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Effects of the applied magnetic field and anisotropy on the spin wave gap in ultrathin magnetic films at zero temperature

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ABSTRACT

We investigate the calculated spin wave gap of two-dimensional magnetic films under the combined influence of the in-plane direction of the applied magnetic field and different kinds of magnetic anisotropies. We also compute the spin wave gap as a function of the applied magnetic field at zero temperature. We discuss the results in connection with experimental data reported for epitaxial Fe-deficient yttrium garnet (YIG) films grown by pulsed laser deposition (PLD) technique onto the different faces of the $Gd_3Ga_5O_{12}$ single crystal.

1. Introduction

There has been a growing interest in thin films and two dimensional magnetic materials connected with the magnetic anisotropy which is closely related to the utilization of direction of magnetization for new technologies. Under the influence of film thickness, temperature and external magnetic field, these materials exhibit complicated phenomena [1–4], arising from film properties such as structure and morphology, which in turn are determined by the growth conditions [5].

Magnetic anisotropy plays a key role and leads to an energy gap in the spin wave spectrum. Such a gap behaves as an energy barrier to the excitation of long wavelength spin waves, therefore allowing for a finite order parameter at finite temperatures. The spin wave gaps in ultrathin films under the combined influences of the applied magnetic field and with different kinds of magnetic anisotropies were extensively studied [6–14].

The size-effect for the temperature of magnetic transition seen in experiments on MnF_2 epitaxial films with orthorhombic crystal structure in thick films is attributed to the low anisotropy energy deduced from the spin wave gap [14]. Investigations of the nature of magnetic anisotropy for iron garnet films grown by rf-sputtering [15,16] and PLD technique [17,18] are of great interest owing to their remarkable magneto-optic properties. These materials are also of interest in practice because of their significant magneto-optic and non-reciprocal effects [19]. Popova et al. [19] reported that the production of the magnetophotonic crystal structure reduces the magnetocrystalline and uniaxial in-plane anisotropies, including a partial out-of-plane magnetization. Recently, Manuilov and Grishin [20] observed an unusual magnetic anisotropy in epitaxial Fe-deficient yttrium iron garnet (YIG) films pulsed laser deposited onto the (1 1 1) and (0 0 1) face of $Gd_3Ga_5O_{12}$ single crystal and attributed these effects to reduced cubic and strong negative growth induced uniaxial magnetic anisotropy for such films.

The stabilization mechanism of magnetization is closely related to the in-plane anisotropy [21] and therefore this raises the important question concerning the influence of the in-plane anisotropy contribution and the direction of the applied field, which requires control of the spin wave gap. In a previous work [22] we calculated the spin wave gap of two dimensional magnets at zero temperature in an applied magnetic field which was perpendicular to the plane. It is of interest to look at the spin wave gap of two-dimensional films as a function of magnetic field which is applied parallel to the film plane at zero temperature. We perform two types of calculations: we calculate the spin wave gap as a function of (i) the direction of the applied field and (ii) the strength of applied field. In each case we change an arbitrary ratio of in-plane-to-cubic anisotropy in order to demonstrate how the spin wave gap condition varies with the influence of the in-plane anisotropy contribution. We need to know that the spin wave gap depends on the involved anisotropy, the direction of the applied external field, and the direction of the saturation magnetization.

2. Basic expressions

We first consider the effect upon the spin wave spectrum of an anisotropy within the easy plane. In bulk $Y_3Fe_5O_5$ crystals, the

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cubic crystalline magnetic anisotropy is negative. As a result, the cube body diagonal direction becomes the magnetic easy axis, the face diagonal direction becomes the medium axis, and the hard axis is parallel to the cubic edge direction [20]. For a film in the (x, y) plane, we assume that the magnetic anisotropy energy density has the following form:

$$E = K_u\,(\boldsymbol{e_z}\cdot\boldsymbol{s})^2 + K_{in}(\boldsymbol{e_y}\cdot\boldsymbol{s})^2 - E_c \quad (1)$$

so that the film is a cubic material, with the z axis being taken as the surface normal. In Eq. (1), K_u is the second-order uniaxial anisotropy constant which includes the surface anisotropy term of the film, K_{in} is the uniaxial in-plane anisotropy constant which breaks the fourfold symmetry, $\boldsymbol{e_y}$ and $\boldsymbol{e_z}$ are the unit vectors defining the anisotropy axes respectively, $\boldsymbol{s} = f(\theta, \varphi)$, $\|\boldsymbol{s}\| = 1$, and E_C is the contribution of the cubic anisotropy energy which is defined by

$$E_c = K_c\,(s_x^2 s_y^2 + s_y^2 s_z^2 + s_z^2 s_x^2). \quad (2)$$

Here K_c is the modified fourth-order cubic anisotropy constant associated with the crystal symmetry which arises mostly from the spin–orbit coupling. All of the anisotropy constants depend on thickness L. We choose the spherical coordinate system in which θ is the polar angle with respect to the film normal and φ defines the in-plane orientation. The sign convention contained in Eq. (1) implies that positive (negative) values of anisotropy constants favour the magnetization lying perpendicular to the film plane (in the plane). Suppose that the energy will be a minimum for directions θ_o, φ_o. Near this direction the energy surface will be ellipsoidal with the major and minor axes. The equilibrium angles are found from $\partial E/\partial\theta = \partial E/\partial\varphi = 0$ as $\theta_o = \pi/2$ and $\varphi_o = 0$. The anisotropy energy, containing anisotropy terms together with the magnetic field H oriented in the basal plane at angle ψ to the easy direction, is used to evaluate the equilibrium direction of saturation magnetization and the spin wave gap at zero temperature. Therefore, Eq. (1) can be rewritten in the following form:

$$\varepsilon\,(\theta, \varphi) = E\,(\theta, \varphi) - M_S H\,\sin\,\theta\,\cos(\psi - \varphi) \quad (3)$$

where M_S is the saturation magnetization. At equilibrium $\theta = \pi/2$ as before, and

$$\left.\frac{\partial\varepsilon}{\partial\varphi}\right|_{\theta_o,\varphi_o} = -\frac{K_c}{2}\sin\,4\varphi_o + K_{in}\,\sin\,2\varphi_o - M_S H\,\sin(\psi - \varphi_o) = 0. \quad (4)$$

This equation defines φ_o as a function of H. We now introduce the following parameters:

$$H_{in} = \frac{2K_{in}}{M_S}, \quad H_c = \frac{2K_c}{M_S},$$

where H_{in} and H_c are the in-plane and cubic anisotropic fields respectively, and form the dimensionless parameters $h = \frac{H}{H_c}$ and $\eta = \frac{H_{in}}{H_c}$. The parameter $\eta = 0, 1$ is selected to allow us to switch on or off the in-plane anisotropy. Using the approximation from [23], substituting $\psi - \varphi_o = \delta$, we expand the first and second terms in Eq. (4) and then neglecting terms of order δ^2, we obtain the following expression:

$$\psi - \varphi_o = \delta \approx \frac{2\eta\,\sin\,2\psi - \sin\,4\psi}{4(h + \eta\,\cos\,2\psi - \cos\,4\psi)}. \quad (5)$$

In Eq. (5), the $\cos\,2\psi$ and $\cos\,4\psi$ terms, which originate from the twofold and fourfold symmetry, play a dominant role in the rotation of the magnetization. For $\psi = 0$, these terms do not contribute to the magnetization process and full saturation of the magnetization is achieved. For $\psi = \pi/4$, the sign of the $\cos\,4\psi$ term can change from '+' to '−'. With a very strong applied external field, these terms are very small and thus can be neglected. In spite of this, the approach to saturation comes from the uniaxial in-plane and fourth-order cubic anisotropies in origin and also depends strongly on the film thickness (not shown in the figures).

We next consider the more interesting case which is the spin wave gap at zero temperature. The energy gap may be calculated from a quasi-classical argument. In order to obtain the energy gap, the effective force constants must be found from the second derivatives of Eq. (3). By using the approximation mentioned above:

$$\left.\frac{\partial^2\varepsilon}{\partial\theta^2}\right|_{\theta_o,\varphi_o} = 2\,\omega_1(h, \psi) = h\,\sin\,\theta_o - \xi\,\cos\,2\theta_o - \cos\,4\theta_o \quad (6)$$

$$\left.\frac{\partial^2\varepsilon}{\partial\varphi^2}\right|_{\theta_o,\varphi_o} = 2\,\omega_2(h, \psi) = h + \eta\,\cos\,2\psi - \cos\,4\psi + \delta\,(2\,\eta\,a - 4\,b) \quad (7)$$

where $\xi = \frac{H_u}{H_c}$, $a = \sin\,2\psi$ and $b = \sin\,4\psi$. The spin wave energy gap is given by [24],

$$\omega_o = \sqrt{(2\omega_1)(2\omega_2)}. \quad (8)$$

Manuilov and Grishin [20] experimentally obtained the twofold and fourfold anisotropy fields as well as the gyromagnetic g-factor as a

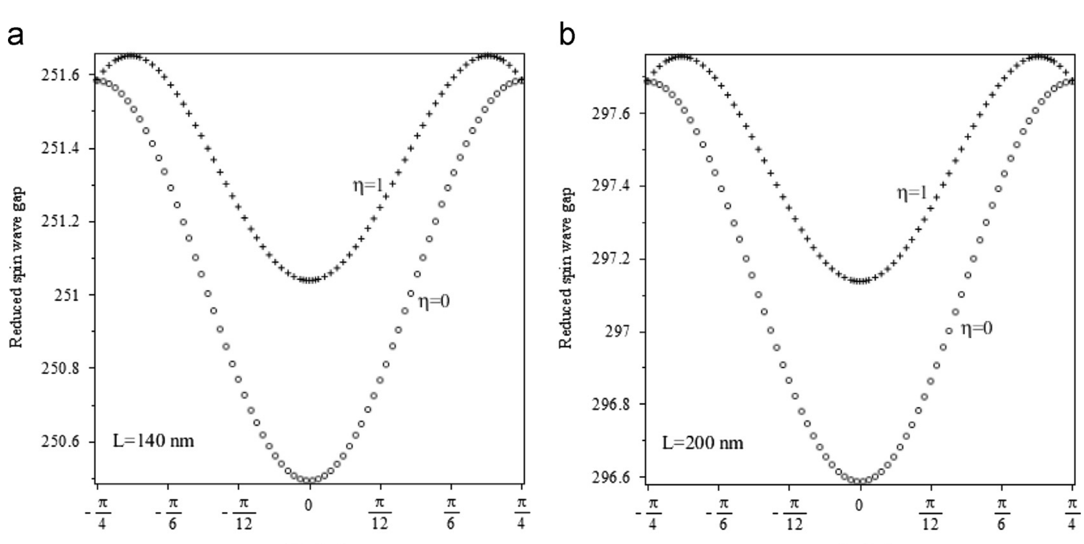

Fig. 1. Reduced spin wave energy gap as a function of the in-plane direction of the reduced external field for (a) $L = 140$ nm and (b) $L = 200$ nm.

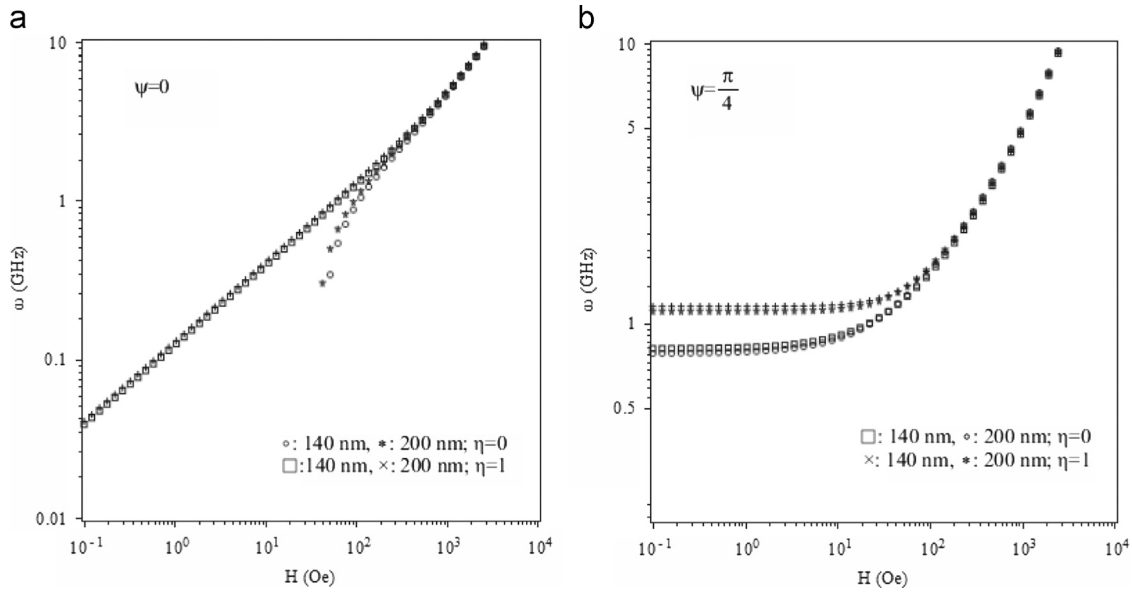

Fig. 2. Magnetic field dependence of the spin wave energy gap for (*a*) $\psi=0$ and (*b*) $\psi=\pi/4$ at the two ultrathin film thicknesses and relative anisotropies.

function of three different external magnetic field orientations: perpendicular to the film plane $H//[0\ 0\ 1]$ and the two in-plane directions $H//[1\ 0\ 0]$ and $H//[1\ 1\ 0]$. The values they found are as follows: in-plane magnetic fields ($H\leq 10^4$ Oe), $H_u=-1987$ Oe, $H_c=-44$ Oe and $g_{\perp}=1.998$ for $L=140$ nm; and $H_u=-2160$ Oe, $H_c=-37$ Oe, and $g_{\perp}=2.003$ for $L=200$ nm of thin films. Although they observed twofold and fourfold anisotropy fields in their two different materials, however they did not mention any measured in-plane term H_{in} which breaks the fourfold symmetry. This attribution only adds to the magnitude of the spin wave gap, which is important for our calculations. The ferromagnetic resonance indicates an occurrence of a soft mode for in-plane magnetic field. The uniform perpendicular magnetized state becomes unstable by nucleation of magnetic domains with in-plane components of magnetization along different directions. They observed only this reorientation phase transition at very low frequencies. Our theoretical results are well suited for their experimental data given, except for in-plane anisotropy. Fig. 1(a) and (b) show the reduced spin wave gaps of YIG films as a function of the in-plane direction of the reduced applied external field measured by the angle ψ with respect to the in-plane approximate $[1\ \overline{1}\ 0]$ and $[1\ 1\ 0]$ directions by using experimental data only at high fields of two different film thicknesses. As can be seen, the highest and the lowest spin wave gaps are different in magnitude for the two different film thicknesses as well as the presence of the in-plane anisotropy. Interestingly, the peaks shift to lower angles in the presence of the in-plane anisotropy. This means that the magnetization is close to saturation and its field dependence is controlled by spin wave excitations.

In the remaining part of this work, we deduce the spin wave gap as a function of applied field along the [1 0 0] and [1 1 0] directions. We can easily write the following expressions from Eqs. (6) and (7),

$$\omega_o^{[1\ 0\ 0]}=g\,\mu_B\,H_c\sqrt{(h+\xi-1)(h+\eta-1)} \tag{9}$$

and

$$\omega_o^{[1\ 1\ 0]}=g\,\mu_B\,H_c\sqrt{(h+\xi-1)(h+1+\frac{\eta^2}{h+1})}. \tag{10}$$

These two equations are the same as in Ref. [20], except for the term of 1 instead of 1/2 in the first parenthesis of Eq. (10) when $\eta=0$. Eq. (10) can also be used to define the spin wave gap at zero magnetic field so that the gap is essentially determined by the magnetic anisotropy. The magnetic field H is given in units of $g\mu_B=g\times 1.391\times 10^{-3}$ GHz/Oe, g being the gyromagnetic ratio and μ_B the Bohr magneton. Fig. 2(a) shows the plot of spin wave gap as a function of the applied field with respect to the [1 0 0] axis for the parameters $\eta=0,1$ in films with different thicknesses. Obviously, the curvatures are different for the case of $\eta=0$ below about 100 Oe. There is a sharp decrease at about 50 Oe. Manuilov and Grishin [20] also observed an indistinct pit at 48 Oe for $\eta=0$, which manifested the presence of spin wave soft mode. At high fields (≥ 100 Oe), the spin wave gap increases almost linearly with increasing magnetic field. For $\eta=1$, the spin wave gap changes linearly at all applied fields in which the two lines of 140 nm and 200 nm exactly coincide. This indicates that the films with different thicknesses are uniformly magnetized. Similarly, in Fig. 2(b), we present the same plot at the applied field with respect to the [1 1 0] axis for the same parameters and films. As can be seen, there is no linear behavior below about 50 Oe both for $\eta=0$ and $\eta=1$. The interesting thing is that the spin wave gap almost closes to a constant value below about 10 Oe. This points out that an easy plane magnet is unstable in two dimensions and hence any small effect which produces stabilization has a dramatic influence. This may be due to strong film distortions which contribute to the spin wave gap. Manuilov and Grishin [20] reported this observation as an unusual anisotropy, which may be neglected in their works.

In conclusion, our calculations confirm that the in-plane anisotropy contribution and the direction of the applied field strongly influence the spin wave gap of ultrathin films with small thickness. The results are applicable to the analysis of the experimental data on spin wave gap measurements. The in-plane anisotropy should dominate in determining the spin wave gap by over an order of magnitude. It is important to rule out the possible effect of an applied field in determining the spin wave gap which validates the presented models. We calculated the spin wave gap at zero temperature for a set of parameters common to both the cases of $\psi=0$ and $\pi/4$. For $\psi=\pi/4$ and a field above 100 Oe, the spin wave energy gap increases linearly. Below this field, it does not vary linearly with in-and-out of plane anisotropies due to strong film distortions. A comparison of our results with the recent measurements of the field dependence of the spin wave gap shows a good agreement between theory and experiment.

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