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Thermally activated magnetization reversal in magnetic tunnel junctions*

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In this paper, the magnetization reversal of the ferromagnetic layers in the IrMn/CoFe/AlO_x/CoFe magnetic tunnel junction has been investigated using bulk magnetometry. The films exhibit very complex magnetization processes and reversal mechanism. Thermal activation phenomena such as the training effect, the asymmetry of reversal, the loop broadening and the decrease of exchange field while holding the film at negative saturation have been observed on the hysteresis loops of the pinned ferromagnetic layer while not on those of the free ferromagnetic layer. The thermal activation phenomena observed can be explained by the model of two energy barrier distributions with different time constants.

Keywords: magnetic tunnel junctions, magnetization reversal, thermal activation, exchange coupling

PACC: 7560, 7570

1. Introduction

Magnetic tunnel junction (MTJ) is a key component for the new generation of spintronic devices such as magnetic random access memory, ultrahigh-density magnetic recording heads and spin-logic devices due to their high-tunnel magnetoresistance.[1−4] For these applications the most useful MTJs are exchange-biased structures in which one of the ferromagnetic (FM) layers is pinned by exchange bias with an antiferromagnetic (AFM) layer.[2] Recently, many experimental results have been published on the thermally activated magnetization reversal of the FM layer in exchange coupled bilayers[5−7] and spin valves.[8,9] It is believed that the hysteresis loop for an exchange biased MTJ will be complex due to the thermally activated reversal of the AFM layer. The reversal mechanism of the pinned FM layer depends not only on the characteristics of the FM layer but also on the interaction between the FM layer and the underlying AFM layer. The interaction with the AFM layer is responsible for both the shift and broadening of the hysteresis loop for the pinned FM layer.

In recent years, the model with two energy barriers was used to explain the thermal activation phenomenon.[7,10] In that model, it is assumed that two energy barrier distributions with different time constants coexist. 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 during the deposition of the film, it is believed that in the deposited state, the AFM moments are aligned along the initial pinning direction and parallel to the adjacent FM moments. A small part 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. However, when there is a saturated applied field antiparallel to the initial bias field, the FM moments are at negative saturation and antiparallel to the unidirectional easy axis of the AFM layer and this is not the lowest energy state due to

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the high exchange energy at the FM and AFM interface. The AFM moments tend to reverse from the positive direction to the negative direction and result in the thermal decay of the exchange bias field. These reversals progress either through coherent reversal of AFM grains or formation and growth of reversed AFM domains.[7,11]

Although MTJ devices are in commercial production and used widely in many fields as mentioned above, study on the thermally activated magnetization reversal in MTJ has not been reported. In this paper, we have investigated how the entire hysteresis loop of the IrMn/CoFe/AlO_x/CoFe MTJ, which reflects the reversal behaviour of both free and pinned layers, is affected by the thermal activation. Special attention has been paid to the difference of the magnetization reversal of the pinned and free FM layers.

2. Experimental details

The MTJ with a structure of // Seed Ta(5 nm) /$Ir_{20}Mn_{80}$(12 nm) / Co_{75} Fe_{25}(5 nm)/AlO_x(0.8 nm) /$Co_{75}Fe_{25}$(5 nm)/ Cap Ta(8 nm) was deposited by magnetron sputtering on silicon wafer substrates with a thermally oxidized surface. The deposition conditions were: base pressure $< 5\times10^{-7}$ Pa, Ar sputtering pressure 7×10^{-2} Pa, deposition rate 0.03–0.12 nm/s. The tunnel barrier was formed by in situ oxidation of a 0.8 nm thick Al layer. An electromagnetic field of 100 Oe (1 Oe = 80 A/m) was applied during sputtering of the FM and AFM layers in order to induce unidirectional magnetic anisotropy. After deposition the films were annealed at 275°C for 1 h in a magnetic field of 3000 Oe parallel to the orienting field.

The magnetometry measurements were made using a vibrating sample magnetometer (VSM). The sweep-rate was kept constant at 3 Oe/s in order to keep contributions from time-dependent effects the same for all the specimens. 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.

In order to investigate the reversal of the AFM layer and in particular its thermal activation, we have concentrated on the reversal process of the AFM layer when the pinned layer is negatively saturated. At this point, there is an approximately constant exchange field present at the interface. The degree of the reversal of the AFM layer could be inferred by examination of the pinned FM layer hysteresis loops measured after the film has been held at negative saturation field of the pinned FM layer for a period of time t_{NS}. By varying t_{NS}, the time dependence of the AFM reversal can be studied. 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_{NS}. 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 given value of t_{NS} so that a cumulative effect of waiting time was observed.

3. Results and discussion

Figure 1 shows an initial hysteresis loop measured at room temperature. It is of interest to note that not only has the pinned layer loop shifted along the axis as expected but also there is a small shift in the free layer loop which shows the complexity of the reversal in this layer. This complexity and the shift in the free layer loop along the field axis are believed to result from the coupling between the layers which can be reasonably accounted for by the Néel dipolar orange-peel coupling.[12]

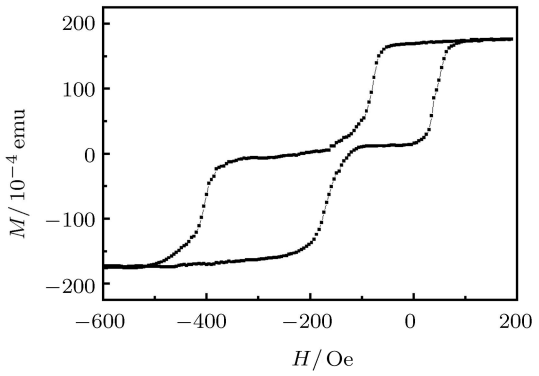


Fig.1. Hysteresis loop for the IrMn/CoFe/AlO_x/CoFe MTJ.

The experimental results show that the reversal mechanism of pinned FM layer in MTJs is very com-

plex. An asymmetry in reversal, a coercivity enhancement, a training effect, and a shift of hysteresis loop towards zero field while holding the film at its negative saturation are all observed. From Fig.1 one can clearly see a loop broadening and the asymmetry on the hysteresis loop of the pinned FM layer compared with that of the free FM layer.

The training effect of exchange bias is referred to the phenomenon that the exchange field decreases with consecutive hysteresis loop measurements. Figure 2 shows the exchange field in the training process in an MTJ. During hysteresis loop measurements, the FM magnetization reverses instantly to align with the applied field, leaving the AFM grains in the position that is not energetically favoured. Consequently, the AFM grains tend to overcome the unidirectional anisotropy energy barriers via thermal activation in order to switch over to reach the lower energy state. As the number of magnetization cycles increases this reversed proportion approaches some equilibrium value so that the difference between a loop and the subsequent one becomes smaller. The training effect on the forward branch of the loop is believed to be a result of thermal activation with a small time constant.

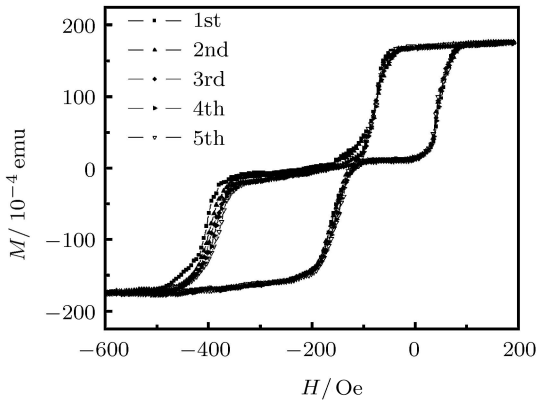


Fig.2. Sequentially recorded hysteresis loops for the IrMn/CoFe/AlO_x/CoFe MTJ showing a training effect.

In fact, the underlying mechanism for this result is the same as that leading to the exchange bias reduction and reversal observed in the earlier experiments[13,14] and explained in our previous study.[7] There are two kinds of behaviours capable of occurring simultaneously for the AFM grains during the relaxation process, i.e., the forward and recoil branches of the hysteresis loop follow different mechanisms of magnetization reversal. While coherent rotation has been observed at the coercive field H_{c2}, domain nucleation and wall propagation dominate in the vicinity of H_{c1}. The large training effect observed between the first and second loops originates here from pure 180° domain wall movement, which takes place at H_{c1} during the first magnetization reversal.[15] Very recent Monte Carlo simulations show that the asymmetry of the reversal modes depends on the angle between the AFM easy axis and the applied field in heterostructures which fulfil the prerequisites of the domain state model.[16]

The effect of waiting at negative saturation of the pinned FM layer for different periods of time, $t_{\rm NS}$, (up to 100000 s) was studied. Figure 3 shows the reduction of exchange field $H_{\rm ex}$ as $t_{\rm NS}$ increases. One can see that the entire hysteresis loop shifted along the

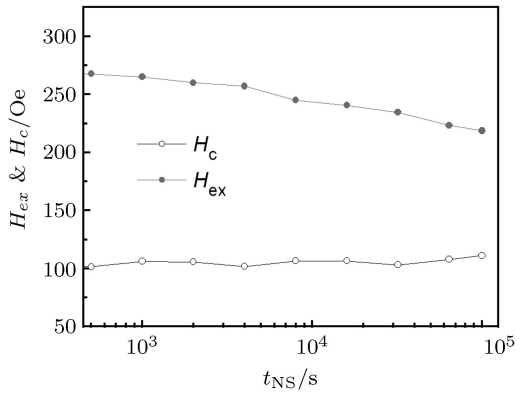


Fig.3. H_{ex} & H_c of the pinned FM layer as a function of $t_{\rm NS}$ for the IrMn/CoFe/AlO_x/CoFe MTJ. The solid lines are a guide for the eye.

applied field axis, resulting in a decrease in the offset of the loop with respect to zero field as $t_{\rm NS}$ increases. Figure 4 shows selected hysteresis loops for $t_{\rm NS} = 0$, 1000, 32000, and 100000 s. It can be seen that the

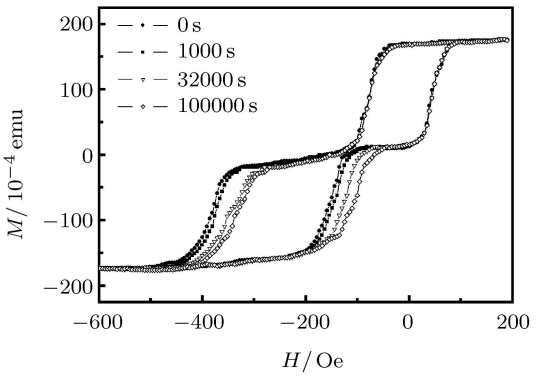


Fig.4. Hysteresis loops for the IrMn/CoFe/AlO_x/CoFe MTJ held at a negative saturation field for different periods of time $t_{\rm NS}$.

coercivity of the pinned FM layer and the mechanism by which the forward and recoil reversals occur remained almost unchanged for values of t_{NS} up to 100000 s. One should note that the waiting time effect is similar to that observed in CoFe/IrMn exchange-coupled bilayers[7] and in NiFeCo/Cu/NiFeCo/FeMn spin valves.[8] It should also be noted that, similar to that reported in Ref.[10], if the film was held at positive saturation between each loop for a period of time $3t_{NS}$, the recoil loop has shifted but the forward loop has not.

As observed in CoFe/PtMn[6] and CoFe/IrMn[7] exchange coupled bilayers and NiFeCo/Cu/NiFeCo/FeMn spin valve structure[8], the waiting time effect of the exchange coupling between pinned FM layer and the adjacent AFM layer is believed to be a result of the reversal of magnetization in regions of the AFM layer driven by thermal activation over a high energy barrier distribution (large time constant), which occurs when the film is held at negative saturation. With t_{NS} increasing, the exchange coupling between the pinned FM and AFM layer causes more of the AFM layer magnetization to rotate antiparallel to the UEA, and thus reduces the original unidirectional anisotropy, which results in a shift of the recoil loop towards zero. Furthermore, a shift of the forward loop towards zero occurs because the film is not held at positive saturation. This can be explained by that more of the AFM moment is exchange coupling the pinned FM moment antiparallel to the original UEA, which lowers the energy barrier to reversal of the pinned FM layer along the forward loop. As t_{NS} increases, the degree of AFM moment rotation is increased and the loop shift increases. As also shown in Fig.4, the coercivity of the pinned FM layer remains almost unchanged while holding the film at its negative saturation and the slight variation observed is believed to result from the training effect as these loops are recorded right after holding at the negative saturation field without any cycling between negative and positive magnetic fields. The fact that there is no change in the reversal mechanism with t_{NS} increasing can be explained as follows: the domain structure and the magnetization reversal process along the forward loop are dominated by the pinned FM layer rather than by the AFM layer and, therefore, do not change. In addition, no change of the recoil loop reversal mechanism is seen because the extra pinning sites induced by the thermally activated reversal of the AFM are more widely spaced than those that give rise to the loop broadening.

It is clear that no training effect or waiting time effect can be observed in the free FM layer. As the composition and thickness is the same for the free FM layer and the pinned FM layer, the magnetization reversal mechanism of the free FM layer should be similar to that of the pinned FM layer. The different phenomena observed on the training effect and waiting time effect for the free and pinned layer demonstrate that the training effect and waiting time effect must be a result of the reversal of magnetization in regions of the AFM layer driven by thermal activation through the exchange coupling between the pinned layer and adjacent AFM layer.

4. Conclusion

The magnetization reversal of the pinned FM layer in MTJs exhibits a very complex behaviour resulting from its complex structure. The asymmetry of reversal, the loop broadening and the training effect have been observed on the hysteresis loops of the pinned FM layer. The exchange bias field H_{ex} decreases while the film is held at its negative saturation. No training effect or waiting time effect can be observed in the free FM layer. It is believed that the training effect and waiting time effect in MTJs is a result of the reversal of magnetization in regions of the AFM layer driven by thermal activation through the exchange coupling between the pinned FM layer and adjacent AFM layer, which can be explained by the model of two energy barrier distributions with different time constants.

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