Temperature Dependence of Coercivity and Magnetic Reversal in SmCo$_x$ Thin Films

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Purpose of Work

1) Look at thickness dependence of permanent properties of SmCo$_5$

2) Determine the best preparation/treatment route to obtain strongly exchange coupled SmCo$_5$ – Co two-phase films

Previous work by us on this material:
Structure of Sm-Co

SmCo$_5$ (hexagonal)

Sm$_2$Co$_{17}$ (rhombohedral)

Exchange-Spring Magnet

Hard Phase + Soft Phase
(nanostructured)

Small crystallite size
→ high coercivity

Large interface area
→ SmCo and Co coupled.


<table>
<thead>
<tr>
<th>Properties of phases</th>
<th>K ergs/g</th>
<th>M emu/g</th>
<th>Tc °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SmCo5</td>
<td>1x10^8</td>
<td>105</td>
<td>685</td>
</tr>
<tr>
<td>Sm2Co17</td>
<td>3x10^7</td>
<td>126</td>
<td>810</td>
</tr>
<tr>
<td>Co</td>
<td>3x10^7</td>
<td>162</td>
<td>1115</td>
</tr>
</tbody>
</table>
Sm-Co studies

For SmCo$_5$: Vary thickness (d = 60 nm → 500 nm)
- homogeneous SmCo$_5$
- do permanent magnetic properties depend on thickness?

For SmCo$_x$, x ≥ 5 (d ~500 nm): Two starting geometries
- multilayers and homogeneous SmCo$_x$
- vary Co content to improve of energy product
Sample Preparation ($\text{SmCo}_5$)

for thickness dependence

Homogeneous

$\text{Nb}$

$\text{d nm}$

$\text{SmCo}_5$

$\text{Si subst}$

$\text{d} = 6 - 540 \text{ nm}$

Anneal to crystallize Sm-Co

Vacuum anneal (20 minutes)

Or

Rapid thermal anneal (30 seconds)
Sample Preparation ($\text{SmCo}_x$)

Homogeneous

$\begin{align*}
\text{Nb} & \quad \text{SmCo}_x \\
\text{Si subst.} & \\
\end{align*}$

$500 \text{ nm}$

$x: 5 \to 25$

Anneal to crystallize Sm-Co

Vacuum anneal (20 minutes)

Or

Rapid thermal anneal (30 seconds)

Multilayer

$\begin{align*}
\text{Nb} & \quad \text{SmCo}_5(23 \text{ nm}) \\
\text{Co}(y \text{ nm}) & \\
\text{Si subst.} & \\
\end{align*}$

$y: 0 \to 20 \text{ nm}$

equivalent to $x: 5 \to 12.3$

compare properties
Sputter Deposition

Homogeneous SmCo$_5$:
Sputter directly from a SmCo$_5$ target

Multilayers of SmCo$_5$/Co:
Si substrate switched between SmCo and Co sputter guns

Homogeneous SmCo$_x$:
Add pieces of Co to SmCo$_5$ target
Sputter target: $\text{SmCo}_{12}(\text{Fe},\text{Cu},\text{Zr})$
X-ray diffractograms for the 540 nm initially homogeneous SmCo$_5$ sample

SmCo$_5$ films - SmCo$_5$ and trace of elemental Co phases identified

SmCo$_x$ films - SmCo$_5$ and elemental Co phases identified

Texture – No significant texture found

Grain size – 12 → 25 nm
Structure of annealed homogeneous films - Nb/SmCo$_x$/Nb

x = 12
(700ºC, 30 sec)

x = 7.5
(550ºC, 20 min)

x = 5
(750ºC, 30 sec)

- Sm$_2$Co$_{17}$
- Co
- SmCo$_5$
Magnetization isotherms at selected measurement temperatures for an initially homogeneous SmCo$_{12}$ film after an anneal at 700 °C for 30 seconds.

The slight constriction centered on -20 kOe indicates the soft and hard phases are not completely coupled on reversal in this sample.

Coercivity shows a strong dependence on temperature (analyzed later).
Homogeneous SmCo$_{12}$

- **T = 300 K**
  - Annealed 700°C

- **T = 300 K**
  - Annealed 750°C

- **T = 400 K**
  - Annealed 750°C
In some cases there is a small amount of in-plane anisotropy
High field magnetization ($M_s$), coercivity ($H_{ci}$) and energy product ($BH_{\text{max}}$) as a function of anneal temperature for several thicknesses of initially homogeneous SmCo$_5$ as indicated.

Generally the thickest samples (540 nm) have the best values of $M_s$, $H_{ci}$ and energy product $BH_{\text{max}}$.

For thin samples a 30 sec anneal is more effective than a 20 min anneal for high values of $M_s$, $H_{ci}$ and energy product $BH_{\text{max}}$.

Once more $M_s$ decreases and $H_c$ increases with increasing anneal temperature. This leads to a maximum in energy product at intermediate anneal temperature.
$H_c$, $BH_{max}$ versus composition $x$

- Initially homogeneous samples, best $H_{ci}$ and $BH_{max}$

- Rapid anneal preferable to longer time anneal

- Anneal temperatures for homogeneous samples < multilayers
High field magnetization ($M_s$), coercivity ($H_{ci}$) and energy product ($BH_{max}$) as a function of anneal temperature and anneal time for several compositions of initially multilayered SmCo$_x$.

Once more $M_s$ decreases and $H_c$ increases with increasing anneal temperature. This leads to a maximum in energy product at intermediate anneal temperature.
Multilayers (RT)

\[ x = 8.7 \]

\[ BH_{\text{max}} \text{ (MG.Oe)} \]

\[ T_a \text{ (°C)} \]

\[ M \text{ (emu/g)} \]

\[ H_c \text{ (kOe)} \]

\[ 30 \text{ secs} \]

\[ 20 \text{ mins} \]
Multilayers (RT)

\( x = 12.3 \)

\( H_c (\text{kOe}) \)

\( M (\text{emu/g}) \)

\( BH_{\text{max}} (\text{MG.Oe}) \)

\( T_a (\text{oC}) \)
Coercivity and energy product as a function of measurement temperature for three selected Sm-Co samples

In going from 10 K to 400 K a 60% decrease in $H_{ci}$ and a 4% decrease in $M_s$ (not shown) occur.

These produce a roughly 20% decrease in $BH_{max}$. 
Modified magnetization plot (see axes labels) for homogeneous SmCo$_5$ annealed at 600 °C for 20 minutes, and initially multilayered SmCo$_{6.8}$ annealed at 500 °C for 20 minutes.

A linear behavior is expected if the coercivity is determined by domain walls pinned by narrow inhomogeneities [Kronmuller et al, Jour. Magn. Magn. Mater. 74, 291 (1988)].

A fit yields a homogeneity size of about 0.5 nm.
The largest values of coercivity $H_{ci}$ and energy product $BH_{\text{max}}$ are given for each sample type along with the composition where that value was obtained.

<table>
<thead>
<tr>
<th>Initial sample form</th>
<th>$H_{ci}$ (kOe)</th>
<th>$BH_{\text{MAX}}$ (MG.Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3x[SmCo$_5$(d nm)/Nb(36 nm)] Isolated homogeneous SmCo$_5$ layers</td>
<td>38 (x = 5)</td>
<td>5.5 (x = 5)</td>
</tr>
<tr>
<td>10x[SmCo$_5$(24nm)/Co(y nm)] Initially multilayered SmCo$_x$, x&gt;5*</td>
<td>35 (x = 6.5)</td>
<td>12.5 (x = 8.7)</td>
</tr>
<tr>
<td>SmCo$_x$ (d nm) Initially homogeneous SmCo$_x$, x&gt;5</td>
<td>34.8 (x = 6.8)</td>
<td>19 (x = 12)</td>
</tr>
</tbody>
</table>

* x is calculated from the SmCo$_5$ and Co layer thicknesses
## Comparison with other thin film work

<table>
<thead>
<tr>
<th>Author</th>
<th>Ref.</th>
<th>Sample</th>
<th>Method</th>
<th>$BH_{\text{max}}$ MG.Oe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kato et al</td>
<td>J. Appl. Phys. 87, 6125 (2000)</td>
<td>SmFe$_{12}$/α-Fe</td>
<td>Sputter, 1 μm</td>
<td>18.5</td>
</tr>
<tr>
<td>Cadieu et al</td>
<td>J. Appl. Phys. 76, 6059 (1994)</td>
<td>SmCo</td>
<td>Sputter, 118 μm</td>
<td>16</td>
</tr>
</tbody>
</table>
Anneal time dependence of $H_{ci}$, $BH_{max}$

Multilayer SmCo$_{8.7}$
Conclusions

- Thicker samples have best permanent magnet properties.

- A 30 sec anneal is most beneficial, especially for thinner samples.

- Best values of $BH_{\text{max}}$ are:

  Other Exp.:
  - Zhou et al, Paper GD-10, this conference – 16.6 MG.Oe

  Theory:

- $H_{ci}(T)$ is fitted well by a domain wall pinning theory and is consistent with a pinning inhomogeneity size of about 0.5 nm.

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>$BH_{\text{max}}$ (MG.Oe)</th>
<th>(kJ/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>21</td>
<td>166</td>
</tr>
<tr>
<td>300</td>
<td>19</td>
<td>150</td>
</tr>
<tr>
<td>400</td>
<td>17</td>
<td>134</td>
</tr>
</tbody>
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