on the order of □)

- Co/Pt multilayers deposited on nanoimprinted silicon templates

- direct exchange between dots via deposits on the sidewalls of the dots



(a)

SEM of 60nm Ni dots in a 80nm periodicity array

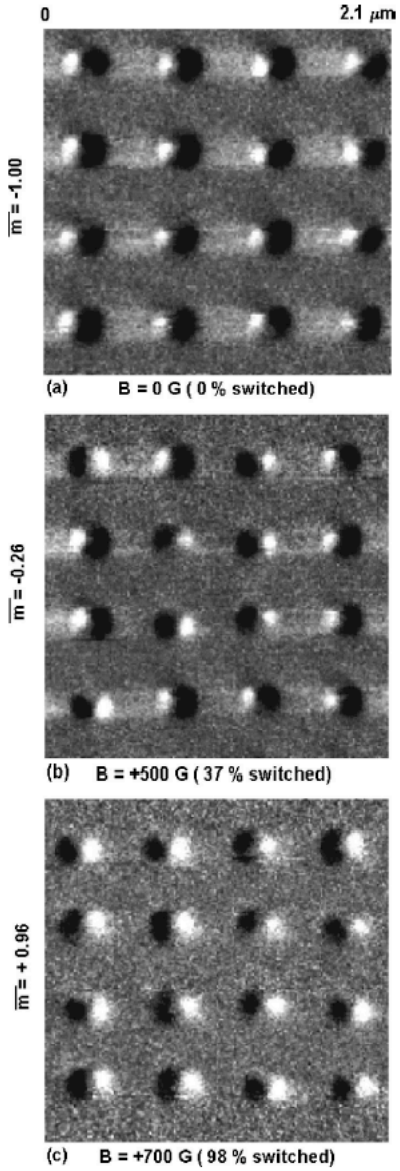
(b)

MFM of 60nm Ni Dots are single domain

Moritz et al. JAP 91 7314 (02)

Single Domain Dots

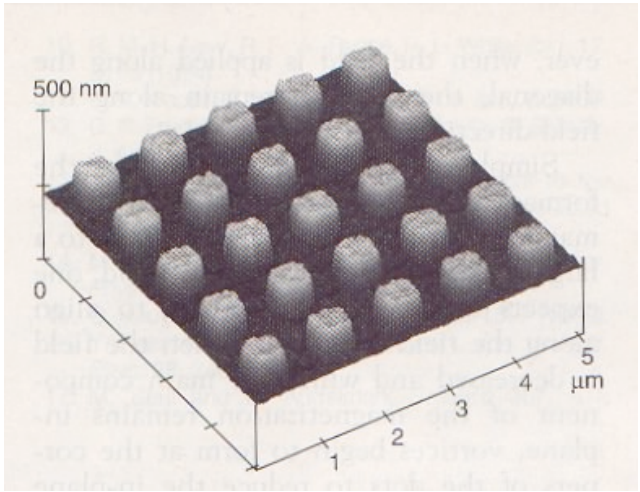
- 80x140x(14-30)nm Co rectangles
- In-plane single domains for t<20nm
- Double domain configuration in t~30nm
- Dipolar interactions among islands in densely packed arrays



Evoy et al. JAP 87 404 (00)

Single Crystalline Submicron Co Dots

- Perpendicular anisotropy of Co dots 0.5μm diameter and 25-50nm thick
- In 25nm thick dots, the main component of magnetization is in-plane along with a small concentric ring structure of the perpendicular component



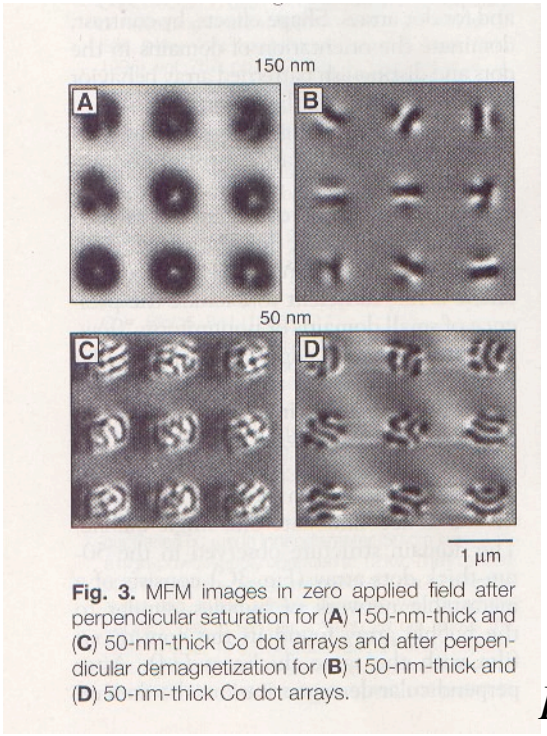


Fig. 3. MFM images in zero applied field after perpendicular saturation for (**A**) 150-nm-thick and (**C**) 50-nm-thick Co dot arrays and after perpendicular demagnetization for (**B**) 150-nm-thick and (**D**) 50-nm-thick Co dot arrays.

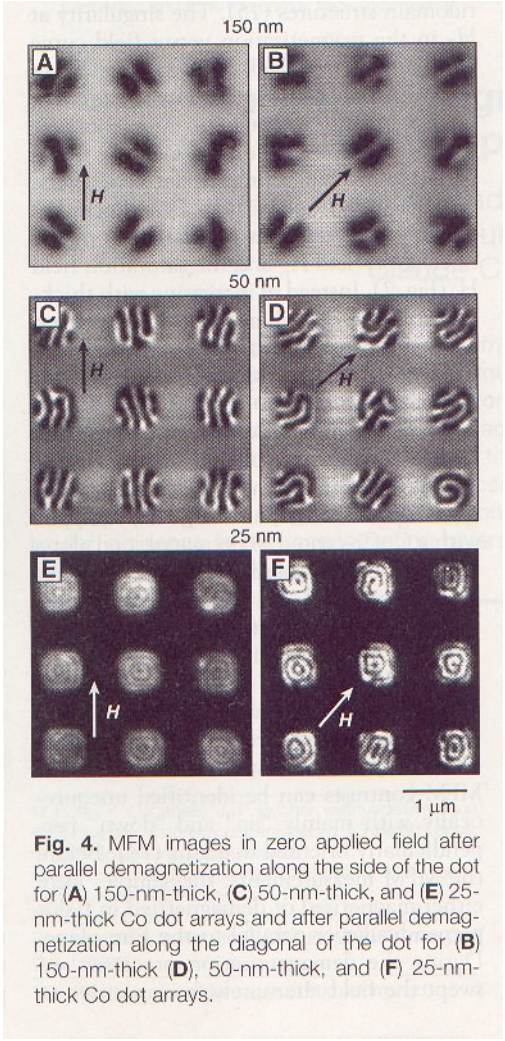
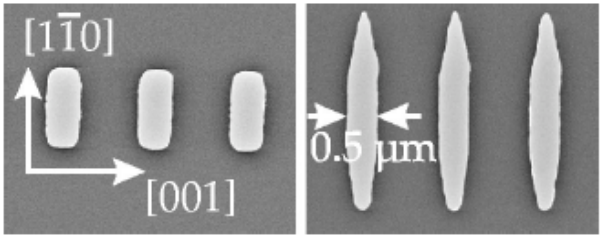
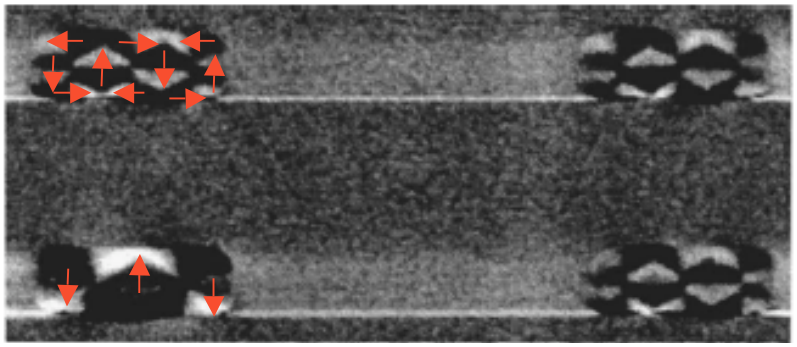


Fig. 4. MFM images in zero applied field after parallel demagnetization along the side of the dot for (**A**) 150-nm-thick, (**C**) 50-nm-thick, and (**E**) 25-nm-thick Co dot arrays and after parallel demagnetization along the diagonal of the dot for (**B**) 150-nm-thick (**D**), 50-nm-thick, and (**F**) 25-nm-thick Co dot arrays.

Hehn et al. Science 272 1782 (96)

Competing Anisotropies





Rectangular and needle-shaped ends of (110) 50nm thick Fe exhibit different reversal behavior due to competing magnetic anisotropies:

shape, crystal and *strain*

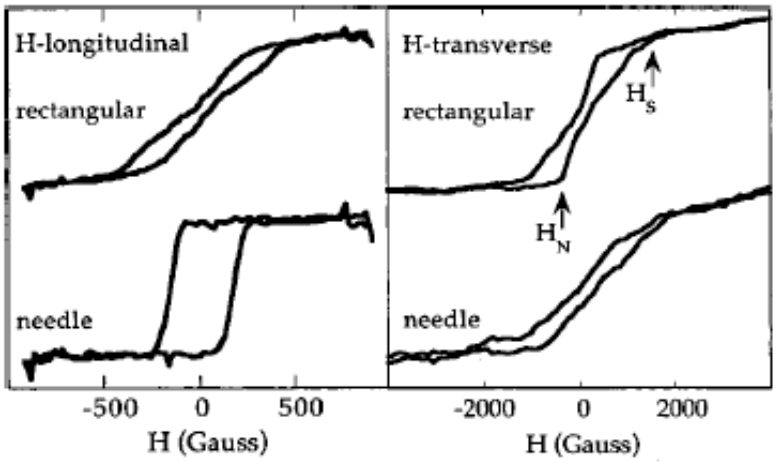
MFM of rectangular Fe elements at H=0 after longitudinal saturation

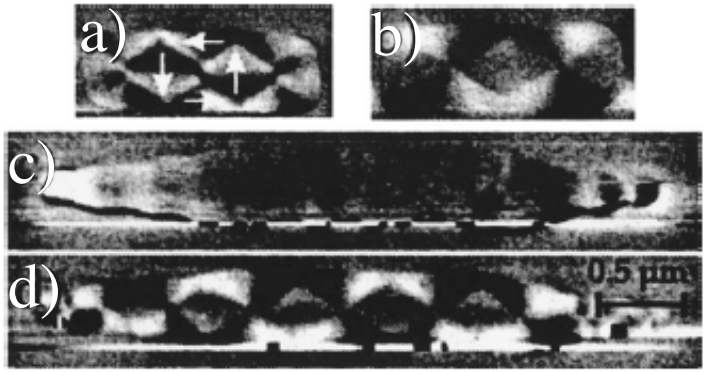
$$E_{anis} = (K_1 + K_u)\sin^2\theta - 3K_1/4\sin^4\theta + \frac{\mu_0}{2}\int_V M^2 N_d dV$$

where θ is the angle between the magnetization and [001] and K_1 and K_u are the magnetocrystalline and uniaxial strain anisotropies respectively

Yu et al. JAP ***85*** *5501 (99)*

Competing Anisotropies



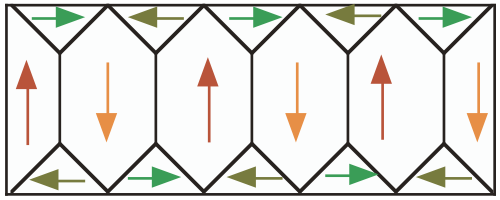


MFM of rectangular Fe elements at H=0 after longitudinal (a,c) and transverse (b,d) saturation

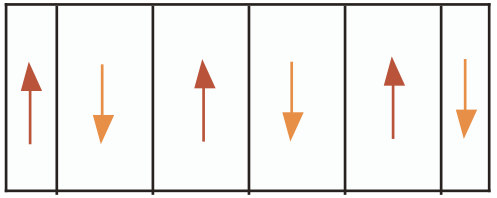
- *When magnetic easy axis is perpendicular to the long axis of the structure, a stripe domain configuration minimizes the free energy.*
- *When ratio of anisotropy to demagnetization energy $Q = K/2\pi M^2 < 1$, then flux closure domains at H=0 are also favored.*
- *Nucleation barriers to overcome for the formation of stripes.*

Competing Energies

- Ratio of anisotropy to demagnetization energy $Q=K/2\pi M_s^2$ determines whether we should expect closure domains.



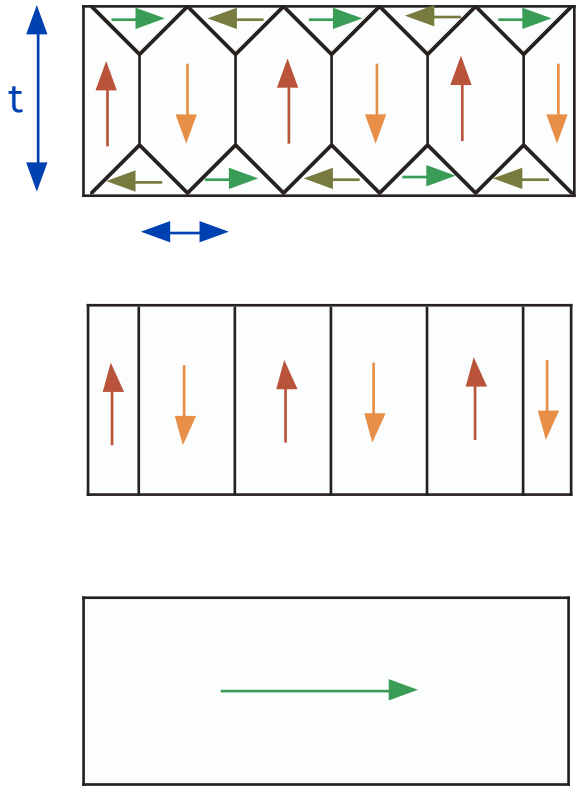
$Q<<1$



$Q>1$

- Exchange thickness ($\sqrt{A}/M_s$) dictates that the surface domain structure (as observed by MFM) is a good measure of most of the film thickness.

Competing Energies *continued*



$E = \underbrace{\gamma_w[2\sqrt{2}+(t-d)/d]}_{E_{domain}} + \underbrace{\sigma_a d/2}_{E_{anisotropy}}$

$E_{min} = (2\sqrt{2}-1)\gamma_w + (2\gamma_w t\sigma_a)^{1/2}$

γ_w = surface energy density of Bloch wall

σ_a = anisotropy energy density

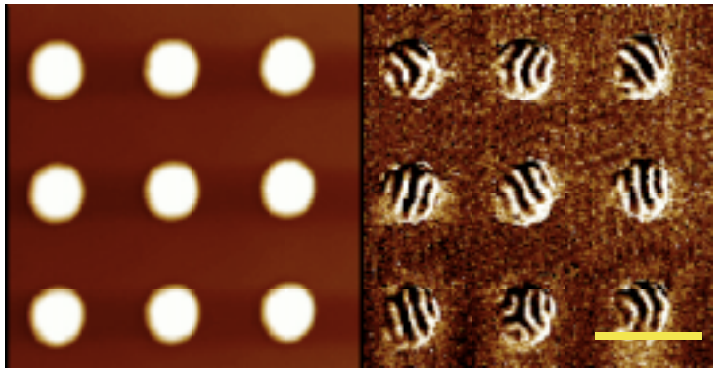
$E = \underbrace{1.7M_s^2 d}_{E_{magnetic}} + \underbrace{\gamma_w t/d}_{E_{domain}}$

$E_{min} = 2(1.7\gamma_w t)^{1/2}M_s$ $\quad t > d$

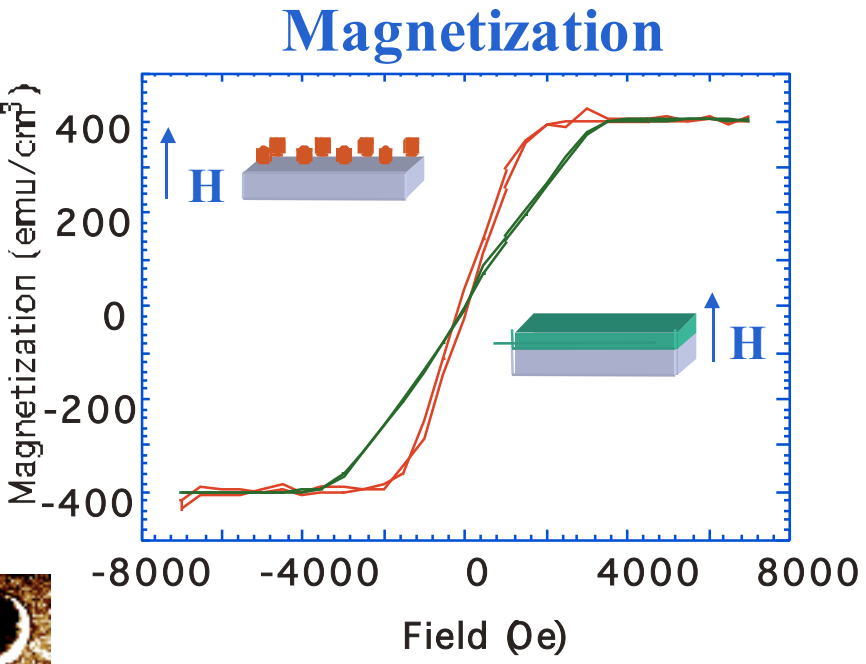
$E = \underbrace{\sigma_a t}_{E_{anisotropy}}$

Kittel, Phys. Rev. 70 965 (46)

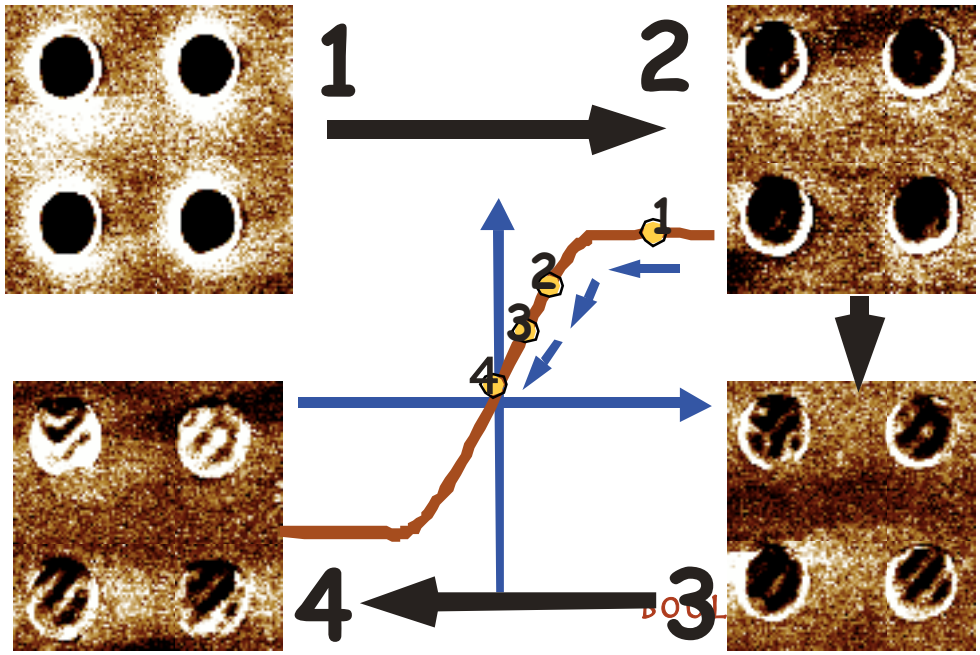
Magnetic Islands of Colossal Magnetoresistance Materials



topographic and magnetic images of $La_{0.7}Sr_{0.3}MnO_3$ islands

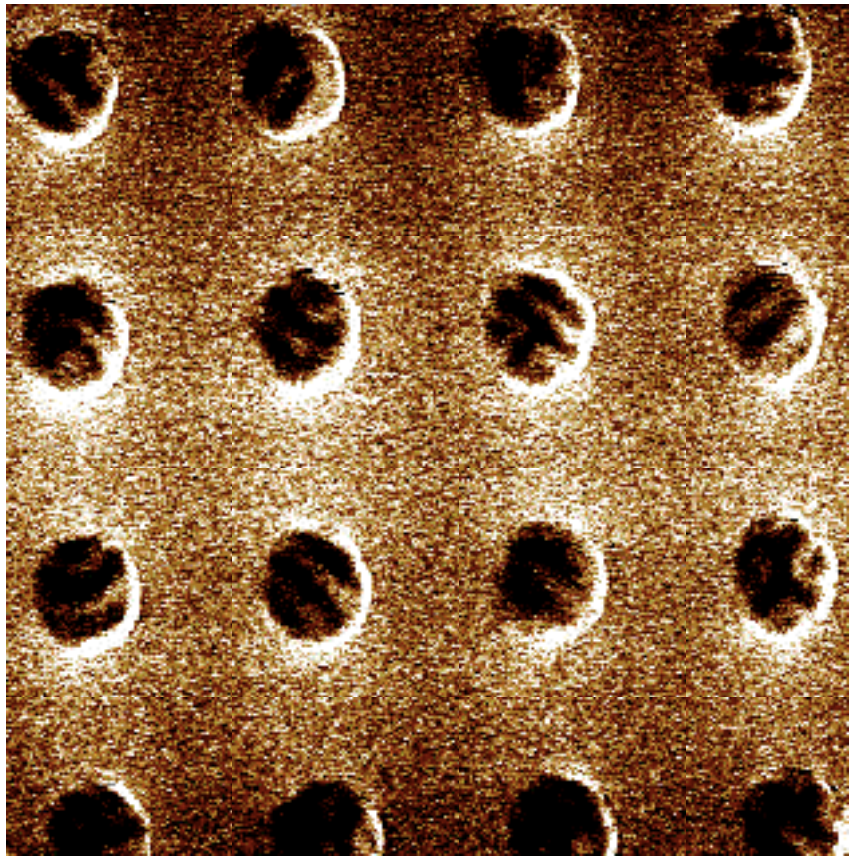


Magnetization loops show the effect of shape on the magnetic response.

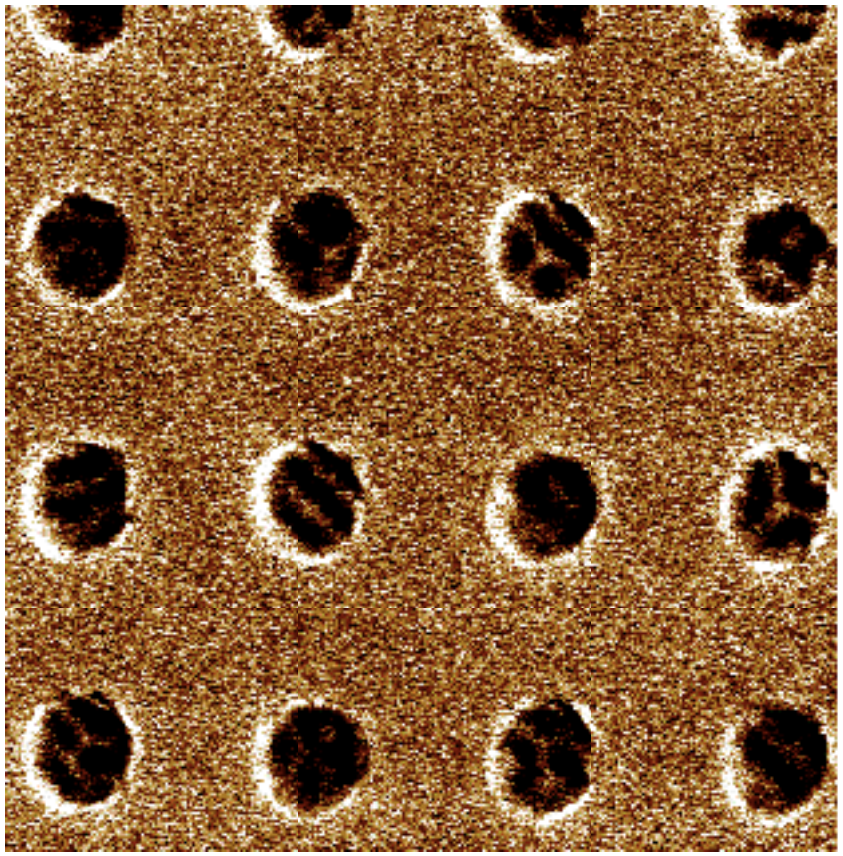


Wu, Matsushita & Suzuki
PRB ***64*** *R220404 (2001)*

Magnetization Reversal of LSMO/LAO Islands



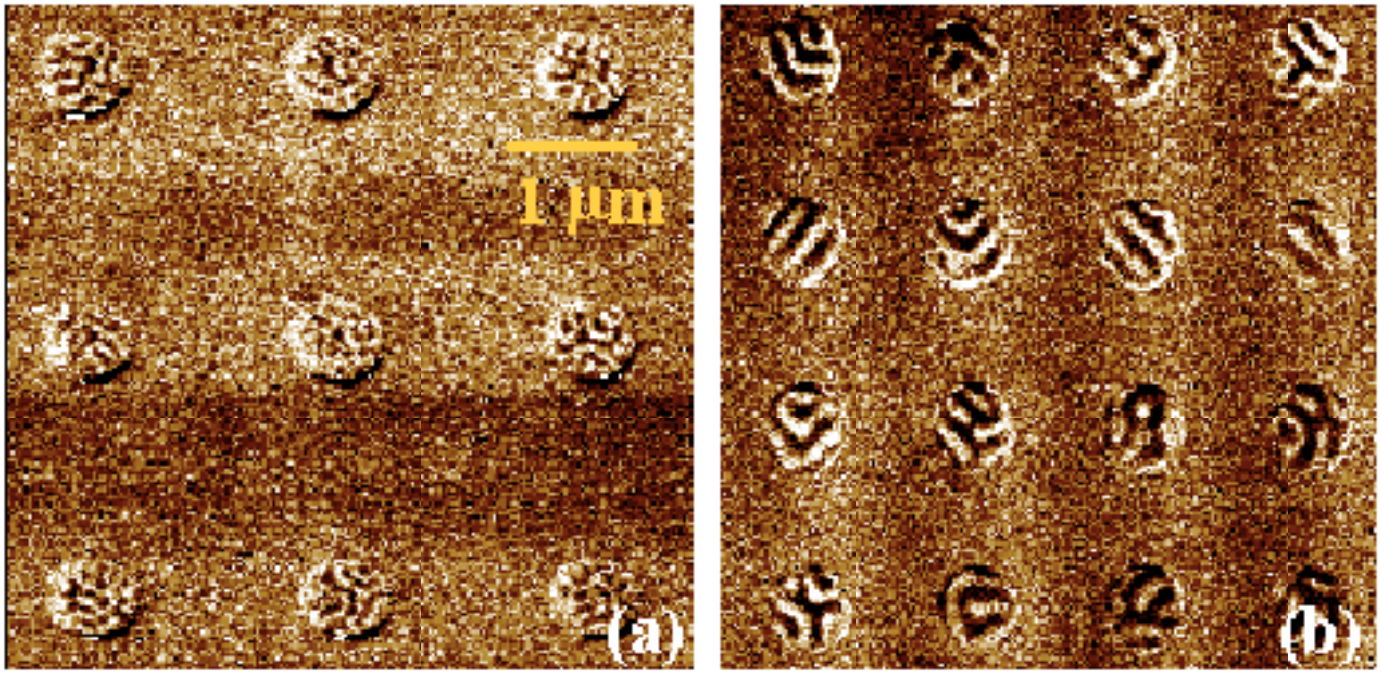
Under a -450 Oe field ⊗ perpendicular to the film.



Under a 450 Oe field ⊙ perpendicular to the film.

*Wu et al. PRB **64** R220404 (01)*

Thickness Dependence of CMR Islands



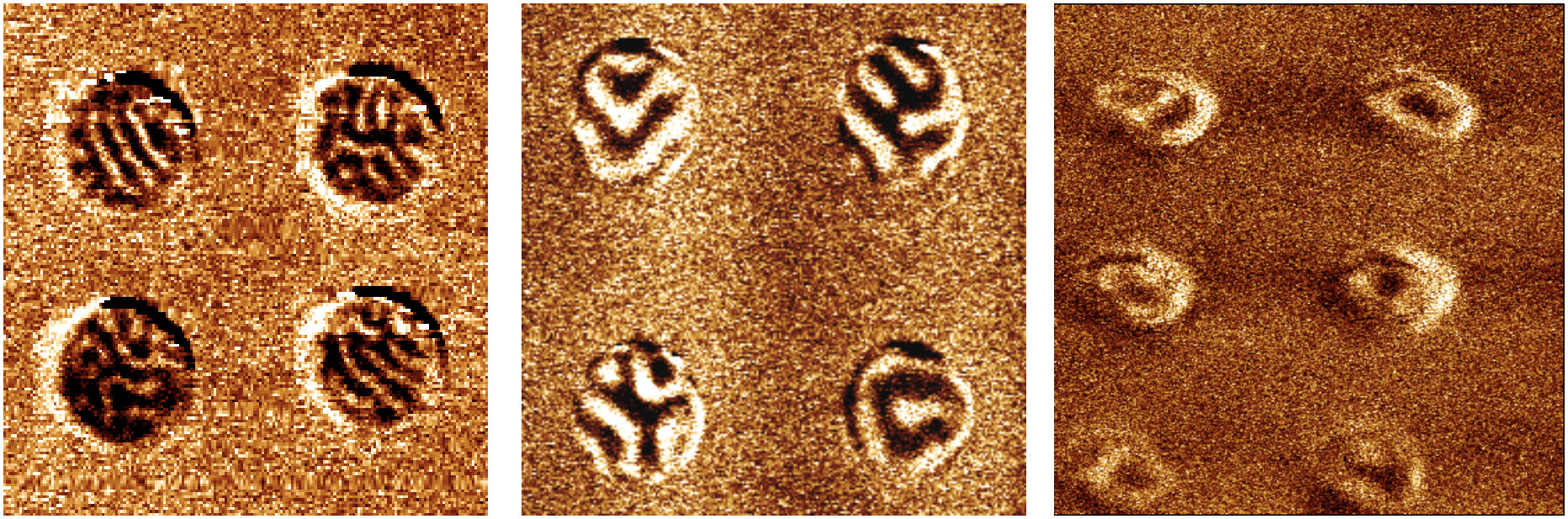
70 nm high

90 nm high

*Wu et al. PRB **64** R220404 (01)*

Aspect Ratio and Domain Structures

Aspect Ratio: 0.09 0.14 0.33



Magnetic Force Microscopy images of LSMO dots

Wu and Suzuki

Lectures on Fabricated Magnetic Structures

- Synthesis and fabrication techniques for magnetic structures
- Magnetic behavior in small magnetic structures
- Magnetic Junction Devices
  - Patterning of Junction Devices
  - Spin Polarization
  - Interfaces