High Anisotropy $L1_0$ FePt Media for Perpendicular Magnetic Recording Applications

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Acknowledgements

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  – Dr. Wei Chuan GOH
  – Mr. Wai Lwin PHYOE
  – Mr. Yuan Kwang LIM
Areal Density Growth Chart

Growth of Areal Densities for Conventional Recording

- Thermal Stability Limited Region
- "Superparamagnetic" effect

Simple scaling allowed for increasing areal density for many years at 30% CGR

Acceleration to 60-100% CGR thin-film head, media, channels

"Superparamagnetic" effect now posing a significant challenge
Perpendicular + other new technologies introduced

Year of Introduction


Areal Density (Gb/in²)

0.001 0.01 0.1 1 10 100 1000

(Adapted from Roger Wood, Intermag 06, CA-01)
Bit Cell Dimensions at Demonstrated Densities

<table>
<thead>
<tr>
<th>Density</th>
<th>Year</th>
<th>Value</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>720 kbpi x 141 ktpi</td>
<td>1997</td>
<td>12.1 Gbit/in²</td>
<td>35nm x 180 nm</td>
</tr>
<tr>
<td>850 kbpi x 131 ktpi</td>
<td>1999</td>
<td>23.8 Gbit/in²</td>
<td>30nm x 194 nm</td>
</tr>
<tr>
<td>2500 kbpi x 400 ktpi</td>
<td>2000</td>
<td>63 Gbit/in²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>102 Gbit/in²</td>
<td>35nm x 180 nm</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>63.8 Gbit/in²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>111 Gbit/in²</td>
<td>30nm x 194 nm</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>1000 Gbit/in²</td>
<td>10nm x 64nm</td>
</tr>
</tbody>
</table>
Superparamagnetic Limits

To preserve SNR, number of grains in a bit must be constant.

$$\text{SNR} \sim \log_{10}(N)$$

Therefore higher densities require smaller grains

Higher thermal stability $\Rightarrow$ high $K_u$ materials

$$\tau = f_0^{-1} \exp \left( \frac{K_u V}{k_B T} \right)$$

$$\frac{K_u V}{k_B T} = 40 - 60$$ is considered acceptable

The smaller bits have a higher probability of flipping and the data is unstable
# Why choose FePt?

<table>
<thead>
<tr>
<th>Alloy System</th>
<th>Material</th>
<th>$K_u$ (10^7 erg/cc)</th>
<th>$M_s$ (emu/cc)</th>
<th>$H_k$ (kOe)</th>
<th>$T_c$ (K)</th>
<th>$D_p$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Co-alloys</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CoCr$<em>{20}$Pt$</em>{15}$</td>
<td>0.20</td>
<td>298</td>
<td>13.7</td>
<td>--</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>Co</td>
<td>0.45</td>
<td>1400</td>
<td>6.4</td>
<td>1404</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>Co$_3$Pt</td>
<td>2.0</td>
<td>1100</td>
<td>36</td>
<td>--</td>
<td>4.8</td>
</tr>
<tr>
<td><strong>$L_1_0$ Phases</strong></td>
<td>FePd</td>
<td>1.8</td>
<td>1100</td>
<td>33</td>
<td>760</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>FePt</strong></td>
<td></td>
<td>6.6-10</td>
<td>1140</td>
<td>116</td>
<td>750</td>
<td>3.3-2.8</td>
</tr>
<tr>
<td><strong>CoPt</strong></td>
<td></td>
<td>4.9</td>
<td>800</td>
<td>123</td>
<td>840</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>MnAl</strong></td>
<td></td>
<td>1.7</td>
<td>560</td>
<td>69</td>
<td>650</td>
<td>5.1</td>
</tr>
<tr>
<td><strong>Rare-earth transition metals</strong></td>
<td>Fe$_{14}$Nd$_2$B</td>
<td>4.6</td>
<td>1270</td>
<td>73</td>
<td>585</td>
<td>3.7</td>
</tr>
<tr>
<td>(RE-TM)</td>
<td>SmCo$_5$</td>
<td>11-20</td>
<td>910</td>
<td>240-400</td>
<td>1000</td>
<td>2.7-2.2</td>
</tr>
</tbody>
</table>

![Graph showing $K_u$ vs. $D_p$](image)

1Tbits/in$^2$
FePt Phase Diagram

Phase Diagram

\[ T_c(\gamma) \rightarrow (\alpha-\text{Fe}) \]

\[ (\alpha-\text{Fe}) \rightarrow (\alpha-\text{Fe}) \]

\[ (\gamma-\text{Fe,Pt}) \text{ or } \gamma \]

\[ T_c(\text{ordered}) \]

\[ T_c(\gamma) \]

\[ fcc \]

\[ fct \]

\[ 1811\,\text{K} \]

\[ 1702\,\text{K} \]

\[ 1667\,\text{K} \]

\[ 1573\,\text{K} \]

\[ 1623\,\text{K} \]

\[ 1573\,\text{K} \]

\[ 1623\,\text{K} \]

\[ 1181\,\text{K} \]

\[ 1043\,\text{K} \]

\[ 823\,\text{K} \]

\[ 973\,\text{K} \]

\[ 1573\,\text{K} \]

\[ 1623\,\text{K} \]

\[ 1181\,\text{K} \]

\[ 1043\,\text{K} \]

\[ 823\,\text{K} \]

\[ 973\,\text{K} \]
FePt Atomic Structure

Face-centered cubic (fcc)

Face-centered tetragonal (fct)

Body-centered tetragonal (bct)

Bravais Lattice
Lattice Mismatch Strain

Before deposition

After deposition

film
substrate

Before deposition: $a_f < a'_f$, $c_f > c'_f$

After deposition: $a'_f > a_f$, $c'_f < c_f$
Heteroepitaxial relationship of FePt magnetic layer with Cr underlayer

- fct-FePt (001)[100] \parallel CrX (002)[110]
  - Misfit of lattice constant between FePt (001)[100] and Cr (002)[110] is 5.8%
  - Strain from misfit helps expand \( a \)-axis and shrink \( c \)-axis, and thus \( L_1 \) FePt (001) texture was obtained at lower deposition temperature
  - According to Vegard’s Law, the lattice constant is related to the atomic radius of element \( X \)
Challenges for FePt films as recording media for 1 Tbits/in² and beyond

- Controlling the texture of FePt (001) for perpendicular recording since FePt (111) is preferably formed as it is the closest packed plane
- Narrow easy axis distribution (< 5°)
- Reducing the phase transformation temperature of FePt from fcc to L1₀ FePt
- Control of microstructure to grain size of < 5 nm grain size with 15% standard deviation.
- To develop a suitable soft underlayer for FePt media
Research teams on the control of FePt texture and phase transformation temperature

- Prof. D.J. Sellmyer, University of Nebraska, USA, high temperature post-deposition annealing of Fe/Pt multilayers (above 550°C to break the multilayers by diffusion to form $L1_0$ FePt (001) films)
- Dr. T. Maeda, Toshiba Corporation, doped with Cu followed by post-deposition anneal to reduce the temperature (300°C), but the texture is FePt (111) oriented
- Dr. Toshio Suzuki, Akita Research Institute of Advanced Technology, MgO underlayer on glass, FePt(001) texture at 375°C.
- Prof. D.E. Laughlin, Carnegie Mellon University, USA, Ag underlayer on Si, FePt (001) texture is not good and temperature is 375°C
- Prof. Takao Suzuki, Toyota Technology University, FePt/MgO multilayer by high temperature annealing (600°C)
- Others mainly focus on magnetic properties of FePt (001) on MgO (001) single crystal substrate or post-deposition anneal FePt on glass substrate without too concerned with the texture (fundamental research)
Experimental Details

- All samples deposited using custom built dc/rf magnetron sputtering system and deposition conditions as follows:
  - Base pressure: $5 \times 10^{-8}$ Torr

Characterisation tools: X-ray diffractometer, vibrating sample magnetometer, FEG-HRTEM 300kV

![Custom designed dc/rf sputter system](image)

Typical film structure:
- Corning glass substrate
- CrX underlayer
- Buffer layer
- FePt mag. layer

Custom designed dc/rf sputter system
Growth of FePt on MgO single crystal substrate with different intermediate layer

<table>
<thead>
<tr>
<th>Sample</th>
<th>Intermediate layer</th>
<th>$a_1$ (Å) (on MgO)</th>
<th>$a_2$ (Å) (on glass)</th>
<th>Epitaxial relationship</th>
<th>$\varepsilon$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Pt</td>
<td>3.9281</td>
<td>3.9231</td>
<td>MgO(100)&lt;001&gt;</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Cr</td>
<td>2.8839</td>
<td>2.8776</td>
<td>MgO(100)&lt;001&gt;</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Cr$_{95}$Mo$_5$</td>
<td>2.8976</td>
<td>2.8912</td>
<td>MgO (100)&lt;001&gt;</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Cr$<em>{90}$Mo$</em>{10}$</td>
<td>2.9152</td>
<td>2.9114</td>
<td>MgO(100)&lt;001&gt;</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>MgO</td>
<td>4.2112</td>
<td>4.2112</td>
<td>MgO(100)&lt;001&gt;</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
- $a_1$: Lattice constant of intermediate layer (grown on MgO single crystal substrate)
- $a_2$: Lattice constant of intermediate layer (grown on glass substrate)
- $\varepsilon$: Lattice mismatch
A critical lattice mismatch near to 6.33% was believed to be most suitable to improve the chemical ordering of FePt films.

$(I_{001}/I_{002})^{1/2}$ was used to represent the chemical ordering parameter in this study. $I_{001}$ and $I_{002}$ are the integrated peak intensities of the FePt (001) and (002) peaks respectively.
Low Temperature Growth of FePt on CrRu

Perpendicular anisotropic FePt with high $K_u$ and was successfully fabricated at temperature below 350° C, far below the 600° C phase transformation temperature to obtain $L_1_0$ phase of FePt by other methods.
Initial Layer Growth in FePt Perpendicular Media

• In perpendicular recording media, it has long been discovered that an initial growth layer or also known as nucleation layer or dead layer of low $M_s$ and low $K_u$
• Formed in the magnetic layer during the early film growth stage regardless of whether on top of an underlayer or on substrates.
• The formation of the initial growth layer was attributed to the poor easy axis orientation in the initial stage of the film growth
• The initial growth layer resulted in the decrease of measured $H_{c\perp}$ and $S$ of the magnetic film

Solution: Introduce buffer layer
The purpose of the buffer layer (immiscible with underlayer and recording layer) is to block diffusion from the underlayer and promotes heteroepitaxial growth of the $L1_0$ phase

2 nm Pt buffer was introduced between CrRu underlayer and FePt magnetic layer
Effect of Pt Buffer Layer on Crystallographic Properties

FePt on 2 nm Pt buffer layer  FePt on CrRu underlayer
Hysteresis Loops of FePt on Pt buffer layer and CrRu underlayer

FePt on 2 nm Pt buffer layer    FePt on CrRu underlayer
Evaluation of $t_{\text{initial}}$ by zero $M_s$ Method

<table>
<thead>
<tr>
<th>Segment, n</th>
<th>FePt film thickness from interface (nm), bottom up</th>
<th>$M_{s(n)}$ on CrRu underlayer</th>
<th>$M_{s(n)}$ on Pt buffer layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>10-20</td>
<td>533 emu/cc</td>
<td>732 emu/cc</td>
</tr>
<tr>
<td>3</td>
<td>5-10</td>
<td>556 emu/cc</td>
<td>602 emu/cc</td>
</tr>
<tr>
<td>2</td>
<td>3-5</td>
<td>442 emu/cc</td>
<td>599 emu/cc</td>
</tr>
<tr>
<td>1</td>
<td>$\leq$ 3</td>
<td>373 emu/cc</td>
<td>481 emu/cc</td>
</tr>
</tbody>
</table>

(a) without Pt buffer layer
$t_{\text{initial}} = 1.4 \text{ nm}$

(b) with Pt buffer layer
$t_{\text{initial}} = 0.8 \text{ nm}$
Evaluation of $t_{\text{initial}}$ by zero $K_u$ Method

It is very difficult to accurately determine the demagnetisation factor of the film.
Change of $M_s$ and $K_u$ over FePt film thickness

2 nm FePt on Pt buffer layer is soft magnetic
New intermediate layer?

1. The interface between FePt and Pt is sharper than that between FePt and CrRu.

2. The initial growth layer thickness estimated by $K_u$ model is larger than that estimated by $M_s$, suggesting that there were structural defects existing at the interface which resulted in small anisotropy. But $M_s$ does not change due to the structure defect.

3. In order to further reduce the initial growth layer thickness, new intermediate layer with suitable crystallographic structure, more difficult to diffuse, is required.

**Solution:** MgO was proposed as the buffer layer since sputter deposited MgO formed the (200) texture due to the lowest surface energy plane, and the MgO (200) texture can heteroepitaxially induce the fct-FePt (001) texture.
Advantages of MgO Buffer Layer

• Advantages of using MgO as buffer layer:
  – Immiscible with FePt recording layer and CrRu underlayer
  – Lattice relationship: MgO (100)<001> $\parallel$ FePt (001)<100>, mismatch of 8.66%. Lattice strain maintained

• Motivation:
  – To study interfacial effects of MgO layer on texture and magnetic properties of FePt as FePt fabrication is carried out at elevated temperature. Interface roughness is expected to change with temperature.

\[ a = 0.4214 \text{ nm} \]
• MgO layer appeared continuous
• MgO-FePt interface also well-defined
• MgO (200) and FePt (001) planes are parallel to the film plane
HRTEM image of 2 nm MgO deposited at 350 °C

- Island-like growth of MgO layer, rough interface
- FePt (111) and (001) oriented grains identified, defect
Magnetic properties (MgO deposited at 50 °C)

- (a) shows out-of-plane and in-plane loops of FePt film when MgO is 4 nm.
- Shows perpendicular anisotropy and increases with increasing MgO thickness.
- Isotropic magnetization when MgO is 1 nm
- Shows perpendicular anisotropy with increasing MgO thickness, from 4 nm
- $H_c$ higher than when MgO deposited at 50°C, due to defects
## Summary of effect of MgO deposition temperature and thickness on film properties

<table>
<thead>
<tr>
<th></th>
<th>50 °C</th>
<th>350 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;4nm</td>
<td>≥4nm</td>
</tr>
<tr>
<td>MgO layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>MgO-FePt Interface</td>
<td>Mostly smooth</td>
<td>Smooth</td>
</tr>
<tr>
<td>Dominant FePt texture</td>
<td>(001)</td>
<td>(001)</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>Perpendicular</td>
<td>Perpendicular</td>
</tr>
</tbody>
</table>
Reduction of Initial Growth Layer Thickness by MgO Buffer Layer

\[ M_s \times t_{FePt} (\times 10^3 \text{emu/cc} \times \text{nm}) \]

\[ t_{initial} = 0.6 \text{ nm} \]
XRD spectra of 12 nm FePt film deposited at various temperatures

- Dominant FePt (001) orientation even at 280°C
- FePt (001) integrated peak intensity increased with deposition temperature
- Slight shift of broad peak (45°-50°) to higher angle → increase in chemical ordering
Magnetic properties of 12 nm FePt film deposited at various temperatures

- Out-of-plane anisotropic even at 280°C
- Significant increase in $H_{ci}^\perp$ with increasing temperature to 400°C
Plan View TEM Images of FePt Doped with Carbon

(a) 20 nm

(b) 20 nm

- Normalized Kerr

- Applied Field (kOe)

- Grain size (nm)

- Ratio of grains

- Normalized Kerr

- Applied field (kOe)

- d = 9.88 nm
- Std. = 2.3 nm

- d = 5.57 nm
- Std. = 1.6 nm

- 10 vol.% C

- 20 vol.% C
TEM images of 5 to 30 nm thick FePt:C films (15 vol.% C) deposited at 350°C.

FePt:C grain growth observation: It confirms the proposed two-step growth model.
Microstructure of FePt+C on Pt buffer layer

Model proposed
Thin film growth modes

Layer by layer growth due to almost similar surface energy of Pt layer and FePt layer (2.9 J/m²)

How about oxide underlayer? MgO (1.1 J/m²)

Interface interaction between oxide and metal should be higher than between that of metal and metal
Microstructure of FePt+ x vol%C on MgO buffer layer

- Pure 20 nm
- FePt+C MgO CrRu 20% 10 nm
- FePt+C MgO CrRu 25% 10 nm

$M_{\text{prep}} / M_S$ vs. Applied field (kOe)

- 0% C
- 10% C
- 15% C
- 20% C
- 25% C
Columnar structure of FePt + x vol%C on MgO buffer layer

- 2-layer microstructure not favorable for recording application.
- Adatom mobility of Fe and Pt on substrate were reduced by increasing deposition rate and formed small grain size.
- Well-isolated FePt-C grains of size about 7.5 nm formed on MgO buffer layer.

Summary

• Lattice strain induced ordering aided in the reduction of FePt ordering temperature to 350°C and below

• Buffer layer based on oxide material (MgO) played an important role in lowering the deposition temperature while still keeping chemical ordering high

• Columnar structure of C doped FePt successfully fabricated