Journal of Magnetics 4(3), 88-91 (1999)

Effect of Columnar Structures on Exchange Anisotropy Field in Magnetoresistive NiO/NiFe Bilayers

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(Received July 9, 1999)

A series of NiO/NiFe bilayer films are deposited with the variation of Ar sputtering pressure for the NiO layers only. As the pressure for the NiO layers increases, the exchange anisotropy field (H_{EX}) decreases gradually and becomes extinct at 2.5 mTorr, at which the maximum coercive force (H_C) in the NiO/NiFe films is obtained. Randomly oriented columnar structures with H_{EX} a few tens of Oe and oriented columnar structures with zero H_{EX} are observed in the NiO layers by high-voltage high-resolution transmission electron microscopy. The vanishing of the H_{EX} in the oriented structures is attributed to the lack of exchange anisotropy energy (E_{EX}) between NiO and NiFe layers, which results in little contribution of interfacial unidirectional pinning anisotropy to the interface of NiO/NiFe bilayer.

1. Introduction

Applying giant magnetoresistive (GMR) phenomenon to magnetic read-out heads will provide a breakthrough for achieving the areal recording density of 10 Gbits/inch^2 inch by the year 2,000 because of its high sensitivity and large output signal [1, 2]. The suppression of noise from Barkhausen jumps in the GMR magnetic heads [3] can be achieved by the introduction of various antiferromagnetic materials, such as FeMn, NiO and NiMn. These materials act as biasing layers, which are exchange, coupled with a pinned layer [4-6]. Among the above antiferromagnetic materials, the NiO film is one of the potential candidates as a pinning layer, due to its superior chemical stability, insulating characteristics, relatively high blocking temperature, large exchange coupling field and simple fabrication process.

The recent results of the research which has mainly focused on the improvement of exchange anisotropy field (H_{EX}) indicate that the H_{EX} in a NiO/NiFe bilayer film is strongly affected by the grain size (domain size) [7, 8] of the NiO film, rather than by the interfacial roughness [7, 9] or crystalline texture of the NiO film [9]. However, little work has been conducted on the extinction of the H_{EX} in the NiO/NiFe film to figure out the origin of the H_{EX}. To understand the effect of the microstructural configuration on the extinction of the H_{EX}, it is necessary to observe the cross-section of NiO/NiFe bilayer films in atomic scale by high-voltage high-resolution transmission electron microscopy (HVHRTEM) associated with their magnetic properties.

2. Experimental Procedures

A series of the Si/NiO/NiFe/Ta bilayer films with the change of Ar sputtering pressure in the NiO layers only were deposited on Si (100) substrates by an RF sputtering method. The NiO layers were deposited by sputtering Ni oxide target at the pressure range from 1 to 6 mTorr. To induce H_{EX} in the NiO layers, 300 Oe of bias magnetic field from a NdFeB permanent magnet was applied during the deposition. The thickness of the NiO layer was about 600 Å. The same deposition conditions (40 W DC of input power, 1 mTorr of Ar pressure and 100 Å of film thickness) were applied to all the NiFe layers in this experiment. Tantalum (Ta) layers were later deposited on the NiFe layers for protection. The crystallographic structures of the NiO/NiFe layers were analyzed by using an X-ray diffractometer (XRD). The cross-sections of NiO/NiFe films were observed by using HVHRTEM with an acceleration voltage of 1,250 kV. A vibrating sample magnetometer (VSM) was used to measure the hysteresis loops of the bilayer films to 100 Oe.

3. Results and Discussion

Changes in H_{EX}, coercive force (H_C) and grain size of NiO/NiFe bilayer films are shown in Fig. 1 with respect to Ar sputtering pressure in the NiO layers only. As the pressure increases, H_{EX} decreases and vanishes above 2.5 mTorr. In the case of H_C, it reaches maximum value at the vanishing pressure of H_{EX} and then decreases. The changes of grain sizes estimated from FWHM (Full Width Half Maximum) of NiO (200) peaks in the XRD patterns are inversely proportional to those of the H_{EX}.

Our experimental results of the H_{EX} and grain size coincide with the previous researches [7-9]; H_{EX} is inversely proportional to the grain size, based on the Malozemoff's random field model [10], in which H_{EX} arises from an energy difference ($\Delta\sigma$) per unit area of ferromagnetic - antiferromagnetic interface between two principal time-reversal ferromagnetic directions, and is expressed as the following;

$$H_{EX} = \Delta\sigma / 2M_F t_F \qquad (1)$$

where M_F and t_F are the magnetization and thickness of the ferromagnet, respectively.

By using random statistics, the average random-field energy per area is found to be $\Delta\sigma \propto f_i J/aL$. Therefore,

$$H_{EX} \propto f_i J/(2M_F t_F aL) \qquad (2)$$

where f_i: Parameter related to the randomness of spin orientations with the value of order unity
J: Atomic interfacial exchange
a: Atomic spacing
L: Characteristic domain size

C. H. Lai *et al.* [7] suggested that the domain size of the NiO layer is approximately equal to the grain size in a polycrystalline structure, because the antiferromagnetic domains exchange-coupled across grain boundaries are severely disrupted and domain walls are easily formed at the grain boundaries. However, the extinction of H_{EX} above 2.5 mTorr cannot be explained by a change of the domain size derived from the Malozemoff's random field model. Furthermore, magnetic training effect [11] cannot apply to the extinction of H_{EX}, since the HC shows the maximum at the extinction of the H_{EX} in Fig. 1. To figure out the origin in the extinction of H_{EX}, structural configurations of the NiO/NiFe films are investigated by XRD and HVHRTEM, and compared to the magnetic properties of the films in Fig. 1.

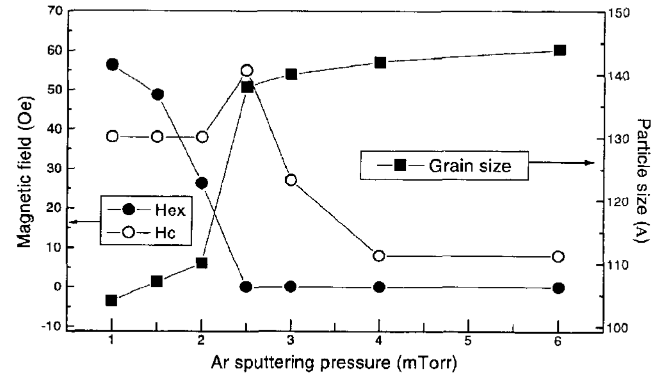

Fig. 1. Changes in exchange anisotropy field (H_{EX}), coercive force (H_C) and grain size of the NiO/NiFe bilayer films with respect to Ar sputtering pressure in NiO layers only.

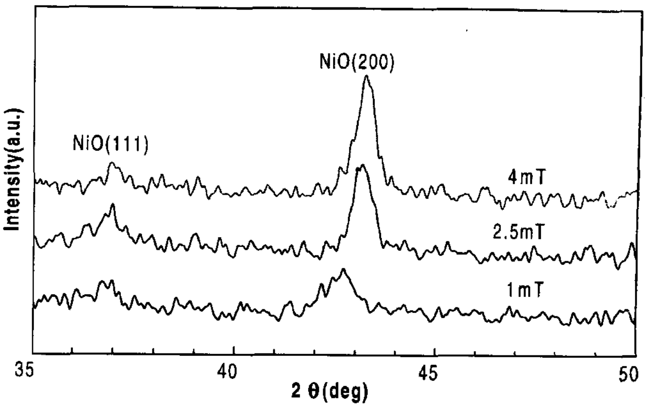

Fig. 2. Changes in X-ray diffraction curves of NiO/NiFe bilayer films in terms of Ar sputtering pressure in NiO layers only.

Fig. 2 shows the changes in X-ray diffraction curves of NiO/NiFe bilayer films in terms of Ar sputtering pressure in the NiO layers only. The curve of the film at 1 mTorr with H_{EX} a few tens of Oe shows no preferential crystalline growth orientation in the NiO layer. But as the increase of the Ar pressure, the crystalline orientations of NiO (200) are preferred at 2.5 and 4 mTorr which reveals the zero H_{EX} in the NiO/NiFe films in Fig. 1. From these facts, it can be estimated that the preferential orientations might strongly affect the extinction of the H_{EX}. To understand the relationship between the extinction of H_{EX} and the preferential orientations, the cross-sectional views of the NiO/NiFe bilayers are observed by HVHRTEM.

Fig. 3 shows the cross-sectional views of NiO/NiFe bilayer films deposited at 1 (A), 2.5 (B) and 4 (C) mTorr of the NiO layers only. The NiO/NiFe film at 1 mTorr with H_{EX} a few tens of Oe shows the same microstructural configuration as one that was reported by C. H. Lai *et al.* [7], with randomly oriented columnar structures (RCS) in the NiO layer and clear NiO/NiFe interface. However, both NiO layers deposited at 2.5 (B) and 4 mTorr (C) with zero H_{EX} values show (200) oriented columnar structures (OCS) and rougher interfaces than that at 1 mTorr. The maximum in H_C at 2.5 mTorr may be explained by the result of D. G. Hwang *et al.* [8]; the large interfacial roughness with a large slope induced many magnetic poles at NiO/NiFe interface and created a large local demagnetizing field that enhanced H_C [12]. The minimum H_C with zero H_{EX} at 4 mTorr results from the disappearance of exchange coupling between NiO and NiFe layers, due to no appreciable interface between the two layers shown in Fig. 3 (C).

To explain the extinction of the H_{EX} above 2.5 mTorr, we regard the columnars as magnetic domains, like those in polycrystalline structures [7] and show the schematic diagram in Fig. 4. As shown in Fig. 4, the magnetic domains of NiO layer in RCS (A) are displayed in the film plane, but the magnetic domains of NiO layer in OCS (B) are arranged perpendicular to the interface of the NiO/NiFe film. The related magnetic exchange energy (E_{EX}) in RCS

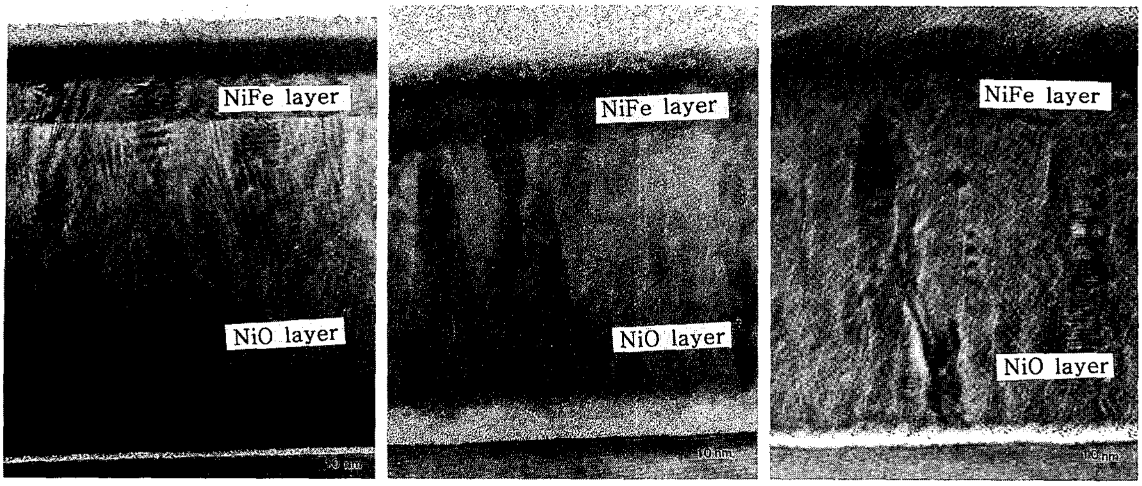

Fig. 3. (A), (B), and (C): Cross-sectional views of Si/NiO/NiFe/Ta films deposited at 1, 2.5 and 4 mTorr, respectively by high-voltage high-resolution transmission electron microscopy (HVHRTEM).

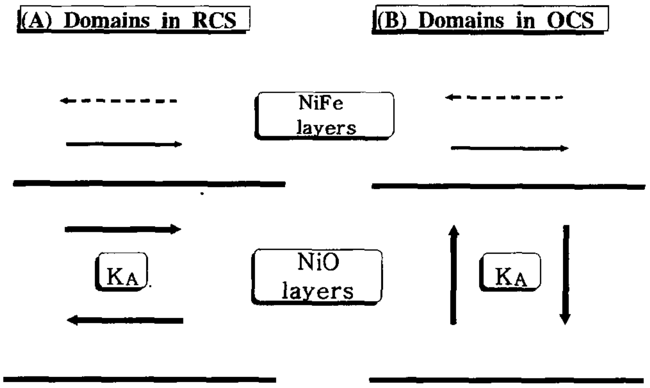

Fig. 4. (A) and (B): Schematic diagrams of magnetic domain structures in NiO/NiFe layers with randomly oriented columnar structures (RCS) and oriented columnar structures (OCS), respectively.

and OCS between the NiO and NiFe layers can be described as below,

$$E_{EX} \propto J_{NiO}J_{NiFe} \cos\theta \qquad (3)$$

J_{NiO}, J_{NiFe}: Magnetic momentum of NiO and NiFe, respectively

$\cos\theta$: Angle in magnetic momentum between NiO and NiFe.

The random distribution of magnetic domains in NiO layer reserves E_{EX} with finite value of $\cos\theta$ in RCS, but the perpendicular distribution of magnetic domains in NiO layer makes the zero value of $\cos\theta$ and vanishes E_{EX} between the NiO/NiFe layers in OCS.

The energy difference ($\Delta\sigma$) in Eq. 1 corresponds to $f_i(A_AK_A)^{1/2}$ in the chain model [13], where A_A and K_A are the exchange stiffness and uniaxial in-plane anisotropy per unit volume in the antiferromagnetic layer, respectively. So, H_{EX} can be expressed as follows,

$$H_{EX} = E_{EX}/2M_{NiFe}\,t_{NiFe} \propto f_i\,(K_A)^{1/2} / M_{NiFe}\,t_{NiFe} \propto K_S/ M_{NiFe}\,t_{NiFe} \qquad (4)$$

M_{NiFe} and t_{NiFe}: Magnetization and thickness of the ferromagnetic NiFe layer, respectively

f_i: Parameter related to the randomness of spin orientations

K_A: Uniaxial in-plane anisotropy in the antiferromagnetic layer

K_S: Interfacial unidirectional pinning anisotropy

The values of M_F t_F in our NiO/NiFe films should be constant because the same deposition conditions were applied to all the NiFe layers. Valuable H_{EX} in Eq. 4 is only available when antiferromagnetic and ferromagnetic layers are exchange-coupled, and the randomness of spin orientations is permitted at the interface.

As shown in Fig. 4 (A), since the preferred magnetic anisotropy of NiO layer in RCS is allowed by the valuable E_{EX}, the uniaxial in-plane anisotropy term (K_A) of Malozemoff's one-dimensional chain model [13] permits a randomness along with the interfacial plane and so interfacial unidirectional pinning anisotropy (K_S) is available, which makes the H_{EX} remained in the random structures. However, when the preferred magnetic anisotropy in the OCS is aligned perpendicular to the interface with zero value of E_{EX} as shown in Fig. 4 (B), the uniaxial in-plane anisotropy term (K_A) can provide little randomness in the NiO layer which results in no contribution of K_S to the interface and then zero value of the H_{EX} in the NiO/NiFe layers.

4. Conclusions

A series of the NiO/NiFe bilayer films were deposited on Si (100) substrates with the change of Ar sputtering pressure in the NiO layers only. Above 2.5 mTorr of the Ar pressure, exchange anisotropy field (H_{EX}) of the bilayer films was vanished with the oriented columnar structures of the NiO layers perpendicular to NiO/NiFe interfaces. The extinction of the H_{EX} in the films attributed to the formation of preferred magnetic anisotropy perpendicular to the interface which results in the lack of the exchange anisotropy energy between NiO and NiFe layers and so the loss of the interfacial unidirectional pinning anisotropy at the interfaces of NiO/NiFe layers. To obtain the valuable H_{EX} in SV-GMR head, the preferred crystalline orientation of antiferromagnetic NiO layer should be randomly oriented columnar structure.

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