FMR doublet in two-layer iron garnet films

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Resonance microwave absorption in two-layer iron garnet films, of which one layer is in a saturated state and the other is in a demagnetized state, is investigated. It was established that the exchange interaction between the layers, cubic anisotropy, and the dissipative fields of the domains splits the FMR line in a thin saturated layer into two lines. The line intensity ratio in the doublet is determined by the ratio of the areas occupied by the white and black domains. The magnitude and anisotropy of the resonance fields agrees with the model of an isolated layer magnetized by the domains of the neighboring film.

1. Interest in multilayer epitaxial iron garnet films has been increasing in the last few years. This is due to the promising applications of such films in magnetic-bubble technology for suppressing rigid bubbles and in information processing systems based on magnetostatic waves. The dipole and exchange couplings of spins lying in different layers results in the existence of new types of oscillations in and give rise to the characteristic resonance properties of these structures. Thus a homogeneously magnetized two-layer film exhibits in each layer, besides two lines of the homogeneous ferromagnetic resonance (FMR), a series of spin-wave resonances at frequencies between the frequencies corresponding to FMR in the separate layers.[1] These resonances are due to the reflection of spin waves at the boundary of the layer with the higher homogeneous-FMR frequency.

The picture becomes much richer when one layer is in a demagnetized state. In Ref. 2 it was observed that in this case the FMR line of the saturated layer splits into two lines, and it was conjectured that two types of domains in the neighboring demagnetized layer are responsible for this effect. In the present work we have obtained direct experimental proof that the line intensity of such an FMR doublet is determined by the area occupied by the corresponding domains in the demagnetized layer. The resonant fields and their angular dependence, which were calculated taking into account the fringe fields of the domains, agree with the experimental values.

2. The films were prepared by the method of liquid-phase epitaxy on gallium-gadolinium garnet substrates with (111) orientation.[3] The first layer grown on the $(Y, Gd, La)_3(Fe,Ga)_5O_{12}$ substrate had thickness $d_1 \approx 0.1$ μm and saturation magnetization $4\pi M_1 = 380$ G. The second layer had the composition $(Y, Eu, Tm, Lu)_3(Fe, Mn, Ga)_5O_{12}$, thickness $d_2 = 2.88$ μm, and $4\pi M_2 = 148$ G. The exchange constants in layers 1 and 2 are, respectively, $A_1 = 2.5 \cdot 10^{-7}$ ergs/cm and $A_2 = 2 \cdot 10^{-7}$ ergs/cm; the gyromagnetic ratios are $\gamma_1 = 1.76 \cdot 10^7$ $(\text{sec} \cdot \text{Oe})^{-1}$ and $\gamma_2 = 1.47 \cdot 10^7$ $(\text{sec} \cdot \text{Oe})^{-1}$; the damping constants are $\alpha_1 = 8 \cdot 10^{-3}$ and $\alpha_2 = 2 \cdot 10^{-2}$; the uniaxial magnetic anisotropy constants are $K_{u1} = 0$ and $K_{u2} = 7.7 \cdot 10^3$ ergs/cm^3; and the cubic anisotropy constants are $K_1 = -1.8 \cdot 10^3$ ergs/cm^3 and $K_2 = -4.1 \cdot 10^2$ ergs/cm^3. The domain-collapse field is $H_{c2} = 56$ Oe, and the planar saturation field is $H_{s2} = 1060$ Oe (the calculated value is $H_{s2} = 2K_{u2}/M_2 - 4\pi M_2 = 1160$ Oe).

The total thickness of the layers was determined by the interference method and the thickness of each layer was determined from the etching time. The magnetization of layer 2 was calculated from the characteristics of the stripe domain structure and the bubble-collapse field.[4] The magnetization of layer 1 was estimated indirectly from the degree of substitution of the iron sublattice forming the base of the layer of yttrium iron garnet. The gyromagnetic ratios were determined from the field dependence of the resonance frequencies in the saturated film. The uniaxial anisotropy constants were determined from the angular dependence of the FMR field. The damping constants *a* were determined from the widths of the FMR lines. The exchange constants *A* were calculated from the Néel temperature.[5]

3. First, the overall dependence of the resonance frequencies on the in-plane magnetic field H_p was obtained in a wide range of frequencies 0.4–4 GHz (see Fig. 1). At high frequencies and fields above H_{s2} two FMR lines exist in layers 1 and 2 and a series of spin-wave resonances exists in layer 2. We have described these resonances previously in Ref. 1. At intermediate frequencies and fields below H_{s2} domain resonances (DFMR_2) can be seen in layer 2. Here the FMR line of layer 1 splits into a doublet. This doublet lies in the range of fields $H_{s1} < H_p < H_{s2}$, where layer 1 is magnetized uniformly and layer 2 contains domains. The following discussion will concern these two resonance lines.

The domain structure of layer 2 was monitored with the help of a polarization microscope and was formed as follows. A constant magnetic field stronger than the saturation field H_{s2} was applied in the plane of the film and was then decreased to zero. The domain structure arising in the process depended on the orientation of the magnetizing

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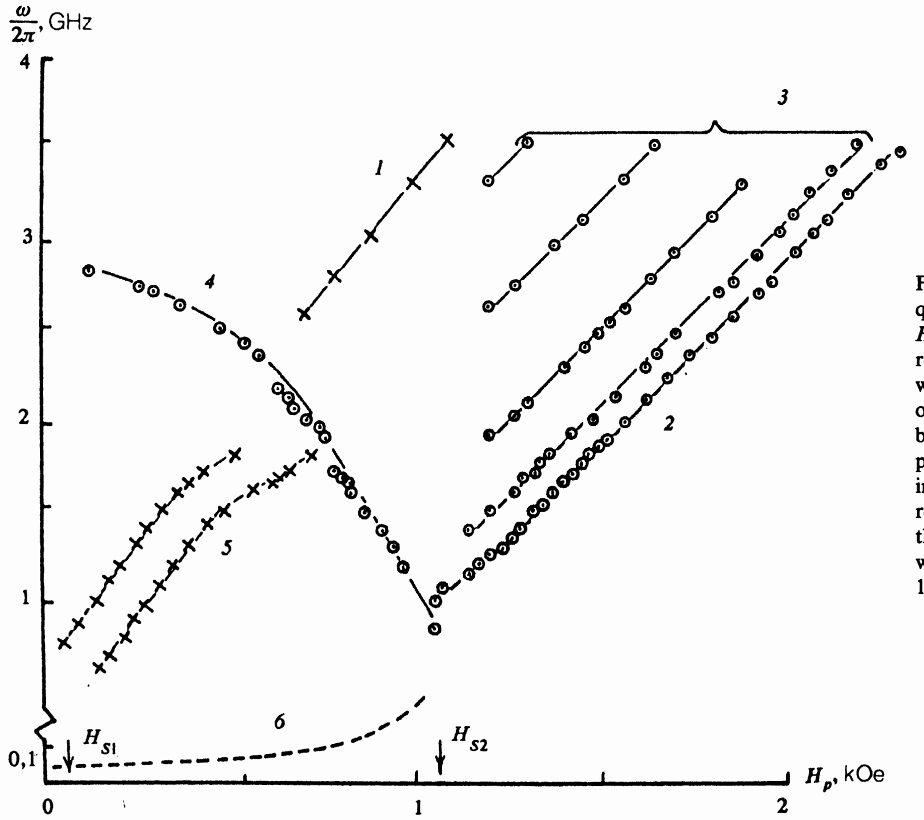

FIG. 1. Experimentally determined resonance frequencies as a function of the in-plane field $H_p \parallel$ [112]: *1* and *2*—homogeneous ferrimagnetic resonance lines in layers 1 and 2; *3*—series of spin-wave resonances in layer 2; *4*—ferrimagnetic resonance in the domains of layer 2; *5*—FMR doublet in layer 1; the dashed line 6 represents the position of the resonance line of the domain walls in layer 2. The series of spin-wave resonances is resolved only in sufficiently thin bubble films. For this reason, the spectrum *3* is presented for a film whose second layer was etched to a thickness of 1.2 μm.

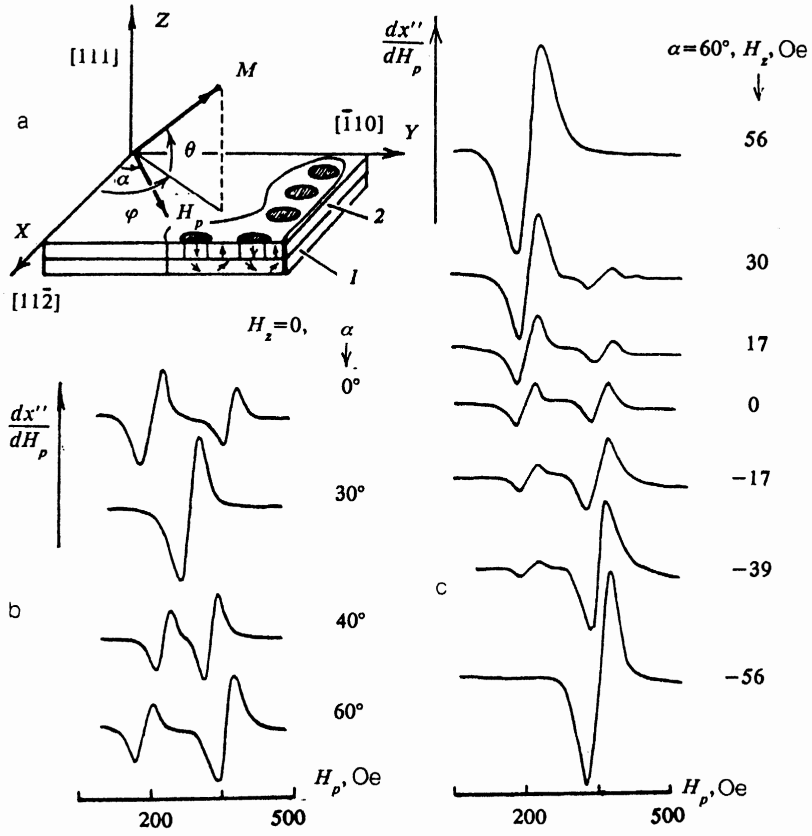

FIG. 2. a) Coordinate system for a film with (111) orientation. The external magnetic field $\mathbf{H}_p$ lies in the (111) plane of the film at an angle α to the [11$\bar{2}$] axis; θ and φ are the angles of orientation of the magnetization of layer 1 with respect to the film plane and the [11$\bar{2}$] direction, respectively; b) experimental field dependence of the derivative of the dissipative part of the susceptibility with respect to the magnetic field $\partial\chi''/\partial H_p$ at the frequency $\omega/2\pi = 1.2$ GHz for $H_z = 0$ and different orientations of the external in-plane magnetic field $\mathbf{H}_p$ (angles α); c) experimental plot of $\partial\chi''/\partial H_p$ versus H_p at the frequency $\omega/2\pi = 1.2$ GHz for $\alpha = 60°$ ($\mathbf{H}_p \parallel$ [$\bar{1}2\bar{1}$]) for different values of the external bias field H_z.

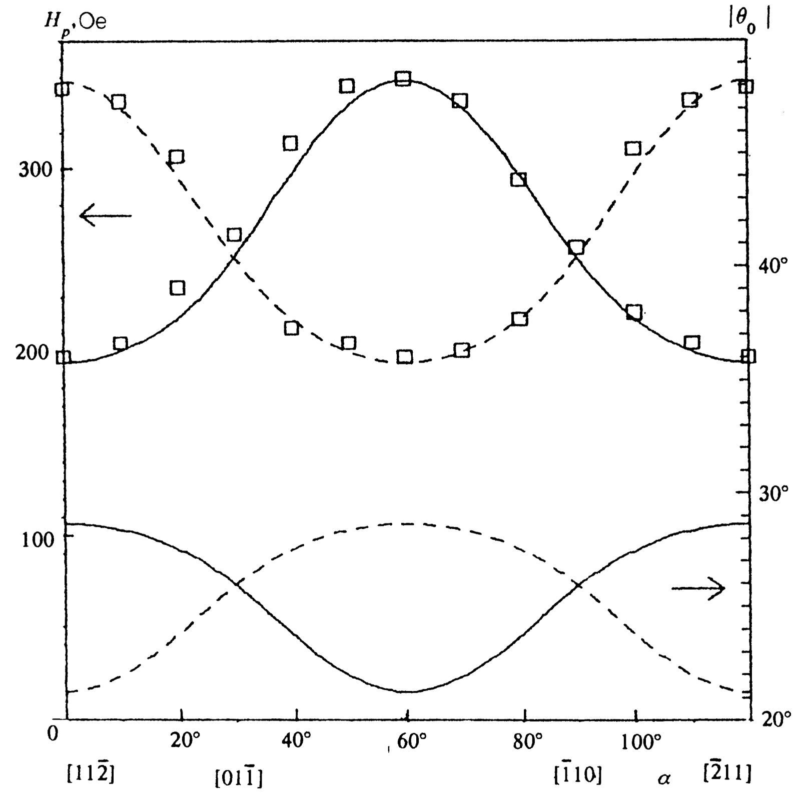

FIG. 3. Anisotropy of the resonant magnetic fields H_p and of the equilibrium orientation θ_0 of the magnetization of layer 1. Here α determines the direction of the external in-plane field; the squares represent the experimental data at the frequency $\omega/2\pi=1.2$ GHz with $H_z=0$; the solid lines represent the calculation for magnetization $\mathbf{M}_1$ with $\theta>0$; the dashed lines are for $\theta<0$; the curves were constructed for $K_1=-1.8\cdot10^3$ ergs/cm^3 and $H_{\text{eff}}=300$ Oe.

field $\mathbf{H}_p$ in the plane of the film (the angle α, see Fig. 2a). When the field was applied along the $[11\bar{2}]$ axes, a lattice of either black or white bubbles was formed. When the field was oriented parallel to the $[\bar{1}10]$ axes, however, black and white bubble domains were observed in equal phase ratios.$^{1)}$ The ratio of the areas occupied by white and black domains was changed by varying the magnitude of the bias field $H_z<60$ Oe, which was produced perpendicular to the plane of the film with the help of a magnetizing coil. As the resonant absorption was recorded (the dissipative susceptibility χ'' versus H_p), the domain structure in layer 2 was checked visually. This domain did not change, since the resonant fields H_p were much weaker than the saturation field H_{s2}.

4. Figure 2c displays the intensity of the FMR-doublet lines as a function of the bias field H_z. As H_z increased and the black-to-white ratio changed, one line in the doublet became stronger while the other line became weaker. When the field H_z reached the bubble-collapse field, the layer 2 became saturated and one of the lines vanished. This effect was completely symmetric with respect to the sign of H_z.

Resonant absorption was investigated for different orientations of the field $\mathbf{H}_p$ in the plane of the film. It is evident from Fig. 2b that the intensity of the lines in the doublet and the distance between them depend on the angle α. The resonant field versus the angle α is represented by the squares in Fig. 3. If the magnetic field is in the $[\bar{1}10]$ direction, then the double lines in the doublet merge and the intensity of the resonance is doubled.

It was also observed that if a bubble array with a different polarity is produced, then for the same angles α the lines in the doublet are interchanged. If an array of stripe domains is formed, then both line intensities increase by a factor of 1.5–2. When layer 2 is saturated, the FMR line is approximately 20% narrower, and the line is stronger (see Fig. 2c). For stripe domains the lines are stronger and narrower than in the case of bubbles.

5. The magnitude and angular dependence of the resonance fields $H_p(\alpha)$ can be calculated in the simple model in which layer 1 is isolated and layer 2 is inhomogeneously magnetized by the domains.

Specifically, layer 1 of the film is in an in-plane field stronger than the saturation field H_{s1} and is influenced by layer 2, which is demagnetized. Some sections of layer 1 are under black domains and others are under white domains. Since layer 1 is thinner than layer 2 and its thickness is less than the size of the domain, layer 1 is affected mainly by the exchange field and the normal component of the fringe fields.

It is evident in Fig. 4 that the fringe fields of an isolated bubble create inhomogeneous magnetization of layer 1 in the plane of the film. This results in a shift and inhomogeneous broadening of the FMR line in layer 1. The center of the resonance line is determined by the contribution of the regions of layer 1 where the fringe field $\mathbf{H}_d$ varies slowly. The region beneath the center of the domain, where both field components reach their extremal values

$$H_{dz}=0.707\cdot4\pi M_2,\qquad H_{dr}=0 \tag{1}$$

makes the greatest contribution to FMR. The region beneath the bubble wall contributes to the wings of the resonance line. In regions of layer 1 which are located far from the bubble we have $\mathbf{H}_d\equiv0$.

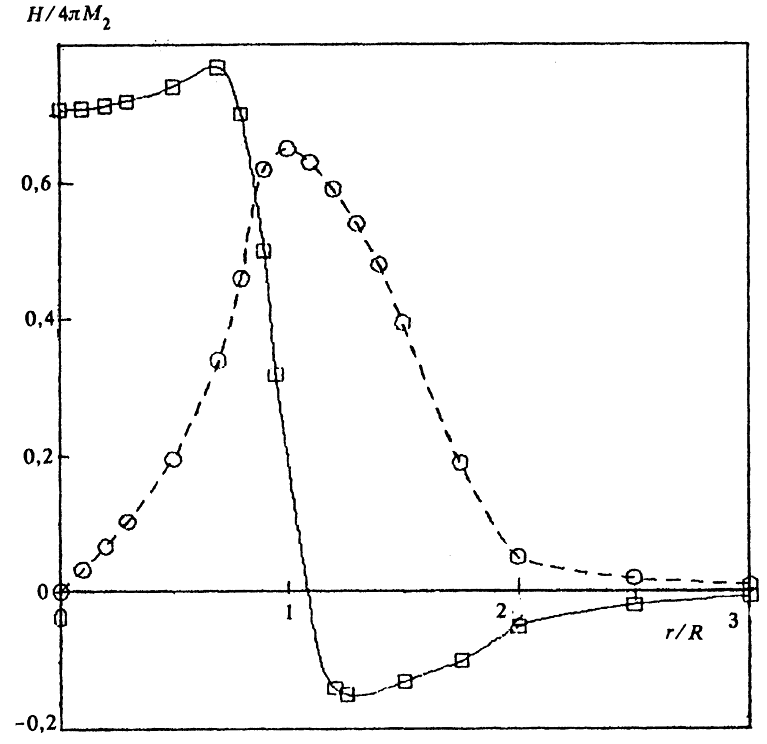

FIG. 4. Distribution of the fringe fields of a single bubble.[8] The bubble radius $R=d_2$; the solid curve represents the normal component H_z of the field at the surface and the dashed curve represents the radial component H_r at a distance $0.1R$ from the surface of the bubble film.

In the case of a stripe structure or bubble arrays with an equal ratio of black and white phases the z component of the field "jumps" symmetrically and the radial component has a maximum on the domain wall. This means that beneath the center of the domains the fringe fields can be assumed to be approximately constant and equal to

$$H_{dz}=\pm 0.707\cdot 4\pi M_2, \qquad H_{dr}=0. \tag{2}$$

The exchange interaction between the spins in layers 1 and 2 also contributes to the field H_z. The thickness of layer 1 is on the order of the thickness of the "domain wall" in this layer $\Delta_1=\sqrt{A_1/2\pi M_1^2}\approx 0.06\,\mu\text{m}$. For this reason, the maximum exchange field in layer 1 can be estimated as

$$H_e=A_2/M_1\Delta_2^2,$$

$$\Delta_2=\sqrt{2A_2/(2K_{u2}-\mathbf{H}_p\mathbf{M}_2-4\pi M_2^2)}\approx 0.086\ \mu\text{m},$$

where Δ_2 is the thickness of the domain wall in layer 2. It is easy to see that the exchange field $H_e\approx(H_{s2}-H_p)M_2/2M_1$ in fields $H_p=200$–350 Oe, where the FMR doublet is observed, is equal to 160–190 Oe. This field is in the same direction as $\mathbf{H}_d$. For this reason, the effective field acting on layer 1 is

$$H_{\text{eff}}=H_{dz}+H_e. \tag{3}$$

6. Thus we shall assume that the energy of the magnetic moments in layer 1 is determined by the cubic anisotropy, the demagnetization fields, the external in-plane magnetic field $\mathbf{H}_p$, and the effective H_{eff}:

$$W=K_1\left(\frac{\cos^4\theta}{4}+\frac{\sin^4\theta}{3}-\frac{\sqrt{2}}{3}\cos^3\theta\sin\theta\cos 3\varphi\right)$$
$$+2\pi M_1^2\sin^2\theta-H_pM_1\cos\theta\cos(\varphi-\alpha)$$
$$+H_{\text{eff}}M_1\sin\theta. \tag{4}$$

Here the angles θ and φ determine the orientation of the vector $\mathbf{M}_1$ (see Fig. 2a). The equilibrium values of the angles φ_0 and θ_0 are solutions of the equations

$$\left.\frac{\partial W}{\partial\varphi}\right|_{\varphi_0}=0, \qquad \left.\frac{\partial W}{\partial\theta}\right|_{\theta_0}=0. \tag{5}$$

The resonant frequency ω is determined by the well-known relation

$$\frac{\omega}{\gamma_1}=\frac{1}{M_1\cos\theta_0}\left[\frac{\partial^2W}{\partial\theta^2}\frac{\partial^2W}{\partial\varphi^2}-\left(\frac{\partial^2W}{\partial\theta\,\partial\varphi}\right)^2\right]^{1/2}_{\theta_0\varphi_0}. \tag{6}$$

Substituting here the solutions of Eqs. (5) we obtain the resonant field H_p as a function of α. The resonant field for a domain structure with equal ratio of black and white domains [H_{dz} from Eq. (2)] is displayed in Fig. 3 by the solid line for regions with $\theta>0$ ($H_{dz}=+0.707\cdot 4\pi M_2$) and the dashed line for regions with $\theta<0$($H_{dz}=-0.707\cdot 4\pi M_2$). In this figure the squares represent experimental points. The figure also displays the equilibrium slope angle θ_0 as a function of the direction of the external field $\mathbf{H}_p$ in the plane of the film.

If the magnetic field is oriented in the $[\bar{1}10]$ directions, the lines of the FMR doublet merge into a single line. This orientation corresponds to the degenerate case, when the equilibrium orientations of the magnetization vector $\mathbf{M}_1$ beneath the black and white domains are identical. For all other orientations α the cubic anisotropy splits the FMR line in layer 1 into two lines.

The best approximation of the experimental values of the resonant field by the computed relations is achieved with $H_{\rm eff} \approx 300$ Oe (see Fig. 3). This value of $H_{\rm eff}$ from Eq. (3) agrees with the independently measured values of the $4\pi M_2$ and K_{u2} $(H_{\rm eff}=H_{dz}+H_e \approx 280$ Oe).

7. We have established experimentally and theoretically that the splitting of the ferromagnetic resonance line in a two-layer iron garnet film is caused by the exchange interaction between the layers, cubic anisotropy, and the fringe fields of the domains in the unsaturated layer. The working characteristics of both layers of the film were determined from measurements of the magnitude and anisotropy of the resonant fields.

[1)] Domain nucleation in an in-plane field are studied in detail in Refs. 6 and 7.

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