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Interlayer coupling and magnetic compensation in Co/Ti/(Gd-Co)/Ti multilayers

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Abstract

The magnetic properties of $[Co/Ti/Gd_{0.36}Co_{0.64}/Ti]_4/Co$ multilayered structures were investigated by means of torque magnetometer, vibrating sample magnetometer and transversal magneto-optic Kerr effect (TMOKE) measurements. Due to interlayer exchange interaction, Co and Gd-Co layers form a macroscopic ferrimagnetic system. A change in sign of the TMOKE hysteresis loops near the compensation temperature and field induced magnetic phase transition were found. The later shows a critical field with a linear variation with temperature. The magnetic properties of these multilayers are similar to those of bulk ferrimagnets.
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Magnetic layered structures made of a rare earth (RE) and transition metals (TM) attract attention both on account of basic interest and for their applications in magnetic storage devices and sensors [1,2]. For technological applications of these structures it is better to replace the pure RE layers by RE-TM alloyed layers because the later have a Curie temperature far above of the room temperature [3]. The introduction of non-magnetic spacers between magnetic layers expands the possibility of controlling the multilayer properties [4].

In present study we describe the magnetic behaviour of $[Co/Ti/Gd_{0.36}Co_{0.64}/Ti]_4/Co$ multilayers, in which the $Gd_{0.36}Co_{0.64}$ alloy plays the role of RE layers in classic RE/TM multilayers. Different thicknesses of the non-magnetic Ti layer have been used to study the effect of a non-magnetic spacer on the coupling between the pure Co and GdCo layers.

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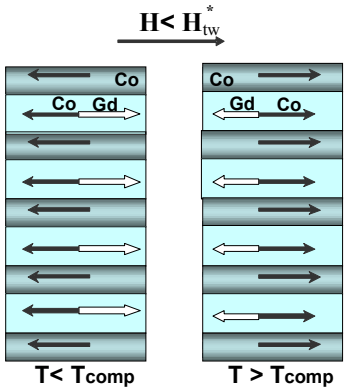

Fig.1. Principal diagram of the (Gd-Co)-aligned and Co-aligned phases with respect to the temperature range. In the (Gd-Co)-aligned phase the moments of the Gd-Co layers are large and aligned with the external field. In the Co-aligned phase at $T>T_{comp,}$ the Gd-Co moments are small and the Co layers moments align with the field.

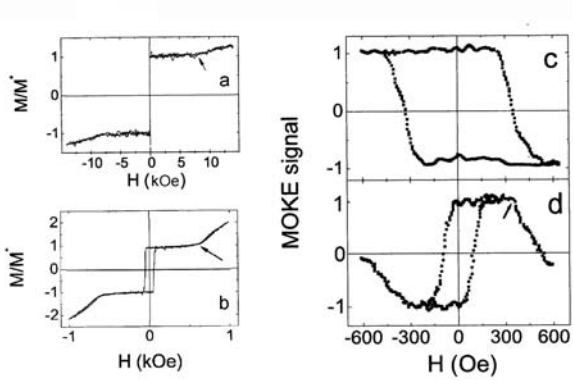

Fig. 2. Magnetization vs. applied magnetic field curves measured by VSM at 300 K for $[Co/(Gd-Co)]_4/Co$ multilayers with L_{GdCo} = 12 nm (a) and 24 nm (b); TMOKE hysteresis loops measured for $[Co/Ti(0.3nm)/(Gd-Co(24nm))/Ti(0.3nm)]_4/Co$ multilayers at 272 K (c) and 295 K (d). Arrows indicate the non-collinear magnetic structure arising at $H = H^*$. M^* is the temporarily saturated magnetization in magnetic fields lower than H^*, and corresponds to the difference between Gd-Co and Co layers magnetization.

$[Co/Ti/Gd_{0.36}Co_{0.64}/Ti]_4/Co$ multilayers were deposited using a three target RF sputtering system. The background pressure was 1×10^{-6} mbar. The deposition was performed in Ar at 2×10^{-4} mbar. Samples were deposited on glass substrates at room temperature. Multilayers had a fixed nominal thickness of 7 nm for the Co layers and 12 or 24 nm for the $Gd_{0.36}Co_{0.64}$ layers (L_{GdCo}). The thickness of the Ti spacer layers (L_{Ti}) ranged from 0.3 to 1.5 nm. The deposition rates of Gd-Co, Co and Ti thin films were previously calibrated by low angle X-ray reflectometry and atomic force microscopy, yielding 3.5 nm/min for Co, 4 nm/min for Gd-Co, and 3 nm/min for Ti respectively. A magnetic field of 100 Oe was applied during deposition in order to induce a magnetic anisotropy in the plane of the film.

The magnetic properties were measured using a torque magnetometer at temperatures from 100 K to 380 K, and a vibrating sample magnetometer, VSM, at room temperature. The transverse magneto-optic Kerr effect, TMOKE, was measured at temperatures of 180 K to 340 K with a maximum field of 650 Oe applied in the sample plane along the easy axis. The light penetration depth can be estimated to be around 30-40 nm [5], i.e. roughly one and a half times the multilayer period.

On the basis of the data of previous studies [6], Ti was chosen for the spacers because it has minimal influence on the structure-chemical condition of Gd-Co and Co layers. Further confirmation of this fact was obtained in the present study. The root-mean-square roughness (R_{rms}) for a glass substrate and multilayer without and with Ti spacers of 1.5 nm thickness were obtained by Atomic Force Microscopy, AFM. In all cases under consideration R_{rms} is quite low (0.4 ± 0.1 nm for glass substrate and 0.6 ± 0.1 nm for both multilayers). Considering that the final surface roughness reflects, up to a certain point, the state of the internal interfaces in the multilayer, the relatively similar values for both multilayers seem to indicate that Ti layers, for L_{Ti} = 1.5 nm, has a little effect on the Co and Gd-Co layers' structure.

The $Gd_{0.36}Co_{0.64}$ composition of the amorphous RE-TM layer was selected so that, in all investigated temperature interval, its saturation magnetization would be dominated by the Gd. Because of exchange interaction near the interface, the total magnetic moments of Gd-Co and Co layers are antiparallel. Thus, $[Co/Ti/(Gd-Co)/Ti]_4/Co$ multilayers form an artificial ferrimagnet (Fig.1). When the temperature increases the magnetization of the $Gd_{0.36}Co_{0.64}$ layers decreases, while the magnetization of the Co layer remains almost

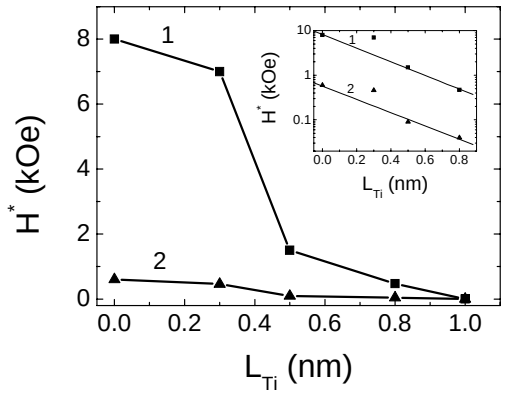

Fig. 3. The dependences of the critical field on the thickness of nonmagnetic spacers for [Co/Ti/(Gd-Co)/Ti]$_4$/Co multilayers with L_{GdCo} = 12 nm (1) and 24 nm (2) measured by VSM at 300 K. In insert H^* is shown in a logarithmic scale as a function of L_{Ti}.

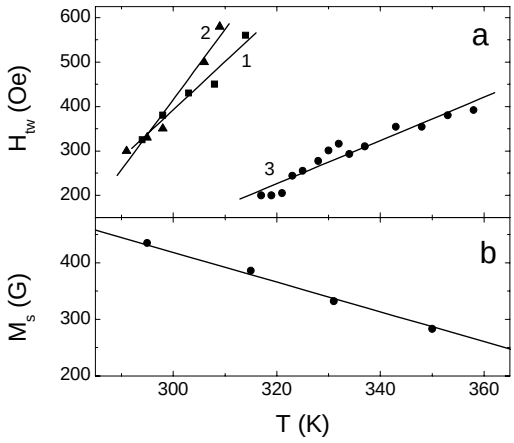

Fig. 4. Temperature dependences of spin-flop field (a) measured by TMOKE for [Co/Ti/(Gd-Co(24nm)/Ti]$_4$/Co multilayers with L_{Ti} = 0 nm (1); 0.3 nm (2) and 0.5 nm (3). Temperature dependence of magnetization for the $Gd_{0.36}Co_{0.64}$ single layer film (b).

constant. Therefore the [Co/Ti/(Gd-Co)/Ti]$_4$/Co multilayers can show magnetic compensation state for which the net magnetization is equal to zero at a compensation temperature, T_{comp}.

Fig.2 shows the typical magnetization curves measured by VMS at 300 K for [Co/(Gd-Co)]$_4$/Co multilayers with L_{GdCo} = 12 nm (a) and 24 nm (b). The magnetization behaviour of these multilayers can be described like that found in Co/X/Gd multilayers [7]. In low fields the magnetization of Co and Gd-Co layers are aligned in antiparallel along the direction of the applied field (Fig.1). If the field is higher than the critical field H^* the moments of both the Co and Gd-Co layers deviate from the field direction. At H = H^* VSM curves show a "kink", but the effect is better shown in MOKE curves (Fig. 2c,d), as we shall comment below. Such behaviour was observed for RE/TM multilayers but only for low temperatures. However, for our samples the non-collinear magnetic structure can appear above room temperature too. H^* is also shown to decrease with increasing of the L_{GdCo} (Fig.2a,b).

The introduction of the Ti spacer leads to a decrease in interlayer exchange interaction between Co and $Gd_{0.36}Co_{0.64}$ layers and of H*. The dependence of H^* on the spacer thickness, $L_{Ti,}$ is shown in Fig. 3. In the insert of Fig.3 H^* is shown in a logarithmic scale as a function of L_{Ti}. Quite good linear relationships for both L_{GdCo} is observed, indicating exponential decay of H^* with increasing L_{Ti}, if we exclude the points for L_{Ti} = 0.3 nm. It can be assumed that the Ti layers of a nominal thickness of 0.5 nm deposited by the sputtering technique are not continuous, but display an island-like structure. At the low thickness the Ti atoms do not form even the island-like structure, but rather behave like the admixture atoms which decrease the density of magnetic atoms at the interfaces. The spacers of the large thickness can have higher continuity. The behaviour of the $H^*(L_{Ti})$ dependences reflects the sequential stages of the Ti spacer formation.

The ferrimagnetic character of [Co/Ti/(Gd-Co)/Ti]$_4$/Co multilayers can be determined by means of TMOKE hysteresis loops measured at different temperatures. As an example, for [Co/Ti(0.3nm)/(Gd-Co(24nm))/Ti(0.3nm)]$_4$/Co sample a clear inversion on the hysteresis loops measured below and above of T_{comp} is observed (Fig. 2c and 2d). The change of sign in the magneto-optic hysteresis loops was observed for samples with L_{Ti} from 0 to 0.8 nm. The TMOKE signal comes almost entirely from the Co atoms [8]. Therefore, an inverted hysteresis loop is observed when the Co magnetic moments are antiparallel to the external field. This occurs below T_{comp} when the magnetic moment of $Gd_{0.36}Co_{0.64}$ layers are parallel to the applied field and the magnetic moments of Co

layers are antiparallel. Above T_{comp} the moments of the Co layers are parallel to the field direction and $Gd_{0.36}Co_{0.64}$ layers moments are antiparallel. For L_{Ti} = 1.5 nm the hysteresis loops have complicated shape and almost do not change in all temperature range. This behaviour is completely different from that of the other samples. This suggest that multilayers are coupled and behave as a whole structure for L_{Ti} up to 0.8 nm, but for L_{Ti} = 1.5 nm the Co and Gd-Co layers are practically uncoupled and respond independently to the field.

Like for VSM curves, the "kink" is observed clearly on TMOKE hysteresis loops at $H = H^*$ for L_{Ti} of 0; 0.3 and 0.5 nm (Fig.2d, as example). For these samples H^* changes with temperature and decreases approaching T_{comp} (Fig.4a) which is near room temperature, like in standart ferrimagnets. For the samples with L_{Ti} = 0 and 0.3 nm H^* has similar values but it is smaller for L_{Ti} = 0.5 nm. Thus the spacer has practically no influence on interlayer exchange interaction for L_{Ti} < 0.5 nm, but reduces it strongly for larger values. For L_{Ti} > 1 nm the interlayer coupling does not play essential role.

An important result is that H^* changes linearly with temperature (Fig.4a). Following [9], for uniform ferrimagnet H^* is proportional to the difference between the magnetization of the sublattices. For $[Co/Ti/(Gd\text{-}Co)/Ti]_4/Co$ multilayers $H^*(T)$ correlates with the linear change of $M_{Gd\text{-}Co}(T)$ in this temperature interval (Fig.4b). (Co layers magnetization practically does not change). In TM/RE multilayers the negative exchange interaction between RE and TM layers is stronger than the exchange interaction within RE layers. As a result the TM/RE multilayers display the so called twisted magnetic phases. These non-collinear magnetic structures are formed basically in the RE layers, and can be characterized by angular and amplitude variations of the local magnetization. Therefore $H^*(T)$ has a complicated variation [10]. Our TM/RE-TM multilayers are more similar to bulk (non-layered) ferrimagnets than TM/RE multilayers are.

In conclusion, the $[Co/Ti/(Gd\text{-}Co)/Ti]_4/Co$ multilayers show bulk-like ferrimagnetic behaviour. The temperature dependence of the spin-orientation transition field can be described in the framework of the phenomenological model of the standard ferrimagnets magnetization. The introduction of Ti spacers leads to decrease in interlayer exchange interaction between magnetic layers and expands the possibility of controlling the properties of the multilayer structures.

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References

[1] O. F. K. McGrath, N. Ryzhanova, C. Lacroix, D. Givord, C. Fermon, C. Miramond, G. Saux, S. Young, A. Vedyayev, Phys. Rev. B 54 (1996) 6088.
[2] R.E. Camley, W. Lohstroh, G.P. Felcher, N. Hosoito, H. Hashizume, J. Magn. Magn. Mater. 286 (2005) 65.
[3] Y.-H. Fan, H. Brückl, Appl. Phys. Lett. 83 (2003) 3138.
[4] G.S. Patrin, V.O. Vas'kovskiy, D.A. Velikanov, A.V. Svalov, M.A. Panova, Phys. Lett. A. 309 (2003) 155.
[5] C. Dehesa-Martinez, L. Blanco-Gutierrez, M. Velez, J. Diaz, L.M. Alvarez-Prado, J.M. Alameda, Phys. Rev. B 64 (2001) 024417.
[6] A.V. Svalov, V.O. Vas'kovskiy, E.A. Kataeva, G.V. Kurlyandskaya, Phys. Met. Metall. (2005) to be published.
[7] K. Takanashi, H. Fujimori, H. Kurokawa, J. Magn. Magn. Mater. 126 (1993) 242.
[8] K.H.J Buschow, in E.P. Wohlfarth, K.H.J. Buschow (Eds.) Ferromagnetic Materials, Vol. 4 (1988) (Amsterdam: Elsevier).
[9] K.P. Belov, A.K. Zvezdin, A.M. Kadomceva, R.Z. Levitin, (1972) Orientational Transition in Rare Earth Magnets (Moscow: Nauka) (in Russian).
[10] V.O. Vas'kovskiy, A.V. Svalov, G.V. Kurlyanskaya: in *Encyclopedia of Nanoscience and Nanotechnology* Vol. 4, ed. by H.S. Nalwa (American Scientific Publishers 2004), pp. 925-947 and references therein.