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STRESS INDUCED ANISOTROPY AND APPLIED FIELD DEPENDENCE OF SECOND ORDER PERTURBED ENERGY OF THICK FERROMAGNETIC FILMS

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ABSTRACT

The energy of thick ferromagnetic films up to 10000 layers has been explained in this report using classical Heisenberg Hamiltonian with second order perturbation. Especially the effect of applied magnetic field and stress on energy of sc(001) ferromagnetic thick films has been investigated. Under the influence of perpendicular magnetic field given by $\frac{H_{out}}{\omega}$ = 6, the sc(001) ferromagnetic film with 10000 layers can be easily oriented in 0.5 radians direction. The easy direction of sc(001) ferromagnetic film with 10000 layers was found to be 0.6 radians when the in-plane magnetic field of $\frac{H_{in}}{\omega}$ = 4.2 is applied. Because the easy axis oriented magnetic films are useful in magnetic memory devices and monolithic microwave integrated circuits (MMIC), the determination of easy direction is important. If the stress given by $\frac{K_s}{\omega}$ = 2.6 is applied in perpendicular direction to the film plane, the film can be easily oriented in direction of 3 radians. Energy under influence of perpendicular magnetic field is larger than the energy under the influence of in-plane magnetic field. After introducing the second order perturbation to the Heisenberg Hamiltonian, even some small variations of energy could be investigated as indicated in the graphs in this manuscript.

Keywords: Ferromagnetic materials, thick films, Heisenberg Hamiltonian, stress induced anisotropy

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INTRODUCTION

The energy of oriented thick ferromagnetic films has been studied using classical Heisenberg Hamiltonian (Samarasekara, 2006). The energy curves of these oriented thick ferromagnetic films were smooth, and the angle between easy and hard directions was 90^0 for bcc(001) lattice. The energy was calculated for discrete and continuous variation of thickness, and the calculated energy using both methods was same (Samarasekara, 2006). Previously the variation of energy of thick sc(001) and fcc(001) ferromagnetic films with 10000 number of layers has been investigated using second order perturbed Heisenberg Hamiltonian (Samarasekara & Silva, 2007). According to this study, although the angle between easy and hard directions was 90^0 for sc(001) lattice, this angle was not 90^0 for fcc(001) lattice. Also the energy separation between the easy and hard direction is very small for 22 and 44 layers for sc(001) and fcc(001) ferromagnetic materials, respectively (Samarasekara & Silva, 2007). Introducing the second order perturbation has introduced some overshooting by destroying the smoothness of the energy curve. In addition to these, Heisenberg Hamiltonian with second order perturbation has been used to study the energy of ultra-thin ferromagnetic films (Samarasekara, 2006). The angle between easy and hard directions for sc(001), bcc(001) and fcc(001) ultra-thin ferromagnetic films was found to be 90^0 (Samarasekara, 2006).

Exchange anisotropy has been widely studied in last decade, because of the difficulties of physical understanding of exchange anisotropy and to its application in magnetic media technology and magnetic sensors (Lederman *et al*., 2004). The magnetic properties of thin films of ferromagnetic materials have been investigated using the Bloch spin-wave theory earlier (Klein & Smith, 1951). Due to the strain induced distortion in the inner layers, bulk anisotropy energies will appear absent or very small in the ideal crystal. Some thin films indicate a tetragonal distortion resulting in stress-induced uniaxial anisotropy energy in the inner layers with perpendicular orientation of easy axis. The magnetic in-plane anisotropy of a square two-dimensional (2D) Heisenberg ferromagnet in the presence of magnetic dipole interaction has been determined earlier (Dantziger *et al*., 2002). The long range character of the dipole interaction itself is sufficient to stabilize the magnetization in 2-D magnet. Also the easy and hard axes of the magnetization with respect to lattice frame are determined by the anisotropies. Magnetic properties of the Ising ferromagnetic thin films with alternating superlattice layers were investigated (Bentaleb *et al*., 2002). In addition to these, Monte Carlo simulations of hysteresis loops of ferromagnetic thin films have been theoretically traced.

MODEL

The Heisenberg Hamiltonian of any ferromagnetic film can be generally represented by following equation (Samarasekara, 2006; Samarasekara & Silva, 2007).

$$H= -\frac{J}{2}\sum_{m,n}\vec{S}_m.\vec{S}_n+\frac{\omega}{2}\sum_{m\neq n}\left(\frac{\vec{S}_m.\vec{S}_n}{r_{mn}^{\;3}}-\frac{3(\vec{S}_m.\vec{r}_{mn})(\vec{r}_{mn}.\vec{S}_n)}{r_{mn}^{\;5}}\right)-\sum_m D_{\lambda m}^{\;(2)}(S_m^{\;z})^2-\sum_m D_{\lambda m}^{\;(4)}(S_m^{\;z})^4$$
$$-\sum_{m,n}[\vec{H}-(N_d\vec{S}_n/\mu_0)].\vec{S}_m-\sum_m K_s Sin2\theta_m$$

Here m (or n), N, J, $Z_{|m-n|}, \Phi_{|m-n|}$, ω, θ_m (or θ_n), $D_m^{(2)}$, $D_m^{(4)}$, H_{in}, H_{out}, N_d, K_s are indices of layers, total number of layers, spin exchange interaction, number of nearest spin neighbors, constants arisen from partial summation of dipole interaction, strength of long range dipole interaction, azimuthal angles of spins, second order anisotropy, fourth order anisotropy, in plane applied field, out of plane applied field, demagnetization factor and the stress induced anisotropy factor, respectively.

Finally following equation of total energy can be obtained (Samarasekara & Silva, 2007).

$$E(\theta)=-\frac{J}{2}[NZ_0+2(N-1)Z_1]+\{N\Phi_0+2(N-1)\Phi_1\}\left(\frac{\omega}{8}+\frac{3\omega}{8}\cos 2\theta\right)$$
$$-N\left(\cos^2\theta D_m^{\;(2)}+\cos^4\theta D_m^{\;(4)}+H_{in}\sin\theta+H_{out}\cos\theta-\frac{N_d}{\mu_0}+K_s\sin 2\theta\right)$$
$$-\frac{[-\frac{3\omega}{4}(\Phi_0+2\Phi_1)+D_m^{\;(2)}+2D_m^{\;(4)}\cos^2\theta]^2(N-2)\sin^2 2\theta}{2C_{22}}$$
$$-\frac{1}{C_{11}}[-\frac{3\omega}{4}(\Phi_0+\Phi_1)+D_m^{\;(2)}+2D_m^{\;(4)}\cos^2\theta]^2\sin^2 2\theta \qquad \textbf{(1)}$$

Here $C_{11}= JZ_1-\frac{\omega}{4}\Phi_1(1+3\cos 2\theta)-2(\sin^2\theta-\cos^2\theta)D_m^{\;(2)}$

$$+4\cos^2\theta(\cos^2\theta-3\sin^2\theta)D_m^{\;(4)}+H_{in}\sin\theta+H_{out}\cos\theta-\frac{2N_d}{\mu_0}+4K_s\sin 2\theta$$

$C_{22}= 2JZ_1-\frac{\omega}{2}\Phi_1(1+3\cos 2\theta)-2(\sin^2\theta-\cos^2\theta)D_m^{\;(2)}$

$$+4\cos^2\theta(\cos^2\theta-3\sin^2\theta)D_m^{\;(4)}+H_{in}\sin\theta+H_{out}\cos\theta-\frac{2N_d}{\mu_0}+4K_s\sin 2\theta$$

RESULTS AND DISCUSSION

For sc(001) lattice, $Z_0 = 4$, $Z_1 = 1$, $\Phi_0 = 9.0336$ and $\Phi_1 = -0.3275$ (Usadel & Hutch, 2002).

Experimental values of J, ω, $D_m^{(2)}$, $D_m^{(4)}$, N_d and K_s have not been measured by any researcher previously. So this simulation will be carried out for some selected reasonable values of J, ω, $D_m^{(2)}$, $D_m^{(4)}$, N_d and K_s as following. As shown in figure 1, some energy minimums can be observed at different values of angles and $\frac{H_{out}}{\omega}$. Film can be easily oriented in some directions by applying some perpendicular external magnetic field. For example, film can be easily oriented in particular directions by applying magnetic field $\frac{H_{out}}{\omega} = 6$. The angle corresponding to this $\frac{H_{out}}{\omega} = 6$ can be found from figure 2. The maximum and minimum can be observed at 2.3 and 0.5 radians, respectively. Although it is easier to magnetize this film in the direction given by 0.5 radians, it is hard to magnetize this thin film in the direction given by 2.3 radians. Determination of easy and hard directions is really important in magnetic memory devices.

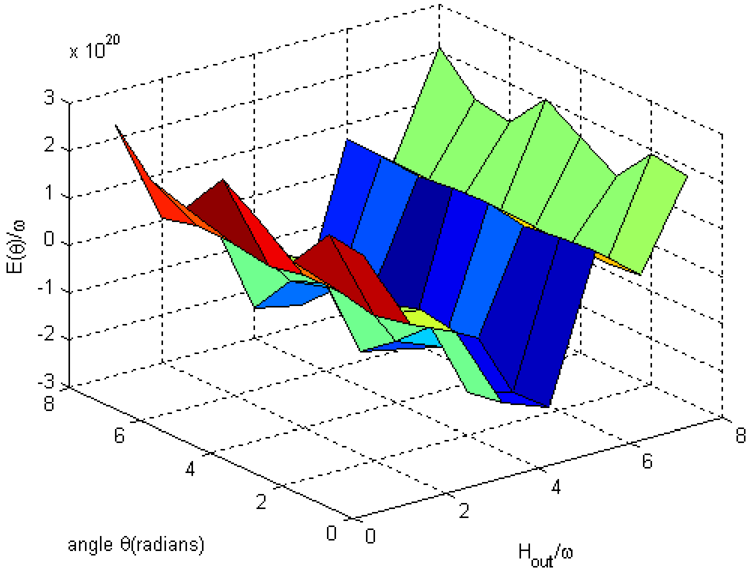

Figure 1: 3-D plot of energy versus angle and $\frac{H_{out}}{\omega}$ for sc(001) lattice with N=10000 and $\frac{J}{\omega} = \frac{D_m^{(2)}}{\omega} = \frac{N_d}{\mu_0 \omega} = \frac{K_s}{\omega} = 10, \frac{D_m^{(4)}}{\omega} = 5$, $H_{in} = 0$.

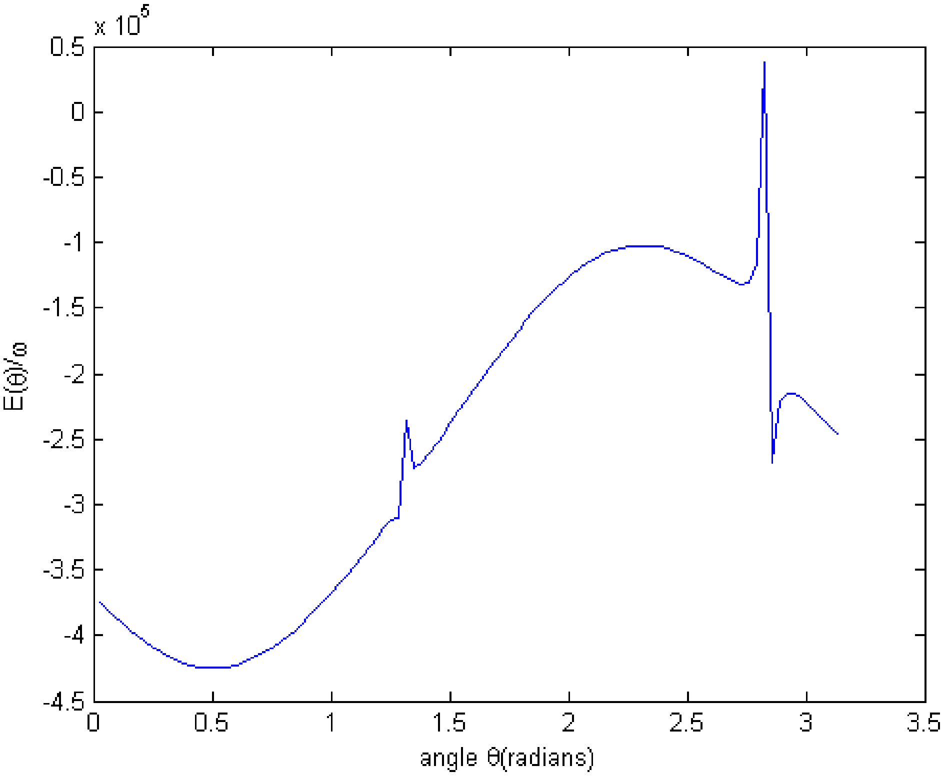

Figure 2: Energy versus angle at $\frac{H_{out}}{\omega}$ = 6 for N=10000

Although this graph number 3 is different from the first graph, several minimums can be observed at different values of angles and $\frac{H_{in}}{\omega}$ indicating that films can be easily oriented in those directions by applying this in-plane magnetic field. As an example, the energy is minimum at $\frac{H_{in}}{\omega} =$ 4.2. The angle of easy direction corresponding to this $\frac{H_{in}}{\omega} =$ 4.2 can be found from figure 4. Minimum and maximum of energy curve can be observed at 0.6 and 2.3 radians, respectively. This film can be easily oriented in the direction given by 0.6 radians.

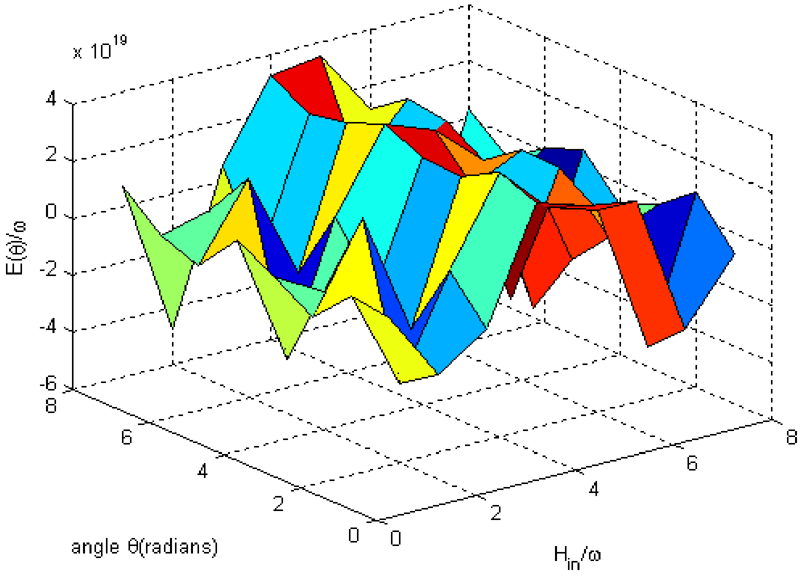

Figure 3: 3-D plot of energy versus angle and $\frac{H_{in}}{\omega}$ **for sc(001) lattice with N=10000 and** $\frac{J}{\omega}=\frac{D_m^{(2)}}{\omega}=\frac{N_d}{\mu_0\omega}=\frac{K_s}{\omega}=10, \frac{D_m^{(4)}}{\omega}=5$, **$H_{out}$=0.**

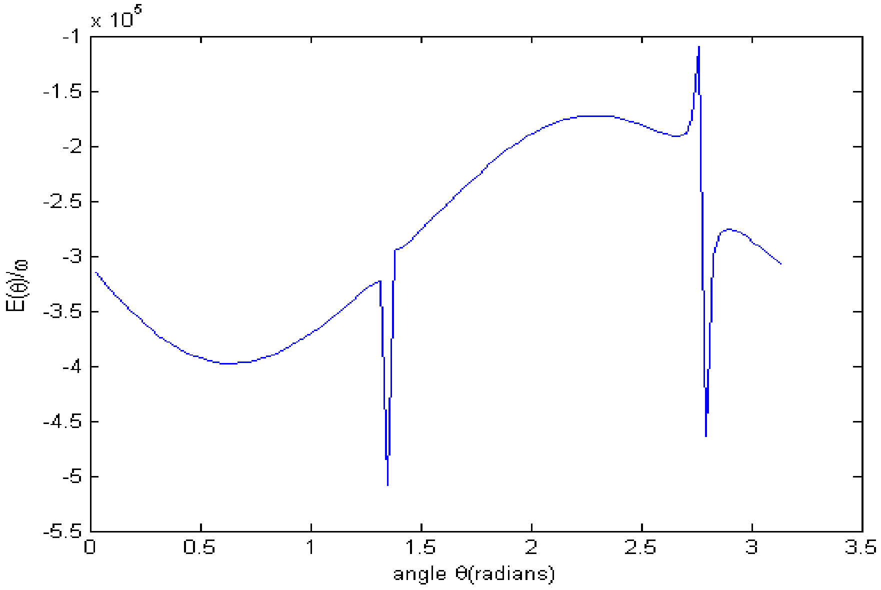

Figure 4: Energy versus angle at $\frac{H_{in}}{\omega}$ **= 4.2 for N=10000**

As shown in figure 5, at $\frac{K_s}{\omega}$ = 2.6 and angle of 3 radians, the energy is minimum. The film with 10000 layers can be easily oriented in direction given by 3 radians under the influence of stress $\frac{K_s}{\omega}$ = 2.6. According to our early experimental researches, a stress is induced in the film due to the difference between thermal expansion coefficients of film and the substrate, when the film is heated or cooled down during fabrication or annealing process of magnetic thin film. The magnetic anisotropy and energy depend on the induced stress of the magnetic film, which is determined by the thermal expansion coefficients and the temperature difference (Samarasekara & Cadieu, 2001; Samarasekara, 2003).

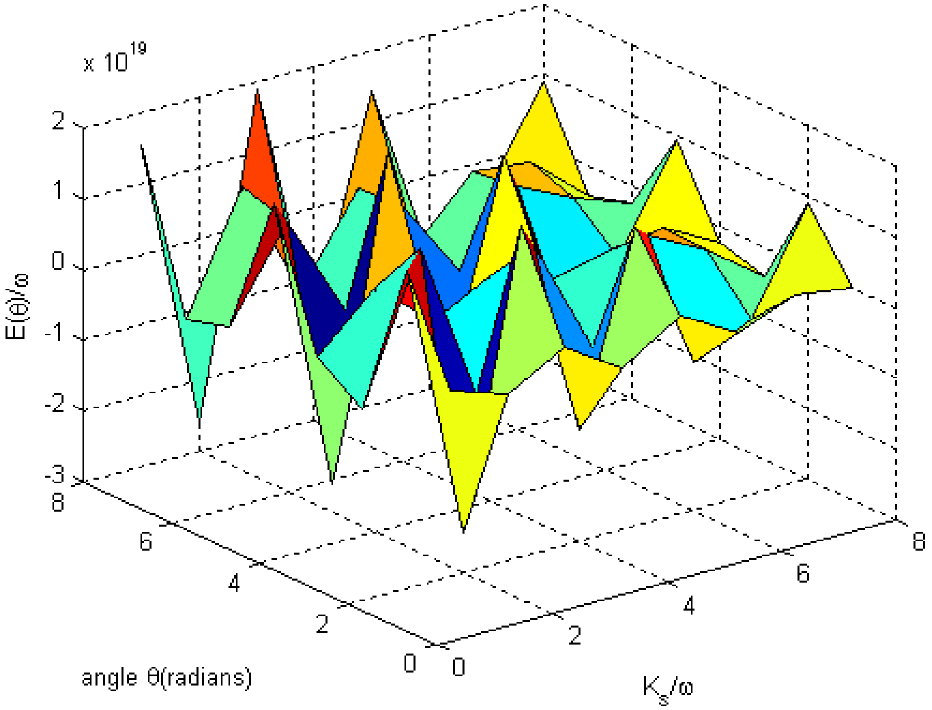

Figure 5: 3-D plot of energy versus angle and $\frac{K_s}{\omega}$ for sc(001) lattice with N=10000 and $\frac{J}{\omega}=\frac{D_m^{(2)}}{\omega}=\frac{H_{in}}{\omega}=\frac{H_{out}}{\omega}=\frac{N_d}{\mu_0\omega}=10, and\,\frac{D_m^{(4)}}{\omega}=5$.

CONCLUSIONS

According to 2-D and 3-D plots, the energy varies in a periodical manner with applied magnetic field, angle and stress. This implies that the film can be easily oriented in some directions by applying certain magnetic field or stress. By applying the perpendicular magnetic field given by $\frac{H_{out}}{\omega}$=6, the sc(001) ferromagnetic film with N=10000 can be easily oriented in 0.5 radians direction. The easy direction of sc(001) ferromagnetic film with 10000 layers is given by 0.6 radians under the influence of in-plane magnetic field $\frac{H_{in}}{\omega}$=4.2. Under the stress given by $\frac{K_s}{\omega}$=2.6 the film can be easily oriented in direction of 3 radians. These easy directions are valid only for the parameters used in this report, and the easy direction depends on the values of these parameters.

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