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Spin-wave resonance frequency in a multi-layer film

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ABSTRACT

The spin-wave resonance (SWR) frequency in a ferromagnetic bilayer or triple-layer film (for bilayer or triple-layer films, including symmetric and asymmetric films) with single-ion anisotropy has been studied by using the linear spin-wave approximation and Green's function technique. The effects of interfacial coupling, surface anisotropy, interface anisotropy, bulk anisotropy and external magnetic field on the SWR frequency have been investigated. For a ferromagnetic bilayer or triple-layer film, the SWR frequencies (for the same spin-wave modes) all increase with increasing external magnetic field, surface anisotropy, interface anisotropy and bulk anisotropy and with decreasing film thickness. As the interfacial coupling increases, the SWR frequencies of some modes increase, while the SWR frequencies of the other modes do not change. The SWR frequencies of a triple-layer film are different from those of a bilayer film and the SWR frequencies of an asymmetric film are also different from those of a symmetric film. The present results show the method to enhance and adjust the SWR frequency of ferromagnetic multi-layer films.

1. Introduction

Nowadays, a high permeability of magnetic materials at high frequencies is a requirement for electromagnetic interference suppressors, microtransformers, etc. [1–4]. This is because electro–magnetic interference (EMI) between microwave and electric devices (LSI, CPU, etc.) has become a serious problem [5]. There has been a great increase in the number of communication devices that use GHz-range microwave radiation, largely due to high data transfer rates (e.g., 2.4 and 5.8 GHz are typical frequencies for bluetooth technology [6]). Since the frequency used for communication devices is being developed to be higher, it is expected that the resonance of magnetic materials as microwave absorbers will be shifted to a higher frequency range with a wide resonance band. However, the enhancement in the resonance frequency of bulk magnetic materials is limited in accordance with the Snoek's limit [7]. Magnetic thin films or multilayer materials are expected to extend Snoek's limit and have higher resonance frequencies. The resonance frequency of FeNiCo/Teflon film was enhanced to the 3.0–4.7 GHz range [8]. Fe–Co soft-magnetic films, electrodeposited onto ITO conductive glass substrates, were found to have tunable high-frequency magnetic properties [9]. A significant shift of the FMR frequency f_r from 1.1 to 4.2 GHz can be manipulated by the electrolyte temperature and an applied magnetic field [9]. Compared with a simple magnetic film, the multilayer magnetic film is expected to have a much higher resonance frequency and with a much wider band [10,11]. The static and high-frequency magnetic properties of multilayers $(Co_{90}Nb_{10}/Ta)n$ have been investigated [10]. The results show that the in-plane uniaxial magnetic anisotropy fields can be adjusted from 12 to 520 Oe only by decreasing the thickness of the Ta interlayers from 8.0 to 1.8 nm. As a consequence, the resonance frequencies of the multilayers continuously increase from 1.4 to 6.5 GHz [10].

For magnetic multilayer films, there are spin-wave resonances (SWRs) and ferromagnetic resonances (FMRs) that have clear absorptions under certain conditions. In order to find a magnetic multilayer film with high resonance frequency and wide resonance band, in addition to FMR, the study on SWR also has significant importance. FMR experiments have been performed on $[Co(50Å)/Cu(4Å)]_{20}$ multilayers at room temperature by using an X-band ESR spectrometer and a series of spin-wave modes have been observed when the external field is perpendicular to the film plane. These spin-wave modes were analyzed by the SWR theory of multilayers and the interlayer exchange coupling constant has been obtained [12]. The influence of the interface anisotropy on the SWR characteristics has been investigated and the accuracy of sample preparation necessary to compare the experimentally obtained SWR spectra of magnetic multilayers with theoretical predictions has been estimated. The transfer matrix approach has been applied to the calculation of the energy and relative

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intensities of SWR spectra as a function of the spacer thickness. Various pinning conditions at the external surfaces have been considered and the role of interface anisotropy have been discussed in detail [13]. The FMR spectra of sputtered Fe/Ti multilayers were obtained as a function of orientation of the applied magnetic field from in-plane to out-of-plane and were fitted theoretically to determine the magnetic anisotropy. Spin-waves resonance modes were observed in Fe/Ti multilayers (t_{Fe}=40 and 60 Å) [14]. The magnetic properties of sputtered Ni/V multilayers have been studied in a vibrating sample magnetometer, torque magnetometer and by FMR. The SWR modes were observed for perpendicular geometry, which implies that spin waves are sustained by the whole film and propagate through V layers in some Ni/V multilayers. The relation of the resonance field H_n with the mode number n obeys the so-called n^2 law and the interlayer exchange constants were determined [15]. The exchange-dominated surface and bulk SWR spectra were studied in a single period of CoFe/PtMn/CoFe trilayer film [16]. An FMR study of sputtered Ru(7 nm)/NiFe(t_{FM})/IrMn(6 nm)/Ru(5 nm) exchange-biased bilayers at X- and Q-band microwave frequencies reveals the excitation of spin-wave and NiFe resonance modes. Angular variations of the in-plane resonance fields of spin-wave and NiFe resonance modes show the effect of the unidirectional anisotropy, which is about two times larger for the spin-wave mode due to spin pinning at the NiFe/IrMn interface. A modified theoretical model which also includes the contribution of a rotatable anisotropy provides a good description of the experimental results [17].

Theoretically, the FMR effect observed in multilayer films has been considered predominantly based on the phenomenological approach [12,17–23]. Puszkarski [24–26] presented a microscopic theory of standing SWRs in exchange-coupled bilayer films, in which the analysis is based on the exact solution of the eigenvalue problem of a bilayer film achieved with the interface rescaling approach. Here, the effects of interfacial coupling, interface and surface anisotropies of a symmetric bilayer film on SWR were studied. SWR spectra in a composite ferromagnetic trilayer [A|B|A] have been calculated by means of the transfer matrix method [27]. SWR spectra of an asymmetric ferromagnetic bilayer film have been presented using the interface-rescaling approach and quantum theory [28].

Most of the previous theoretical work mainly uses a classical or semiclassical method, while the quantum methods have been seldomly employed. It is valuable to develop some quantum methods to study the microwave properties of magnetic multilayer films. According to earlier work, the microwave properties of a magnetic multilayer thin film are significantly affected by magnetic surface anisotropies [13,25,27,28], interface anisotropies [13,24–26], interfacial couplings [24–26] and an external magnetic field [14,25,28]. Therefore, our present proposal is to utilize the linear spin-wave approach and Green's function technique to study the SWR frequency (including FMR frequency) in a ferromagnetic multilayer thin film with single-ion surface, interface and bulk anisotropies. Our present work presents a natural extension of our previous results [29], derived for single-layer films only. The motivation of the present paper is to show how to obtain high and controllable SWR frequencies (including FMR frequencies) of a ferromagnetic multilayer film with a wide band.

The outline of this paper is as follows: The SWR frequencies in a ferromagnetic bilayer and triple-layer films are discussed in Sections 2 and 3, respectively. In Section 4 conclusions are presented.

2. SWR frequency in a bilayer ferromagnetic film

2.1. Model and calculation procedure

We consider the Heisenberg model with a single-ion anisotropy on a simple cubic lattice for multilayer ferromagnetic films built up by N monolayers parallel to two infinitely extended surfaces. A schematic diagram of the bilayer film is given in Fig. 1 (a) and (b). For the bilayer film, the first layer A consists of N_1 monolayers and the second layer B of N_2 monolayers. The Hamiltonian is:

$$H = -\sum_{lj l'j'} J_{ll'} S_{lj} S_{l'j'} - \sum_{lj} D_l (S_{lj}^z)^2 - \sum_{lj} g\mu_B B\, S_{lj}^z \tag{2.1}$$

In Eq. (2.1), the magnetic ions are specified by the set of indices lj, where l is an integer labeling the monolayers and j is a two-dimensional lattice vector in the yz-plane. The summation in the first term is over the nearest-neighbor (NN) spins only. The second (anisotropy) term of Eq. (2.1) comprises the surface, interface and bulk anisotropy effects. The assumptions for the NN exchange terms and the definition of the surfece, interface and bulk anisotropy terms involved in the Hamiltonian are shown in Table 1. The bulk coupling (J) and interfacial coupling (J_{AB}) all are ferromagnetic. The direction of the spins in the initial state in a ferromagnetic film is along the positive z-axis. The external magnetic field B is also along the positive z-axis. By use of the Holstein–Primakoff transform [30] and the linear spin-wave approximation [31], introducing the spin-wave operators$b_{lk_{//}}(b_{lk_{//}}^{+})$ $(l = 1-N)$, we can rewrite Eq. (2.1) as follows:

$$\begin{aligned} H = &-n\left((N-4)DS^2 + \sum_{l=1,N} D_l S^2 + 2D_{\text{int}}S^2\right) - 6S^2 nJ\,(N-\frac{2}{3}) - 2S^2 nJ_{AB} \\ &- g\mu_B BNnS + \sum_{\substack{l=2\\(l\neq N_1,N_1+1)}}^{N-1} (12JS + 2SD + g\mu_B B)\sum_{k_{//}} b_{l,k_{//}}^{+} b_{l,k_{//}} \\ &+ \sum_{l=1,N} (10JS + 2SD_l + g\mu_B B)\sum_{k_{//}} b_{l,k_{//}}^{+} b_{l,k_{//}} \\ &+ \sum_{l=N_1,N_1+1} (10JS + 2J_{AB}S + 2SD_{\text{int}} + g\mu_B B)\sum_{k_{//}} b_{l,k_{//}}^{+} b_{l,k_{//}} \\ &- \sum_{l=1}^{N-1} 2SJ_{l,l+1}\sum_{k_{//}} (b_{l,k_{//}} b_{l+1,k_{//}}^{+} + b_{l,k_{//}}^{+} b_{l+1,k_{//}}) \\ &- 4SJ\sum_{l=1}^{N}\sum_{k_{//}} \gamma_{k_{//}} (2b_{l,k_{//}} b_{l,k_{//}}^{+} - 1) \end{aligned} \tag{2.2}$$

Note that,

$$\gamma_{k_{//}} = \frac{1}{4}\sum_{\delta_{//}} e^{ik_{//}\cdot\delta_{//}} \tag{2.3}$$

where $\delta_{//}$ represents that only the exchanges between the nearest neighbors in yz–planes are taken into account. There are n sites on each layer-lattice, and, in total, nN sites in the system.

We define the N-order matrix retarded Green's functions:

$$G(k_{//}, f) = [G_{i,j}]_{N\times N} \tag{2.4}$$

here

$G_{i,j} = \langle\langle b_{ik_{//}}; b_{jk_{//}}^{+}\rangle\rangle_f$ (i=1-N;j=1-N)

By using the equation of the Green's functions, we obtain the solution of the Green's function as follows:

$$G(k_{//}, f) = \frac{D^*(f)}{\det(D(f))} \tag{2.5}$$

Where the matrix D^* is adjoint matrix of matrix D. And

$$D(f) = \left[W_{i,j}\right]_{N\times N} + \left[H_{i,j}\right]_{N\times N} \tag{2.6}$$