Effect of dynamic spin pinning at an interlayer boundary on the propagation of surface spin waves in multilayer ferrite films

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An effect of dynamic pinning of spins at an interlayer boundary on the propagation of spin waves has been distinguished in two-layer epitaxial films of yttrium iron garnet. In ferrite films magnetized tangentially in fields $H_0 \ll 4\pi M_{01,2}$, an interlayer exchange interaction gives rise to a pinning of spins at the boundary between layers. The effect of this interaction on the propagation of spin waves is minimal at degeneracy frequencies of the spin-wave-resonance spectra of the layers. © *1995 American Institute of Physics.*

1. The effect of dynamic pinning of surface spins on the propagation of spin waves in ferrite films has been studied in detail for the case in which the pinning results from a surface anisotropy.[1–3] At internal boundaries in multilayer films, an interlayer exchange may contribute to the pinning of surface spins.[4] Just which pinning mechanism is predominant is determined by the ratio of the surface-anisotropy constant K_S to the interlayer exchange constant A_{12} (Ref. 5). A surface anisotropy, which tends to reduce the dynamic part of the magnetization $\mathbf{m}$ ($\mathbf{m} \to 0$ as $|K_S| \to \infty$; Ref. 6), prevents the occurrence of an interlayer exchange, whose energy can be estimated from $W_{12} \sim A_{12}\mathbf{m}_1\mathbf{m}_2$.

2. In this letter we report a study of the propagation of surface spin waves in a two-layer ferrite film grown by liquid-phase epitaxy on (111) gadolinium–gallium garnet substrates. The first layer, $Y_2Fe_5O_{12}$, in contact with the substrate, has a thickness $d_1 = 6$ μm, a saturation magnetization $4\pi M_{01} = 1750$ G, an exchange stiffness $A_1 = 3 \times 10^{-7}$ erg/cm, and a ferromagnetic-resonance linewidth $\Delta H_1 = 0.3$ Oe. The second layer, $Y_3Fe_4Ga_{0.8}Sc_{0.2}O_{12}$, has $d_2 = 8$ μm, $4\pi M_{02} = 640$ G, $A_2 = 1 \times 10^{-7}$ erg/cm, and $\Delta H_2 = 0.25$ Oe. The values of the gyromagnetic ratio in the layers are $\gamma = 2.8$ MHz/Oe. Waves are excited and detected by microstrips 30 μm wide and 5 mm long, separated by a distance of 6 mm. The magnetic field H_0 is oriented in the plane of the film, parallel to the microstrips. This configuration corresponds to the excitation of surface spin waves in the structure.[7] Experiments were carried out over the frequency range $f = 0.3$–2 GHz and the field range $H_0 = 30$–100 Oe at room temperature.

Figure 1 shows an amplitude–frequency characteristic of a prototype system in a field $H_0 = 73$ Oe. Signal transmission regions I and II correspond to the propagation of surface spin waves in the structure. They are at frequencies at which surface spin waves exist in the first and second layers, respectively: $f_{0l} < f < f_{Sl}$ (Ref. 7), where

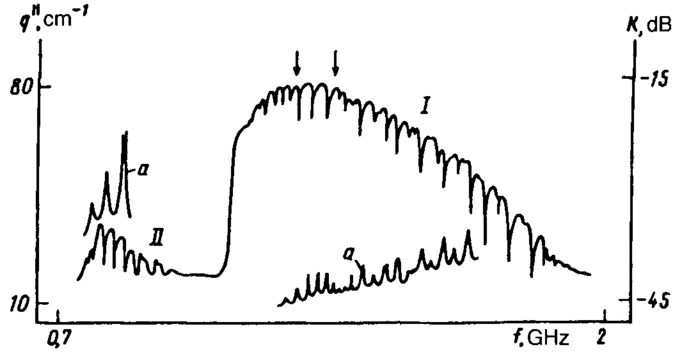

FIG. 1. Amplitude–frequency characteristic of a prototype system, along with the frequency dependence of the spatial damping rate of the surface spin waves for $H_0=73$ Oe.

$f_{0l}=\sqrt{f_H(f_H+f_{ml})}$, $f_{Sl}=f_H+f_{ml}/2$, $f_H=\gamma H_0$, $f_{ml}=\gamma 4\pi M_{0l}$, and $l=1,2$. In regions I and II there are some narrow minima, which should be associated with a resonant interaction of surface spin waves and exchange modes of the layers.[1-3] This assertion is supported, on the one hand, by the resonant growth of the spatial damping rate of surface spin waves, which is characterized by the imaginary part q'' of the wave number $q=q'+iq''$ of the surface spin waves (curves a in Fig. 1). On the other hand, the frequencies at which the increase in the loss of surface spin waves is observed have values close to the frequencies of a spin-wave resonance of the films:[6]

$$F_{Nl}=\sqrt{(f_H+f_{ml}+f_{ex_1})(f_H+f_{ex_1})}. \qquad (1)$$

Here $f_{ex_1}=\gamma(2A_l/M_{0l})Q_{Nl}^2$, and Q_{Nl} is the wave number of the Nth mode of the spin-wave resonance of the corresponding layer. In region I we find the modes of the spin-wave resonance of both this layer itself ($N_1\sim 1,\ldots,38$) and the layer with a lower magnetization ($N_2\sim 39,\ldots,78$).

When the sign of the field H_0 is changed, the depth of the minimum and the magnitude of the damping rate for the surface spin waves in region II of the amplitude–frequency characteristic remain essentially the same, while in region I these quantities exhibit oscillations. Figure 2 illustrates the transformation of the part of region I bounded by the arrows in Fig. 1 as the field H_0 is changed. As H_0 is changed, we see a change in the depth and the number of the "exchange" minima on the amplitude–frequency characteristic. At the field value $H_0=73$ Oe, this part of the curve contains three exchange minima (a, b, c). As the field is weakened, the depth of the these minima decreases, and two additional exchange minima (d and e) simultaneously arise between them. The depth of these additional minima increases, becoming comparable to the depth of exchange minima a, b, and c at field $H_0=68$ Oe. At a field $H_0=64$ Oe the original minima disappear completely, while the depth of minima d and e reaches a maximum. A further decrease in H_0 leads to a decrease in the depth of minima d and e. At the same time, minima a, b, and c are restored, and the part of the amplitude–frequency characteristic which we have singled out resumes its original shape at a field $H_0=54$ Oe.

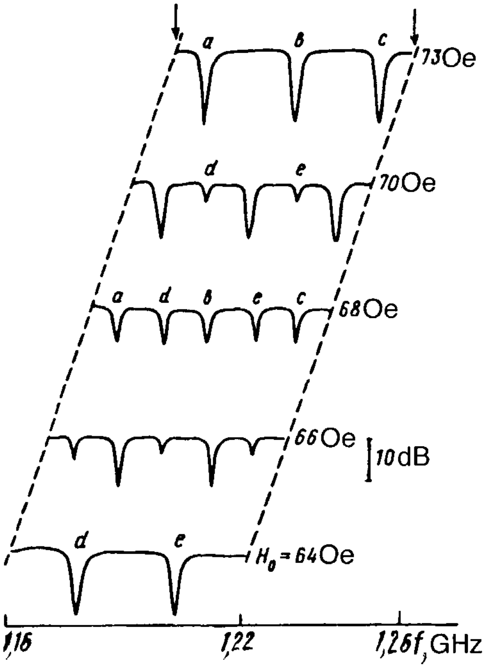

FIG. 2. Transformation of a part of the amplitude–frequency characteristic of the prototype system as the field H_0 is varied.

3. This behavior of the amplitude–frequency characteristic as a function of the field H_0 stems from the existence of an exchange interaction between layers. Another consequence of the interlayer exchange—in addition to the pinning of spins at the boundary of the layers—is a "repulsion" of the spin-wave resonance modes at frequencies of their degeneracy.

If we assume that there is no interlayer exchange in this structure, then we can easily show, with the help of (1), that in the field and frequency ranges corresponding to Fig. 2 the frequencies of spin-wave resonance modes $N_1 \sim 15-17$ of layer I and modes $N_2 \sim 48-51$ of layer II should have coincided twice. In this case, the minima on the amplitude–frequency characteristic corresponding to these spin-wave resonance frequencies should also have coincided. However, the frequency interval between the minima in Fig. 2 remains essentially constant, corresponding to the idea of a repulsion of the spin-wave resonance modes of the layers. It implies an exchange coupling of the layers.[5] In this case, the contribution of interlayer exchange to the pinning of spins at the boundary between layers is nonzero.

We now note that ferrite films are characterized by a normal uniaxial surface anisotropy.[8] In the case of tangential magnetization, the pinning of surface spins in such films is described by an effective surface-anisotropy constant[6]

$$K^{\mathrm{eff}}=0.5K_S\left(1-\frac{1}{\sqrt{1+(2f/f_m)^2}}\right). \tag{2}$$

It is easy to see from (2) that at $H_0 \ll 4\pi M_{01,2}$ we have $K^{\mathrm{eff}} \sim K_S f/f_m \to 0$, and we can ignore the contribution of surface anisotropy to the pinning of spins at the surfaces of the structure. We now make use of a relationship between the depth of a minimum on the amplitude–frequency characteristic and the extent of the pining of the surface spins in the films.[1-3] We will show that oscillations of the depth of the minima on the amplitude–frequency characteristic are due to an oscillatory behavior of the pinning due to the interlayer exchange. For this purpose, we use the exchange boundary conditions at the boundary between layers in the form proposed by Hoffman:[4]

$$\frac{\partial \varphi_1}{\partial z}-\frac{A_{12}}{A_1}(\varphi_1-\varphi_2)=0\Big|_{z=0}, \quad \frac{\partial \varphi_2}{\partial z}+\frac{A_{12}}{A_2}(\varphi_2-\varphi_1)=0\Big|_{z=0}. \tag{3}$$

Here we have discarded the surface-anisotropy contribution and have assumed that the z axis runs normal to the surface of the structure. The field H_0 is parallel to the y axis; film 1 is in the region $0<z<d_1$; and we have $\varphi_1=m_1/M_0$ and $\varphi_2=m_2/M_0$. It can easily been seen from (3) that the spins are free at the boundary of the layers if the precession angles in the layers are approximately the same. In this case there should be no minima on the amplitude–frequency characteristic.

To determine the frequencies at which the surface spins in the structure are free, we consider an expression for the spectrum of the spin-wave resonance of exchange-coupled films[5] when we ignore the effect of the surface anisotropy and also terms on the order of $f/f_m \ll 1$:

$$D_1 D_2-\frac{A_{12}}{A_1 Q_1}D_2-\frac{A_{12}}{A_2 Q_2}D_1=0, \tag{4}$$

where

$$Q_l=\left(\sqrt{\frac{\pi M_0^2}{A}}\sqrt{\sqrt{1+\eta^2}-1-\eta_H^2}\right)_l, \quad \eta l=\frac{f}{f_{ml}}, \quad \eta_{HL}=\frac{2f_H}{f_{ml}},$$

and $D_l=\tan Q_l d_l=0$ determine the spectra of the spin-wave resonance of isolated films. At the degeneracy frequencies of the spectra of the spin-wave resonance of the isolated films ($D_1=D_2=0$), Eq. (4) describes a "repulsion" of the spectra and has solutions given by the equations

$$D_1=0; \tag{5.1}$$

$$D_2=\frac{A_{12}}{A_1 Q_1}+\frac{A_{12}}{A_2 Q_2}. \tag{5.2}$$

If the exchange coupling of the layers is ferromagnetic ($A_{12}>0$), Eq. (5.1) corresponds to in-phase oscillations of the magnetization in the films at $z=0$ and to free surface spins. For out-of-phase oscillations of the magnetization in the layers, the exchange coupling leads to a pinning of the spins at the boundary between layers, and the frequency of the "repelled" mode of the spin-wave resonance is found from (5.2). If the coupling is

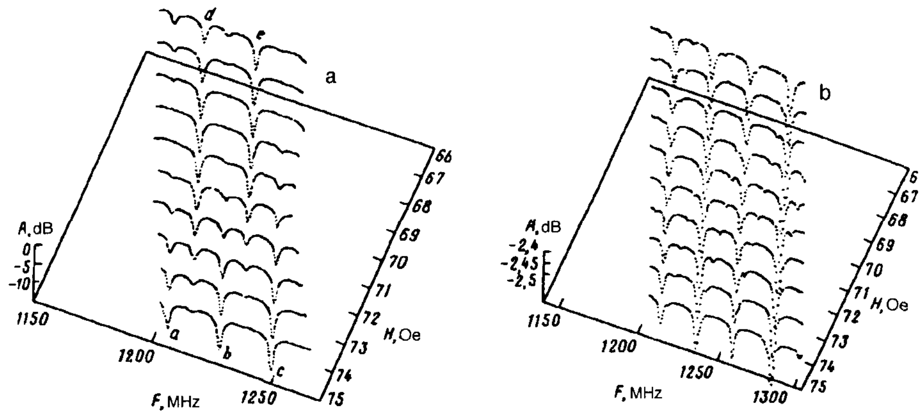

FIG. 3. Results calculated on the transformation of a part of the amplitude–frequency characteristic as H_0 is varied. a—for $A_{12}=0.5$ erg/cm^2; b—$A_{12}=0$.

instead antiferromagnetic ($A_{12}<0$), the spins are pinned at the $z=0$ boundary for in-phase oscillations, while they are free for out-of-phase oscillations.[9] The magnitude of the right side of (5.2) obviously characterizes the pinning of the spins at the boundary between layers.

4. Let us compare the experimental results and their interpretation given above with the results of a numerical calculation of the amplitude–frequency characteristic of a prototype apparatus with the parameter values corresponding to the experiments. If the losses during the transformation are ignored and if direct electromagnetic pickup is also ignored, the shape of the amplitude–frequency characteristic is determined completely by the relation $A(f)=-8.68q''(f)$ dB (Fig. 3). Values of $q=q'+iq''$ were calculated as in Refs. 2, 3, and 9. It was assumed that the surface-anisotropy constants at the surfaces of the structure have values $K_S=0.01$ erg/cm^2, which are typical of ferrite films.[6,8] The interlayer exchange constant was taken from the condition for observation of the repulsion of modes of the spin-wave resonance of the films at degeneracy frequencies.[5] It can be seen that only when interlayer exchange is taken into account (Fig. 3a) do we find a correspondence between the theoretical and experimental amplitude–frequency characteristics of the prototype apparatus: We observe a "repulsion" and oscillations of the depth of the minima.

In the absence of an exchange between layers ($A_{12}=0$), the magnitude of the "exchange" oscillations of the amplitude–frequency characteristic is much lower [as we would expect on the basis of (2)], and the "repulsion" of the spin-wave-resonance modes, which is due in this case to only the dipole fields, is not observed at the relaxation parameters corresponding to the structure (Fig. 3b).

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