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Reorientation of Magnetization in Thin Films

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Abstract

The spin wave energy is determined by the competition between uniaxial and cubic anisotropy. We discuss the reorientation temperature T_R of magnetization in two-dimension and calculate its dependence on the exchange, J, and the uniaxial anisotropy, G, parameters within random phase approximation. We find that T_R varies as $\sqrt{JG}$ in the planar regime.

Experiments have shown that thin films of Fe on Ag (100) for a thickness less than a few monolayers [1, 2] show a phase transition at a temperature which is some fraction, typically of the order of a half of T_c (Curie temperature). It has been argued that this transition is driven by the large entropy associated with a planar magnet. In the past, numerous theoretical work has been done in order to understand this effect [3, 4, 5, 6, 7, 8].

It could be shown that the reorientation of the magnetization vector is a consequence of the competition between the surface anisotropy which may favor a perpendicular magnetization and the long-range dipole interaction which favors an in-plane magnetization. It was shown that both first and second order transitions are possible but the result is not physically very transparent [7, 8].

In the present paper, we focus on the order of the reorientation transition and on its dependence on system parameters. We have chosen to look at this problem using an RPA (random phase approximation) [9] spin wave approach which is valid in the uniaxial regime. We consider the spin wave theory for a two-dimensional ferromagnet with uniaxial anisotropy. The important fluctuations occur at long wavelength so that the effect of uniaxial anisotropy and anisotropic exchange are equivalent. In the uniaxial case the magnetization $\underline{M}$ is perpendicular to the wave vector $\underline{k}$, and the effects of dipolar interactions are not important in the spin wave regime and they can be safely neglected.

In order to determine the anisotropic part of the free energy, which is responsible for the existence of easy magnetization directions, we start with the Hamiltonian

$$H = H_0 + H_a, \tag{1}$$

where

$$H_0 = -J \sum_{\langle ij \rangle} \underline{S_i} \cdot \underline{S_j} \tag{2}$$

is the Heisenberg Hamiltonian and J in Equation (2) is the ferromagnetic nearest-neighbour coupling constant and

$$H_a = -G \sum_i (S_i^z)^2 + K_p \sum_i [(S_i^z S_i^y)^2 + (S_i^y S_i^z)^2 + (S_i^z S_i^z)^2] \tag{3}$$

describes the spin anisotropy. The first term on the right hand side (rhs) of Eq. (3) represent the uniaxial anisotropy constant and the second term is the cubic anisotropy constant. The inclusion of the entropic effects at high temperature is to reduce the importance of G. We study this by defining a variational free energy which is derived from Hamiltonian H', which is the same as Eq. (1) except that G has been replaced by a variational parameter g which is in Eq. (3).

We consider the effect upon the spin wave spectrum of an anisotropy within the easy plane. It is convenient to write the spins in terms of linearized spin wave variables [10]. Let us suppose that at temperature T the mean magnetic moment $\langle S \rangle = m$, which is independent both of g and T. The quantity m denotes the relative magnetization.

In the case of classical limit the total Hamitonian can be written in the following form[10]

$$H = \sum_k \left[a_k^+ a_k (\varepsilon_k + \xi) + \frac{1}{2} (a_k^+ a_{-k}^+ + a_k a_{-k}) \nu \right]. \tag{4}$$

We define $\xi = 2m(g + m^2 K_p)$ and $\nu = 0$ and note that ξ is independent of the wave vector $\underline{k}$ and arises from the anisotropy energy. The term ε_k arising from the exchange forces has the form Dk^2 in the region of interest in which $D \simeq 2Jma^2$ for sc, bcc and fcc lattices of lattice constant a. The spin wave energy is given by:

$$\hbar \omega_k = \left(A_k^2 - B_k^2 \right)^{1/2} \tag{5}$$

where $A_k = \varepsilon_k + \xi$ and $B_k = 0$. Using Equation (5) we find the spin wave energy for $\hbar = 1$

$$\omega_k = \varepsilon_k + 2m(g + m^2 K_p). \tag{6}$$

For the anisotropy energies with field applied parallel or perpendicular to the plane, these can be calculated from a quasi-classical argument. We consider the ground state energy as a function of the magnetization direction $F(g, \theta)$. We obtain:

$$F_{\parallel}(g, \theta) = -h_o m \sin\theta - g m^2 \cos^2\theta + \frac{1}{4} m^4 K_p \sin^2 2\theta \tag{7}$$

$$F_{\perp}(g,\theta) = -h_o m\cos\theta - gm^2\cos^2\theta + \frac{1}{4}m^4 K_p \sin^2 2\theta \tag{8}$$

where $h_o = g\mu_B H$. The main result of an applied field parallel to the film is that the equilibrium angle θ_o in low temperature phase $T < T_R$ is not exactly zero but assumes the field and temperature dependent value given by

$$\sin\theta_o = \frac{h_o}{2mg + 2m^3 K_p \cos 2\theta_0}. \tag{9}$$

In particular, when $h_o = 2m(g - m^2 K_p)$, i.e. for sufficiently high fields, a spin flop phase transition proceeds, with the perpendicular component going to zero. Similarly, a perpendicular applied field modifies the angle assumed by the magnetization after the transition to a value given by

$$\cos\theta_o = \frac{-h_o}{2mg + 2m^3 K_p \cos 2\theta_0}. \tag{10}$$

When $h_o = -2m(g + K_p m^2)$ the system undergoes a phase transition characterised by the parallel component of M vanishing.

Experiments show that for many systems the direction of the magnetization is a sensitive function of the temperature. At low temperatures the magnetization vector is perpendicular to the surface, which is attributed to a strong surface anisotropy, by increasing the temperature the magnetization vector switches to an in-plane direction [1]. This switching temperature decreases with increasing film thickness [11, 12, 13].

Jensen and Benneman[4] have used a classical mean field spin model. They find that T_R depends only on the surface anisotropy and is independent of the exchange provided that $J >> G$. This is unsatisfactory because $T_R << T_C$ (critical temperature) for all $J >> G$. An alternative approach has been used by Pescia and Pokrovsky[3] who show that the axial magnetic state becomes unstable to a Kosterlitz-Thouless phase. They find that T_R is proportional to T_C and hence that T_R can be appreciable fraction of T_C even for small anisotropy. However it was shown by Yafet et al[14] that the planar Heisenberg model is stabilised by dipolar interactions and that the Kosterlitz-Thouless transition is suppressed. Our result differs from these two earlier results [3, 4] in that the in-plane magnetization appears when the perpendicular magnetization goes to zero. To show it we write the total free energy F of the system as the following:

$$F(g,\theta) = F_o(g,\theta) + < H - H' >_o \tag{11}$$

where

$$F_o(g,\theta) = F_{\parallel}(g,\theta) + k_B T \sum_k \ln\left(1 - e^{-\beta\omega_k}\right) \tag{12}$$

and the angular brackets denote the thermal average. Since the only $\underline{k}$ dependence of ω_k comes from ε_k, the sum, which is the second term of Eq. (12), may be transformed

into an integral in two dimension between the energy gap and the first Brillouin zone boundary.

The total free energy is minimized with respect to g and the result is:

$$\frac{h_o}{2m(g-m^2K_p)^2}\left(-h_om+2Gm^2-2m^4K_p\right)=\frac{k_BT}{4\pi J}\ln(\frac{k_BT}{\omega_o}), \tag{13}$$

where ω_o is the spin wave energy gap which is calculated by using Equation (6) at k=0. The expression for the reorientation temperature T_R is found from the condition that Equation (13) has a solution for $g \to 0$ at low temperatures. We find

$$T_R = \eta\sqrt{JG}, \tag{14}$$

where $\eta = \left(32\pi m^4/k_B^2\right)^{1/2}$. We find that at $T = 0$ $g = G$ as expexted and that for $T > 0$, g decreases and that the reorientational transition occurs at $T = T_R$ as $g \to 0$. This result is in agreement with the low temperature results of Chui [7].

We also compared our result with the experimental observations on the system Fe/Ag (100) obtained by Krebs et.al. [1] and Stampanoni et.al. [2]. They reported that the disappearance of the ground state perpendicular remanence at temperatures $\leq 100K$, i.e. well below the Curie temperature of the system. Our theory gives a reasonable explanation of this important experimental finding. Thus a reorientation transition occurs in a temperature region $T_R < T_c$ as where explored.

As a conclusion, reorientation temperature is driven by the large entropy associated with a planar magnet. The reorientation temperature of magnetization was calculated by using the RPA spin wave approach which is valid in the uniaxial regime. We found that the spin wave velocity varies as $\sqrt{JG}$ in the planar regime, which is a suggestive result.

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