Magnetization reorientation in ferrimagnetic $Gd_{27.5}Fe_{59}Co_{13.5}/Dy_{28}Fe_{60}Co_{12}$ double layers

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We present experimental results on magnetization reversal for double-layer (GdFeCo/DyFeCo) magneto-optical films. The structure of interest consists of a 40 nm DyFeCo layer with perpendicular magnetization and a 50 nm layer of GdFeCo with in-plane magnetization. A transition from in-plane to perpendicular orientation of the magnetization in GdFeCo film caused by the effect of exchange interaction with DyFeCo has been observed in just a small temperature range. For higher temperatures, the exchange effect becomes smaller and GdFeCo magnetization returns back to in-plane orientation. On the basis of a micromagnetic model, we predict a change in orientation of GdFeCo magnetization from in-plane to perpendicular when it is coupled to DyFeCo film in a certain temperature range. This transition is sensitive to the magnetic properties of each layer that are dependent on temperature and on the values of compensation and Curie temperatures of both GdFeCo and DyFeCo films. [S0163-1829(98)05314-4]

I. INTRODUCTION

Amorphous rare-earth transition-metal (RE TM) alloys have been considered the more important candidates for magneto-optical (MO) storage technology. The magnetic multilayers of such alloys are the subject of strong interest with the possibility to increase the data transfer rate[1,2] or to achieve high storage density by magnetic super-resolution methods (MSR).[3–7] The MSR is a thermomagnetic effect based on a local optical aperture thermally induced in a planar magnetic layer by the laser spot during the readout process.

More recently, Murakani *et al.*[6] have proposed a new type of MSR consisting of two layers, one with in-plane magnetization (readout layer) and the other with perpendicular magnetization (memory layer). Those systems are called ''mixed'' exchange coupled double layers (ECDL's).

Nishimura and co-workers[8] have worked with the same MO double layer and conclude that it is difficult to achieve a transition from in-plane to perpendicular magnetization in readout layer without an initializing layer inserted between film 1 and film 2.

In this paper we use MO measurements to study the processes of magnetization reversal in a double layer of film 1 (GdFeCo) and film 2 (DyFeCo). We investigate the influence of both the composition and thickness of film 1 on the magnetization profile of the two films. It shows that the magnetization of GdFeCo rotates from in plane to perpendicular to the film orientation in a special temperature range that depends both on double-layer composition and thickness. Some of the bilayers studied in a previous work[9] show a transition from ferromagnetic to antiferromagnetic coupling of the layers. In this study, we present a bilayer system that undergoes a transition from being a mixed system (in plane/perpendicular) to being a perpendicular system.

To explain this unusual result we use a micromagnetic model to calculate the angular orientation $\theta(z)$ of the in-plane film at different position z. We find that $\theta(z)$ is very sensitive to the magnetic parameters of the two layers, which in turn depend strongly on the temperature.

Films of GdFeCo/DyFeCo were rf sputtered in an argon environment onto Corning glass substrates and coated against corrosion with 10 nm of Si_3N_4 overlayer. The magnetic hysteresis curves of monolayers and bilayers were measured by MO Faraday rotation under a magnetic field up to 18 kOe. The saturation magnetization was measured at ambient temperature T_{amb} with vibrating sample magnetometer and calculated by mean-field theory[10–13] from T_{amb} to the Curie temperatures of film 1 (T_{C1}) and film 2 (T_{C2}).

The compositions of the MO layers were analyzed by electron probe microanalysis. The compositions of the two films were adjusted in order to obtain film 1 and film 2 rich in Gd and Dy, respectively. It means that their compensation temperatures (T_{CP1} and T_{CP2}) are both greater than T_{amb} and so their intrinsic MO hysteresis loops are inverted because in the range of composition we have used (about 70 at. % TM) Faraday rotation (FR) is caused mainly by the TM sublattice magnetization.[14,15]

II. MAGNETIZATION PROCESS

We study a magnetic double layer, where the easy axis is in-plane in film 1, GdFeCo, while it is perpendicular to the plane in film 2, DyFeCo. The angular orientation $\theta(z)$ of magnetization in this double-layer system is assumed to vary spatially only along the z coordinate running through the film thickness. The angle $\psi(z)$ of the magnetization from the x axis (Fig. 1) has been supposed equal to $\pi/2$ to simplify the total energy density that is given by[16,17]

$$E=\int_0^{t_1}\left[A_1\left(\frac{d\theta}{dz}\right)^2-K_1\sin^2\theta+M_1H\cos\theta\right]dz+\int_{-t_2}^{0}\left[A_2\left(\frac{d\theta}{dz}\right)^2+K_2\sin^2\theta+M_2H\cos\theta\right]dz, \quad (1)$$

where $A_{1,2}$, $M_{1,2}$, $K_{1,2}$, and $t_{1,2}$ are the exchange constant, the saturation magnetization, the effective anisotropy energy, and the thickness in the planar film 1 and perpendicular film 2, respectively. The effective anisotropy $K_{1,2}$ corresponds to

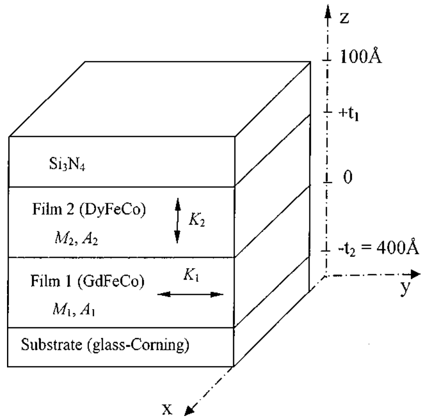

FIG. 1. Geometry of two magnetooptical layers with in-plane and perpendicular anisotropies.

the intrinsic uniaxial anisotropy ($K_{U1}<0$ in film 1 and $K_{U2}>0$ in film 2) corrected by the demagnetizing contribution $2\pi M_{1,2}$.[2] The values of K_1 and K_2 are positive.

III. MAGNETIC PROPERTIES OF $Gd_{27.5}Fe_{59}Co_{13.5}$ AND $Dy_{28}Fe_{60}Co_{12}$

$Gd_x(FeCo)_{1-x}$ are ferrimagnetic amorphous alloys with a compensation temperature T_{CP1} and Curie temperature T_{C1} steeply dependent on the concentration.[11–13] We have prepared a 50 nm-thick layer of $Gd_{27.5}Fe_{59}Co_{13.5}$ in the same deposition conditions as the exchange coupled double layer. By MO Faraday rotation we measure its compensation and Curie temperatures which are 190 °C and 320 °C, respectively. The saturation magnetization M_1 of film 1 was measured by a vibrating sample magnetometer at room temperature and is equal to 180 emu/cm^3.

A 40 nm-thick $Dy_{28}Fe_{60}Co_{12}$ amorphous alloy exhibits a uniaxial anisotropy in a direction perpendicular to the plane of sample. The hysteresis curves measured by MO Faraday rotation show an inversion of sign at T_{CP2} equal to 70 °C. Its Curie temperature T_{C2} is 170 °C and its saturation magnetization at room temperature M_2 is equal to 30 emu/cm^3.

In Fig. 2, experimental FR hysteresis curves of $Gd_{27.5}Fe_{59}Co_{13.5}/Dy_{28}Fe_{60}Co_{12}$ bilayer are represented for various sample temperatures. This method utilizes the MO effects to sense especially the TM moments of both film 1 and film 2 as a function of the applied field that is perpendicular to sample plane. The film 2 with easy axis perpendicular to the sample plane, switches at H_{C2} but $\mathbf{M}_1$ rotates coherently up to saturation field H_{S1}, The fields H_{S1} and H_{C2} are the saturation and coercive fields of film 1 and film 2, respectively in the exchange coupled double layer system; that means we have to take into account the exchange interaction between the layers.[9,17] This situation observed at room temperature occurs until 75 °C when H_{S1} and H_{C2} have the same magnitude and another kind of hysteresis curves appears. From 25 °C to 88 °C we obtain a simple situation that has been evoked in part of a previous work.[9]

Figure 3 shows representations of hysteresis loops that have been observed experimentally from T_{amb} to 88 °C. The increase of H_{C2} with temperature is due to the increase of the coercive field of film 2 (with no exchange coupling with film

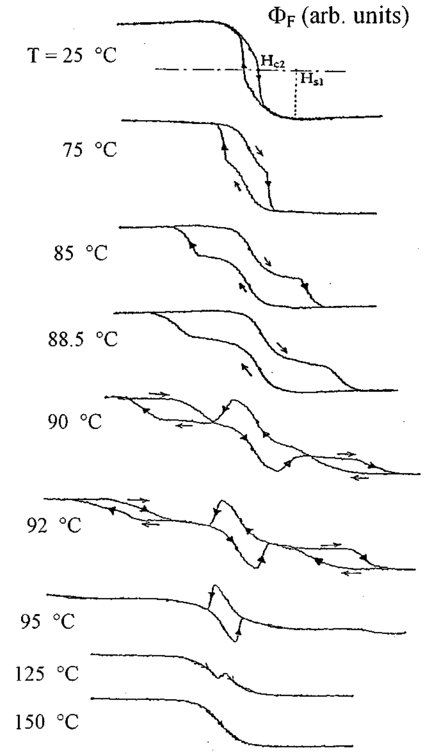

FIG. 2. Experimental hysteresis curves at various temperatures for $Gd_{27.5}Fe_{59}Co_{13.5}$ (500 Å)/$Dy_{28}Fe_{60}Co_{12}$ (400 Å).

1) near its compensation temperature T_{CP2}, and the effect caused by film 1 to film 2 that is observed experimentally between 85 °C and 88 °C by a relatively slow reversal process of film 2 magnetization and a beginning of the reorientation of film 1 magnetization out plane as shown schematically by a hysteresis loop with small remanence.

The curves observed at moderate temperature (from 90 °C to 95 °C) in Fig. 2, show an unusual situation with three hysteresis loops, two of which are similar and symmetric about the $H=0$ axis. Similar results have been observed by

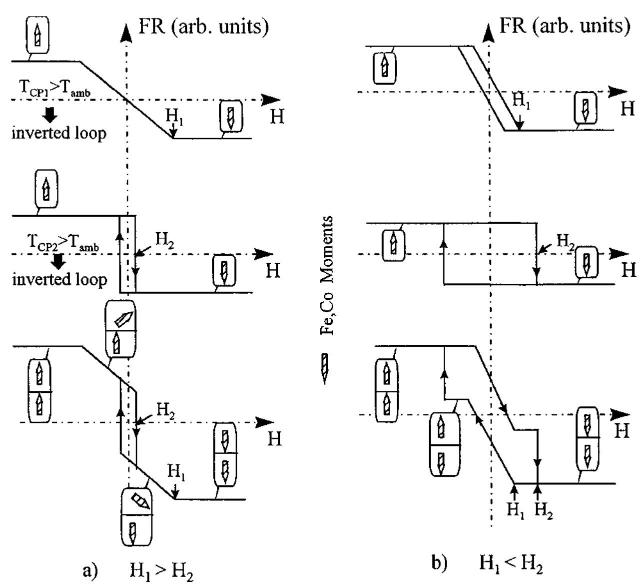

FIG. 3. Magnetization process proposed for the bilayers with mixed anisotropies, for $T=25$ °C (a) and T between 75 and 88 °C.

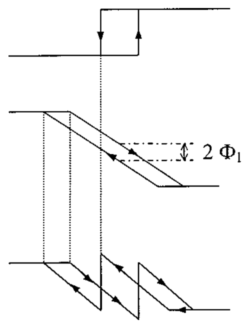

FIG. 4. Representative MO hysteresis loops for bilayer and corresponding in-plane and perpendicular magnetization single layer for $T=90$ to 95 °C.

other authors in perpendicular/perpendicular exchange-coupled bilayer systems.[18–20] To explain this phenomenon, we begin first by a decomposition of this hysteresis loop in two parts as is sketched in Fig. 4. This is the only possible combination that can give us a description of this case of loops. As it has been described by Kobayashi *et al.*,[19] the two similar and small hysteresis loops represent a reversal process of just one layer (film 1 in our case) and are shifted from $H=0$ axis by the exchange bias field H_b due to film 2 (Fig. 2). On the other hand, we have to take into account the mutual exchange interaction that begins at the interface and propagates in film 2 depending on the characteristic of the two films.[21] The amplitude of the MO signal of the small hysteresis loop is equal to twice Φ_1, the remnant FR of film 1, as shown in Fig. 2 ($T=90$ °C). It is clear that Φ_1 is higher for temperature 90 °C than for 92 °C, so the perpendicular characteristic of film 1 is sensitive to the temperature. A second important result of this work is that the transition from in plane to perpendicular orientation of film 1 induced by the exchange-coupling interaction with perpendicular magnetization film 2 occurs just in a narrow temperature range. We note that the transition from in plane to perpendicular orientation in GdFeCo film 1 is evident in the temperature range between 75 °C and 88 °C.

IV. THEORETICAL PREDICTION OF MAGNETIZATION TRANSITION

The temperature dependencies of the magnetic parameters $M_{1,2}$, $K_{1,2}$, and $A_{1,2}$ in films 1 and 2, respectively, are calculated by mean-field theory. In a previous work[21] we have determined numerically $\theta(z)$ by changing just one of the magnetic parameters and supposing all the others to be constant. In this study all parameters except the magnetic applied field (which is fixed at zero) become variable because of their great dependence on temperature. Figure 5 shows dependencies on temperature of saturation magnetizations in films 1 and 2 (M_1 and M_2). The uniaxial anisotropies K_{U1} and K_{U2} of both layers are determined from the pair model[10–13] and the exchange stiffnesses A_1 and A_2 dependencies on temperature are determined by mean-field theory and the Heisenberg model of the exchange energy density.[12,22]

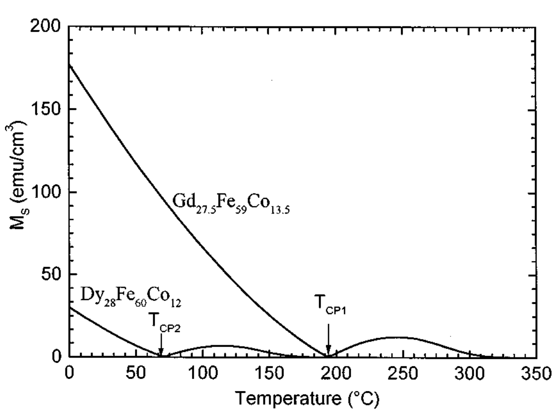

FIG. 5. Calculated saturation magnetization versus temperature for $Gd_{27.5}Fe_{59}Co_{13.5}$ and $Dy_{28}Fe_{60}Co_{12}$ monolayer films calculated from mean-field theory.

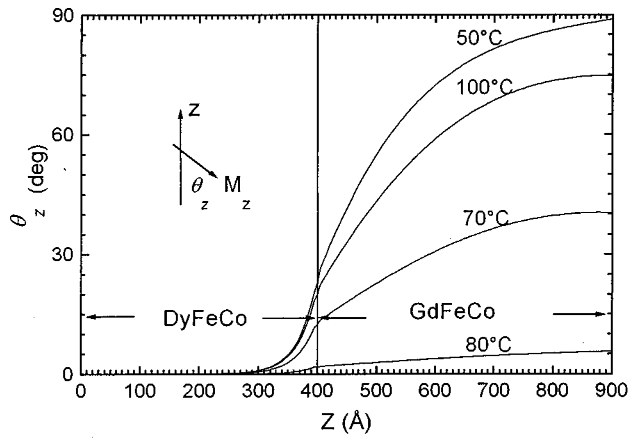

FIG. 6. Calculated profile of magnetization direction at various temperatures for $Gd_{27.5}Fe_{59}Co_{13.5}$ (500 Å)/$Dy_{28}Fe_{60}Co_{12}$ (400 Å).

In Fig. 6, we show the magnetization distribution from the bottom of film 2 to the surface of film 1 at three different temperatures. For $T=50$ °C and 100 °C, the in-plane and perpendicular characteristics are slightly modified in films 1 and 2, respectively. But at 80 °C the magnetization of each film is nearly perpendicular. In another step, we have calculated the mean values of angle $\theta(z)$ in films 1 and 2 that are really measured in FR geometry and so to be compared with experimental FR measurements. In Fig. 7, we represent the mean values of the magnetization projection in film 1, the experimental values have been measured from FR hysteresis

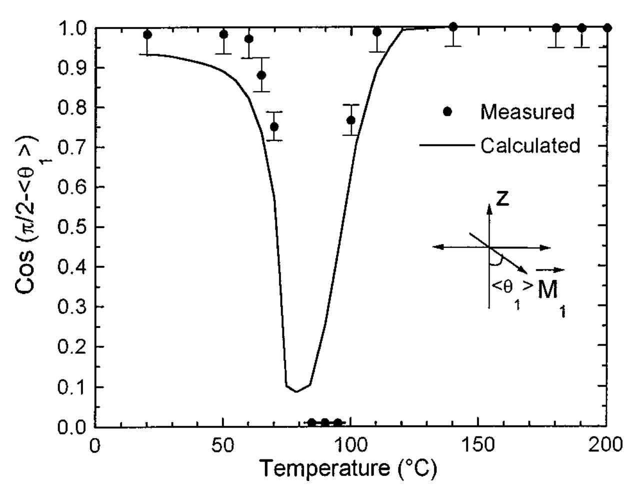

FIG. 7. Temperature dependence of in-plane component of magnetization in ECDL structure.

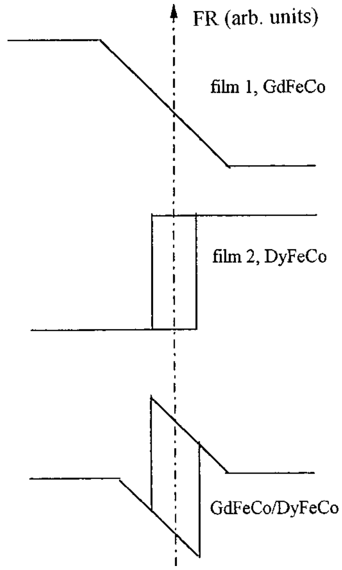

FIG. 8. Representative MO hysteresis for bilayer and corresponding in-plane and perpendicular magnetization single layer ($T = 95\ °C$).

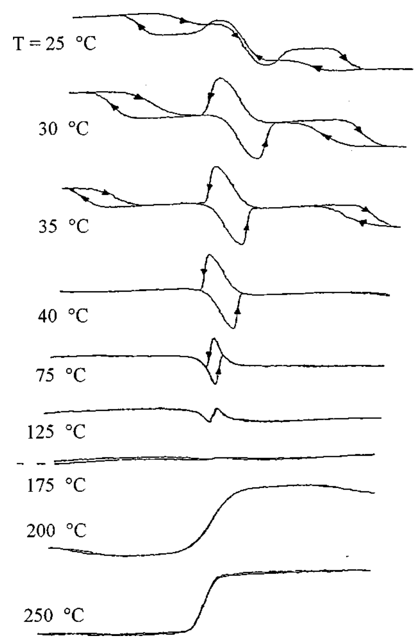

FIG. 9. Experimental hysteresis curves at various temperatures for $Gd_{27.5}Fe_{59}Co_{13.5}$ (350 Å)/$Dy_{28}Fe_{60}Co_{12}$ (400 Å).

loops at remanence, normalized after substrate FR of DyFeCo from bilayers one. We establish that temperature range ΔT predicted by micromagnetic model slightly displaced from experimental temperature range. In this model we have not taken into account diffusion between the two MO layers. On the other hand, perpendicular magnetization of film 2 has been deposited with optimal composition; i.e., the film has high perpendicular anisotropy and a compensation temperature not far from T_{amb}. Consequently, a small variation of its thickness causes a change of its intrinsic magnetic properties.[23,24] In micromagnetic model it is preferred to add an interfacial energy term due to the formation of a few atomic layers between GdFeCo and DyFeCo, as was used by Smith and Cain.[25]

At higher temperatures (more than 95 °C), we again find a simple hysteresis loops characteristic of two exchange-coupled magnetic layers with in-plane and perpendicular magnetization, respectively, as schematically sketched in Fig. 8. The switching field H_{C2} decreases when temperature increases until 125 °C at which H_{C2} becomes zero. For higher temperatures ($T > T_{C2}$), the signal of film 2 disappears and we obtain a situation with just an in-plane magnetic film 1. We note the change of the FR sign at 197 °C, corresponding to the compensation temperature of film 1 in an exchange-coupled double-layer situation.

The unusual hysteresis loop observed for $Gd_{27.5}Fe_{59}Co_{13.5}/Dy_{28}Fe_{60}Co_{12}$ bilayer at 90 °C until 95 °C have been observed again in another bilayer (Fig. 9). The only difference between the two bilayers is just the thickness t_1 of the in-plane film 1 and that it has been reduced to 35 nm in the second one. Consequently, the transition from in-plane to perpendicular orientation of the GdFeCo magnetization appears at room temperature and occurs at about 15 °C. We note that at 25 °C, the FR at no external field (remanence) is essentially zero. This and other confirmation for the reorientation of the magnetization of GdFeCo from in plane to out plane by exchange coupling with DyFeCo; i.e., in this case the sublattice magnetization of Fe and Co in the two layers are equal in magnitude and opposite in direction (one film is rich in TM and the other is rich in RE).

V. CONCLUSION

A transition from in-plane to perpendicular magnetization of the GdFeCo layer occurs in a temperature range as a result of a strong exchange effect with the DyFeCo perpendicular layer. The particular values of both T_{CP1} and T_{CP2} and, consequently, the temperature dependence of magnetic properties of the two layers is of great importance for the existence or nonexistence of this transition and the range of temperatures at which it occurs.

In our $Gd_{27.5}Fe_{59}Co_{13.5}/Dy_{28}Fe_{60}Co_{12}$ bilayer, the micromagnetic calculation has predicted a transition in a small temperature range that is slightly translated from experimental ΔT values (experimentally ΔT is of 20 °C). We think it is because in the theoretical model an interface energy term must be added to explain the diffusion between the two layers. This temperature induced transition depends both on thickness and on the intrinsic properties of the two layers.

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