

## Annealing Temperature Dependence of Exchange Bias Effect in Short Time Annealed NiFe/NiMn Bilayer Thin Film by FMR Measurement

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The NiMn/NiFe bilayer structure which was short time annealed in order to induce unidirectional anisotropy were studied as a function of annealing temperature. The maximum exchange bias field of NiMn/NiFe bilayer was presented at 250 °C after short time annealing process with no external field. The appearance of exchange bias was due to phase transformation of NiMn layer. In plane angular dependence of a resonance field distribution which measured by FMR was analysed as a combined effect of unidirectional anisotropy and uniaxial anisotropy. The resonance field and the line width from FMR measurement were also analysed with annealing temperature.

**Key words :** exchange bias, NiMn, unidirectional anisotropy, uniaxial anisotropy, FMR

### 1. Introduction

The exchange bias phenomena have been extensively studied due to their potential applications in spin valve structure and the physical interest to magnetic coupling mechanism in multilayer structure. The revealed results indicate that the exchange coupling between ferromagnet (FM) and antiferromagnet (AFM) comes from their spin configuration at the interface [1]. The exchange coupling strength which is caused by interfacial spin configuration of FM/AFM, depends on the thickness of FM and AFM and/or their domain structure [1, 2]. Especially, the AFM domain structure plays an important role to determine the characteristic properties such as the formation of unidirectional anisotropy and the enhancement of coercivity [3, 4]. The unidirectional anisotropy can be induced by post annealing process after deposition [5]. The annealing conditions such as temperature and process time are important to determine the exchange bias properties and also an interfacial structure [5]. In particular, an intermetallic alloys for AFM layer need to a long time annealing process [6]. Recently, Groudeva-Zotova *et al.* reported the exchange bias effect of NiMn based bilayer after short time anneal-

ing process [7]. The formation of exchange bias effect was explained by a fast phase transformation of NiMn alloy. Ferromagnetic resonance (FMR) measurement represents a powerful tool for studying the magnetic anisotropy [8]. The latter can be determined by the intrinsic property of the FM layer and/or an exchange coupling in the case of an exchange biased thin film [9].

In this study, we demonstrate the formation of exchange bias effect for NiFe/NiMn bilayer structure after short annealing process. The unidirectional exchange anisotropy and an uniaxial anisotropy, induced by short post annealing process were studied by FMR measurements.

### 2. Experimentals

The NiMn(50 nm)/NiFe(10 nm) thin films were fabricated by magnetron sputtering on Si(100) wafer with a seed layer of Ta(5 nm) at room temperature. Ta(5 nm) was deposited on the top of all samples, to prevent oxidation. The base pressure of the chamber was below  $5 \times 10^{-8}$  torr and the Ar working pressure was 2 mtorr. During the deposition, a magnetic field of 200 Oe was applied to form the uniaxial anisotropy in the NiFe layer. The post annealing for deposited thin films was performed with no applying external field at vacuum atmosphere during 20 minute. The annealing temperature was varied

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from 250 °C to 400 °C. The temperature increased by 1° per minute. The cooling was processed by natural cooling after annealing. The hysteresis loop were obtained by vibrating sample magnetometer (VSM). The FMR measurements were performed at 9.4 GHz (X band) with a JEOL JES-TE300 ESR Spectrometer. The angular dependence of the resonance field was measured by rotating the sample to an in plane direction with respect to the applied magnetic field.

### 3. Results and Discussions

Fig. 1 shows the XRD pattern for NiMn/NiFe bilayer structure with annealing temperature. The as-deposited thin film exhibits only NiFe (111) peak because NiMn is an amorphous phase at as-deposited state [10]. With annealing temperature increase, NiMn (111) and (200) peaks were appeared and the NiFe (111) peak merged into NiMn peak. All of annealed thin films showed no change in their peak position with the increase of temperature. It indicates that the phase transformation of NiMn was occurred at 250 °C annealing temperature. The reported results for NiMn phase transformation takes place from amorphous phase at ad-deposited state to fcc phase after annealing process and then fct phase for further annealing process [7, 10]. In our case, we did not confirm the fct phase even though annealing was processed to enough temperature for the phase transformation from fcc to fct phase. It may come from not optimized texture structure

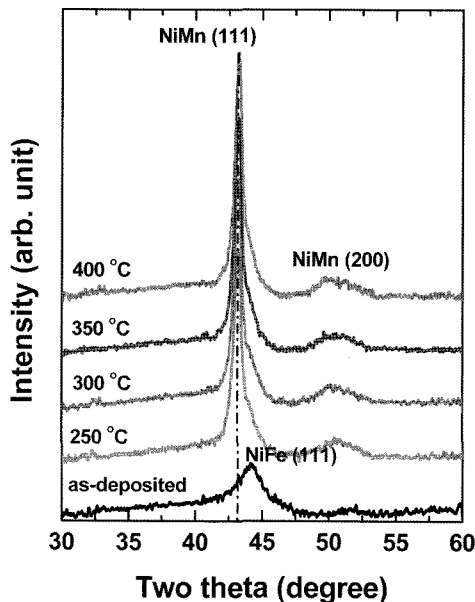


Fig. 1. XRD pattern of NiMn/NiFe thin films as a function of annealing temperature. The dash line indicates NiMn (111) 2θ position.

depending on deposition condition.

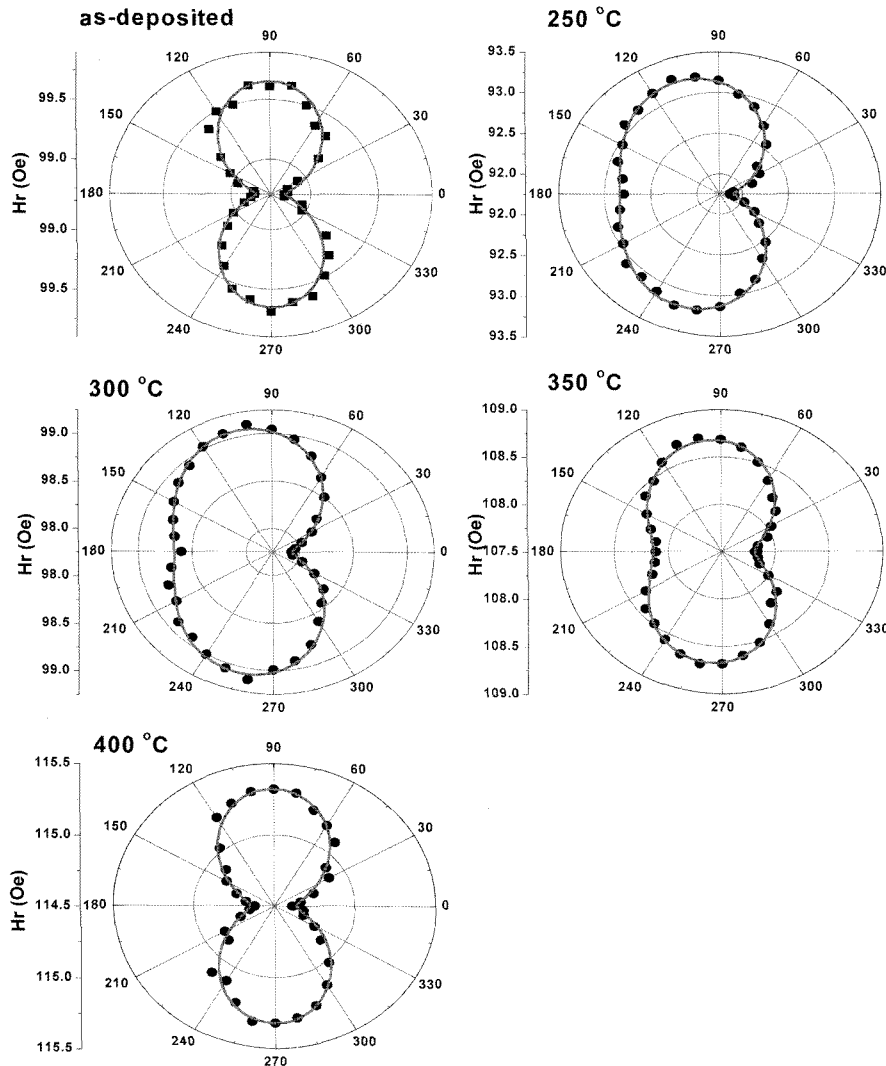
In plane angular dependence of the resonance field ( $H_r$ ) for the exchange biased thin films was determined by FMR measurements. In Fig. 2, the as-deposited thin film shows unbiased shape of  $H_r$ . It could be corresponded to uniaxial shape of NiFe layer. With the annealing temperature increase, however, the angular variation in  $H_r$  shows a manifest unidirectional behavior for the NiMn/NiFe thin film except to 400 °C annealed thin film, as shown in Fig. 2. The  $H_r$  curve shape for 400 °C annealed thin film is similar to that of as-deposited thin film indicating the small exchange anisotropy induced after annealing. The resonance field distribution with angular measurement implies combined effect of the unidirectional anisotropy and the uniaxial anisotropy [11]. The unidirectional anisotropy field ( $H_{ex}$ ) and the uniaxial anisotropy field ( $H_k$ ) can be extracted by the phenomenological expression [11] of cosine series neglecting high order term as follows,

$$H_r(\varphi_H) = H_{r0} - H_{ex}\cos\varphi_H - H_k\cos2\varphi_H \quad (1)$$

where  $\varphi_H$  indicates the azimuthal angle between the applied field direction and the easy axis of FM layer.  $H_{r0}$  is an average resonance field indicating angular independent term. The second term represents the exchange coupling between FM and AFM layer and the third term describes the uniaxial anisotropy of the FM layer as expressed by  $H_k = 2K_u/M_F$ . The Angular variation of  $H_r$  for NiMn/NiFe bilayer thin films were well fitted by eq. (1) as can be seen by solid lines in Fig. 2.

Fig. 3(a) shows the hysteresis loop for 250 °C annealed thin film indicating the loop shift due to exchange bias effect. The variation of  $H_{ex}$  and  $H_k$ , which were extracted from eq. (1) are shown in Fig. 3(b) with annealing temperature. The  $H_{ex}$  values exhibit a decrease with the annealing temperature increase. The maximum value on  $H_{ex}$  was obtained at annealing temperature of 250 °C. It means that the 250 °C is optimum annealing temperature for our NiMn/NiFe thin film. This results comes from the phase transformation of NiMn that is shown by XRD result. The further annealing can lead to interfacial diffusion between NiMn and NiFe layers and it causes  $H_{ex}$  reduction [12].

The  $H_k$  values for NiMn/NiFe thin films indicate a small variation with annealing temperature. The uniaxial anisotropy of exchange biased FM layer would be induced by the exchange interaction with AFM layer. Consequently, the direction of the uniaxial anisotropy is parallel to the unidirectional anisotropy [13]. The small change of the induced uniaxial anisotropy on NiFe layer could be explained by interfacial structural change with increase of annealing temperature.

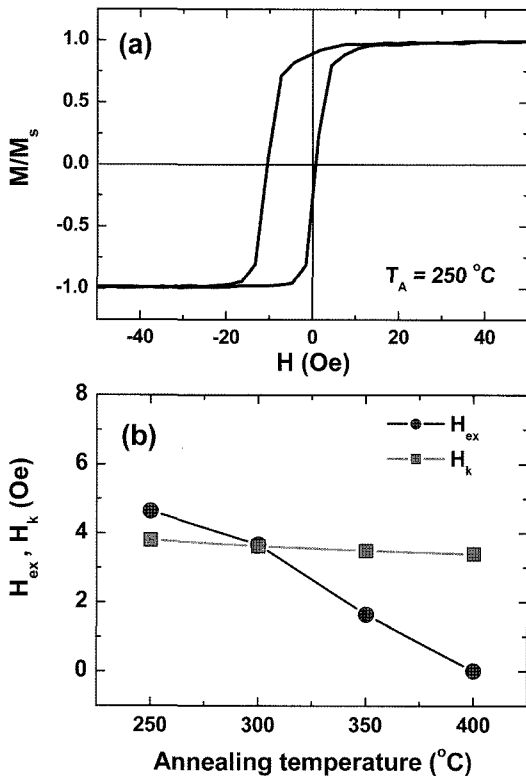


**Fig. 2.** Angular dependence of the  $H_r$  for NiMn/NiFe thin films as a function of annealing temperature. The solid lines indicate data fitted to eq. (1).

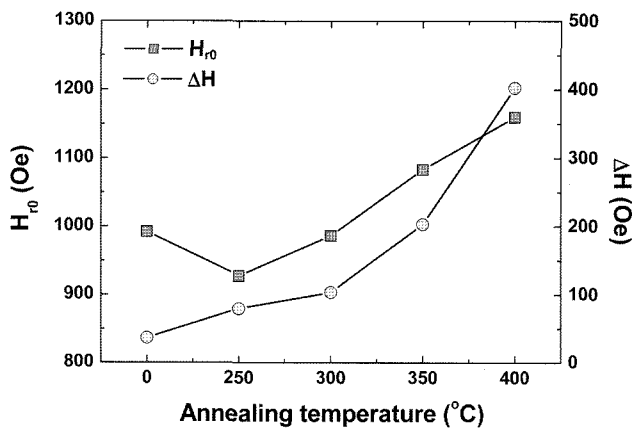
In plane resonance field of exchange biased FM thin film exhibits a resonance field shift from unbiased single FM thin film. According to McMichael *et al.*, the shift of resonance field in FMR measurement was due to a rotatable anisotropy which comes from irreversible AFM domain behavior [14]. The size distribution of AFM domain near the interface with FM layer produces a pinning field affecting magnetization reversal of FM layer. The temperature and AFM thickness dependence of  $H_r$  were explained by the rotatable anisotropy [9, 14]. These results indicate that temperature and AFM thickness affect to the AFM domain behavior corresponding to  $H_{ex}$  variation. Fig. 4 shows the variation of  $H_{r0}$  and line width ( $\Delta H$ ) with annealing temperature, respectively. The  $H_{r0}$  value decreased at 250 °C annealed thin film and then increased for further annealed one. Commonly, the exchange biased

FM/AFM bilayer with the uniform layer thickness exhibits the negative resonance field shift with compared to an unbiased FM single layer [14, 15]. The  $H_{r0}$  decrease at 250 °C annealed sample can be explained well as above reason. On the other hand, the increase of  $H_{r0}$  for further annealed sample might be caused by another effect. The positive  $H_{r0}$  shift was considered to come from the interfacial diffusion which gives rise to change of spin configuration of AFM layer [16].

In addition to the resonance field distribution in FMR measurement, a line broadening gives useful information to study of exchange coupling in FM/AFM thin films. The line broadening in FMR measurement comes from intrinsic properties such as anisotropy, structural defects, measuring frequency and inhomogeneous coupling in case of multilayer [5]. The exchange biased thin film



**Fig. 3.** (a) Hysteresis loop of 250 °C annealed NiMn/NiFe thin film. (b) Variation of  $H_k$  for NiMn/NiFe thin films as a function of annealing temperature.



**Fig. 4.** Variation of resonance field  $H_{r0}$  and line width  $\Delta H$  for NiMn/NiFe thin films as a function of annealing temperature.

exhibits larger line broadening than that of unbiased single layer thin film [9]. Speriosu *et al.* reported that the line broadening of exchange biased film is caused from a local pinning of FM layer due to an inhomogeneous surface anisotropy based on Malozemoff's model [17]. So, the amount of line broadening varies in proportion to exchange bias strength in FM/AFM thin film. In our case, the mean peak-to-peak line width increased with anneal-

ing temperature increase, as shown in Fig. 4. The broad line width is the result of intrinsic structural change in thin film such as the interfacial structure.

#### 4. Conclusion

The exchange bias effect of NiMn/NiFe thin films was studied by FMR analysis. The unidirectional anisotropy was induced by short annealing time with no applied external field. The maximum exchange bias value was reached at 250 °C annealed NiMn/NiFe thin films. The angular dependence of resonance field from FMR measurement was described by the combined effect as unidirectional anisotropy and uniaxial anisotropy. The resonance field shift and the line width can be explained by interfacial diffusion with annealing temperature.

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