Metal/native oxide multilayers: 
A new material for recording head applications

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Outline

I. Motivations for new shield materials
II. Metal/Native Oxide Multilayers
   Structure, Fabrication
III. Magnetic characteristics of MNOMs
IV. Surprising properties of the native oxide
V. Conclusions
Magnetic Recording Head

Shield Functions:
1) Shield read sensor from stray flux
2) Act as lower pole in write operations

- High Permeability ($\mu$)
- Low Coercivity ($H_c$)
- High Saturation Magnetization ($M_s$)
- Well-Defined In-Plane Anisotropy ($H_k$)
- High resistivity ($\rho$)
Eddy Currents in Shield Materials

Changing Magnetic Flux ⇒ Screening (Eddy) Currents

**Eddy currents:**
- Flow in a surface layer with thickness $\alpha \sqrt{\rho/f}$
- Shield interior from field (decreased effective permeability)
- Result in losses $\propto f^2/\rho$

Eddy currents minimized by *increasing resistivity*
Metal/Native Oxide Multilayer (MNOM)

Magnetic Oxide leads to
• Increased resistivity (1~10 mΩ-cm*) – inhibits eddy currents
• Increased saturation magnetization compared to films with nonmagnetic layers, (>1300 emu/cc*)
• Exchange coupling between nanocrystalline layers (large exchange length ⇒ soft magnetic properties)

*G. S. D. Beach, et. al, Appl. Phys. Lett. 79 (224) 2001
MNOM Fabrication:
\[ \text{[Co}_x\text{Fe}_{1-x}(t_0)/\text{oxide}]_N \]

I. Deposit Co\textsubscript{x}Fe\textsubscript{1-x} layer (nominal thickness “t\textsubscript{0}”)

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**MNOM Fabrication:**

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II. Expose to O$_2$, forming native oxide layer (~10 s, 7x10$^{-5}$ Torr)
**MNOM Fabrication:**

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II. Expose to O\(_2\), forming native oxide layer (~10 s, 7x10\(^{-5}\) Torr)  
III. Deposit additional layers (total “\(N\)”)

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Cross-Sectional TEM: $[\text{Fe}(20 \text{ Å})/\text{oxide}]_{50}$
$M(H)$: Continuous Film vs. MNOM

MNOM:
- Dramatically lower coercivity
- Increase in squareness
- Large magnetization
Soft Magnetic Properties of MNOMs

- Well-defined in-plane anisotropy
- Low easy axis coercivity (up to an order of magnitude decrease)
- Ideal closed hard-axis loop

Easy axis defined by deposition field
Soft Properties of $[\text{Co}_x\text{Fe}_{100-x}(20 \text{ Å})/\text{oxide}]$

- Soft properties (low coercivity, low hard-axis dispersion) for wide composition range.

![Graph showing the relationship between magnetic properties and Co concentration](image-url)

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Composition Dependence:
[Co$_x$Fe$_{100-x}$ (20 Å)/oxide]

Soft properties appear near $x=90$

With metal fraction $f$ (from Mössbauer, EXAFS), can determine oxide moment:

$$M_{MOM} = f \cdot M_{metal} + (1-f) \cdot M_{oxide}$$

Soft properties coincide with onset of oxide magnetism

*G. S. D. Beach, et. al, J. Appl. Phys. 79 (7526) 2002*
Oxide Magnetism

• Soft properties coincide with onset of oxide magnetism.

• Understanding the oxide is vital to understanding MNOM behavior.

Therefore,

• We have studied the \([\text{Fe}(t_0)/\text{oxide}]_N\), as a function of \(t_0\).
  → Simple MNOM system (one element; Mössbauer).
  → Can determine whether metal influences oxide properties.
  → Allows independent measurement of metal and oxide moment.
Outline:  
Native oxide study

• Native oxide consists of 2 phases; both phases are magnetic.

• The minority phase behaves as a frustrated spin system, with no net moment.

• The majority phase cannot be identified with a bulk phase. It has a Fe$^{3+}$ valence, a moment 50% higher than any bulk Fe oxide phase, and couples ferromagnetically to the metal.
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1) Mössbauer spectroscopy used to characterize Fe phases.
2) Combined with magnetometry ⇒ average oxide moment
3) Temperature dependence shows net oxide moment from only 1 component of oxide ⇒ moment of that component.
Mössbauer Spectrum: Hyperfine Field

Magnetic ordering causes spectrum to split into 6 lines.

- Splitting due to internal magnetic field at the nucleus
- Splitting related to atomic moment.

Hyperfine Field ($H_{HF}$): magnitude of sextet splitting; related to magnetic state of Fe
Nonzero Fe valence causes a horizontal shift of the spectrum.

- Shift due to s-electron density at the nucleus. Sensitive to Fe valence.
- Can be used to distinguish Fe valence (metal, oxide fractions).

Isomer Shift (IS): magnitude of horizontal shift; related to valence of Fe
Mössbauer Spectroscopy: Fe MNOMs

- MNOM spectrum contains two components: metal and oxide
- Spectrum fitted with metal and oxide subspectra.

Subspectra:
- Metal (Fe\(^0\)): Fe metal has bulk parameters.
- Oxide: Magnetically-split. Forms from 8.6 Å of metal.
Measurement of Oxide Moment: 
\[[\text{Fe}(t_0)/\text{oxide}]_N\]

Mössbauer spectroscopy gives fraction of Fe as metal

Magnetization measurement gives average moment of MNOM

\(f\) : fraction of Fe as metal

\(\mu_s\) : sample moment (in \(\mu_B/\text{Fe atom}\))

\(\mu_{\text{metal}}\) : moment of the metallic Fe

\(\mu_{\text{oxide}}\) : average moment of oxide phase(s)

\[
\mu_s = f \cdot \mu_{\text{metal}} + (1-f) \cdot \mu_{\text{oxide}}
\]

\(\mu_s\) is linear in \(f\)

Can independently determine \(\mu_{\text{oxide}}\) and \(\mu_{\text{metal}}\) by varying \(f\).

\[\rightarrow\] Accomplished by varying \(t_0\) (oxide thickness stays constant).

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Sample Moment vs Metal Fraction:
\[[\text{Fe}(t_0)/\text{oxide}]_N\]

Above a critical layer thickness \( t_0 \approx 15 \, \text{Å}, \mu_s \) is linear in \( f \):

\[
\mu_s = (\mu_{\text{metal}} - \mu_{\text{oxide}}) f + \mu_{\text{oxide}}
\]

**Slope:** \( \mu_{\text{metal}} - \mu_{\text{oxide}} \)

**Intercept:** \( \mu_{\text{oxide}} \)

\[
\mu_{\text{metal}} = 2.1(1) \, \mu_B \\
\mu_{\text{oxide}} = 1.40(7) \, \mu_B (\text{average!})
\]
Results I

• Oxide is magnetic, with average moment $1.40(7) \mu_B$.
  (compare to $\gamma$-Fe$_2$O$_3$ (1.15 $\mu_B$) and Fe$_3$O$_4$ (1.35 $\mu_B$))

• Oxide always forms from $8.6(3)$ Å of metal.

• Oxide moment deteriorates if metal layer too thin; oxide moment constant for $t_0>15$ Å.
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Is oxide homogeneous? (we only have average oxide moment)
Oxide Hyperfine Field (HF) Distribution: 
\[ \text{[Fe(20 Å)/oxide]}_{50} \]

Oxide fitted with subspectra with a HF distribution

2 Oxide “Phases”:
• 70% of oxide in 3 main subspectra (Fe\(^{3+}\), unique hyperfine field)
• 30% of oxide in weakly magnetic “tailing”
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Is it possible to study the two oxide phases separately?
→ Yes - temperature dependence!
Temperature Dependence: Hyperfine Fields

HF and atomic moment have the same temperature dependence.

- Average HF of 3 main subspectra shows small change between 4.2 K and 300 K.
- Average HF of tailing drops by factor of ~4 from 4 K to room temperature.
Temperature Dependence: 
**HF vs. Moment**

Magnetometer measures *net* moment.

Net sample moment changes by ~2% from 5 K to 300 K, same as for bulk Fe

“Tailing” HF (and thus atomic moment) changes by a factor of 3.

Tailing accounts for 13% of Fe in sample⇒ Tailing has no *net* moment!
Implications for Oxide Moment

\[ \mu_{\text{oxide}} = \text{average oxide moment} = 1.40(7) \left( \mu_{B}/\text{oxide Fe} \right) \]

\[ \mu_{\text{oxide}} = 0.3 \cdot \mu_{\text{tailing}} + 0.7 \cdot \mu_{\text{3main}} \]

\[ \Rightarrow \mu_{\text{3main}} = \frac{\mu_{\text{3main}}}{0.7} \]

\[ \mu_{\text{3main}} = 2.0(1) \left( \mu_{B}/\text{oxide Fe} \right) \]

Oxide phase in 3 main subspectra has a moment 50% larger than that of magnetite (Fe₃O₄)!

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Results II

• Oxide is composed of 2 magnetic phases.

• 30 % of oxide is weakly magnetic at room temperature, with no net moment (similar to spin glass, antiferromagnet)

• 70 % of oxide is strongly magnetic, with well-defined hyperfine field (magnetic environment).

• Majority phase has a net moment of 2.0(1) \( \mu_B \).
  [compare to \( \gamma \)-Fe\(_2\)O\(_3\) (1.15 \( \mu_B \)) and Fe\(_3\)O\(_4\) (1.35 \( \mu_B \))]

• Majority phase is Fe\(^{3+}\), and has average \( H_{HF}=385 \) kOe.
  [compare to \( \gamma \)-Fe\(_2\)O\(_3\) (~520 kOe)]
Conclusions

• We have developed a novel Metal/Native Oxide Multilayer (MNOM) structure.
• Magnetic/structural properties are ideal for high-frequency applications.
  → magnetically soft
  → high moment
  → high resistivity
• The native oxide plays important role in soft properties.
• The native oxide is a unique interfacial oxide phase with a considerable moment. Can the moment be increased further?