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Interlayer couplings and magnetoresistance effects of Fe/Cr/Fe/Ni–Fe/NiO sandwiches

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Interlayer coupling between Fe layers and magnetoresistance effect have been investigated in Fe/Cr/Fe/Ni–Fe/NiO sandwiches. The interlayer coupling between two Fe layers oscillates as the thickness of Cr layer changes. The strongest antiferromagnetic coupling is observed when the thickness of the Cr layer is 1.2 nm. The highest magnetoresistance ratio due to spin-dependent scattering is only 0.13%. The low magnetoresistance ratio is thought to be caused by high resistivity of the Cr layer.

1. Introduction

The first interlayer couplings between two Fe layers were found in Fe/Cr/Fe sandwiches by Grunberg *et al.* [1]. They used light scattering technique to observe the interlayer couplings. After their report, the interlayer couplings between magnetic layers have been observed in many sandwiches [2–8]. The oscillations of the interlayer couplings, 90° couplings (biquadratic couplings), magnetoresistance effects have been also reported. The most typical way to observe the interlayer couplings is using the Kerr effect technique for the samples with wedge-shaped non-magnetic spacers [3, 4, 6].

We observed the interlayer couplings between two Fe layers in Fe/Cr/Fe/Ni–Fe/NiO/Si (1 0 0) sandwiches. The NiO layers are antiferromagnetic. Therefore, the Ni–Fe layers are exchange-biased, and thus the Fe layers neighbouring Ni–Fe layers are also exchange-biased indirectly. Due to the above layered structure, one of the Fe layers is biased by only interlayer coupling through the Cr layer. Therefore, we could easily observe the interlayer couplings by using a vibrating sample magnetometer (VSM).

2. Experimental procedures

We prepared r.f.-sputtered NiO layers on Si (1 0 0) substrates. The thicknesses of 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 were deposited. The ion current was changed to 60 mA when the Fe and Cr layers were deposited. The deposition rates were 0.02–0.03 nm s^{-1}. Argon pressure during sputtering was 0.02 Pa.

The samples were 7 mm square. The sandwiches were grown with a layer structure of [Fe (4.0 nm)/Cr (0.6–4.0 nm)/Fe(1.6 nm)/Ni–20 at %Fe (3.0 nm)/NiO (50 nm)/Si]. The thicknesses were measured with a quartz oscillating thickness monitor located adjacent to the substrate holder. The Ni–Fe layers are exchange-biased by NiO layers because of the antiferromagnetic properties of the NiO layers. Therefore, the Fe layers neighbouring the Ni–Fe layers are also exchange-biased indirectly.

The magnetization curves and the magnetoresistance ratios of the sandwiches were measured at room temperature. A vibrating sample magnetometer was used to measure the magnetization curves with a maximum magnetic field of 80 kA m^{-1}. The magnetoresistance ratios were measured using the four-terminal method. The magnetic field was applied parallel or normal to the current. The magnetoresistance ratio was defined as the ratio of the total resistivity change to the resistivity at a magnetic field of 80 kA m^{-1}.

3. Experimental results

3.1. Interlayer couplings between two Fe layers

Fig. 1 shows the magnetization curves of Fe/Cr/Fe/Ni–Fe/NiO/Si sandwiches. Fig. 1 indicates that the magnetizations of the two magnetic layers, one of them is the Fe layers (upper magnetic layers) and another is the Fe/Ni–Fe double layers neighbouring the NiO layer (lower magnetic layers), turn at the same applied field, when the thickness of the Cr spacer is 0.8 nm. It also indicates that the magnetization curve is shifted by the exchange bias of the NiO layer. It is understood that the interlayer coupling between two

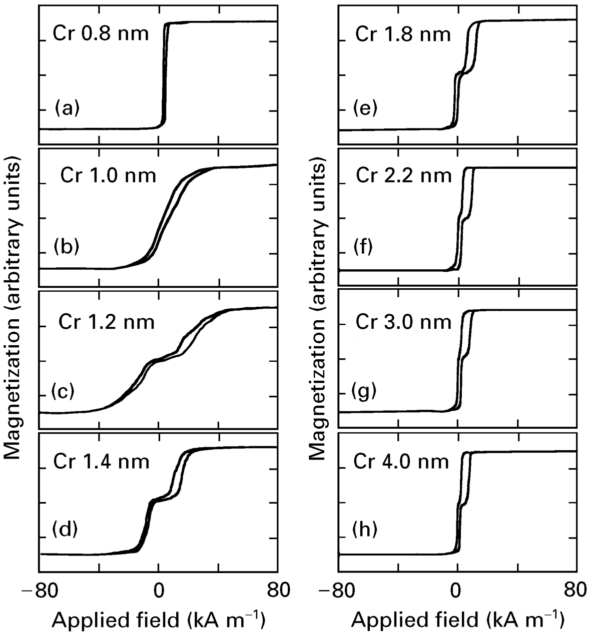

Figure 1 Magnetization curves of [Fe (4.0 nm)/Cr (t nm)/Fe (1.6 nm)/Ni–Fe (3.0 nm)/NiO (50 nm)/Si] sandwiches. $t =$ (a) 0.8 nm, (b) 1.0 nm, (c) 1.2 nm, (d) 1.4 nm, (e) 1.8 nm, (f) 2.2 nm, (g) 3.0 nm, (h) 4.0 nm.

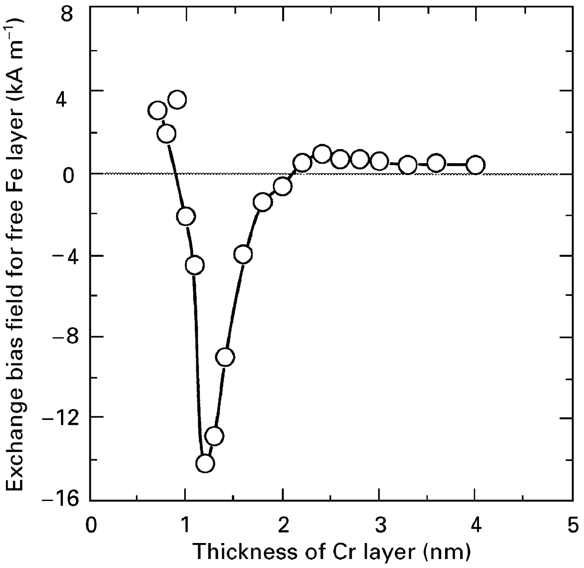

Figure 2 Relationship between thickness of Cr spacer and exchange bias field applied to upper magnetic layer in [Fe (4.0 nm)/Cr (t nm)/Fe (1.6 nm)/Ni–Fe (3.0 nm)/NiO (50 nm)/Si] sandwiches.

Fe layers are ferromagnetic and strong, and thus the magnetizations of the two magnetic layers turn at about the same applied field.

The saturation field becomes high when the thickness of the Cr spacer is 1.0 nm. This is due to antiferromagnetic interlayer coupling between two magnetic layers. When the thickness of the Cr spacer is 1.2 nm, the saturation field becomes higher, and the magnetizations of two magnetic layers turn at the opposite applied field directions. The magnetization curve of the lower magnetic layer, the Fe/Ni–Fe double layer, shifts to a positive magnetic field direction. That of the upper magnetic layer, the Fe single layer, shifts to a negative magnetic field direction. This is because the upper magnetic layer is exchange-biased by the interlayer coupling between two magnetic layers and the interlayer coupling is antiferromagnetic.

When the thickness of the Cr spacer is 1.4 nm, the shift of the magnetization curve of the upper magnetic layer is smaller than that for the sandwich with 1.2 nm thick Cr layer. This is because the antiferromagnetic interlayer coupling is weaker than that of the sandwich with 1.2 nm thick Cr layer. When the thickness of the Cr spacer is 1.8 nm, the antiferromagnetic interlayer coupling becomes much weaker. When the thickness of the Cr spacer is above 2.2 nm, the magnetization curves of the upper magnetic layers shift to a positive magnetic field direction. This is because the interlayer couplings between two magnetic layers are ferromagnetic.

Figure 2 shows the relationship between the thickness of the Cr spacer and the exchange bias field applied to the magnetic layer made of the Fe single layer through the Cr spacer. When the thickness of the Cr spacer is below 0.9 nm, the interlayer coupling is ferromagnetic. The interlayer coupling is antiferromagnetic, when the thickness of the Cr spacer is between 1.0 and 2.0 nm. The strongest antiferromagnetic coupling is observed at 1.2 nm.

The interlayer coupling is ferromagnetic, when the thickness of the Cr spacer is above 2.2 nm. The local maximum of ferromagnetic interlayer coupling is observed when the thickness of the Cr spacer is 2.4 nm. The ferromagnetic interlayer coupling becomes weaker as the thickness of the Cr spacer increases above 2.4 nm.

As mentioned above, we could easily detect whether the interlayer coupling was ferromagnetic or antiferromagnetic, and the interlayer coupling was strong or weak by means of VSM measurements. This is because the sandwiches are deposited on antiferromagnetic NiO layers.

3.2. Magnetoresistance effects

Figure 3 shows the relationship between the thickness of the Cr spacer and the electric resistivity of the sandwich. The resistivity does not include NiO layers because the resistivity of the NiO layer is very high. The resistivity is between 60 and $70 \times 10^{-8}\,\Omega$m.

Fig. 4 shows the magnetoresistance curves of the sandwich with 1.2-nm-thick Cr spacer. The observed magnetoresistance effects include both magnetoresistance effects due to spin-dependent scatterings and anisotropic magnetoresistance effects. The spin-dependent scatterings are thought to occur at the interfaces between the magnetic layers and the Cr spacers. When the applied field H is parallel to the current I, the observed magnetoresistance ratio is $MR_S - MR_A$, where the MR_S is magnetoresistance ratio due to spin-dependent scattering, and the MR_A is magnetoresistance ratio due to anisotropic magnetoresistance effect. When the applied field H is normal to the current I, the observed magnetoresistance ratio is $MR_S + MR_A$. Therefore, the average of the two magnetoresistance curves indicates the magnetoresistance

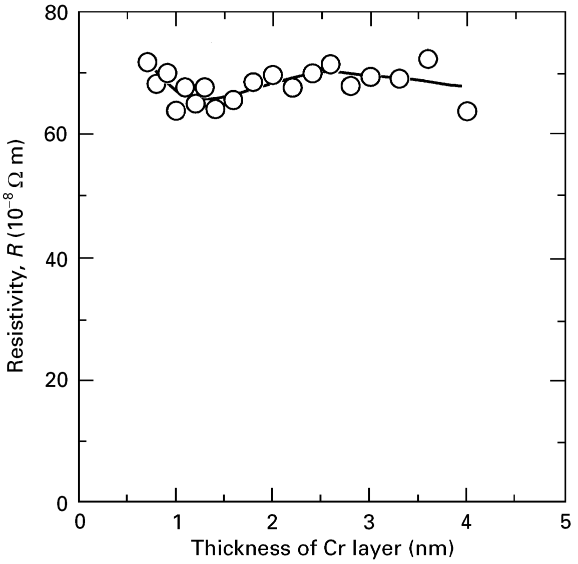

Figure 3 Relationship between thickness of Cr spacer and electric resistivity of the sandwich in [Fe (4.0 nm)/Cr (t nm)/Fe (1.6 nm)/Ni–Fe (3.0 nm)/NiO (50 nm)/Si] sandwiches.

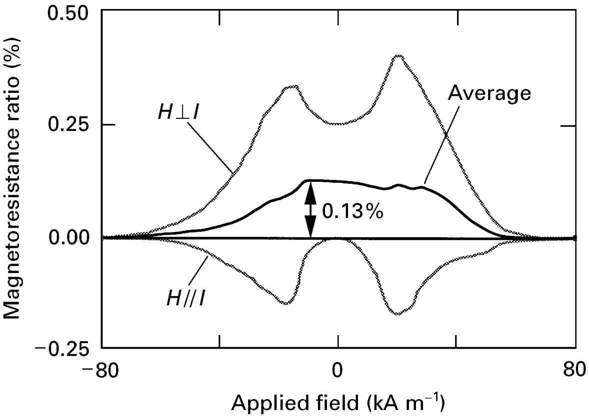

Figure 4 Magnetoresistance effects of [Fe (4.0 nm)/Cr (1.2 nm)/Fe (1.6 nm)/Ni–Fe (3.0 nm)/NiO (50 nm)/Si] sandwich.

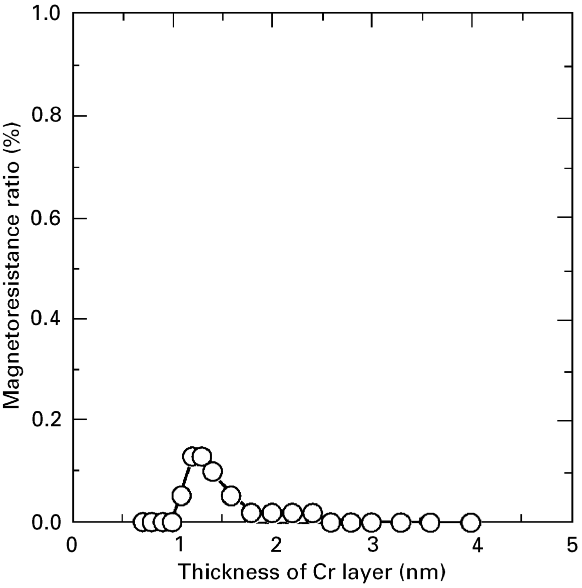

Figure 5 Relationship between thickness of Cr spacer and magnetoresistance ratio MR_S in [Fe (4.0 nm)/Cr (t nm)/Fe (1.6 nm)/Ni–Fe (3.0 nm)/NiO (50 nm)/Si] sandwiches.

curve due to the spin-dependent scattering. The magnetoresistance ratio MR_S is only 0.13%.

Figure 5 shows the relationship between the thickness of the Cr spacer and the magnetoresistance ratio MR_S of the sandwich. The highest magnetoresistance ratios of 0.13% are observed when the thickness of the Cr spacer is 1.2 or 1.3 nm. The reason for the highest magnetoresistance ratios is thought to be as follows. When the thickness of the Cr spacer is 1.2 or 1.3 nm, the antiferromagnetic interlayer couplings are strong. Because of the strong antiferromagnetic interlayer couplings, the magnetizations of the two magnetic layers become antiparallel sufficiently when the applied magnetic field is about zero. Therefore, the magnetizations of the two magnetic layers change between parallel and antiparallel when the applied field is varied. Thus, the magnetoresistance effects cause the relatively high magnetoresistance ratios when the thickness of the Cr spacer is 1.2 or 1.3 nm. However, the magnetoresistance ratios of 0.13% are much lower than those of the Fe/Cr/Fe sandwiches reported by Binasch *et al.* [2] and the Fe/Cr multilayers reported by Baibich *et al.* [9].

4. Discussion

As mentioned above, the magnetoresistance ratios in this study are much lower than those of the Fe/Cr/Fe sandwiches and the Fe/Cr multilayers reported formerly. The reason for the low magnetoresistance ratios in this study is thought to be as follows.

As shown in Fig. 3, the resistivities of the sandwiches are very high. Therefore, it is thought that the resistivities of the Cr spacers are also high in the sandwiches. It is thought that the Cr spacers which have high resistivities obstruct the conduction electrons to travel between the two magnetic layers with keeping their polarizations. Therefore, the obstruction may decrease the magnetoresistance ratio due to the spin-dependent scattering.

5. Conclusions

We investigated interlayer couplings between two Fe layers and magnetoresistance effects in Fe/Cr/Fe /Ni–Fe/NiO/Si (1 0 0) sandwiches. The following results were obtained.

1. As the thickness of the Cr layer changes, the interlayer coupling between two Fe layers oscillates between ferromagnetic and antiferromagnetic.

2. The strongest antiferromagnetic interlayer coupling is observed when the thickness of the Cr layer is 1.2 nm.

3. The electric resistivity of the sandwich is between 60 and 70×10^{-8} Ω m.

4. The highest magnetoresistance ratios (0.13%) due to the spin-dependent scatterings are observed when the thickness of the Cr layer is 1.2 or 1.3 nm.

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