Journal of Alloys and Compounds 423 (2006) 260–263

Journal of ALLOYS AND COMPOUNDS

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Structural and magnetic properties of Cr/Gd multilayers

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Received 5 August 2005; received in revised form 13 December 2005; accepted 21 December 2005
Available online 29 March 2006

Abstract

The Cr/Gd multilayers (substrate/Mo/Cr_x/Gd30, where x = 10, 20, 30 Å) were deposited on 200 Å thick Mo buffer using molecular beam epitaxy (MBE) UHV technique. Two different types of monocrystalline substrates were used—MgO (1 0 0) and Al_2O_3 (1 1 −2 0).

It was shown that the roughness of the Cr/Gd interface strongly depends on the type of the substrate—the samples grown on the sapphire substrate were smoother than those grown on MgO. A strong influence of substrate temperature on Cr/Gd interface formation was also observed—samples grown at room temperature have smoother interfaces than samples grown at 250 °C. The strong in-plane anisotropy has been observed from the hysteresis loop analysis. The magnitude of coercivity field was found to increase with increasing the Cr layer thickness. The Curie temperature dependence on Cr layer thickness was also investigated.

Keywords: Magnetic films and multilayers; Vapor deposition; X-ray diffraction; Magnetic measurements

1. Introduction

Rare-earth based alloys and compounds attract a great attention due to the unique physical and chemical properties. Magnetism of rare-earth (RE) elements originates from the inner incomplete 4f shell which being buried deeply inside atom is well shielded by the outer electrons. The magnetic moments of RE atoms are coupled via the indirect Ruderman-Kittel-Kasuya-Yasida (RKKY) interactions.

Rare-earth/transition metal (RE/TM) nanoscale structures have been a subject of intensive investigation because they are promising materials for technological applications. Since the valence electrons are responsible for mediating indirect RKKY interactions, the magnetic properties of multilayer structures depend critically on the magnetic layer thickness [1,2], non-magnetic layer thickness like W, Mo [2,3], interface quality and interdiffusion between the elements constituting multilayer. Deposition conditions, such as substrate temperature [4] and deposition rate [5] as well as a substrate choice also play important role in magnetic properties of obtained multilayer structures. In this paper, we report on the influence of type of the substrate (MgO or Al_2O_3), deposition temperature (room temperature or 250 °C) and Cr layer thickness on the magnetic properties of Cr/Gd multilayers.

2. Experimental details

Ultra high vacuum molecular beam epitaxy (UHV MBE) was used to grow Cr/Gd metallic multilayer structures. Epi-polished MgO (1 0 0) and Al_2O_3 (1 1 −2 0) single crystals were chosen as substrates. The 200 Å Mo buffer layer was deposited on a substrate prior to deposition of Cr/Gd multilayers. In order to prevent the oxidation all the samples were covered with 100 Å Cr cap layer. Electron guns were used as evaporation sources for Mo and Gd whereas Cr was evaporated from Knudsen-type effusion cell. Deposition rates were kept at 0.32 Å/s for Cr and 0.3 Å/s for Gd layers, respectively. Deposition was carried out in the pressure of residual gases below 5×10^{-10} Torr. The individual layer thickness was controlled by both the temperature flux calibration in the case of Cr source and by using Electron Induced Photoemission technique in the case of Mo and Gd. During deposition the substrates were kept at room temperature or at 250 °C. Reflection high-energy electron diffraction (RHEED) with electron beam energy of 12 keV was used in situ during the deposition to control the growth mode of individual layers. The X-ray reflectometry (XRR) and high-angle diffraction measurements were performed at room temperature in order to determine the structure of studied samples. The wavelength used was 1.54 Å and the angle θ-range for XRR was from 0° to 5°. The magnetization measurements in the temperature range from 5 to 250 K were performed using a high-resolution vibrating sample magnetometer (VSM). The magnetic field up to 1 T was applied parallel and perpendicular to the sample surface.

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doi:10.1016/j.jallcom.2005.12.117

3. Results and discussion

3.1. Structural characterization

Due to the fact that chromium and gadolinium are immiscible and do not form any intermetallic compounds which is apparent from the Gd–Cr phase diagram they are suitable for a high quality multilayer formation [5].

Indeed several Bragg peaks resulting from stacking of Cr/Gd bilayer can be observed on the reflectivity pattern (see Fig. 1) proving periodical and well-defined compositional modulation. All the experimental curves were fitted by Simulreflec software [7] based on Parratt [6] algorithm in order to get structural information about the samples (individual layer thickness and interface roughness). In order to obtain more accurate fitting it was necessary to introduce in the simulation model the chromium oxide layer Cr_2O_3 on the top of Cr cap layer. Computer simulations of experimental curves definitely show that 200 Å Mo buffer layer grown on the Al_2O_3 substrates is noticeably smoother than the one grown on the MgO substrate (see Figs. 1 and 2). It seems that this effect is related to the growth direction of Mo buffer—Mo (1 0 0) layer in case of MgO (1 0 0) and Mo (1 1 0) for Al_2O_3 (1 1 −2 0) substrate. Rougher surface of Mo buffer layer leads in consequence to the increased roughness of Cr/Gd interface. Data obtained from the computer simulations are presented in Tables 1 and 2. These results are in accordance with RHEED images analysis where streaks for Mo on MgO are more diffused than for Mo grown on sapphire. Cr/Gd interface roughness of all the samples grown on the Al_2O_3 substrate does not exceed 3.5 Å and does not depend significantly on the Cr layer thickness. In order to study the influence of the growth temperature on Cr/Gd interface formation, one of samples, MgO/Mo200/(Cr20/Gd20) × 15/Cr100, was grown at 250 °C. It is clear from the XRR data that the roughness of the Cr/Gd interface of the latter sample is significantly higher than the Cr/Gd interface roughness of samples grown at room temperature. It is even difficult to observe the Bragg peaks resulting from multilayer stacking (Fig. 3) suggesting complete Cr–Gd intermixing and only Kiessig fringes resulting from the total sample thickness are present. Similar influence of the substrate temperature is described in [8].

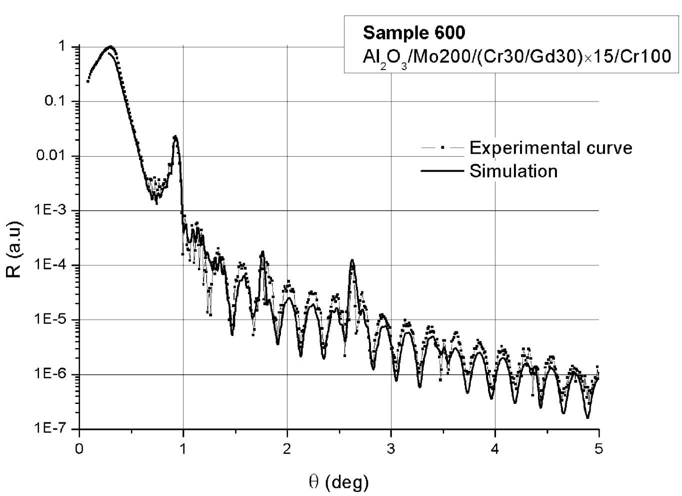

Fig. 1. Experimental and simulation reflectivity curves for sample Al_2O_3/Mo200/(Cr30/Gd30) × 15/Cr100 grown at room temperature.

Table 1
Individual layer thickness and roughness for the sample MgO/Mo200/(Cr20/Gd20) × 25/Cr100 obtained from computer simulation

Layer	Thickness (Å)	RMS roughness (Å)
MgO (substrate)	–	4.6
Mo (buffer)	190.5	6.3
Cr (multilayer)	17.9	5.5
Gd (multilayer)	13.9	7.8
Cr (cap layer)	99	4.9
Cr_2O_3	15	4

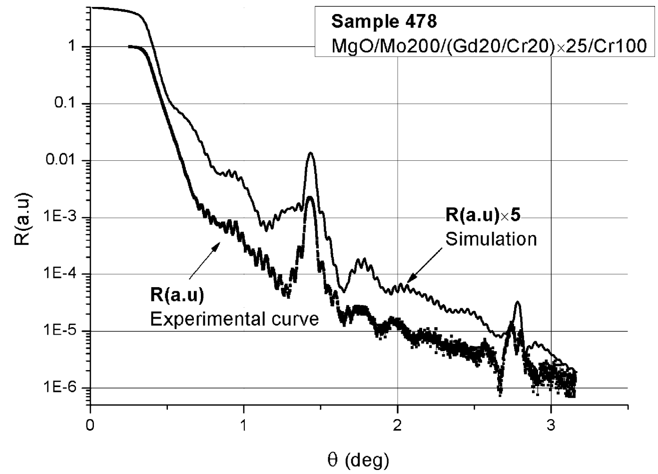

Fig. 2. Experimental and simulation reflectivity curves for MgO/Mo200/(Cr20/Gd20) × 25/Cr100 multilayer grown at room temperature. The intensity of simulated curve was multiplied by a factor of 5 in order to easily distinguish both curves.

Table 2
Individual layer thickness and roughness for the sample Al_2O_3/Mo200/(Cr30/Gd30) × 15/Cr100 obtained from the simulation

Layer	Thickness (Å)	RMS roughness (Å)
Al_2O_3 (substrate)	–	1
Mo (buffer)	191	1
Cr (multilayer)	27.3	3.5
Gd (multilayer)	23.5	3.5
Cr (cap layer)	85	10
Cr_2O_3	2	9

3.2. Magnetic measurements

Cr/Gd multilayers grown on sapphire substrates are of better quality (smoother interfaces) than those deposited on MgO, so further discussion concerns only the magnetic properties of the samples deposited on Al_2O_3.

Different types of magnetic measurement were performed in order to get comprehensive information about the magnetic properties of Cr/Gd multilayers. The magnetization versus applied field was measured in the temperature range from 5 to