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Study of annealing and exchange bias effects in PtMn based magnetic tunnel junction system

T. Y. Peng[*,1], **Y. D. Yao**[1,2], **S. Y. Chen**[1], **Y. H. Wang**[3], **W. C. Chen**[3], **M. J. Gao**[3], and **D. D. Tang**[4]

[1] Department of Materials Science and Engineering, National Chiao Tung University Hsinchu 300, Taiwan
[2] Institute of Physics, Academia Sinica Taipei 115, Taiwan
[3] Electronics Research and Service Organization, Industrial Technology Research Institute, Hsinchu 310, Taiwan
[4] Taiwan Semiconductor Manufacturing Company, Ltd, Hsinchu 300, Taiwan

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The crystallization structure and thickness of PtMn layer in a magnetic tunnel junction system are important factors to improve its exchange bias effect. This study shows that the PtMn layer could be changed from a FCC (111) structure to a FCT (111) structure after annealing above 270 °C. The minimum thickness of PtMn layer is found to be 10 nm for exchange coupling effect to be occurred in our MTJ system. The magnetic exchange effect between PtMn and SAF layers is near 4,300 Oe. Annealing temperatures can be higher than 400 °C for samples without patterning; however, temperature at 275 °C is too high for samples after patterning. This may be due to the breakdown of edges of the patterned samples as well as the complicated environments around the patterned samples.

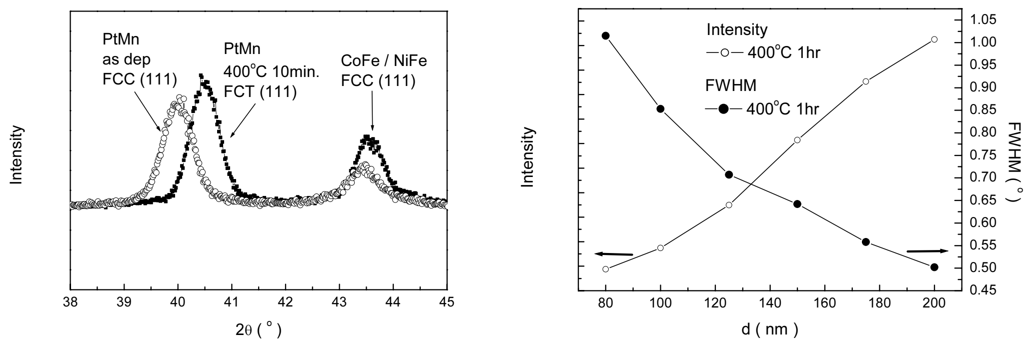
1 Introduction After annealing roughly above 240 °C, the structure of PtMn film will change from a disordered face center cubic (FCC) (111) to an ordered face center tetragonal (FCT) (111) [1–3]. According to Kim et al. [3], the optimal exchange coupling field (H_{ex}) can be obtained for PtMn annealed at 270 °C for 35 hours. The ferromagnetic/antiferromagnetic (F/AF) coupling is a key effect in a magnetic tunnel junction (MTJ) system, and in many cases, the AF layer is arranged by a ferromagnetic/nonmagnetic/ferromagnetic structure named synthetic antiferromagnetic layer (SAF). The enhancement of H_{ex} to near 1,100 and 2,500 Oe had been observed in PtMn/Co/Ru/Co and PtMn/CoFe/Ru/CoFe structures, respectively [4–6]. However, very few studies have been focused on the effect of a short time annealing treatment as well as post-annealing after patterning for MTJ samples with PtMn layer. The purpose of this study is to indicate how the structure, magnetization and the interlayer coupling in MTJ system with PtMn layer varies with the annealing temperature and annealing time. We believe that these results will be useful for a better design of the magnetic random access memory (MRAM) manufacturing process.

2 Experimental methods The MTJ samples were deposited on thermally oxidized Si substrates in a RF multi-target sputtering system. The sample structures were substrate/Ta/NiFe/PtMn (d)/CoFe/Ru/CoFe/Al_2O_3/CoFe/NiFe/Ta, with d = 8, 10, 12.5, 15, 17.5, and 20 nm. X-ray diffraction (XRD) with Cu-K source was employed to verify the crystal structures and phase transformation of the PtMn, CoFe, and NiFe layers. The magnetization and the exchange coupling were measured by a vibrat-

[*] Corresponding author: e-mail: TerencePeng@itri.org.tw

ing sample magnetometer (VSM). The magnetorsistance (MR) was measured by a conventional 4-point probe system.

3 Results and discussion Figure 1 (a) shows the XRD intensity for PtMn, CoFe and NiFe as a function of diffraction angles for samples (with PtMn thickness of 15 nm) without annealing and annealing at 400 °C for 10 minutes. The diffraction peak at 2θ = 40.1° represents PtMn FCC (111) structure, and peak at 2θ = 40.4° is for PtMn FCT (111) structure. This shows clearly that the structure of the sample transformed from FCC (111) to FCT (111) after annealing at 400 °C for 10 minutes. The atomic layer distance between two PtMn structures could be calculated, and it changes from 2.24 Å (FCC) to 2.22 Å (FCT). The diffraction peak at 2θ = 43.5 ° relates to FCC (111) for either CoFe or NiFe layers, roughly speaking, the angle position is almost not changed for this peak, but its intensity increases after annealing. Both XRD intensity and full width at half maximum (FWHM) of PtMn peak for samples with d varied from 8 to 20 nm and annealing at 400 °C for 1 hour are plotted in Fig. 1 (b). It shows that the intensity increases and FWHM decreases monotonically with increasing the thickness of the PtMn layer. In general, these peaks of XRD became stronger and narrower as increasing the thickness and increasing the annealing time. For the XRD peak of CoFe/NiFe FCC (111), after annealing, it also showed stronger intensity and narrower peak. This suggests the improvement of the crystal structure of the magnetic multi-layers after annealing. According to the result shown above, we might suggest that better crystallization structure may provide a channel for Mn to diffuse into magnetic or insulator layers, and it will degrade the MTJ system.

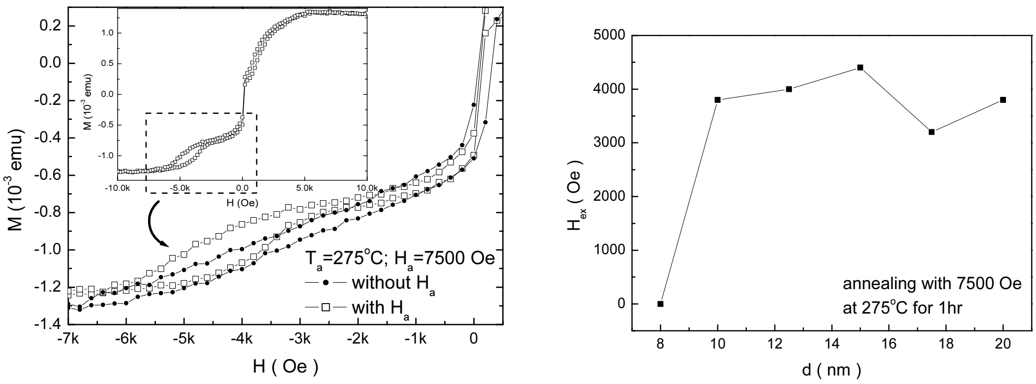


(a) (b)

Fig. 1 (a) The XRD intensity for PtMn, CoFe and NiFe as a function of diffraction angles for samples (with PtMn thickness of 15 nm) without annealing and annealing at 400 °C for 10 minutes. (b) XRD intensity and FWHM of PtMn peak for samples with d varied from 8 to 20 nm and annealing at 400 °C for 1 hour.

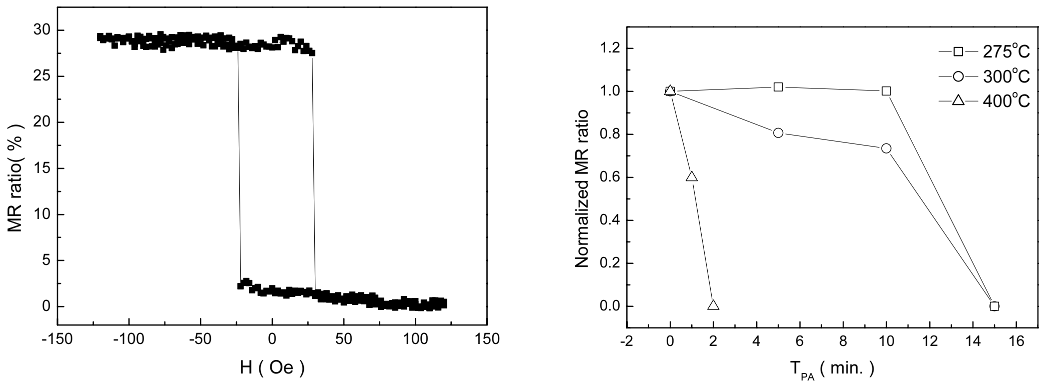
The magnetization as a function of applied magnetic field (H) for samples with d = 15 nm and annealing at 275 °C for 1 hour indicated as the inserted figure in Fig. 2 (a). In Fig. 2 (a) the curve with dots (●) shows data for sample annealing without external magnetic field (H_a); and the curve with squares (□) presents data for sample annealing under an applied field of 7,500 Oe. The hystersis loop near 4,300 Oe is manifested for curve with squares. This is related to the magnetic exchange effect between PtMn and SAF layers. The stronger coupling of SAF with PtMn would make the larger value for the H_{ex} in MTJ. Fig. 2 (b) shows the H_{ex} as a function of the thickness (d) of PtMn layer for samples annealed at 275 °C for 1 hour within magnetic field of 7,500 Oe. H_{ex} is almost near zero for d ≦ 8 nm, and it increases to

4,000 Oe for samples with d ≧ 10 nm. Besides, our studies told us that if the field during annealing was not strong enough, the H_{ex} would not be induced or showed a smaller value. In the annealing cases with temperature higher than 400 °C, the H_{ex} would not found even with annealing time as short as 10 minutes.



(a) (b)

Fig. 2 (a) The PtMn base MTJ showed stronger H_{ex} after field annealing (□) (T_a = 275 °C, H_a = 7,500 Oe) near 4,300 Oe instead of the weaker H_{ex} after annealing without field (●). (b) H_{ex} induced by PtMn was as a function of PtMn thickness (d).



(a) (b)

Fig. 3 (a) The MR loop of the PtMn based MTJ after patterning showed a MR ratio near 30 %. (b) Normalized MR ratio versus post-annealing time, T_{PA}, for different annealing temperature.

For investigating the practical usage of our samples in the MRAM system, the MR was studied for samples after patterning. The MTJ sample with d = 15 nm, which had an ellipse shape with 2:1 ratio between long axis and short axis, showed near 30% MR ratio after annealing with 270 °C for 5 hours at 8.5 kOe field as shown in Fig. 3 (a). Figure 3 (b) shows the MR ratio of the sample in Fig. 3 (a) measured as a function of post-annealing time (T_{PA}). It is clear that 400 °C is too high for our patterned samples. However, in the temperature range near 275 °C, 10 minutes is the up-limit for our samples. By comparing the annealing processes of our samples with and without patterning, it shows clearly that the annealing temperatures can go up to 400 °C to improve the structure of samples without patterning. However, annealing temperature of 275 °C is too high for samples after patterning. The structure phase transformation temperature for PtMn is near 270 °C, and, therefore, annealing process above 270 °C for samples without patterning is necessary. For samples after patterning, the degrading of MR ratio might be come from the breakdown of the edges of the patterned samples as well as the complicated environments around the patterned samples.

4 Conclusion The annealing and exchange coupling effects of the PtMn based MTJ was studied experimentally. The structure of PtMn layer in our MTJ system is transformed from FCC (111) to FCT (111) with annealing temperatures above 270 °C. The minimum thickness of PtMn layer is 10 nm for exchange coupling effect to be occurred in our MTJ system. The magnetic exchange effect between PtMn and SAF layers is near 4,300 Oe. Annealing temperatures can be higher than 400 °C for samples without patterning; however, temperature at 275 °C is too high for samples after patterning. This may be due to the breakdown of edges of the patterned samples as well as the complicated environments around the patterned samples.

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