Substrate materials dependence of magnetic domain formation in CoFe nanolayer electrode patterns

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1. INTRODUCTION

Spin electronic devices have attracted much attention in recent years as their device performances, e.g., non-volatile and low-power characteristics, are promising for the future device components. High spin injection efficiencies from ferromagnetic thin film electrodes into III-V compound semiconductor materials have been reported on the structures both with and without MgO interlayers [1-3]. Our long-term goal, among them, is to design and fabricate spin electronic devices using vertically free-standing semiconductor nanowires and ferromagnetic nanolayer electrode patterns [4,5]. In our previous studies, magnetic domains in CoFe/MgO nanolayer electrode patterns, in which CoFe layer thicknesses are 35, 20, and 10 nm and MgO layer thickness is 4 nm, respectively, on single-crystalline GaAs (001) wafers were investigated, directly observing magnetic response by magnetic force microscopy (MFM) [6]. In this study, we report on the substrate materials dependences of magnetic domain formation in ferromagnetic CoFe nanolayer electrode patterns with CoFe layer thicknesses of 35 nm using direct observations by MFM. The substrate materials in the current study are MgO nanolayers, whose thicknesses are 1 and 4 nm, deposited on GaAs (001) wafers and amorphous SiO_2 layers with the thickness of 1 μm thermally oxidized on Si (111) wafer surfaces. The influence of heterointerfaces on magnetic domain formation in CoFe nanolayer electrode patterns is also discussed.

2. EXPERIMENTAL PROCEDURES

$Co_{0.8}Fe_{0.2}$/MgO nanolayers (CoFe layer thickness, t: 35 nm) were deposited at room temperature using radio frequency (RF) magnetron sputtering with argon gas. After the deposition on single-crystalline GaAs (001) wafers, CoFe/MgO nanolayer electrode patterns containing 16 different shapes were fabricated using conventional lift-off processes following electron beam lithography. The thicknesses of the MgO interlayers are approximately 1 and 4 nm. Cross-sectional transmission electron microscopy observations conducted at JAIST confirmed that the CoFe and MgO nanolayers were polycrystalline in all the samples in the current study (not shown here). In addition, to investigate the influences of heterointerfaces between CoFe nanolayers and substrate materials on magnetic domain formation in CoFe, CoFe nanolayer electrode patterns directly deposited on amorphous SiO_2/Si (111) wafers, i.e., without MgO interlayers, were prepared for comparison. Amorphous SiO_2 layers, whose thickness is 1 μm, were obtained by thermal oxidation of Si (111) surfaces of the wafers. All the samples were directly observed using MFM. In all the MFM observations in this study, the high-resolution MFM probe was typically maintained at a height of 50 nm above the sample surface. The MFM images were obtained without any application of an external magnetic field, B, at room temperature before and during the MFM observations, i.e., under the as-deposition condition of all the samples.

3. RESULTS AND DISCUSSION

Figures 1(a) and 1(b) show MFM images of CoFe/MgO (MgO: (a) 1 nm and (b) 4 nm) nanolayer electrode patterns before applying B. First, in Figures 1(a) and 1(b), they show that all the magnetization is spontaneous. In Figure 1(a), we primarily observe reflux, double reflux, and multiple magnetic domain structures in all 16 nanolayer patterns (i.e., no single magnetic domain is observed). On the other hand, as indicated by white arrows in Figure 1(b), the nanolayer patterns with a relatively large aspect ratios, e.g., 4, tend to exhibit a single magnetic domain with the magnetization orientation, M, which is due to the shape magnetic anisotropy, whereas those with a relatively small aspect ratios tend to have reflux and double reflux magnetic domains. Comparing the nanolayer electrode patterns with a relatively large aspect ratio of 4 in between Figures 1(a) and 1(b), in which the MgO layer thicknesses are different, a single magnetic domain is observed in Figure 1(b), whereas reflux, double reflux, and multiple magnetic domains are formed in Figure 1(a). In Figures 1(a) and 1(b) with different MgO layer thicknesses, single magnetic domains (as shown with white arrows, M) are observed in the nanolayer electrode patterns with the aspect ratios larger than 1, e.g., four patterns of 0.75 × 0.50, 1.0 × 0.50, 2.0 × 0.50, and 0.5 × 2.0 μm², in Figure 1(b), for which the reflux or multiple magnetic domains are obtained for the same four patterns in Figure 1(a). In addition, when comparing the patterns with the largest size and the smallest aspect ratio of 1, i.e., 2.0 × 2.0 μm² (i.e., no shape magnetic anisotropy),

reflux magnetic domains are markedly observed in the case of CoFe/MgO (4 nm) nanolayer electrode pattern, whereas the CoFe/MgO (1 nm) nanolayer electrode pattern exhibits multiple magnetic domains, in which the magnetic domains are markedly divided into large number of small magnetic domains. Figure 1(c), next, shows a typical MFM image of CoFe nanolayer electrode patterns formed on amorphous SiO_2 (1 μm) substrates in the absence of B at room temperature. The general tendency of magnetic domain formation in CoFe nanolayer electrode patterns in Figure 1(c) is similar to the case in Figure 1(b), although no single magnetic domain is observed. Figure 2 shows, particularly, the comparison among the highly magnified MFM images for CoFe nanolayer electrode patterns with the size of 2.0×2.0 μm². We have confirmed that the mean surface roughness of CoFe nanolayer electrode patterns increases with decreasing the nanolayer thickness in the case of our RF magnetron sputtering. [7] Therefore, it may possibly suggest that the MgO layer thickness under the CoFe nanolayer electrode patterns affects the magnetic domain formation in CoFe, as it is reported in previous studies [8,9] that the magnetic properties are markedly influenced by the surface roughness of thin films. It possibly appears that the surface roughness of 1-nm-MgO interlayers is larger than that of 4-nm-MgO interlayers, resulting in the larger roughness of CoFe nanolayer electrode patterns on 1-nm-MgO interlayers than on 4-nm-MgO ones. That leads to the formation of small poly-crystalline domains on the CoFe surfaces, which act as physical barriers, inducing the formation of small multiple magnetic domains. This understanding may possibly be supported by the fact that the same reflux magnetic domains with the case in Figure 2(b), i.e., the CoFe on 4-nm-MgO interlayers, are observed in the CoFe nanolayer electrode patterns in Figure 2(c), which were fabricated on the thermally oxidized 1-μm-SiO_2 layer surface presumably with long-period undulation of surface roughness, comparing to the sputtered layer surface.

4. CONCLUSIONS

Without any application of B, we observed the marked reflux, double reflux, and single magnetic domains in the case of the samples with relatively thick buffer layers under CoFe. The CoFe nanolayer electrode patterns with 1-nm-MgO layers formed large number of (or multiple) small magnetic domains. These results suggest that the surface roughness of buffer layers plays an important role for magnetic domain formation in CoFe.

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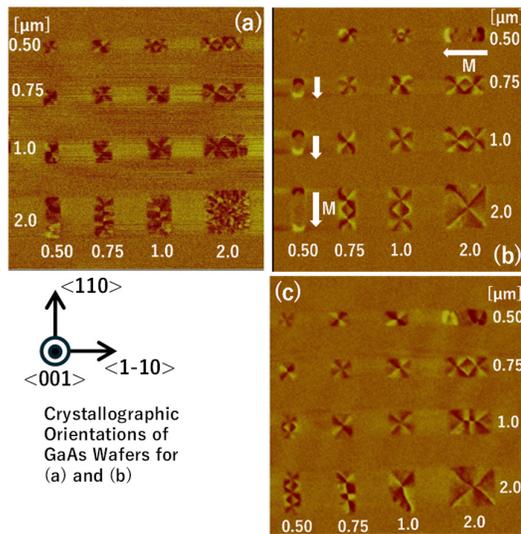[9] C.H. Lin et al., Thin Solid Film **519**, 8379 (2011).

Fig.1 MFM images of CoFe nanolayer electrode patterns. **(a)** CoFe/MgO/GaAs: the thicknesses, *t*, of CoFe and MgO are 35 and 1 nm, respectively. **(b)** CoFe/MgO/GaAs: *t* of CoFe and MgO are 35 and 4 nm, respectively. **(c)** CoFe/SiO₂/Si: *t* of CoFe and SiO₂ are 35 nm and 1 μm, respectively. White arrows in (b) represent the magnetization directions, *M*, judging from the magnetic responses from the samples.
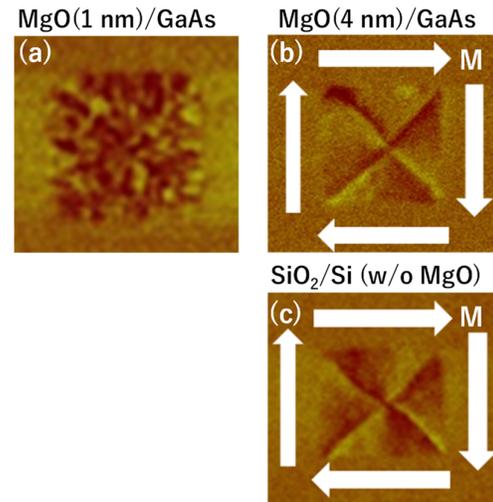

Fig.2 Highly magnified MFM images for CoFe (35 nm) nanolayer electrode patterns with the area of 2.0×2.0 μm². Buffer layers (or, substrates) and wafers under CoFe nanolayers are: **(a)** MgO (1 nm)/GaAs, **(b)** MgO (4 nm)/GaAs, and **(c)** amorphous SiO₂ (1 μm)/Si. White arrows in (b) and (c) represent the magnetization directions, *M*, judging from the magnetic responses from the samples.