Journal of Magnetics 2(1), 7-11(1997)

Magnetoresistance of Co/Cu/Co Spin Valve Sandwiches

S. J. Choi, K. L. Choi, M. Y. Kim and J. R. Rhee
Dept. of Physics, Sookmyung Women's University, Seoul 140-742

D. G. Hwang and S. S. Lee
Dept. of Physics, Sangji University, Wonju 220-702

K. A. Lee and C. M. Park
Dept. of Physics,Dankook University, Cheonan 330-704, Korea

(Received 28 January 1997)

The dependence of magnetoresistance (MR) ratio on various variables like the thickness of the second Co layer, on the presence of cap layer, on deposition field (H_{dep}) and on annealing in Co/Cu/Co sandwiches was investigated. Spin-valve sandwiches were deposited on the corning glass by means of the 3-gun dc magnetron sputtering at a 5 mTorr partial Ar pressure and r oom temperature. The deposition field was varied from 70 Oe to 720 Oe. The MR curve was measured by the four-terminal method with applied magnetic field up to 1000 Oe perpendicular to the direction of a current in the film plane. The MR ratio of glass/Fe(50 Å)/Co(17 Å)/Cu(24 Å)/Co(t Å) fabricated by making 50 Å of Fe buffer layer has the maximum value of 8.2% when the thickness of the second Co layer was 17 Å and the deposition field was 350 Oe. In the case of glass/Fe(50 Å)/Co(17 Å)/Cu(24 Å)/Co(t Å) with Cu cap layer on top, the decrease in the MR ratio seemed to relate with the oxidation of the second Co layer. Samples prepared with deposition field showed greater MR ratios through the formation of more complete spin valve films. After annealing for 2 hours at 300℃, the MR ratio of the samples prepared with deposition field decreased rapidly while the MR ratio of the sample prepared without the field remained.

I. Introduction

The discovery of giant magnetoresistance (GMR)[1] has provoked the intensive research on artificial magnetic multilayer characteristics. In many multilayers, the MR ratios are higher than 10% at room temperature. However, the saturation magnetic fields of the multilayers are very high because of the strong antiferromagnetic couplings between the ferromagnetic layers.

NiFe/Cu/Co[2] sandwiches and Co/Cu/Co[3] sandwiches also show the GMR effect. In these samples, GMR effects are observed at lower magnetic field than the exchange coupled multilayers. These phenomena have drawn great attention among the researchers.

In the uncoupled exchange interaction sandwich film [4-5] shows high MR ratio due to the spin dependent scattering, when the moment of adjacent ferromagnetic layer changes from parallel to antiparallel. It is referred to spin-valve effect[4]. There are largely three major methods to make sandwich film to have antiparallel spin alignment due to uncoupled exchange interaction : One method is using the different thickness of ferromagnetic layers which are made of same material that leads different coercivity among two layers. Another method may be suppressing one of the moment of ferromagnetic layers by applying bias magnetic field. The third method is to prepare two ferromagnetic layers with different materials.

In this work, the sandwich film Co/Cu/Co with 17 Å, 24 Å, and t Å respectively, was produced on glass substrate by dc-magnetron sputtering. Then, the MR was measured at room temperature by the four-terminal method. Magnetic properties were investigated by vibrating sample magnetometer (VSM). The dependence of the MR ratio on the thickness of the second Co layer, on the presence of capping layer, deposition field and annealing in Co/Cu/Co sandwiches were investigated.

II. Experimentals

We used Fe, Co, and Cu, targets of 3-inch diameter to prepare the sandwich film. The sputter that is used in this experiment is equipped with three dc magnetron guns that contain Fe, Co, and Cu targets. Also three dividers and three apertures are implemented to prevent the interferences of plasmas that originated from these three different targets.

Stepping motor rotates the rotary plate attached to the substrate for making sample, and the shutter on/off switch is controlled by a computer. Distance from the target to the substrate was maintained at about 8 cm. Deposition rate was monitored by calculating the layer thickness determined by small angle X-ray diffraction. As for the substrate, corning glass cut into several pieces of 15 × 15 mm^2 was washed out with neutral detergent, ultrasonic cleaned in the trichloroethylene solution, and then dried after immersed in acetone and alcohol to remove organic metal remnants and moisture.

In the preparation of the sandwich film glass/Fe/Co/Cu/Co, with Fe as a buffer layer, we fixed the first Co layer thickness and Cu layer thickness of Co/Cu/Co sandwich film to be 17 Å and 24 Å respectively, and changed the second Co layer thickness from 4 Å to 70 Å. We made deposition field varied from 70 Oe to 700 Oe, for the examination of the MR ratio depending on deposition field for Co/Cu/Co sandwich film. Also, we changed the thickness of Cu and Fe, to examine the dependence of MR ratio on Cu and Fe thicknesses, and performed annealing at 300℃ for 2 hours to observe annealing effect. We maintained base pressure at around 1 × 10^{-6} Torr and Ar partial pressure at 5 mTorr in the deposition of sandwich film. We established a measurement system using an electromagnet to measure the MR effect. To obtain the MR curve depending on external magnetic field, we measured electric resistance while applying magnetic field in the range -1000 ~ 1000 Oe in four-terminal method at room temperature by connecting digital multimeter and digital gaussmeter that can measure applied current and resistance synchronously to the computer. Thin plate mask was used to fabricate the sample for the measurement of MR.

The MR ratio from the MR curve was defined as;

$$MR(\%) = [(R_{max} - R_{min}) / R_{min}] \times 100,$$

where, R_{max} is the maxmum value of the resistance and R_{min}, the high field saturated value.

Magnetic properties was measured at room temperature using VSM.

III. Results and Discussions

Fig. 1 shows dependence of the MR ratio on the thickness of the second Co layer for glass/Fe(50Å)/Co(17Å)/Cu(24Å)/Co(tÅ) sandwich film produced at different thicknesses of the second Co layer by fixing the thickness of the first Co layer to 17 Å and the thickness of Cu layer to 24 Å. The MR showed a sharp positive slope with the increase of the second Co layer thickness, and reached a maximum value when its thickness is 17 Å. Then, it decreased gradually with the increase of the thickness. From this result, we found that the thickness of the second Co layer showing the maximum MR ratio in Co/Cu/Co sandwich film shall be the same as the thickness of the first Co layer, that is, the thicknesses of both Co layer should be equal.

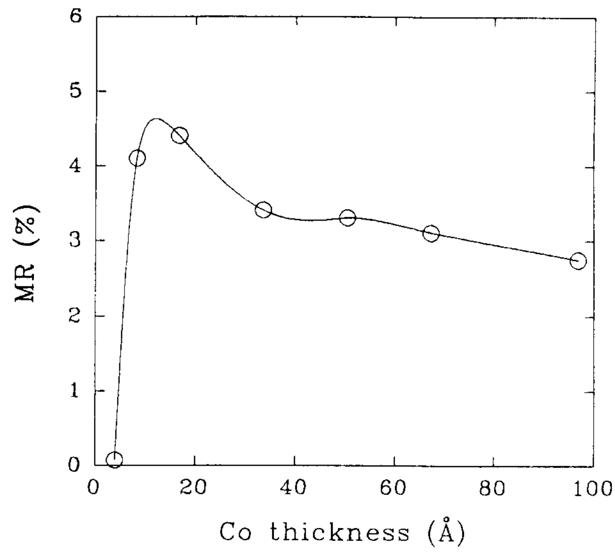

Fig. 1. Dependence of the MR ratio on the thickness of the 2nd Co layer for Fe(50Å)/Co(17Å)/Cu(24Å)/Co(tÅ) sandwich films.

Fig. 2 shows the magnitude of the coercivity with respect to the thickness change of the second Co layer, which was derived from the hysterisis curve obtained using VSM. As

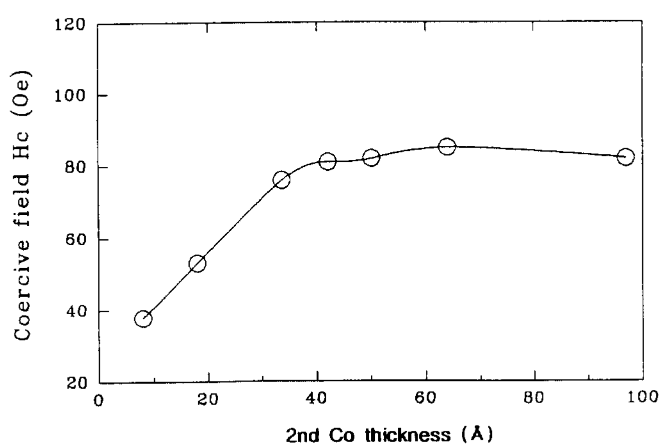

Fig. 2. Coercive field(H_C) with the thickness of the 2nd Co layer for Fe(50 Å)/Co(17Å)/Cu(24Å)/Co(tÅ) sandwich films.

the thickness of the second Co layer increases, the coercivity increases and is saturated at the thickness of 60 Å.

Fig. 3 shows the variation of the MR when the deposition field (H_{dep}) applied to the sample are 0 Oe, 70 Oe, 350 Oe, and 700 Oe respectively. When the deposition field was 350 Oe, the maximum MR value was shown, and MR value reduced to 5.2% at 700 Oe. Since the uniaxial anisotropy is induced coincidentally with sputtering, the formation of uniform film becomes more difficult due to the influence of magnet upon the Co particle during sputtering when the magnitude of the magnetic field inducing anisotropy is excessively strong. From this the strength of the deposition field appropriate to form induced anisotropy in Co/Cu/Co sandwich film seems to be around 350 Oe.

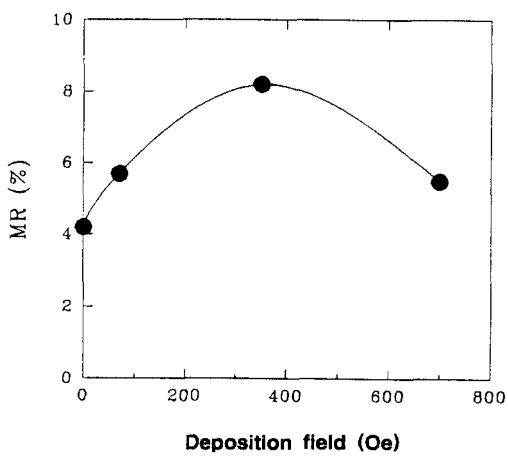

Fig. 3. Dependence of the MR ratio on the deposition fields(H_{dep}) for Fe(50Å)/Co(17Å)/Cu(24Å)/Co(17Å) sandwich films.

Fig. 4(a) and (b) show hysterisis curve and the MR curve for Co/Cu/Co sandwich film in the presence of the deposition field and for $[Co/Cu]_{20}$ multilayer, respectively. In both samples Fe buffer layer is 50 Å, Co layer is 17 Å, and Cu layer is 24 Å thick. $[Co/Cu]_{20}$ multilayer showed higher MR ratio of 13% than the sandwich film. Such a high MR in the multilayer occurs because antiparallel state of magnetization is made by the antiferromagnetic coupling of adjacent Co layers. Hysterisis curve shows smooth magnetization variation up to saturation magnetic field (Hs) reflecting antiferromagnetic coupling between adjacent Co layers in the multilayer system. Contrary to this, in Co/Cu/Co sandwich film, both the hysterisis curve and the MR curve show different behavior from those of the multilayer. In hysterisis curve of sandwich film, there is distinct difference between magnetic fields for the magnetization reversal of two Co layers since the magnetic field for the magnetization reversal of the second Co layer is high and magnetic field for the magnetization reversal of the first Co layer is relatively low. The MR ratio showed steep variation in the response of magnetization for the magnetization reversal of the first Co layer in the region of low magnetic field. The reason why considerable change of the MR is caused in such a low magnetic field is that the parallel and the antiparallel states are made due to the difference of the magnetic fields for the magnetization reversal between two Co layers. The reason why the magnetic field for the magnetization reversal is increased for the second Co layer is that the surface of the second Co layer was naturally oxidized after the sample being exposed to the atmosphere, which caused the enhancement of the coercivity of the second Co layer relative to the first Co layer.

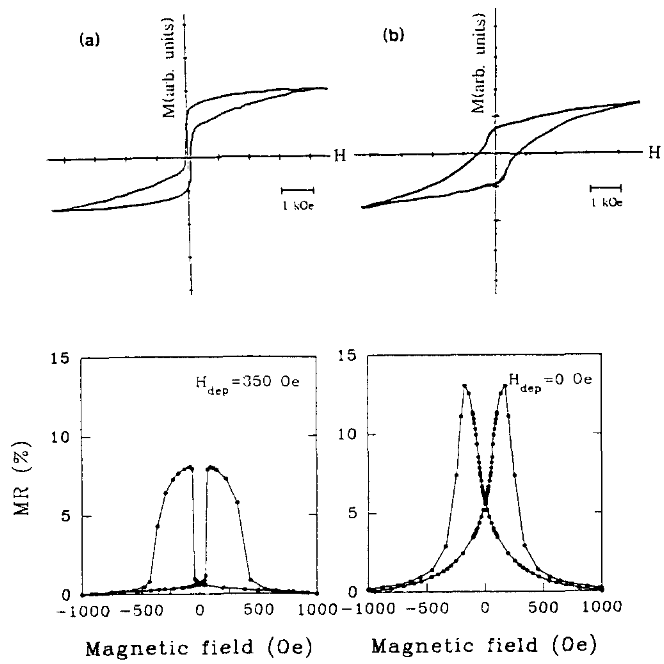

Fig. 4. MR curves and magnetization curves for (a) Fe(50Å)/Co(17Å)/Cu(24Å)/Co(17Å) sandwich film and (b) Fe(50Å)/[Co(17Å)/Cu(24Å)]20 multilayers.

To confirm this, we probed the effect of deposited Cu layer of 52 Å thickness on the second Co layer as shown in Fig. 5. The MR ratio of 8.2% was shown when there is non Cu capping layer, and 5% when Cu capping layer is deposited. In the MR curve of the sample with Cu capping layer, we found the magnetic field for the magnetization reversal between two Co layers are nearly equal.

From the above results, we suggest that the increase of the magnetic field for the magnetization reversal is caused by the formation of oxidized film on the surface of second Co layer, and high MR ratio was obtained through parallel and antiparallel magnetization in the switching field due to the difference of the magnetic field for the magnetization reversal between two Co layers.

Fig. 6 shows the dependence of the MR ratio on the thickness of Fe and Cu layer for Fe(tÅ)/Co(17Å)/Cu(s

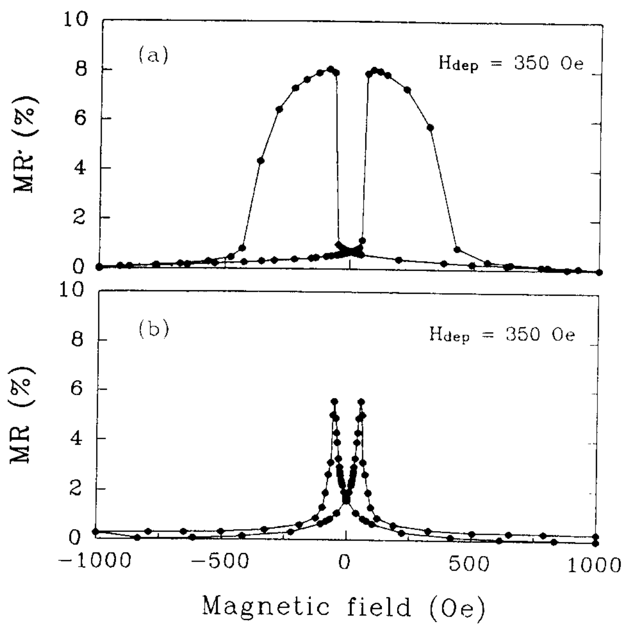

Fig. 5. MR curves for (a) non capping spin valve sandwich : Fe(50Å)/Co(17Å)/Cu(24Å)/Co(17Å) and (b) capping spin valve sandwich : Fe(50Å)/Co(17Å)/Cu(24Å)/Co(17Å)/Cu(52Å).

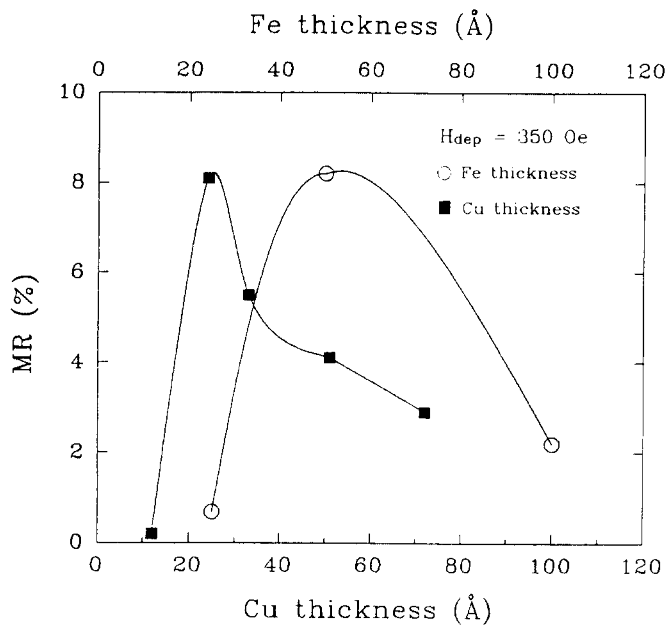

Fig. 6. Dependence of the MR ratio on the thickness of Fe and Cu layer for Fe(tÅ)/Co(17Å)/Cu(sÅ)/Co(17Å) sandwich films.

Å)/Co(17Å) sandwich films prepared after fixing the first Co layer thickness and the second Co layer thickness to 17 Å in the presence of the deposition field. At this time, the maximum MR ratio was obtained when the thickness of a Cu layer was 24 Å. When the thickness was over 24 Å, the MR decreased monotonically with the increase of Cu thickness. The maximum MR ratio was observed in Co/Cu/Co sandwich film with Fe buffer layer thickness of 50Å . Fe buffer layer shows two effects; the effect of enhancing the MR property by ferromagnetic coupling with the first Co layer, and the effect of extending difference of the coercivity of the first Co layer from the second Co layer by softening the first Co layer. However, when Fe buffer layer is thinner than 50Å , such role cannot be done sufficiently, so decrease of the MR is resulted.

In addition, in case that the thickness of Fe buffer layer is thicker than 50 Å, the MR ratio will be reduced due to the current shunting effect[6] as for the multilayer. It is known by Barnas[7] et al. that Fe buffer layer of appropriate thickness couple with the first Co layer to improve interfacial scattering effect and bulk scattering effect.

The MR curve depending on the second Co layer thickness for samples prepared under 350 Oe of deposition field was shown in Fig. 7 when the first Co layer thickness and Cu layer thickness are fixed to 17 Å and 24 Å, respectively. When the thickness of the second Co layer is 17 Å, the maximum MR ratio of 8.2% was observed and then as the thickness was increased, the ratio was decreased gradually. Such a result seemed to be caused by the decrease of extension effects of the saturated magnetic field, therefore this might result the imperfect antiparallel state of magnetization between two Co layers due to the thickening of the second Co layer.

Fig. 8 shows the dependence of the MR curve on the thickness of the first Co layer when the thickness of Cu intermediate layer is fixed to 24 Å and the thickness of the

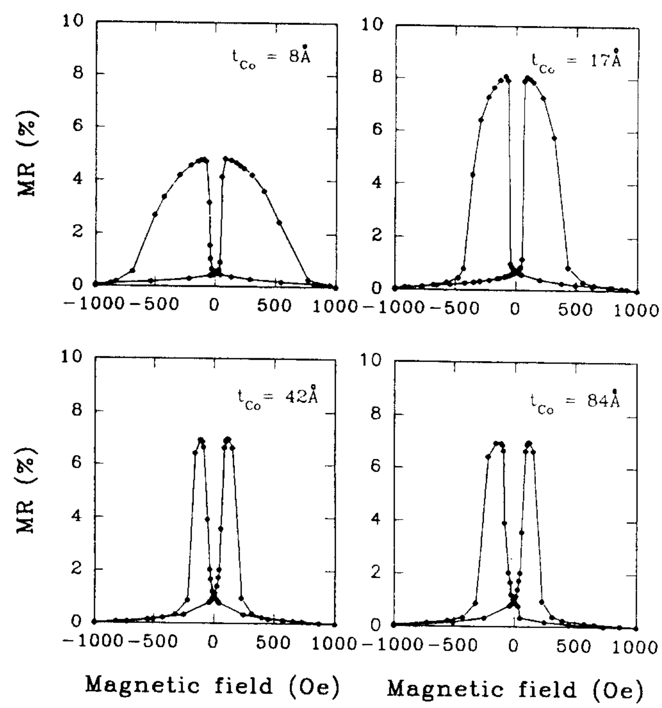

Fig. 7. Dependence of the MR curves on the thickness of the 2nd Co layer for Fe(50Å)/Co(17Å)/Cu(24Å)/Co(tÅ) sandwich films under H_{dep}=350 Oe.

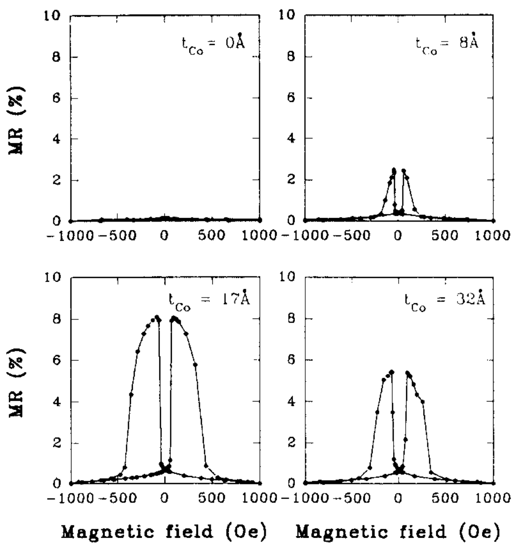

Fig. 8. Dependence of the MR curve on the thickness of the 1st Co layer for Fe(50Å)/Co(tÅ)/Cu(24Å)/Co(17Å) sandwich films.

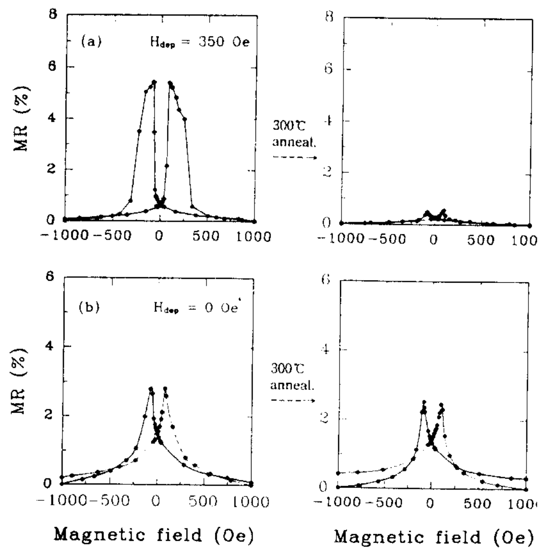

Fig. 9. Annealing effect of MR curves in (a) the Fe(50Å)/Co(32Å)/Cu(24Å)/Co(17Å) films with H_{dep}=350 Oe and (b) the Fe(50Å)/Co(32Å)/Cu(24Å)/Co(17Å) films with H_{dep}=0 Oe.

second Co layer is fixed to 17 Å. As in the case of varying the thickness of the second Co layer, the maximum MR was shown when the first Co layer thickness is 17 Å and then the MR was decreased as the thickness of the first Co layer increases. It is thought that this is because the difference of the coercivity from the second Co layer is reduced when the thickness of Co layer increases.

Fig. 9 is a curve indicating the change of the MR after annealing when we perform annealing at 300℃ for 2 hours both for the sample with applied deposition field and for the sample without applied field. In Fig. 9(a), the sample with applied deposition field showed high MR ratio and this ratio severely decreased after annealing compared with that of the sample before annealing. On the other hand, in Fig. 9(b), the sample without applied deposition field maintained the similar MR ratio even after annealing. Therefore, it seems that the magnetic moment aligned to one direction was disrupted by annealing and caused the reduction of the MR ratio.

IV. Conclusions

1. In case that the thickness of Cu of Co/Cu/Co sandwich film produced in this experimental is 24 Å, the maximum MR ratio was observed when the thickness of the first and second Co layers are equally 17 Å, and the thickness of Fe buffer layer is about 50 Å.

2. The second Co layer of Co/Cu/Co sandwich film showed greater coercivity than the first Co layer due to the natural oxidation, and the difference in the magnetic field for the magnetization reversal is made between two Co layers. According to this effect, antiparallel state is induced causing the increase of the MR ratio by spin-valve effect.

3. The magnitude of deposition field which gives the maximum MR ratio is about 350 Oe. In addition, the sample produced with applying deposition field has the greater MR ratio due to the formation of more distinct spin-valve film than the sample without applied deposition field.

4. When the sample was annealed at 300℃ for 2 hours, the sample produced with applied deposition field lost uniaxial anisotropy, which means the reduction of the MR ratio is more severe for the uniaxially magnetized sample than for the sample without applied deposition field due to the anneal.

References

[1] M. N. Baibich, J. M. Broto, A. Fert, Nguyen Van Dau, F. Petroff, P. Etienne, G. Crezet, and J. Chazelas, Phys. Rev. Lett., **61**, 2742 (1988).

[2] H. Yamamoto, T. Okuyama, T. Shinjo, J. Mag. Magn. Mat., **99**, 243 (1991).

[3] T. R. McGuire, T. S. Plaskett, and R. J. Gambino, IEEE Trans. Magn., **29**(6), 2714 (1993).

[4] B. Dieny, V. S. Speriosu and S. S. P. Parkin, Phys. Rev., **B43**, 1297 (1991).

[5] C. Dupas. P.Beauvillain and C. Chappert, J. Appl. Phys., **67**, 5680 (1990).

[6] M. E. Tomlinson, R. J. Pollard, D. J. Lord, P. J. Grundy, and Z. Chun, IEEE Trans. Magn., **28**(5), 2662 (1992)

[7] R. E. Camley and J. Barnas, Phys. Rev. Lett., **63**, 664 (1989).