Journal of Magnetics 10(2), 52-57 (2005)

Effects of Rapid Thermal Annealing on Thermal Stability of FeMn Spin Valve Sensors

Seung-young Park, Yeonbong Choi and Soonchul Jo*

School of Electronic Engineering, Soongsil University, Seoul 156-743, Korea

(Received 8 March 2005)

In this research, magnetoresistance (MR) ratio (*MR*), resistivity, and exchange coupling field (H_{ex}) behaviors for sputter deposited spin valves with FeMn antiferromagnetic layer have been extensively investigated by rapid thermal annealing (RTA) as well as conventional annealing (CA) method. 10 s of RTA revealed that interdiffusion was not significant up to 325 °C at the interfaces between the layers when the RTA time was short. The *MR* of FeMn spin valves were reduced when the spin valves were exposed to temperature of 250 °C, even for a short time period of 10 s prior to CA. H_{ex} was maintained up to 325 °C of CA when the specimen was subjected to 10 s of RTA at 200 °C prior to CA, which is 25 °C higher than the result obtained from the CA without prior RTA. Therefore, the stability of H_{ex} could be enhanced by a prior RTA before performing CA up to annealing temperature of 325 °C. *MR* and sensitivity of the specimens annealed without magnetic field up to 275 °C were recovered to the values prior to CA, but H_{ex} was not recovered. This means that reduced MR sensitivity and *MR* during the device fabrication can be recovered by a field RTA.

Key words : GMR, spin valve, RTA, CA, thermal stability

1. Introduction

A ferromagnet (FM)/antiferromagnet (AFM) combination structure [1-3] utilizing Mn alloy type AFM materials such as FeMn, IrMn, PtMn are used to obtain exchange coupling field (H_{ex}) of several hundreds Oe before and after annealing process. Like other Mn alloys, FeMn films have also been extensively investigated [4-6] as the pinning layers of spin valves. In many cases, the spin valves are exposed to high temperatures during the manufacturing processes and device operation [7, 8]. For application to spin valve read heads, the H_{ex} and magnetoresistance ratio (*MR*) should not be affected by temperature up to 250 °C during the device production and operation [9-11]. Failure of spin valve sensors due to electrostatic discharge (ESD) event [11] have also been related to thermal stability [12]. Therefore, the study of developing high temperature endurable and high exchange field materials has been going on for a long time. Thermal annealing of spin valves has been researched by numerous researchers. However, high temperature curing process such as rapid thermal annealing (RTA) has been tried by only a few researchers [9, 13].

*Corresponding author: Tel: +82-2-815-6471,
e-mail: jschul@ssu..ac.kr

In this research, *MR*, resistivity (ρ), and H_{ex} behaviors for sputter deposited spin valves with FeMn AFM layer have been extensively investigated by RTA as well as conventional annealing (CA) method.

2. Experiment

2.1. Spin valve fabrication and measurement

The spin valves of Ta(35 Å)/NiFe(100 Å)/CoFe(36 Å)/Cu(22 Å)/CoFe(28 Å)/FeMn(120 Å)/Ta(50 Å) were fabricated to investigate annealing effects. The films were deposited in a magnetic field of 600 Oe on silicon substrate with 2,000 Å SiO_2 layer by a direct current (DC) magnetron sputtering deposition method. Base pressure was 1.3×10^{-7} Torr. A photo lithography process was utilized to make spin valve patterns. The patterns were 200 μm wide and 5 mm long. MR was measured by a four point probe method with an applied DC magnetic field of up to 2 kOe at room temperature.

2.2. Rapid thermal annealing

A custom made vacuum furnace system is shown in Fig. 1(a) which was utilized in annealing spin valves for both the CA and RTA. Heat sources were halogen lamps and annealing temperature was sensed at the surface of the specimen. A pair of electromagnets were utilized for

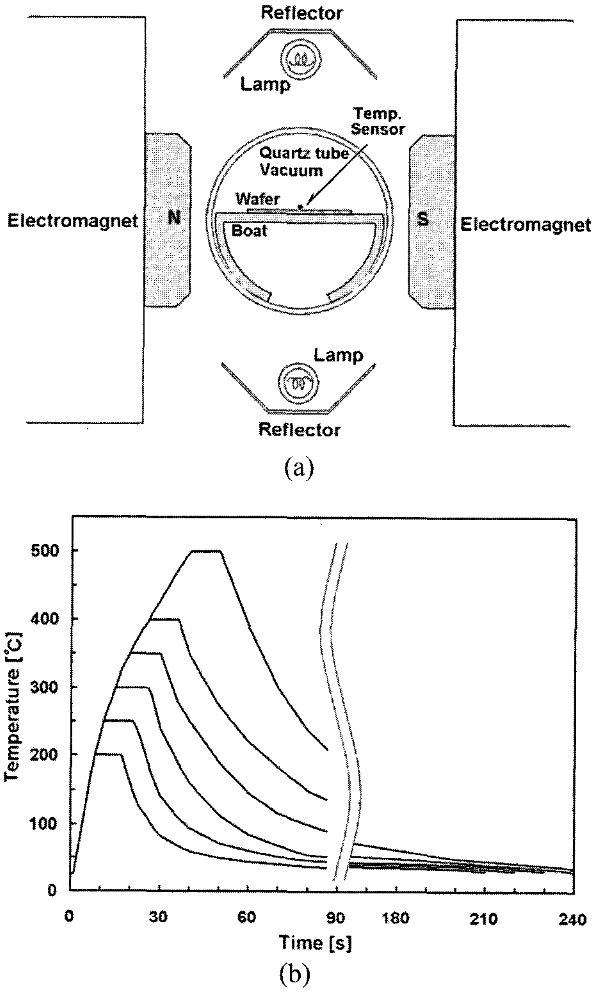

Fig. 1. (a) Cut away view of custom made furnace system having halogen lamps and electromagnets and (b) temperature profiles at the surface of substrates during RTA process.

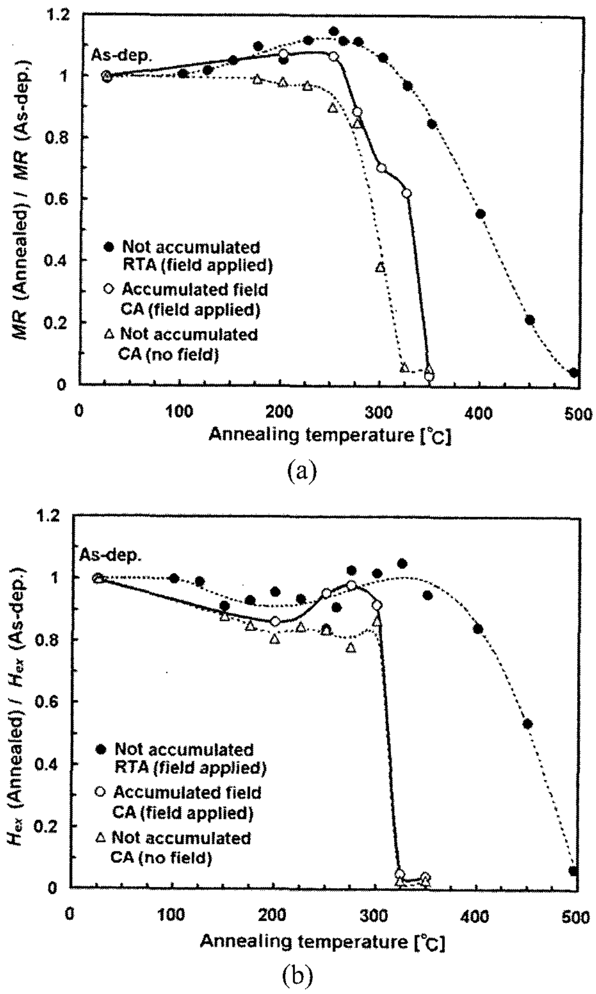

Fig. 2. (a) Magnetoresistance ratio (*MR*) and (b) exchange coupling field (H_{ex}) behaviors depending on annealing method (CA and RTA) and temperature.

applying magnetic field to specimens. The working pressure of the furnace for both the CA and RTA was less than 1×10^{-1} Torr. The specimens were coated with photoresist to prevent oxidation.

Figure 1(b) shows temperature profiles at surface of substrates during RTA process. It took about 40 s to elevate the temperature to 500 °C and 3 min to cool down the substrates to near room temperature after 10 s holding. Also, it took about 10 s to elevate the temperature to 200 °C and 1 min to cool down the substrates to near room temperature. When CA processes were carried out, the temperature was raised slowly. It took 15 min to elevate the temperature to 250 °C and 60 min to cool down the substrates to near room temperature.

3. Results and Discussion

Figure 2(a) shows the normalized *MR* behaviors with annealing temperature variation for the two different annealing methods. Filled circles and open circles represent *MR* behaviors by RTA for 10 s and CA for 1 hour, respectively. Each data point was obtained from different specimens fabricated with the same sputtering conditions. The RTA processes were not accumulated and CA processes were accumulated. The *MR* behaviors after the RTA and CA were almost the same up to the annealing temperature of 250 °C. The *MR* after the CA process was rapidly decreased as the annealing temperature increased over 250 °C and reduced to near zero at 350 °C. On the other hand, the MR measured after the RTA process was slowly decreased compared with that after the CA process as the annealing temperature was increased over 250 °C and reached near zero at 500 °C. Triangles show the results for the CA performed without magnetic field. The *MR* reduced rapidly after 275 °C annealing.

Figure 2(b) shows the H_{ex} behaviors on annealing methods (CA and RTA) and the same specimens used in Fig. 2(a). Both (CA and RTA) results showed that H_{ex} initially decreased somewhat and then increased until 275 °C for the CA and 350 °C for the RTA. The H_{ex} for the CA decreased rapidly after 300 °C anneal and for RTA after 350 °C. The CA without magnetic field showed nearly monotonic decrease of H_{ex}.

At lower annealing temperature, defects would be reduced and FM/Cu/FM interfaces would become flattened and chemically sharp, resulting in the increase of *MR* and H_{ex}. At higher annealing temperature, interfacial mixing (interdiffusion) at the interfaces between non-magnetic Ta, Cu and FM layers, and also FM and AFM (FeMn) layers has been known as a dominant reason for *MR* and H_{ex} reduction [14-16]. The above results indicate that in 10 s of RTA annealing time, interdiffusion may not be significant up to 325 °C at the interfaces among the layers.

Figure 3 shows normalized *MR*, resistivity and H_{ex} behaviors depending on annealing temperature as a function of accumulated cycle time of RTA process. The as-deposited values of *MR* and H_{ex} were 6.5% and 200 Oe, respectively. For this experiments each specimen was annealed repeatedly up to 8 times at 200 °C and 250 °C, respectively. The open circles, squares and triangles show *MR*, resistivity and H_{ex} variations due to the repeated RTA, 10 s each, at 200 °C, respectively and the filled symbols represent the same thing at 250 °C.

When the RTA temperature was 200 °C, *MR* and resistivity did not change much but H_{ex} decreased significantly, down to 175 Oe. However, when the RTA temperature was 250 °C, *MR* and resistivity started to decrease, but H_{ex} did not change appreciably from the values at 200 °C.

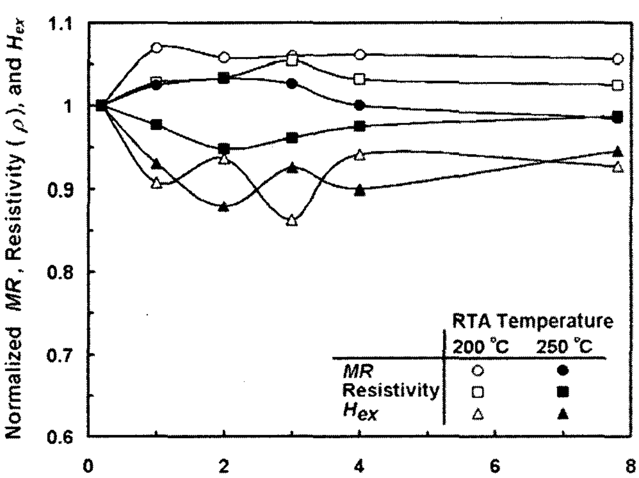

Fig. 3. Normalized magnetoresistance ratio (*MR*), resistivity, and exchange coupling field (H_{ex}) behaviors of spin valve sensors depending on temperature and accumulated cycle time of rapid thermal annealing.

The specimens were initially rapid thermal annealed and then, sequentially annealed for 1 hr at each temperature up to 350 °C. Five specimens were used. The two were subjected to prior RTA at 200 °C and the other two at 250 °C. One did not undergo the RTA. *MR*, resistivity and H_{ex} behaviors depending on annealing temperature and cycle time of the RTA processes are represented as a function of CA temperature in Fig. 4(a), 4(b) and 4(c), respectively.

As shown in Fig. 4(a), *MR* by all annealing conditions did not change much until CA temperature of 200 °C and then, started to decrease except the specimen without any prior RTA, which started to decrease at 275 °C. However, *MR* behaviors were similar to each other for the specimens undergone 200 °C RTA process and for the specimen without the prior RTA process. For the specimens undergone 250 °C RTA process, *MR* started to decrease early and reduced to near zero at 300 °C, 50 °C lower than the specimens undergone 200 °C RTA process. The the number of the accumulated RTA process, one or eight did not make much difference in the *MR*. These results indicate that *MR* of FeMn spin valves become smaller when they are exposed to temperature of 250 °C, even for a short time period of 10 s prior to CA compared with the *MR* values after CA without the prior RTA. Resistivity trends shown in Fig. 4(b) clarifies the reason for decreasing *MR* at the annealing temperature of 250 °C. The resistivity, ρ starts to increase much more rapidly for the specimens undergone the prior RTA at 250 °C when the CA temperature reaches 250 °C. Then *MR*, $\Delta\rho/\rho$. decreases if the $\Delta\rho$ does not increase at the similar rate to ρ. Dominant reason for these resistivity increase has been attributed to interdiffusion and interfacial mixing at FM/Cu/FM interfaces [14]. On the other hands, resistivity of the specimen with no RTA (represented as open circles) was reduced at 250 °C CA, causing slight increase of *MR*.

The behaviors of exchange coupling field depending on the accumulated annealing temperature and cycle time of the RTA process are represented as a function of the CA temperature in Fig. 4(c). H_{ex} of the specimen undergone RTA once at 200 °C, maintained the as-deposited value of 200 Oe until the CA temperature of 300 °C and was reduced by only 10 Oe at 325 °C. The specimen without the prior RTA showed almost zero of H_{ex} at 325 °C, which suggests that we can increase the stability of H_{ex} by a prior RTA of 10 s at 200 °C before performing the CA. The increase of *MR* for a TMR structure after CA including prior RTA was reported by K. Shin *et al.* [13].

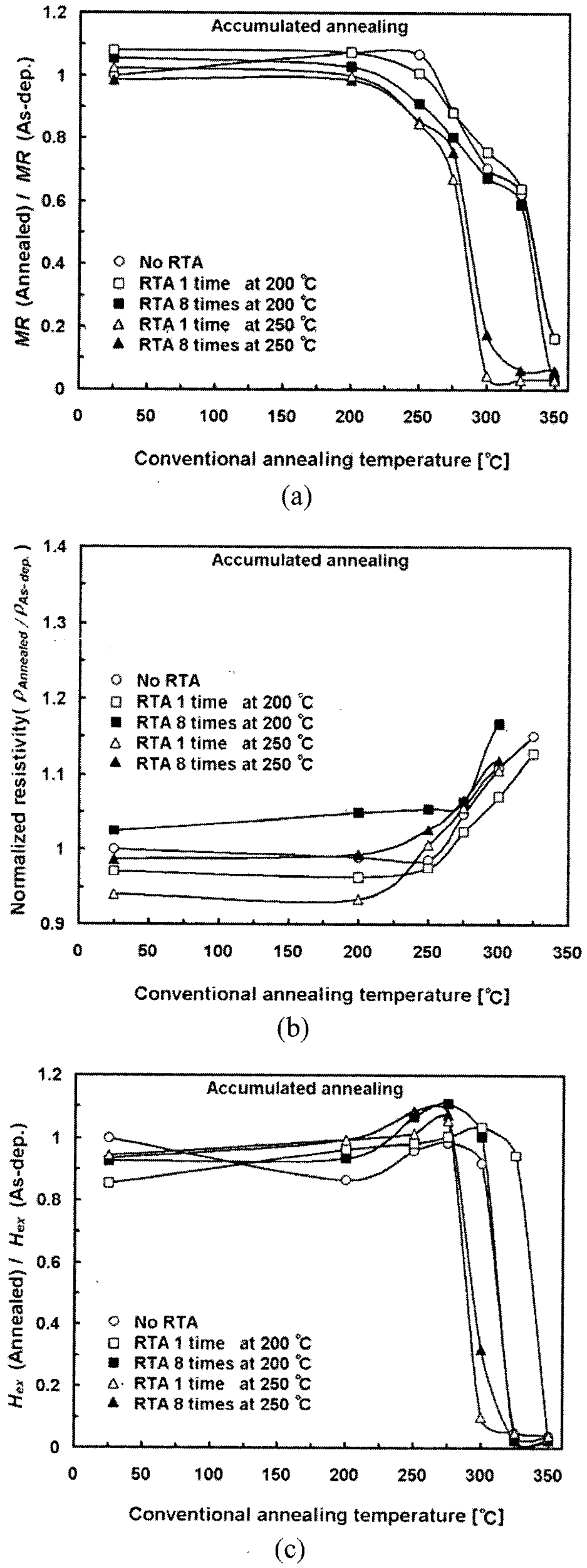

Fig. 4. (a) Magnetoresistance ratio (*MR*), (b) resistivity (ρ), and (c) exchange coupling field (H_{ex}) behaviors of spin valve sensors depending on annealing method, temperature and accumulated cycle time of rapid thermal annealing.

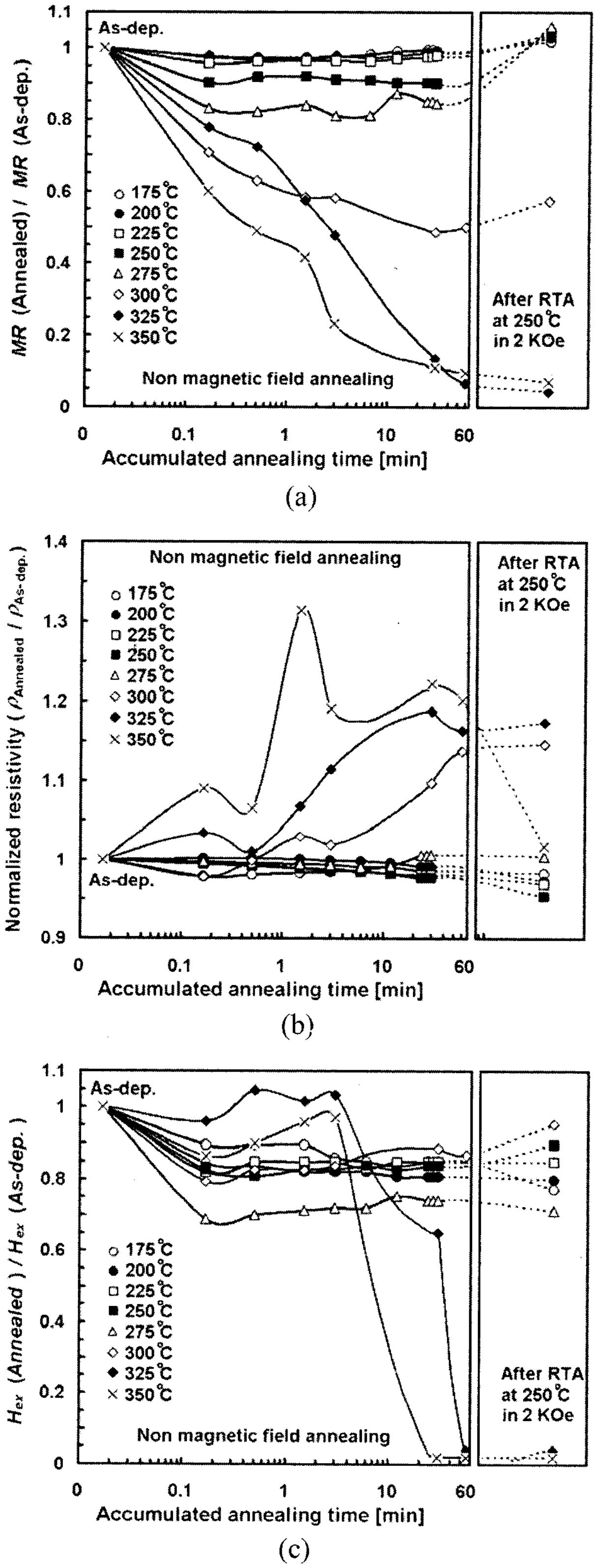

Fig. 5. Normalized (a) Magnetoresistance ratio (*MR*), (b) resistivity (ρ), and (c) exchange coupling field (H_{ex}) behaviors of spin valve sensors depending on annealing temperature and time. The annealing (CA) time was accumulated up to 60 min and then, RTA was performed for 10 s.

In contrast, H_{ex} of the specimens cured by 1 time and 8 times of RTA at 250 °C were decreased to near zero after 300 °C of CA.

Dominant reason for these exchange coupling field behaviors by annealing has been attributed to Mn diffusion from the FeMn layer [7, 8, 13-15]. If the interdiffused regions on the CoFe side of interface of the pinned layer are Mn rich, they are no longer ferromagnetic. Thus the exchange coupling in these regions can not be accomplished. Therefore, the above results show that even a short time of 10 s exposed at 250 °C, is enough to diffuse Mn in the FeMn layer to the CoFe layer and to affect the exchange coupling.

In Fig. 5 shown are the results for annealing experiments without the magnetic field followed by a short RTA. The annealing is performed at different temperatures from 175 °C to 350 °C for an increasing time interval and the accumulated annealing time is indicated in the horizontal axis. The specimens underwent the RTA at 250 °C in 2 kOe of magnetic field for 10 s at the end of CA (total of 60 min.).

Fig. 5(a) shows *MR* behaviors depending on annealing temperature of specimens annealed without magnetic field. The values of *MR* did not change much at all up to annealing temperature of 225 °C. Up to 275 °C, the values of *MR* were decreased in 10 s and the *MR* did not change appreciably afterward. The interesting results of the RTA are shown in the right side of Fig. 5(a). *MR*s of the specimens annealed up to 275 °C were recovered to values even slightly higher than the as-deposited values after longer annealing time. The specimen annealed at 300 °C showed a slight increase of the *MR* and the specimens annealed at higher than 300 °C showed no increase in *MR*.

Fig. 5(b) shows normalized resistivity variations of the specimens used in Fig. 5(a). The resistivity decreased somewhat due to defect reduction and flattened FM/Cu/FM interface at low annealing temperature of up to 275 °C. At higher annealing temperature, the resistivity increased rapidly as the accumulated annealing time was increased, which corresponded to the rapid MR reduction shown in Fig. 5(a).

Fig. 5(c) shows H_{ex} behaviors depending on annealing temperature during the accumulated CA process without magnetic field. H_{ex} is reduced considerably unlike the specimens undergone field annealing even after 175 °C of anneal. H_{ex} reduction occurred within 10 s of annealing and maintained the values afterwards except the specimens annealed at 325 °C and 350 °C. Unlike the *MR*, H_{ex} was not recovered by RTA. Since it is believed that Mn in the FeMn layer is diffused to the CoFe layer resulting in reduction of H_{ex} [7, 8, 13-15], it seems like that Mn diffusion occurs at lower temperature without magnetic field and the Mn diffusion process is irreversible by RTA unlike resistivity.

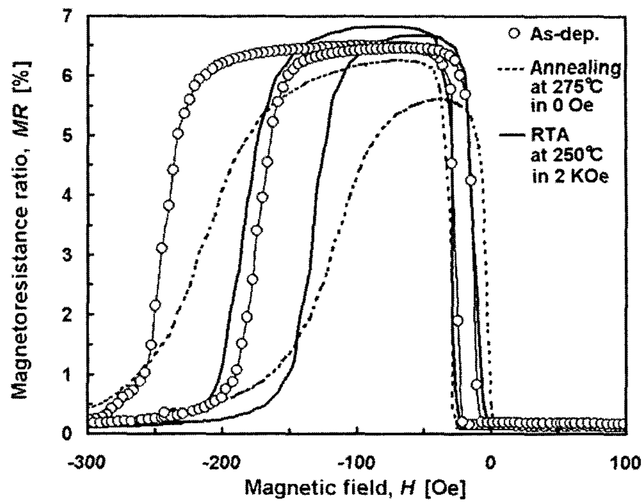

Fig. 6. Recovering *MR-H* characteristics after RTA with applied magnetic field.

Fig. 6 shows *MR* versus magnetic field plots of a spin valve when the spin valve was as-deposited, conventionally annealed at 275 °C without magnetic field, and rapid thermally annealed at 250 °C in 2 kOe for 10 s. The results show that the *MR* was recovered to the values prior to the CA as was indicated in Fig. 5(a). Also, the sensitivity of the *MR-H* curve was recovered, but H_{ex} was not recovered as was indicated in Fig. 5(c). Therefore, 10 s of field RTA at 250 °C was enough to recover the *MR* after CA without magnetic field up to 275 °C. This means that reduced MR sensitivity and *MR* during the device fabrication can be recovered by a field RTA.

4. Conclusion

In this research, *MR*, resistivity, and H_{ex} behaviors for sputter deposited spin valves with FeMn AFM layer have been extensively investigated by RTA as well as CA method.

Firstly, *MR* and H_{ex} results obtained after 10 s of RTA annealing time, revealed that interdiffusion was not significant up to 325 °C at the interfaces between the layers when the RTA time was short.

Secondly, *MR*, resistivity and H_{ex} behaviors depending on annealing temperature and accumulated cycle time of RTA process were investigated. When the RTA temperature was 200 °C, *MR* and resistivity did not change much, but H_{ex} decreased. However, when the RTA temperature was 250 °C, *MR* and resistivity started to decrease, but H_{ex} did not change appreciably from the values at 200 °C.

Thirdly, the *MR* of FeMn spin valves were reduced when they were exposed to temperature of 250 °C, even for a short time period of 10 s prior to CA. H_{ex} was maintained up to 325 °C of CA when the specimen was subjected to 10 s of RTA at 200 °C prior to CA, which was 25 °C higher than the results obtained from CA without prior RTA. Therefore, the stability of H_{ex} could be enhanced by a prior RTA of 10 s at 200 °C before performing CA at higher temperature up to 325 °C.

Lastly, *MR* and sensitivity of the specimens annealed up to 275 °C were recovered to values slightly higher than the as-deposited values but H_{ex} was not recovered by RTA. This means that reduced MR sensitivity and *MR* during the device fabrication can be recovered by a field RTA.

Acknowledgment

This work was supported by Soongsil University research fund.

References

[1] J. Y. Hwang, M. Y. Kim, J. R. Rhee, S. S. Lee, D. G. Hwang, S. H. Lee, and S. C. Yu, IEEE Trans. Magn. **38**(5), 2764 (2002).
[2] G. Reiss, H. Bruckl, A. Thomas, M. Justus, D. Meyners, and H. Koop, J. of Magnetics **8**(1), 24 (2003).
[3] Y. Hu, C. Kim, T. Stobiecki, C. Kim, and K. Hong, J. of Magnetics **8**(1), 33 (2003).
[4] Tsann Lin, Ching Tsang, Robert E, Fontana, and J. Kent Howard, IEEE Trans. Magn. **31**(6), 2585 (1995).
[5] Mao-Min Chen, Ching Tsang, and N. Gharsallah, IEEE Trans. Magn. **29**(6), 4077 (1993).
[6] Tsann Lin, Daniele Mauri, IEEE Trans. Magn. **35**(5), 2607 (1999).
[7] B. K. Kim, J. Y. Lee, S. H. Han, S. K. Lee, and D.G. Hwang, J. Kor. Mag. Soc. **13**(2), 53 (2003).
[8] B. K. Kim, J. Y. Lee, S. S. Kim, D. G. Hwang, S. S. Lee, J. Y. Hwang, M. Y. Kim, and J. R. Rhee, J. Kor. Mag. Soc. **13**(5), 187 (2003).
[9] G. Pan, S. Huo, D. J. Mapps, and W. Clegg, IEEE Trans. Magn. **35**(5), 3916 (1999).
[10] S. W. Kim, J. K. Kim, J. H. Kim, B. K. Kim, J. Y. Lee, S. S. Lee, D. G. Hwang, and J. R. Rhee, J. Appl. Phys. **93**(10), 6602 (2003).
[11] A. Wallash and Y. K. Kim, IEEE Trans. Magn. **34**(4), 1519 (1998).
[12] G. W. Anderson, M. Pakala, and Y. Huai, IEEE Trans. Magn. **36**(5), 2605 (2000).
[13] K. Shin, W. Lee, Y. Park, K. Lee, and J. Ha, Korea patent, 10-0407907 (2003).
[14] V. S. Sperious, J. P. Nozieres, B. A. Gurney, B. Dieny, T. C. Huang, and H. Lefakis, Phys. Rev. B **47**(17), 11579 (1993).
[15] Y. Choi, S. Park, J. Kang, and S. Jo, J. Kor. Mag. Soc. **9**(6), 297 (1999).
[16] Y. Wu, G. Han, and T. Chong, J. Appl. Phys. **89**(11), 7616 (2001).