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Spin-wave resonance frequency in ferromagnetic thin film with interlayer exchange coupling and surface anisotropy

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ABSTRACT

We have investigated the dependence of spin-wave resonance(SWR) frequency on the surface anisotropy, the interlayer exchange coupling, the ferromagnetic layer thickness, the mode number and the external magnetic field in a ferromagnetic superlattice film by means of the linear spin-wave approximation and Green's function technique. The SWR frequency of the ferromagnetic thin film is shifted to higher values corresponding to those of above factors, respectively. It is found that the linear behavior of SWR frequency curves of all modes in the system is observed as the external magnetic field is increasing, however, SWR frequency curves are nonlinear with the lower and the higher modes for different surface anisotropy and interlayer exchange coupling in the system. In addition, the SWR frequency of the lowest (highest) mode is shifted to higher (lower) values when the film thickness is thinner. The interlayer exchange coupling is more important for the energetically higher modes than for the energetically lower modes. The surface anisotropy has a little effect on the SWR frequency of the highest mode, when the surface anisotropy field is further increased.

1. Introduction

In recent years, the search for magnetic materials has received strong impetus when it was used as microwave absorbers and communication devices [1–4]. It is well known that the higher resonance frequency is more beneficial for communication devices. The enhancement of resonance frequency found by Snock is limited for bulk magnetic materials [5]. So, to extend Snoek's limit [6] and obtain higher resonance frequency [7,8] with a wide frequency band [9,10], magnetic thin films or multilayer materials are investigated in the experience [9–15] and the theory [16–20]. The SWR is a newly emerged method for studying surface magnetic anisotropy in thin films. For instance, experimentally, the resonance frequency of (Co90Nb10/Ta)n multilayers was adjusted from 1.4 to 6.5 GHz by controlling the thickness of Ta interlayers [9]. On the other hand, Several theoretical models have been developed to explain the SWR phenomena [21–26]. But most of the previous work mainly used a classical or semiclassical method [25–28]. The quantum methods [24], however, which is found to be more accurate and touch to the physical essential to consider the effect of quantum fluctuation, had been seldomly employed for the magnetic multilayer materials. Therefore, it is valuable to use quantum methods to study the microwave properties of the magnetic thin film. This paper aims to illustrate the effect of interlayer exchange coupling and surface anisotropy on the SWR frequency for ferromagnetic thin film by the linear spin-wave approach and Green's function technique. The motivation is to show how to obtain high and controllable SWR frequency of a ferromagnetic thin film with a wide band.

The outline of this paper is organized as follows.The model, Hamiltonian of the system, and calculation procedure will be presented in Section 2. Section 3 discusses the effect of the surface anisotropy, film thickness, interlayer exchange coupling, mode number, external symmetrical magnetic field on SWR frequency in a ferromagnetic thin film. Section 4 gives a conclusion.

2. Model and calculation procedure

We consider the Heisenberg model with n-monolayer parallel ferromagnetic thin film on a simple cubic lattice. Each layer is of the unlimited extension, and the surface is assumed to lie in the y-z plane, with the x axis normally directed. The sketch of the present model for n-monolayer ferromagnetic thin film is illustrated in Fig. 1. For simplicity, we assume that there are N lattices on each layer, the number

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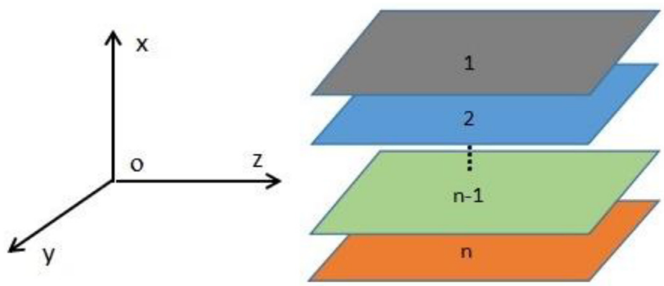

Fig. 1. The sketch of the present model for *n*-monolayer ferromagnetic thin film.

of total sites is nN in this system. Here, only the nearest neighboring spins within the film are considered with ferromagnetic interlayer exchange coupling J. Putting the system into external uniform magnetic field along the positive z axis direction. With all these consideration, the Hamitonian of the system can specifically be written as:

$$H = -\sum_{lil'i'} JS_{li}S_{l'i'} - \sum_{(l=1,n)i} g\mu_0 K_S S_{li} - \sum_{li} g\mu_B B_0 S_{li} \quad (1)$$

The first term in Eq. (1) represents the interlayer exchange coupling between the nearest neighbor lattices. The surface anisotropy energy (including surface anisotropy energy of the up and down film, respectively) is displayed in the second, K_S the surface anisotropy field, and g, $\mu_0$represent the Landé factor and the Vacuum magnetic permeability, respectively. The last term is the Zeeman energy associated with the applied magnetic field B_0along the positive z axial direction, and μ_B is the Bohr magneton. Where, l is the number of sub-layer in the ferromagnetic thin film, i is a two-dimensional lattice vector in y-z planes. By using the Holstein-Primakoff transform and the linear spin-wave approximation method, introducing the spin-wave operators $b_{lk_{//}}(b^+_{lk_{//}})(l = 1 \sim n)$, so the Eq. (1) can be rewritten as:

$$\begin{aligned} H = & -6N\left(n - \frac{1}{3}\right)JS^2 - \sum_{l=1,n} Ng\mu_0 K_S S - nNg\mu_B B_0 S \\ & + \sum_{l=2}^{n-1} (12JS + g\mu_B B_0) \sum_{k_{//}} b^+_{l,k_{//}} b_{l,k_{//}} \\ & + \sum_{l=1,n} (10JS + g\mu_0 K_S + g\mu_B B_0) \sum_{k_{//}} b^+_{l,k_{//}} b_{l,k_{//}} \\ & - \sum_{l=1}^{n-1} 2JS \sum_{k_{//}} \left(b_{l.k_{//}} b^+_{l+1,k_{//}} + b^+_{l,k_{//}} b_{l+1.k_{//}}\right) \\ & -4JS \sum_{l=1}^{n} \sum_{k_{//}} \gamma_{k_{//}} \left(2b^+_{l,k_{//}} b_{l,k_{//}} + 1\right) \end{aligned} \quad (2)$$

Note that,

$$\gamma_{k_{//}} = \frac{1}{4} \sum_{\delta_{//}} e^{ik_{//}\delta_{//}} \quad (3)$$

Where $\delta_{//}$ represents only the exchanges between the nearest neighbors in y-z planes and can take four different values within the layer, so $\gamma_{k_{//}}$is real. The n-order matrix retarded Green's function is defined as:

$$G(k_{//}, f) = [G_{i,j}]_{n\times n} \quad (4)$$

Here, $G_{i,j} = \langle\langle b_{ik_{//}}; b^+_{jk_{//}} \rangle\rangle_f (i = 1 \sim n; j = 1 \sim n)$

The solution of the Green's function obtained by the equation of the Green's function as follows:

$$G(k_{//}, f) = \frac{1}{\det(D(f))}[M_{i,j}]_{n\times n} \quad (5)$$

Where the matrix M is the adjoint matrix of D (f), and

$$D(f) = [W_{i,j}]_{n\times n} + [H_{i,j}]_{n\times n} \quad (6)$$

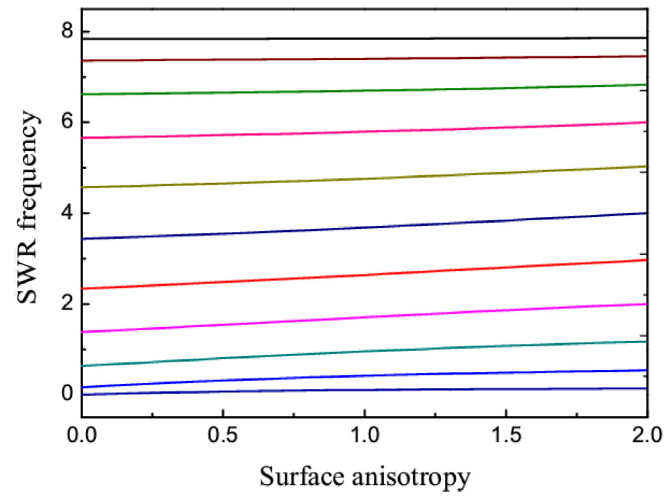

Fig. 2. Spin-wave resonance (SWR) frequencies as a function of the surface anisotropy $K = g\mu_0 K_S$ for the 11-monolayer ferromagnetic thin film with $S = 1.0$, $J = 1.0$, and $B_0 = 0$.

For the n-order matrix W, only diagonal elements W_{ii} $(i = 1 \sim n)$ are not zero and equal to f. f represents energy spectrum of the system. The matrix H is a three-diagonal matrix, the matrix elements H_{ij} $(i, j = 1 \sim n)$ as follows:

$$\begin{aligned} & H_{i,i} = 8JS\left(1 - \gamma_{k_{//}}\right) + 4JS + g\mu_B B_0 \quad (i = 2 \sim (n-1)) \\ & H_{1,1} = 8JS\left(1 - \gamma_{k_{//}}\right) + 2JS + g\mu_0 K_S + g\mu_B B_0 \\ & H_{n,n} = 8JS\left(1 - \gamma_{k_{//}}\right) + 2JS + g\mu_0 K_S + g\mu_B B_0 \\ & H_{i,i+1} = 2JS \quad (i = 1 \sim (n-1)) \\ & H_{i,i-1} = 2JS \quad (i = 2 \sim n) \end{aligned} \quad (7)$$

Making the determinant of a matrix to zero, that is $\det(D(f)) = 0$, the n numerical solution for the SWR frequency spectra of the ferromagnetic film are obtained.

In this paper, we study the effect of the surface anisotropy, interlayer exchange coupling, mode number, film thickness and the external magnetic on the SWR frequencies in the ferromagnetic thin films. In the calculations, the dipole-dipole interaction is vanished and neglected in our model, because of $k_{//} = 0$ [29,30]. And the interlayer exchange coupling $J = 1.0$ of the nearest neighboring spins in the ferromagnetic film is set to unit [18].

3. Result and discussion

Fig. 2 shows the shift of the SWR frequency as a function of the surface anisotropy in 11-layer ferromagnetic thin film. There are 11 SWR frequency, the mode numbers are orderly $m = 0,1,2\ldots,10$, starting from the energetically lowest mode. Notice that when the surface anisotropy K increases, the 11 SWR frequencies all increase, while the resonance frequency of spin waves with mode numbers $m = 0$, 10 increase more slowly than others. Namely the energetically highest and lowest spectrum curves are all almost level. However, for the mid-layer modes, such as the mode number $m = 3$, 4, 5, 6, 7, the growth trend is more obvious, and these curves are almost parallel and linear. The result obtained is that surface anisotropy has a little(large) effect on the SWR frequency of surface(mid-lower) modes.

The SWR frequency with the applied magnetic field is shown in Fig. 3 for the three different surface anisotropy constants. We assumed the magnetic field applied along the z axial for in-plane direction. Linear behavior is observed in system for different surface anisotropy. From Fig. 3, when surface anisotropy becomes stronger, the resonance frequencies of all modes are enhanced. The phenomenon appeared may be accounted for the same effect of the homogeneous magnetic field on the uniform structure film. In addition, it is seen that the gap of resonance