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Exchange couplings between two Fe layers in Fe/Al/Fe/Ni-Fe/NiO sandwiches

R. NAKATANI, K. HOSHINO, H. HOSHIYA, Y. SUGITA*
Central Research Laboratory, Hitachi, Ltd., Kokubunji, Tokyo 185-8601, Japan
E-mail: nakatani@crl.hitachi.co.jp

Exchange couplings between two Fe layers have been investigated in polycrystalline Fe/Al/Fe/Ni-Fe/NiO and Fe/Al/Fe/Ni-Fe sandwiches. Linear exchange couplings between the two Fe layers were strong and ferromagnetic when the thickness of the Al spacer was between 0.7 and 2.2 nm. We observed biquadratic exchange couplings (90 degree couplings) when the thickness of the Al spacer was between 2.5 and 4.0 nm.

1. Introduction

The first exchange couplings between two Fe layers were found in Fe/Cr/Fe sandwiches by Grünberg *et al.* [1]. They used light scattering technique to observe the exchange couplings. After their report, the exchange couplings between magnetic layers have been observed in many sandwiches [2–8]. The oscillations of the linear exchange couplings, the biquadratic exchange couplings (the 90 degree couplings), magnetoresistance effects have been also reported. The most typical way to observe the exchange couplings is using the kerr effect technique for the samples with wedge-shaped nonmagnetic spacers [3, 4, 6]. However, the kerr effect technique requires the single-crystalline samples, because the magnetic domain structures of the polycrystalline samples are complicated, and the complicated magnetic domain structures cause difficulties in the observations of the exchange couplings.

We observed the exchange couplings between two Fe layers in polycrystalline Fe/Al/Fe/Ni-Fe/NiO/Si(100) sandwiches. The NiO layers are antiferromagnetic. Therefore, the Ni-Fe layer is exchange-biased by the NiO layer, and thus the Fe layer neighboring the Ni-Fe layer is also exchange-biased with the Ni-Fe layers in each sandwich. Due to the above layered structure, one of the Fe layers is biased by only exchange coupling through the Al spacer. Therefore, we could easily observe the exchange couplings by using a vibrating sample magnetometer (VSM), even though the sandwiches were polycrystalline.

2. Experimental

We prepared rf-sputtered NiO layers on Si(100) substrates. The thicknesses of the NiO layers were 50 nm. The sandwiches were prepared on the NiO layers using an ion beam sputtering apparatus. The acceleration voltage of the ion gun was 300 V with an ion current of 30 mA when the Ni-Fe layers and the Al layers were deposited. The ion current was changed to 60 mA when the Fe layers were deposited. The deposition rates were 0.02–0.03 nm/s. A magnetic field of 32 kA/m was applied to the samples during the sputtering. Argon pressure during the sputtering was 0.02 pa.

The samples were 7 mm square. The sandwiches were grown with layer structures of Fe(4.0 nm)/Al(0.7–4.0 nm)/Fe(1.6 nm)/Ni-20at%Fe(3.0 nm)/NiO(50 nm)/Si. In this study, the Fe layers, which are neighboring only the Al spacers, are called as the Fe single layers. The Fe/Ni-Fe layers, which are neighboring the NiO layers, are called as the Fe/Ni-Fe dual layers. The sandwiches with layer structures of Fe(4.0 nm)/Al(1.0–3.5 nm)/Fe(1.6 nm)/Ni-20at%Fe(3.0 nm)/Si were also prepared in order to investigate the biquadratic exchange couplings. The thicknesses were measured with a quartz oscillating thickness monitor located adjacent to the substrate holder.

The magnetization curves were measured at room temperature. A vibrating sample magnetometer was used to measure the magnetization curves with a maximum magnetic field of 20 kA/m.

3. Experimental results and discussion

Fig. 1 shows the magnetization curves of the polycrystalline Fe/Al/Ni-Fe/NiO/Si sandwiches with the various Al spacer thicknesses. The each magnetization curve of Fig. 1 includes the magnetizations of the two magnetic layers, one of them is the Fe single layer and another is the Fe/Ni-Fe dual layer. In the sandwiches, the Fe/Ni-Fe dual layers are directly exchange-biased by the NiO antiferromagnetic layers, the Fe single layers are exchange-biased by only exchange couplings through the Al spacers. Fig. 1a shows the magnetization curves which are observed when the applied field direction is parallel to the direction of the exchange bias field caused by the NiO antiferromagnetic layer. Fig. 1b shows the magnetization curves which are observed

* *Present address*: Research Institute of Electrical Communication, Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan.

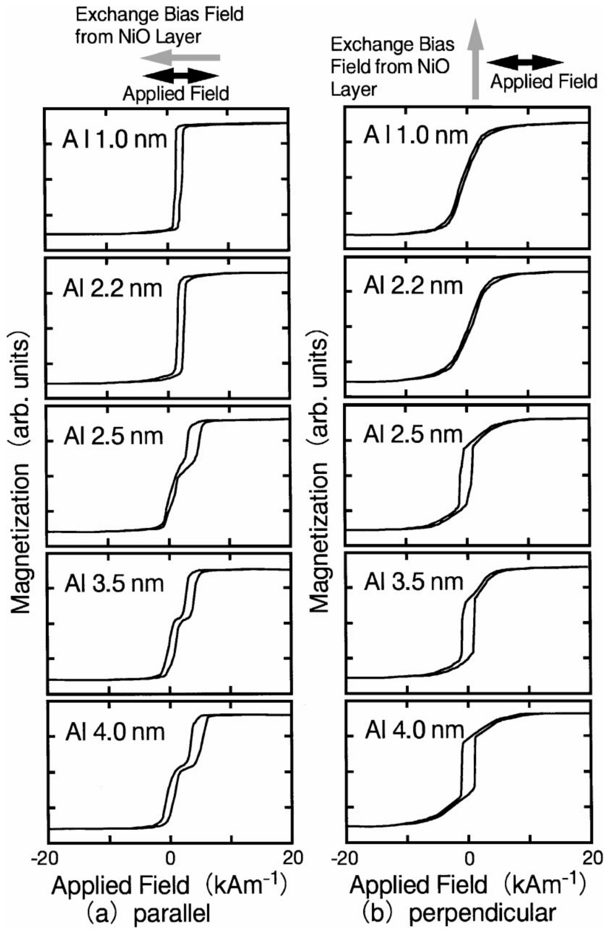

Figure 1 Magnetization curves of polycrystalline Fe(4.0 nm)/Al(t nm)/Fe(1.6 nm)/Ni-Fe(3.0 nm)/NiO(50 nm)/Si sandwiches.

when the applied field direction is perpendicular (in plane) to the direction of the exchange bias field caused by the NiO antiferromagnetic layer.

When the thickness of the Al spacer is 1.0 and 2.2 nm, the magnetizations of the Fe single layer and the Fe/Ni-Fe dual layer turn at the same applied field as shown in Fig. 1a. The magnetization curves are shifted by the exchange bias fields from the NiO layers. It is understood that the linear exchange coupling between the two Fe layers is ferromagnetic and strong, and thus the magnetizations of the two magnetic layers turn at about the same applied field. Fig. 1b shows that the saturation field is high when the thickness of the Al spacer is 1.0 and 2.2 nm. This is because the Fe/Ni-Fe dual layers are exchange-biased by the NiO layers, and thus the magnetizations of the Fe/Ni-Fe dual layers are not easily rotated to the applied field direction by the low applied fields. The Fe single layers are strongly exchange-biased through the Al spacers, because the linear exchange couplings between the two Fe layers are ferromagnetic and strong. Thus, the direction of the magnetizations of the Fe single layers are about the same as those of the Fe/Ni-Fe dual layers.

When the thickness of the Al spacer is 2.5, 3.5 and 4.0 nm, the magnetizations of the Fe single layer and the Fe/Ni-Fe dual layer turn at the different applied fields as shown in Fig. 1a. The magnetization curves of the Fe/Ni-Fe dual layers shift to the higher applied field positions than those for the Fe single layers. Moreover, the magnetization of the Fe single layer turns at around zero field. These show that linear exchange couplings between the Fe single layer and the Fe/Ni-Fe dual layer are not so strong.

When the thickness of the Al spacer is 2.5, 3.5 and 4.0 nm, the each magnetization curve is thought to consist of the magnetization curve for the magnetic layer which is easily saturated and that for the magnetic layer which is not easily saturated, as shown in Fig. 1b. The magnetic layer, which is not easily saturated, is thought to be the Fe/Ni-Fe dual layer. This is because the Fe/Ni-Fe dual layer is strongly exchange-biased by the NiO layer, and the direction of the exchange bias field is perpendicular to the applied field direction. The magnetic layer, which is easily saturated, is thought to be the Fe single layer. This is because the effect of the NiO layer is weak when the thickness of the Al spacer is 2.5, 3.5 and 4.0 nm.

Next, we investigated the exchange bias fields applied to the Fe single layers. The exchange bias fields are caused by the exchange couplings between the two Fe layers through the Al spacers. The exchange bias fields are obtained by the magnetization curves which are observed when the applied field direction is parallel to the direction of the exchange bias field caused by the NiO antiferromagnetic layer. When the exchange coupling between the two Fe layers is strong, the magnetizations of the two magnetic layers turn at about the same applied field as shown in Fig. 2a. In this case, the exchange bias field Hb for the Fe single layer is obtained as shown in Fig. 2a. When the exchange coupling

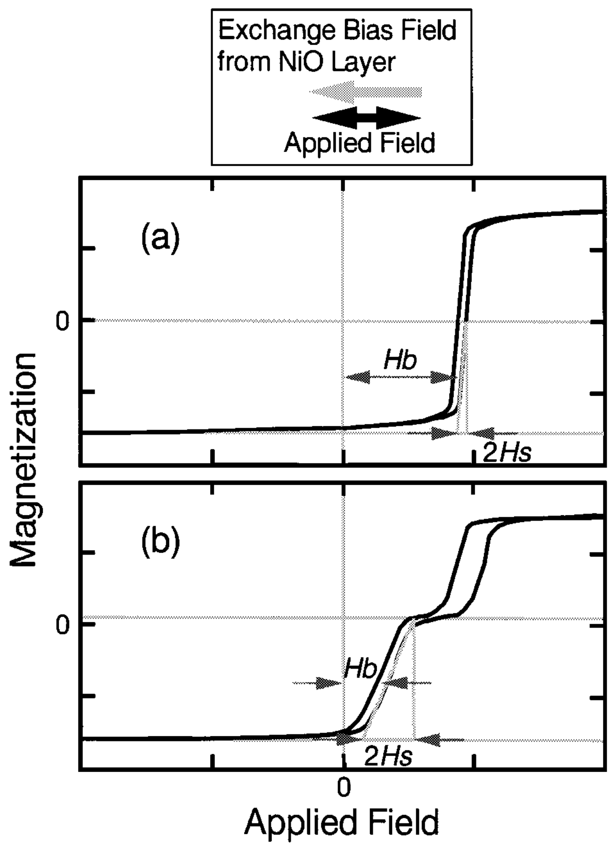

Figure 2 Schematic diagrams to obtain exchange bias fields Hb and effective saturation fields Hs for the Fe single layers.

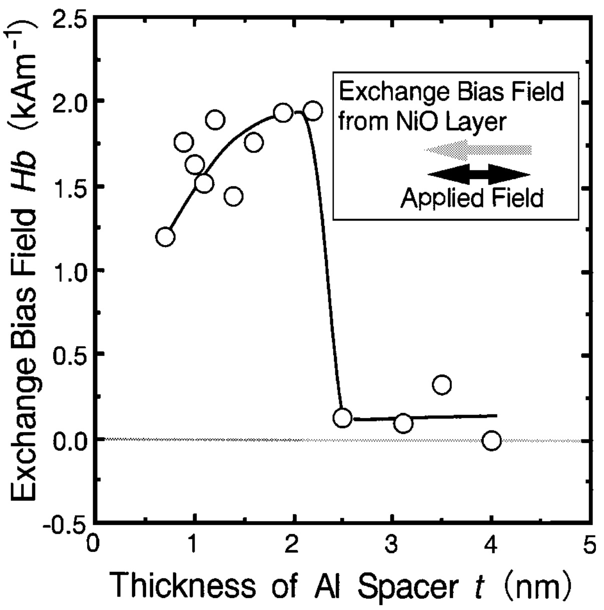

Figure 3 Relationship between thickness of Al spacer and exchange bias field Hb applied to the Fe single layer in Fe(4.0 nm)/Al(t nm)/Fe(1.6 nm)/Ni-Fe(3.0 nm)/NiO(50 nm)/Si sandwiches.

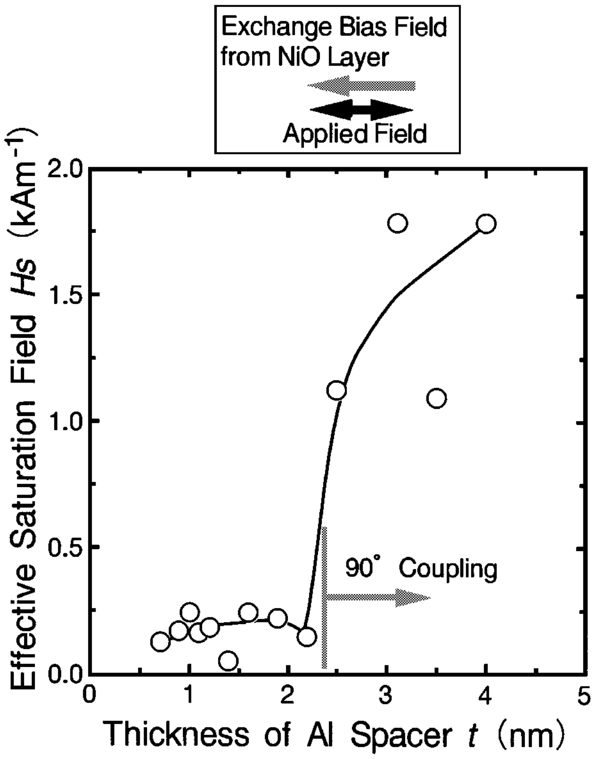

Figure 4 Relationship between thickness of Al spacer and effective saturation field Hs of the Fe single layer in Fe(4.0 nm)/Al(t nm)/Fe(1.6 nm)/Ni-Fe(3.0 nm)/NiO(50 nm)/Si sandwiches.

between the two Fe layers is not strong, the magnetizations of the two magnetic layers turn at the different applied fields as shown in Fig. 2b. In this case, the exchange bias field Hb for the Fe single layer is obtained as shown in Fig. 2b. Fig. 2 also shows the method to obtain the effective saturation field Hs of the Fe single layers. The effective saturation fields are discussed later.

Fig. 3 shows a relationship between the thickness of the Al spacer and the exchange bias field Hb applied to the Fe single layer. The exchange bias field increases as the thickness of the Al spacer increases up to 2.2 nm. The positive high exchange bias fields indicate that the linear exchange couplings are ferromagnetic and strong. The exchange bias field abruptly decreases between 2.2 and 2.5 nm. The exchange bias field are low and positive at the Al spacer thicknesses between 2.5 and 4.0 nm. The low exchange bias fields indicate that the linear exchange couplings between the two Fe layers are weak. And the positive exchange bias fields indicate that the linear exchange couplings are ferromagnetic.

Fig. 4 shows a relationship between the thickness of the Al spacer and the effective saturation field Hs of the Fe single layer. The effective saturation field is relatively low when the thickness of the Al spacer is between 0.7 and 2.2 nm. The low effective saturation fields indicate that the linear exchange couplings are dominant. The effective saturation field is high when the thickness of the Al spacer is between 2.5 and 4.0 nm. The high effective saturation fields indicate that the Fe single layers are exchange-biased through the Al spacers, and the direction of exchange bias fields is perpendicular to the applied field direction. Thus, the exchange coupling between the two Fe layers is the biquadratic exchange coupling when the thickness of the Al spacer is between 2.5 and 4.0 nm.

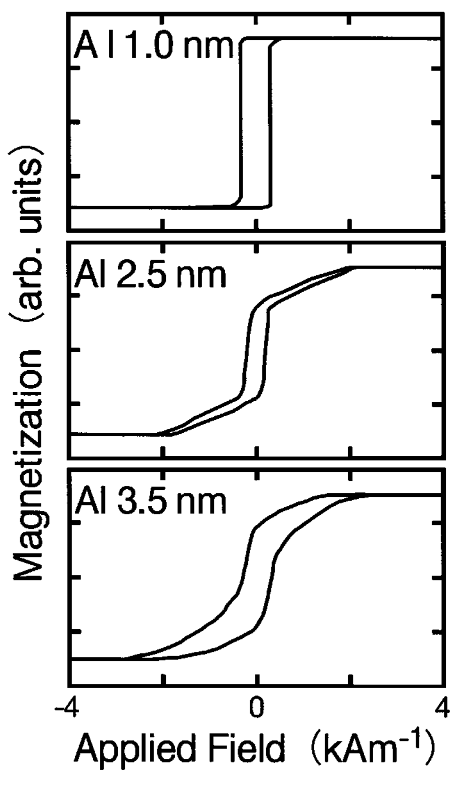

Figure 5 Magnetization curves of polycrystalline Fe(4.0 nm)/Al(t nm)/Fe(1.6 nm)/Ni-Fe(3.0 nm)/Si sandwiches.

In order to observe the biquadratic exchange couplings more easily, the Fe/Al/Fe/Ni-20at%Fe/Si sandwiches were also prepared. Fig. 5 shows the magnetization curves of the Fe/Al/Fe/Ni-20at%Fe/Si sandwiches.

When the thickness of the Al spacer is 1.0 nm, the magnetizations of the Fe single layer and the Fe/Ni-Fe dual layer turn at the same applied field. This is because the exchange coupling between the two Fe layers is ferromagnetic and strong. When the thickness of the Al spacer is 2.5 and 3.5 nm, one of the magnetic layer magnetically saturates at relatively low fields, another magnetic layer magnetically saturates at relatively high fields. These indicate that the exchange couplings between the two Fe layers are biquadratic.

As mentioned above, we could easily investigate the exchange couplings between the two Fe layers in the polycrystalline Fe/Al/Fe/Ni-Fe/NiO sandwiches and the Fe/Al/Fe/Ni-Fe sandwiches by means of VSM measurements. We observed both the linear exchange couplings and the biquadratic exchange couplings (the 90 degree couplings).

4. Conclusions

We investigated exchange couplings between two Fe layers in polycrystalline Fe/Al/Fe/Ni-Fe/NiO/Si(100) sandwiches and the Fe/Al/Fe/Ni-Fe/Si(100) sandwiches. The following results were obtained.

(1) The linear exchange coupling between Fe layers is ferromagnetic and strong when the thickness of the Al spacer is between 0.7 and 2.2 nm.

(2) The linear exchange coupling between Fe layers is weak and the biquadratic exchange couplings between Fe layers are caused when the thickness of the Al spacer is between 2.5 and 4.0 nm.

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