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Enhancement of exchange field in CoFe/IrMn by Os/Cu buffer layer

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Enhancement of exchange field (H_{ex}) and thermal stability of the textured CoFe/IrMn with Os/Cu buffer layer and Os diffusion barrier layer were studied. As revealed by x-ray Diffraction (XRD), an Os (0002) surface mesh was observed to form on Cu (100)/Si (100). The growth of CoFe (111)/IrMn (111) on such a template is parallel to the Os (0002). With the Os/Cu buffer layer, the CoFe/IrMn presents an enhancement of 70 Oe on H_{ex} larger than that without Os/Cu. The H_{ex} of the textured sample was 230 Oe at room temperature and it was increased to 330 Oe after 250 °C annealing. When the temperature reached 350 °C, H_{ex} vanished. The increment of the temperature at which the textured and the nontextured sample obtaining their maximum H_{ex} and the vanishing temperature of H_{ex} were 50 and 75 °C, respectively. Furthermore, the CoFe/Os (d)/IrMn slowed down the H_{ex} degradation. The sample with $d=0.3$ nm obtained its maximum H_{ex} at 250 °C and vanished when it reached 400 °C. The combination of CoFe/IrMn with Os/Cu buffer layer and Os barrier layer made the H_{ex} higher and also better thermal stability. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2670324]

INTRODUCTION

Recently, the rapid development of the spintronic devices has been well expanded. The magnetic layers are the essential ingredients of spintronics and properties such as structure, thermal stability, and magnetization have large influences on the overall performances. A suitable buffer layer is needed for an antiferromagnetic (AFM) layer to induce the ferromagnetic/antiferromagnetic (FM/AFM) coupling in magnetic tunnel junction (MTJ) or spin valve (SV) structures.[1] Hexagonal closed-packed (hcp) buffer layers, such as Ti, Hf, and Zr, could enhance the face center cubic (fcc) (111) structure of the IrMn to induce exchange field (H_{ex}) on Si substrates.[2] However, there are no papers stating the growth of IrMn with the hcp structure osmium (Os) buffer layer and the uses of the Os are also rare. On the other hand, the thermal degeneration of magnetic films is also an important issue during manufacturing. According to our previous work,[3] the coercivity and hysteresis loop squareness of the CoFe are retained after 400 °C annealing with a thin Os layer inserted between the CoFe/MnOs interface. In this article, we extend our previous work[4] to investigate the Os acted as a buffer layer and a diffusion barrier simultaneously in the textured CoFe/IrMn.

EXPERIMENTS

Textured samples with layers of Ta (1)/CoFe (10)/Os (d)/IrMn (30)/Os (t_b)/Cu (30)/Si (100) were magnetron sputtering growth, where the number in brackets was shown in nanometers. The bottom Os layer acted as a buffer layer for IrMn growth and fixed t_b at 30 nm while the upper Os layer was a diffusion barrier and d was varied from 0 to 1 nm. Before deposition, Si wafers were first cleaned to degrease themselves and then dipped into 10% HF solution to form a hydrogen-terminated surface. Immediately after that, they were loaded into the vacuum chamber. According to the metal-metal epitaxy on silicon (MMES) method,[5,6] the Cu (002) seed layer will grow epitaxially on the H–Si wafer first. The following Os film was deposited at the pressure of 5 mTorr pure Ar gas without breaking the vacuum. No external heating was applied to the substrates during film growth. The textured and nontextured samples were denoted as the CoFe/IrMn with and without the Os seed layer, respectively. Between the textured CoFe/IrMn interface, the Os diffusion barrier was inserted to check the thermal stability. After deposition, all samples were subjected to magnetic field annealing at 3 kOe and at different temperatures ranged from 150 to 400 °C for 30 min. Magneto-optical Kerr effect (MOKE) and a vibrating sample magnetometer (VSM) were used to examine the magnetic behaviors, while the crystal structures were studied by x-ray diffraction (XRD) with a Cu $K\alpha$ source.

RESULTS AND DISCUSSION

The Os $(10\underline{1}1)$ $(2\theta=43.67°)$ in the JCPDS database is the 100% relative intensity (Ref. 7); however, it is actually the MMES method that made the Os film grown along its [0002] direction on Cu/H–Si (100). From the standard XRD scan, a strong Os (0002) diffraction peak was found at 41.69°, which was much stronger than the Os $(10\underline{1}1)$ one. As

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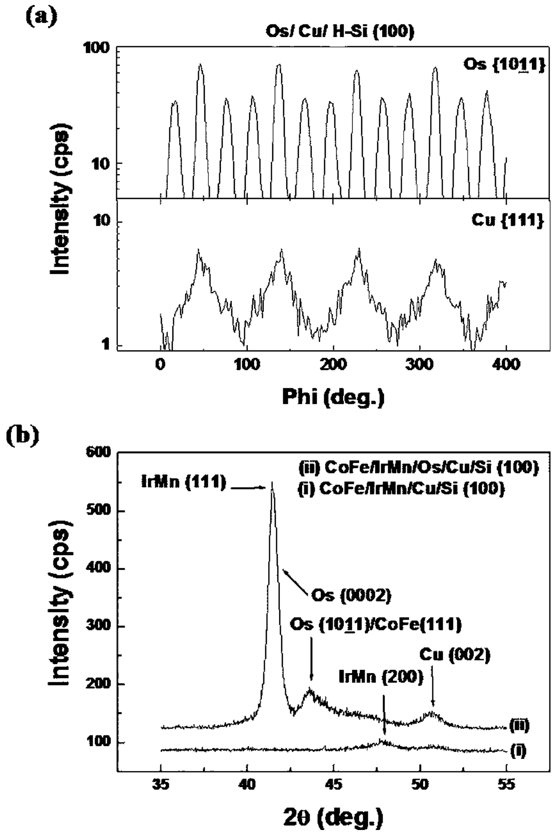

FIG. 1. (a) The XRD φ scan results indicate that the Os 30/ Cu 30 buffer layer grown on H–Si (100) showed a roughly epitaxial crystallization. The Os (0002) and Cu (002) have 12-fold and four-fold symmetries, respectively. (b) XRD patterns of the CoFe/IrMn grown with and without Os seed layer. With Os/Cu buffer layer, the CoFe/IrMn is grown along the fcc [111] direction with highly textured structure.

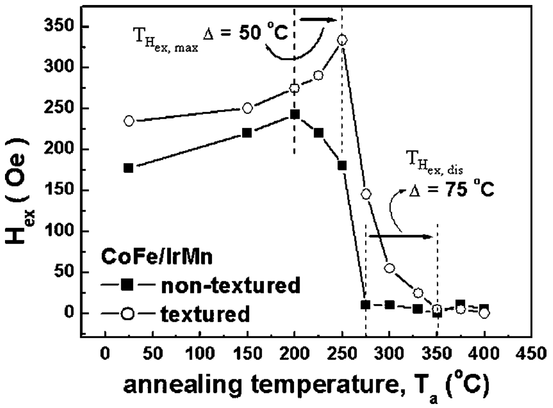

FIG. 2. The H_{ex} of the textured and nontextured samples is a function of T_a. The textured CoFe/IrMn film shows better thermal stability. The 50 and 75 °C improvements on the temperature of at which $H_{\text{ex,max}}$ appeared and H_{ex} disappeared are found clearly, respectively.

seen from Fig. 1(a), the XRD φ scan results indicated that Cu (002) showed a four-fold symmetry as deposited. Since the lattice mismatch for Os–Cu is too large, an improved lattice mismatch for Os–Cu is achieved by a 45° rotation of the Os (0002) plane around its [0002] axis during film growth. Thus, the Os 30/Cu 30 buffer layer on H–Si (100) showed a rough epitaxial structure and the Os (0002) was clearly observed with a special 12-fold symmetry.[8] This also implied that the Os/Cu buffer layer is with in-plane symmetry. This type of plane with order atomic arrangement is suitable for growing films with good crystallinity. As shown in Fig. 1(b), the strong diffraction peak including Os (0002) and IrMn (111) (2θ=41.57°) is clearly observed and indicates the Os/Cu buffer made the whole films highly oriented. Since the Os is a hcp structure, its (0002) surface has the same atomic arrangement with the fcc (111) plane. Thus, all other fcc metals growing on top of the Os would also grow along the Os [0002] direction, which is parallel to the fcc [111] one, to form the fcc (111) orientation due to lower mismatch energy. As presented in our previous work,[9] the lattice mismatches between each layer were calculated as 6.8% (Cu/Os), −2.64% (Os/IrMn), and −5.64% (IrMn/CoFe), respectively. These lattice mismatches are smaller than 7% and that is why these films can be grown without any external heating. Figure 1(b) also shows the XRD pattern of the CoFe/IrMn on only Cu buffer. Neither clear Os (0002) nor IrMn (111) diffraction peaks appear and just a weak IrMn (002) peak (2θ=47.8°) is found. Such a sample did not show clear crystallinity as Cu (002) was not a suitable surface to grow fcc (111) oriented films. Magnetic films such as NiFe, CoFe, and IrMn with fcc (111) orientation obtained higher exchange biases in the bottom type FM/AFM multilayer film.[2] That is the main reason why the film structure should be well controlled. The CoFe film on IrMn/Os/Cu did not show an obvious (111) (2θ near 43.5°) peak and was due to its thin thickness.

Since the CoFe/IrMn crystal structures were determined by the Os seed layer, the dependence of CoFe/IrMn crystallinities on magnetic and thermal behaviors can be examined easily. The H_{ex} as a function of annealing temperature (T_a) for the nontextured, and the textured samples are shown in Fig. 2. The H_{ex} of the textured samples (~230 Oe) is larger than that of the nontextured samples (~180 Oe) at as deposited. The Os seed layer provided a very suitable surface mesh; therefore the magnetic films grown with very high textured fcc (111) crystallinity showed more coherent magnetic moment alignment. According to the ideal interface model,[10] these high textured samples have more ideally interfaces. The regular magnetic moments alignment made the θ_F (the angle between magnetization of FM and easy axis) near zero and brought the highest exchange anisotropy energy ($K_e \cos \theta_F$, K_e: the interfacial coupling constant). Thus, the textured samples showed a larger H_{ex} than the nontextured ones. Furthermore, it is clearly found that the nontextured samples reached maximum H_{ex} ($H_{\text{ex,max}}$) at 200 °C and H_{ex} disappeared abruptly when T_a was higher than 250 °C. However, the textured ones reached $H_{\text{ex,max}}$ at 250 °C and H_{ex} was lost gradually as T_a increased. The H_{ex} of the textured samples vanished at 350 °C while roughly no H_{ex} appeared for the nontextured samples after the 275 °C annealing. By using Os/Cu buffer layer, the improvements on temperature, at which the $H_{\text{ex,max}}$ appeared and the H_{ex} disappeared, are 50 and 75 °C, respectively. Some studies point out that the diffusion of Mn atoms into the ferromagnetic layer reduced the H_{ex}.[11] In these two types of samples, the nontextured samples could be seen as with a crystal matrix with more grain boundaries coming from its random surface atomic arrangement while the textured ones exhibited fewer

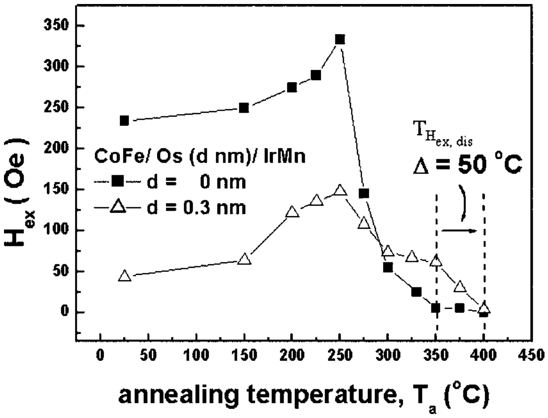

FIG. 3. The textured CoFe/IrMn film shows similar thermal stability dependence tendency as the annealing temperature increased. The 50 °C improvement on temperature at which the H_{ex} disappeared can be found.

grain boundaries due to its much better crystallinity. The loose atomic arrangement made the occurrence of diffusion appeared easily. Since the grain boundaries were at disorder regions, they provide a lower barrier for Mn atom diffusion. More grain boundaries provided more diffusion channels[12] for Mn atoms to diffuse into the CoFe layer. When samples were annealed at high temperatures, the diffusion at the grain boundaries occurred more easily. Thus, the textured samples showed better thermal stability after high temperature annealing.

On the other hand, a thin additional Os barrier between the CoFe and IrMn layers can also stop the Mn atom interdiffusion.[4] From the XRD data, no obvious changes were found in both kinds of samples and hence, this indicated that the insertion of the Os barrier did not affect the crystallinity after growth. The $H_{ex,max}$ of textured sample with $d=0.3$ nm appeared at 250 °C. However, it decreased more slowly than that of the textured sample with $d=0$ nm. When the temperature was raised to 400 °C, H_{ex} vanished, as shown in Fig. 3. The textured samples with $d=1.0$ nm showed similar dependence between H_{ex} and T_A as that with $d=0.3$ nm. They showed that $H_{ex,max}$ of 15 Oe at 250 °C and a very small H_{ex} still existed after 400 °C annealing. This decreased H_{ex} was agreed with the study by Thomas *et al.*[13] that the interlayer between the FM/AFM layers reduces the exchange coupling. The similar tendency appeared in the temperature dependence on the H_{ex} for all the textured samples with $d>0$. The dependence of H_{ex} on d is shown in Fig. 4. With $d=0$, H_{ex} decreased immediately from 230 Oe in the as-deposited state to 50 Oe after 300 °C annealing; however, when $d>0$, all 300 °C annealed textured samples showed larger H_{ex} than that of the as-deposited state. H_{ex} decreased as d increased due to far separation of FM and AFM layers; however, thicker d slowed Mn diffuse into CoFe, thus these textured CoFe/IrMn with $d>0$ showed larger H_{ex} after annealing. Furthermore, H_{ex} of the textured CoFe/Os (0.1)/IrMn increased from 170 to 180 Oe after 300 °C annealing. This indicated the 0.1 nm of Os layer was thick emough to retain the H_{ex} of CoFe/IrMn after annealing. This indicated that the magnetic properties were retained after annealing even though the Os barrier was as thin as 0.1 nm.

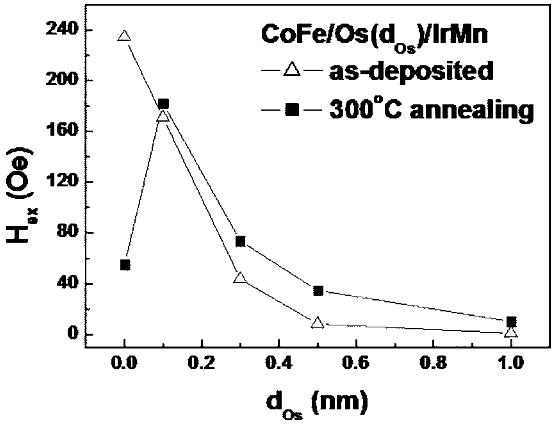

FIG. 4. The H_{ex} of the textured sample is a function of Os barrier thickness, d. When $d>0$, all the 300 °C annealed samples show larger H_{ex} than that of as-deposited state. But when $d=0$, the 300 °C annealed samples show a very small H_{ex} compared to the as-deposited sample.

CONCLUSIONS

The enhancement of H_{ex} and thermal stability of the textured CoFe/IrMn with Os/Cu buffer layer were studied systematically. The crystallinity of CoFe/IrMn can be well controlled by the Os (0002)/Cu seed layer. The CoFe/IrMn induced a 230 Oe and a 180 Oe of H_{ex} with and without Os seed layer, respectively. There was an improvement on the CoFe/IrMn crystallinity and it was because the reduced grain boundaries brought better thermal stability. The textured film showed 50 and 75 °C remarkable improvements on the temperature at which $H_{ex,max}$ appeared and H_{ex} disappeared. On the other hand, with additional thin Os barrier, all annealed textured films showed larger H_{ex} than that of the as-deposited state.

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