Optical and Magneto-Optical Properties of Permalloy Thin Films

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Introduction

Permalloy, A New Magnetic Material of Very High Permeability
By H. D. ARNOLD and G. W. ELMEN

Syntops: The magnetic alloy described in this paper is a composition of about 78.5% nickel and 21.5% iron and at magnetizing fields in the neighborhood of 0.4 gauss and with proper treatment has a permeability running as high as 90,000. This is about 200 times as great as the permeability of the best iron for these low magnetizing fields. This high permeability is attendant upon proper heat treatment and also upon other factors.
Samples & goals

- AFM
- XRD, XRR
- Spectroscopic ellipsometry
- Magneto-optical Kerr effect spectroscopy (MOKE)

Ion beam sputtering

\[
\varepsilon = \begin{pmatrix}
\varepsilon_{xx} & i\varepsilon_{xy} & 0 \\
-i\varepsilon_{xy} & \varepsilon_{xx} & 0 \\
0 & 0 & \varepsilon_{xx}
\end{pmatrix}
\]
XRD results

Lattice constant (0.335±0.004) nm

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XRR results

<table>
<thead>
<tr>
<th>Nominal sample thickness, nm</th>
<th>10</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide layer thickness, nm</td>
<td>3.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Permalloy layer thickness, nm</td>
<td>9.5</td>
<td>131.5</td>
</tr>
</tbody>
</table>
AFM results

<table>
<thead>
<tr>
<th>Sample thickness</th>
<th>10 nm</th>
<th>150 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>bare film</td>
<td>1.0 nm</td>
<td>0.4 nm</td>
</tr>
<tr>
<td>gold-coated</td>
<td>~ 0.3 nm</td>
<td></td>
</tr>
</tbody>
</table>

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Ellipsometry considerations

- Woollam RC2-DI ellipsometer & software
- Mueller matrix at 55, 60, 65, 70 deg

Iron oxides
- $\alpha\text{-Fe}_2\text{O}_3$
- $\text{Fe}_3\text{O}_4$
- FeO
- $\text{Fe}^{2+}$
- NiO

Nickel oxides
- $\text{Fe}_2\text{O}_3$
- $\text{Fe}_3\text{O}_4$

Lorentz oscillators & Drude term

$\varepsilon_{\text{Drude}}(E) = \frac{-\hbar^2 e^2 N_0}{\varepsilon_0 \mu m_e E^2 + i e \hbar E}$

$\varepsilon_{\text{Lorentz}}(E) = \frac{Amp \ Br \ En}{En^2 - E^2 - i E Br}$
Ellipsometry results

<table>
<thead>
<tr>
<th></th>
<th>10 nm</th>
<th>150 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bare film</td>
<td>gold-coated</td>
</tr>
<tr>
<td>Roughness, nm</td>
<td>1.01</td>
<td>0.32</td>
</tr>
<tr>
<td>Oxide thickness, nm</td>
<td>4.32</td>
<td>-</td>
</tr>
<tr>
<td>Gold thickness, nm</td>
<td>-</td>
<td>2.70</td>
</tr>
<tr>
<td>Permalloy thickness, nm</td>
<td>8.66</td>
<td>9.82</td>
</tr>
<tr>
<td>Interlayer thickness, nm</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

12.4 \ldots 16.8 \text{ eV}

13.9

150 nm bare film
60 deg

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Ellipsometry results

<table>
<thead>
<tr>
<th>Ni: 7-16 eV</th>
<th>Fe, Ni &amp; Fe alloys: 10-12 eV</th>
</tr>
</thead>
</table>

- Energy range: [12.4 ... 16.8] eV
- Roughness, nm:
  - 1.01 (bare film)
  - 0.32 (gold-coated)
  - 0.42 (bare film)
  - 0.52 (gold-coated)
- Oxide thickness, nm:
  - 4.32 (bare film)
  - - (gold-coated)
  - 2.30 (bare film)
  - - (gold-coated)
- Gold thickness, nm:
  - - (bare film)
  - 2.70 (gold-coated)
  - - (bare film)
  - 2.77 (gold-coated)
- Permalloy thickness, nm:
  - 8.66 (bare film)
  - 9.82 (gold-coated)
  - 150 (bare film)
  - 150 (gold-coated)
- Interlayer thickness, nm:
  - 4 (bare film)
  - 4 (gold-coated)
  - 4 (bare film)
  - 4 (gold-coated)

13% thickness reduction
Diagonal permittivity

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Diagonal permittivity

Transitions between $W$ and $K$ points

Ni: 1.4 eV

Transitions around $L$ point

4.5-5 eV
Diagonal permittivity

Ni:

- 0.3-0.4 eV
- 0.7 eV
- 1 eV
- 1.4 eV
- 2-2.5 eV
- 4.5-5 eV

Unconfirmed
Diagonal permittivity

Transitions in zone face (direction $K$, points $P$)

Ni: 0.3-0.4 0.7 1 1.4 Fe 2.5 4.5-5 eV

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Diagonal permittivity

Ni: 0.3-0.4, 0.7, 1, 1.4, Fe: 2.5, 4.5-5 eV

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Raw MOKE spectra

### Table: Kerr Rotation and Ellipticity

<table>
<thead>
<tr>
<th></th>
<th>10 nm</th>
<th></th>
<th>150 nm</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bare film</td>
<td>gold-coated</td>
<td>bare film</td>
<td>gold-coated</td>
</tr>
<tr>
<td>Max. Kerr rotation, deg</td>
<td>0.13</td>
<td>0.10</td>
<td>0.22</td>
<td>0.19</td>
</tr>
<tr>
<td>Max. Kerr ellipticity, deg</td>
<td>0.20</td>
<td>0.07</td>
<td>0.20</td>
<td>0.17</td>
</tr>
</tbody>
</table>

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Yeh’s matrix formalism

- 4 x 4 transfer matrix formalism
- Suitable for anisotropic multilayers
- Treats an arbitrary $\varepsilon$ tensor

\[
\begin{bmatrix}
E_{01}^{(0)} \\
E_{02}^{(0)} \\
E_{03}^{(0)} \\
E_{04}^{(0)}
\end{bmatrix}
=
\begin{bmatrix}
M_{11} & M_{12} & M_{13} & M_{14} \\
M_{21} & M_{22} & M_{23} & M_{24} \\
M_{31} & M_{32} & M_{33} & M_{34} \\
M_{41} & M_{42} & M_{43} & M_{44}
\end{bmatrix}
\begin{bmatrix}
E_{01}^{(N+1)} \\
E_{02}^{(N+1)} \\
E_{03}^{(N+1)} \\
0
\end{bmatrix}
\]

\[
M = \prod_{n=1}^{N+1} T^{n-1,n}
\]

\[
T^{(n-1,n)} = (D^{(n-1)})^{-1} D^{(n)} P^{(n)} E_0^{(n)}
\]

\[
P^{(n)} =
\begin{bmatrix}
\exp\left(j\varepsilon_{x}^{(n)} x^{(n)}\right) & 0 & 0 & 0 \\
0 & \exp\left(j\varepsilon_{y}^{(n)} y^{(n)}\right) & 0 & 0 \\
0 & 0 & \exp\left(j\varepsilon_{z}^{(n)} z^{(n)}\right) & 0 \\
0 & 0 & 0 & \exp\left(j\varepsilon_{\alpha}^{(n)} \alpha^{(n)}\right)
\end{bmatrix}
\]

\[
D^{(s)} =
\begin{bmatrix}
\tilde{p}^{(s)} & \tilde{p}^{(s)} & -q^{(s)*} & -q^{(s)*} \\
-p^{(s)} \cos\varphi^{(s)} & -p^{(s)} \sin\varphi^{(s)} & -q^{(s)*} \cos\varphi^{(s)} & -q^{(s)*} \sin\varphi^{(s)} \\
q^{(s)} \cos\varphi^{(s)} & q^{(s)} \sin\varphi^{(s)} & p^{(s)*} \cos\varphi^{(s)} & p^{(s)*} \sin\varphi^{(s)} \\
-N^{(s)} q^{(s)} & N^{(s)} p^{(s)} & -N^{(s)} p^{(s)*} & N^{(s)} q^{(s)*}
\end{bmatrix}
\]

Off-diagonal permittivity
Off-diagonal permittivity

**Ni** 1.5 eV  
**Fe** 1.7 eV

Delocalized transitions in the vicinity of $N$ point
Off-diagonal permittivity

- 5 eV in pure Ni
- $d$ band width
- Lattice constant:
  - Permalloy $1\% > \text{Ni}$
  - Permalloy $24\% > \text{Fe}$
  - Si substrate 0.543 nm

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Off-diagonal permittivity

- Zigzag structure present in pure Ni or Fe because of energy shifts of the minority- and majority-spin contributions.

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Figure of merit

\[ FOM = \sqrt{R(\theta_K^2 + \varepsilon_K^2)} = \sqrt{\left(\frac{n-1}{n+1}\right)^2 (\theta_K^2 + \varepsilon_K^2)} \]
Summary

- Complete complex permittivity tensor recovered in 0.7-6.4 eV
- Metallic optical properties with average Drude frequency of 13 eV
- Optical response dominated by nickel
- Noticeable differences in case of 10 nm samples
- Influence of oxidation on roughness, layer thickness, magneto-optical properties