Journal of Magnetics 2(4), 143-146 (1997)

The Effects of Deposition Rates on Exchange Coupling and Magnetoresistance in NiO Spin-Valve Films

D. G. Hwang, C. M. Park*, S. S. Lee, and K. A. Lee*

Physics Department, SangJi University, 220-702, Wonju, Korea

* *Physics Department, Dankook University, 330-704, Cheonan, Korea*

(Received 25 April 1997)

The effects of deposition rate on exchange coupling field H_{ex} and coercive field H_c in NiO spin-valves are discussed. The H_{ex} and H_c increased with deposition rate of NiO film. The rms roughnesses of the NiO deposited at 6 Å/min (NiO-Low) and 30 Å/min (NiO-High) were almost similar, however, the short-range roughness increased with the deposition rate. The H_{ex}, H_c and surface morphologies for the modulated NiO spin-valve films such as NiO-Low\NiO-High\NiO-Low and NiO-High\NiO-Low were investigated.

1. Introduction

Nickel oxide films with NaCl-type structure are very useful for the antiferromagnetic layer of spin-valve films because of their chemical stability, good corrosion resistance, and relatively high blocking temperature of around 230 ℃ [1]. The spin-valve sandwiches with NiO films have been reported [2]. Although extensive works have been carried out to study various kinds of exchange coupled systems, the exchange coupling mechanism is not yet fully understood.

Traditional understanding of anisotropic exchange coupling mechanism have been known that the degree of (111)-orientation strongly correlates with exchange coupling field (H_{ex}) due to uncompensated spins [3]. However, based on the work reported recently by Michel et al. [4], the correlation of interface exchange energy with the x-ray intensity ratio of the NiO(111)/NiO(200) has shown there is no clear trend of increasing H_{ex} for film with greater (111) texture. In our previous study, the H_{ex} of the NiO/NiFe bilayers epitaxially deposited on MgO(111), (110) and (100) substrates were independent on the crystallographic orientation of NiO films [5]. Also Lai, et. al., reported that the H_{ex} of the exchange-coupled bilayers does not depend on both the degree of interfacial roughness and the existence of (111) texture at all, but rather it is enhanced in the small-grained NiO due to the formation of small domains in NiO [6].

In this article, we describe more detailed investigation of exchange coupling properties, crystal orientations and surface morphologies of NiO films formed by different deposition rates and modulated by deposition method.

2. Experimental

NiO films (thickness 600~900 Å) were deposited on Corning glass 7059 substrates using a sintered powder target of 3-inch diameter by rf-magnetron sputtering in a chamber of 1.5 mTorr and free of oxygen. The deposition rates of the NiO film were varied from 6 Å/min to 30 Å/min. The $NiFe_{50Å}$ and $NiFe_{50Å}/Cu_{20Å}/NiFe_{50Å}$ layers were deposited over the NiO films in the same chamber without vacuum breaking using dc-magnetron sputtering at the rate of about 1 Å/sec. The uniaxial magnetic field during deposition was applied to 320 Oe. The NiO films were modulated by varying deposition rates such as glass/NiO-Low(300 Å)/NiO-High(t Å)/NiO-Low(300 Å) and glass/NiO-High(300 Å)/NiO-Low (300 Å), where NiO-Low and NiO-High stand for the NiO films deposited at the rates of 6 Å/min and 30 Å/min, respectively. The thickness t of the inserted NiO-High layers are varied up to 500 Å.

The H_{ex} and coercive field (H_c) for the NiO/NiFe bilayers were decided from magnetoresistance (MR) curves, and the value were agreed with the results of hysteresis measurement by SQUID magnetometer [7]. The crystal orientations and surface morphologies of NiO films were characterized using a x-ray diffractometer and an atomic force microscopy (AFM), respectively.

3. Results and Discussions

The H_{ex} and H_c as a function of the deposition rate of the NiO film in glass/$NiO_{600Å}/NiFe_{50Å}$ bilayers are shown in figure 1. The H_{ex} and H_c of the bilayer deposited at 6 Å/min are

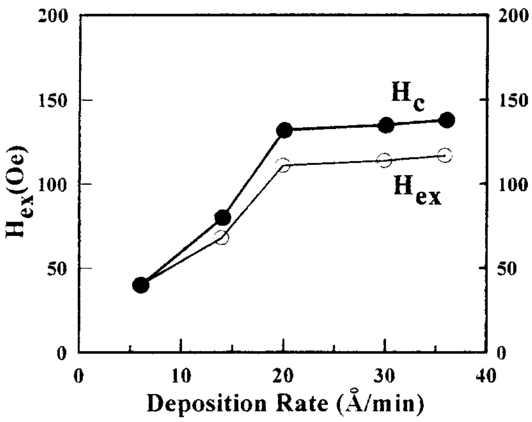

Fig. 1. The H_{ex} and H_c as a function of the deposition rate of the NiO film in glass/$NiO_{600\,Å}$/$NiFe_{50\,Å}$ bilayers.

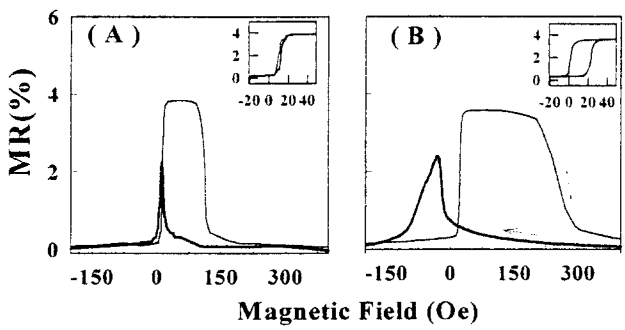

Fig. 2. The MR curves of the $NiO_{600\,Å}$/$NiFe_{50\,Å}$/$Cu_{20\,Å}$/$NiFe_{50\,Å}$ spin valves on the NiO deposited at (a) 6 Å/min and (b) 30 Å/min.

almost same values of 40 Oe and 38 Oe, respectively. These fields increased with deposition rate, and saturated to H_{ex} = 111 Oe and H_c = 132 Oe around 20 Å/min. Therefore, as the deposition rate of NiO was high, the coercive field has a larger than the exchange coupling field. It means that the pinned NiFe layer is strongly exchange-coupled, and due to a rough surface with many defects originated from high deposition rate of NiO. The MR curves of the $NiFe_{50\,Å}$/$Cu_{20\,Å}$/$NiFe_{50\,Å}$ spin-valves on the NiO films deposited at 6 Å/min and 30 Å/min, as shown in figure 2, have a almost same MR ratio of 4 %, but the shapes are very different due to the change of the H_{ex} and H_c. Particularly, in the minor MR curves, the H_c of the free NiFe layer in the case of 6 Å/min is about 2~3 Oe, however, the H_c of 30 Å/min increased to about 10 Oe. It can be considered that if the free NiFe is not correlated with the exchange coupling of NiO, the increase of H_c is due to the magnetic domain wall movement constrained by the defects such as small grain boundary, precipitation, and residual stress, and the demagnetization field created by the roughly bowed NiFe layer.

Figure 3 shows the x-ray diffraction patterns of the $NiO_{600\,Å}$ films deposited at (a) 6 Å/min and (b) 30 Å/min. It was observed that the NiO-Low film revealed a preferred NiO (200) crystal growth, however, the NiO-High deposited film consisted of NiO (111), (200) and (220) peaks.

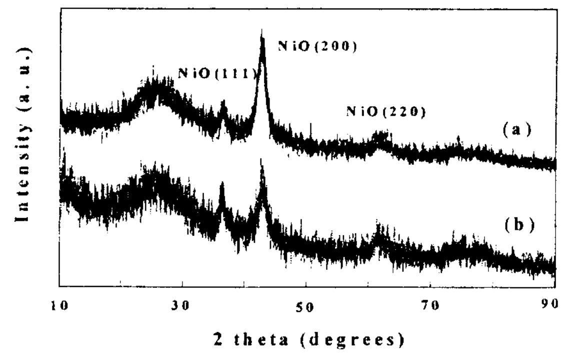

Fig. 3. The x-ray diffraction patterns of the $NiO_{600\,Å}$ films deposited at (a) 6 Å/min and (b) 30 Å/min.

To investigate the effects of the grain growth and interfacial roughness for the $NiO_{600\,Å}$ films deposited under different rates, as shown in figure 4-a and 4-b, the surface morphologies were measured by AFM. The root-mean-square (rms) roughnesses for 6 Å/min and 30 Å/min are similar: 4.2 Å and 5.5 Å, respectively. However, as shown in the AFM images, the morphology of NiO-High (Fig. 4-b) has a very finer cluster than that of NiO-Low (Fig. 4-a). It is related with the increased coercive field and exchange coupling field in the highly deposited NiO/NiFe bilayer.

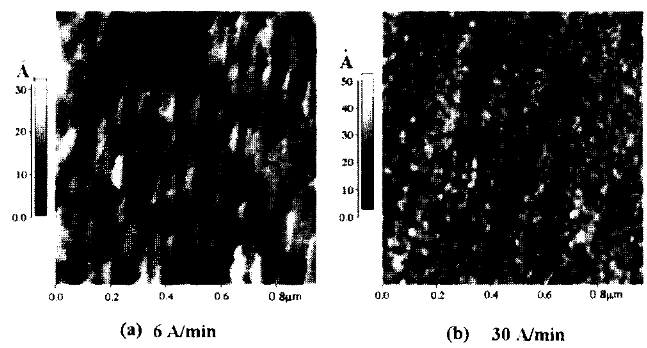

Fig. 4. The AFM images of the $NiO_{600\,Å}$ films deposited at (a) 6 Å/min and (b) 30 Å/min.

To distinguish the effects of grain growth and interfacial roughness, NiO was deposited on Si substrates intentionally roughened to different degrees by polishing [6]. The H_{ex} and H_c for the NiO/NiFe bilayers on these polished substrates were almost not varied. These results suggested that interfacial roughness has little effect on exchange coupling fields, leaving only grain size as a significant variable. In our study, the NiO bilayers and spin-valves on the substrates with different substrate roughnesses such as Corning 7059 and slide glass have a almost analogous properties.

Root-mean-squared roughness in the AFM images, given by the standard deviation of the N data points, cannot be a suitable parameter for thin magnetic films. Because the rms roughness is calculated by the height of individual AFM image data points, this does not include information for slope and wavelength between the peak and valley of a cluster. The H_{ex} and H_c in NiO spin-valves are not related to the rms roughness, but rather to the average slope of clusters in AFM images because of the increase of magnetostatic energy. If the average half-wavelength and peak-to-valley of the clusters in the AFM images are defined to W and h, respectively, h/W is the average slope of clusters. The rms roughnesses for 6 Å/min and 30 Å/min are similar to 4.2 Å and 5.5 Å, respectively, however the morphology of NiO-High (Fig. 4-b) has a very finer cluster than that of NiO-Low (Fig. 4-a), and the average slope h/W of NiO-High and NiO-Low are about 1/12 and 1/60, respectively. The high deposition rate increases the kinetic energy of adatoms, and it forms hill-locks of fine clusters due to the increase of residual stress in thin film. Although the rms roughness of 6 Å/min and 30 Å/min samples are almost same, the surface of fast deposited NiO film has a large short-range roughness, which can be related with the morphology having a slope of hill-locks above 1/20. Therefore, the increased H_{ex} in the high-rate NiO/NiFe bilayer is due to the increase of short-range roughness having a high slope of clusters.

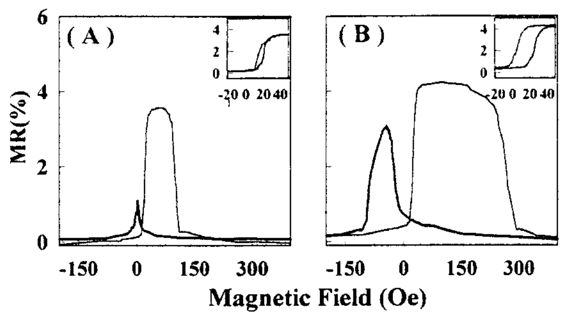

Fig. 5. The MR curves of the $NiFe_{50Å}/Cu_{50Å}/NiFe_{50Å}$ spin-valves on the modulated NiO films such as (a) glass/NiO-High(300 Å)/NiO-Low(300 Å) and (b) glass/NiO-Low (300 Å)/NiO-High (300 Å)/NiO-Low(300 Å), where NiO-Low and NiO-High were deposited at 6 Å/min and 30 Å/min, respectively.

Figure 5 shows the MR major and minor curves of $NiFe_{50Å}/Cu_{50Å}/NiFe_{50Å}$ spin-valves on the modulated NiO films such as (a) glass/NiO-High(300 Å)/NiO-Low(300 Å) and (b) glass/NiO-Low(300 Å)/NiO-High(300 Å)/NiO-Low(300 Å). The MR curve of the first sample (Fig. 5-a) is similar to that of the NiO-Low spin-valves deposited at 6 Å/min, as shown in figure 2-a. And, In figure 6-a, the AFM image of the modulated NiO -High(300 Å)/ NiO-Low(300 Å) film is analogous to the NiO-Low surface, as shown in figure 4-a, even if the rms roughness of the modulated NiO film increased to 8.5 Å. The MR curve of the second sample (Fig. 5-b) is similar to that of the NiO-High spin-valves deposited at 30 Å/min, whose the rms roughness in the AFM image of figure 6-b is 6.4 Å. However, the average slope h/W of the second sample is steeper than that of the first sample, corresponding to about 1/16 and 1/45, respectively. Therefore, it seems that the correlation between exchange coupling field and rms roughness in NiO/NiFe interface is poor, but steep slope of roughness, so called short-range roughness, exert an important effect on coupling field and coercive field.

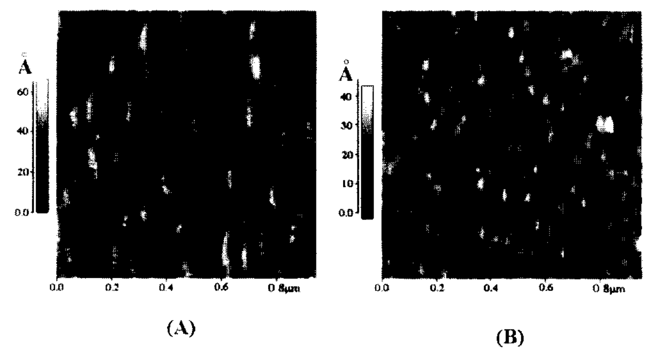

Fig. 6. The AFM images of the modulated NiO films such as (a) glass/NiO-High (300 Å)/NiO-Low(300 Å) and (b) glass/NiO-Low (300 Å)/NiO-High(300 Å)/NiO-Low(300 Å).

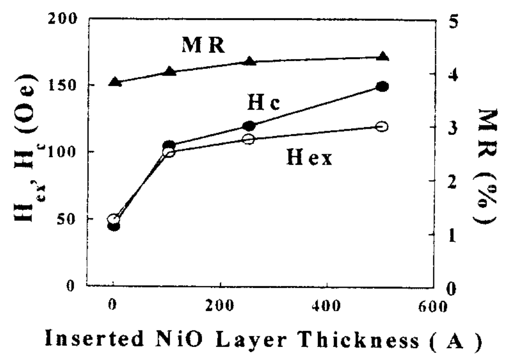

Fig. 7. The MR ratio, H_{ex}, and H_c as a function of the inserted NiO-High(t Å at 30 Å/min) layer thickness in the bilayers and spin-valves with glass/NiO-Low (300 Å)/NiO-High (t Å)/NiO_L (300 Å).

The MR ratio, H_{ex} and H_c as a function of the inserted NiO-High (t Å at 30 Å/min) layer thickness in the spin-valves on NiO-Low(300 Å)/NiO-High(t Å)/NiO-Low(300 Å) are shown in figure 7. The MR ratios do not varied with the inserted NiO-High(t Å at 30 Å/min) layer thickness, but the H_{ex} and H_c are strongly dependent on the inserted NiO layer. The short-range roughness increases with the thickness. When the NiO-High layer is at the bottom, both of the samples over-deposited by NiO-Low layer does not change. However, in cases that NiO-High layer is inserted in middle of NiO-Low layer, or is over-deposited on NiO-Low layer, the coupling field changes sensitively with the thickness of NiO-High layer. It was confirmed that the inserted NiO-High layer plays significant roles of exchange coupling at interface between the free NiFe and the upper NiO-Low layer.

4. Conclusions

The H_{ex} and H_c increased with deposition rates of NiO film, which can be attributed to the slope of hill-locks rather than rms roughness in AFM images. The exchange coupling in the modulated NiO films depends on inserted NiO-High and top NiO-High rather than bottom NiO-High.

Acknowledgements

This work was supported by the Korea Science and Engineering Foundation under Grant No. 971-0210-145-1, and by Korea Basic Science Institute.

References

[1] W. L. Roth, Phys. Rev. **110**, 1333 (1958).
[2] M. J. Carey and A. E. Berkowitz, Appl. Phys. Lett. **60**, 3060 (1992).
[3] W. L. Roth, J. Appl. Phys. **31**, 2000 (1960).
[4] R. P. Michel, A. Chaiken, Y. K. Kim, and L. E. Johnson, IEEE Trans. on Magnetics, **32**, 4651 (1996).
[5] S. S. Lee, D. G. Hwang, C. M. Park, K. A. Lee, and J. R. Rhee, J. Appl. Phys. **81**, 5298 (1997).
[6] C. H. Lai, H. Matsuyama, and R. L. White, IEEE Trans. on Magnetics, **31**, 2609 (1995).
[7] C. M. Park, D. G. Hwang, S. S. Lee, and K. A. Lee, Ungyong Mulli **10**, 221 (1997).