Anisotropy of the intensity of the ferromagnetic-resonance line in thin bilayer iron garnet structures

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It has been established experimentally and theoretically that the interaction between thin layers under conditions such that their resonant fields coincide leads to an anisotropic intensity of the fundamental spin-wave-resonance modes.

Bilayer iron garnet structures have attracted interest in connection with the development of the physical principles of spin-wave electronics.[1] The interaction between layers may lead to a repulsion of spin-wave-resonance (SWR) modes,[2] or it may be manifested through a ferromagnetic resonance in closing domains.[3]

In this letter we are reporting a study of the angular distribution of the resonant fields H_r and the intensities of the fundamental SWR modes in the (110) plane, which is normal to the surface of the sample. The experiments were carried out over the frequency range 4–10 GHz at room temperature. We studied two structures.

The first structure, which was approximately the same as that described in Ref. 3, had a (111) gallium-gadolinium garnet substrate 0.5 mm thick. The first layer (which we will call the "sublayer") grown on the substrate was $(Y, Gd, La)_3(Fe, Ga)_5O_{12}$, with a thickness $d_1 \approx 0.05$ μm and a saturation magnetization $4\pi M_1 = 380$ G. The second layer to be grown (the "main layer") was $(Y,Eu,Tm,Lu)_3(Fe,Mn,Ga)_5O_{12}$, with a thickness $d_2 = 2.85$ μm and $4\pi M_2 = 148$ G. The exchange constants in the layers were $A_1 = 2.5\times 10^{-7}$ erg/cm and $A_2 = 2\times 10^{-7}$ erg/cm. The gyromagnetic ratios were $\gamma_1 = 1.76\times 10^7$ $s^{-1}\cdot Oe^{-1}$ and $\gamma_2 = 1.47\times 10^7$ $s^{-2}\cdot Oe^{-1}$. The dimensionless damping parameters were $\alpha_1 = 6\times 10^{-3}$ and $\alpha_2 = 25\times 10^{-3}$. The constants of the uniaxial magnetic anisotropy were $K_1^u = 0$ and $K_2^u = 7.7\times 10^3$ erg/cm^3. The constants of the cubic magnetic anisotropy were $K_1 = 1.1\times 10^3$ erg/cm^3 and $K_2 = 4.1\times 10^2$ erg/cm^3.

In the second structure, the sublayer was the same as that in the first structure, while the main layer, with a composition similar to that of the sublayer, differed from it only in thickness ($d_2 = 0.2$ μm) and in uniaxial-anisotropy constant ($K_2^u = 3\times 10^3$ erg/cm^3).

The constants characterizing the structure were measured: d_2 by an interference method, d_1 by the rate of chemical etching, $4\pi M$ on a vibration magnetometer, A from the Curie point and also from the SWR spectra, and K^u, K, γ, and α by a ferromagnetic-resonance method. Single-layer "witness" samples were used to refine some of the parameters. To see how the thickness of the main layer affects the intensity of the ferromagnetic-resonance line of the sublayer, we prepared a series of samples 5 mm in diameter from the first structure by a chemical-etching method. Figure 1a shows the angular distribution of the intensity for these samples with $d_2 = 0$ and 2.85 μm; Fig. 1b shows corresponding results for the second structure.

In contrast with Ref. 2, when the resonant fields of the sublayer (H_{r1}) and of the main layer (H_{r2}) coincide, i.e., under the condition $H_{r1} = H_{r2}$, we do not observe a repulsion of the SWR modes. As can be seen from Fig. 1, there is an obvious anisotropy in the intensities of these modes in the sublayer (J_1) and the main layer (J_2). For the first structure, at a frequency $F = 4.86$ GHz the condition $H_{r1} = H_{r2}$ holds for a polar angle $\theta = 35°$, and the peak in J_1 is at $\theta = 45°$. At $F + 8.73$ GHz, we find $H_{r1} = H_{r2}$ for $\theta = 45°$, and the peak in J_1 is at $\theta = 55°$. In other words, the anisotropy of J_1 and J_2 results exclusively from the interaction of the layers and is observed at $H_{r1} = H_{r2}$. When there is no second layer ($d_2 = 0$), there is no anisotropy in J_1 (Fig. 1a). Figure 2 shows the peak value $J_{1,\max}$ in the sublayer as a function of the thickness d_2. We see that $J_{1,\max}$ has its highest value in the sample with $d_2 = 1$ μm; this result may be of practical importance.

It was suggested that the behavior of J is governed by the phase relations between the coupled oscillations of the magnetization **M** in the main layer and the sublayer in the vicinity of $H_{r1} = H_{r2}$, as in the case involving oscillations of the magnetic compo-

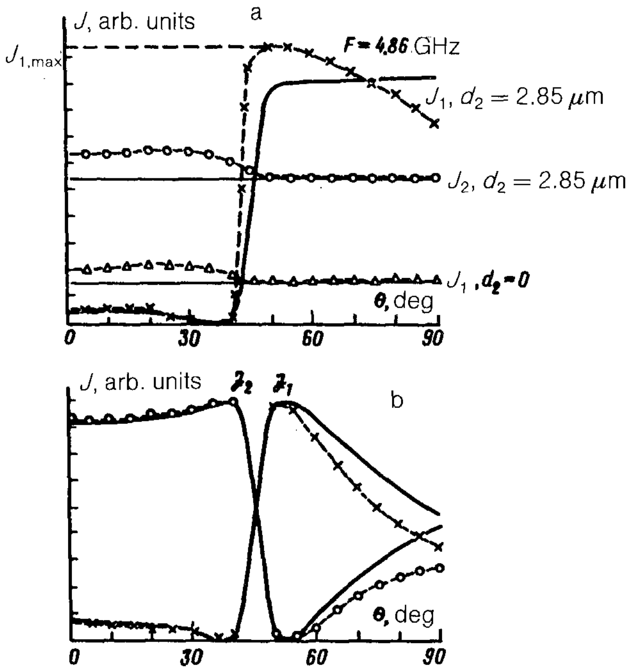

FIG. 1. a—Intensities of the ferromagnetic resonance lines of the sublayer (J_1) and of the main layer (J_2) versus the polar angle θ for the first structure (the solid lines are theoretical); b—intensities of the ferromagnetic-resonance lines of the sublayer (J_1) and the main layer (J_2) versus the polar angle θ for the first structure (the solid lines are theoretical).

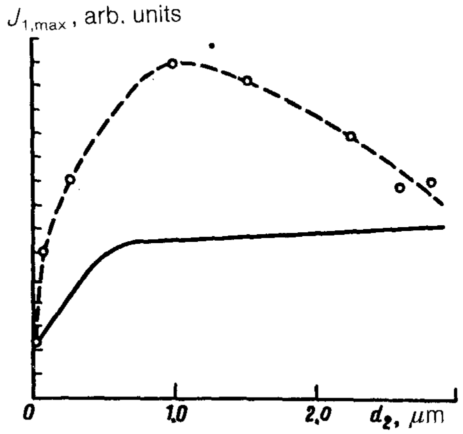

FIG. 2. Maximum amplitude of the ferromagnetic resonance line of the sublayer, $J_{1,max}$, versus the thickness d_2. The solid line is theoretical.

nent (h) of the microwave field and the precession of the magnetization (m) near the point of a magnetic resonance.

To construct a theoretical model, we write the Landau–Lifshitz equation for each of the layers, taking the exchange interaction into account:

$$-A_1^0 \frac{d^2 m_1}{dz^2} + (\chi_1^0)^{-1} m_1 = h,$$

$$-A_2^0 \frac{d^2 m_2}{dz^2} + (\chi_2^0)^{-1} m_2 = h, \tag{1}$$

where z is the coordinate along the normal to the film surface, $A^0 = A/M^2$ has the dimensionality of a length squared and characterizes the inhomogeneous exchange, and χ^0 is the magnetic susceptibility of the uniformly magnetized film.[4] We assume that there is no pinning at the outer boundaries of the structure:

$$\frac{dm_1(z)}{dz} = 0, \qquad \text{at} \quad z = d_1,$$

$$\frac{dm_2(z)}{dz} = 0, \qquad \text{at} \quad z = -d_2, \tag{2}$$

We also assume that the boundary conditions are determined by the surface exchange interaction. The surface density of the exchange energy is $W = -\beta M_1 \cdot M_2$.

The effective surface fields are thus $H_1 = \beta M_2$ in the sublayer and $H_2 = \beta M_1$ in the main layer. Substituting these fields into (1) for the surface magnetization, and ignoring pinning, we find boundary conditions at the inner surface:

$$\frac{A_1^0}{\beta} \frac{dm_1(z)}{dz} + Gm_1(z) - m_2(z) = 0,$$

$$M_1 A_1^0 \frac{dm_1(z)}{dz} = M_2 A_2^0 \frac{dm_2(z)}{dz}, \qquad \text{at} \qquad z = 0. \tag{3}$$

Here M_1 and M_2 are the magnetizations of the layers. The constant β has the dimensionality of a length, and at fixed M_1 and M_2 it tends to put the dynamic magnetizations M_1 and M_2 in a parallel configuration. We are also using $G = M_2/M_1$. Solving Eqs. (1) under boundary conditions (2) and (3), we find the susceptibility of the structure to be

$$\chi = d_1\chi_1^0 + d_2\chi_2^0 + \frac{\Delta_1}{\Delta}\frac{\sin k_1 d_1}{k_1} + \frac{\Delta_2}{\Delta}\frac{\sin k_2 d_2}{k_2}, \tag{4}$$

where

$$\Delta_1 = k_2 B_2 \sin k_2 d_2 (\chi_2^0 - G\chi_1^0),$$
$$\Delta_2 = -k_1 B_1 \sin k_1 d_1 (\chi_2^0 - G\chi_1^0),$$
$$\Delta = (k_1 B_1 \sin k_1 d_1 + G\cos k_1 d_1) k_2 B_2 \sin k_2 d_2 + k_1 d_1 \cos k_2 d_2,$$
$$k_1^2 = -\frac{1}{A_1^0 \chi_1^0}, \quad k_2 = -\frac{1}{A_2^0 \chi_2^0}, \quad B_1 = \frac{A_1^0}{\beta}, \quad B_2 = \frac{A_2^0}{\beta} G,$$

and k_1 and k_2 are some complex numbers. The solid line in Fig. 1 shows theoretical results on J_1 and J_2 versus the angle θ. For the first structure we have $\beta = -1\ \mu$m, and for the second $\beta = -0.3\ \mu$m. The solid line in Fig. 2 is a theoretical plot of $J_{1,\max}$ versus d_2 for the first structure.

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