Application of Ferromagnetic Resonance Method to Study of Multilayer Nanostructures

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Abstract—The ferromagnetic resonance spectra of multilayer nanostructures synthesized from magnetic layers based on amorphous \textit{Co$_{45}$Fe$_{45}$Zr$_{10}$} and nonmagnetic layers of the amorphous semiconductor \textit{α-Si} have been experimentally studied. It is shown that the character of the spectrum depends strongly on thicknesses of magnetic and nonmagnetic layers and the structure of the boundary layer. The resonant fields are calculated within the effective-medium approximation. In some cases, the calculation results describe well the experimental data.

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Currently, one of intensively developed lines of research in solid-state physics is the investigation of nanomagnets, including magnetic multilayers and granular ferromagnetic-metal–semiconductor structures. This new class of synthesized materials, due to their properties (in particular, possibility of controlling electron beam through the interaction of electron spins with magnetic fields, nonlinear magneto-optical effects, giant magnetoresistance), is promising for developing unique technical devices of spintronics—new field of science and technique [1–3]. An important problem in the physics of such systems is the investigation of their high-frequency properties and establishment of the relationship between their static and high-frequency characteristics.

In this paper, we report the results of studying the ferromagnetic resonance (FMR) spectra of multilayer films \textit{\{(Co$_{45}$Fe$_{45}$Zr$_{10}$)$_m$(Al$_2$O$_3$)$_{100−m}$\}(α-Si)$_z\}}, obtained by ion-beam deposition. The thickness of bilayers, \(d = x + y\), was varied from 1.5 to 32 nm and the number \(z\) of bilayers was varied from 6 to 215.

Four series of samples with different structures of magnetic layers were investigated. Magnetoresistive effect was observed in all samples. We measured the field and orientation dependences of the FMR spectra (the direction of the external magnetic field \(\mathbf{H}\) was characterized by the angle \(\alpha\) with respect to the normal to the film plane) and magnetization curves for \(\alpha = 0\) and \(90°\). The FMR spectra were recorded on electron-spin resonance (ESR) spectrometers at the frequencies \(\omega/2\pi = 9.27\) and \(9.4\) GHz (derivatives of the absorption signal were recorded). Measurements were performed at room temperature.

The samples were multilayer structures composed of \textit{Co$_{45}$Fe$_{45}$Zr$_{10}$} magnetic layers and semiconductor interlayers of amorphous \textit{α-Si} \((m = 100\text{ at }\%\), \(0.3 < f = x/(x + y) < 0.8\), where \(f\) is the parameter proportional to the magnetic phase concentration).

FMR Spectra

In the samples with the thickness \(x\) of magnetic layers in the range 11–24 nm \((z = 54)\), the nonmagnetic interlayers almost do not affect the resonant properties of amorphous multilayers. At a tangential bias, the spectrum consists of a single line, and the resonant field \(H_{\text{res}}\) is about 800 Oe, independent of the thickness \(x\) of magnetic layers. The same value \(H_{\text{res}}\) was observed for a bulk sample of amorphous \textit{Co$_{45}$Fe$_{45}$Zr$_{10}$} and for the samples obtained by layer-by-layer deposition of \textit{Co$_{45}$Fe$_{45}$Zr$_{10}$} without semiconductor interlayers. From the resonance condition in the absence of anisotropy at \(\alpha = 90°\)

\[ (\omega/\gamma)^2 = H_{\text{res}}(H_{\text{res}} + 4\pi M), \]  

where \(\gamma\) is the gyromagnetic ratio and \(M\) is the magnetization, we obtain the following value for the magnetic material of the layers: \(4\pi M \cong 13 000\) G.

At smaller \(x\), a dependence of the resonant field on both the thickness \(x\) of magnetic layers and the thickness \(y\) of nonmagnetic interlayers is observed. This fact indicates that the effective fields of the interface and neighboring magnetic layers stronger affect the FMR conditions at \(x < 11\) nm.
Currently, there are two methods of analysis of FMR spectra of multilayer structures:

(i) Behavior of the magnetization vector is considered separately in each layer. The effect of the other part of the film is taken into account by introducing the corresponding effective fields determined through the magnetic energy of the entire system.

(ii) The multilayer structure is replaced with some effective medium having an average magnetization, determined from the condition \( \langle M \rangle = M_0 f \), where \( M_0 \) is the layer magnetization.

The neutron-diffraction data [4] show that there is no clear boundary between layers in the samples under study, and, at \( x, y < 2 \) nm, an island structure is observed, which facilitates penetration of Co ions into nonmagnetic layers and leads in some cases to the formation of direct contacts between magnetic layers. This fact is in favor of the second method in our case. Then, for the tangential bias, one can use formula (1), replacing \( M \) with the average magnetization. Figure 1 shows the theoretical dependence (solid line) of \( H_{\text{res}} \) on \( f \) for tangential magnetization \( (\alpha = 90^{\circ}) \), which was obtained under the assumption that the sample magnetization is proportional to the magnetic phase concentration and that \( \gamma = 2.8 \) MHz/Oe. The same figure shows the experimental data (denoted by markers), obtained for four sets of samples with different ratios of thicknesses of magnetic and semiconductor layers. It can be seen that some sets show good agreement between the theoretical and experimental data; other sets are characterized by a very narrow range of magnetic phase concentrations where this approximation is valid.

It was shown in [5] for multilayer Fe/Si samples that the type and concentration of the silicides formed in nonmagnetic interlayers upon sample synthesis may significantly affect the magnetic properties of nanostructures. To estimate the effect of these factors in our case, we performed static magnetic measurements of the samples from set 1.

**Static Measurements**

The magnetization curves for a field \( \mathbf{H} \) parallel to the film plane indicate that in all samples (except for the thinnest ones) the interaction is ferromagnetic. Small uniaxial anisotropy with a spread in the directions of easy-magnetization axes is observed in the film plane. The average magnetization of the samples is not proportional to the magnetic phase concentration parameter: at \( y > 3 \) nm, the saturation magnetization decreases much more rapidly than \( f \) [6]. In Fig. 1, the dotted line shows the theoretical dependence of \( H_{\text{res}} \) for the samples of the first set on the magnetic phase concentration parameter with due regard to the real effective magnetization, calculated from the magnetization curves. In this case, the agreement between the experimental and theoretical data is quite satisfactory.

Samples with semiconductor interlayers thinner than 0.95 nm are characterized by antiferromagnetic interaction since such samples either exhibit a significant magnetoresistive effect [4] or have a very high concentration of superparamagnetic particles.

At thicknesses of magnetic layers larger than 2 nm, additional absorption peaks arise in the spectrum. The larger the number of bilayers, the earlier the spectrum distortion begins (see [6] for more details).

The island structure of the magnetic layers (at \( x < 2 \) nm), the possibility of direct contacts between them, and the absence of clear boundaries between the layers hinder analysis of the spectra observed. In [7], it was proposed to use a granular metal–insulator system as a material for magnetic layers. The presence of a barrier dielectric layer should prohibit the formation of compounds at the composite/semiconductor interface.

**SERIES 2**

The samples were granular films with magnetic grains 2–5 nm in size, embedded in the \( \text{Al}_2\text{O}_3 \) dielectric matrix \( (x = 5 \ \mu\text{m}, y = 0, z = 1) \). The magnetic phase concentration \( m \) ranged from 30 to 80 at %. The percolation threshold \( m = m_p = 45 \) at %.

For the samples of this series, the behavior of resonant fields is described well from the formulas obtained for homogeneous films in the effective-medium approximation. The value \( \Delta H \) monotonically decreased with an increase in the magnetic phase concentration (from 1200 Oe for \( m = 30 \) at % to 300 Oe for \( m = 55 \) at %). The data obtained on the samples of this series were used in the analysis of the FMR spectra of the samples of series 3 and 4.