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Magnetic and magneto-optical properties of NdFeB/Mo and NdFeB/FeB amorphous bilayers

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Magnetic and magneto-optical properties of NdFeB/Mo and NdFeB/FeB amorphous bilayers, grown by dc triode sputtering on cooled glass substrates, were studied. Transverse Kerr effect, transverse biased initial susceptibility and SQUID magnetometry measurements were performed. Glass/film interface effects, regarding magnetization and anisotropies (dead layers, isotropic sublayers), were found in NdFeB films.

Amorphous sandwiches consisting of ferro- and ferrimagnetic layers present a variety of interesting magnetic properties such as peculiar magnetic transitions observed under applied fields [1–3]. Our aim at present is to study the magnetic and magneto-optical properties of films consisting of a soft ferromagnetic layer ($Fe_{80}B_{20}$) sandwiched between hard ferromagnetic layers ($Nd_{15}Fe_{77}B_8$). Some results are reported here. The magnetic and magneto-optical properties of related NdFeB single layers are also reported. From this study, interface effects are evidenced.

The films were prepared by dc triode sputtering at the L. Néel Lab. (Grenoble). The sputtering chamber, pumped to a base pressure of 5×10^{-7} Torr, was raised to a constant residual argon pressure of 10^{-3} Torr during sputtering. The deposition rates were close to 12 and 5 nm/min for NdFeB and FeB films, respectively. The thickness of the layers was controlled by a quartz oscillator device. Calibration was performed on thicker samples. The targets were obtained from high purity elements by induction melting. In order to induce different as-grown magnetic anisotropies, series of three small glass substrates were placed radially on a rotating sample holder and cooled down to about 77 K by liquid nitrogen. Dependences of both magnetic anisotropy and magnetization ripple on the radial location of the substrates were found. Here we are concerned only with the samples located farthest from the center of rotation. In this case the easy axis of uniaxial anisotropy is along the radial direction in the sample holder. Slight self-shadowing effects might be invoked to explain this behaviour, as will be discussed elsewhere. Two main series of NdFeB/FeB/NdFeB sandwiches were prepared. (In the following, t_1 and t_2 are denoted as the thickness for NdFeB and FeB layers, respectively.) For one of the series, t_2 was fixed close to 200 nm while t_1 was varied from 7.5 to 75 nm. For the other one, t_2 was close to 75 nm while 7.5 nm $\leqslant t_1 \leqslant$ 37.5 nm. Related single magnetic layers of FeB and NdFeB were also prepared in the same experimental conditions. Finally, a film of Mo (100 nm thick) was deposited as protective layer for sandwiches and single layers.

Transverse biased initial susceptibility (TBIS) measurements, using the magneto-optical transverse Kerr effect, were performed on the glass side of the samples. The experimental set-up has already been described elsewhere [4]. Magnetization was determined by using the SQUID facilities of the L. Néel Laboratory (Grenoble).

First, we shall report on the magneto-optical properties of NdFeB/Mo and NdFeB/FeB systems. Fig. 1 evidences the NdFeB-thickness dependence of the transverse Kerr effect parameter δ, the latter being the fraction of the reflectivity modulated by the magnetization [5]. It should be

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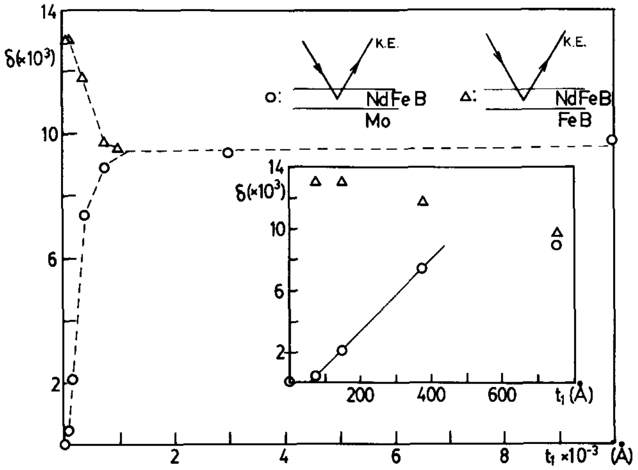

Fig. 1. Experimental δ vs. NdFeB thickness t_1. Open circles: NdFeB/Mo. Open triangles: NdFeB/FeB. Insert: low thickness range behaviour. (Lines are intended as visual guides only.)

noted that δ is higher for FeB than for NdFeB. This also is the case for the magnetization. The behaviour shown in fig. 1 agrees qualitatively with that predicted from the calculations (see fig. 2) concerning the transverse Kerr effect in modulated structures. The details of such calculations

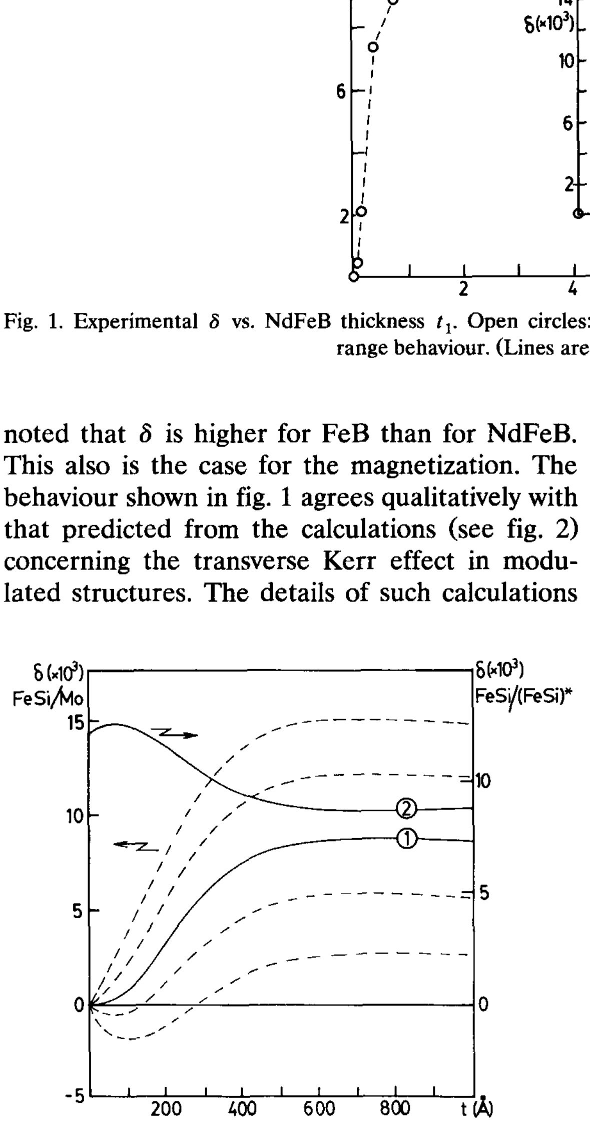

Fig. 2. Calculated curves for δ vs. overlayer thickness in $Fe_{0.64}Si_{0.36}$/Mo and $Fe_{0.57}Si_{0.43}/Fe_{0.77}Si_{0.23}$ bilayers using the experimental optical and magneto-optical constants from ref. [7] (full lines 1 and 2, respectively). The dashed lines are curves predicted for FeSi/Mo by slightly changing the values of the magneto-optical parameters, with respect to the experimental ones. The wavelength and the incidence angle of the light are taken equal to 617 nm and 60°, respectively.

will be reported elsewhere [7]. Fig. 2 shows the calculated behaviour for FeSi/Mo and FeSi/(FeSi)* bilayers. In these cases, the optical and magneto-optical constants for the individual layers are known from experiments [6,7]. Note that the main features observed in fig. 1 are also found in fig. 2. Furthermore, fig. 1 evidences that the effective penetration length of the light falling on our amorphous metallic samples is smaller than 50 nm. However, fig. 2 shows that δ vs. t_1 behaviour could be non-linear for low values of t_1. This invalidates the use of magneto-optical effects alone as a way to detect "dead layers", as could be deduced incorrectly from fig. 1 for the case of NdFeB/Mo (see insert of fig. 1). (Note that in calculations shown in fig. 2 no dead layers are supposed in FeSi films.)

Careful magnetization measurements were performed on NdFeB/Mo films, taking into account the contribution arising from glass substrates. Results are given in fig. 3, where the nominal thickness t_1 is used to calculate M_s in emu/cm^3. In fig. 4 we show $M_s t_1$ vs t_1, for room temperature measurements. Both figs. 3 and 4 suggest that real NdFeB/Mo films are not magnetically homogeneous (note the high value of t_1 obtained from the linear extrapolation to vanishing $M_2 t_1$ (fig. 4) and the dramatic decrease of the intrinsic magnetization even in samples as thick

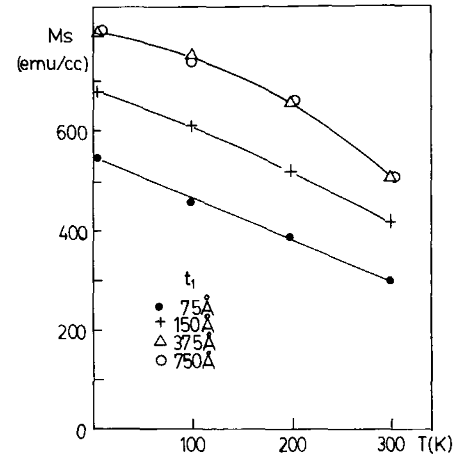

Fig. 3. M_s vs. temperature for NdFeB/Mo bilayers. Lines are intended as visual guides only.

as 15 nm (fig. 3)). A low cost hypothesis could be layer with reduced magnetization located at the glass/NdFeB or at the NdFeB/Mo interfaces. In the most simple case, a "dead layer" with a thickness close to 3 nm could be deduced from these results. Accordingly, M_s(RT) for bulk NdFeB will be close to 550 emu/cm. If that were the case, the high value for the thickness of the "dead layer" would suggest that it could be located at the glass/NdFeB interface and originated by trapping of gases in cold substrates prior to deposition of the film.

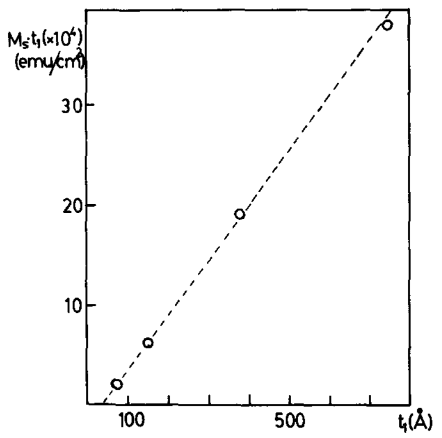

Fig. 4. Room temperature $M_s t_1$ vs. t_1 for NdFeB/Mo bilayers. Line is intended as visual guide only.

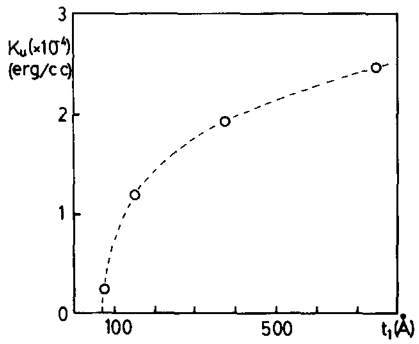

Fig. 5. K_u vs. t_1 for NdFeB/Mo bilayers. Line is intended as visual guide only.

Further insight into these facts is obtained from the behaviour of the magnetic anisotropy, as deduced from TBIS measurements. Fig. 5 shows room temperature K_u vs. t_1, where K_u is the energy density constant for the in-plane uniaxial magnetic anisotropy. Note that K_u was obtained from the values of the effective anisotropy fields, directly determined by TBIS, and the magnetization values given in fig. 3. The extrapolation of the curve to vanishing K_u, cuts the abscissa at a thickness which is clearly larger than 3 nm. A further analysis of these results suggests the existence of a magnetic layer with reduced magnetic anisotropy with respect to the bulk. If this layer were taken as isotropic, the estimated thickness would be close to 3 nm. Then, from magnetization and anisotropy measurements, it can be concluded that the magnetic behaviour of NdFeB single films could be explained by a glass/film interface constituted by a layer (3 nm) magnetically "dead" and sublayer (3 nm) with a value of magnetization close to that of the bulk, but nearly isotropic. In this case, room temperature bulk values for magnetization and anisotropy are close to 550 emu/cm and 2×10^4 erg/cm^3, respectively. This interface structure is similar to that proposed in YCo amorphous films in order to explain the properties at the film/air interface [5]. The oxidation of Nd due to the existence of trapped gases on cold substrates prior to deposition, provide an explanation for the results found in the present work [8,9].

A full study about the magnetic properties of NdFeB/FeB/NdFeB sandwiches, regarding topics as efective anisotropy, magnetization ripple and coercive forces, will be reported elsewhere. In this paper is only reported the fact that the experimental values for effective anisotropy fields (H_k^{eff}) of the sandwiches are explained in most cases by $H_k^{eff} = m_1 H_{k1} + m_2 H_{k2}$ where, m_i and h_{ki} are the normalized magnetization fractions and the experimental anisotropy fields, respectively, for NdFeB and FeB single layers. As an example, $H_k^{eff} = 10$, 16 and 26 Oe were obtained in sandwiches where $t_2 = 230$ nm and $t_1 = 7.5$, 15 and 37.5 nm, respectively. Accordingly, coercive forces depend on the ratio between t_1 and t_2. As an example, $H_c = 0.5$, 6 and 8.5 Oe were found in samples with $t_2 = 230$, 75 nm and NdFeB single layers respectively ($t_1 = 15$ nm).

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