ECE 5320
Lecture #9
Nanoparticle vs. Magnetic Properties
Magnetic Anisotropy

\[ H_{ex} = -2 \sum_{i<j} J_{ij} \vec{S}_i \cdot \vec{S}_j - K \sum_i (S_{zi})^2 \]

Uniaxial Magnetic Anisotropy

Bulk Co in its demagnetized, multi-domain state

Minimization of magnetostatic energy

\[ U_B = \frac{1}{2 \mu_0} \int_B^2 d\tau \]

leads to domain wall formation

Anisotropy Field

\[ H_{an} = \frac{2K}{\mu_0 M_s} \]

Exchange energy per unit area of Bloch wall

\[ \sigma_{BW} = \pi \sqrt{AK} \quad \text{where} \quad A = \frac{2J_{ex}S^2}{a} \]

for a simple cubic lattice with lattice constant \( a \).
The hysteresis loop defines the technological properties of the magnetic material:

\[ M_s = \text{Saturation Magnetization} \]
\[ M_r = \text{Remnant Magnetization} \]
\[ H_c = \text{Coercivity} \]
Critical Size for SMD Particles

Magnetostatic vs. wall energy as a function of particle size for a spherical particle of radius $r$

$$R_C = R_{SMD} = \frac{6\sqrt{AK}}{\mu_0M_s^2}$$

Below $R_c$ the particle is a Single Magnetic Domain, and thus permanently magnetized. The demagnetized state cannot be formed.

$R_c \sim 100$ nm
Coercivity as a function of particle size

Nanomagnetism: Coercivities and Spin Reversal Mechanisms

Single-magnetic domain particle
Coherent spin rotation

Multi-magnetic domain structure
Magnetic wall movement

Nanoparticle
$K \approx 10^5 \text{ J/m}^3$

Bulk
$K \approx 10^3 \text{ J/m}^3$

Maximum coercivity
$H_c = \frac{2K}{\mu_0M_s}$

Particle Diameter $D$

$H_c$

$0$ $D_p$ $D_s$
Origin of magnetic anisotropy enhancement in nanoparticles

\[ K_{\text{eff}} = K_c + \frac{6K'_s}{D} \]

\[ K_{\text{eff}} = K_c + K_s + K_{\sigma} + K_{sh} \]

c = core
s = surface
\( \sigma \) = stress
\( sh \) = shape
Nanoparticle coercivity for coherent spin rotation (Stoner and Wohlfarth model)

Maximum coercivity for coherent spin rotation of a single magnetic domain particle with uniaxial total effective anisotropy

$$H_c = \frac{2K_u}{\mu_0 M_s}$$

Spin Dynamics in Magnetic Nanoparticles

Temperature dependence of coercivity

\[ H_c = \frac{2 K_u}{\mu_0 M_s} \left[ 1 - \left( \frac{25 kT}{K_u V} \right)^{1/2} \right] \]

(thermally assisted spin reversals)

Superparamagnetic relaxation time

\[ \tau = \tau_0 \exp \left( \frac{K_u V}{kT} \right) \]

Due to fast moment reversals at elevated temperatures the internal magnetic order of the particle escapes detection. You must either lower the temperature or use ultrafast measuring techniques that can record the moment before it flips.
Superparamagnetism of Small Magnetic Particles

Energy barrier
\[ \Delta E = KuV \]

where \( Ku \) is the effective uniaxial magnetic anisotropy
Energy density and \( V \) is the particle volume

Relaxation Time
\[ t_{RELAX} = t_0 \exp \left( \frac{KuV}{kT} \right) \]

Magnetocrystalline Anisotropy
Shape Anisotropy

Surface effects

Observe net magnetic moment when
\[ t_{MEAS} < t_{RELAX} \]
Micro-magnetics and Spin Dynamics

-Mössbauer spectroscopic measurements

Probe local magnetic moments and internal magnetic fields, with a response time of

$$\tau_m = \tau_{\text{Möss}} = 10 \text{ ns}$$

-DC Magnetization measurements

Probe global magnetic properties in an applied field, with a response time of

$$\tau_m = \tau_{\text{SQUID}} = 10 \text{ s}$$
Hysteresis Loops for CoFe$_2$O$_4$ Block Copolymers

Hysteresis due to particle moment rotation away from the particle’s easy axis to the direction of the applied magnetic field.

The temperature at which the coercivity vanishes defines the blocking temperature $T_B$ for SQUID magnetometry.

**Modeling Dynamical Spin Fluctuations in Isolated Nanostructures**

**Determination of Blocking Temperature**

Experimentally the temperature at which the Mössbauer spectra pass from magnetic, six-line spectra to paramagnetic or quadrupolar, two-line spectra defines $T_B$ for Mössbauer. Theoretically, $T_B$ is defined by:

$$
\tau_m = \tau_0 \exp \left( \frac{K_u V}{kT_B} \right) \rightarrow T_B = \frac{K_u V}{k \ell \ln(\tau_m / \tau_0)}
$$

**Spectrum Key**

**Magenta:** spectral signature of magnetic particle core (internal iron sites)

**Green:** spectral signature of surface layers (surface iron sites)

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Mössbauer spectra of lyophilized, *in vitro* reconstituted HoSF ferritin.

$T_B = 40 \text{ K}$
Zero-field cooled and field-cooled magnetization of lyophilized HoSF ferritin

25-nm thick protein shell

Note: Saturation magnetization is \( \sim 0.05 \) emu/g, weakly magnetic.
Determination of $K_u$ for an ensemble of superparamagnetic nanoparticles

\[ \tau = \tau_0 \exp\left(\frac{K_u \langle V \rangle}{kT}\right) \quad \rightarrow \quad \tau_m = \tau_0 \exp\left(\frac{K_u \langle V \rangle}{kT_B}\right) \]

1. Determine average particle volume $\langle V \rangle$ by TEM

2. Determine $T_B$ with two different techniques, whose measuring response times lie in different time windows

3. Use the Arrhenius equation above to determine $\tau_0$ and $K_u$
Surface Effects: Temperature Dependence of Mössbauer Magnetic Hyperfine Fields

Collective magnetic excitations below $T_B$

$$H_{hf}(T) = H_{hf}^0 \left( 1 - \frac{kT}{2K_{eff}V} \right)$$

S. Mørup and H. Topsøe, Appl. Phys. 11 (1976) 63
Mössbauer Spectra of $\gamma$-Fe$_2$O$_3$/Solid Silica Nanoarchitectures

Bare 12 nm particles

12 nm particles with 25 nm SiO$_2$ shell

Spectral Key: **Blue** A-sites, **Green** B-sites of spinel structure

Effect of silica shell on the RT Mössbauer Spectra

Behavior typical of strongly interacting particles

Bare $\gamma$-Fe$_2$O$_3$ nanoparticles

$\gamma$-Fe$_2$O$_3$ nanoparticles with 4 nm silica shell

$\gamma$-Fe$_2$O$_3$ nanoparticles with 25 nm silica shell

Magnetization of $\gamma$-Fe$_2$O$_3$/Solid Silica/Mesoporous Silica Nanoarchitectures

A-bare *
B-4 nm (S)
C-25 nm (S)
D-25 nm (S) + 10 nm (MS)
E-25 nm (S) + 21 nm (MS)

Typical behavior of strongly interacting magnetic nanoparticles, spin-glass-like systems.

* Bare particles are covered with a very thin layer ($\sim$1 nm) of oleic acid. Saturation magnetization of the order of $\sim$ 8 emu/g, strongly magnetic
Ferrihydrite is an *antiferro*-magnet. Magnetization of ferritin is due to uncompensated spins at the surface → Weak magnetism. Protein coat of only 2.5 nm thickness sufficient to magnetically isolate the ferritin iron cores

Maghemite is a *ferri*-magnet due to uncompensated spin sublattices in its spinel structure. In small particles uncompensated spins at the surface also contribute → Strong magnetism. Silica coat of 23 nm thickness insufficient to isolate the $\gamma\text{-Fe}_2\text{O}_3$ cores

Dipole-dipole interaction $\sim \frac{\vec{\mu}_1 \cdot \vec{\mu}_2}{r^3}$
Heat Assisted Magnetic Recording Media - Topics

Introduction
Magnetic Recording Media background and areal density projections
Chemically ordered $L1_0$ FePt media
Key media parameters and requirements
Microstructure
Magnetics
Status and ongoing efforts

Summary
Seagate HAMR Demo
1007 Gbpsi (1975 kbpi x 510 ktpi)

Demo Criteria
• Adjacent tracks written both sides at track pitch with the same laser power and pattern as data track
• On-track bit error rate = $10^{-2.0}$ with no correction/iterations

Limiting factors
• Head Media Spacing
  • much larger than state-of-the-art PMR
  • media roughness, coating thickness, head thermo-mechanical, and clearance management
• Media Distributions
  • distributions much larger than PMR
  • large effective gradient helps
• Electronic Noise
  Lower Mrt and high HMS

Successful 2012-2013 for HAMR

<2012>

In March Seagate announced a 1.0 TBPSI demonstration of HAMR on spin stand

Later in October, TDK announced a 1.5 TBPSI demonstrated on spin stand

Seagate CEO ran his annual investor relations talk off a HAMR drive in September

<2013>

October 2013, Japan
Argus HAMR drives were demonstrated in a Win7 computer at CEATEC 2013 Japan

Nov. 2013, Ninxbo China
WD demonstrated HAMR enabled 2.5” drive

http://www.youtube.com/watch?v=5BYHBV2PTx4
Ultimate Areal Density – HAMR + BPM

Mark H Kryder IEEE Houston, 03-08

updated by Steve Hwang 2012

Perpendicular Recording (to ~1 Tbpsi)

Heat Assisted Magnetic Recording (HAMR) to ~10 Tbpsi?

HAMR on Bit Patterned Media (to 50 Tbpsi?)

5?

10?
Nanostructured Disks Suppress Noise
Issue: Smaller grains require higher fields to write & maintain thermal stability

Smaller grains
“Lower” exchange
Tighter Distributions

Physical Grains <D>
Magnetic Clusters <D*>
Key Elements of HAMR Media Design

Good Microstructure

Well Defined Thermal Profile

Compared to CoCrPt alloys used in PMR, FePt L1_0 materials used for HAMR media offer:
- higher anisotropy \( \Rightarrow \) larger stability
- lower \( T_C \)
- larger \( dH_K/dT \)
- tunable by doping, e.g., with Ni or Cu

Magnetic & Distributions

HAMR vs PMR Media Loops

Steve Hwang
Seagate 2012
Media Design Constraints – “Trilemma”

Media SNR

\[ \text{SNR} \sim \log_{10}(N) \]

Small Grains (V)

Thermal Stability

\[
E_B \approx K_u V \left[ 1 - \frac{|H_d|}{H_0} \right]^2
\]

\[ K_u V = 40-80 \ \text{k}_B \text{T} \]

Writability

\[
H_0 = \alpha \frac{2K_u}{M_s} - N_{\text{eff}} M_s
\]

\[ H_0 < \text{Head Field} \]

We are now down to 6-10 grains per bit!

Smallest thermally stable grain size - details

\[ \tau = f_0^{-1} e^{\frac{E_B}{k_B T_S}} \]

\[ E_B = K V \left( 1 - \frac{4 \pi M_S}{H_K} \right)^2 \]

- \( f_0 \): attempt frequency \( \approx \alpha \gamma H_K \approx 10^9 - 10^{12} \text{Hz} \)
- \( E_B/k_B T_S = \ln (f_0 \tau) = r_K \approx 50 \) for \( \tau = 10 \text{ years} \)

\[ D_p = \left( \frac{2 \cdot r_K \cdot k_B T_S}{H_K M_S \left( 1 - \frac{4 \pi M_S}{H_K} \right)^2} \right)^n \]

- \( n = 1/2, k = 4/\pi \delta \) for cylinders
- \( n = 1/3, k = 1 \) for cubes
- \( n = 1/3, k = 6/\pi \) for spheres
- \( n = 1/3, k = 1/4 \) for prisms

HAMR media: high anisotropy, low Curie temp, small grains


<table>
<thead>
<tr>
<th>alloy system</th>
<th>material</th>
<th>$K_u$ (10^7 erg/cm^3)</th>
<th>$M_S$ (emu/cm^3)</th>
<th>$T = 350$ K</th>
<th>$H_K$ (kOe)</th>
<th>$T_C$ (K)</th>
<th>$D_p$ (a) (nm)</th>
<th>$D_p$ (b) (nm)</th>
<th>$D_p$ (c) (nm)</th>
<th>$D_p$ (d) (nm)</th>
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<tbody>
<tr>
<td>Co-alloys</td>
<td>CoCr$<em>3$Pt$</em>{2.2}$</td>
<td>0.7</td>
<td>500</td>
<td>28.0</td>
<td>1000$^a$</td>
<td>7.3</td>
<td>7.5</td>
<td>8.7</td>
<td>6.4</td>
<td></td>
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<tr>
<td></td>
<td>Co$_3$Pt</td>
<td>2</td>
<td>1100</td>
<td>36.4</td>
<td>1200</td>
<td>4.3</td>
<td>5.3</td>
<td>6.1</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CoPt$_3$</td>
<td>0.5</td>
<td>300</td>
<td>33.3</td>
<td>600</td>
<td>8.6</td>
<td>8.3</td>
<td>9.7</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>CoX/Pt(Pd)</td>
<td>Co$<em>3$/Pt$</em>{10}$</td>
<td>1.2</td>
<td>450</td>
<td>53.3</td>
<td>$\sim$700$^b$</td>
<td>5.5</td>
<td>6.2</td>
<td>7.2</td>
<td>5.4</td>
<td></td>
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<tr>
<td>multilayers</td>
<td>Co$<em>3$/Pd$</em>{10}$</td>
<td>0.6</td>
<td>360</td>
<td>33.3</td>
<td>$\sim$700$^b$</td>
<td>7.8</td>
<td>7.8</td>
<td>9.1</td>
<td>6.8</td>
<td></td>
</tr>
</tbody>
</table>

PMR

$\sim$10x higher $Ku$ “low” $Tc$ 2x smaller grain dia

<table>
<thead>
<tr>
<th>ordered phases</th>
<th>FePd</th>
<th>1.8</th>
<th>1100</th>
<th>32.7</th>
<th>760</th>
<th>4.5</th>
<th>5.4</th>
<th>6.3</th>
<th>4.7</th>
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<tbody>
<tr>
<td>Ld$_1$/Ld$_1$</td>
<td>FePt</td>
<td>7.0</td>
<td>1140</td>
<td>122.8</td>
<td>750</td>
<td>2.3</td>
<td>3.5</td>
<td>4.0</td>
<td>3.0</td>
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<td></td>
<td>CoPt</td>
<td>4.9</td>
<td>800</td>
<td>122.5</td>
<td>840</td>
<td>2.7</td>
<td>3.9</td>
<td>4.5</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>MnAl</td>
<td>1.7</td>
<td>560</td>
<td>60.7</td>
<td>650</td>
<td>4.7</td>
<td>5.5</td>
<td>6.4</td>
<td>4.8</td>
</tr>
</tbody>
</table>

HAMR

| rare-earth transition metals | Fe$_{14}$Nd$_2$B | 4.6 | 1270 | 72.4 | 585 | 2.8 | 4.0 | 4.6 | 3.4 |
|                             | SmCo$_5$       | 20  | 910  | 439.6 | 1000 | 1.4 | 2.4 | 2.8 | 2.1 |

$D_p$ is the average thermally stable grain diameter assuming $KV/k_BT = 60$ and $T = 350$ K, $k_B = 1.3807 \times 10^{-16}$ erg K$^{-1}$ and volumes (a) $V = \pi/4 \times D^2 \times 10 \text{ nm}$ (cylinders), (b) $V = D^3$ (cubes), (c) $V = 4/3 \times \pi \times (D/2)^3$ (spheres) and (d) $V = \pi/4 \times D^2 \times \delta$ (cylinders with $\delta/D = 2$). The thickness $\delta$ is 10 nm or larger in today’s media but will drop for smaller diameters going forward.

$^aT_C$ in today’s alloy media depends on the Cr and Pt content and has increased.

$^bT_C$ in multilayers strongly depends on the Co thickness.
Composition and growth temperature of $\text{Co}_{1-x}\text{Pt}_x$ alloys

25 at% Pt

400$^\circ$C

$S=0.5$

Narrowing Grain Size and Distribution

1990 LMR
← CoCrPt →
2000 LMR

10 Gbit/in²
product media
12 nm grains
σ_{area} ≈ 0.9
J. Li, et al.,

CURRENT

35 Gb/in²
prototype media
8.5 nm grains
σ_{area} ≈ 0.6
M. Doerner et al.,

2008 PMR

600 Gb/in²
prototype media
8.5 nm grains
σ_{area} ≈ 0.36
Tanahashi et al.
TMRC 2008

FUTURE

FePt
HAMR, SOMA

S. Sun et al.,

Nanoparticle arrays
4 nm particles
σ_{area} ≈ 0.05

Current PMR product densities of ~ 750 Gb/in² are extendable to ~1-1.3 Tb/in²
Future HAMR technology may start around 1-1.5 Tb/in²

Key: the number of grains per bit went down from 1000 to < 10
note: σ_{area} = 2x σ_{diameter}
Annealing leads to formation of ordered, high-K$_U$ ferromagnetic phase.

It also leads to particle agglomeration & disorder in the array.

**SOMA FePt Nanoparticles – fcc-fct phase transformation**

- Annealing at 600°C
- Oleic acid and oleyl amine stabilizers
- As-Deposited
- Annealed@530°C
- Annealed@650°C

**Chemically disordered**
- fcc structure
- Superparamagnetic

**Chemically ordered**
- fct structure
- Ferromagnetic

**A1**
- a/c = 1

**L1$_0$**
- a/c $\approx$ 0.96


HAMR

Next major technology for AD extendibility with minimal system impacts.

To record on this type of media we must first heat the media until it becomes writeable with conventional recording fields.
Seed layer for L1\textsubscript{0} order for FePt

**MgO** seed layer (5-20 nm)

- MgO: FCC rocksalt, \( a = 0.421\,\text{nm} \)
  - \( <001> \) orientation, 9% mismatch
- Others: CrRu, CrMo, TiN, TiC, Cr, Ag, Pt

Heat Sink / Plasmonic Underlayer: smooth

- Examples: Ag, Al, Cu, Cr, Au, NiAl, NiTa

**Adhesion layer**

- Example: NiTa

Hi T Glass up to 650\textdegree}C

**Heatsink/Plasmonic Underlayer (20-200 nm)**

- Heating 400-650\textdegree}C

**FePt + segregant X**

- Segregants promote grain isolation and define grain shape
- Carbon, SiO\textsubscript{2}, SiN\textsubscript{x}, B\textsubscript{2}O\textsubscript{3}
- other nitrides, oxides, carbides

**A1 – L1\textsubscript{0} chemical ordering transition**
“Early” FePt HAMR media microstructure – spherical grains

Granular FePtAg-C media grown at ~550°C 2011

Graphitic Sheets

- Used a new Lean 200 sputter tool w/ 20 chambers
- Low thickness δ ~ 7 nm and relatively high roughness
- Average grain size <D>~7.2 nm, grain pitch <P>~9 nm
- Grain aspect ratio δ/D~1
- Many small grains D<3 nm (thermally unstable)
Importance of Columnar Grains

Advantages of columnar grain growth:

- Decouple grain diameter from grain thickness.
- Thicker media will increase readback signal.
- Smoother surfaces and better flyability.
- Get laterally smaller, thermally-stable grains.
- Narrow distribution in optical absorption and consistent vertical heat flow from grain to grain.
- Enable functional layered structures.

DSI: Data Storage Institute, Singapore
K. Hono - Nat’l Institute of Materials Science Japan (NIMS)

Currently working on C and Y₂O₃ or Cr₂O₃ segregants to combine these 2 effects
FePt dual layer media with more cylindrical grains

Granular FePtX-C/Y media grown at ~620°C

- Higher thickness δ ~ 10 nm → improved read back signal
- Average grain size <D> ~ 6.3 nm, grain pitch ~ <P> ~ 7.3 nm
- Grain aspect ratio δ/D ~ 1.6
- Less grains with D < 3.5 nm
- Smoother surface
- BUT: “worse” grain size distribution

FePt triple layers w/ less smaller grains

Granular FePtX-Y media grown at ~640°C

\[ D_p \approx 8.5 \text{nm} \]
\[ \sigma_p = 28\% \]

\[ <P> = 8.55 \]
Width = 0.28

\[ \sigma_p = 28\% \]

\[ \approx 11 \text{ nm} \]
\[ \approx 5 \text{ nm} \]
Cluster size – 16.9 nm

\[ H_c = 3.6 \text{ T} \]
iSFD = 12.6 kOe
\[ H_{\text{external}} = 4.1 \text{ kOe} \]
Improved grain size distribution

Packing fraction = 68%
\[\langle D \rangle = 8.4 \text{ nm}, \quad \sigma_D = 0.18\]
\[\langle P \rangle = 10.0 \text{ nm}, \quad \sigma_P = 0.20\]

\[\delta/D \approx 1.5\]

- reduced amount of tiny grains
- significantly improved size distribution
HAMR media microstructure evolution

- small grains
- tight size distribution
- spherical grains
- low signal
- rough media

- larger grains
- tight size distribution
- more columnar grains
- increased signal
- reduced roughness

- smaller grains
- tight size distribution
- columnar grains
- further increased signal
- smoother surface
Minor Loop Analysis: Switching Field Distribution (300K) 2011

Small $eSFD \rightarrow$ small cluster size (14nm) $\rightarrow$
low exchange and magnetostatic interactions

Large $iSFD:$

$$\sigma_{int}^2 = \sigma_{vol}^2 + \sigma_{axis}^2 + \sigma_{HK}^2$$

$\sigma_{int} = 15$ kOe (VSM)

Grain volume distribution: $\sigma_{vol} = 3.7$ kOe
- from TEM grain size analysis

Grain texture distribution: $\sigma_{axis} = 6.6$ kOe
- from rocking curve width, XRD

Anisotropy distribution: $\sigma_{HK} = 12.9$ kOe
- from VSM, may arise from variations in $L1_0$ order, lattice strain & defects

Micromagnetic model needed to go beyond these estimates

What is $iSFD$ at the recording temperature, near $Tc$?

S. Pisana et al., Effects of grain microstructure on magnetic properties in FePtAg-C JAP 113, 043910 (2013)
Magnetic properties of “early” FePt-C samples


IFW Dresden

\[ H_C \sim 5T \quad H_K \sim 10T \quad M_S \sim 1040 \text{ emu/cm}^3 \text{ at } 290K \]
\[ K_U \sim 5.2 \times 10^7 \text{ erg/cm}^3 <D>=\text{nm grain diameter} \]


Radboud University, Nijmegen

\[ H_C \sim 5T \quad H_K \sim 10T \quad M_S \sim 950 \text{ emu/cm}^3 \text{ at } 290K \]
\[ K_U \sim 4.8 \times 10^7 \text{ erg/cm}^3 \]
\[ H_C = 8.2T \text{ at } 4.2K \]
\[ \alpha \sim 0.1 \text{ damping parameter in FMR} \]
Modified deposition parameters result in suppression of very small grains and reduced noise in recorded media.

Quantifying amount of in-plane easy axis grains with XRD and VSM

**OOP XRD**

- FePt 001
- FePt 002
- FePt 200

**IP XRD**

- FePt 001
- FePt 110

**Norm. Magn. vs Field (kOe)**

- Older media: Mr/Ms = 93%
- Improved media: Mr/Ms = 89%

**Intensity (cps) vs 2θ (degrees)**

- Older media: 200 / (002+200) ~ 5.7%
- Improved media: 200 / (002+200) ~ 1.9%
Chemical ordering $S$ and Curie temperature $T_C$ vs grain size

**Experiments**


**Experiments and Modeling**

H. M. Lu, et al. 2008: Nanjing, China JAP103,123526

**Recent Modeling by Seagate and HGST**


Effect of grain size and aspect ratio on $T_C$ - Modeling

Finite size scaling theory \[
T_c(D) = T_c(\infty)\left(1 - x_o D^{-1/\nu}\right)
\]

$v \approx 0.7 \pm 0.09$

- $T_C$ smaller than 750 K due to exchange truncation/abandonment in single particle modeling
- Cylindrical grains with an aspect ratio of $\sim 2$ reduce $x_o$ by $\sim 20\%$, i.e. “minimize” the grain size induced reduction of $T_C$
- $v=0.7+/−0.09$ is compatible with 3D Ising/Heisenberg models
- $T_c$ determined from peak susceptibility $\chi(T)$ using Monte Carlo method

Variations in $T_c$ arise from the dispersion in grain size and chemical order.

Recording performance is highly sensitive to $T_c$ and $H_K$ distributions.

Reducing $D$ increases $\sigma_{T_c}/T_C$ from $\sim 1\%$ ($D=8\text{nm}$) to $\sim 2.5\%$ ($D=4\text{nm}$).

A. Lyberatos, et al, “Memory erasure and write field requirements in HAMR using L1$_0$-FePt nanoparticles” (2014)
HAMR Media Design Challenges

Structure-Property Relationships

- DC Noise is still high in HAMR media
- Origin is likely caused by defected media grains
- Need to quantify problem...

Aug 12, 2014

Ramamurthy Acharya
Western Digital, 1710 Automation Parkway, San Jose, CA 95131

Contribution:
Starting to count individual atoms …

At ~3 nm diameter particles have 25-30% atoms on surface! Properties change as a result of that!

Oleg Mryasov, 2003 (Seagate)
Particle Size Effects: 3d(Fe,Co)-5d/4d(Pt/Pd) High Anisotropy Alloys

Curie Temperature Reduction

Anisotropy Energy Reduction

Surface to volume fraction increases to 20-40% for 3 nm FePt particles (1000 atoms)

\[ d_{ij}^{(2)} = \frac{k_{Pt}^{(0)}}{[J_{\mu}^{0}]^2} \sum_{\mu} J_{i\mu}^{Fe-Pt} J_{j\mu}^{Fe-Pt} \]

Finite size effects due to interactions mediated by induced Pt magnetic moment

Strong dependence of $T_C$ on chemical ordering $A1 \rightarrow L1_0$ ($\Delta T_C = 165K$)

Forming ternary alloys to improve ordering

FePtCu

(FePt)$_{1-x}$Cu$_x$

Three Mixed Phase

Two Mixed Phase

L1$_0$

L1$_2$

A2

A1

Fe

Pt


UC Davis – Seagate
Composition dependence in Fe$_x$Pt$_{1-x}$–C and Fe$_x$Cu$_y$Pt$_z$

**Optimal values of coercivity and anisotropy at x=50%**

Curie temperature reduction to 600-650K by adding 9-13at% Cu


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**Granular**

Hc, Hk (kOe)

Fraction of Fe Content

Ms

Core Ms (emu/cc)

**Continuous**

M/M$_{300K}$

T (K)

T$_C$~730K

Optimal values of coercivity and anisotropy at x=50%

Curie temperature reduction to 600-650K by adding 9-13at% Cu
Grain Size and Microstructure from CoCrPt PMR to FePt HAMR 2013

Typical PMR  
HAMR Media  
HAMR: more Voronoi and columnar

Improved Grain Size (Pitch) & Distributions

- Typical PMR: $\langle P \rangle = 9.29 \text{ nm}$, $\sigma = 0.22$
- HAMR Media: $\langle P \rangle = 8.70 \text{ nm}$, $\sigma = 0.24$
- HAMR: more Voronoi and columnar, $\langle P \rangle = 7.36 \text{ nm}$, $\sigma = 0.24$