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Tunable perpendicular magnetic anisotropy in GdFeCo amorphous films

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ABSTRACT

We report the compositional and temperature dependence of magnetic compensation in amorphous ferrimagnetic $Gd_xFe_{93-x}Co_7$ alloy films. Magnetic compensation is attributed to the competition between antiferromagnetic coupling of rare-earth (RE) with transition-metal (TM) ions and ferromagnetic interaction between the TM ions. The low-Gd region of x between 20 and 34 was found to exhibit compensation phenomena characterized by a low saturation magnetization and perpendicular magnetic anisotropy (PMA) near the compensation temperature. Compensation temperature was not observed in previously unreported high-Gd region of $x=52$–59, in qualitative agreement with results from recent model calculations. However, low magnetization was achieved at room temperature, accompanied by a large PMA with coercivity reaching ~6.6 kOe. The observed perpendicular magnetic anisotropy of amorphous GdFeCo films probably has a structural origin consistent with certain aspects of the atomic-scale anisotropy. Our findings have broadened the composition range of transition metal-rare earth alloys for designing PMA films, making it attractive for tunable magnetic anisotropy in nanoscale devices.

1. Introduction

Magnetic materials with perpendicular magnetic anisotropy (PMA) have attracted large interest over the past few years from the viewpoint of both academic research and technological applications. It is predicted that magnetic tunnel junctions or spin valves with perpendicularly magnetized electrodes are able to facilitate faster and smaller data-storage magnetic bits, compared with the normal in-plane ones [1]. For devices, it is preferable to use a single film layer with perpendicular magnetic anisotropy instead of multilayer in order to avoid the complicated fabrication process and decrease the total thickness of the devices. One well-known candidate is amorphous rare-earth transition-metal (RE-TM) thin films with strong perpendicular magnetic anisotropy [2–4].

Amorphous GdFeCo films have been known to have a low saturation magnetization, preventing magnetization curling at the film edge. Furthermore, they possess Curie temperatures well above room temperature for a wide range of compositions [5]. Gd is a unique member of the lanthanide series in that its ground-state electronic configuration is $4f^7(5d6s)^3$ with the highest possible number of majority spin electrons and no minority spin electron in its 4f state according to Hund's rule. In addition, because the 4f states of Gd are half filled, their orbital moment and spin-orbit coupling are zero. This $L=0$ state of Gd provides a favorable condition for the low Gilbert damping, which is preferable in spin-torque-transfer devices. Amorphous GdFeCo alloys are ferrimagnets in which the Fe(Co) sublattices are antiferomagnetically coupled to the Gd sublattice in a collinear alignment, while the exchange coupling in the Fe(Co) sublattice is ferromagnetic [6]. These ferrimagnetic GdFeCo alloys tend to exhibit magnetic compensation behavior characterized by a vanishing magnetization below the Curie temperature [7]. Also, depending on the composition, amorphous GdFeCo films generally possess a uniaxial anisotropy with an anisotropy axis either perpendicular or parallel to the film plane.

In this study, we have obtained amorphous GdFeCo films for a wide range of Gd content via the combinatorial growth technique. We have investigated the compositional and temperature dependence of magnetization compensation in these amorphous ferrimagnetic $Gd_xFe_{93-x}Co_7$ films and demonstrated the tunability of perpendicular magnetic anisotropy. Possible mechanisms for the observed perpendicular magnetic anisotropy are discussed.

2. Experimental procedure

The $Gd_xFe_{93-x}Co_7$ (GdFeCo) films were prepared at ambient temperature on thermally oxidized Si substrates using *rf* magnetron sputtering. The base pressure of the sputtering chamber was ~7×10^{-7} Torr. GdFeCo alloy films were deposited by means of co-sputtering with the elemental targets under a processing Ar gas

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pressure around 5×10^{-3} Torr. The capping MgO layer was formed directly from a sintered MgO target to protect the GdFeCo layer from oxidation. All the samples deposited at room temperature had a typical structure consisting of Si(100)/SiO_2/$Gd_xFe_{93-x}Co_7$($15\leq x\leq59$ at %)/MgO(6 nm) with a fixed thickness of GdFeCo layer ~50 nm. The film thickness of all samples were measured by X-ray reflectivity, and film compositions were determined using inductively coupled plasma-mass spectrometry (ICP-MS) after chemically dissolving the films, and confirmed by X-ray fluorescence (XRF) using peak ratios. The magnetic properties of the samples were investigated by a vibrating sample magnetometer (VSM) and magneto-optic Kerr effect (MOKE) measurements, with a maximum field of 20 kOe. Structural characterization of the films was performed by X-ray diffraction (XRD) with Cu $K\alpha$ ($\lambda=1.541$ Å) radiation (Smart-lab®, Rigaku Inc.) and transmission electron microscopy (TEM, FEI Titan). Atomic Force Microscopy (Cypher™, Asylum Research Inc.) was used to characterize surface morphology.

3. Results and discussions

The amorphous structures of the as-deposited samples were confirmed by TEM and XRD observations. Fig. 1(a) shows a typical cross-sectional TEM image obtained from as-deposited $Gd_{22}Fe_{71}Co_7$ film on the Si/SiO_2 substrate. The microstructure was dense with no visible cracks or holes, and all layers in the structure were well adhered to each other. The uniform thickness of $Gd_{22}Fe_{71}Co_7$ film was measured to be 52 nm in Fig. 1(a). The high resolution TEM image in Fig. 1(b) revealed the featureless nanoscale structure that indicated the lack of long-range order. The broad ring pattern in the fast Fourier-transform (FFT) image in the inset of Fig. 1(b) indicated the lack of crystallinity. In addition, XRD scans showed that there were no diffraction peaks other than those from the substrate for GdFeCo films with different compositions (not shown here). The XRD results were consistent with the TEM, indicating that all the as-deposited samples were amorphous in nature, without the formation of a long-range structural order. Atomic force microscopy (AFM) measurements showed that the surfaces were free of pinholes and were flat with roughness less than 1 nm.

3.1. Low Gd-content films

The magnetization of GdFeCo films were characterized in the in-plane and out-of-plane directions using the VSM option in Quantum Design VersaLab. Fig. 2 shows the temperature dependence of saturation magnetization of as-deposited GdFeCo films for several compositions. Saturation magnetization (M_s) was extracted from the hysteresis loops measured as a function of temperature between 100 K and 400 K. Compensation temperature (T_{comp}) was defined as the temperature at which $M_s(T)$ reached its minimum. The saturation moments at the compensation temperatures were below 100 emu/cc. The observed small saturation moment was due to the ferrimagnetism of amorphous RE-TM alloys. The TM–TM ferromagnetic interaction aligns the magnetic moments among Fe and Co ions, which are coupled antiferromagnetically with the magnetic moments of Gd. As a result, the net moment is the difference between the magnetic moments of Gd and Co(Fe). At the compensation temperature, the moments of the two magnetic sublattices were nearly equal, giving rise to a low saturation magnetization.

Due to the different temperature dependences of the sublattice magnetizations, compensation temperature can be varied, depending on the compositions. The variation of M_s with temperature (Fig. 2) resembled the expected compensation behavior when approaching the compensation point. The GdFeCo films with $x=22$, 27 and 30 at% exhibited the compensation temperatures T_{comp} at 300 K, 350 K and 378 K, respectively. However, for several other compositions, there was no compensation point within the investigated temperature interval from 100 to 400 K. For $Gd_{35}Fe_{58}Co_7$ film, the compensation point was not obtained due to the limitation of the measurement temperature range. For the sample $Gd_{15}Fe_{78}Co_7$, the dependence of saturation magnetization on T (not shown) indicated that the magnetization of the Fe(Co) sublattices exceeded the magnetization of the Gd sublattice in the whole temperature range. This was due to the fact that ferromagnetic exchange of the Fe(Co) sublattices dominates the magnetic behavior at low Gd content. As the Gd content increases and Fe(Co) content decreases, there is a corresponding increase in the antiferromagnetic coupling relative to the ferromagnetic exchange, and magnetic compensation emerges. Further increase in the Gd concentration resulted in the increase in T_{comp}, as shown in the inset of Fig. 2.

According to magnetization measurements, the perpendicular magnetic anisotropy in GdFeCo films appeared near their compensation temperatures, whereas the magnetic easy axis was in-plane. Fig. 3(a) shows the typical normalized out-of-plane hysteresis loops of the as-deposited $Gd_{27}Fe_{66}Co_7$ films at various temperatures. At 250 K, far from T_{comp}~350 K, magnetization was dominated by in-plane anisotropy. Near the compensation point, perpendicular magnetic anisotropy was dominant, and a square hysteresis loop was established in the out-of-plane direction with coercivity near 100 Oe.

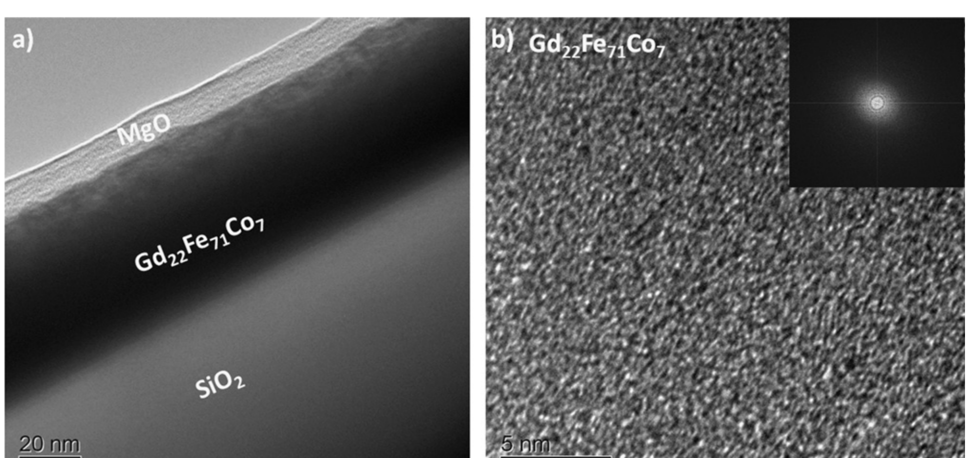

Fig. 1. (a) Cross-sectional TEM image of as-deposited $Gd_{22}Fe_{71}Co_7$ film on SiO_2/Si substrate. 6 nm MgO layer was used to cap the film, and (b) high-resolution TEM image of the $Gd_{22}Fe_{71}Co_7$ film. The inset is a FFT pattern of the image.