Structure and magnetic hysteresis of Gd/Fe multilayers patterned into periodic line patterns

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The structure and magnetic properties are reported for Gd/Fe multilayers with periodic line patterns fabricated by alternating UHV evaporation combined with photolithography or interference lithography and liftoff. In cross-sectional TEM images, the Fe layers show a grain structure, while no contrast was observed in the Gd layers. Magnetic hysteresis measurements show that the coercive field increases with line periodicity and magnetic layer thickness. This behavior might be attributed to not only the demagnetization field, but also the pinning effects of the crystal grain boundaries on the domain walls, and/or the influence of exchange coupling at the interface between Fe and Gd layers.

Key words: interference lithography, nano-scaled structure, rare earth/transition metal multilayer

1. INTRODUCTION

Thanks to the ability to control sample geometry on the nanoscale by thin film processing technology, both spin alignment and current flow can be controlled efficiently in magnetic thin film materials. Alternating deposition of different materials in ultra high vacuum (UHV) has made it possible to control magnetic structure by multilayering on an atomic scale. In particular, rare earth (RE)/transition metal (TM) multilayers are interesting materials, since novel magnetic behaviour is expected due to the exchange interaction between RE and TM magnetic moments at the interface [1-4]. TM/Gd multilayers are known to behave as ferrimagnets, that is the magnetizations of TM and Gd layers couple antiparallel due to the antiferromagnetic exchange interaction at the interface. It is important to know the details of the magnetic configuration, that is, the magnitude and the direction of the magnetic moment in each atomic layer.

Using lithography techniques, magnetic films can be fabricated into patterns such as periodic lines or dots. The behavior of periodic patterned multilayers is governed both by the multilayer structure in the out-of-plane direction and the in-plane patterning. However, to date there is limited data available on the behaviour of patterned RE/TM multilayers.

The purpose of this study is to demonstrate fabrication of periodic line patterns from a Gd/Fe magnetic multilayer and to measure their magnetic hysteresis. We use both interference lithography and traditional photo-mask lithography in order to produce the in-plane lateral periodicity, and alternating evaporation of Fe and Gd in a UHV chamber in order to produce the multilayer structure perpendicular to the plane.

2. EXPERIMENTAL

Line patterns in photo-resist of several widths were prepared by two lithography techniques. One is Interference Lithography using a Lloyd’s Mirror (LM), as shown in Fig.1, for line widths less than 1 \(\mu\)m, and the other method is the Photo Mask (PM) method, as shown in Fig.2, for line widths more than 3 \(\mu\)m. As a light source, a HeCd laser (325nm) and an h-line laser (405nm) were used for the LM method and PM method, respectively. In the LM method, which utilizes the interference between the direct beam launched from the laser source and reflected light from the mirror [5], we can change the line width by exposure time and mirror angle. The technique can produce large patterns whose area is more than several square centimeters. Four sample geometries were made using each method.

After exposure and development, Gd/Fe multilayers were deposited on the photoresist layer using an electron beam evaporator for Fe, and a high-temperature (~1400ºC) heating cell for Gd, both operated in the same
Three types of multilayers were grown as follows, with the same total thickness:

(i) Gd10nm/Fe10nm,
(ii) [Gd5nm/Fe5nm]x2
(iii) [Gd2.5nm/Fe2.5nm]x4

All multilayers were capped with a GaAs layer of 15nm thickness to prevent oxidization. Finally, the films were lifted-off with acetone, yielding line patterns of the Gd/Fe magnetic multilayers.

Surface morphology was imaged by Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM), and cross-sections of the multilayers by Transmission Electron Microscope (TEM). The magnetic properties were evaluated by Alternating Gradient Magnetometer (AGM).

3. RESULT AND DISCUSSION

3.1 Structure

Fig.3 shows SEM images of line-patterned samples with multilayer structure (i), fabricated by the LM method. An AFM image and depth profile of a sample of multilayer (i) with pattern LM1 are shown in Fig.4. The line scan from the AFM measurement shows that the surface of the patterned lines has high flatness. Parameters of the line patterns evaluated from SEM images are shown in Table.1 for LM samples, and in Table.2 for PM samples, respectively. The pattern period produced by the LM technique is expected to be independent of exposure dose, and the differences in period are attributed to inhomogeneity of the interference pattern over the wafer.

Cross-sectional TEM images of line pattern LM1 are shown in Fig.5 for all three multilayer structures. In Fig.5 (a), a Pt layer is observed at the topmost surface, which was intentionally deposited in order to protect the surface structure during the thinning process for TEM observation. Fig.5 (a) also shows indentation in the space between lines, which is caused by ion milling of the substrate during the thinning process. In Fig.5 (b), (c), (d), it is clear that the Gd and Fe form alternating stacking with layers close to the nominal thickness. In the Fe layers of all samples, as shown in Fig.5 (b), (c), (d), there are dark grains and light grains with the contrast due to the difference in the crystal orientation, while no such grains are observed in Gd layers. This suggests that Fe layers are formed as a polycrystalline structure whereas Gd layers are amorphous. The amorphous structure of the Gd could result from some degree of oxidation during growth. From TEM, the effect of interface roughness appears to become more significant as the number of layers increased and they became thinner.

3.2 Magnetic properties

Room temperature magnetization vs magnetic field curves (M-H curves) are shown in Fig.6 (a) and (b), where the direction of the in-plane magnetic field is
parallel and perpendicular to the patterned lines, respectively. When the magnetic field is parallel to the lines, the magnetization shows a square loop with coercive field of around 100 Oe. On the other hand, when the magnetic field is perpendicular to the lines, the loop is a hard axis sheared loop as a result of shape anisotropy [7] in the lines.

Fig.7 shows M-H curves of LM patterned samples with multilayer structure Gd 10nm/Fe 10nm at room temperature, where the magnetic field is parallel to the lines. Patterned samples have larger coercive field than the unpatterned sample. Fig.7 also shows an increase in coercive field as the linewidth decreases. We plotted the coercive field of all samples made by both LM and PM methods as function of line width in Fig.8, where this trend is evident.

M-H curves of Gd/Fe multilayers of structure (i), (ii), and (iii), with line pattern LM1, at room temperature are shown in Fig.9, where the magnetic field is parallel to the lines. Fig.9 indicates that the coercive field is higher for the multilayer sample with the thicker magnetic layers.

At room temperature, the Fe layers provide the major contribution to the magnetization of the Gd/Fe multilayers because the Curie temperature of Gd is approximately 20 ºC and the Gd layers have almost no net magnetic moment. The saturation magnetizations of the films measured at room temperature, which are obtained from Fig.7 and Fig.9, have values in the range of 900-1700 emu/cm³. These values are less than or similar to the bulk value of Fe, ~1750 emu/cm³. A reduction compared to the moment of bulk Fe could be attributed to the small Gd magnetic moment remaining at room temperature. The magnetic moments of Gd and Fe exchange-couple antiparallel to each other [6], in other words, the Gd magnetic component, which is oriented opposite to the Fe magnetic moment and the applied magnetic field, subtracts from the total magnetization in the samples. The magnetization decreases more for samples with a greater number of thinner layers, which may indicate some intermixing at the interfaces; the magnetization is also lowered by patterning which could indicate that the layered structure is also disrupted near the edges of the lines.
In Fig. 7 and Fig. 9, the M-H curve of an unpatterned sample, i.e., a continuous film of Gd/Fe multilayer, is plotted. The coercive fields of unpatterned samples are much smaller than those of patterned samples. This illustrates the relatively easy magnetization reversal in the unpatterned film by domain wall motion, whereas in the patterned samples shape anisotropy is present.

From the results of Fig. 7, 8 and 9, it is clear that the coercive field depends strongly on the aspect ratio of the magnetic lines, i.e., the ratio of the line width to the magnetic layer thickness in the line, increasing as the layer thickness increases and the line width decreases. A number of factors contribute to coercive field, including:

1. The shape anisotropy changes with patterning and layer thickness, as does the saturation magnetization.
2. The pinning effect of the grain structure on domain wall motion [8] increases with layer thickness of the Fe.
3. Exchange coupling with the Gd may affect reversal of the Fe at the interface and lead to spin-flop behavior.
4. Strain in the films, which varies with thickness and line width, may provide a magnetoelastic contribution to the anisotropy.

An assessment of the relative importance of these factors is the subject of future research.

3. CONCLUSION

UHV-evaporated Gd/Fe multilayers were patterned into arrays of lines using interference lithography and photo-mask lithography. The lines had widths of 0.6 – 10 µm and total thickness 20 nm, and the Gd and Fe layers were 2.5 - 10 nm thick. TEM images show that Fe layers have crystal grains, while the Gd showed no contrast. The saturation magnetization decreased as the number of interfaces increased, and by patterning. As the line period decreased or the magnetic layer thickness increased, the coercive field increased. This trend may be related to changes in shape anisotropy, domain wall pinning by the polycrystalline microstructure, strain or exchange coupling at the interfaces between Fe and Gd.

REFERENCES


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