Vol 11 No 1, January 2002
1009-1963/2002/11(01)/0054-04
Chinese Physics
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Magnetic behaviour investigation on symmetric spin valves of Co/Cu/NiFe and NiFe/Cu/Co*

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(Received 18 May 2001; revised manuscript received 9 September 2001)

In this paper, we have obtained and investigated the magnetic behaviours of the ferromagnetic layer in the symmetric spin valves of Co/Cu/NiFe and NiFe/Cu/Co by measuring with a vibrating sample magnetometer and analysing in terms of the multi-domain Ising models. It has been found that some magnetic layer can have quite different magnetic behaviours in different structures of spin valves, depending on the properties of the under-layer. In our investigation, we have found that the magnetic behaviour of a Co layer depends mainly on the magnetization of the under-layer, whereas this is not the case for the NiFe layer.

Keywords: magnetic property, spin valve, giant magnetoresistance, sandwich
PACC: 7215G, 7570

1. Introduction

As one of the most important giant magnetoresistance (GMR) materials, spin valves are attractive for their high sensitivity.[1−9] Two kinds of spin valve have been developed using different preparation methods: one is the different coercivity spin valve,[2,3] and the other is the pinned spin valve.[1] In any case, the GMR effect appears only when the anti-ferromagnetic alignment is achieved. When one of the magnetic layers changes its magnetic moment with the applied field, the anti-ferromagnetic alignment between the magnetic layers can be achieved in the spin valves and a high sensitivity can be gained. In the pinned spin valve, as an anti-ferromagnetic layer is formed in the neighbourhood of a ferromagnetic layer, which can pin the magnetic moment in the magnetic layer, this usually results in a better anti-ferromagnetic alignment and higher sensitivity.

As the anti-ferromagnetic alignment is related to the magnetic behaviours between the two magnetic layers, the latter is very important for the spin valve design. Unfortunately, the magnetic behaviours of each layer in the spin valve are usually difficult to know.

In our previous research,[7] we have investigated the influence of different buffer layers on the GMR of the Co/Cu/Co sandwich, and successfully analysed the magnetic behaviours of the two Co layers by using the multi-domain Ising model. It was found that the Ni buffer layer could strongly affect the structural and magnetic behaviours of the two magnetic layers.

In this paper, two different materials, Co and NiFe, have been chosen for the magnetic layer. We investigate the symmetric spin valves Co/Cu/NiFe and NiFe/Cu/Co, and the magnetic behaviours of the ferromagnetic layers. The relationship between the magnetic layer and their under-layers will be presented.

2. Multi-domain Ising model[10]

The multi-domain Ising model treats each magnetic film as if it were composed of many magnetic domains, allowing each to be orientated along or opposed to the applied field direction. The magnetization reversal is accomplished through the abrupt magnetization reversal of the separated domains. The hysteresis loops, which reflect the net moment, are a measure of the fraction of the film pointing along the applied field, i.e.

$$M_{\mathrm{Ising}}(H) = M_0[f^{\uparrow}(H) - f^{\downarrow}(H)] = M_0[2f^{\uparrow}(H) - 1], \quad (1)$$

where M_0 is the maximum moment and $f^{\uparrow}$ ($f^{\downarrow}$) is the fraction of the film pointing along (opposed to) the field direction. For two magnetic layers, if the directions of the moment of domains in the two films are uncorrelated, the measurements of the two independent hysteresis loops can be used to determine the

*Project supported by the Shanghai Research Center for Applied Physics (Grant No. 99JC14003), and the Shanghai Research and Development Foundation for Application Materials (Grant No. 98006).

fractions of the films that are aligned and anti-aligned with each other.

Generally, it can be considered that there are only two domain configurations that contribute to the overall resistivity, when the current flows between the two domains of aligned orientation. Because these two configurations represent two well-defined resistance states parallel to each other, if the domains are large compared with the additional resistivity associated with the current flow between the domains within the same magnetic layer, the total film resistance is given by

$$R(H) = \frac{R_A}{F_A(H)} \Big\| \frac{R_P}{f_P(H)} = \frac{R_A R_P}{R_A f_P + R_P f_A}, \qquad (2)$$

where $R_P(R_A)$ is the resistance of the film in the completely aligned (anti-aligned) state. The magnetoresistance can be expressed as (note that $f_P + f_A$=1)

$$\begin{aligned} \mathrm{MR_{Ising}}(H) =& \frac{R(H) - R_P}{R_P} \\ =& G \frac{f_A}{f_A + (R_A/R_P) f_P}, \end{aligned} \qquad (3)$$

with $G = (R_A - R_P)/R_P$. If G is small, then $R_A \approx R_P$. After using Eq.(1), Eq.(3) can be written as

$$\begin{aligned} &\mathrm{MR_{Ising}}(H) \sim G f_A \\ =& G[f_1^{\uparrow}(H) f_2^{\downarrow}(H) + f_1^{\downarrow}(H) f_2^{\uparrow}(H)] \\ =& \frac{G}{2}\left[1 - \frac{M_1}{M_{10}} \cdot \frac{M_2}{M_{20}}\right]. \end{aligned} \qquad (4)$$

The term in the brackets is the fraction of the two films which are anti-aligned (in the absence of domain correlation).

As the exchange-like coupling between the two magnetic layers will decrease rapidly with the increasing thickness of Cu,[11] when a thick Cu layer is used, the exchange-like coupling can be omitted. Thus, the directions of moments of the domains in the two magnetic films can be treated as uncorrelated, and the magnetic behaviour of the spin valve can be considered as a linear addition of the hysteresis curves of the two magnetic layers. As the hysteresis loops of the spin valve and the lower magnetic layer can be measured by a vibrating sample magnetometer (VSM), the hysteresis curve of the upper magnetic layer can be obtained by the subtraction between the above two curves. Therefore, in this paper, the structures of Cr 6.0nm/NiFe 6.0nm/Cu 3.5nm/Co 5.5nm and Cr 6.0nm/Co 5.5nm/Cu 3.5nm/NiFe 6.0nm are chosen. Cr/NiFe and Cr/Co layers with the same thickness are also fabricated.

3. Experimental details

The sandwiches were prepared using a Balzers ultra-high vacuum electron beam evaporation system. The base pressure was about 5×10^{-7}Pa, and the purity of the materials, Ni, Co and Cu, was better than 99.9%. Chemically etched Si(100) rectangles of a size 1.5cm×0.7cm were used as substrates and the deposition rates were controlled at 0.05nm/s. The thickness of each layer was controlled by a quartz oscillating thickness monitor and calibrated by a high-resolution electron microscope.

The hysteresis loops and the magnetoresistance (MR) ratios of the samples were measured at room temperature, where the MR ratio was defined as the ratio of the total resistivity change to the resistivity at a magnetic field of 2.4kA/m. The magnetic field was applied in-plane and parallel to the current. The MR ratios were obtained using the four-terminal method in a magnetic field of 2.4kA/m. An EG&G PAR 4500-14A VSM was used to measure the hysteresis loops.

4. Results and discussion

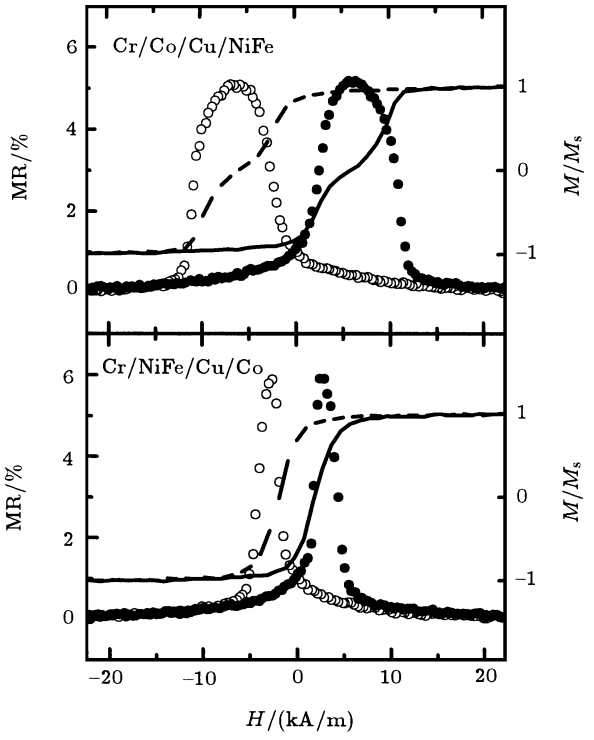


Fig.1. The MR curves and the hysteresis loops of Cr/Co/Cu/NiFe and Cr/NiFe/Cu/Co spin valves.

Figure 1 shows the hysteresis loops and the MR

curves of the Cr/Co/Cu/NiFe and Cr/NiFe/Cu/Co spin valves. It can be found that the MR curves and the hysteresis loops of the two spin valves are different from each other, although both GMR values are about 6%. In the figure, the saturation field of Cr/Co/Cu/NiFe is about 0.88kA/m, which is larger than that of Cr/NiFe/Cu/Co (about 0.66kA/m). Furthermore, unlike Cr/NiFe/Cu/Co, the hysteresis loop of Cr/Co/Cu/NiFe showed a typical wasp-waisted curve, which indicates a large difference between the magnetic behaviours of the two magnetic layers in the spin valve. A similar GMR value and different saturation field imply that the two spin valves would show different GMR sensitivities.

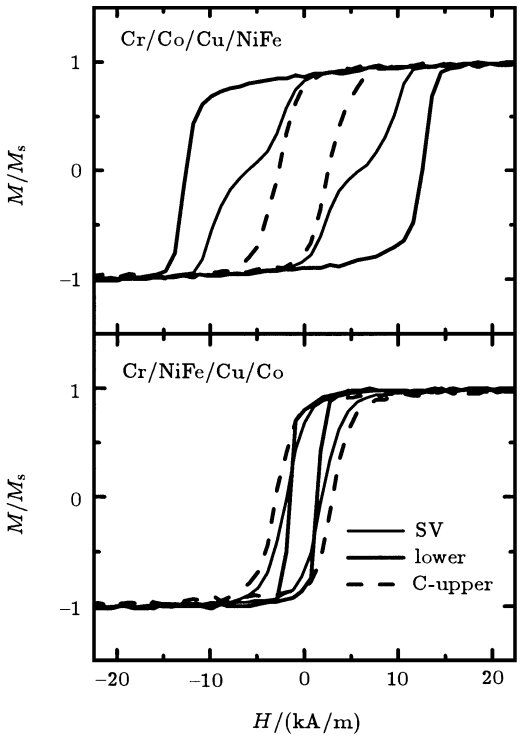


Fig.2. The magnetic behaviours of the lower magnetic layers (thick solid lines) in Co/Cu/NiFe and NiFe/Cu/Co spin valves and the corresponding calculated magnetic behaviours (dashed lines) of the upper magnetic layers. The hysteresis loops of the spin valves are also presented as thin solid lines.

As mentioned in section II, because the hysteresis loops of the lower magnetic layers (Cr/NiFe and Cr/Co) and the spin valves (Cr/NiFe/Cu/Co and Cr/Co/Cu/NIFe) have been measured by a VSM, the magnetic behaviours of the upper magnetic layers can be calculated by using these curves. All the calculated and normalized loops are shown in Fig.2. It can be found that the coercivity of Cr/NiFe is 1.14kA/m, and that of Cr/Co is 10.06kA/m; while the coercivity of the Cu/Co layer in Cr/NiFe/Cu/Co is about 2.4kA/m, and that of the Cu/NiFe layer in Cr/Co/Cu/NiFe is only 2.0kA/m. In other words, the difference between the coercivities of the upper and lower magnetic layers in Cr/Co/Cu/NiFe is 8kA/m, while the difference in Cr/NiFe/Cu/Co is only 1.2kA/m. This explains well the different magnetic behaviours between the spin valves in Fig.1.

According to Eq.(4), the experimental MR data can be fitted by the above curves. The results are shown in Fig.3. It can be found that the fitted curves can describe the variation tendency of the experimental data very well. On the other hand, it is suggested that the magnetic behaviour of the magnetic layers in Fig.2 is believable.

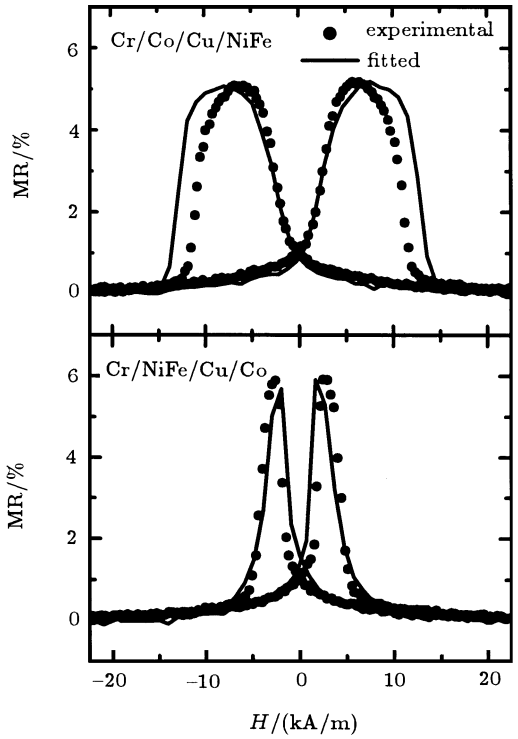


Fig.3. The experimental and the fitted MR curves of the Co/Cu/NiFe and NiFe/Cu/Co spin valves.

It is interesting that the NiFe and Co layers with same thickness present different magnetic behaviours in different structures of spin valves. In general, the magnetic differences of the layers can result from the crystallinity, roughness and magnetization of the under-layer.[7] In order to find the influences of the under-layer on the magnetic layers, the Cu/Co and Cu/NiFe layers have been fabricated and their magnetic behaviours measured. The hysteresis loops of the samples and the calculated curves with the same structure in different spin valves are shown in Fig.4.

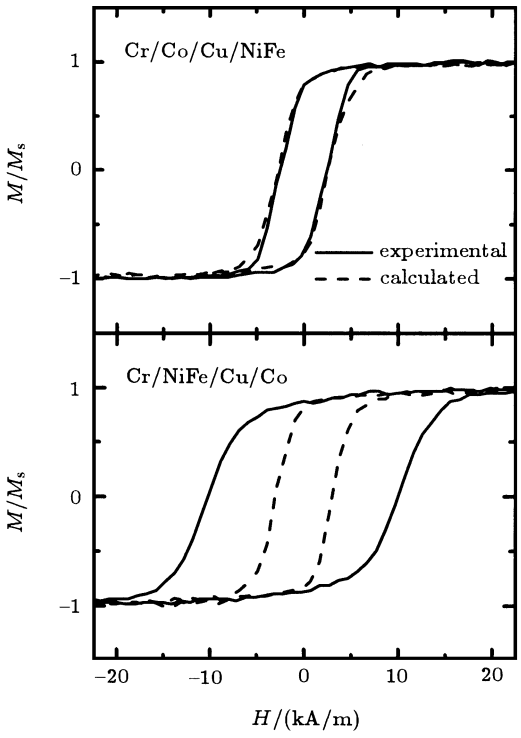


Fig.4. The calculated hysteresis loops of the upper magnetic layers in Cr/Co/Cu/NiFe and Cr/NiFe/Cu/Co spin valves with the experimental curves of Cu/Co and Cu/NiFe.

From the results listed in Table 1, the coercivity of the Cu/Co layer is 8.0kA/m, while that of the Cu/Co layer in the Cr/NiFe/Cu/Co spin valve is only 2.4kA/m (in Cr/Co/Cu/Co it is about 8.0kA/m).[7] It can also be found that the coercivity of the Cr/Co layer is 10.0kA/m, while that of the Ni/Co layer is 1.6kA/m.[7]

According to our former investigation,[7] the existence of the Cu layer, and the roughness difference in Cu, NiFe and Cr, cannot explain the above results. A possible explanation for the differences is that the coercivities of the Co layer depend strongly on the magnetic properties of the under-layers. The magnetic property of the under-layer affects the growth of the crystal and magnetic domains in the Co layer, which reduces the coercivity of the Co layer to about 2.4kA/m. However, the non-magnetic or anti-magnetic under-layers will cause the coercivity of the Co layer to be as large as 8kA/m.

However, a similar result cannot be found in the Cu/NiFe layer. Although the magnetizations of Cu and Cr/Co/Cu are different, the magnetic behaviours of the Cu/NiFe layer are almost the same (Fig.4). The reason for this may be that NiFe is an alloy, and its magnetic property is strongly affected by the roughness and crystallization of the layer.[7]

Table 1. Coercivity (units: kA/m) of the Co layer and the under-layers, where the magnetic properties of the under-layers are also noted in the brackets: NM, non-magnetic; FM, ferromagnetic; AFM, anti-ferromagnetic.

	Cu/Co	Cr/NiFe/Cu/Co	Cr/Co	Ni/Co
Under-layer	/(Cu,NM)	0.8(Cr/NiFe,FM)	/(Cr,AFM)	0.8(Ni,FM)
Co	8.0(Cu/Co)	2.4(Cu/Co)	10.0(Cr/Co)	1.6(Ni/Co)

5. Conclusion

The magnetic layer in spin valves can have different magnetic behaviours when prepared in different structures. Its magnetic behaviour depends on the different properties of the under-layer. For example, the magnetic behaviour of the Co layer depends mainly on the magnetization of the under-layer, which is not the case for the NiFe layer.

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