Antiferromagnetic Coupling in NiFe/Co/Cu/Co Sandwiches

Toshio TANUMA, Seichirou TAKAHASHI, Minoru KUME, and Kazuhiko KUROKI

New Materials Research Center, SANYO Electric Co., Ltd., 1-1 Dainichi-higashimachi, Moriguchi, Osaka 570, Japan

Maximum $\Delta\rho/\rho$ change exceeding 4% for a magnetic field increase of 4 Oe is obtained at room temperature in NiFe/Co/Cu/Co sandwiches when two ferromagnetic components, NiFe/Co and Co, with different coercivities are magnetically coupled across a nonmagnetic Cu spacer. It is shown that the MR ratio oscillates as a function of Cu layer thickness and that the magnetic moment decreases under magnetically coupled states. This suggests the presence of antiferromagnetic coupling between the two ferromagnetic components. The measuring field direction which causes high sensitivity for a large MR change rotates perpendicularly to the intrinsic anisotropy axis at about 2.8 nm. This rotating spin-axis direction and very high sensitivity are thought to be due to the phenomenon known as spin flopping associated with antiferromagnetic coupling.

I. INTRODUCTION

The increase in resistance in the so-called giant magnetoresistance (GMR) effect [1]–[3] is due to the antiparallel alignment of magnetizations between ferromagnetic layers. This characteristic has been reported for such structures as Cu/Co/Cu/NiFe multilayers [4], Co/Cu/Co sandwiches [5], NiFe/Cu/NiFe/FeMn spin-valve structures [6], and antiferromagnetically coupled Co/Cu multilayers [7]. In antiferromagnetically coupled multilayers, unfortunately, high magnetic sensitivity has not been achieved. In contrast, a sharp rise in magnetoresistance (MR) has been observed in the spin-valves and multilayers where ferromagnetic layers possess different coercivities. Since the adjacent ferromagnetic layers in the latter materials are magnetically isolated from each other, the existence of antiferromagnetic (AF) coupling is expected to affect the steep MR change.

In this paper, we report new magnetic and MR properties for NiFe/Co/Cu/Co sandwiches having AF coupling. A spin flop transition model is proposed for explaining the high sensitivity in the magnetically coupled sandwich materials.

II. EXPERIMENTAL

Sandwich films possess a basic structure as schematically shown in Fig. 1. To prepare this structure, an ion beam sputtering system with 6×10^{-5} Torr Ar atmosphere (base pressure: 2×10^{-7} Torr) is employed. The acceleration voltage of the ion beam is held constant at 300 V. The change of three targets (Ni80Fe20 in at%, Cu, and Co) is controlled by a computer system without breaking the vacuum. All the substrates are cooled by water and a magnetic field (H_a) of about 60 Oe is applied during the deposition. The MR is measured using a conventional four-probe

method at room temperature. The magnetic field is applied parallel and normal to the H_a in the film plane.

The magnetic properties are measured in both directions using a vibrating sample magnetometer. To avoid the influence of demagnetization, the MR and magnetic measurements are made on disc samples 8 mm in diameter.

Fig. 1. Structure of NiFe(6 nm)/Co(0.6 nm)/Cu(X nm)/Co (4 nm) sandwich layers.

III. RESULTS

The samples possess a layered structure, i.e. NiFe(6 nm)/Co(0.6 nm)/Cu(X nm)/Co(4 nm); the Cu layer thickness varies between 2 and 4 nm. The thinner Co layer is formed to enhance interfacial scattering [8], which increases the MR ratio. However, the magnetic moment of this Co layer is always parallel to that of the NiFe layer because of a strong exchange coupling. Therefore, the sandwich structure comprises of two ferromagnetic components (Co (4 nm) and Co(0.6 nm)/NiFe(6 nm)) with different coercivities.

Figure 2 shows the Cu thickness dependence of the MR ratio for NiFe(6 nm)/Co(0.6 nm)/Cu(X nm)/Co(4 nm) sandwiches. The filled circles are for the measuring field parallel to H_a and the open circles are for the field perpendicular to H_a . The MR ratio is found to oscillate as a function of the Cu layer thickness. When the Cu thickness is below 2 nm, the samples do not show magnetization curves associated with different

coercivities, resulting in a negligibly small MR change. This suggests that the NiFe/Co and Co components are ferromagnetically coupled with each other at this Cu thickness. At $X=2.3$ nm, a gradual decrease in the magnetic moment is observed as field decreasing from saturated states and in accordance with the magnetic moments gradual increase in resistivity is observed. More interestingly, a comparatively rapid magnetization transition in the magnetic moment takes place after the gradual decrease; a rapid decrease in resistivity can also be observed (Fig. 3(a), Fig. 3(b)).

Fig. 2. MR ratio versus Cu thickness for NiFe(6 nm)/Co(0.6 nm)/Cu(X nm)/Co(4 nm) sandwiches.

We can assume the existence of AF interlayer interactions by the fact that the magnetic moment decreases before magnetization transition and that there seems to be hardly any difference in coercivity. The difference in coercivity between the two ferromagnetic components can be gradually enhanced by increasing the Cu layer thickness. This is clearly seen in the rectangular hysteresis loop associated with different coercivities for $X=2.6$ nm (Fig. 3(c)). This sample showed a large MR ratio and high sensitivity (4.2% change for a field increase of 4 Oe). At $X=2.8$ nm, the MR ratio, under the condition the magnetic field is applied parallel to H_a , is smaller than that for the case the field is applied normal to H_a (see Fig. 2). Figure 4 shows the dependence of the MR ratio for this sample on the angle between the measuring field and H_a . The experimental result implies that the rotation of the spin-axis direction is responsible for the angle dependence of the MR ratio which will be discussed in the next section. As shown in Fig. 3(g), the magnetization curve of the same structure with X of 3 nm clearly indicates the presence of two magnetic components with different H_c values. In addition, the feature of the MR curve corresponds well with that of the magnetization curve. After reaching its peak in Fig. 2, the MR ratio starts to decrease. For the same

Fig. 3. Magnetic moments and MR ratio as a function of H for NiFe(6 nm)/Co(0.6 nm)/Cu(X nm)/Co(4 nm) sandwiches. The measuring field is parallel to H_a . (a)(b): $X=2.3$ nm; (c)(d): $X=2.6$ nm; (e)(f): $X=2.8$ nm; (g)(h): $X=3$ nm; (i)(j): $X=4$ nm.

Fig. 4. MR ratio versus the angle between the measuring field H and substrate field H_a for NiFe(6 nm)/Co(0.6 nm)/Cu(2.8 nm)/Co(4 nm) sandwiches.

structure with a 3.5 nm-thick Cu layer (Fig. 3(i)), the magnetization curve and MR changes are similar to those of the sandwiches with $X=2.3$ nm. This is probably due to the enhancement of antiferromagnetic coupling.

IV. DISCUSSION

We have examined magnetic coupling between adjacent ferromagnetic layers in sandwich structures, with a view of coupling them antiferromagnetically through nonmagnetic layers; like in magnetic multilayers. The possibility exists for magnetizations to be aligned in an antiparallel manner by both antiferromagnetic (AF) coupling and induced ferrimagnetism which is derived from the antiparallel alignment of magnetizations with different coercivities [4]. At this moment, however, we cannot predict the upper limit where AF coupling disappears. In addition, ferromagnetic coupling is certainly weakened for Cu layer thicknesses over 2.3 nm, and AF coupling seems to emerge.

The increase in the MR ratio for the sandwich layers with $X=2.3$ nm was due to AF coupling by the fact that the magnetic moment decreased before magnetization transition. A similar magnetization curve and similar MR changes were obtained for the sandwich films with $X=3.5$ nm. We assume that the AF coupling force was enhanced at these Cu thicknesses and that they corresponded with the 2nd and 3rd peak Cu thicknesses, respectively, for magnetoresistance in multilayer structures.

The new results for the magnetization curve and MR changes (Fig. 3a,3b,3i,3j) can be explained by the spin flop transition model[9]. The magnetizations of both the lower coercivity layer and the higher coercivity layer rotated simultaneously under AF coupling. Figure 5 shows the general idea of the model adopted to antiferromagnetically coupled sandwich films. In this model, the magnetizations of two ferromagnetic layers aligned in parallel to the saturation field gradually get into an antiparallel alignment (perpendicular to the external field in the film plane) as they rotate with decreasing field (fig. 5a $\rightarrow$ fig. 5b $\rightarrow$ fig. 5c). The gradual decrease in the magnetic moment and gradual increase in the resistivity correspond with these spin axis rotations. The magnetization energy of antiferromagnetically coupled sandwich films has been predicted to be smaller for an orientation perpendicular to the field H than for an orientation parallel to H as is the case with some antiferromagnetic materials.

The following equation (1) must hold to provide the spin flopping[10].

$$K \leq 1/2(\chi_{\perp} - \chi_{\parallel})H^2 \quad \text{--- (1)}$$

where K is the uniaxial magnetic anisotropy energy, $\chi_{\perp}$ is the perpendicular susceptibility, and $\chi_{\parallel}$ is the parallel susceptibility. The right side of the equation represents the magnetization energy. Sandwich layers seem to have a K small enough to satisfy equation (1) even with the application of a substrate field (60 Oe) during deposition. The field of spin flop transition H_s is determined by the following equation (2)[10].

$$H_s = \sqrt{2K/(\chi_{\perp} - \chi_{\parallel})} \quad \text{--- (2)}$$

The rapid decrease in resistivity corresponding to the magnetization transition is brought on by sudden changes in the orientation of both magnetizations occurring from antiparallel to parallel with spin flopping (Fig. 5c $\rightarrow$ Fig. 5d).

It seems that the AF coupling force at $X=2.6$ nm and $X=3$ nm is not so strong as that at $X=2.3$ nm and $X=3.5$ nm. This is probably because there exist some differences in coercivities between sandwich layers in the magnetization curve at $X=2.6$ nm and $X=3$ nm. In spite of the weaker AF coupling, larger MR changes are observed at $X=2.6$ nm and $X=3$ nm than at $X=2.3$ nm and $X=3.5$ nm. Namely, not so strong AF coupling as to cause observed differences in coercivities is suited for getting a large magnetoresistance. The reason for the large MR changes at $X=2.6$ nm and $X=3$ nm is probably due to an existing well-ordered antiparallel alignment that is perpendicular to the measuring field under the influence of intrinsic magnetizations of individual layers. We think that a rectangular magnetization curve combined with a high coercivity layer and a low coercivity layer is derived from spin flopping. And high sensitivity in MR changes in agreement with the magnetization curve is also derived from the spin flopping.

Fig. 5. In-plane spin flopping model for NiFe(6nm)/Co(0.6 nm)/Cu(X nm)/Co(4 nm) sandwiches.

The magnetization energy is low for parallel alignment to the intrinsic anisotropy axis. In AF coupling states, however, a perpendicular alignment to

an external field seems to be stable because the perpendicular susceptibility is greater than the parallel susceptibility for spin flopping sandwiches. One case of the spin flopping is parallel alignment to the intrinsic anisotropy axis in saturated states in magnetization, and perpendicular alignment that is antiparallel to the intrinsic anisotropy axis in AF coupling states. Another case of the spin flopping is non-parallel alignment to the intrinsic anisotropy axis in saturated states in magnetization. The former is stable when the anisotropy energy is small enough in comparison with the magnetization energy in antiparallel alignment states. This is because the antiparallel alignment emerges perpendicular to the intrinsic anisotropy axis. The latter case is thought to be stable as the anisotropy energy begins to increase. Namely, the measuring field direction which causes spin flopping is determined by the energy balance between the anisotropy energy in parallel alignment in saturated magnetization states and the antiparallel magnetization energy perpendicular to the measuring field. This is possibly the reason why the spin axis following spin flopping is rotated for sandwiches with X of 2.8 nm. Consequently, the rotational states of the spin axis can exist in spin flopping. However, we cannot accurately predict when the rotation of the spin axis takes place. More detailed studies are necessary to find a solution.

Rectangular hysteresis loops and a large MR ratio of high sensitivity to the field seem to be peculiar properties with spin flop sandwiches. AF coupling may stabilize the antiparallel alignment of magnetizations and introduce a large MR ratio of high sensitivity to the field for sandwich films with different coercivities.

V. CONCLUSION

We have found evidence that AF coupling exists in certain sandwich layers with different coercivities. A peculiar MR change in agreement with the magnetization curve as a function of the measuring field H can be explained by the spin flopping model. Namely, the spin axis parallel to H in saturated magnetization states rotates perpendicular to H in AF coupling states. The measuring field which causes spin flopping does not necessarily agree with the intrinsic anisotropy axis. This is possibly due to the spin axis rotation. The difference in coercivity between sandwich layers may operate to stabilize antiparallel alignment perpendicular to H in good order. We think that large magnetoresistance values and high sensitivity to the field are derived from the spin flop sandwiches.

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