The thermal decay in the IrMn-based spin valve

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Abstract. Thermal decay of the top spin valve with a structure of // Seed Ta (5nm) / Co₁₇Fe₂₅ (5nm) / Cu (2.5nm) / Co₁₇Fe₂₅ (5nm) / Ir₂₀Mn₈₀ (12nm) / Cap Ta (8nm) deposited at room temperature by magnetron sputtering has been investigated by means of holding the film in its negative saturation field at various temperatures. Vibrating sample magnetometer has been used to record the magnetic hysteresis loops at room temperature. The recoil loop of the pinned ferromagnetic layer shifts towards the positive field and the exchange bias field \( H_{ex} \) decreases monotonously while holding the film in a negative saturation field. The decrease of \( H_{ex} \) while holding the film in a negative saturation field indicates a thermally decay process. Due to the exchange coupling at the antiferromagnetic/ferromagnetic interface, the antiferromagnetic moments reverse by thermal activation over an energy barrier distribution, which may change in some way as the temperature increases.

1. Introduction
Thermal stability is one of key factors concerned in spin valve heads for high density recording systems and related giant magnetoresistance devices. The thermal decay of exchange bias of antiferromagnetic (AFM) layer to the pinned ferromagnetic (FM) layer results from the fact that the unidirectional anisotropy of the AFM layer decreases, and thus the AFM layer gradually loses its pinning effect to the FM layer, as the temperature increases and/or holding the film at a negative saturation field of the pinned FM layer. It is important for the AFM layer in the exchange coupled structure to keep enough pinning effects at high temperature since the operating temperature of magnetoerotic devices is sometimes higher than 100 °C [1]. Thermal decay becomes more critical for Mn alloy based spin valves because the Mn in the AFM layer can diffuse into adjacent layers easily [2]. The effect of temperature on the exchange bias field \( H_{ex} \) has been studied extensively [3-5]. The time dependence of the reversal of the AFM layer has also been studied by measuring the recoil loops of films spent different periods of time while the pinned FM layer maintained at its negative saturation at various temperatures [6,7].

The thermal decay is a long-term gradual degradation of exchange anisotropy under an applied magnetic field. Usually, in decay testing, an accelerated method, i.e., testing at a high temperature, is used, since testing for long time at room temperature (RT) is unpractical. The aim of this work is to find out the intrinsic stability of the spin valve by means of holding the film in a negative saturation field at various temperatures. Testing temperatures were selected properly in order to accelerate the thermal decay while not damage the film.
2. Experimental Details

The spin valve with a structure of //Seed Ta (5nm) / Co\textsubscript{75}Fe\textsubscript{25} (5nm) / Cu (2.5nm) / Co\textsubscript{75}Fe\textsubscript{25} (5nm) / Ir\textsubscript{20}Mn\textsubscript{80} (12nm) / Cap Ta (8nm) was deposited by magnetron sputtering on silicon wafer substrates with a thermally oxidized surface. The deposition conditions were: base pressure <5×10\textsuperscript{-7} Pa, Ar sputtering pressure 7×10\textsuperscript{-3} Pa, deposition rate 0.03~0.12 nm/s. An electromagnetic field of 100 Oe was applied in order to induce magnetic anisotropy during FM and AFM films sputtering.

The magnetometry measurements were made using a vibrating sample magnetometer (VSM) equipped with a heater, which is used for in-suit heating in this study. The sweep-rate was kept constant at 3 Oe/s for all measurements. The magnetic field was applied parallel or antiparallel to the unidirectional easy axis (UEA), which coincides with the direction of the field applied during film growth.

Waiting time experiments have been undertaken at various temperatures. Testing temperatures are selected as RT, 50 °C, 75°C, 100°C and 125°C. Individual spin valve specimen is first held in a negative saturation field at a given temperature for various periods of time, and then the hysteresis loop is recorded at RT. The hysteresis loop was recorded from the positive saturation field of the film and the applied field was swept to a negative value, which saturates the pinned FM layer in the opposite direction to its initial state. The film was then held at negative saturation field for a given period of time $t_{\text{sat}}$. During this waiting time, some proportion of the AFM layer was expected to reverse as a result of the exchange coupling between the pinned FM and AFM layers and driven by thermal activation. The recoil loop was finally measured as the applied field swept to the starting point. The reversal of the pinned FM layer and therefore the loop position will be governed by the proportion of AFM layer which has reversed. The procedure was repeated for a different value of $t_{\text{sat}}$ so that a cumulative effect of waiting time was observed.

It is evident that the hysteresis loop for an exchange biased spin valve will be complex due to the thermally activated reversal of the AFM layer. A classical seven point model of the reversal process in the pinned layer of an exchange biased system has been suggested by Goodman \textit{et al.} [8], which describes the loop of the pinned layer by emphasizing seven important features common to a large range of systems (shown in Figure 1). These seven points will be used as an aid to discussion in our study. Also shown on the diagram are the definitions of the forward and recoil coercive fields ($H_{m}$ and $H_{d}$; respectively) and the exchange field ($H_{ex}$).

![Figure 1. Schematic diagram of the hysteresis loop for a spin valve structure showing the seven-point model.](image-url)
3. Results and discussion

A series of hysteresis loops for the pinned layer recorded at RT after held at its negative saturation for different periods of time, $t_{\text{sat}}$, are shown in Figure 2. Only the pinned layer loops have been shown for clarity. As the AFM layer is not reset in between recorded loops so the magnetizing branches of the loops are not identical. The shift in the recoil loop ($H_d$) is used to characterize the degree of AFM reversal, which represents the point at which 50% of the pinned FM layer has reversed and so it also represents the position on the recoil loop at which the reversal of the AFM layer ceases. Beyond this point, the AFM layer will begin to reverse in the opposite direction as the net FM moment has reversed. Furthermore, the shifting of $H_d$ towards positive field means that some proportion of the AFM layer has reversed while the pinned layer is held at a negative saturation, i.e., waiting at point 4 the AFM layer is reordering and the shift of the loop at point 7 towards positive fields is corresponding to the degree of this reordering.

Figure 2. Hysteresis loops for the pinned layer of the spin valve, with different waiting time $t_{\text{sat}}$ at negative saturation of the pinned layer. The lines are an aid to eyes.

Figure 3 shows the exchange bias field $H_{\text{ex}}$ as a function of time for films held in a negative saturation field at various temperatures. Firstly, one can see that the exchange field $H_{\text{ex}}$ measured at RT decreases as the temperature, at which specimens have been experienced shortly, increases. This may arise from the interlayer interdiffusion and strain relief. This observation agrees well with ref. [9]. Secondly, the exchange bias field decreases while holding the film in a negative saturation field at a given temperature. This decay of the pinning field is believed to be a result of thermal activation occurred in the AFM layer, which has been well discussed [6,7,10,11]. Finally, one can see that increasing the temperature at which the film has been held at its negative saturation enhances the decay of exchange field.

The two energy barriers model was used to explain the thermal activation phenomena [12, 13]. In that model the energy barrier with small time constant contributes the enhanced coercivity of the pinned FM layer and that with large time constant results in the thermal decay of the exchange bias field. As a magnetic field was applied at the deposition of the spin valve, it is believed that in the deposition state, the AFM moments are along the initial pinning direction and parallel to the adjacent FM moments. Some portion of the AFM moments are easy to reverse to the opposite direction over the energy barrier with small time constant, which results in the enhanced coercivity of the pinned FM layer. Most of the AFM moments need to overcome a high energy barrier (with large time constant) to reverse to their opposite direction. As a result of that the AFM moments stay along the initial pinning direction if there is no field applied in the heating process and no change occurs in the bias field. However, when there is an applied field of 800Oe antiparallel to the initial bias field, the FM moments

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Symposia D, E and F from MRS International Materials Research Conference  
Journal of Physics: Conference Series 152 (2009) 012037  
doi:10.1088/1742-6596/152/1/012037
are at negative saturation and antiparallel to the unidirectional easy axis of the AFM layer. This state is not the lowest energy state due to the high exchange energy at the FM and AFM interface. The lowest energy state is another state, in which the AFM moments and the FM moments are parallel, i.e. both parallel to the negative magnetic field. Thus the AFM moments tend to reverse from the positive direction to the negative direction. The height of the energy barrier between these two states is determined by the anisotropy energy of the AFM layer and the exchange interaction energy between the FM layer and the AFM layer. Since the anisotropy energy of AFM layer is given by the product of the anisotropy constant $K_a$ and the volume of the AFM grains, a smaller AFM grain has a lower energy barrier. As a result, a smaller AFM grain reverses its moment more easily than a larger AFM grain by thermal activation. The reverse process is a dynamic process and the number of reversed AFM grains increases over time, which results in the $t_{sat}$ dependence of $H_{ex}$.

The different rate of the change of the $H_{ex}$ with $t_{sat}$ at different temperature indicates that the energy barrier distribution may be different. Coherent rotation of the AFM moments is used to be assumed, which means that all the spins in an AFM grain overcomes the highest anisotropy energy at a same time during its reversal process. However, if incoherent rotation occurs in an AFM grain, only some portion of the spins go through the highest energy site at the one time during the reversal process. Previous studies [5,14] show that a twisting pattern of spins may appear in the AFM layer in the reversal process at elevated temperature. This kind of incoherent magnetic reversal of the AFM layer needs relatively low and wide activation energy distribution than does the coherent rotation of the AFM layer. Incoherent rotation is probably dominant above 75 °C, which results in an enhanced decay of exchange bias field.

Figure 4 shows the $t_{sat}$ dependence of the $H_d$. One can see that the $H_d$ has an approximately logarithmic dependence on $t_{sat}$ as indicated by the fitted straight lines. As $t_{sat}$ increases, the degree of the AFM moment reverse, and thus the loop shift, increases. The logarithmic dependence observed here agrees well with previous work [15]. In reality, the thermal decay follows a logarithmic law, which results from a distribution of energy barrier over which the AFM moments reverse. One can also see that the increase of the temperature at which the film is held at negative saturation has accelerated the reversal of the AFM moments, which agrees well with the prediction that the energy barriers over which the AFM moments reverse decreases as the temperature increases.

![Figure 4](image)

**Figure 4.** The field at which point 7 occurs in the hysteresis loop, $H_d$, is plotted against $\ln(t_{sat})$. The solid line is a logarithmic fitting.

There is another point one should note that these straight lines have different slopes, although they almost all obey the logarithmic law at temperatures studied. The slope increases with the temperature increasing up to 75°C and as the temperature increases further the slope reduces. This implies that the
energy barrier may be changed in some way as the temperature increases. The origin of this phenomenon is still unclear.

4. Conclusion
It has been shown that the recoil loop of the pinned FM layer shifts towards positive fields and $H_{ex}$ decreases monotonously while holding the film in a negative saturation field at various temperatures. The decrease of $H_{ex}$ while holding the film in a negative saturation field indicates a thermally decay process. Due to the exchange coupling at the AFM/FM interface, the AFM moments reverse by thermal activation over an energy barrier distribution, which may change in some way as the temperature increases.

Acknowledgements
This work is supported by the National Natural Science Foundation of China under grant No.50671048. The authors wish to acknowledge Professor Xiu-feng Han in the Institute of Physics (CAS) for the support on the preparation of specimens.

Reference
[1] Prakash S, Pentek K, and Zhang Y 2001 IEEE Trans. Magn. 37 1123
[2] Yoon S Y, Lee D H, Jeon D M, Kim J H, Yoon D H and Suh S J 2004 J. Magn. Magn. Mater. 272-276 1879
[3] Anderson G W, Huai Y, and Pakala M 2000 J. Appl. Phys. 87 5726
[4] Mao S, Mack A, Singleton E, Chen J, Xue S, Wang H, Gao Z, Li J, and Murdock E 2000 J. Appl. Phys. 87 5720
[5] Nishioka K, 1999 J. Appl. Phys. 86 6305
[6] Hughes T, O’Grady K, Laidler H, and Chantrell R W 2001 J. Magn. Magn. Mater. 235 329
[7] Hughes T, Laidler H, and O’Grady K 2001 J. Appl. Phys. 89 5585
[8] Goodman A M, Laidler H, O’Grady K, Owen N W, and Petford-Long A K 2000 J. Appl. Phys. 87 6409
[9] Rickart M, Guedes A, Franco N, Barradas N P, Diaz P, MacKenzie M, Chapman J N and Freitas P P 2005 J. Phys. D: Appl. Phys. 38 2151
[10] Heijden P A A van der, Maas T F M M, Jonge W J M de, Kools J C S, Roozeboom F, and Zaag P J van der 1998 Appl. Phys. Lett. 72 492
[11] Heijden P A A van der, Maas T F M M, Kools J C S, Roozeboom F, Zaag P J van der, and Jonge W J M de 1998 J. Appl. Phys. 83 7207
[12] Wang Y G and Petford-Long A K 2002 J. Appl. Phys. 92 6699
[13] Wang Y G, Petford-Long A K, Hughes T, Laidler H, O’Grady K, and Kief M T 2002 J. Magn. Magn. Mater. 242-245 1081
[14] Stamps R L 2000 Phys. Rev. B 61 12174
[15] Gaunt P 1986 J. Appl. Phys. 59 4129