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Research articles

Thickness dependence of magnetic properties of thin amorphous ferrimagnetic rare earth–transition metal multilayers

A.V. Svalov [a,*], O.A. Adanakova [b], V.O. Vas'kovskiy [b], K.G. Balymov [b], A. Larrañaga [c], G.V. Kurlyandskaya [b,d], R. Domingues Della Pace [e], C.C. Plá Cid [f]

[a] Department of Solid State Magnetism, Institute of Natural Sciences and Mathematics, Ural Federal University, 620002 Ekaterinburg, Russia
[b] Department of Magnetism and Magnetic Nanomaterials, Ural Federal University, 620002 Ekaterinburg, Russia
[c] SGIker, Servicios Generales de Investigación, Universidad del País Vasco (UPV/EHU), 48080 Bilbao, Spain
[d] Departamento de Electricidad y Electrónica, Universidad del País Vasco (UPV/EHU), 48080 Bilbao, Spain
[e] Departamento de Física, Universidade Federal do Rio Grande do Norte, 59078-900 Natal, RN, Brazi
[f] Laboratório Central de Microscopia Eletrônica, Universidade Federal de Santa Catarina (LCME/UFSC), 88040900 Florianópolis, Brazil

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Gd-Co/Ti multilayers were prepared by magnetron sputtering deposition onto glass substrates. The temperature dependence of magnetization of the multilayered structures depends on the Gd-Co layer thickness. It was shown that the obtained experimental results can be satisfactorily described in the framework of the joint application of models of the "size factor" and the "molecular field". In addition, the possible effect of the electronic structure of titanium on the average magnetic moment of Co atoms, the efficiency of which depends on the thickness of the magnetic layers was also taken into account.

1. Introduction

Amorphous thin films such as rare earth-transition metal (RE-TM) first attracted attention in the 1970s. This was due to the discovery in them of a large perpendicular magnetic anisotropy near the state of magnetic compensation, which made it possible to use such multilayered structures as the materials for magneto-optical recording of information on magnetic bubble domain [1]. As a result of years of intensive research, answers were found to the fundamental questions of the physics of these materials, which then made it possible to create magneto-optical discs based on the RE-TM films, which occupied their niche in the market of information recording devices [2]. In subsequent years, interest in these films somewhat decreased, although it remained at a certain stable level. The second wave of interest in RE-TM films arose in the early 2000s, when their promising properties were proposed for applications in magnetic tunnel junctions that are the basis of nonvolatile memory devices and spin-valve structures [3–5]. At present, there is a third wave of interest in amorphous RE-TM films caused by the phenomenon of ultrafast magnetization reversal induced by femtosecond laser pulses, which opens up fundamentally new possibilities for a significant (in thousands of times) increase in the speed of magnetic recording of information [6–11]. However, the question of the influence of the thickness of RE-TM films on their magnetic properties has so far been poorly studied, especially in the nanometer range [12–14]. Perhaps this is the reason for the discrepancy in the estimates of the chemical composition range in which the state of magnetic compensation in the amorphous Gd-Co layers takes place, in comparison with the experimentally observed data reported by different research groups [3,15]. It is known, that thickness has an appreciable effect on the magnetic properties of ferromagnetic films in the nanometer – tens of nanometers range of thicknesses. In particular, a thickness dependence of the Curie temperature (T_C) has been observed in various thin ferromagnetic films [16,17]. This finite-size effect seems to be caused by the reduced number of atoms in the direction perpendicular to the film plane leading to a decrease of the total magnetic exchange energy [18]. In this work, the role of the thickness of the ferrimagnetic Gd-Co layers in the formation of the magnetic properties of Gd-Co/Ti multilayers was studied.

* Corresponding author at: Department of Solid State Magnetism, Institute of Natural Sciences and Mathematics, Ural Federal University, Mira 19, 620002 Ekaterinburg, Russia.

E-mail address: andrey.svalov@urfu.ru (A.V. Svalov).

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2. Experiment

Gd-Co films and Gd-Co/Ti multilayered structures were prepared by magnetron sputtering deposition onto glass substrates kept at room temperature. Background pressure was 3×10^{-7} mbar and the working gas (Ar) pressure during deposition was 3.8×10^{-3} mbar. Gd-Co layers were obtained using a composite mosaic target of Gd tablets symmetrically distributed onto a cobalt plate. The direct current input power was 20 W for Gd-Co and 60 W for Ti target, respectively. The thickness of the Gd-Co layers (L_{Gd-Co}) was varied in a wide interval from 250 nm to 0.8 nm. The thickness of Ti spacers was kept constant (2 nm) for all Gd-Co layers thicknesses. The deposition rates were 5 nm/min for Gd-Co and 4 nm/min for Ti layers. Each sample had a protective coating layer of Ti(10 nm). A magnetic field of 250 Oe was applied during sample deposition parallel to the substrate surface in order to induce a uniaxial magnetic anisotropy. The compositional ratios of Gd and Co in the Gd-Co layers were determined by energy dispersive X-ray spectroscopy (EDX). Low angle X-ray diffraction (XRD) and high resolution transmission electron microscopy (HRTEM) were used in order to determine the quality of the layered structures and degree of possible intermixing. Low angle XRD data were collected on a Bruker D8 Advance diffractometer equipped with a Cu tube, Ge(111) incident beam monochromator (λ = 1.5406 Å) (fixed slit 1 mm) and a Sol-X energy dispersive detector (fixed slit 0.06 mm). Transmission electron microscopy (TEM) cross-sectional images of selected multilayers deposited onto Si substrates were taken at 200 kV using a JEOL JEM-2100. TEM images were acquired in bright field imaging mode. Magnetization measurements were performed with a vibrating sample magnetometer (VSM) and SQUID magnetometer.

3. Results and discussion

Low-angle X-ray diffraction profiles provide detailed information about multilayer quality and periodicity. The period of a multilayered structure can be accurately determined by a modified Bragg's law suggested by Sugawara et al. [19]. Fig. 1 shows an example of the low-angle X-ray diffractogram for the case of [Gd-Co(12 nm)/Ti(2 nm)]$_{10}$ multilayers. The observed bright peaks allow the determination of the period of the multilayered structure (14 nm) which agrees well with the expected value from the deposition time. Cross-sectional TEM images confirm uniform periodicity in the multilayered structures. Fig. 2 shows an example of cross-sectional TEM image for the case of [Gd-Co(3 nm)/Ti(2 nm)]$_{30}$ sample. The XRD and TEM data clearly confirmed the existence of a well-defined multilayered structure in all the cases under consideration.

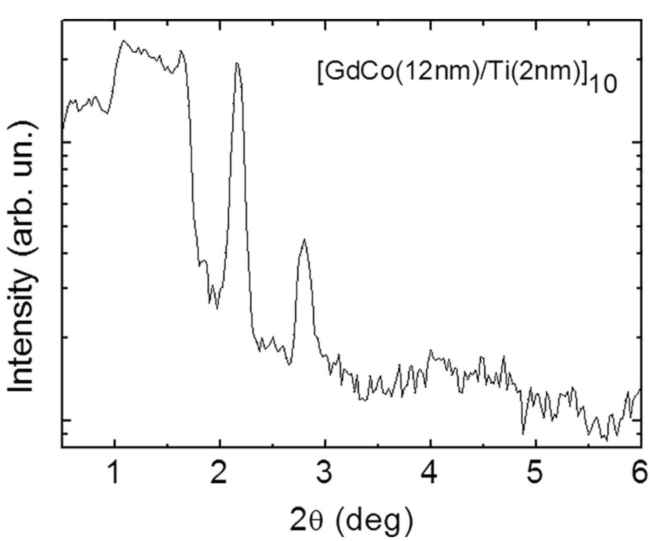

Fig. 1. Low-angle X-ray diffraction for [Gd-Co(12 nm)/Ti(2 nm)]$_{10}$ multilayered structure.

The amount of gadolinium determined by EDX analysis was as high as 22.1 at.% for the thick Gd-Co(250 nm) film. This composition satisfactorily correlated with the composition obtained by indirect method from magnetic measurements. It is known, that in ferrimagnetic RE-TM films, both T_C and magnetic compensation state and the compensation temperature (T_{comp}) are determined by correlation of amount of RE and TM atoms [15,20]. In amorphous Gd-Co films, the magnetizations of the Co and Gd sublattices are exchange coupled antiferromagnetically and different temperature dependence of magnetization corresponds to each sublattice. For alloy compositions in the interval of 17–24 at.% Gd, the existence of such difference of the temperature dependences leads to the appearance of a magnetic compensation temperature, where the magnetizations of both sublattices are equal in magnitude and opposite in direction [15]. Outside this interval of composition, the net magnetization is parallel or antiparallel to the Co sublattice at all temperatures, and only one more critical temperature exists – the Curie temperature. Fig. 3(a) shows the temperature dependence of magnetization $M(T)$ for Gd-Co(250 nm) thin film. T_{comp} = 425 K taken in conjunction with the reported composition dependence of T_{comp} [15] corresponds to the composition of 23 at.% Gd. The T_C for 23 at.% Gd composition lies above 600 K [15], i.e. outside the range of possible temperature measurements of our equipment.

The decrease of Gd-Co thickness leads to significant changes of the temperature dependence of magnetization. Magnetic compensation state disappears for Gd-Co thickness below 12 nm (Figs. 3(b and c) and 4(a and b)). Taking into account that magnetic properties of RE-TM thin films are determined by the ratio of different types of atoms, i.e. the short-range order [15,20], one can expect, that the finite-size effect in these films can have interesting peculiarities. Due to the reduction of the number of atoms in the direction perpendicular to the thin film plane the change in the ratio of different types of neighbours for each particular atom can be expected. In the case of multilayers, the situation becomes even more complex because the material of Ti spacers can add additional factors changing the properties of magnetic layers. In particular, the Co atom moment can be reduced by the process of the electron charge transfer from atoms of Ti spacer to atoms of transition metals. It is probable that a combination of these factors causes the peculiarities of finite-size effect in each particular case.

It is known that the spontaneous magnetization M_s of amorphous Gd-Co films can be quite well described by the phenomenological theory of the collinear ferrimagnetism of Neel, which is based on the mean field model [20,21]. In accordance with [20],

Fig. 2. Cross-sectional TEM image for [Gd-Co(3 nm)/Ti(2 nm)]$_{30}$ multilayered structure.

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