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Surface and bulk magnetostatic modes in a ferromagnetic/nonmagnetic superlattice

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We have studied finite and infinite ferromagnetic/nonmagnetic superlattices in which the surface layer has a different magnetization. The magnetostatic limit is used, and the magnetic potentials in any region are obtained by solving recurrence relations. The equation giving the frequency for all the spin waves for a finite system is derived. It is shown that in the infinite limit, in addition to the usual Damon and Eshbach mode, two additional surface modes appear when the surface magnetization is larger than the host one. The finite results for eight layers are also shown.

I. INTRODUCTION

With the advances in experimental techniques[1] such as sputtering[2,3] and epitaxy,[4-6] it is nowadays possible to fabricate magnetic superlattices out of materials in which the composition and thickness can be controlled from layer to layer. In one type of superlattices,[2-6] one has a set of ferromagnetic films separated from each other by a nonmagnetic material. If the separations are sufficiently large (greater than 20 Å), the short-range exchange coupling can be neglected, and the spin waves of the magnetic films couple through the long-range dipole fields.

The spin excitations in magnetic systems have been discussed often in the magnetostatic limit. Damon and Eshbach obtained the bulk and surface magnetostatic (DE) modes in a ferromagnetic/nonmagnetic interface[7] as well as a ferromagnetic slab.[8] The magnetostatic potentials were used, and electromagnetic boundary conditions employed. The same method has been extended for finite[9,10] as well as semi-infinite[11,12] superlattices made from alternate layers of ferromagnetic and nonmagnetic films. In Refs. 9–12, the ferromagnetic layers are of the same composition and thickness a, and both bulk and surface superlattice spin-wave modes are found. If the in-plane propagation wave vector of the spin wave is perpendicular to the in-plane saturation magnetization and external field (the Voigt geometry), one finds bulk superlattice waves made up of surface waves from each film (forming a band in the infinite case) and the amplitude is sinusoidal. On the other hand, a surface superlattice wave, also composed of surface waves from each film, has amplitude decreasing as one penetrates into the superlattice. The surface superlattice wave exists only when $a > a_0$ (thickness of the nonmagnetic layer), and its frequency in the semi-infinite system is the same as that for the DE surface wave.[7]

In this paper, we study a ferromagnetic/nonmagnetic superlattice in which the top (or surface) ferromagnetic layer has a different magnetization M_1 from the rest. We will find that, in addition to the spin wave present originally, there is a new surface superlattice spin wave if the wave vector is greater than a critical k_c for a given M_1. Another surface mode appears as a DE mode modified by the presence of M_1.

We will use the electromagnetic boundary conditions in the magnetostatic limit to match the magnetic potentials in different layers. The resultant recurrence relations are solved exactly. Equations giving the frequency of the spin waves for both finite and infinite systems are derived. Although similar recurrence relations have been written down before[9-12] and solved for finite system,[9] our formalism has the advantage that it can be extended easily to systems with surface modification. Also, both extended and surface states are treated on the same footing; and the results for semi-infinite systems follow by taking a simple limit. Equivalent problems for electronic states[13] and plasma oscillations[14] have previously also been discussed using the same formalism.

II. SUPERLATTICE WITH A MODIFIED SURFACE FERROMAGNETIC LAYER

We study the superlattice (Fig. 1) made up of N ferromagnetic layers and $(N-1)$ nonmagnetic layers. All the nonmagnetic layers have thickness a_0. All the ferromagnetic layers except one have thickness a and magnetization M. The surface (or Nth) ferromagnetic layer has thickness a_1 and magnetization M_1. All the M's and the external field H_0 are in the plane of the layers in the z direction. The superlattice axis is in the x direction. We will consider only the spin-wave vector in the y direction,

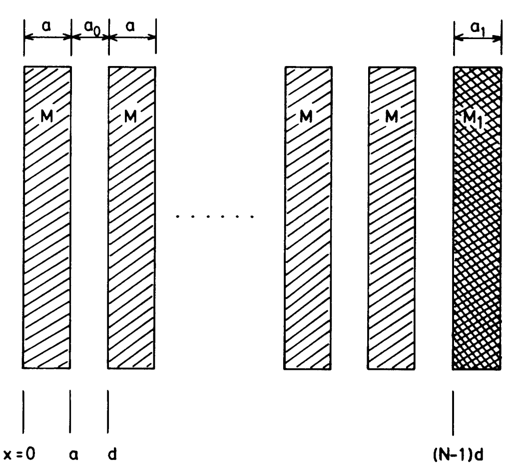

FIG. 1. Model of finite ferromagnetic nonmagnetic superlattice.

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then the small oscillating magnetostatic potential in the nonmagnetic region can be written[9–12,15]

$$\Phi=[\phi_m^+ e^{k[x-d(m-1)-a]}+\phi_m^- e^{-k[x-d(m-1)-a]}]e^{iqy} , \quad (1)$$

where $m=1,\ldots(N-1)$, $d=a+a_0$, k is positive, and $q=\pm k$.

Employing the continuity of the normal component of $\mathbf{B}$ and the tangential component of $\mathbf{H}$ at every interface,[9–12,15] i.e., at $x=(m-1)d$ and $(m-1)d+a$ and solving the resultant recurrence relations as in Refs. 13 and 14, we have

$$\phi_m^+=\{[N_{++}\sin(m\theta)-\sin(m-1)\theta]\phi_0^+ + N_{+-}\sin(m\theta)\phi_0^-\}/\sin\theta ,$$
$$\phi_m^-=\{N_{-+}\sin(m\theta)\phi_0^+ + [N_{--}\sin(m\theta)-\sin(m-1)\theta]\phi_0^-\}/\sin\theta ,$$
$$m=1,\ldots(N-1) . \quad (2)$$

Here

$$v=\frac{4\pi M(\omega/\gamma)}{H_0^2-(\omega/\gamma)^2} , \quad \chi=\frac{4\pi M H_0}{H_0^2-(\omega/\gamma)^2} , \quad \chi_\pm=\frac{1}{2}(\chi\pm v) ,$$
$$N_{++}=e^{ka_0}\{e^{ka}[1+\chi+\tfrac{1}{4}(\chi^2-v^2)] - e^{-ka}\tfrac{1}{4}(\chi^2-v^2)\}/(1+\chi) ,$$
$$N_{--}=e^{-ka_0}\{e^{-ka}[1+\chi+\tfrac{1}{4}(\chi^2-v^2)] - e^{ka}\tfrac{1}{4}(\chi^2-v^2)\}/(1+\chi) , \quad (3)$$
$$N_{+-}=e^{-ka_0}(e^{ka}-e^{-ka})\chi_+(1+\chi_-)/(1+\chi) ,$$
$$N_{-+}=e^{ka_0}(e^{-ka}-e^{ka})\chi_-(1+\chi_+)/(1+\chi) .$$

where ω, γ are the frequency and the gyromagnetic ratio, respectively.

$$b\equiv\cosh(ka)\cosh(ka_0) + \sinh(ka)\sinh(ka_0)\left[1+\frac{\chi^2-v^2}{2(1+\chi)}\right]$$

and

$$\cos\theta=b \quad \text{for } |b|\le 1 . \quad (4)$$

For $|b|>1$, $\cosh\lambda\equiv|b|$, and one replaces $\sin(m\theta)$ by $\sinh(m\lambda)$ for $b>1$, and $(-1)^m\sinh(m\lambda)$ for $b<-1$.

Equations (2) and (3) are written for $+ve$ values of q. For negative values of q, a negative sign is added to v. To study our model (Fig. 1) with a surface (or last) layer with a different thickness a_1 and magnetization M_1, we note that the magnetostatic potential must be zero at $x=-\infty$ and $+\infty$.

Then, using the boundary conditions at $x=(N-1)d$ and $x=(N-1)d+a_1$, we have

$$(N'_{++}N_{++}+N'_{+-}N_{-+})\sin(N-1)\theta-N'_{++}\sin(N-2)\theta =0 , \quad (5)$$

where N'_{++}, N'_{--}, N'_{+-}, N'_{-+} are obtained from (3) with a_1, M_1, and γ_1 appropriate for the last ferromagnetic layer.

Equation (5) gives the frequency for all the N spin waves of the finite system of N layers. Note that for $|b|>1$, the hyperbolic equivalents of (4) must be used.

In the semi-infinite limit $N\to\infty$, we have

$$(\pm)\frac{\sinh(N-1)\lambda}{\sinh N\lambda}\to(\pm)e^{-\lambda}$$

and Eq. (5) becomes

$$N'_{++}N_{++}+N'_{+-}N_{-+}-(\pm)e^{-\lambda}N'_{++}=0 . \quad (6)$$

We consider first the effect of having $a_1\ne a$, but $M_1=M$. Analysis of (6) with (3) and (4) shows that the only solution is still the DE mode with frequency $\omega=\gamma H_0+2\pi\gamma M$. For $q+ve$, the wave is localized at layer 1 (on the left), whereas for $q-ve$, the wave is localized at the Nth layer (on the right). The only trivial modification is that the right mode has a changed value for the potential in the last layer.

We next study the effect of having $M_1\ne M$. We will keep $a_1=a$, although this is not necessary. Cases $q=+k$ and $q=-k$ must be considered separately as the equations are not even in q.

III. NUMERICAL WORKS AND DISCUSSIONS

For numerical works, we have selected the host ferromagnetic material to be cobalt with $4\pi M=1.7\times10^4$ G and $\gamma=1.85\times10^7\ \mathrm{s^{-1}\,G^{-1}}$. The magnetic field is chosen to be $H_0=2\times10^3$ G. The nonmagnetic material may be Cu, Ag or other materials. Different thicknesses for the layers have been used. For most of the figures, we have selected a (ferromagnetic) = 80 Å, a_0 (nonmagnetic) = 40 Å; and $a=a_0=50$ Å. We have varied the surface magnetization M_1, but for most of the figures shown, we have used $4\pi M_1=2.2\times10^4$ G, $\gamma_1=\gamma$ corresponding to iron (Fe). The surface thickness a_1 is the same as a.

In Fig. 2, we have shown all the surface modes for $a=80$ Å, $a_0=40$ Å, $4\pi M_1=2.2\times10^4$ G obtained by

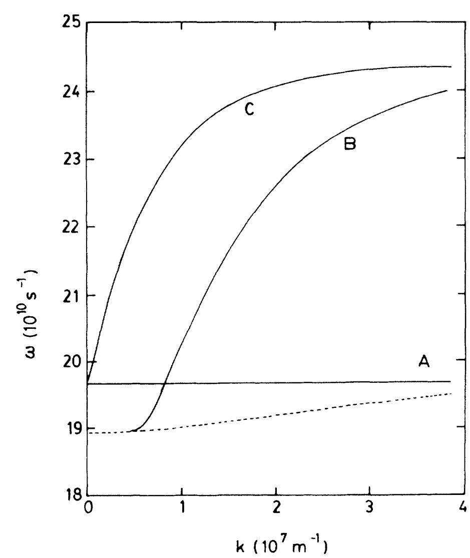

FIG. 2. The surface modes for a semi-infinite system. Curves A and B are for waves with positive q, whereas C is for negative q. The upper bulk edge is also shown.

solving (6) numerically. Two surface modes A and B are obtained for positive q. Mode A is the usual superlattice DE mode, and is localized at the left (Fig. 3). Mode B is a new surface mode, which appears only for M_1 different from M. This surface mode arises above the bulk band ($b>1$) only when $k>k_c$, a critical value. The mode has the maximum of the potential at the right (Fig. 3). Both surface modes come from interaction of the surface waves at the left interface of each magnetic layer (corresponding to positive q). For negative q, there is only one surface mode C. This represents the original DE mode at the right, as modified by the presence of the M_1 layer (Fig. 3). It starts at $k=0$, and is a result of interaction of the surface waves at the right interface of each magnetic layer (corresponding to negative q).

Note that when $a \le a_0$, the DE mode A disappears. There are only two surfaces modes B and C.

We have also studied the case $M_1 < M$. Here the surface mode B appears below the bulk band at another critical value of k. In this case $b<-1$, and neighboring potentials are out of phase. The surface mode C can also be below the bulk band.

Equation (6) has the solution B only if $k>k_c$. This critical value k_c can be obtained from Eqs. (6) and (4) by putting $b=1$. In Fig. 4, we have shown k_c as a function of $M_1>M$ for the two sets of thickness $a=80$ Å, $a_0=40$ Å and $a=a_0=50$ Å. For $M_1<M$, similar critical curves can be obtained.

We have also solved (5) numerically for a finite system of $N=8$ layers with the last layer $M_1=2.2\times10^4$ G. The results shown in Fig. 5 are for positive q. There are six extended modes inside the bulk band. The top two modes are the DE (A) and the new (B) surface modes. They interact strongly when the frequencies become close because of the finite separation. For large k, they do not interact, and their frequencies coincide with the infinite case.

Superlattices of the type we consider can be fabricated by sputtering[1-3] or molecular-beam epitaxy.[1,4-6] For example, fcc cobalt films have been grown epitaxially on Cu(001),[4,5] and bcc iron films have been grown on Ag(001).[6] Ferromagnetic/nonmagnetic superlattices with a top ferromagnetic layer different from the rest may be realized in the near future. As an example, the nonmagnetic layer may be Cu, the host ferromagnetic layer Co,

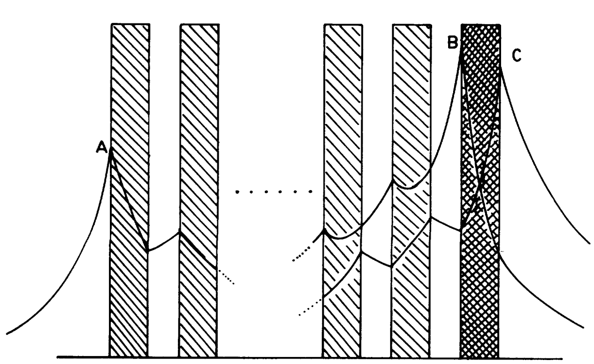

FIG. 3. The magnetic potentials for the three types of surface modes.

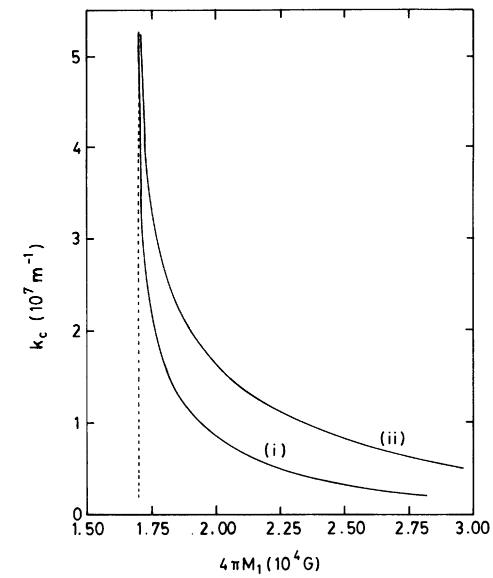

FIG. 4. The critical k_c as a function of M_1. The two curves are for (i) $a=80$ Å, $a_0=40$ Å, and (ii) $a=a_0=50$ Å.

and the top ferromagnetic layer iron.

The spin waves in magnetic superlattices can be studied by Brillouin scattering. For example, for superlattices with no change in top layer, Brillouin studies have been made on Ni/Mo,[16] Co/Ni,[17] Fe/Pd, and Fe/W.[18,19]

Enhanced surface magnetism has been predicted theoretically for transition metals with a free surface, and at an interface with noble metals.[20,21] This has been confirmed experimentally for Ni (Ref. 22) and Fe (Ref. 23) free surface, and for Fe/Ag (Refs. 24 and 25) interface. In the superlattices studied in Refs. 16–19, the top ferromagnetic layer has a free surface, in contrast with

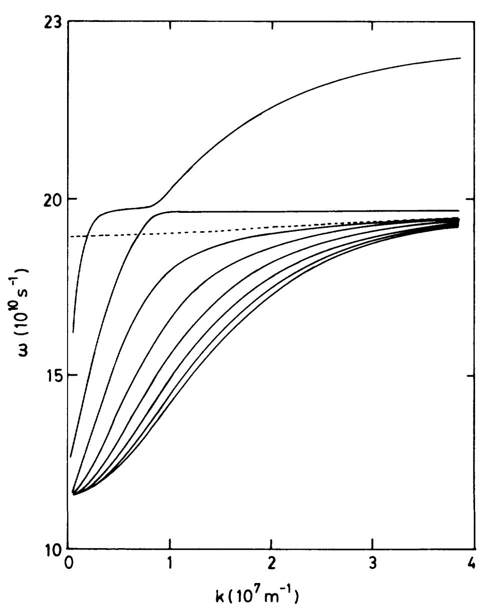

FIG. 5. The eight spin waves for positive q. The top two curves are for the mixing of surface waves A and B. The bulk edges are also shown.

the other ferromagnetic layers, which are between two interfaces with nonmagnetic layers. The effective magnetization M_1 for the top layer may thus be different from the effective magnetization M for the other layers. In Refs. 18 and 19, magnetization of Fe different from the bulk has been discussed, but no effect of a different M_1 has been considered.

Thus our model of a superlattice with a modified M_1 may have relevance to superlattices so far studied experimentally, or superlattices fabricated intentionally in the near future.

[1]For a recent review, see the various articles, in *Growth, Characterization, and Properties of Ultrathin Magnetic Films and Multilayers,* edited by B. T. Jonker, J. P. Heremans, and E. E. Marinero (MRS Symposia Proceedings No. **151**, Materials Research Society, Pittsburgh, 1989).

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