Exchange Bias in Antiferromagnetic-Ferromagnetic Bilayers

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DoE/BES

Condensed Matter Colloquium, Physics Department, UW (11/01)

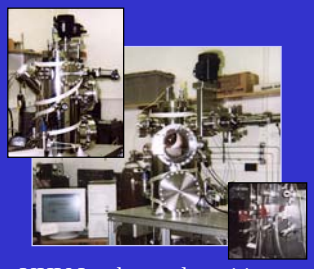
Broad Research Themes and Projects

- **Growth and Properties of Thin Film Structures**
  - Deposition by Ion Beam Sputtering, Sol-Gel Processing
  - ⇨ Exchange Interactions in AFM/FMbilayers
  - Growth mode of complex oxides
  - Magnetically actuated shape memory alloy films
- **Nanoscience and Nanotechnology**
  - Synthesis by chemical, metallurgical and lithography routes (Group)
  - Achieving theoretical coercivity and role of dilution in Fe-Nd-B alloys
  - ⇨ Self-Assembled Magnetic Nanocrystals (Mike Beerman , Yuping Bao)
  - Patterned Media to overcome the superparamagnetic limit (J.D. Wright, G. Kusinski)
- **Advanced Characterization with Electron and Photon Probes**
  - Measurements of Interface roughness and correlation with GMR (M.E. Gomez)
  - Quantitative measurements of elemental segregation in Co-Cr media (Dr. W. Grogger)
  - Detection/Resolution limits of energy-filtered imaging (Dr. W. Grogger, G. Kusinski)
  - Magnetic imaging with electrons and photons - complementarity (G. Kusinski)

UW, UCB/LBNL

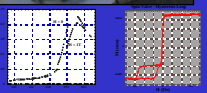
Magnetic Thin Films and Nanostructures

Synthesis & Processing



- UHV Ion-beam deposition
- Chemical synthesis
- *Pulsed Laser Deposition (IML)*

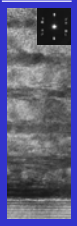
Properties & Phenomena

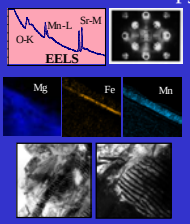


- Magnetic
- Transport

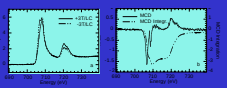
Characterization

NCEM - Electron microscopy





ALS - X-ray magnetic circular dichroism

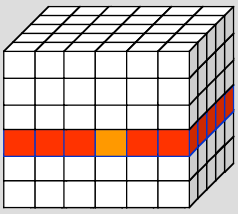


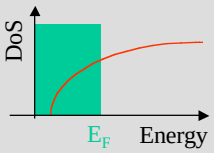
- **Physical phenomena (magnetoresistance, hysteresis etc.) - fundamental studies**
- **Microstructure - unique characterization tools and atomic level control**
- **Technology (Magnetic Recording, MRAM, hard magnets, MEMS, NDE …..)**

Vertically integrated Program

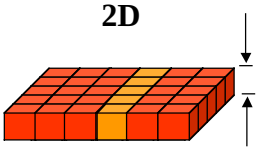
Systems of Reduced Dimensions

3D





2D



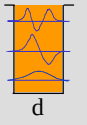
For 2D behavior
Only ONE level within
$\Delta E = \pm kT$ (0.026 eV) of E_F

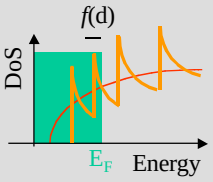
1st estimate, set energy of lowest level ~ $kT \sim p^2/2m$

de Broglie wavelength $\lambda \sim h/p \sim 8$ nm (slab thickness)

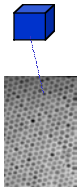
Ultrathin films
Multilayers
Interfaces

1D





0D

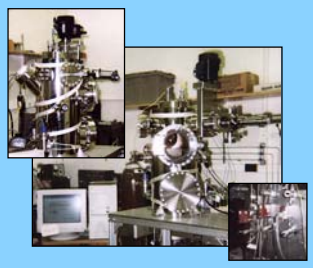


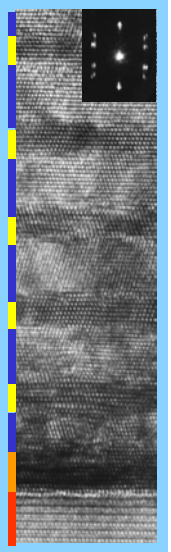
Chemical Synthesis + Self Assembly

And

Lithography

Growth & Novel Properties of 2D Structures

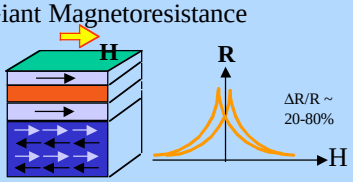




UHV Ion-beam Deposition

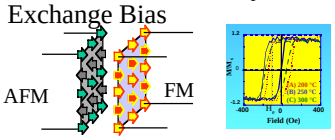
Ultrathin Films
Multilayers
Interfaces

- Giant Magnetoresistance



Cyrille, Kim, Gomez, Santamaria, Leighton, *Krishnan* and Schuller, *Phys. Rev. B.* **62**, 15079-15083 (2000)

- Frustration & Proximity Effects
  Exchange Bias



Cheng, Ahn and *Krishnan*, *J. Appl. Phys.*, **89**, 6597 (2001).

- Perpendicular Interface Anisotropy

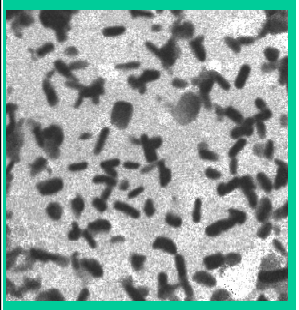
$$E_{an} = K_{eff} \sin^2\theta$$

$$K_{eff} = -2\pi M_s^2 + 2K_s/t_m + K_v$$

Cho, *Krishnan*, Lucas and Farrow, *J. Appl. Phys.* , **72**, 5799 (1992).

0D Structures: Approaches

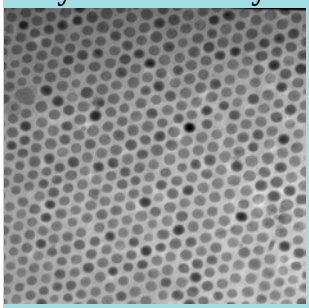
Small Particles



Metallurgical Approach
Achieving theoretical coercivity limits & understanding mechanisms

Girt, *Krishnan*, Thomas and Girt, *J. Mag. Mag. Mat.*, 231, 219 (2001)

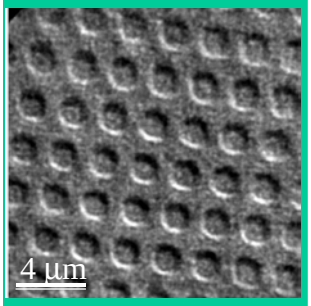
Nanoscale materials by Self-assembly



Chemical method --
Size-selective precipitation
Surfactant controls shape
Bottoms-up approach
Magnetism in systems of reduced dimensions

Puntes, *Krishnan* & Alivisatos, *Science*, 291, 2115 (2001)

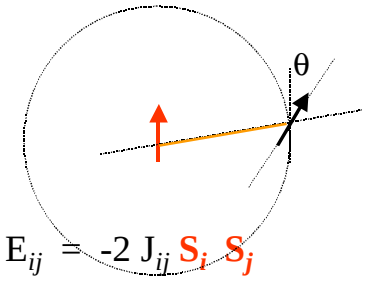
"Patterned" Media



Ion-implantation through Stencil Masks;
Top-down approach
Overcoming the super -paramagnetic limit

Kusinski, *Krishnan*, Denbeaux, Thomas, Weller, Rettner, Terris
Appl. Phys. Lett. 79, 2211(2001)

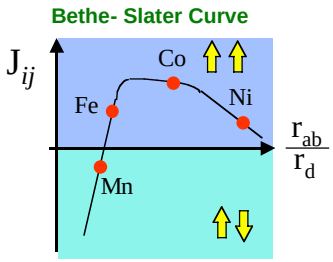
Factors affecting magnetic behaviour: Exchange Interactions



$$E_{ij} = -2\, J_{ij}\, S_i\, S_j$$

$$= J_{ij}\, |S|^2\, \theta^2 \quad \textit{for small } \theta$$

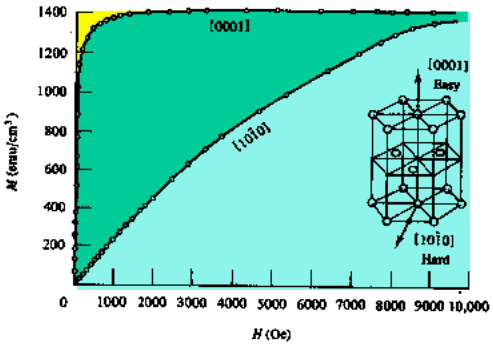
$$J_{ij} = \frac{3\, k_B\, \Theta_c}{2\, Z\, S(S+1)}$$

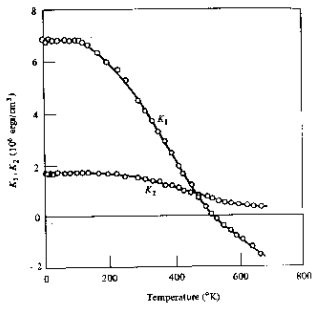


- **No fundamental limit on strength**
- **Isotropic, Amorphous magnets**
- **Determines magnetic order**

Factors affecting magnetic behaviour: Anisotropy

The spin-orbit-lattice interaction





$$E_{mc}^{uniaxial} = K_o + K_{u1}\ \sin^2\theta + K_{u2}\ \sin^4\theta + ..$$

Cobalt $K_{u1} = 4.1 \times 10^5\ J/m^3$ $K_{u2} = 1.0 \times 10^5\ J/m^3$

Determines Magnetic Orientation

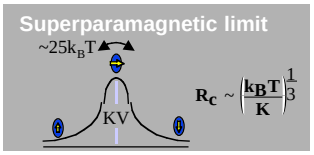
Magnetic Behavior of Ferromagnets & Antiferromagnets

Iron

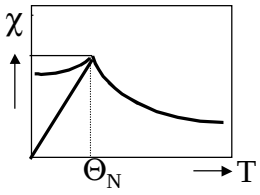
$\Theta_C \sim$ 790°C (1063 K)

Strong magnetic Order

Weak Orientation



Antiferromagnet



Weak Magnetic Order

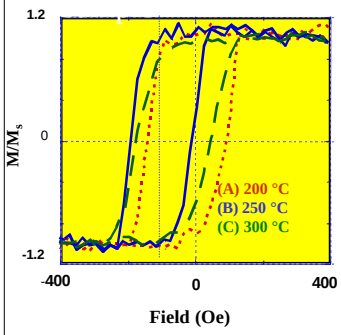
Strong Orientation

AFM + FM heterostructures

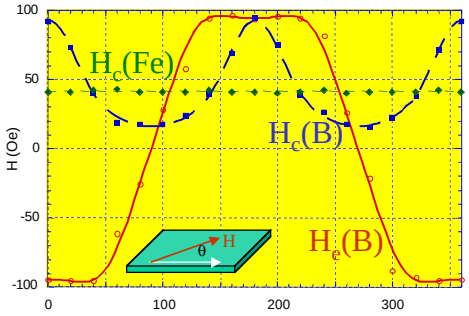
Exchange Bias : Unique Behavior not Observed in Bulk FM

Exchange Bias in AFM/FM Bilayers

Hysteresis



Unidirectional Coupling



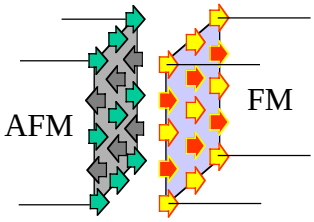
$H_e(B)$= -111Oe [cos(ϑ)-0.15cos(3ϑ)-0.01cos(5ϑ)+0.01cos(7ϑ)+...]

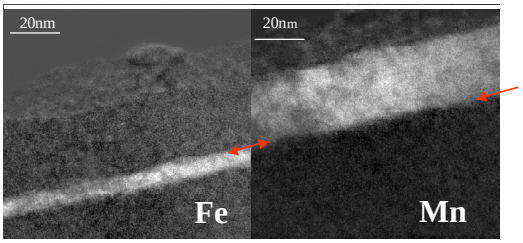
$H_c(B)$= 44Oe [1+0.82cos(2ϑ)+0.24cos(4ϑ)+0.05cos(6ϑ)+...]

$H_e(A)$= -26Oe [cos(ϑ)-0.34cos(3ϑ)+0.13cos(5ϑ)-0.07cos(7ϑ)+...]

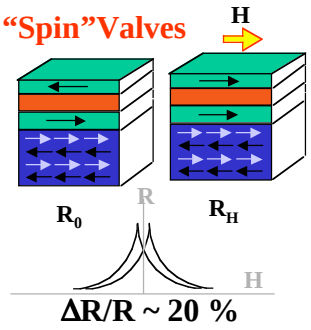
$H_c(A)$= 80Oe [1+0.46cos(2ϑ)-0.04cos(4ϑ)+0.01cos(6ϑ)+...]

Frustration , Interface and Proximity Effects



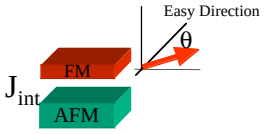


"Spin"Valves



- Phenomenon poorly understood
- Interface effects dominate
- Need element-specific probes
- Growth of ideal structures - epitaxy
- Technology

Exchange Bias: Basics



Free Energy:

$F = H M_{FM} t_{FM} \cos\theta - J_{int} \cos\theta + K_{FM} \sin^2\theta$

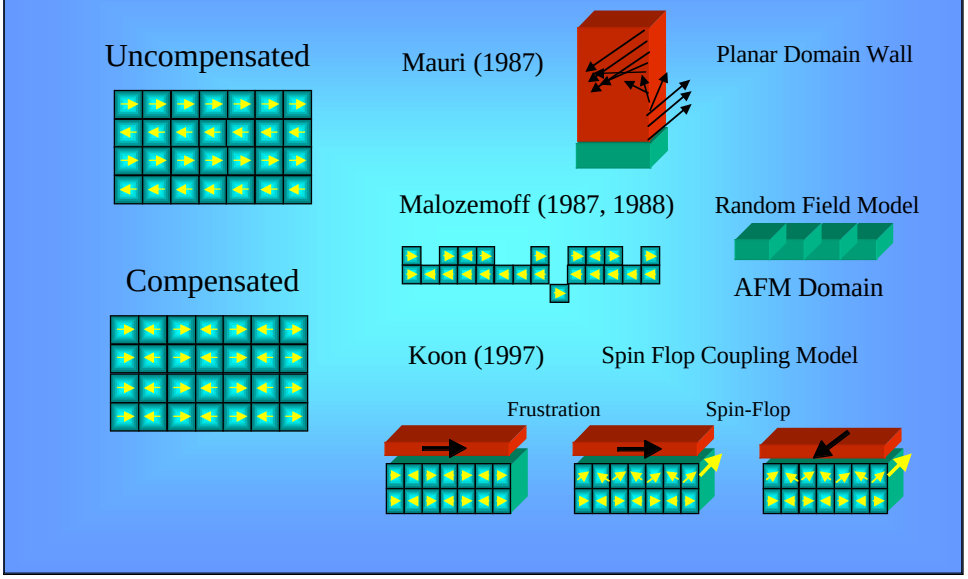
Solution in terms of an effective field

$H' = H - J_{int} / (M_{FM} t_{FM}) = H - H_E$

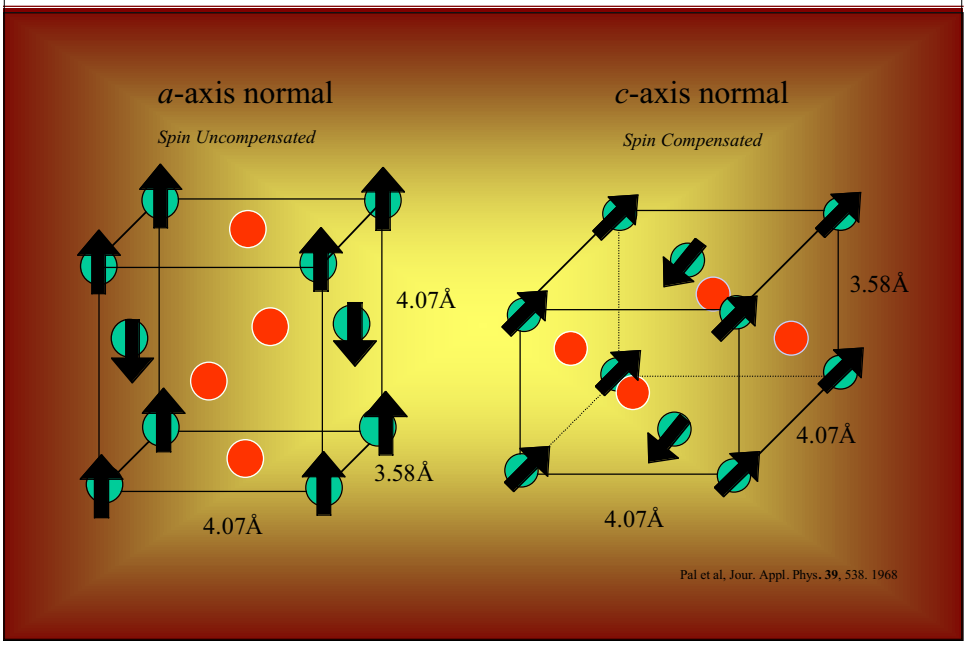
$H_E = J_{int} / (M_{FM} t_{FM})$

If typical values for J_{FM} are used
then observed H_E are too small

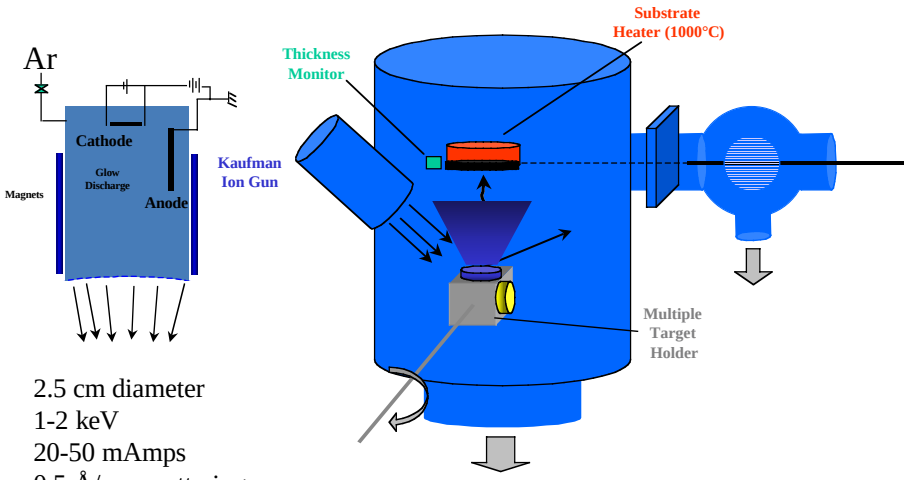
Exchange Bias: Basics ….



Crystal and Spin Structure of AFM $Mn_{50}Pd_{50}$

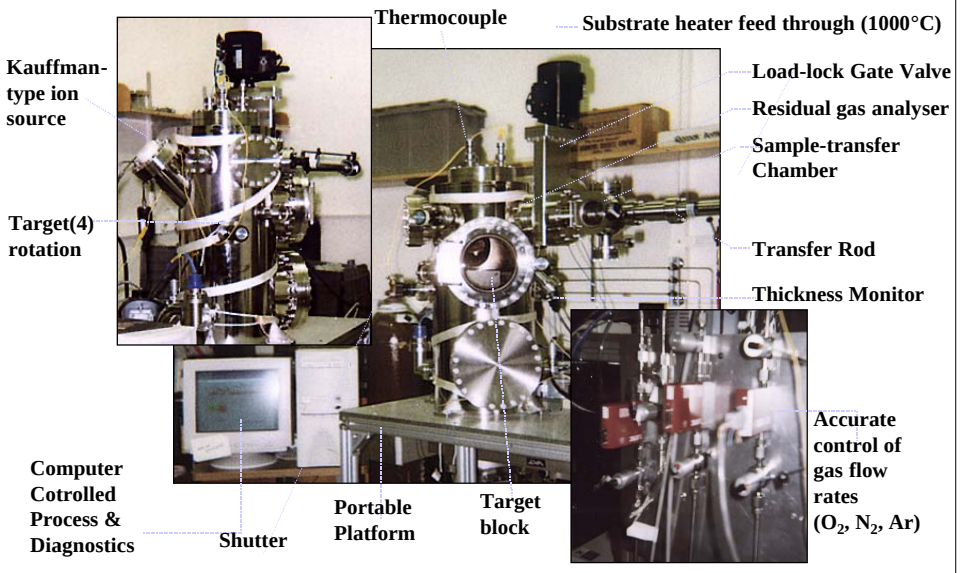


Ion-beam Deposition



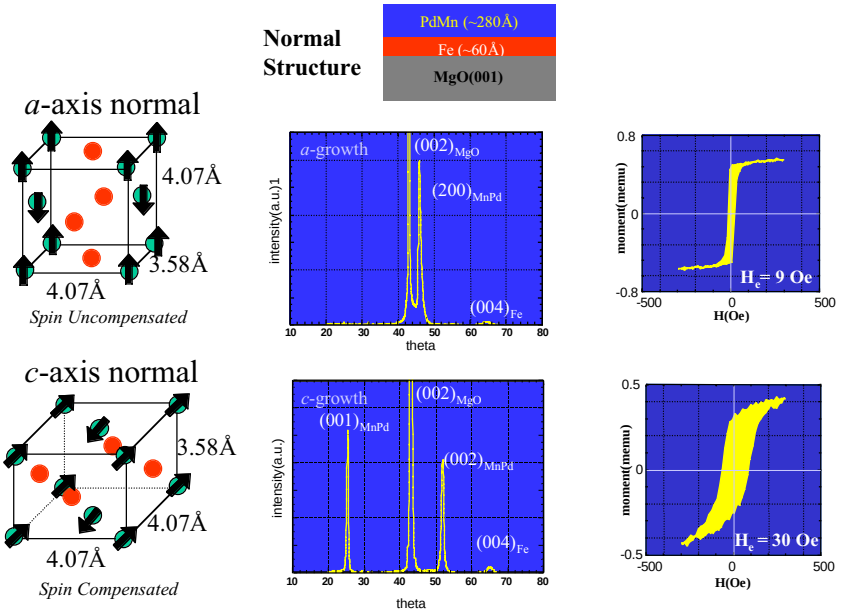
2.5 cm diameter
1-2 keV
20-50 mAmps
0.5 Å/sec sputtering

UHV Reactive Ion-beam Deposition System

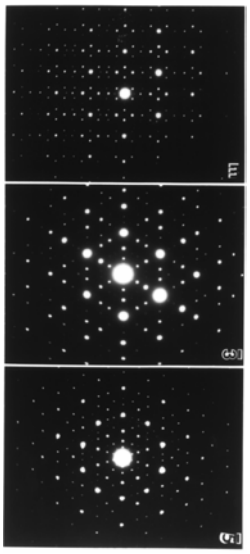


Versatile, Portable (ALS)

Epitaxial growth and exchange biasing of FM/AFM bilayers

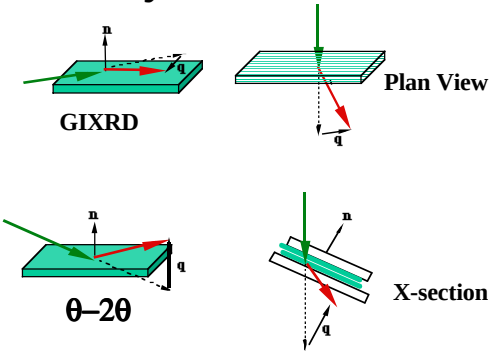


Electron Diffraction in a TEM



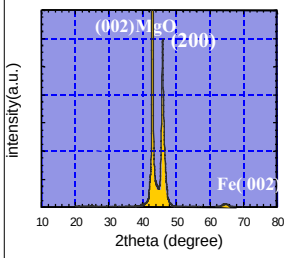
Scattering Geometries:

X-ray **TEM**

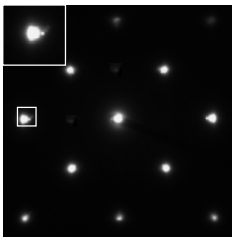


Complementary information for thin films

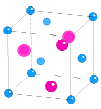
Chemical ordering of *a*-axis grown PdMn by annealing



He ~ 0

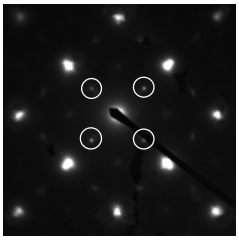


SAD[100]**a**-axis growth
as-grown

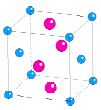


a -disordered

He ~ 8-10 Oe



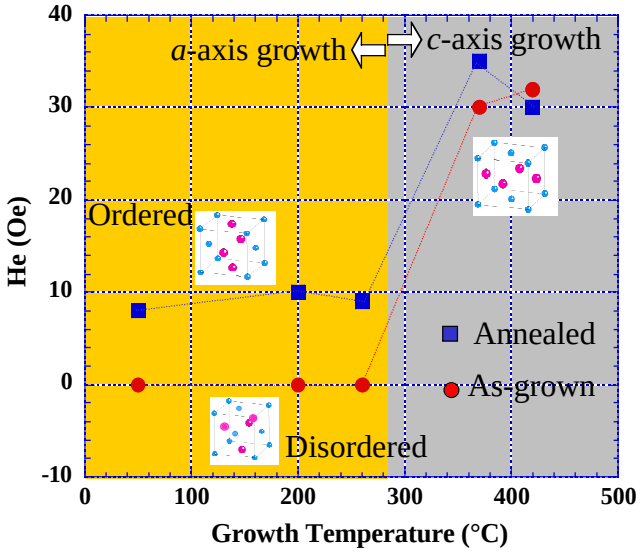
SAD[100]**a**-axis growth
annealed



a -ordered

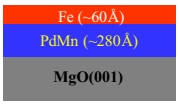
Cheng, Ahn and Krishnan, *JAP* (2001)

PdMn/Fe/MgO : Summary of growth & magnetic properties

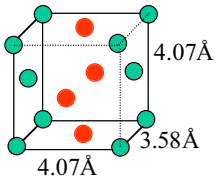


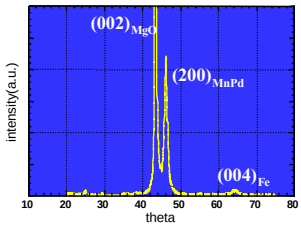
Epitaxial growth and exchange biasing of FM/AFM bilayers

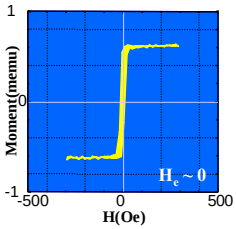
Inverse Structure



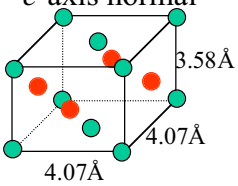
a-axis normal

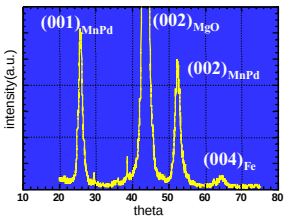


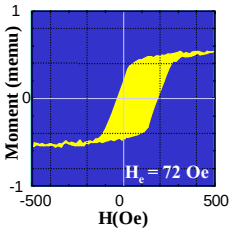




c-axis normal

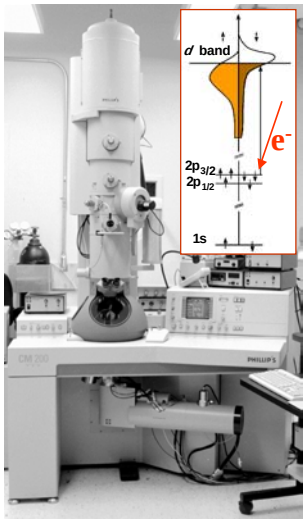






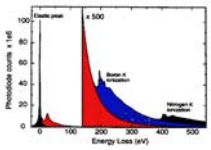
High Resolution EELS Studies in a TEM

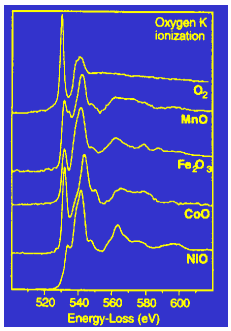
Element-specific spectroscopy and imaging at high spatial resolution



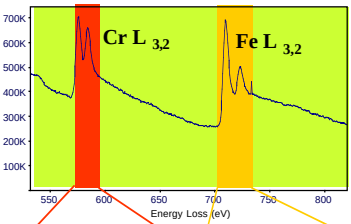
Phillips 200/FEG with Image Filter

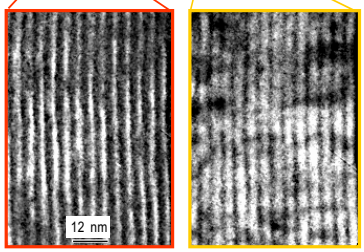
Element-resolved local electronic structure





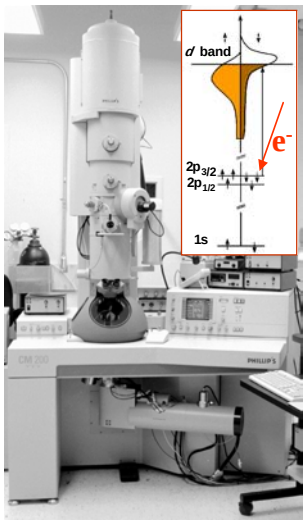
Spatially-resolved measurements





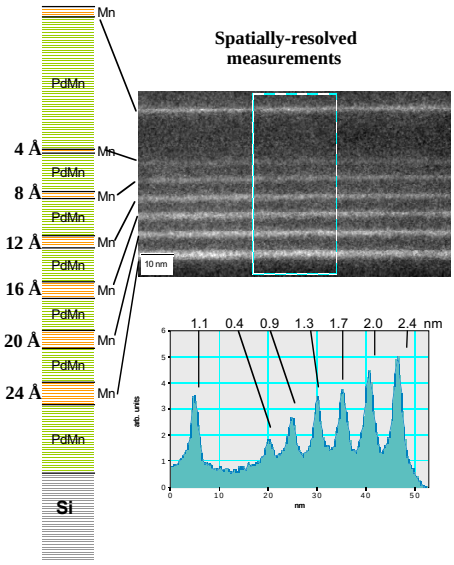
Diplole Selection Rule $\Delta l = \pm 1$ apply

Energy-filtered Imaging in a TEM: Detection Limits

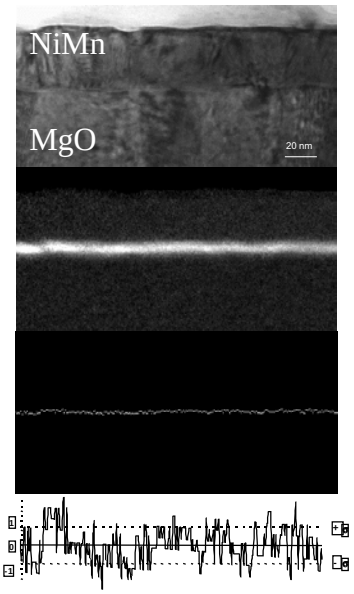


Phillips 200/FEG with Image Filter

Diplole Selection Rule $\Delta l = \pm 1$ apply



Simple Roughness Measurements Using Energy-filtered Images

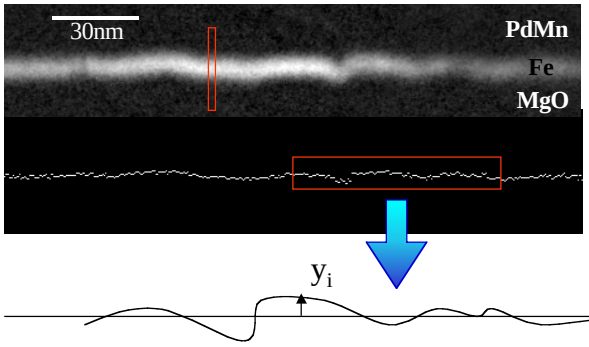


TEM Bright Field Image

Fe-$L_{2,3}$ jump ratio image

Trace or Mean Position

Fe Layer Roughness in Fe/MnPd bilayers



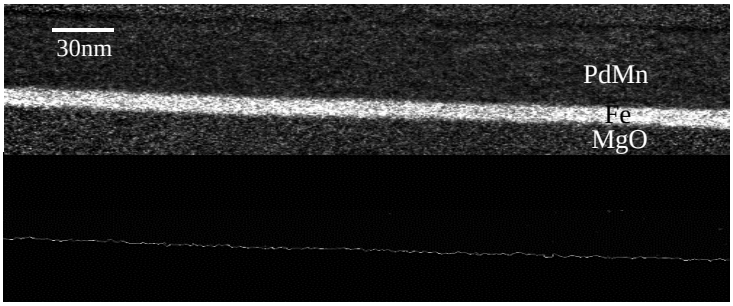
Fe EFTEM image

Trace of Layer

"Roughness":
σ=1.12 ± 0.042nm

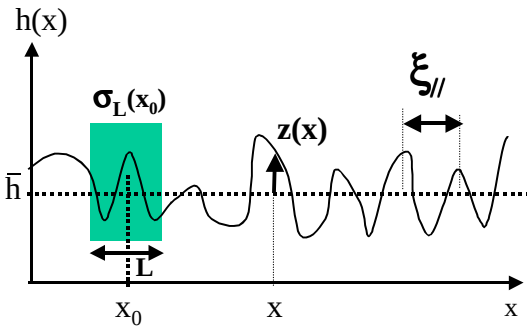
$$\sigma = (\Delta y)^2 = (\frac{1}{N-1}\sum_{i=1}^{N}(y_i - < y >)^2)^{1/2}$$

Layer Roughness for a-axis, c-axis normal and c-axis inverted structures



Layer Roughness:
a-axis normal: 0.501 ± 0.042nm
c-axis normal: 0.574 ± 0.042nm
c-axis inverted: 0.323 ±0.042nm

Definitions: Rough interface with various characteristic length scales



Interface Profile h(x)
Average Value <h(x)> or $\bar{h}$
Height Deviation $z(x) = h(x) - \bar{h}$

Interface width ~ rms roughness
$\sigma(L) \sim < \sigma_L(x_0) >_x$
where the averaging is done over all points x within L and

$\sigma_L(x_0) = < |z(x) - z_{av}(L)|^2 >_L^{1/2}$

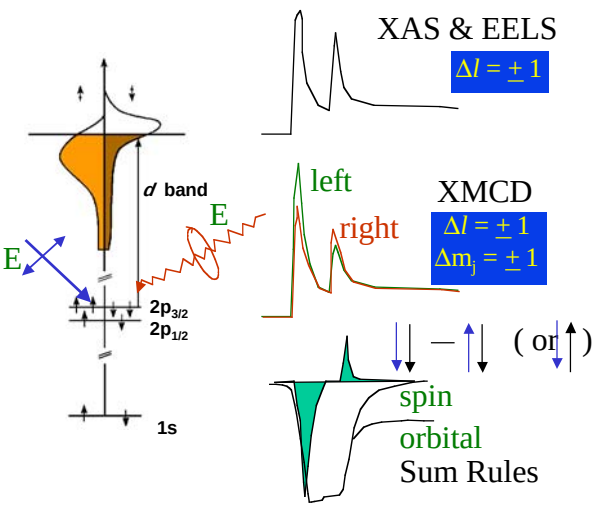
$z_{av}(L)$ is z(x) averaged over L

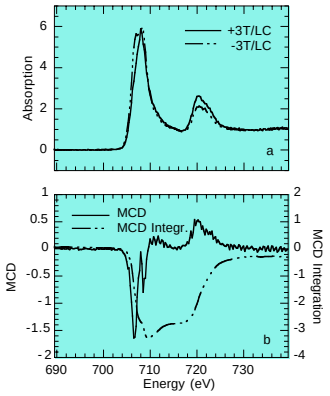
Correlation length, $\xi_{||}$ is extracted by fitting

$\sigma(L) \sim \sigma_{sat} [1- \exp (-L/\xi_{||})]$

Xray Magnetic Circular Dichroism

Element Specific, Spin/Orbital Resolved Magnetic Measurements

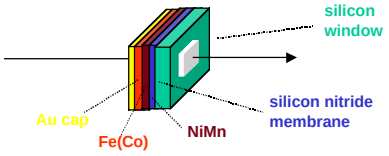


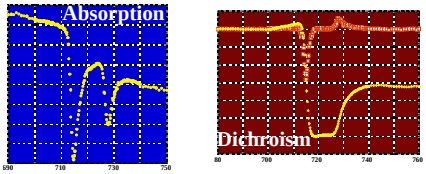


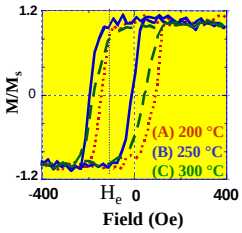
$$\frac{m_{orb}}{m_{spin}} = \frac{2q}{(9p - 6q)}$$

$m_{orb} / m_{spin} = 0.03$

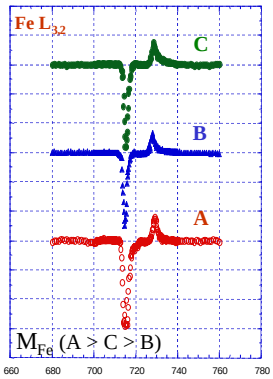
Magnetic structure of AFM-FM bilayer interfaces







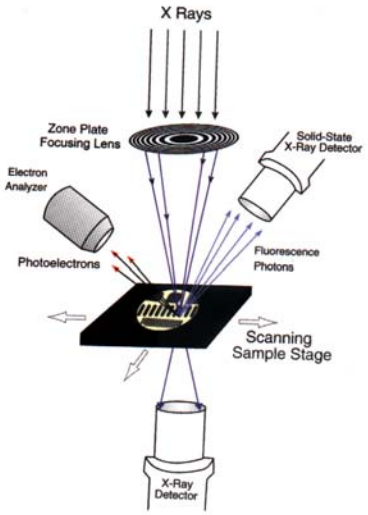
He (B > C > A)

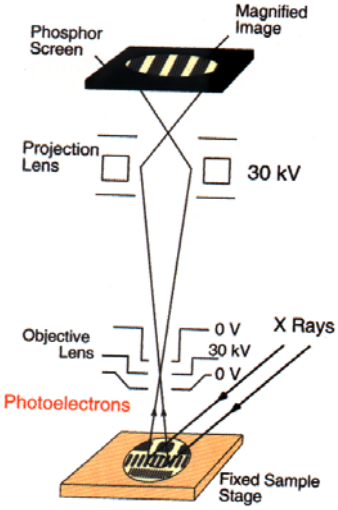


- Iron Moment Correlates inversely with Exchange field
- The films show (111) texture
- (111) is spin compensated
- Iron diffuses into MnNi and orders antiferromagnetically
- The decrease in iron moment suggests ~ 4MLs of diffusion
- Fe-Mn is a well known disordered AFM
- Need to investigate chemical and structural roughness

Cheng, Krishnan, Farrow, Young, Girt , .JAP (in press)

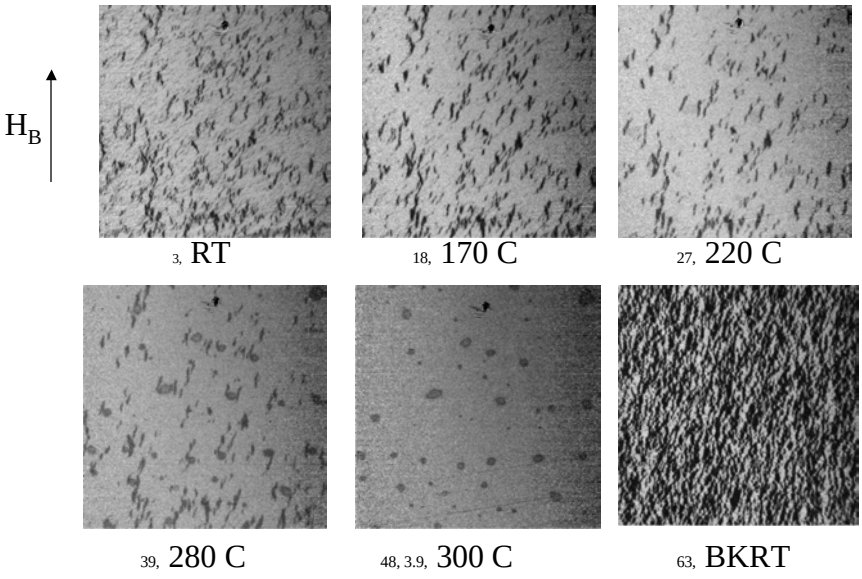
Microspectroscopy & Spectromicroscopy with Photons (ALS)





PhotoEmission Electron Microscope

PEEM : Temperature Dependence

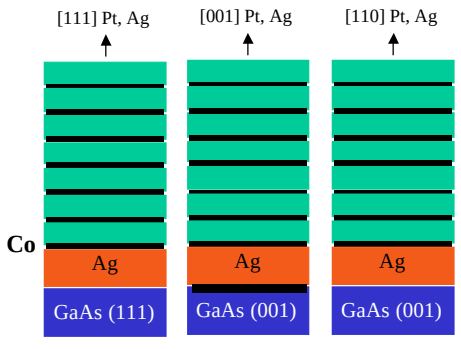


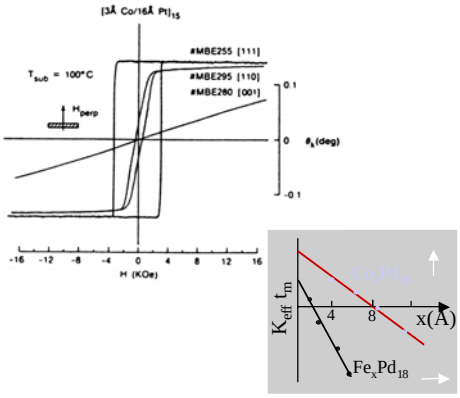
Cheng, Ohldag, Krishnan (2001)

Recent discoveries in artificially structured magnetic films

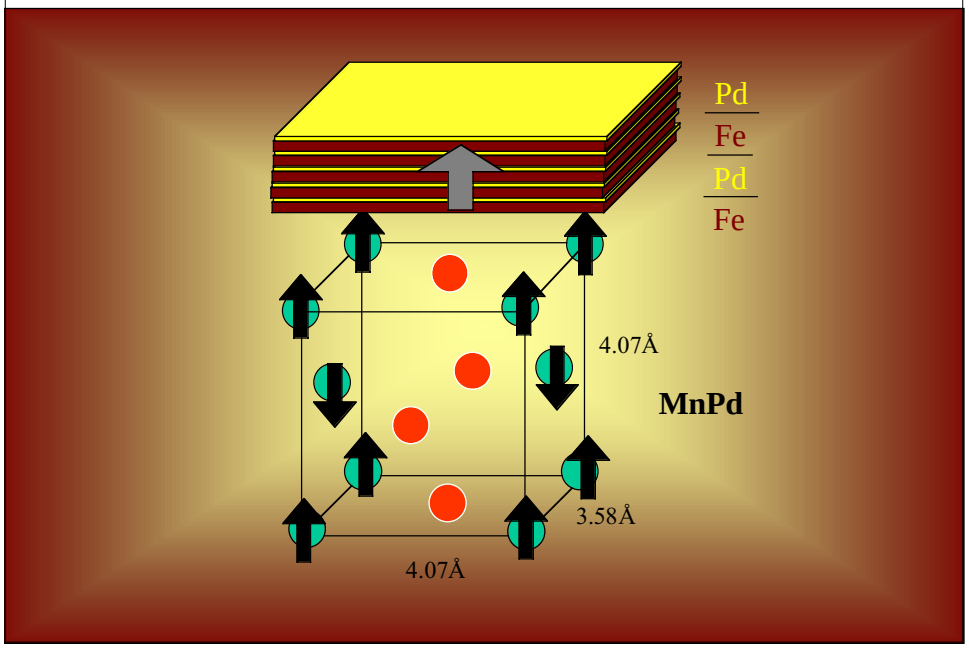
Perpendicular Interface Anisotropy

$$E_{an} = K_{eff}\sin^2\Theta \qquad K_{eff} = -2\pi M_s^2 + \frac{2K_s}{t_M} + K_V$$



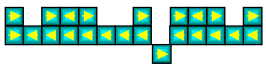


Exchange Bias in Systems with Out-of-Plane Coupling ?



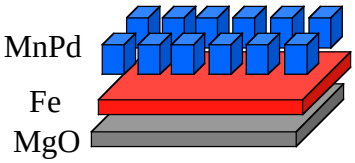
Lithographically Patterned Antiferroamgnetic Elements ?

Malozemoff (1987, 1988)



Random Field Model

AFM Domain



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Dr. H. Ohldag - PEEM Beamline Scientist
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DoE/BES
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