ISSN 1512-1461

UDC: Condensed matter Physics, Solid state Physics, Theoretical Condensed matter Physics

INVESTIGATION OF SPIN REORIENTATION IN NICKEL FERRITE FILMS

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Abstract

The spin reorientation temperature of Nickel ferrite has been studied using the Heisenberg Hamiltonian model of oriented ferrite films. Orientation of easy axis of Nickel ferrite films fabricated on C-plane sapphire substrates using pulsed laser ablation method has been explained by means of the average value of in plane spin component. The experimental value of spin reorientation temperature (930 ^{0}C) could be verified using this theoretical model. According to this model, spin reorientation temperature (T_s) vastly depends on out of plane magnetic field (H_{out}). In addition, T_s is slightly sensitive to the stress induced anisotropy and magnetic dipole interaction. The temperature, at which easy axis is oriented perpendicular to the substrate plane, can be slightly lowered by decreasing in plane magnetic field and second order anisotropy. The lowest value of T_s obtained in this study was 1133 K.

Keywords: *Easy axis orientation, magnetic thin films, ferrites*

I. Introduction:

Easy axis oriented Nickel ferrite films are extensively used in magnetic memory devices and microwave applications [1-3]. So the study of spin orientation temperature is really important to investigate the easy axis orientation. The orientation of easy axis solely depends on the orientation of the substrate and deposition temperature [4]. But in some cases, the orientation of easy axis depends on gas pressure inside the chamber, type of the gas used while deposition and post deposition annealing conditions [5]. Mostly the direction of easy axis varies with the deposition temperature, and easy axis is oriented perpendicular to the film plane at higher temperatures [4]. In some cases, the in plane orientation can be observed at lower temperatures depending on the other deposition conditions [6]. The same kind of variation of easy axis can be obtained for other ferrimagnetic materials such as Lithium mixed ferrite too [7].

But it is difficult to find any early report which relates theoretically obtained spin reorientation temperature of Nickel ferrite to the experimental values. In this manuscript, the behavior of experimentally deposited easy axis oriented Nickel ferrite films has been explained using the 2-D classical Heisenberg Hamiltonian model derived for oriented Nickel ferrite films by us previously [8]. This similar kind of study of spin orientation temperature has been performed for ferromagnetic materials such as Fe and Ni by some other researchers [9]. In our simulations, MATLAB software package has been used to plot all the graphs.

2. Model:

The energy of oriented Nickel ferrite films per unit spin is given by following equation [8].

$$E(\theta) = 2J(26.25N-10) - 48.415\omega N(1+3\cos 2\theta)$$
$$-\cos^2\theta \sum_{m=1}^{N} D_m^{(2)} - \cos^4\theta \sum_{m=1}^{N} D_m^{(4)} + 6N(H_{in}\sin\theta + H_{out}\cos\theta + K_s \sin 2\theta) \quad \textbf{(1)}$$

ISSN 1512-1461

The film has been divided to N number of spin layers parallel to the substrate. All the spins are considered to be parallel to each other in oriented case. Here θ is the angle between the spin and a line drawn perpendicular to the film plane. J is the spin exchange interaction energy constant. ω is the strength of long range dipole interaction. $D_m^{(2)}$ and $D_m^{(4)}$ are second and fourth order anisotropy constants, respectively. Here the last term indicates the change of magnetic energy under the influence of internal stress. K_s depends on the product of magnetostriction coefficient and the stress. K_s can be positive or negative depending on the type of stress whether it is compressive or tensile.

Integer m denotes the indices of planes, and it varies from 1 to N for a film with N number of layers. First, second, third and fourth terms represent the spin exchange interaction, magnetic dipole interaction, second order anisotropy and fourth order anisotropy. $\vec{H}$ is the internal magnetic field (not applied field) on the considered spin due to the effect of surrounding spins. H_{in} and H_{out} are the in plane and out of plane components of this magnetic field. In this 2-D model, all the spins are assumed to be in the plane of y-z. The x component of the spin is always taken to be zero.

3. Results and discussion:

The average value of in plane spin component can be found using following equation for a unit spin.

$$\overline{S}_y = \frac{\int_0^{\pi} e^{-\frac{E}{kT}} \sin\theta d\theta}{\int_0^{\pi} e^{-\frac{E}{kT}} d\theta} \quad \textbf{(2)}$$

Here k (=1.38x10^{-23} J/K) and T are Boltzmann's constant and absolute temperature in Kelvin, respectively. The energy given in equation (1) will be used in equation (2) to derive an expression for the average spin. Finally the average spin can be found as a variable of the temperature. S.I units have been used through out all these simulations.

Because the experimental values of $D_m^{(2)}, D_m^{(4)}, H_{in}, H_{out}, K_s$, J and ω have not been measured by any researcher yet, the simulations were carried out for a reasonable set of $D_m^{(2)}, D_m^{(4)}, H_{in}, H_{out}, K_s$, J and ω values as following. First $\overline{S}_y$ was found for J =10^{-40} Joules, ω=10^{-40} Joules, $\sum_{m=1}^{N} D_m^{(2)}$ =10^{-26} Joules, $\sum_{m=1}^{N} D_m^{(4)}$ =0 Joules, H_{in}=10^{-28} Am^{-1}, H_{out}=10^{-28} Am^{-1} and K_s=10^{-35} Joules. Because the thickness of this Nickel ferrite film is approximately 3.6 μm, the number of layers (N) was calculated to be 4317. The graph of $\overline{S}_y$ versus T is given in figure 1. According to this graph, the in plane spin component becomes zero at 1203 K. Therefore only the spin component perpendicular to the substrate plane survives at 1203 K, implying that the easy axis is oriented perpendicular to the film plane at 1203 K.

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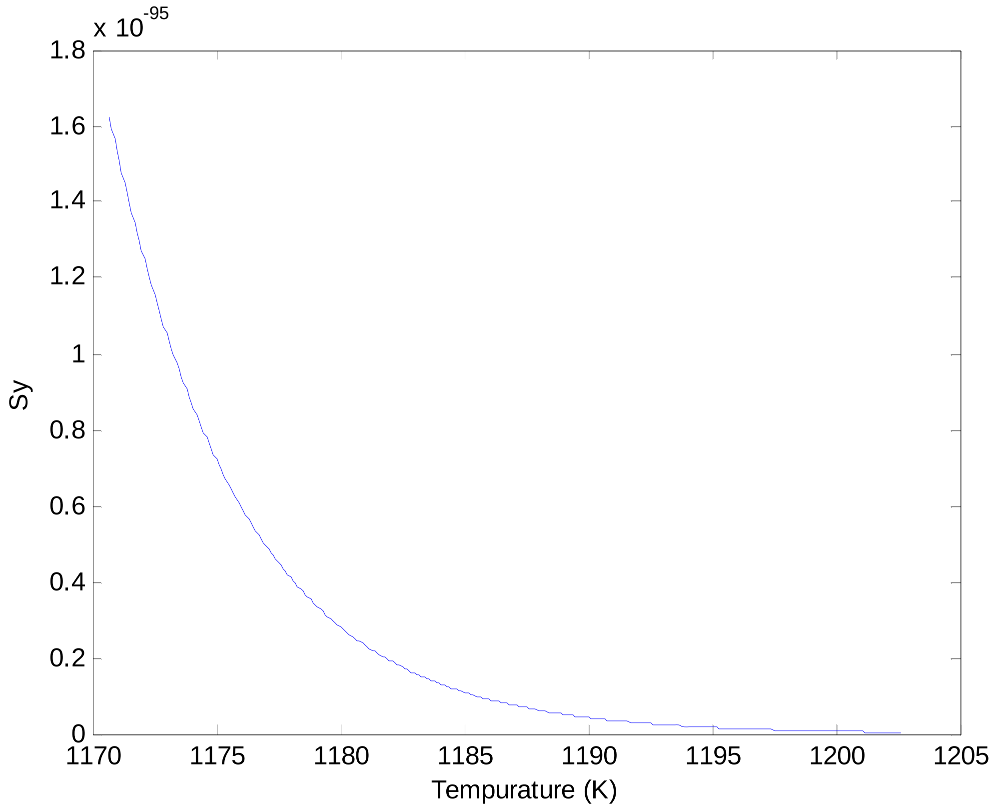

Figure 1: Graph of $\bar{S}_y$ versus temperature at J $=10^{-40}$ Joules, $\omega=10^{-40}$ Joules, $\sum_{m=1}^{N} D_m^{(2)}=10^{-26}$ Joules, $\sum_{m=1}^{N} D_m^{(4)}=0$ Joules, $H_{in}=10^{-28}$ Am^{-1}, $H_{out}=10^{-28}$ Am^{-1} and $K_s=10^{-35}$ Joules.

According to our experimental data, the easy axis of Ni ferrite film synthesized using pulsed laser ablation method was perpendicular to the film plane at 930 ^{0}C on C-plane sapphire substrate [4]. As shown in the X-ray diffraction (XRD) patterns of the experimental work, the film is randomly oriented at low temperatures [4]. But when the temperature was gradually increased, the orientation of the film gradually changed from the random to out of plane oriented state. This perpendicular orientation of easy axis could be obtained only on C-plane sapphire substrates, because many of the energy parameters depend on the type of the substrate too. Therefore, this perpendicular orientation could not be obtained for the Ni ferrite films deposited on other substrates such as A-plane or R-plane sapphire substrates. According to our theoretical data, $\bar{S}_y$ is non zero at low temperatures, and $\bar{S}_y$ gradually

ISSN 1512-1461

decreases to zero as the temperature is increased. Therefore, the experimental data tally with the theoretical data for the values of energy parameters used in this simulation.

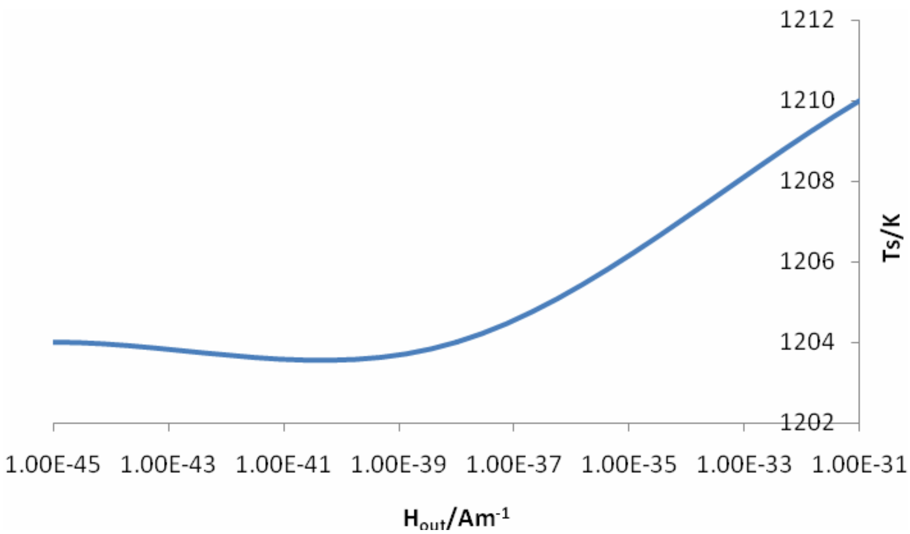

Figure 2: Spin reorientation temperature versus out of plane magnetic field at J $=10^{-40}$ Joules, $\omega=10^{-40}$ Joules, $\sum_{m=1}^{N} D_m^{(2)}=10^{-26}$ Joules, $\sum_{m=1}^{N} D_m^{(4)}=0$ Joules, $H_{in}=10^{-28}$ Am^{-1} and $K_s=10^{-35}$ Joules.

Then the variation of spin reorientation temperatures (T_s) with $D_m^{(2)}, D_m^{(4)}, H_{in}, H_{out}, K_s$, J and ω was studied. Although T_s rapidly varies with H_{out}, it slightly varies with K_s and ω. The variation of T_s is higher, when H_{out} is changed from 10^{-31} to 10^{-45} Am^{-1} and K_s is increased above 10^{-26} Joules. The variation of T_s with H_{out} is given in figure 2. In this plot, the other energy parameters were kept at J $=10^{-40}$ Joules, $\omega=10^{-40}$ Joules, $\sum_{m=1}^{N} D_m^{(2)}=10^{-26}$ Joules, $\sum_{m=1}^{N} D_m^{(4)}=0$ Joules, $H_{in}=10^{-28}$ Am^{-1} and $K_s=10^{-35}$ Joules. The lowest value of T_s was found around $H_{out}=10^{-40}$ Am^{-1}.

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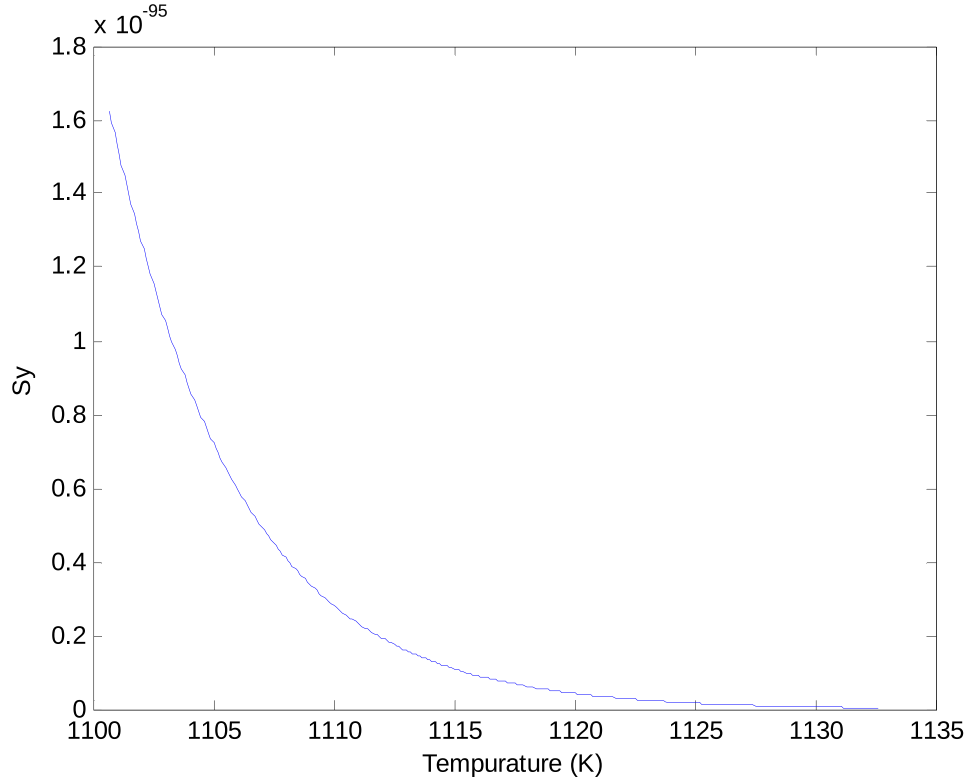

Figure 3: Plot of $\bar{S}_y$ versus temperature at J =10^{-40} Joules, ω=10^{-40} Joules, $\sum_{m=1}^{N} D_m^{(2)}$ =10^{-28} Joules, $\sum_{m=1}^{N} D_m^{(4)}$ =0 Joules, H_{in}=0 Am^{-1}, H_{out}=10^{-28} Am^{-1} and K_s=10^{-35} Joules.

If the thin film can be oriented at lower temperatures, it will be experimentally useful. According to figure 3, the spin reorientation temperature is 1133 K. This graph has been plotted for J =10^{-40} Joules, ω=10^{-40} Joules, $\sum_{m=1}^{N} D_m^{(2)}$ =10^{-28} Joules, $\sum_{m=1}^{N} D_m^{(4)}$ =0 Joules, H_{in}=0 Am^{-1}, H_{out}=10^{-28} Am^{-1} and K_s=10^{-35} Joules. Compared to the graph in figure 1, only H_{in} and $\sum_{m=1}^{N} D_m^{(2)}$ have been varied to plot the graph in figure 3. All the other energy parameters remain the same in figure 1 and 3. When H_{in}=0, the spins can easily rotate to the direction normal to the film plane. This can be the reason for the lower spin reorientation temperature. According to figure 1 and 3, $\bar{S}_y$ decreases toward the zero at the same rate. This same decay rate of $\bar{S}_y$ has been observed in the variation of ω too. According to our data, the rate of change of $\bar{S}_y$ is almost independent of the energy parameters such as $D_m^{(2)}, D_m^{(4)}, H_{in}, H_{out}, K_s$, J and ω.

4. Conclusion:

The 2-D Heisenberg Hamiltonian model of oriented Nickel ferrite films could be used to explain the experimental data obtained for laser ablated Nickel ferrite films synthesized on C-plane single

ISSN 1512-1461

crystal sapphire substrates. Experimentally Nickel ferrite films with easy axis oriented perpendicular to the film plane could be deposited at 1203 K. The variation of average in plane spin component was investigated to understand the orientation of easy axis. Theoretically this temperature (1203 K) could be obtained for J =10^{-40} Joules, ω=10^{-40} Joules, $\sum_{m=1}^{N} D_m{}^{(2)}$ =10^{-26} Joules, $\sum_{m=1}^{N} D_m{}^{(4)}$ =0 Joules, H_{in}=10^{-28} Am^{-1}, H_{out}=10^{-28} Am^{-1} and K_s=10^{-35} Joules. Then the variation of the spin reorientation temperature (T_s) with $D_m{}^{(2)}, D_m{}^{(4)}, H_{in}, H_{out}, K_s$, J and ω was studied using this model. Although T_s mainly depends on H_{out}, it slightly depends on K_s and ω. At J =10^{-40} Joules, ω=10^{-40} Joules, $\sum_{m=1}^{N} D_m{}^{(2)}$ =10^{-28} Joules, $\sum_{m=1}^{N} D_m{}^{(4)}$ =0 Joules, H_{in}=0 Am^{-1}, H_{out}=10^{-28} Am^{-1} and K_s=10^{-35} Joules, T_s was found to be 1133 K.

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Article received: 2012-01-11