Antiferromagnets for Heads and Media

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Antiferromagnets for Spintronics

• **PSMO Manganite**
  – **AF-F Transition**
  – Prelim experiment at PSI
  – HFIR experiments in progress

• **Thin film antiferromagnets**
  – Exchange bias effect
  – Spin ordering transitions
  – Critical exponents
  – Spin waves
  – **IrMn/F**
  – Underlayer optimization

• **Artificial Antiferromagnets**
  – USA
Structural, Magnetic and Transport Properties of $\text{Pr}_{0.5}\text{Sr}_{0.5}\text{MnO}_3$

(H. Kawano et al., PRL 78, 4253, 1997)

- Curie Temperature $T_C \sim 265$ K
- Ferromagnetism and metallic behavior above 140 K due to double exchange interaction
- Néel Temperature $T_N \sim 140$ K (A-type Antiferromagnetic structure)
- Space group: P21/n. Lattice constants; $a=5.360$ Å, $b=7.813$ Å, $c=5.377$ Å (T=110 K)
- Antiferromagnetic state is semiconducting

**A-type Antiferromagnet**

Ref: Poster by Ref. V.V. Krishnamurthy et al.

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PSMO Measured on RITA II

- The RITA II spectrometer is a horizontally focusing monochromator on the Swiss Spallation Neutron Source.
- Sample was grown by John Mitchell of ANL.
- The phase transition behavior indicates that the composition is stoichiometric.
- The detailed scan of the antiferromagnetic ordering peak indicates multiple domains.
- Acquisition time for the phase transition was ~ 1 day.

Ref. V.V. Krishnamurthy et al., submitted to J. Appl. Phys. (Intermag 2004)
RITA II Multicrystal Analyzer

- Analyzer consists of seven graphite monochromator crystal blades which can be rotated separately for horizontal focusing.
- A 4 fold increase of count rate was observed for the monochromatic focusing mode.
- A similar device with nine blades is being developed in collaboration with J.L. Robertson.

Inelastic Neutron Diffraction

- Measures spin wave dispersion relations, $E_g$, $D_{sw}$.
- $E_g$ is energy gap → information about the strength of the coupling (exchange constant) $J$ ($E = J S_1 S_2$)
- $D_{sw}$ is “spin wave stiffness”. $E = E_g + D_{sw} q^2$ tells about dynamics.
- RITA II at PSI was used for this measurement.

Ref: Poster by Ref. V.V. Krishnamurthy et al.

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Spin Waves in PSMO Measured at HFIR

- Spin wave dispersion for $q$ perpendicular to FM planes.
- HFIR HB3 beamline was used – it has a 40x improvement in count rates over RITA II.
- The broad excitation around 14 meV is from Pr crystal fields.
- We will measure charge ordering behavior next.

Ref: Poster by Ref. V.V. Krishnamurthy et al.
F/AF Exchange Bias

- When a ferromagnet (F) is deposited on an antiferromagnet (AF) in an applied field, the hysteresis loop of the F film is altered in two ways:
- There is a bias (or shift) of the hysteresis loop by an amount called $H_p$ or the pinning field.
- There is an enhancement of the coercive field, $H_c$, particularly along the direction of the applied field.
- The origin of this effect is FM defects in the antiferromagnet.
- The anisotropy of the antiferromagnet controls the magnitude of the effect.
Antiferromagnetic Spin Ordering in FePt$_3$

- Two types of spin ordering are observed in the bulk material.
- There is a spin ordering transition from $[1/2 0 0]$ to $[1/2 1/2 0]$ at 100 K.
- The Néel temperature is 165 K for the stoichiometric material and is composition dependent.
- This films on sapphire and MgO were studied with neutron diffraction.

Antiferromagnetic Spin Ordering of FePt$_3$ Films

- The epitaxial films are ~300 nm thick and (111) oriented on sapphire substrates.
- The Fe$_{30}$Pt$_{70}$ film exhibits only $[1/2 \ 0 \ 0]$ spin ordering with a Néel temperature of 140 K.
- The Fe$_{27}$Pt$_{73}$ film exhibits a spin ordering transition from $[1/2 \ 0 \ 0]$ to $[1/2 \ 1/2 \ 0]$ at 100 K and a Néel temperature of 160 K.
- These measurements showed thin films exhibit different behavior than bulk samples.

Spin Hamiltonian

\[ H = -\frac{1}{2} \sum_{R,R'} \left[ J_z (R - R') S_z(R) S_z(R') + J_{\parallel} (R - R') \vec{S}_{\parallel}(R) \cdot \vec{S}_{\parallel}(R') \right] \]

- The anisotropic Heisenberg Hamiltonian is described by two coupling parameters.
- \( J_z \) is the out of plane coupling.
- \( J_{\parallel} \) is the in-plane coupling.
- Special cases are Ising (\( J_{\parallel} = 0 \)), XY (\( J_z = 0 \)), isotropic Heisenberg (\( J_z = J_{\parallel} \)).
- The ratio of \( J_z / J_{\parallel} \) gives the anisotropy.
Relation of Critical Exponent to Dimensionality and Anisotropy

- Contours of constant $\beta$ are shown in the space dimensionality, spin dimensionality plane.
- Subtle differences of $\beta$ are due to microscopic properties of the sample.
- For 3D systems, increasing $\beta$ indicates reduced anisotropy.
- In thin films approaching 1 nm thick, $\beta$ becomes 2D-like.*


Determining Spin Ordering from Power Laws

- The critical behavior depends on the universality class of the system.
- The magnetization power law exponent, $\beta$, is 0.125 for the 2D Ising model, 0.24 for the finite-size 2D XY model and 0.34 for the 3D Heisenberg model.
- Determination of $\beta$ provides an insight into the type of magnetic ordering.
Critical Exponent of an Epitaxial FePt$_3$ Thin Film

- The inset shows the log-log plot of intensity versus the reduced temperatures.
- From the fitting the order parameter exponent is found to be $\beta = 0.368(13)$ which corresponds to 3D Heisenberg model.
- A comparison with bulk indicates the films have a reduced anisotropy.
- Subtle changes in magnetic anisotropy due to lattice strain induced during the epitaxial growth and/or chemical disorder associated with compositional inhomogenieties may be the origin of these differences.
- Future experiments will focus on measurements of spin waves for a similar thin film system.

Ref: V.V. Krishnamurthy et al., submitted to Phys. Rev. B

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Non-linear Relationship between $J$ and $M_s$

G/Ta(20)/Cu(20)/IrMn(10)/FM(t nm)/Cu(2)/Ta(5)

$J = \alpha (M_s - M_{s\text{critical}})^\beta$

- Annealed
  
  \[
  J_{ex} = 0.0059(M_s - 450)^{0.55} \\
  J_{eb} = 0.0034(M_s - 449)^{0.61}
  \]

- As-deposited

\[
J_{ex} = 0.0295(M_s - 589)^{0.29} \\
J_{eb} = 0.0194(M_s - 575)^{0.30}
\]

Ref: Poster by H.S. Jung et al.

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Underlayer optimization of Exchange Biased CoFe/Ru/CoFe/IrMn

A thick Cu seed layer ~ 300 A results in appreciable exchange bias and well separated minor loops.

Ref: Poster by P. Mani et al.
Uniaxial Synthetic Antiferromagnets

- Strong antiferromagnetic exchange coupling was observed in USA structures.
- Distinguishable Easy and Hard axis loops were also observed.
- We can tune the biquadratic coupling effect.

Ref: Poster by Z. Zhao et al.
Uniaxial Synthetic Antiferromagnetic Films

- Comparison of experimental remanence with a calculation which only considers bilinear coupling. The difference is due to biquadratic coupling.
- Dependence of easy axis critical fields $H_{cr1}$ and $H_{cr2}$ on top layer Co thickness. The dotted line is a fit to a minimize energy model.

Ref: Poster by Z. Zhao et al.
Picomotor for Multicrystal Analyzer

- Model 8310 closed-loop Picomotor™ actuator is ideal for applications where closed-loop control and absolute position calibration is required.
- The small footprint, 0.67 in., makes it ideal for the multicrystal analyzer application.
- Driver software and testing is currently in progress.
New Deposition System at UA

- New system will allow fabrication of 2” diameter samples with better uniformity.
- Eight targets *with* in situ chemical analysis makes this system unique.
Outlook

• Antiferromagnetic materials are used in magnetic information storage devices.
• Neutrons allow measurements of the fundamental properties of these materials.
• Our ultimate goal is to perform diffraction and inelastic measurements on thin film samples.
• We have made considerable progress toward achieving this goal.