The nature of the coupling between magnetic excitations in two-layer epitaxial ferrite-garnet films

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We investigate the interaction between the intrinsic ferromagnetic resonance modes of adjacent layers of a two-layer epitaxial structure by studying the gap between the resonance fields at the point of maximum interaction. We establish that one of the fundamental sources of coupling energy leading to the appearance of this gap is the nonuniform component of the exchange interaction energy. © *1996 American Institute of Physics.* [S1063-7761(96)01309-1]

The origin of present-day interest in magnetic excitations of two-layer ferrite-garnet structures lies in the development of physical foundations for spin-wave electronics.[1] Work done in this area has shown that, first of all, the fringing fields of domains strongly influence the magnetic modes of neighboring layers;[2,3] secondly, there exists a strong interaction between magnetic excitations of neighboring layers. On the one hand, this influences the mode spectrum,[4] while on the other hand it leads to a considerable exchange of intensities between the interacting modes.[5,6] From this point of view, the structures under study can nominally be divided into two types—soft and hard. Soft systems are characterized by the fact that they contain one layer with an effective uniaxial anisotropy $H^*=H_a-4\pi M_s$ (where H_a is the uniaxial anisotropy field, and M_s is the saturation magnetization) close to zero and a small thickness $d_1\approx 0.05$ μm, while the second layer has parameters that are normal for a material with magnetic domains.[7] For such structures, a ferromagnetic resonance doublet is clearly observed,[2,3] as well as an exchange of interacting mode intensities.[5,6] We refer to these systems as "soft" because the magnetic moment of the first layer can easily follow any small change in an applied external magnetic field due to the smallness of H^*. Hard structures have a thicker first layer $d_1\approx 0.2$–0.3 μm and a rather strong uniaxial (easy-plane) anisotropy. The second layer is the same as in the soft structure. For these structures, we clearly observe repulsion of the ferromagnetic-resonance and the spin-wave-resonance modes of each of the layers.[4] The parameters of the magnetic structure we will investigate here were given in Ref. 4; here we mention only that the thickness of the first layer was $d_1=0.18$ μm and that of the second $d_2=0.5$ μm.

It is well known[8] that a two-layer structure with sufficiently thick layers behaves like two noninteracting films superimposed on one another. The parameters of two-layer and controlled one-layer films are almost identical within the limits of experimental error.[9] However, as the thickness decreases the effect of the layers on each other increases. Figure 1 shows the dependence of the fields for ferromagnetic and spin-wave resonance in a two-layer film on the orientation of the external magnetic field at a frequency 4.15 GHz. The layer thicknesses were chosen to be quite small; therefore, at a certain orientation of the external magnetic field H the lines for uniform ferromagnetic resonance in each of the layers are accompanied by the excitation of a series of spin-wave resonance lines for each layer separately. From the figure it is clear that for certain angles β between the field H and the normal to the film, the resonance absorption lines corresponding to magnetization modes in the different layers repel each other at points where the partial spectra would intersect. In this case the repulsion of the uniform ferromagnetic resonance lines, which is characterized by a gap δH, is maximized when $\beta\simeq 45°$. The error in measuring the resonance fields does not exceed the widths of the experimental dots in Fig. 1. However, identification of the absorption lines, i.e., associating them with ferromagnetic or spin-wave resonances, is greatly hindered by the strong interaction of all the mode branches near this angle. It is impossible to make these identifications using only the angular dependence of the resonance fields shown in Fig. 1. Only a combined analysis of the angular dependences of the amplitudes and resonance fields can accomplish this. The test of this is the fact that the lines for uniform ferromagnetic resonance are several times larger in amplitude than the spin-wave resonance lines. Analogous measurements at frequencies 2.60, 6.05, and 7.92 GHz gave values of δH of 630, 270, and 240 Oe respectively. Thus, we have established that as the resonance frequency and uniform ferromagnetic resonance fields increase, δH decreases monotonically. Fig. 2a shows the dependence of δH on the value of the external magnetic field (which was chosen to be the average value of the resonance fields at $\beta\simeq 45°$).

The geometry of the experiment is shown in the inset to Fig. 1. From this figure, it is clear that when the external magnetic field is oriented at an angle to the plane of the film, the magnetic moments of the layers $\mathbf{M}_1$ and $\mathbf{M}_2$ are oriented along directions characterized by the angles θ_1 and θ_2. From the equilibrium equations for the magnetization,[10] neglecting cubic anisotropy, it is easy to obtain the relation

$$\sin(\beta-\theta)=\frac{(K-2\pi M^2)}{HM}\sin 2\theta, \tag{1}$$

where β is the value of the angle between the direction of the magnetic field and the film normal, θ is the value of the angle between the magnetization and the film normal, K is the uniaxial magnetic anisotropy constant, and M is the magnetization. By numerically solving Eq. (1), we can obtain the

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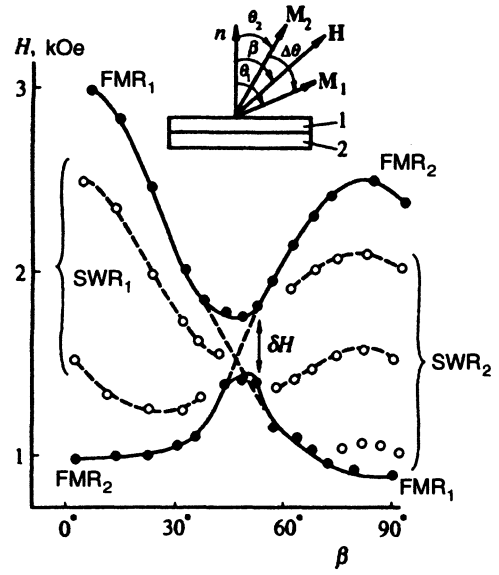

FIG. 1. Experimental dependence of resonance fields for the uniform ferromagnetic and spin-wave resonances (FMR and SWR respectively) at a frequency of 4.15 GHz on the angle β between the external magnetic field H and the normal; FMR_1 and FMR_2 correspond to ferromagnetic resonances, while SWR_1 and SWR_2 correspond to spin-wave resonances in the first and second layers, respectively. The dashed curves in the neighborhood of $\beta=45°$ show the nominal angular dependence of the resonance fields when there is no dynamic interaction between the uniform layer modes, and δH is the gap caused by the presence of this interaction. In the inset we show the experimental geometry: θ_1, θ_2 are the angles between M_1, M_2 and the normal to the film n; $\Delta\theta=\theta_1-\theta_2$, β is the angle between H and n.

values of θ in each of the layers (θ_1 and θ_2 respectively). In Fig. 2b we show the dependence of $\Delta\theta=\theta_1-\theta_2$ on the magnitude of the external magnetic field H.

It should be noted that rigorous inclusion of the exchange interaction between the layers would allow us to more accurately determine the quantity $\Delta\theta$; however, for the thicknesses specified here this contribution to $\Delta\theta$ will be small. However, as the layer thicknesses decrease we should expect an increase in the relative contribution of the exchange energy to the interaction between them.

From Fig. 2 it is clear that there is good correlation between δH and $\Delta\theta$ for every case in fields up to 2–2.5 kOe. We can explain this in the following way. In Ref. 11 it was shown theoretically that the value of the gap δH depends on the coupling energy between the layers. Analogous calculations were also made in Ref. 5. However, the experiments described in Ref. 5 were carried out on soft structures and for values of the external field where the angle between the magnetic moments of the first and second layer was practically zero. In this case there is no need to theoretically take into account the nonuniform exchange interaction between the layers to explain anisotropy of the intensity of the interacting ferromagnetic resonances. In the experiments described in this paper, we used a hard structure, for which passing from one layer to another is usually accompanied by a considerable rotation of the magnetization (this is shown schematically in the inset to Fig. 1), which consequently changes the nonuniform part of the exchange interaction energy connected with this as well. For film structures that are uniform in their planes, Ref. 12 instructs us to write this part of the energy in the following form:

$$U_e=A(\partial\theta/\partial z)^2,$$

where z is the coordinate along which the rotation of the magnetization M is observed, and A is the exchange interaction constant. The rotation of the magnetization as we go from layer 1 to layer 2 takes place over a distance Δz of the same order as the thickness of a domain wall. The exchange energy between layers can be estimated from the quantity $A(\Delta\theta/\Delta z)^2$. Since it is experimentally established that $\Delta\theta$ is well correlated with δH, we may conclude that the main contribution to the value of the mode repulsion δH comes from the nonuniform exchange interaction between the layers.

Furthermore, there is also a considerable contribution from the anisotropy energy by way of the dynamic component of the nonuniform exchange interaction. It is known that in an anisotropic magnet the shape of the AC magnetization trajectory in an anisotropic magnet depends on the anisotropy.[13] In a uniaxial magnet this trajectory resembles an ellipse extended along the axis of easy magnetization. In our structure the anisotropies of the neighboring layers are different: in one layer the easy magnetization axis is directed along the film normal, while in the other it lies in the plane of the film. Consequently, the interacting modes will have trajectories in the form of ellipses extended along different directions, i.e., the polarization of one mode will have a considerable perpendicular component with respect to the other. The larger this component is, the larger is the dynamic part of the nonuniform exchange energy. We can verify that this energy is the predominant contribution to δH, especially as

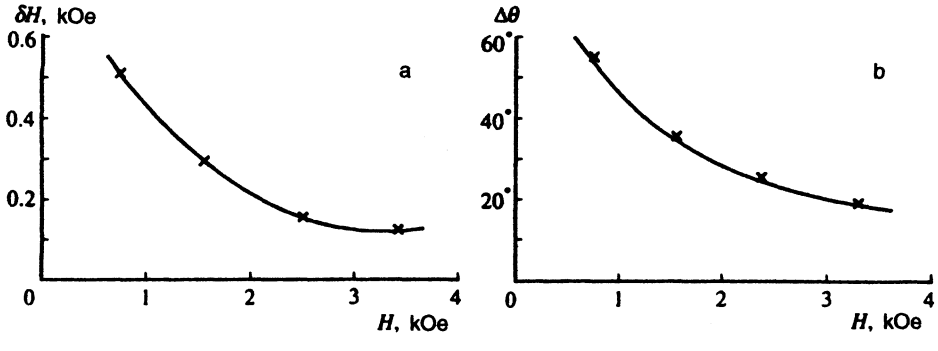

FIG. 2. a) Experimental dependence of δH on external magnetic field H; b) dependence of the calculated angle $\Delta\theta$ on the magnitude of H.

$H \to 0$, by examining the functions shown in Figs. 2a, 2b. Analysis leads us to assert that the dynamic interaction of the uniform magnetization modes of the layers in this structure arises from two contributions: the nonuniform exchange and the dipole interaction. As is clear from Fig. 2, the maximum values of the gaps δH and $\Delta\theta$, and also their derivatives with respect to field $|\partial(\delta H)/\partial H|$ and $|\partial\theta/\partial H|$, occur at a minimum value $H \approx 0.8$ kOe. As the field increases to ~3 kOe, δH and $\Delta\theta$ decrease monotonically. However, for $H \geqslant 3$–3.5 kOe we already have $|\partial(\delta H)/\partial H| \approx 0$, $\delta H \to$ const, whereas in this range of fields $|\partial\theta/\partial H| > 0$. For higher values of H the tendency $\theta \to 0$, $|\partial\theta/\partial H| \to 0$ becomes apparent. From this we may conclude that in the region of fields under study the primary contribution to the dynamic interaction between the uniform magnetization modes of the layers comes from the nonuniform exchange, which is a maximum for $H \to 0$. As the field increases, the nonuniform exchange interaction is significantly suppressed and the dynamic interaction between the layers becomes a superposition of comparable and competing contributions from the nonuniform exchange and the magnetic (dipole) energy. The jump in the normal component of the magnetization at the boundary between the layers can also contribute to the this interaction.[14] As the external magnetic field increases, the dynamic coupling decreases and becomes a much weaker function of the value of this field. This situation is probably realized in fields $H \simeq 3-3.5$ kOe. In such fields, as is clear from Fig. 2a, the gap δH, which arises primarily from the exchange as $H \to 0$, decreases by a factor of 5. Unfortunately, the contemporary state of theory does not allow us to obtain a quantitative expression which could rigorously separate the contributions to δH from the exchange and dipole interactions. Our conclusions are based only on analysis of the experimental results obtained in this paper.

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