Spin-Wave Resonance in Three-Layer NiFe/Dy$_x$Co$_{1-x}$/NiFe Films as a Method for Detecting Structural Inhomogeneities in Amorphous Dy$_x$Co$_{1-x}$ Layers

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The standing spin-wave spectrum was studied by spin-wave resonance in three-layer Ni$_{80}$Fe$_{20}$/Dy$_x$Co$_{1-x}$/Ni$_{80}$Fe$_{20}$ films with an amorphous interlayer of DyCo alloy in the region of compensation compositions. It is shown that the spin-wave resonance (SWR) spectrum in the geometry $k \parallel M$ is observed only for a planar system with a DyCo layer of pre-compensation composition. In the $k \perp M$ geometry, the SWR spectrum was observed for the DyCo systems with both pre- and post-compensation compositions. The exchange stiffness was analyzed as a function of the DyCo layer thickness to formulate a model of microheterophase structure for amorphous DyCo alloys in the compensation region, where the magnetic microstructure accounts for the dynamic and static magnetic characteristics of these materials. © 2002 MAIK "Nauka/Interperiodica".

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Amorphous RE(Dy, Gd, Tb)–TM(Fe, Co) alloys prepared as solid solutions in a broad concentration range are the brightest representatives of a class of amorphous ferrimagnets. The magnetization of these alloys is the sum of antiparallel magnetizations of the RE and TM sublattices. For this reason, the magnetization in these materials becomes zero at a certain compensation temperature ($T_{\text{comp}}$) or composition ($x_{\text{comp}}$). These materials, when prepared as films with near-compensation compositions, are ordinarily used as media for ultrahigh-density thermomagnetic recording [1]. In these films, the coercive force has a sharp maximum at the points $T_{\text{comp}}$ (or $x_{\text{comp}}$). A deviation of only several degrees from $T_{\text{comp}}$ (or of 2–3 at. % from $x_{\text{comp}}$) is sufficient for the coercive force to decrease by several times. The magnetic and atomic structures of these alloys were extensively studied in [2]. However, some of their properties, e.g., dynamic properties, are still poorly understood. For instance, the studies of these films by ferromagnetic resonance (FMR) show that the FMR line width increases as the film composition (temperature) approaches $x_{\text{comp}}$ ($T_{\text{comp}}$) and that no electromagnetically induced microwave absorption is observed (note that such a behavior of the FMR parameters is common to all ferrimagnetic materials [3]).

In this work, we report the results of studying the dynamic magnetic properties of three-layer NiFe/Dy$_x$Co$_{1-x}$/NiFe films, in which the amorphous RE–TM layer is prepared in the region of compensation compositions.

It was established in our experiments that, first, a uniform alternating magnetic field excites standing spin waves in such a three-layer planar composite system. This gives evidence for the exchange interaction between the ferri- and ferromagnetic layers. Second, analysis of the dependence of effective spin-wave stiffness of such a system on the thickness of ferrimagnetic layer allowed the indirect (though reliable) conclusion to be drawn about some features of the real magnetic and chemical structures of DyCo alloy films with compensation composition.

SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUE

Three-layer exchange-coupled Ni$_{80}$Fe$_{20}$/Dy$_x$Co$_{1-x}$/Ni$_{80}$Fe$_{20}$ films were prepared by thermal evaporation in a vacuum of $3 \times 10^{-6}$ torr by sequential deposition of NiFe and DyCo layers on a cover glass substrate from three independent evaporators with ring cathodes. The thicknesses of the Permalloy layers in the planar system were $d_{\text{NiFe}} = 1100$ Å, and the thickness of the Dy$_x$Co$_{1-x}$ layer was varied in the range from 100 to 800 Å. Single-layer 3000-Å-thick films of Ni$_{80}$Fe$_{20}$ Permalloy and single-layer 700-Å-thick Dy$_x$Co$_{1-x}$ films were used as reference samples. The film thicknesses and chemical compositions were monitored by X-ray spectroscopic
analysis. The amorphous state of the DyCo layer was monitored by electron microscopy. The magnetooptical Kerr effect in fields up to 15 kOe was used as a test method for determining the pre-, post-, and compensation compositions of this layer. The same method (by studying the magnetooptical hysteresis loops at both outer and inner surfaces of the DyCo layer) was used to establish that the DyCo films were compositionally homogeneous across their width (this was subsequently confirmed by Auger spectroscopy) and had perpendicular anisotropy. In our case, the room-temperature compensation composition was Dy$_{22}$Co$_{78}$. Two groups of planar structures were prepared: Ni$_{80}$Fe$_{20}$/Dy$_{20}$Co$_{80}$/Ni$_{80}$Fe$_{20}$ and Ni$_{80}$Fe$_{20}$/Dy$_{22}$Co$_{78}$/Ni$_{80}$Fe$_{20}$. Although the chosen compositions of the ferrimagnetic layer are on opposite sides of $\chi_{\text{comp}}$, they have close total saturation magnetizations $M_s = 80$ G, coercive forces $H_c = 4–5$ kOe, and perpendicular magnetic anisotropies $K_\perp = 3 \times 10^5$ erg/cm$^3$.

The spin-wave resonance (SWR) spectra of the planar NiFe/Dy$_x$Co$_{1-x}$/NiFe structures, single-layer NiFe films, and DyCo films were studied on a standard X-band spectrometer with the cavity fundamental frequency $f = 9.2$ GHz at room temperature. The films were placed at the antinode of an alternating magnetic field in the cavity and magnetized in two geometries (either perpendicular or parallel to the surface). In the first geometry, the resonance fields of SWR peaks (in ferromagnetic films) are known to satisfy the equation

$$H_n = \frac{\omega}{\gamma} + 4\pi M - \eta_{\text{eff}} k_n^2, \quad k \parallel M, \quad (1)$$

and, in the second geometry, the equation

$$H_n = \{[(\omega/\gamma)^2 + (2\pi M)^2]^{1/2} - 2\pi M\} - \eta_{\text{eff}} k_n^2, \quad k \perp M, \quad (2)$$

where $\omega = 2\pi f$ is the frequency, $\gamma$ is the gyromagnetic ratio, $\eta_{\text{eff}}$ is the spin-wave stiffness depending on the exchange interaction constant $A$, $M$ is the magnetization, and $k_n = (\pi/d) n$ ($n = 1, 2, 3, \ldots$ and $d$ is the film thickness) is the wavevector of the $n$th mode in the SWR spectrum.

An important point is that the effective exchange stiffness $\eta_{\text{eff}}$, calculated by formula

$$\eta_{\text{eff}} = \frac{H_1 - H_s}{n^2 - 1} \left(\frac{d}{\pi}\right)^2, \quad (3)$$

is independent of the geometry of SWR experiment and must have the same value when recording the SWR peaks in both $k \parallel M$ and $k \perp M$ geometries. Indeed, the SWR spectra for the reference single-layer 300-Å Ni$_{80}$Fe$_{20}$ films were recorded in both geometries: $k \parallel M$ (14 peaks, including the surface peak) and $k \perp M$ (5 peaks) (Fig. 1). Nevertheless, the $\eta_{\text{eff}}$ values calculated by Eq. (3) proved to be nearly the same, with a good accuracy, for both cases and equal to $\eta_{\text{eff}} = 2.5 \times 10^{-9}$ Oe cm$^2$ (this value is consistent with the literature data [3]). No SWR absorption was observed for the reference Dy$_{20}$Co$_{80}$, Dy$_{22}$Co$_{78}$, and Dy$_{24}$Co$_{76}$ films.

**RESULTS AND DISCUSSION**

Figure 2 shows the absorption spectra of the three-layer NiFe/Dy$_x$Co$_{1-x}$/NiFe films studied. The SWR spectrum of the planar Ni$_{80}$Fe$_{20}$/Dy$_{20}$Co$_{80}$/Ni$_{80}$Fe$_{20}$ system in the $k \parallel M$ geometry is given in Fig. 2a, and the SWR spectrum of Ni$_{80}$Fe$_{20}$/Dy$_{22}$Co$_{78}$/Ni$_{80}$Fe$_{20}$ in the same geometry is given in Fig. 2b. The spectra are essentially different; in a planar system with the DyCo interlayer of pre-compensation composition, spin waves are excited, whereas in a planar system with the
DyCo interlayer of post-compensation composition the spectrum is a superposition of the FMR spectra of the two ferromagnetic NiFe layers. Such a sizable distinction is caused by the exchange interaction between the layers and by the orientation of magnetization of the Co sublattice in the DyCo layer about the external magnetic field. Indeed, for a three-layer system with the interlayer of pre-compensation composition the compensation point \( H_c \approx 4–5 \text{kOe} \). Consequently, this field is as high as two or even higher (curves 1, 2), which far exceeds the experimental error (~10%). At the same time, one can see that the values of \( \eta_{\text{eff}} \) measured for the \( \text{Ni}_{80}\text{Fe}_{20}/\text{Dy}_{20}\text{Co}_{80}/\text{Ni}_{80}\text{Fe}_{20} \) system are close to their values in the system \( \text{Ni}_{80}\text{Fe}_{20}/\text{Dy}_{24}\text{Co}_{76}/\text{Ni}_{80}\text{Fe}_{20} \) with the geometry (curve 3) are close to their values in the system with the \( \text{Dy}_{20}\text{Co}_{80} \) interlayer in the \( \text{Ni}_{80}\text{Fe}_{20} \) geometry. On the assumption that the exchange stiffness of a ferromagnetic film does not depend on the SWR geometry, one arrives at the conclusion that \( \eta_{\text{eff}} \) for curves 1 and 2 (Fig. 3) characterize the same magnetic material, while \( \eta_{\text{eff}} \) for curve 3 (Fig. 3) corresponds to a different magnetic material.

In our opinion, these results reflect the fundamental property of amorphous state, namely, the intrinsic structural (fluctuative) inhomogeneity of amorphous alloys. Amorphous alloys are known to contain chemical (phase) nanoscale inhomogeneities. In particular, these inhomogeneities in amorphous ferromagnetic alloys cause the fluctuations of exchange interaction and saturation magnetization, which was repeatedly detected experimentally (including the SWR method [5–8]). The magnitude of concentration fluctuations in these alloys can be as high as several atomic percent of mean concentration. This is the key factor that underlie the specific behavior of DyCo alloys in the compensation region. It is natural to introduce the notion of two magnetic phases for this alloy: the \( \Phi_1 \) phase, for which the inequality \( M_{\text{Co}} > M_{\text{Dy}} \) is satisfied locally and integrally, and the phase \( \Phi_2 \) for which the inequality \( M_{\text{Dy}} > M_{\text{Co}} \) is satisfied on the micro- and macrolevel. In the range of concentrations \( x < x_{\text{comp}} \) or \( x > x_{\text{comp}} \) the magnetic structure of the DyCo alloy is uniquely related to either \( \Phi_1 \) or \( \Phi_2 \). A basically different situation occurs in the region \( x = x_{\text{comp}} \) under condition that \( \Delta c \) falls within the range of fluctuations of local concentrations. In this case, the compensation point \( x_{\text{comp}} \) is determined from...
the requirement that the volumes of chaotically mixed $\Phi_1$ and $\Phi_2$ phases be the same. Then the pre- and post-compensation DyCo alloys are defined by the inequalities $V_{\Phi_2} > V_{\Phi_1}$, $V_{\Phi_1} < V_{\Phi_2}$, respectively. According to simple estimates within the framework of percolation theory, one can state that the percolation near $x_{comp}$ occurs through both $\Phi_1$ and $\Phi_2$ up to the concentrations $x^*$ for which the condition $V_{\Phi_1} = V_{\Phi_2}$ or $2V_{\Phi_1} = V_{\Phi_2}$ is met.

The results of our experiment can naturally be interpreted in terms of the scheme proposed in Fig. 4 (the arrows in this figure indicate the possible magnetization orientations for 3$d$ metals and the magnetization profile across the thickness of a three-layer film in the first SWR geometry). Figure 4a describes the experimental situation presented in Fig. 2a. In Figs. 4a, 4b, 4c, and 4d, $\Phi_1$ and $\Phi_2$ denote, respectively, the matrix and impurity phases in the DyCo three-layer film. The magnetization $M_{Co}$ in phase $\Phi_1$ is aligned with both the external and perpendicular anisotropy fields. Due to the exchange interaction between transition metals, the magnetization of the impurity phase $\Phi_2$ should have the in-plane component. For this reason, the coherent spin wave in the three-layer Ni$_{80}$Fe$_{20}$/Dy$_{24}$Co$_{76}$/Ni$_{80}$Fe$_{20}$ system propagates in the $k \parallel M$ geometry through the phase $\Phi_1$, and, in the $k \perp M$ geometry, through the phase $\Phi_2$ (Figs. 2c and 2d). Then the difference in the $\eta_{eff}$ values for curves 1 and 2 in Fig. 3 is physically understandable, because the effective thickness in this case is contributed by the partial stiffnesses $\eta_i$ of, in fact, different magnetic materials. The situation is reverse for the Ni$_{80}$Fe$_{20}$/Dy$_{24}$Co$_{76}$/Ni$_{80}$Fe$_{20}$ system, where $\Phi_2$ and $\Phi_1$ are the matrix and impurity phases, respectively. In this case, the magnetization $M_{Dx}$ of the $\Phi_2$ phase is aligned with the external field in the SWR geometry ($k \parallel M$), while the magnetization $M_{Co}$ of this phase is antialigned with both external field and NiFe magnetizations. In such a situation, the coherent spin wave can be excited only in the NiFe layers (Figs. 2b and 4b). However, the magnetization $M_{Co}$ of the impurity phase can contain the in-plane component. For this reason, the coherent spin wave in the three-layer Ni$_{80}$Fe$_{20}$/Dy$_{24}$Co$_{76}$/Ni$_{80}$Fe$_{20}$ system can propagate in the $k \perp M$ geometry through the impurity phase $\Phi_1$ (Figs. 2d and 4d). This explains the agreement between the $\eta_{eff}$ values for curves 1 and 3 in Fig. 3.

Thus, the SWR studies of the three-layer planar Ni$_{80}$Fe$_{20}$/Dy$_{24}$Co$_{76}$/Ni$_{80}$Fe$_{20}$ systems containing amorphous DyCo interlayer in the region of compensation compositions enable one not only to judge indirectly (though, in our opinion, reliably) the inhomogeneous structure of these amorphous DyCo films but also propose a model of microheterophase organization of this industrially important class of magnetic materials.

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