High Magnetic Anisotropy Materials

Takao Suzuki
MINT Center
Contents

1. Introduction
2. Origin of Magnetic Anisotropy
3. High Magnetic Anisotropy Materials
4. $L1_0$ FePt
5. $m$-$DO_{19}$ (Co-Ni)$_3$Pt
6. $m$-$DO_{19}$ Fe$_3$Pt
7. Low Temperature Phase (LTP) MnBi
8. Summary
### Magnetic Materials

**Dynamic**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\text{erg/cc}}$</td>
<td>$10^2$ to $10^3$</td>
</tr>
<tr>
<td>$H_k, H_c$ (Oe)</td>
<td>1</td>
</tr>
</tbody>
</table>

**Static**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\text{erg/cc}}$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$H_k, H_c$ (Oe)</td>
<td>1,000</td>
</tr>
</tbody>
</table>

**Sensor Data Storage Magnet**

- Ni$_3$Fe, Fe$_3$Al, Fe$_3$NiMo
- a-CoFeSiB
- a-TbFeCo, CoCrPt, FePt, NdFeB, SmFeN, SmCo$_5$

**Magnetic Materials**

- Sensor
- Data Storage
- Magnet
$H_k \approx \frac{2K}{M_s} > H_c$

$H_k$: Magnetic Anisotropy Field
$K$: Magnetic Anisotropy Constant
$M_s$: Saturation Magnetization
$H_c$: Coercivity
# High Magnetic Anisotropy Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$K$ (MJ/m³)</th>
<th>$M_s$ (MA/m)</th>
<th>$H_k$ (T)</th>
<th>$T_c$ (K)</th>
<th>$(BH)_{max}$ (MGOe)</th>
<th>$\kappa$ ((K/µM²)¹/²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SmCo₅</td>
<td>17.2</td>
<td>0.9</td>
<td>38</td>
<td>1020</td>
<td>19</td>
<td>4.3</td>
</tr>
<tr>
<td>Sm₂Fe₁₇N₃₃</td>
<td>8.6</td>
<td>1</td>
<td>17</td>
<td>749</td>
<td>45</td>
<td>2.1</td>
</tr>
<tr>
<td>FePt</td>
<td>6.6</td>
<td>1.1</td>
<td>12</td>
<td>750</td>
<td>40</td>
<td>2.0</td>
</tr>
<tr>
<td>CoPt</td>
<td>4.9</td>
<td>0.8</td>
<td>12</td>
<td>840</td>
<td>25</td>
<td>2.5</td>
</tr>
<tr>
<td>Nd₂Fe₁₄B</td>
<td>4.9</td>
<td>1.3</td>
<td>7.5</td>
<td>588</td>
<td>60</td>
<td>1.5</td>
</tr>
<tr>
<td>Sm₂Co₁₇</td>
<td>4.2</td>
<td>1</td>
<td>8.4</td>
<td>838</td>
<td>28</td>
<td>1.9</td>
</tr>
<tr>
<td>MnBi</td>
<td>2</td>
<td>0.6</td>
<td>6.7</td>
<td>633</td>
<td>15</td>
<td>4.5</td>
</tr>
<tr>
<td>Fe₃Pt</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>640</td>
<td>15</td>
<td>4.0</td>
</tr>
<tr>
<td>MnAl</td>
<td>1</td>
<td>0.7</td>
<td>2.9</td>
<td>653</td>
<td>10</td>
<td>1.2</td>
</tr>
<tr>
<td>MnGa</td>
<td>1</td>
<td>0.3</td>
<td>6.7</td>
<td>500</td>
<td>10</td>
<td>3.6</td>
</tr>
<tr>
<td>Co</td>
<td>0.7</td>
<td>1.4</td>
<td>1</td>
<td>1400</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Alnico5</td>
<td>0.7</td>
<td>1.1</td>
<td>1.3</td>
<td>1210</td>
<td>5</td>
<td>0.7</td>
</tr>
<tr>
<td>Fe₅₀Ni₅₀</td>
<td>0.6</td>
<td>1</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
</tr>
<tr>
<td>BaFe₁₂O₁₉</td>
<td>0.3</td>
<td>0.4</td>
<td>1.5</td>
<td>740</td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td>MnSb</td>
<td>0.1</td>
<td>0.8</td>
<td>0.3</td>
<td>573</td>
<td>-</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Brown’s Coercivity Paradox
(Rev.Mod.Phys.1945)

The ratio $H_c^{\text{exp}}/H_N$ of permanent magnets developed the last seven decades.

$H_c^{\text{exp}}/H_N$

- Laboratory pms
- Technical pms

MnBi

Courtesy: Kronmuller and Goll
Magnetic Anisotropy

2. Magnitude

$K_1$ (Ni): $4 \times 10^4$ erg/cc  (0.2 $\mu$eV/atom)
$K_1$ (Fe): $5 \times 10^5$ erg/cc  (2 $\mu$eV/atom)
$K_{u1}$ (Co): $5 \times 10^6$ erg/cc  (20 $\mu$eV/atom)
$K$ (Tb, Dy): order of $10^{7-8}$ erg/cc  (0.1 – 1 meV/atom)

<< Binding energy (1 - 10 eV/atom),
Exchange energy (10 – $10^3$ meV/atom)
1 kA/m = 1 emu/cm³
1 kA/m = 12.57 Oe

Magnetic anisotropy K = \( \frac{1}{2} \) \( M_s \times H_s \) = \( \frac{1}{2} \) \( (1,400 \text{ emu/cc} \times 6.5\text{kOe}) \) = \( 5 \times 10^6 \text{ erg/cc} \)
1. Magnetic Anisotropy

Phenomenological expression

**Hexagonal:** \[ E_a = K_1 \sin^2 \theta + K_2 \sin^4 \theta + K_3 \sin^6 \theta + K'_3 \sin^6 \theta \sin 6\phi, \]

**Tetragonal:** \[ E_a = K_1 \sin^2 \theta + K_2 \sin^4 \theta + K'_2 \sin^4 \theta \cos 4\phi + K_3 \sin^6 \theta + K'_3 \sin^6 \theta \sin 4\phi, \]

**Cubic:** \[ E_a = K_{1c} (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) + K_{2c} (\alpha_1^2 \alpha_2^2 \alpha_3^2), \]
Contents

1. Introduction
2. Origin of Magnetic Anisotropy
3. High Magnetic Anisotropy Materials
4. $L1_0$ FePt
5. $m$-$DO_{19}$ (CoNi)$_3$Pt
6. $m$-$DO_{19}$ Fe$_3$Pt
7. Low Temperature Phase (LTP) MnBi
8. Summary
2. Origin of Magnetic Anisotropy

- Magneto-crystalline Anisotropy (Intrinsic)
- Induced Magnetic Anisotropy (Extrinsic)
  - Atomic Pair Model
  - Stress-induced Magnetic Anisotropy through magneto-elastic coupling
  - Interface/surface Magnetic Anisotropy
  - Shape Magnetic Anisotropy
  - Exchange Biased Unidirectional Magnetic Anisotropy
Magnetic Anisotropy
Magneto-crystalline Anisotropy

3d elements
Fe, Ni, Co

RE elements
Tb, Dy, Nd

Mn does not possess a large spin-orbit coupling!

But MnBi, MnAl, MnGa... with high K!

High anisotropy due to the asymmetrical 4f shells that lead to a large spin-orbit coupling.
K~ M(s)^{10} (1954, Zener)
K~ M(s)^{4-8} (1958, Graham)
\[ \frac{\kappa_l(T)}{\kappa_l(0)} = \left[ \frac{m(T)}{m(0)} \right]^{(l+1)2} \]

\( \ell \): the order of polynomial function of \( S \)

H. Callen and E. Callen (1957).


**Fig. 3.** Temperature variation of the first anisotropy constant, \( K_1 \), of YIG. The magnetization has been eliminated by means of the analysis due to Wolf (Ref. 27 shown in Fig. 2, and calculated sublattice magnetizations. There are two adjustable phenomenological parameter in the theory. Figure from Ref. 28.
Ni

\[
\frac{K_1(T)}{K_1(0)} = \left(1 - 1.74 \frac{T}{T_c}\right) \left[\frac{M(T)}{M(0)}\right]^{10}
\]

H. Callen and E. Callen (1957).
Fig. 3. (a) Temperature dependence of $K_{u_1}$ and $K_{u_2}$, together with the data of Honda et al.\textsuperscript{1)} and Sucksmith et al.\textsuperscript{2)}
(b) The direction of the easy axis $\theta$ from the $c$-axis. ---: obtained from eq. (1); ---: obtained from the torque curves.

Nd$_2$Fe$_{14}$B

FIG. 3. Temperature dependencies of the magnetocrystalline anisotropy constants $K_1$, $K_2$, and $K_3$.

Gd

Temperature dependence of K is very complicated!

図 12.16 (a) Gd の結晶磁気異方性定数の温度変化
(b) Gd の容易方向の温度変化
Contents

1. Introduction
2. Origin of Magnetic Anisotropy
3. High Magnetic Anisotropy Materials
4. $L1_0$ FePt
5. $m$-DO$_{19}$ (CoNi)$_3$Pt
6. $m$-DO$_{19}$ Fe$_3$Pt
7. Low Temperature Phase (LTP) MnBi
8. Summary
# High Magnetic Anisotropy Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$K$ (MJ/m$^3$)</th>
<th>$M_s$ (MA/m)</th>
<th>$H_k$ (T)</th>
<th>$T_c$ (K)</th>
<th>$(BH)_{\text{max}}$ (MGOe)</th>
<th>$\kappa$ ((K/$\mu$M$^2$)$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SmCo$_5$</td>
<td>17.2</td>
<td>0.9</td>
<td>38</td>
<td>1020</td>
<td>19</td>
<td>4.3</td>
</tr>
<tr>
<td>Sm$<em>2$Fe$</em>{17}$N$_3$</td>
<td>8.6</td>
<td>1</td>
<td>17</td>
<td>749</td>
<td>45</td>
<td>2.1</td>
</tr>
<tr>
<td>FePt</td>
<td>6.6</td>
<td>1.1</td>
<td>12</td>
<td>750</td>
<td>40</td>
<td>2.0</td>
</tr>
<tr>
<td>CoPt</td>
<td>4.9</td>
<td>0.8</td>
<td>12</td>
<td>840</td>
<td>25</td>
<td>2.5</td>
</tr>
<tr>
<td>Nd$<em>2$Fe$</em>{14}$B</td>
<td>4.9</td>
<td>1.3</td>
<td>7.5</td>
<td>588</td>
<td>60</td>
<td>1.5</td>
</tr>
<tr>
<td>Sm$<em>2$Co$</em>{17}$</td>
<td>4.2</td>
<td>1</td>
<td>8.4</td>
<td>838</td>
<td>28</td>
<td>1.9</td>
</tr>
<tr>
<td>MnBi</td>
<td>2</td>
<td>0.6</td>
<td>6.7</td>
<td>633</td>
<td>15</td>
<td>4.5</td>
</tr>
<tr>
<td>Fe$_3$Pt</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>640</td>
<td>15</td>
<td>4.0</td>
</tr>
<tr>
<td>MnAl</td>
<td>1</td>
<td>0.7</td>
<td>2.9</td>
<td>653</td>
<td>10</td>
<td>1.2</td>
</tr>
<tr>
<td>MnGa</td>
<td>1</td>
<td>0.3</td>
<td>6.7</td>
<td>500</td>
<td>10</td>
<td>3.6</td>
</tr>
<tr>
<td>Co</td>
<td>0.7</td>
<td>1.4</td>
<td>1</td>
<td>1400</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Alnico5</td>
<td>0.7</td>
<td>1.1</td>
<td>1.3</td>
<td>1210</td>
<td>5</td>
<td>0.7</td>
</tr>
<tr>
<td>Fe$<em>{50}$Ni$</em>{50}$</td>
<td>0.6</td>
<td>1</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
</tr>
<tr>
<td>BaFe$<em>{12}$O$</em>{19}$</td>
<td>0.3</td>
<td>0.4</td>
<td>1.5</td>
<td>740</td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td>MnSb</td>
<td>0.1</td>
<td>0.8</td>
<td>0.3</td>
<td>573</td>
<td>-</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Bistable Magnetic MEMS Switch

Microlab, Inc.

- Permalloy beam aligns with external permanent H field
- Clockwise or counter-clockwise tilting depends on magnetization of the beam
- A coil (20 turns) is placed under the beam and a current pulse generates a momentary H field to change the magnetization orientation and thus flip the switch
- Only a short current pulse is needed and no hold-down power is needed → Low Power
- Actuation current/voltage: 80-120 mA/5-6 V
- Switch time: 0.4 ms

Ruan et al, MEMS 2001
High Magnetic Anisotropy Materials

![Graph showing magnetic anisotropy materials comparison](image)
Contents

1. Introduction
2. Origin of Magnetic Anisotropy
3. High Magnetic Anisotropy Materials
4. $L1_0$ FePt
5. $m$-$DO_{19}$ (CoNi)$_3$Pt
6. $m$-$DO_{19}$ Fe$_3$Pt
7. Low Temperature Phase (LTP) MnBi
8. MnRh
9. Summary
High Magnetic Anisotropy Materials

![Graph showing magnetic anisotropy materials]

- SmCo5
- Sm2Fe17
- FePt
- CoPt
- Nd2Fe14B
- Sm2Co17
- MnBi
- Fe3Pt
- MnAl
- MnGa
- Co
- Alnico5
- Fe50Ni50
- BaFe12019
- MnSb

Legend:
- $K(MJ/m) \times 4$
- $Hk(T)$
- $\kappa (\sqrt{\kappa/\mu} M^2 x10)$

MINT Seminar (2/6/2015)
$L1_0$(fct)

Fe-Pt

Co-Pt

Ni-Pt

MINT Seminar (2/6/2015)
Magnetic Anisotropy of L1₀ Ordered Films

H. Kanazawa & T. Suzuki (2001)

MINT Seminar (2/6/2015)
Contents

1. Introduction
2. Origin of Magnetic Anisotropy
3. High Magnetic Anisotropy Materials
4. $L1_0$ FePt
5. $m$-$DO_{19}$ $(CoNi)_3Pt$
6. $m$-$DO_{19}$ $Fe_3Pt$
7. Low Temperature Phase (LTP) MnBi
8. Summary
Co\textsubscript{3}Pt, Ni\textsubscript{3}Pt, Fe-Pt, FePt, FePt\textsubscript{3}, Co-Pt, Ni-Pt

L\textsubscript{12}, m-DO\textsubscript{19} (Pmm\textsubscript{2}), DO\textsubscript{19}

No equilibrium phase in bulk

MINT Seminar (2/6/2015)
Cross-section view of a $\text{Co}_3\text{Pt}$ film
Dependence of Magnetic anisotropy on (c/a)

Substrate: Al₂O₃(00•1)
Thickness: 500 +

Electronic structure calculations of hexagonal and cubic phases of Co$_3$Pt

S. D. Willoughby, R. A. Stern, R. Duplessis, and J. M. MacLaren
Department of Physics, Tulane University, New Orleans, Louisiana 70118

M. E. McHenry and D. E. Laughlin
Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

(Presented on 13 November 2002)

Using first principles electronic structure calculations we investigated structural and magnetic properties of three distinct phases of Co$_3$Pt. Relaxed lattice constants, total energies, magnetocrystalline anisotropies, and density of states were calculated for each phase at their equilibrium lattice constants, as well as under expansion and contraction stresses. These computations may help clarify the results of some recent but ambiguous experiments on Co$_3$Pt.


### TABLE II. Calculated values of magnetocrystalline anisotropy ($\times 10^6$ erg/cm$^3$).

<table>
<thead>
<tr>
<th>Phase</th>
<th>LKKR</th>
<th>Néel model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pmm2</td>
<td>28.27</td>
<td>17.14</td>
</tr>
<tr>
<td>DO$_{19}$</td>
<td>-28.48</td>
<td>-20.94</td>
</tr>
<tr>
<td>disordered</td>
<td>-39.12</td>
<td>-1.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Co–Co interaction</th>
<th>Co–Pt interaction</th>
<th>General expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>$L_2$</td>
<td>$\text{Pmm2}: 0.445<em>L_1 - 1.055</em>L_2$</td>
</tr>
<tr>
<td>-30</td>
<td>-31</td>
<td>$\text{DO}_{19}: -0.897L_1 + 1.63*L_2$</td>
</tr>
</tbody>
</table>
Fe-Pt

Fe₃Pt

Co-Pt

CoPt, CoPt₃

Ni-Pt

NiPt

L₁₂

m-DO₁₉ (Pmm2)

DO₁₉

MINT Seminar (2/6/2015)
Bulk Magnetic Property of Fe$_3$Pt

- Ferromagnetic
- $T_c = 430$ K
- $M_s (4.2 \text{ K}) = 1538$ (75 at%Fe) - ordered phase
  1495 (72 at%Fe) - disordered phase
- $2.13 \sim 2.17 \mu_B$

- $\chi = 1.0 \times 10^{-4}$ emu/cc (ordered)
  $1.5 \times 10^{-4}$ emu/cc (disordered)

- $K : < 10^3$ erg/cc (300 K)
- Very high volume magnetostriction $\omega = 1.7 \times 10^{-2}$ (ordered)
- Invar Property
X-ray diffraction of Fe₃Pt films

E-Beam Evaporation
Deposition rate: 0.1A/s
Thickness: 500 Å
Sub. Dep. Temp: 400 °C
Fe₃Pt/MgO(111)

X-ray
Sample
ϕ
DET.

φ-scan

MgO (111) Fe₃Pt (111)

ambient

250 °C

300 °C

350 °C

400 °C

450 °C

500 °C

550 °C

Intensity (a.u.)

2θ

ω (deg) Φ (deg)

Ts-ambient <220>

(111) (220)

Intensity (a.u.)

2.0° 3.4°

MINT Seminar (2/6/2015)
Magnetic Anisotropy of Fe$_3$Pt alloy thin films

Fe$_3$Pt/MgO(100), Fe$_3$Pt/MgO(111)

\[ K_1 = -4 \times 10^6 \text{ erg/cc}, \quad K_2 = 2 \times 10^7 \text{ erg/cc} \]

Magnetic anisotropy energy in Cub

\[ E = K_1 (\alpha_1^2 \alpha_2^2 \alpha_3^2) + K_2 (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) + \ldots \]

Magnetic anisotropy constants of Fe\(_3\)Pt/MgO

- \( K_1 = -4 \times 10^6 \) erg/cc
- \( K_2 = 2 \times 10^7 \) erg/cc

\(<110>\) is the easy axis, since those \( K_1 \) and \( K_2 \) fulfill the condition

\[ K_2 > -\frac{9}{4}K_1 \]
L vs. $K_1$, $K_2$ for Fe$_3$Pt

|K_1| (10$^6$ erg/cc) vs. L (Å) for Fe$_3$Pt

$L = \sqrt{\left(\frac{a}{2}\right)^2 + \left(\frac{c}{2}\right)^2}$

(L: between atoms in basal plan and neighbors above and below)

$m\text{-DO}_{19}$ ($Pmm2$)

2.66 2.67 2.68

$m\text{INT Seminar (2/6/2015)}$
Phase stability criteria for cubic and orthorhombic Fe$_3$Pt and Fe$_3$Pd

R. R. Duplessis, a) R. A. Stern, and J. M. MacLaren

Department of Physics, Tulane University, New Orleans, Louisiana 70118

(Presented on 6 January 2004)

Using first-principles methods, we have calculated structural and magnetic properties of face-centered (L1$_2$) and orthorhombic (Pmm2, DO$_{19}$) phases of Fe$_3$Pt and Fe$_3$Pd. For both alloys, the L1$_2$ cubic phase was determined to be the ground state. Unlike the related Co$_3$Pt alloy, the Pmm2 phase cannot be artificially stabilized by controlling, that is, slightly increasing or decreasing, the basal lattice constant (by growing the samples on an appropriate substrate). © 2004 American Institute of Physics. [DOI: 10.1063/1.1652422]

Fig. 2 shows that the Pmm2 phase is not likely to occur for either Fe$_3$Pd or Fe$_3$Pt for any reasonable basal plane lattice expansion that could be achieved by growing on a suitably chosen substrate.

In-plane MCA for the Pmm2 phase of Fe$_3$Pt and Fe$_3$Pd were calculated to be 4.9×10$^7$ ergs/cm$^3$ for Fe$_3$Pt and in-plane anisotropy of 4.1×10$^6$ ergs/cm$^3$ for Fe$_3$Pd. The

![Graph showing energy difference between cubic and Pmm2 phases vs percent compression/expansion for Fe$_3$Pt and Fe$_3$Pd.](image)

FIG. 2. Total energy difference between cubic and Pmm2 phases vs % compression/expansion for Fe$_3$Pt and Fe$_3$Pd.
Contents

1. Introduction
2. Origin of Magnetic Anisotropy
3. High Magnetic Anisotropy Materials
4. $L1_0$ FePt
5. $m$-$DO_{19}$ (CoNi)$_3$Pt
6. $m$-$DO_{19}$ Fe$_3$Pt
7. Low Temperature Phase (LTP) MnBi
8. Summary
MnBi

HTP & LTP: $P6_3/mmc$
$(a=4.29\,\text{Å}, c=6.12\,\text{Å}, c/a=1.42)$

QHTP: $P222_1$ (distorted $P6_3/mmc$)
$(a=4.34\,\text{Å}, c=5.97\,\text{Å}, c/a=1.37)$

T. Chen and W. E. Stutius:
LTP MnBi Thin Films

SiO₂ /{Bi(3.2nm)/Mn(2nm)} x 10 / Ru (c-axis oriented film)
3-1 Temperature dependence of magnetic anisotropy

![Graph showing temperature dependence of magnetic anisotropy constant](image)
MnBi

Correlation between K and Ms

First empirical relation!
1. Introduction
2. Origin of Magnetic Anisotropy
3. High Magnetic Anisotropy Materials
4. $L1_0$ FePt
5. $m$-$DO_{19} (\text{CoNi})_3\text{Pt}$
6. $m$-$DO_{19} \text{Fe}_3\text{Pt}$
7. Low Temperature Phase (LTP) MnBi
8. Summary
New materials?

• Stabilization of meta-stable phases
  <--- Manipulation of atomic distance, (c/a)
  for example: \( m-DO_{19}Co_3Pt \), \( m-DO_{19}Fe_3Pt \)
Uniaxial anisotropy constant $K_u$ for (a) $c/a=1.25$ and (b) $c/a=1.15$ as a function of Co content $x$. Open circles represent calculated with CPA (coherent potential approximation) and closed squares do with VCA (virtual potential approximation).

**L1₀ FeNi**

**Fig. 1** Dependence of MAE on the lattice distortion as a function of $c/a$ ratio. Filled circles are obtained by the calculation, and open square notes the measured data⁶)

Measured: $C=3.607Å$, $a=3.582Å$ ($c/a=1.007$)


---

**Fig. 1** Growth temperature dependence of uniaxial magnetic anisotropy of L1₀ type FeNi thin films.
Co$_x$C ($x = 2 \sim 3$) Particles

$M_s = 72$ emu/g at 300K
$H_c = 3.1$ kOe
$(BH)_{max} = 20.7$ kJ/m$^3$

**Figure 5.** Room temperature hysteresis loop of representative sample having $M_s$ of 73 emu g$^{-1}$ and an $H_c$ of 3.1 kOe. The $(BH)_{max}$ is 20.7 kJ m$^{-3}$.

$(BH)_{max} = 20$ kJ/m$^3$