PROGRESS REPORT FOR

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OPTIMIZATION OF FILM SYNTHESIZED

RARE EARTH TRANSITION METAL

PERMANENT MAGNET SYSTEMS

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HIGH COERCIVITY Sm-Fe-Ti-V, Sm-Fe-Zr, AND TWO ELEMENT Sm-Fe
$Sm_5(Fe,T)_{17}$ TYPE CRYSTALLINE PHASES

Related publications:
1. N. Kamprath, N. C. Liu, H. Hegde, and F. J. Cadieu, Magnetic Properties and Synthesis of High $_iH_c$ Sm-Ti-Fe, 4th Joint MMM-Intermag Conference, July 1988, J. Appl. Phys. 64, 5720 (1988).
2. N. Kamprath, X. R. Qian, H. Hegde, and F. J. Cadieu, Magnetic Properties of Sm-Fe-Ti-Al Sputtered Films with $_iH_c$ Greater Than 30 kOe, 34th Magnetism and Magnetic Materials Conference, Boston, Novemver 1989, J. Appl. Phys. 67, 4948 (1990).
3. N. Kamprath, Ph.D. Thesis, "Synthesis and Analysis of Sm-Fe-Ti Sputtered Films With Intrinsic Coercive Force Greater Than 30 kOe", City University of New York, 1990.
4. F. J. Cadieu, H. Hegde, N. Kamprath, A. Navarathna, and R. Rani, High Coercivity Sm-Fe-Ti-V and Sm-Fe-Zr Crystalline Phases, Proceedings Sixth International Symposium on Magnetic Anisotropy and Coercivity in Rare Earth-Transition Metal Alloys, pp. 463-476, editor, S.G. Sankar, Carnegie Mellon University Press, Pittsburgh, October 25, 1990.
5. F. J. Cadieu, N. Kamprath, H. Hegde, K. Chen, A. Navarathna, and R. Rani, Analogous Sm-Fe-Ti High Coercivity Phases in Sm-Fe-V and Sm-Fe-Zr Sputtered Film Samples, 35th Magnetism and Magnetic Materials Conference, Paper FA-10, 1990, J. Appl. Phys. 69, 5608 (1991).
6. F. J. Cadieu, H. Hegde, and R. Rani, Cell Volume Expansion in $Sm_5(Fe,T)_{17}$, T = Ti, V, Magnetic Phases, Matl. Letters 11, 284 (1991).
7. R. Rani, H. Hegde, A. Navarathna, K. Chen, and F.J. Cadieu, "Synthesis and Properties of Magnetically Hard Two Element Sm_5Fe_{17} Phase in Sputtered Films", submitted to Intermag 92, St. Louis, Mar. 1992.

In recent papers we first showed it was possible to crystallize a

Sm-Fe-Ti phase that exhibited a room temperature intrinsic coercivity,

$_iH_c$, of 38.5 kOe as measured at 293 K.[1,2] In subsequent papers we reported measurements for a range of Sm-Fe-(Ti,V) compositions and contrasted the crystal structure and magnetic properties with those of Sm-Fe-Zr for corresponding composition ranges.[3,4] The samples investigated were made by crystallizing in situ originally microcrystalline or "amorphous" sputter deposits of the respective compositions. This method of preparation generally produces fine grained crystallites, 300 to 600 A in diameter. The orientation of such crystallites is expected to be random. The end points for Sm-Fe-Ti and Sm-Fe-V compositions exhibited maximum coercivity values of 37.8 kOe and 15.7 kOe respectively. For an intermediate Ti:V ratio of roughly 2:1 a room temperature maximum coercivity of 45.6 kOe was observed. It was shown that $Sm_5(Fe,T)_{17}$ T = Ti,V, could be crystallized into the same high $_iH_c$ $Sm_5(Fe,T)_{17}$ type structure across the entire range of Ti to V compositions, for Sm concentrations of approximately 20 at.%. The room temperature coercivity for Ti rich SmFe(Ti,V) samples reached approximately 50 kOe. All of the magnetic measurements as shown in Table I were for the as measured hysteresis loop values without any second phase corrections. Whether there was really a maximum coercivity for Ti:V rich samples is uncertain and may reflect details of the crystallizing time and temperatures. Somewhat higher values of coercivity have been observed for rapidly quenched Sm-Fe-Ti samples.[9] Those mechanically alloyed samples were made utilizing the exact composition that we had previously reported as a high $_iH_c$ phase. Samples of the SmFe(Ti,V) system formed into the same high $_iH_c$ crystal phase for similar compositions from Ti to V. In contrast to this, similarly prepared SmFeZr

samples did not exhibit this high $_iH_c$ phase, but instead formed into a disordered 1-5 TbCu$_7$ type structure.[4]

It was also shown for the first time that just the two elements Sm and Fe could be synthesized into the same high $_iH_c$ phase as Sm$_5$Fe$_{17}$.[6] The room temperature $_iH_c$ in that case was 11.9 kOe at 293 K. The room temperature static energy product for this two element Sm$_5$Fe$_{17}$ sample was 5.6 MGOe.[18] For lower temperatures the $_iH_c$ values smoothly rose to 23.4 kOe at 15 K. Up to this point such samples have only been synthesized in our laboratory. This was the first reporting of a two element uniaxial Sm-Fe compound.

Table I. The magnetic properties of subsequently crystallized Sm-Fe-Ti-V and Sm-Fe-Zr films as measured at 293°K are shown for representative compositions. All except those marked with +++, crystallized into the high iHc Sm$_5$(Fe,T)$_{17}$ type phase. Those marked +++, crystallized into the TbCu$_7$ structure.

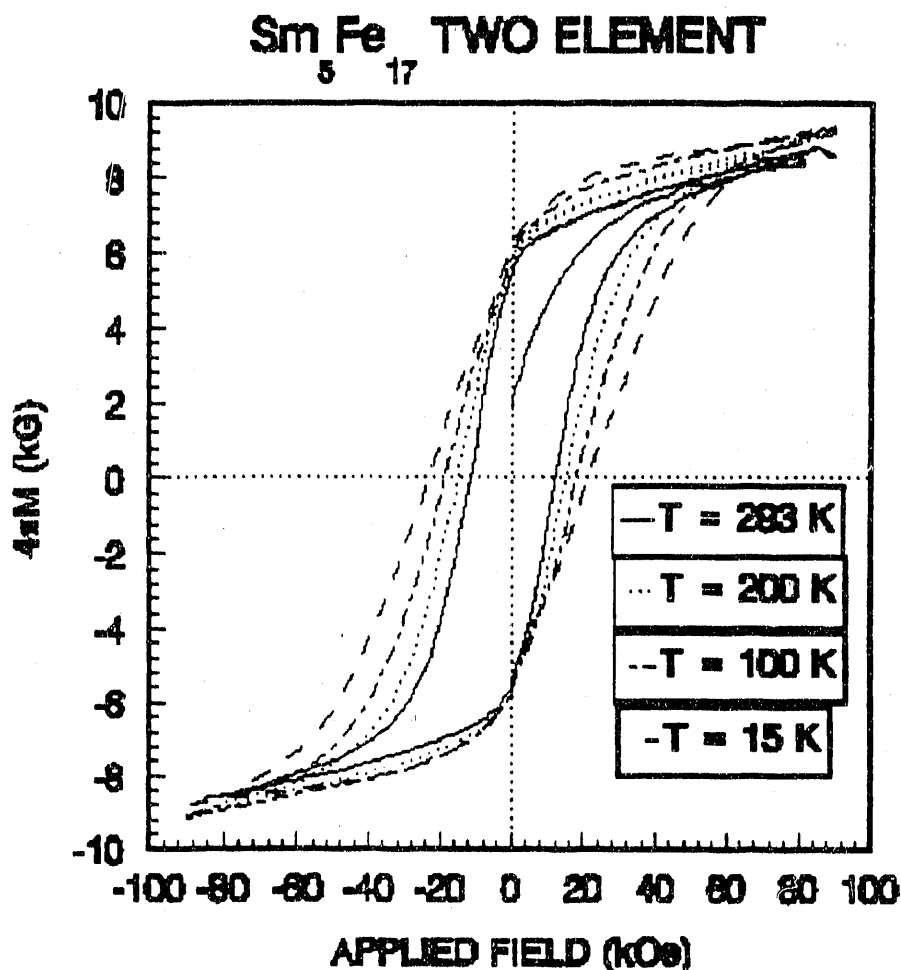| Composition	4πM (KG) @ 90 (KOe)	4πMr (KG)	iHc (KOe)
Sm$_5$Fe$_{17}$	8.9	5.6	11.9
Sm18.9Fe72.7Ti8.4	4.4	3.9	37.8
Sm19.6Fe73.5V6.9	6.3	4.4	15.7
Sm21.5Fe69.1Ti4.7V4.7	5.0	3.2	26.6
Sm15.1Fe70.4Ti10.8V3.7	5.8	3.8	45.6
Sm19.9Fe71.2Zr8.1 +++	5.6*	4.0	6.4
Sm13.3Fe80.7V6.0 +++	8.6*		1.9

* 4πM at 18 KOe

Fig. 1. In plane hysteresis loops are shown for a Sm_5Fe_{17} sample for different measurement temperatures. At 293 K the $_jH_c$ = 11.9 kOe with an energy product of 5.6 MGOe. The coercivities at 293, 200, 100, and 15 K were respectively 11.9, 15.1, 18.8, and 23.4 kOe.

A comparison of the volume changes for $Sm_5(Fe,Ti)_{17}$, $Sm_5(Fe,Ti,V)_{17}$, $Sm_5(Fe,V)_{17}$, and Sm_5Fe_{17} have allowed us to show there is a systematic expansion of the unit cell as the third element either V or Ti is added. These results which are shown in Table II indicated that the third element was actually being added substitutionally for part of the Fe.

A complete indexing of the high coercive force phase based upon a hexagonal cell with a $\approx$ 20.12 A, and c $\approx$ 12.34 A, the 5-17 cell, was recently reported by us in the symposium paper.[3] The indexing reported

was based only on a cell fitting. All possible indices which fit the experimental angles within ±0.05° for the $Cu_{K\alpha}$ diffraction lines were given. All 37 of the diffraction angles observed between 25 and 50° 2θ were fit. That indexing included as a subset the powder pattern based indices that have now been published in Ref. 5. The indexing in each case for Table II was done using only the indicated powder pattern lines from Ref. 5. The hexagonal unit cell volume showed a clear and systematic expansion upon the partial replacement of Fe with V, V-Ti, and Ti. The compositions in each case were very close to $Sm_2Fe_7T_1$, for which it was previously observed that the room temperature $_iH_c$ reached a maximum.

All of these samples were synthesized by at first making an "amorphous" or microcrystalline ≈ 5 μm thick deposit of the desired composition by sputtering the elements, and then subsequently crystallizing in situ that deposit. The compositions, x-ray parameters, and magnetic properties were determined by direct analysis of the films after the subsequent crystallization. The as deposited films only exhibited a weak characteristic amorphous hump in the vicinity of 34° for $Cu_{K\alpha}$ radiation.

Table II. The hexagonal 5-17 lattice parameters, % unit cell expansion over binary Sm_5Fe_{17}, x-ray density, and $_1H_c$ as measured at 293 K, are shown for Sm_5Fe_{17} and for $Sm_5(Fe,T)_{17}$ compositions for T = Ti, V. The x-ray parameters are based on fitting of from 30 to 37 observed diffraction lines from 2θ = 25 to 50° for $Cu_{K\alpha}$ radiation.

Composition	a (A)	c (A)	% Cell Expansion	X-Ray Density (g/cm^3)	$_iH_c$ at 293 K
Sm_5Fe_{17} kOe	20.061	12.282	-----	7.922	12
$Sm_5(Fe_{0.90}V_{0.1})_{17}$ kOe	20.115	12.318	0.83%	7.818	16
$Sm_5(Fe_{0.89}V_{0.055}Ti_{0.055})_{17}$ kOe	20.142	12.336	1.25%	7.769	45
$Sm_5(Fe_{0.89}Ti_{0.11})_{17}$ kOe	20.169	12.354	1.67%	7.724	39

ThMn$_{12}$ Type Pseudobinary SmFe$_{12-x}$T$_x$ (0 $\leq$ x $\leq$ 1.5)

Related Publications:

1. F.J. Cadieu, H. Hegde, A. Navarathna, R. Rani, and K. Chen, High Energy Product ThMn$_{12}$ Sm-Fe-T and Sm-Fe Permanent Magnets Synthesized As Oriented Sputtered Films, Appl. Phys. Letters **59**, 875 (1991).

2. H. Hegde, R. Rani, A. Navarathna, K. Chen and F.J. Cadieu, Film Synthesis and Magnetic Properties of ThMn$_{12}$ Type Sm(Fe$_{1-x}$T$_x$)$_{12}$, x $\leq$ 0.12, Paper KD-02, 5th Joint MMM-Intermag, Pittsburgh, June 18-21, 1991, J. Appl. Phys. (to be published, 1991).

3. A. Navarathna, H. Hegde, R. Rani, and F.J. Cadieu, "Controlled Synthesis of Differently Textured Sm(Fe,T)$_{12}$ T = Ti, Ti+V, V, Sputtered Films", submitted to Intermag 92, St. Louis, Mar. 1992.

During the past year we have made a very important breakthrough in that a high energy product system has been discovered that can be synthesized such that the easy axis of magnetization is directed perpendicular to the film plane.[1,2,7] Binary SmFe$_{12}$ and Sm(Fe,T)$_{12}$ films, where T = Ti and V, crystallized into the ThMn$_{12}$ type structure, have been synthesized as sputtered films such that the c-axes of the crystallites are oriented perpendicular to the film plane. It has been possible to synthesize Sm(Fe,T)$_{12}$ films which exhibit a very dominant (002) texture with intrinsic coercivities of 5 or more kOe. Such films exhibit flux densities, 4πM$_s$, of more than 10 kG perpendicular to the film plane. No discernible columnar structure is exhibited so that the static energy product measured perpendicular to the film plane is nearly 21 MGOe.

Although it has been possible to synthesize bulk 1-12 samples with either high flux density values, or intrinsic coercive force, $_iH_c$, in the 6 to 8 kOe range,[19,20,21] it has been difficult to attain the high remanent flux density and high intrinsic coercivity simultaneously in the same sample which is necessary to realize a high static energy product or magnetic energy density. Generally it was thought that a relatively large third element addition was necessary to stabilize this structure. The usual composition required for bulk samples was approximately $Sm(Fe_{11}Ti_1)$ or $Sm(Fe_{10}V_2)$.[22,23,24]

But by our special sputtering methods, well defined $Sm(Fe_{1-x}T_x)_{12}$ samples with $x < 0.1$ have been synthesized. The crystal structure is of the $ThMn_{12}$ type. In bulk it has not been possible to synthesize this system with x values as low as this, or to make $ThMn_{12}$ bulk samples with aligned crystallites. A sample with a random orientation of crystallites can at most exhibit 25% of the energy product of an aligned sample. In bulk it has not been possible to synthesize $ThMn_{12}$ samples without replacing about 20% of the Fe with a nonmagnetic third element such as Ti. In film form we have been able to make $ThMn_{12}$ type films even when $x = 0.0$, but a x value of about 0.05 is necessary to obtain sufficient coercivity so that a high energy product can be realized. The central part of room temperature hysteresis loops, measured perpendicular to the film plane, and in the film plane, are shown in Fig. 2. The static energy product measured perpendicular to the plane was 20.7 MGOe.
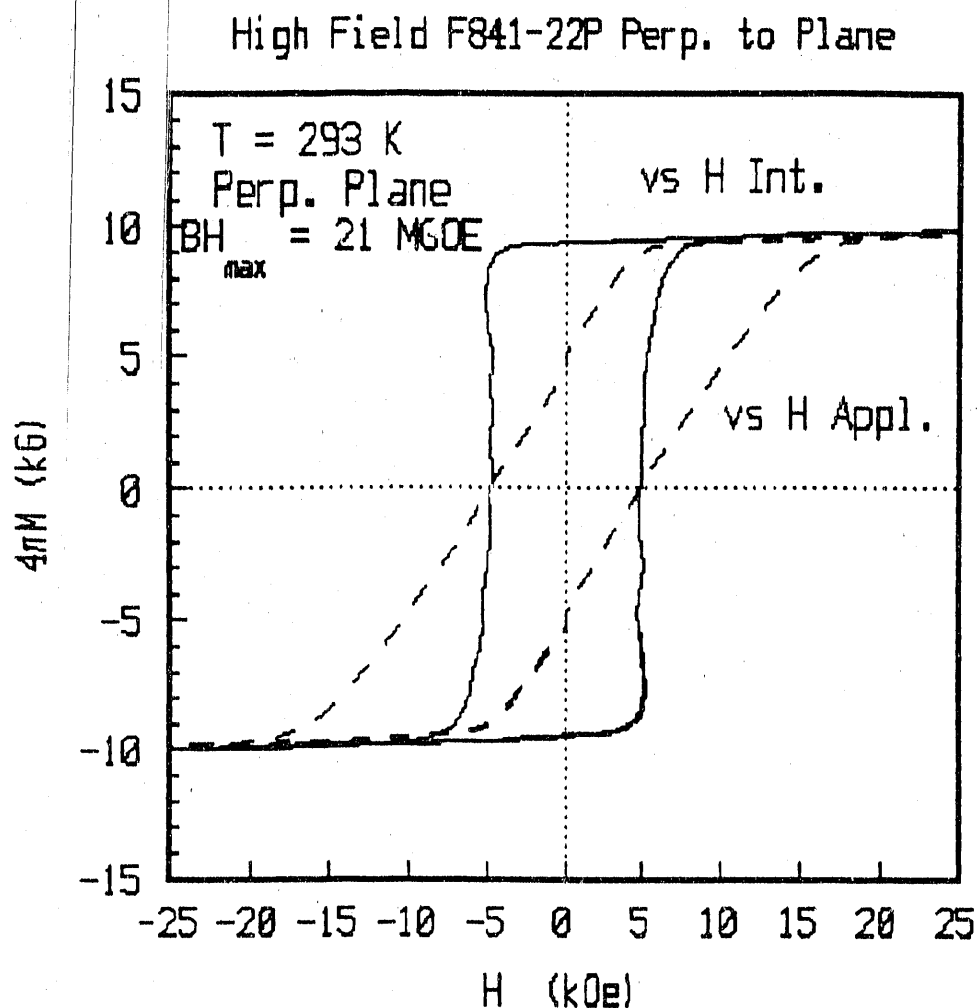
High Field F841-22P Perp. to Plane

Fig. 2. Room temperature hysteresis loops measured perpendicular to the film plane for a highly textured $Sm(Fe,T)_{12}$ sample are shown. The energy product with M directed perpendicular to the film surface was 20.7 MGOe.

High field measurements were necessary to magnetize such samples in the film plane. Hysteresis loops measured to ±90 kOe are shown in Fig. 3. The ±90 kOe applied field when applied perpendicular to the film plane is nearly sufficient to saturate the sample of Fig. 1. The field that would be required to saturate this film to the same value if applied in the film plane is estimated to be 130±10 kOe. For these highly aligned

films which have the crystallographic c-axes oriented perpendicular to the plane this anisotropy field is then the magnetocrystalline anisotropy field.

$ThMn_{12}$ Type $- Sm_{8.04}Fe_{79.16}Ti_{9.11}V_{3.69}$
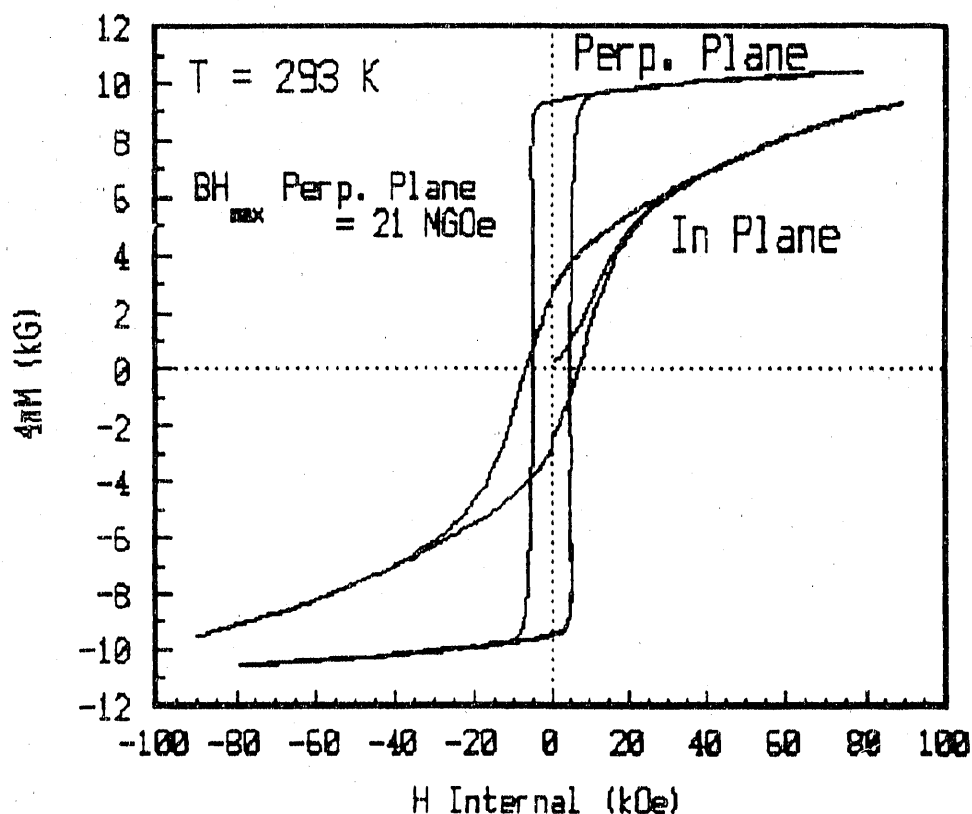
Fig. 3. The room temperature anisotropy field was 130±10 kOe. Since all the c-axes were perpendicular to the film plane, this is a direct measurement of the magnetocrystalline anisotropy field.

All film compositions were determined by directly analyzing film pieces. The perpendicular to the film plane loop as measured versus the applied field is shown as the dashed-dot loop. SEM photographs of fractured sample edges indicate no discernible void or columnar structure for these films. The high flux densities as measured perpendicular to the

film plane also justify the use of $N_d \approx 4\pi$ which would be the case for a dense plate for measurements made perpendicular to the plane. For measurements made in the film plane the demagnetization factor has been taken as 0. The perpendicular to the film plane static energy product as measured at room temperature was 20.7 ± 0.5 MGOe. The intrinsic coercivity, $_iH_c$, in this case was just sufficiently high at 5 kOe so that the static energy product value is not coercivity limited.

The high ratio of the remanent to saturation intrinsic flux densities versus H internal, $4\pi M_r / 4\pi M_s$, observed perpendicular to the film plane for Fig. 2 is only consistent with a uniaxial system that has the easy axes of the crystallites oriented nearly perpendicular to the film plane. $\{4\pi M_r / 4\pi M_s = 0.913\}$ The magnetic properties thus provide very specific expectations to aid in assigning a crystal structure and indexing of the observed x-ray diffraction lines.

Expected powder pattern intensities were published in Ref. 25 for the $ThMn_{12}$ structure. It is expected that certain diffraction lines should be common to the $CaCu_5$, $TbCu_7$, 2-17 rhombohedral, and tetragonal $ThMn_{12}$ structures. Certain corresponding lines in the 1-12 indexing are connected by the following matrices.

$$
\begin{bmatrix} h \\ k \\ l \end{bmatrix}_{2-17} = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix} \begin{bmatrix} h \\ k \\ l \end{bmatrix}_{1-5}
$$

$$
\begin{bmatrix} h \\ k \\ l \end{bmatrix}_{1-12} = \begin{bmatrix} -1 & 1 & 0 \\ 0 & 0 & 2 \\ 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} h \\ k \\ l \end{bmatrix}_{1-5}
$$

For the $ThMn_{12}$ structure, reflections which would have some indices negative have been shifted to equivalent ones with all indices $\geq$ 0. In addition to these transformation connected lines the 1-12 structure exhibits a higher density of lines because the structure is not in agreement with the ideal structure transformation size which would have $a_{1-12} = 2 \cdot c_{1-5}$, and $c_{1-12} = a_{1-5}$. The deviations from this ideal case are driven by the ordering at the dumbbell sites and leads to the much higher density of observed lines of the 1-12 superstructure, as opposed to that possible for the fundamental 1-5 structure. The 1-12 structure is the only one that accounts for all the observed lines.

In addition to the fact that all the observed x-ray lines can only be fit by the 1-12 phase, the magnetic properties very strongly support that indexing and provide conclusive evidence against the 1-5, 1-7, and 2-17 phases as possible structures. It has already been noted that the magnetic properties are only consistent with a uniaxial system which has the c-axes of the crystallites strongly aligned perpendicular to the film plane. As the films become more highly textured as illustrated in Fig. 2(a), the texturing in the extreme becomes only (002) for the 1-12 tetragonal indexing . This indexing is consistent with the observed extreme perpendicular anisotropy. This x-ray corresponds to the magnetic properties as illustrated in Fig. 2. In contrast to this, the transformations and indexing illustrates that the a axis of the 1-5 structure corresponds to the c-axis of the 1-12 structure. The (002) c-axis reflection of the 1-12 structure would correspond to the c-axis in plane (110) line of the 1-5 phase, and the c-axis in plane (300) line of the rhombohedral 2-17 phase. Hysteresis loops for a binary $SmFe_{12}$ film were shown in Ref. 12. Other (002) textured $SmFe_{12}$ samples exhibit a

nearly flat topped hysteresis loop when measured perpendicular to the plane, but then fewer x-ray lines can be detected. The extreme in film plane anisotropy observed for (110) textured $TbCu_7$ type films,[17] or (300) textured 2-17 films,[26] cannot be confused with the extreme perpendicular anisotropy observed for the $SmFe_{12}$ films. The $Sm_2Fe_{17}N_x$ phase has been shown to become uniaxial for up to three N per formula unit with up to a 6% cell volume expansion.[27] This phase cannot account for the observed x-ray lines, and the magnetic properties would have to exhibit in plane, not perpendicular, anisotropy. Mossbauer measurements have also shown the extreme perpendicular anisotropy films to be a uniaxial system with c-axes oriented perpendicular to the film plane.[7]

As the third element addition has been reduced to zero, it has still been possible to form a well defined $SmFe_{12}$ phase which can be made so as to exhibit extreme perpendicular anisotropy. The large values of $4\pi M_r/4\pi M_s$ and the perpendicular magnetic anisotropy are only consistent with a collection of uniaxial crystallites which have c-axes strongly aligned perpendicular to the film plane. The film compositions, magnetic properties, and possible x-ray indexing all support the identification of these dense deposits as $ThMn_{12}$ type films.

SPUTTER PROCESS CONTROL FOR THE SYNTHESIS OF PRECISELY TEXTURED

RE-TM MAGNETIC FILMS

Principal publications:
1. F. J. Cadieu, H. Hegde, and K. Chen, Enhanced Crystal Texture Control For Sm-Co Based Films Sputtered In Ar-Xe Gas Mixtures, Paper presented at 8th International Conference on Thin Films, San Diego, April 1990, Thin Solid Films 193/194, 857 (1990).
2. H. Hegde, Ph.D. Thesis, "Sputter Synthesis of RE-TM 2-17 Type Magnetic Films With Strong Alignment of Easy Axes of Grains", City University of New York, 1990.
3. F.J. Cadieu, "Permanent Magnet Thin Films" in Physics of Thin Films, Vol. 16, Academic Press, NY (to be published, 1991).
4. K. Chen, H. Hegde, and F.J. Cadieu, "Strong In-Plane Uniaxial Anisotropy Induced Through External Magnetic Field in Amorphous Sm-Co Sputtered Films", submitted to Intermag 92, St. Louis, Mar. 1992.

Over the last few years we have been able to synthesize a great many rare earth transition metal permanent magnet systems which exhibit well defined crystallite growth textures. This is necessary if an energy product is desired which is more than can be expected from the isotropic systems. Such preferentially textured films are synthesized by sputter depositing the atoms onto sufficiently heated substrates so that the deposit is immediately crystallized. Such films are said to be directly crystallized. Crystalline films of the RE-TM magnetic systems can also be made by first making an amorphous deposit which is subsequently crystallized. Such films made by subsequently crystallizing an amorphous deposit generally consist of a random collection of single domain grains for the systems of interest. The coercivity can be near optimal, but the remanent flux densities are low because of the isotropic crystallite distribution. Such films correspond most closely to bulk samples made by mechanical alloying.

In contrast to this processing, direct crystallization allows for the direct growth of highly textured films. If properly done, sputter process control can be used to favor the growth of crystallites with specific crystallite orientations over competing growth modes. It is thus possible to grow relatively thick highly textured films onto polycrystalline substrates by utilizing sputter process control dynamics. An x-ray diffractometer trace for a highly textured $Sm(Fe_{1-x}T_x)_{12}$ film is shown in Fig. 4. For this sample the c-axes of the vast majority of the crystallites are aligned perpendicular to the substrate plane.
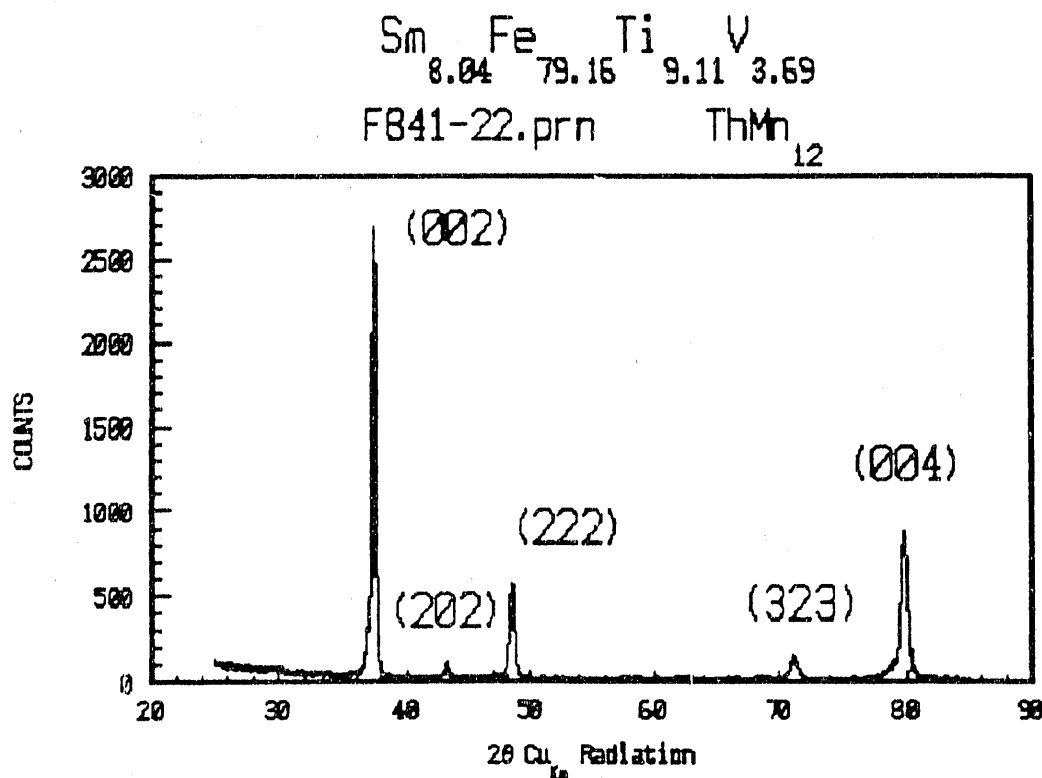

$Sm_{8.04} Fe_{79.16} Ti_{9.11} V_{3.69}$

F841-22.prn $ThMn_{12}$

Fig. 4. An x-ray diffractometer trace for a directly crystallized (002) textured $Sm(Fe,Ti,V)_{12}$ film is shown.

We have come to understand the dynamics of texture control to a great extent during our studies of RE-TM systems. The most complete

description of the dynamics of textured film growth is contained in the article titled "Permanent Magnet Thin Films" which is scheduled to appear momentarily in Thin Film Physics, Vol. 16.[15] At the present time the growths possible for a particular system can, to a large extent, be predetermined from a knowledge of the crystal structure, and ferromagnetic Curie point.

Three factors have been defined which determine the favored growth textures.[15] The first is the self demagnetization energy which favors the growth of uniaxial crystallites with c-axes aligned toward the substrate plane. This mechanism can only be useful for systems which can be directly crystallized below their Curie point. The second factor is the c/a ratio for the crystal unit cell. Ratios which appreciably differ from 1, either greater than 1, or less than 1, can be used to promote preferential growth. The third factor is called the stacking sequence complexity factor. The second and third factors do not depend on the systems being grown in a magnetic state below their Curie point. These factors can be used to also control the growth textures of nonmagnetic systems.

For any of these texture control factors to be effective requires that the energy and momentum of the sputtered atoms be controlled so that the sensitive factors favoring the growth of certain textures are not randomized. Some form of thermalized or selectively thermalized sputtering is normally required to synthesize highly textured RE-TM permanent magnet systems.

The influence of energetic neutral sputtered atoms impinging during the growth of crystalline textured rare earth transition metal films has been experimentally studied and modeled. The main system modeled has been $Sm_2(Co,Fe,Cu,Zr)_{17}$ films that have been directly crystallized by

sputtering onto heated sapphire and polycrystalline Al_2O_3 substrates. By varying the sputtering pressures and gas compositions, the composition of the films sputtered from the same targets could be shifted so that either a disordered hexagonal $TbCu_7$ type structure was formed, or for richer Sm concentrations, a hexagonal 1-5 type structure was formed.[28] Films exhibiting the $TbCu_7$ type structure were the principal interest for these studies. The magnetic anisotropy field of these films was sufficiently high that the magnetic properties were a very sensitive indicator of the presence of crystallites that had c-axes skewed out of the film plane. It has been possible to sputter such films, with thicknesses from 1 to >50 µm, with in plane energy products of ≈20 MGOe in Ar-Xe sputtering gas mixtures such that no crystallites that have c-axes skewed out of the film plane can be detected. A principal result of the modelling, which used a distribution of sputtered neutral atom energies, is that the fraction of nonthermal atoms striking the crystallizing films can be appreciably lowered by using Ar-Xe mixtures at much lower total pressures than if Ar alone were used as the sputtering gas. To obtain agreement between the modeling and the experimental results it was necessary to use energy dependent scattering cross sections for the sputtered atom – sputtering gas atom collisions. Figure 5 shows the calculated distribution of energies for Co atoms sputtered from a RE-TM target in 60 mTorr of Ar-50%Xe.[15]
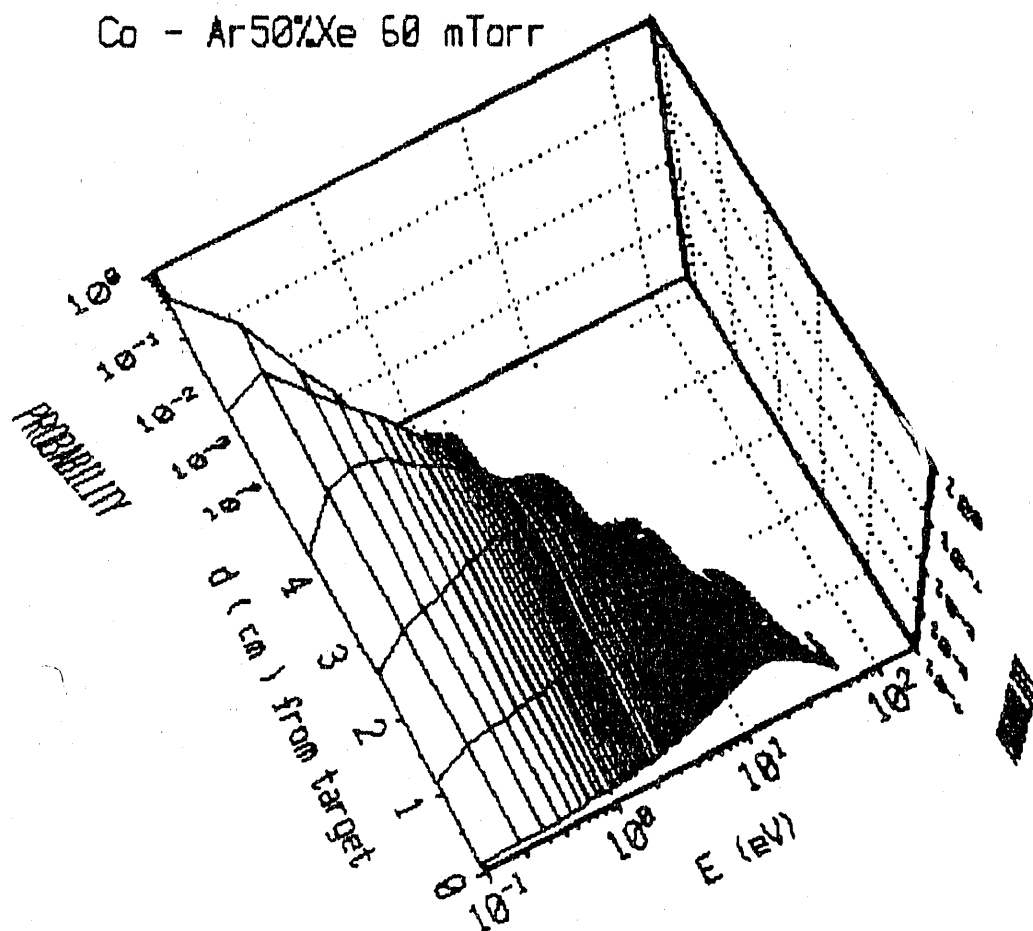
Co - Ar50%Xe 60 mTorr

Fig. 5. The calculated energies as a function of the target to substrate distance for Co atoms sputtered in 60 mTorr Ar-50%Xe is shown. The model uses an energy dependent collision cross section. Such a modeling is required to agree with the experimental pressures required to obtain completely textured Sm(Fe,Co,Cu,Zr) type films. If a simpler energy independent cross section were used, then thermalization is expected for lower pressures than are actually required.[15]

October 15, 1991

1. F. J. Cadieu, High Coercive Force and Large Remanent Moment Magnetic
Films With Special Anisotropies, Invited Paper, 31st Magnetism and
Magnetic Materials Conference, 17-20 November 1986, J. Appl. Phys.
$\underline{61}$, 4105 (1987).

2. F. J. Cadieu, Selectively Thermalized Sputtering for the Deposition of
Magnetic Films With Special Anisotropies, Invited Paper, 34th National
Vacuum Symposium, 2-6 November 1987, J. Vac. Sci. and Tech. A, $\underline{6}$,
1668 (1988).

3. N. Kamprath, N. C. Liu, H. Hegde, and F. J. Cadieu, Magnetic Properties
and Synthesis of High $_iH_c$ Sm-Ti-Fe, 4th Joint MMM-Intermag
Conference, July 1988, J. Appl. Phys. $\underline{64}$, 5720 (1988).

4. N. Kamprath, X. R. Qian, H. Hegde, and F. J. Cadieu, Magnetic
Properties of Sm-Fe-Ti-Al Sputtered Films with $_iH_c$ Greater Than 30
kOe, 34th Magnetism and Magnetic Materials Conference, Boston,
Novemver 1989, J. Appl. Phys. **67**, 4948 (1990).

5. F. J. Cadieu, H. Hegde, and K. Chen, Enhanced Crystal Texture Control
For Sm-Co Based Films Sputtered In Ar-Xe Gas Mixtures, Paper
presented at 8th International Conference on Thin Films, San Diego,
April 1990, Thin Solid Films **193/194**, 857 (1990).

6. N. Kamprath, Ph.D. Thesis, "Synthesis and Analysis of Sm-Fe-Ti
Sputtered Films With Intrinsic Coercive Force Greater Than 30 kOe",
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University of New York, 1990.

8. F. J. Cadieu, H. Hegde, N. Kamprath, A. Navarathna, and R. Rani, High
Coercivity Sm-Fe-Ti-V and Sm-Fe-Zr Crystalline Phases, Proceedings
Sixth International Symposium on Magnetic Anisotropy and Coercivity
in Rare Earth-Transition Metal Alloys, pp. 463-476, editor, S.G.
Sankar, Carnegie Mellon University Press, Pittsburgh, October 25,
1990

9. F. J. Cadieu, N. Kamprath, H. Hegde, K. Chen, A. Navarathna, and R. Rani, Analogous Sm-Fe-Ti High Coercivity Phases in Sm-Fe-V and Sm-Fe-Zr Sputtered Film Samples, 35th Magnetism and Magnetic Materials Conference, Paper FA-10, 1990, J. Appl. Phys. **69**, 5608 (1991).

10. F.J. Cadieu, H. Hegde, A. Navarathna, R. Rani, and K. Chen, High Energy Product $ThMn_{12}$ Sm-Fe-T and Sm-Fe Permanent Magnets Synthesized As Oriented Sputtered Films, Appl. Phys. Letters 59, 875 (1991).

11. F. J. Cadieu, H. Hegde, and R. Rani, Cell Volume Expansion in $Sm_5(Fe,T)_{17}$, T = Ti, V, Magnetic Phases, Matl. Letters 11, 284 (1991).

12. H. Hegde, R. Rani, A. Navarathna, K. Chen and F.J. Cadieu, Film Synthesis and Magnetic Properties of $ThMn_{12}$ Type $Sm(Fe_{1-x}T_x)_{12}$, x ≤ 0.12, Paper KD-02, 5th Joint MMM-Intermag, Pittsburgh, June 18-21, 1991, J. Appl. Phys. (to be published, 1991).

13. F.J. Cadieu, "Permanent Magnet Thin Films" in <u>Physics of Thin Films, Vol. 16</u>, Academic Press, NY. This volume has been scheduled by Academic Press to appear in March 1992.

14. K. Chen, H. Hegde, and F.J. Cadieu, "Strong In-Plane Uniaxial Anisotropy Induced Through External Magnetic Field in Amorphous Sm-Co Sputtered Films", submitted to Intermag 92, St. Louis, Mar. 1992.

15. R. Rani, H. Hegde, A. Navarathna, K. Chen, and F.J. Cadieu, "Synthesis and Properties of Magnetically Hard Two Element Sm_5Fe_{17} Phase in Sputtered Films", submitted to Intermag 92, St. Louis, Mar. 1992.

16. A. Navarathna, H. Hegde, R. Rani, and F.J. Cadieu, "Controlled Synthesis of Differently Textured $Sm(Fe,T)_{12}$ T = Ti, Ti+V, V, Sputtered Films", submitted to Intermag 92, St. Louis, Mar. 1992.

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