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# Exchange Bias Coupling Depending on Uniaxial Deposition Field of Antiferromagnetic FeMn Layer

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**The relationship between ferromagnet anisotropic magnetization and the antiferromagnet atomic spin configuration was investigated for various angles of the uniaxial deposition magnetic field of the FeMn layer in the Corning glass/Ta(5nm)/NiFe(7nm)/FeMn(25nm)/Ta(5nm) multilayer that was prepared by the ion beam sputter deposition. The exchange bias field ($H_{ex}$) obtained from the measurement of the easy-axis MR loop decreased to 40 Oe at the deposition field angle of 45°, and to 0 Oe at the angle of 90°. When the difference between the uniaxial axis between the ferromagnet NiFe and the antiferromagnet FeMn was 90°, the strong antiferromagnetic dipole moment of FeMn caused the weak ferromagnetic dipole moment of NiFe to rotate in the interface.**

**Keywords :** exchange bias coupling, NiFe/FeMn bilayer, uniaxial deposition field, deposition field angle

## 1. Introduction

Studies are being conducted on the microscopic origin of the exchange bias coupling field ($H_{ex}$) in several models, such as the existence of an interfacial uncompensated spin, the dilution of the intrusion of the antiferromagnetic (AFM) layer into the ferromagnetic (FM) layer, and the orange coupling field [1, 2]. In case of NiFe/FeMn bilayer structure, possible mechanism is required for the change of exchange bias, based on following two points: (1) AFM atomic spin could be independent from deposition field condition when the magnetic energy is considered. (2) The interfacial atoms of NiFe could be influenced by the initial deposition of FeMn via re-deposition of NiFe or inter-diffusion of them [3].

In this study, the exchange coupling depending on the uniaxial depostion field of the FeMn layer in a NiFe/FeMn/NiFe trilayer film was measured. NiFe/FeMn multilayers with Ta seed and capping layers were prepared through ion beam sputter deposition. The $H_{ex}$ of the multilayer with the crystalline (1 1 1) texture dominantly increased as the thickness of FeMn increased [4, 5]. The value of $H_{ex}$ was due to the uniaxial components of the magnetic anisotropy energy. To make sense of the exchange biasing mechanism, an NiFe/FeMn bilayer was prepared under several unidirectional magnetization axes of the external field during the deposition for only the antiferromagnetic FeMn film. Different degrees of angular dependence and symmetry were observed for the exchange field's top and bottom $H_{ex}$.

The inspection of the experiment data showed clear evidence of the above observation. The bottom $H_{ex}$ at the unidirectional angle of 90° during the growth of the FeMn film almost disappeared. The effect of the uniaxial deposition field of the FeMn layer in the NiFe/FeMn bilayer was shown. The switching of the uniaxial anisotropy in the plan of the multilayer to a direction perpendicular to the direction of the growth field was clearly observed at a peculiar angle point, which could be attributed to the angle dependence of the antiferromagnetic layer. Further study is needed to develop a full model of the exchange bias coupling effect in the new observation.

## 2. Experiment Method

The FM-AFM bilayer sample that was used in this research was made with a multilayer of Ta(5 nm)/NiFe (7 nm)/FeMn(25 nm)/Ta(5 nm) on a glass substrate (Corning #7059) using the IBD (ion beam deposition) sputtering system at normal temperature [6, 7]. An ultra-high vacuum chamber was set up with a target ion gun,

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for etching a substrate, and six 3-inch targets were mounted in the main IBD system chamber. The base pressure of the main vacuum chamber was maintained at $5\times10^{-9}$ Torr. The ion gun was a Kauffmann source, which was as large as a 3-cm graphite grid. The distance between the target and the substrate holder was about 100 mm. The partial pressure of the argon gas for the creation of an ion beam was $3\times10^{-4}$ Torr. The acceleration voltage that determined the deposition rate, the discharge voltage of the anode, the voltage, and the electric current of the ion beam were 100 V, 35 V, 800 V, and 6.0 mA, respectively. Under these conditions, the deposition rate of the targets, Ta, $Ni_{80}Fe_{20}$, and $Fe_{50}Mn_{50}$, were 0.02 nm/s, 0.032 nm/s, and 0.023 nm/s, respectively. The intensity of the magnetic field that was used to induce the uniaxial anisotropy was 350 Oe.

Fig. 1(a) shows a schematic of a typical ion source, target, and substrate configuration inside the IBD system for the fabrication of the Corning glass (7059)/Ta/NiFe/FeMn/Ta multilayer structure. Especially, Fig. 1(a) shows a schematic of a typical ion source, target, and substrate configuration that are suitable for rotating the transport rod with a unidirectional deposition magnetic field application to the NiFe/FeMn bilayer. Fig. 1(b) shows a schematic of the sample with 4-probe electrodes that were prepared using a shadow mask during the deposition of the multilayer. Here, the arrows point to the easy and hard axis, respectively. The schematic configuration of the conventional type with a Ta(buffer)/NiFe/FeMn/Ta(cover) multilayer is shown in Fig. 1(c). Fig. 1(d) shows three different anisotropy deposition field angles of the unidirectional field between FeMn and NiFe.

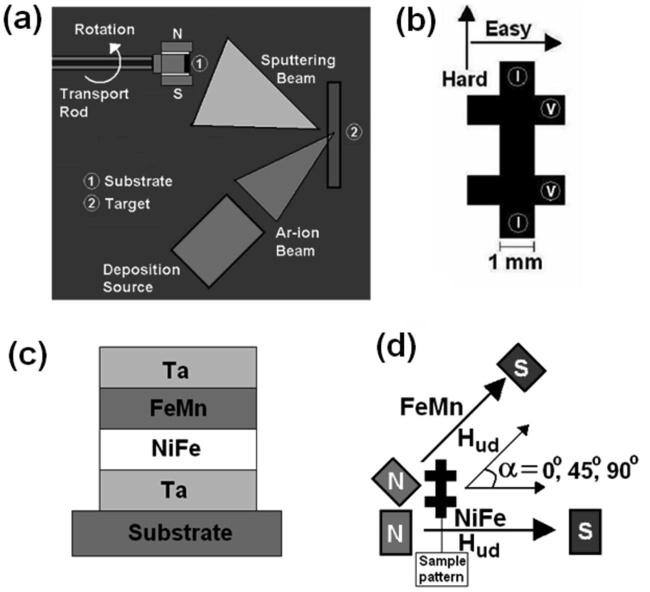

**Fig. 1.** (a) Schematic of a typical ion beam source, and the substrate configuration suitable for the rotating transport rod with uniaxial deposition magnetic field application to the NiFe/FeMn bilayer. (b) Schematic of the sample with 4-probe electrodes that was prepared using a shadow mask during the deposition of the NiFe/FeMn bilayer. (c) Schematic configurations of the conventional-type NiFe/FeMn bilayer and (d) the three different anisotropy deposition field angles of the uniaxial applied field between the NiFe layer and the FeMn layer.

The relationship of the ferromagnet anisotropic magnetization and the antiferromagnet atomic spin configuration was investigated for various angles of the uniaxial deposition magnetic field of the FeMn layer in the Corning glass/Ta(5nm)/NiFe(7nm)/FeMn(25nm)/Ta(5nm) multilayer that was prepared by the IBD sputtering system. The three uniaxial deposition field angles of the FeMn layer were 0°, 45°, and 90°, respectively. The $H_{ex}$ of all the samples was determined from the anisotropic magnetoresistance (AMR) curves of the easy axis and the hard axis.

## 3. Results and Discussion

In the case of the FM/AFM bilayer system, the magnetization direction of the NiFe layer can be induced towards the direction of the spin magnetization of the FeMn layer by the exchange coupling field that is created between the FM layer and the AFM layer [8, 9]. The current flow through the 1 mm width of the sample in the schematic in Fig. 2(b) represents the AMR effect. Fig. 2 shows two AMR curves and MH loops, and the definitions of the exchange bias coupling field and the coercivity from the (b) easy and (c) hard MR loops for the as-deposited glass/Ta(50 Å)/NiFe(7nm)/FeMn(25nm)/Ta(5nm) multilayer. The AMR measurement, which resulted in ±200 Oe, was performed using a four-probe method at room temperature. The measured values of $H_{ex}$ and $H_c$ according to the easy and hard axes were noted in the

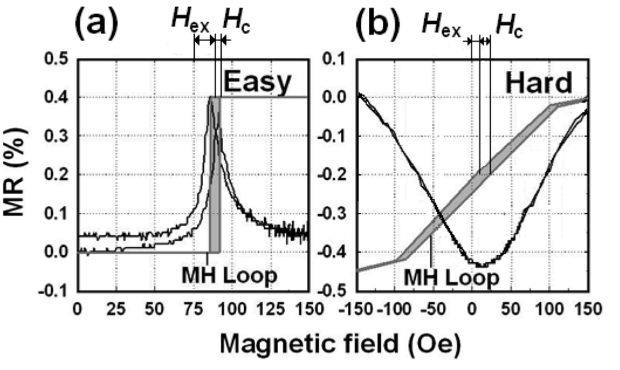

**Fig. 2.** MH loops and definitions of exchange bias coupling field ($H_{ex}$) and coercivity ($H_c$) from the (a) easy and (b) hard AMR curves of NiFe/FeMn bilayer.

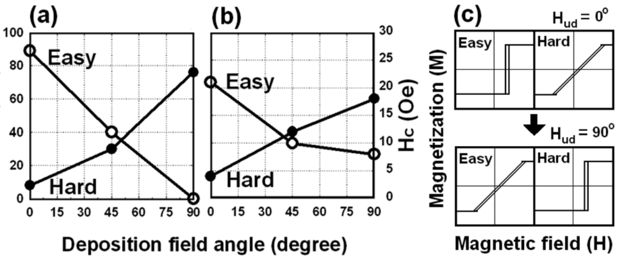

**Fig. 3.** (a) Exchange bias coupling fields ($H_{ex}$) and coercivities ($H_c$) of the easy and hard axes of the NiFe/FeMn bilayer as functions of the anisotropy deposition field between the FeMn layer and the NiFe layer. (c) Change in the easy and hard AMR curves depending on the two deposition field angles. Here, the easy and hard AMR curves completely switched at the two angles of 0° and 90°, respectively.

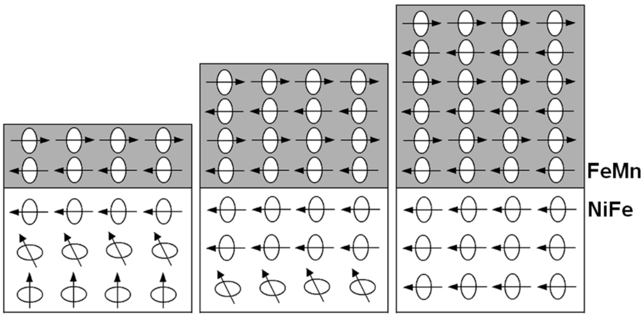

**Fig. 4.** Ferromagnetic and antiferromagnetic interfacial transitions in the NiFe/FeMn bilayer due to the increase in the FeMn thickness. The arrows represent the magnetic dipole moments.

AMR curves, respectively. These results, i.e., $H_{ex} = 89$ Oe and $H_c = 4$ Oe for the easy axis and $H_{ex} = 8$ Oe and $H_c = 12$ Oe for the hard axis, corresponded to the magnetic properties that were characterized using a vibrating sample magnetometer (VSM). The IBD difference from the magnetron DC sputter deposition and the crystal growth of the thin films were affected by the inclined angle of the deposited atomic ion from the difference between the incident angle of the ion beam and the surface plane of the target.

Fig. 3(a) shows the exchange bias coupling fields $H_{ex}$ for the easy and hard axes of the NiFe/FeMn bilayer as functions of the anisotropy deposition field angles of the unidirectional field between FeMn and NiFe. The $H_{ex}$ that was obtained from the measurement of the easy-axis MR loop decreased to 40 Oe at the deposition field angle of 45°, and abruptly decreased to 0 Oe at the angle of 90°. One the other hand, the $H_{ex}$ that was obtained from the measurement of the hard-axis MR loop increased to 35 Oe at the deposition field angle of 45°, and to 79 Oe at the angle of 90°. It was completely conversed to each other for the easy axis and the hard axis of the AMR curves, as shown in Fig. 3(c). Fig. 3(b) shows the coercivities of $H_c$ for the easy and hard axes of the NiFe/FeMn bilayer as functions of the anisotropy deposition field angles of the unidirectional field between FeMn and NiFe. The $H_c$ that was obtained from the measurement of the easy-axis MR loop decreased to 10 Oe at the deposition field angle of 45°, and to 8 Oe at the angle of 90°. One the other hand, the $H_c$ that was obtained from the measurement of the hard-axis MR loop increased to 4 Oe at the deposition field angle of 0°, to 12 Oe at the deposition field angle of 45°, and to 18 Oe at the angle of 90°. As in the case of the exchange bias coupling fields $H_{ex}$, it is completely conversed to each other for the easy axis and the hard axis of the AMR curve, as shown in Fig. 3(c). From this effect of the uniaxial deposition field of the FeMn layer in the NiFe/FeMn bilayer, the switching of the uniaxial anisotropy in the plan of the multilayer to a direction perpendicular to the direction of the growth field was clearly observed at a peculiar angle point, which could be attributed to the angle dependence of the antiferromagnetic layer [9, 10].

The magnetization of FM strongly depended on the magnitude of the applied magnetic field. From the hysteresis curve of the MH loop, the coercivity of the soft NiFe film for the easy axis magnetization had only a few Oe. Fig. 4 shows the ferromagnetic and antiferromagnetic interfacial transition in the NiFe/FeMn bilayer due to the increase in the FeMn thickness. The arrows represent the magnetic dipole moments. In the less than 8nm-thick FeMn film for the NiFe/FeMn bilayer, as in the first schematic transition shown in Fig. 5, the just interfacial FM layer between the NiFe layer and the FeMn layer had the same configuration of the magnetic dipole moment of AFM, which was performed by the applied magnetic field. In the more than 8nm-thick FeMn film for the NiFe/FeMn bilayer, as in the third schematic transition shown in Fig. 4, the almost interfacial FM layer between the NiFe layer and the FeMn layer had the same configuration of the magnetic dipole moment of AFM, which was performed by the applied magnetic field. Although the difference in the uniaxial axis between the ferromagnet NiFe and the antiferromagnet FeMn was 90°, the strong antiferromagnetic dipole moment of FeMn caused the weak ferromagnetic dipole moment of NiFe to rotate in the interface. This result implies that one of the origins of the exchange coupling mechanism depends on the effect of the magnetic field angle during the deposition of the antiferromgnet FeMn layer.

## 4. Conclusion

The relationship of ferromagnet anisotropic magnetization and the antiferromagnet atomic spin configuration was investigated for various angles of the unidirectional deposition magnetic field of the FeMn layer in the Corning glass/Ta(5nm)/NiFe(7nm)/FeMn(25nm)/Ta(5nm) multilayer that was prepared by IBD sputtering ststem. The three unidirectional deposition field angles of the FeMn layer were 0°, 45°, and 90°, respectively. The exchange bias field ($H_{ex}$) that was obtained from the measurement of the easy-axis MR loop decreased to 40 Oe at the deposition field angle of 45°, and to 0 Oe at the angle of 90°. One the other hand, the $H_{ex}$ that was obtained from the measurement of the hard-axis MR loop increased to 35 Oe at the deposition field angle of 45°, and to 79 Oe at the angle of 90°. The ferromagnetic and antiferromagnetic interfacial transition models in the NiFe/FeMn bilayer due to the increase in the thickness during the deposition of the antiferromgnet FeMn layer suggest that one of the origins of the exchange coupling mechanism depends on the effect of the applied magnetic field.

## Acknowledgment

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