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In Plane Oriented Strontium Ferrite Thin Films Described by Spin Reorientation

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Abstract

For the first time, in plane orientation of magnetic easy axis of sputtered strontium hexaferrite thin films has been explained using modified Heisenberg Hamiltonian model with stress induced anisotropy term. The variation of average value of in plane spin component with temperature was plotted in order to determine the temperature at which easy axis is oriented in the plane of the strontium ferrite film. The average value of in plane spin component in this 2-D model reaches zero at one particular temperature. This particular temperature obtained using our theoretical model agrees with the experimental value of the temperature of rf sputtered polycrystalline strontium ferrite thin films deposited on polycrystalline Al_2O_3 substrates (500°C). This spin reorientation temperature solely depends on the values of energy parameters used in our modified Heisenberg Hamiltonian equation.

Keywords: *Spin, orientation, easy axis, hexaferrite*

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INTRODUCTION

Ferrite thin films are prime candidates in the application of magnetic memory devices and monolithic microwave integrated thin films (MMIC). Both strontium and barium ferrites belong to M-type hexagonal category. Due to its hard magnetic and uniaxial properties, hexagonal ferrites are unique among other ferrite materials. Strontium ferrite thin films have been synthesized on Al_2O_3 polycrystalline substrates using rf sputtering [1, 2], magnetron sputtering [3] and pulsed laser deposition [4]. The orientation of magnetic easy axis of ferrites vastly depends on the deposition or annealing temperature, orientation of the substrate and gas pressure inside deposition chamber.

Spin was assumed to be in the plane of y-z, and only two spin components (S_y and S_z) were taken into account in this 2-D model. The average value of in plane (S_y) component was determined as a function of the temperature. By plotting S_y versus temperature, the temperature at which S_y approaches zero was investigated. Below this particular temperature (T_s), the magnetic easy axis orients in the plane of the film. Different values of spin exchange interaction, long range magnetic dipole interaction, second order magnetic anisotropy, fourth order anisotropy and stress induced anisotropy were plugged in the equation of our modified Heisenberg Hamiltonian, in order to determine the variation of T_s. The out of plane easy axis orientation of barium ferrite thin films belonging to hexagonal ferrite has been previously explained by us using this model [5]. In addition, the easy axis orientations of soft spinel ferrite [6] and ferromagnetic [7] thin films have been explained previously. In all these cases, S_y component was plotted against the temperature in order to investigate the orientation of magnetic easy axis. Furthermore, the total magnetic energy of Nickel ferrite films has been explained using the second order [8] and third order perturbed [9] Heisenberg Hamiltonian. However, the unperturbed Heisenberg Hamiltonian has been employed in this report.

MODEL

The total energy of a magnetic thin film is given by following modified Heisenberg Hamiltonian [8,9]:

$$H= - J\sum_{m,n}\vec{S}_m.\vec{S}_n + \omega\sum_{m\neq n}\left(\frac{\vec{S}_m.\vec{S}_n}{r_{mn}^{\ 3}} - \frac{3(\vec{S}_m.\vec{r}_{mn})(\vec{r}_{mn}.\vec{S}_n)}{r_{mn}^{\ 5}}\right) - \sum_m D_{\lambda_m}^{(2)}(S_m^{\ z})^2 - \sum_m D_{\lambda_m}^{(4)}(S_m^{\ z})^4$$
$$-\sum_m \vec{H}..\vec{S}_m - \sum_m K_s Sin^2\theta_m \qquad (1)$$

Here *J*, *ω*, *θ*, $D_m^{(2)}, D_m^{(4)}, H_{in}, H_{out}, K_s$, *m* and *n* represent spin exchange interaction, strength of long range dipole interaction, azimuthal angle of spin, second and fourth order anisotropy constants, in plane and out of plane internal magnetic fields, stress induced anisotropy constant and spin plane indices, respectively. When the stress applies normal to the film plane, the angle between mth spin and the stress is θ_m.

The long range magnetic dipole interaction of hexagonal ferrite calculated in one of our previous research articles has been used to find the total energy per unit spin given in the following equation [5]:

$$E(\theta) = 3NJ+5(N-1)J+\omega[N(88.3197 \sin^2\theta+11.3541 \sin\theta\cos\theta -127.9435 \cos^2\theta)$$
$$+(N-1)(93.0605 \sin^2\theta +25.3002 \sin\theta\cos\theta - 15.423 \cos^2\theta)]$$
$$-\cos^2\theta\sum_{m=1}^{N}D_m^{(2)} - \cos^4\theta\sum_{m=1}^{N}D_m^{(4)} + 3N(H_{in}\sin\theta + H_{out}\cos\theta + K_s\sin^2\theta) \qquad (2)$$

Here $\sum_{m=1}^{N}D_m^{(2)}$ and $\sum_{m=1}^{N}D_m^{(4)}$ represent the total second and fourth order anisotropy constants in the whole film.

Because only the Fe^{+3} ions contribute to the net magnetic moment of hexagonal ferrites, the equation derived for barium ferrite can be applied for strontium ferrite too.

RESULTS AND DISCUSSION

The average value of in plane spin component is given by

$$\bar{S}_y = \frac{\int_0^{\pi} e^{-\frac{E}{kT}}\sin\theta d\theta}{\int_0^{\pi} e^{-\frac{E}{kT}} d\theta} \qquad (3)$$

Here *E*, *k* and *T* indicate the total magnetic energy given in Eq. (2), Boltzmann's constant and absolute temperature. Thickness of the strontium ferrite films incorporated for these simulations were approximately 2.5 μm thick. So value of N employed for these investigations was 998.

Figure 1 indicates the variation of $\bar{S}_y$ with temperature. When J = 10^{-33} Joules, ω=10^{-30} Joules, $\sum_{m=1}^{N}D_m^{(2)}$ =10^{-29} Joules, $\sum_{m=1}^{N}D_m^{(4)}$ =10^{-42} Joules, K_s= 10^{-30} Joules, H_{in}=10^{-32} Am^{-1} and H_{out}=10^{-39} Am^{-1}, $\bar{S}_y$ reaches zero at 773 K. This implies that in plane orientation of easy axis vanishes above 500°C. Therefore, our experimental results of polycrystalline strontium ferrite thin film can be explained using this theoretical model [1]. The spin reorientation temperature (T_s) vastly depends on the energy parameters. When J = 10^{-33} Joules, ω=10^{-29} Joules, $\sum_{m=1}^{N}D_m^{(2)}$ =10^{-29} Joules, $\sum_{m=1}^{N}D_m^{(4)}$ =10^{-42} Joules, K_s= 10^{-30} Joules, H_{in}=10^{-32} Am^{-1} and H_{out}=10^{-39} Am^{-1}, $\bar{S}_y$ approaches zero at 160 K as shown in Figure 2. This means that T_s can be reduced by increasing ω.

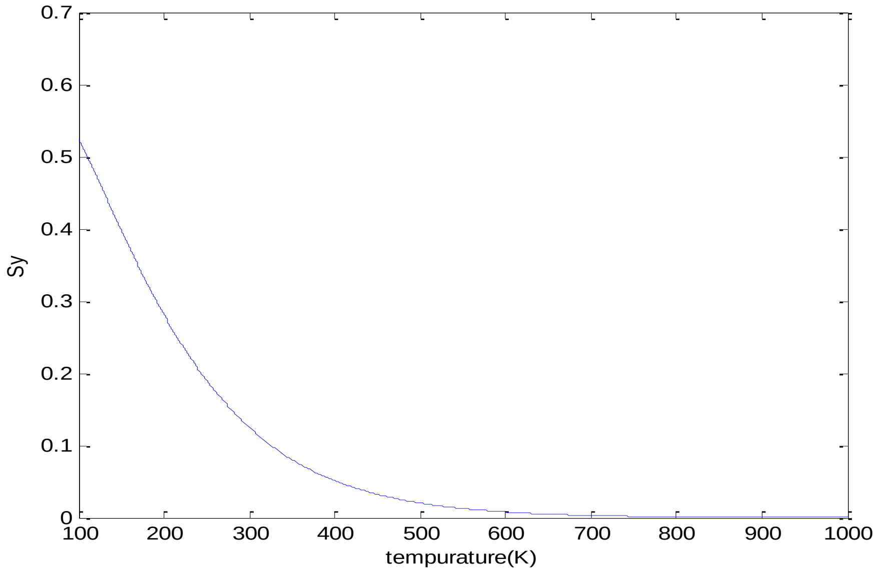

***Fig. 1:** $\overline{S}_y$ versus Temperature for the First Set of Values of Energy Parameters.*

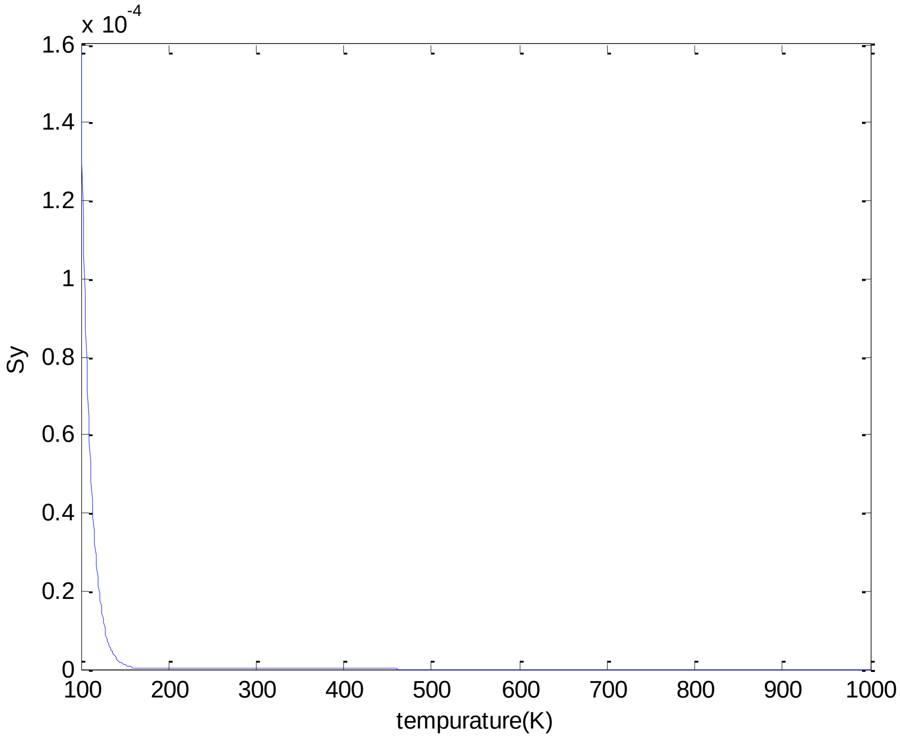

***Fig. 2:** $\overline{S}_y$ versus Temperature for the Second Set of Values of Energy Parameters.*

The variation of T_s with J is given in Figure 3. Other values of energy parameters were kept at $\omega=10^{-30}$ Joules, $\sum_{m=1}^{N} D_m^{(2)}=10^{-29}$ Joules, $\sum_{m=1}^{N} D_m^{(4)}=10^{-42}$ Joules, $K_s= 10^{-30}$ Joules, $H_{in}=10^{-32}$ Am^{-1} and $H_{out}=10^{-39}$ Am^{-1} for this simulation. So T_s gradually increases with J. A rapid variation of T_s can be observed above $J=10^{-30}$ Joules, whereas T_s doesn't vary with J below $J=10^{-31}$ Joules. T_s slightly varies with J between $J=10^{-30}$ and 10^{-31} Joules. Spin exchange interaction is related to the coupling between spins. So spins are restricted to rotate freely in a particular direction at higher values of J. As a result, T_s increases with J.

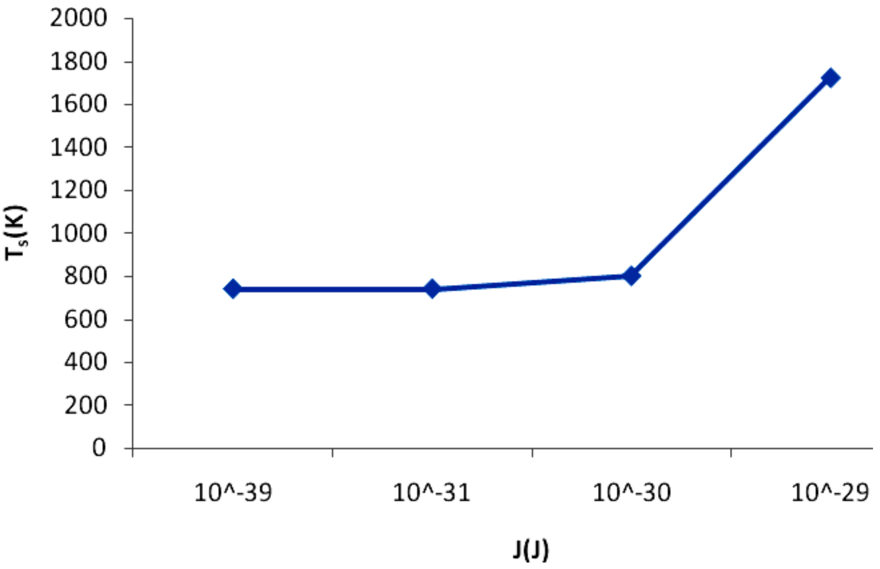

Fig. 3: *Variation of T_s with J.*

Figure 4 shows the variation of T_s with K_s. Below $K_s=10^{-29}$ Joules, T_s slightly varies with K_s. Above $K_s=10^{-29}$ Joules, T_s drastically decreases with K_s. Other energy parameters were set to J = 10^{-33} Joules, $\omega=10^{-30}$ Joules, $\sum_{m=1}^{N} D_m^{(2)} = 10^{-29}$ Joules, $\sum_{m=1}^{N} D_m^{(4)} = 10^{-42}$ Joules, $H_{in}=10^{-32}$ Am^{-1} and $H_{out}=10^{-39}$ Am^{-1} in this simulation. Due to in plane stress, spins prefer to align in the in plane direction [10]. As a matter of fact, T_s decreases with K_s. As shown in Figure 5, T_s varies with H_{in}. Other parameters were kept at J = 10^{-33} Joules, $\omega=10^{-30}$ Joules, $\sum_{m=1}^{N} D_m^{(2)} = 10^{-29}$ Joules, $\sum_{m=1}^{N} D_m^{(4)} = 10^{-42}$ Joules, $K_s= 10^{-30}$ Joules and $H_{out}=10^{-39}$ Am^{-1} for this simulation. Below $H_{in}=10^{-29}$ Am^{-1}, T_s doesn't vary with H_{in}. Above $H_{in}=10^{-29}$ Am^{-1}, T_s rapidly decreases with H_{in}. At larger values of internal in plane magnetic field, spins can easily rotate in the in plane direction. Then T_s decreases with H_{in}.

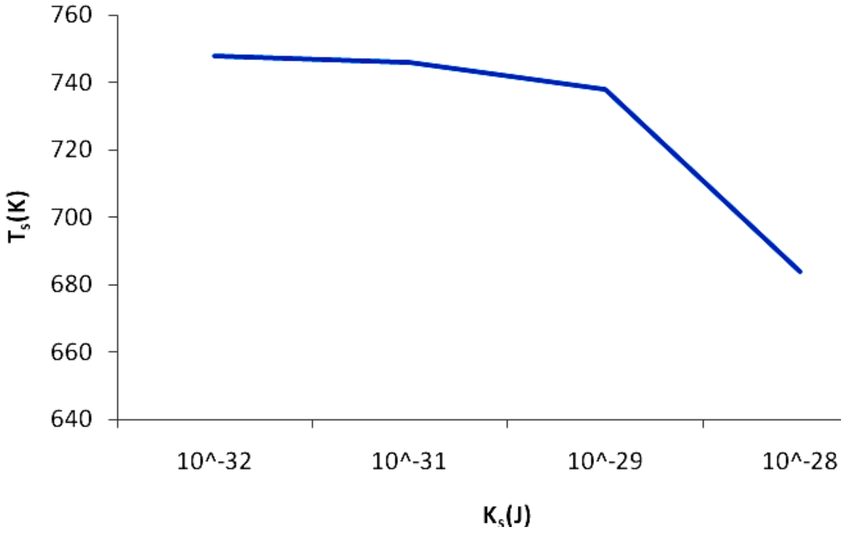

Fig. 4: *Plot of T_s versus K_s.*

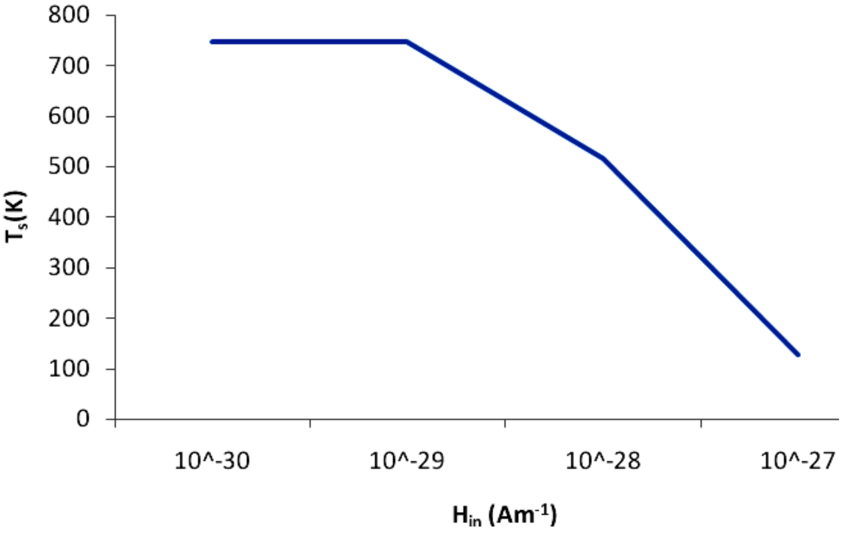

Fig. 5: *Dependence of T_s on H_{in}.*

CONCLUSION

The easy axis orientation of polycrystalline strontium ferrite thin films sputtered on polycrystalline Al_2O_3 substrates could be explained using our modified Heisenberg Hamiltonian model. The total energy of oriented hexaferrite thin films derived from this model was employed in this case, rather than considering 2nd or 3rd order perturbation. Variation of average value of in plane spin component with temperature was investigated. The spin reorientation temperature solely depends on ω J, K_s and H_{in}. However, T_s is slightly sensitive to other energy parameters too. Below 500°C, the easy axis of strontium ferrite is oriented in the plane of the film. This particular spin reorientation temperature could be obtained at J = 10^{-33} Joules, ω=10^{-30} Joules, $\sum_{m=1}^{N} D_m^{(2)}=10^{-29}$ Joules, $\sum_{m=1}^{N} D_m^{(4)}=10^{-42}$ Joules, $K_s= 10^{-30}$ Joules, $H_{in}=10^{-32}$ Am^{-1} and $H_{out}=10^{-39}$ Am^{-1}. However, the spin reorientation temperature could be varied in a wide range by changing the values of J, ω, $\sum_{m=1}^{N} D_m^{(2)}$, $\sum_{m=1}^{N} D_m^{(4)}$, K_s, H_{in} and H_{out}. Because the exact experimental values of J, ω, $\sum_{m=1}^{N} D_m^{(2)}$, $\sum_{m=1}^{N} D_m^{(4)}$, K_s, H_{in} and H_{out} of strontium thin films can’t be found, a reasonable set of values has been employed for these explanations.

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