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Thermally Activated Reversal in Exchange-Coupled Structures

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***Abstract*—In this paper, we study the thermally activated reversal of IrMn/CoFe exchange-coupled structures using Lorentz microscopy and magnetometry. An asymmetry and a training effect were found on the hysteresis loops both with and without holding the film at negative saturation of the ferromagnetic layer. Holding the film at negative saturation results in the hysteresis loop shifting toward zero field. We believe that, in this system, two energy barrier distributions with different time constants coexist. The large-time-constant thermally activated reversal of the antiferromagnetic layer contributes to a increasing shift of the entire hysteresis loop toward zero field with increased period of time spent at negative saturation of the ferromagnetic layer. The small-time-constant thermal activation contributes to asymmetry in the magnetization reversal and training effects.**

***Index Terms*—Exchange-coupling, IrMn/CoFe, magnetization reversal, thermal activation.**

I. Introduction

EXCHANGE coupling at the interface between a ferromagnetic (FM) layer and an antiferromagnetic (AFM) layer results in several unique macroscopic magnetic properties, such as an offset of the hysteresis loop and an enhanced coercivity of the FM layer [1]. Various devices with applications in information storage, such as spin-valves and spin-tunnel junctions, rely critically on exchange coupling between an AFM layer and an FM layer, and because of this the exchange coupling at the AFM/FM interface has been the subject of a great deal of theoretical and experimental study [2], [3]. It is believed that the interface spin structure does not remain stable below T_N if large enough fields are applied [4], but that reversal of the AFM layer takes place when the adjacent FM layer reverses because of the exchange field on the AFM layer exerted by the FM layer [5]–[9]. This reversal process is driven by thermal activation over an energy barrier distribution of some form. The reversal of the AFM layer has been modeled theoretically [10] and observed experimentally [5], [6], [8], [10], [11]. This effect results in a shift of the entire hysteresis loop toward zero field while the FM layer is at negative saturation.

Here, we have investigated the reversal mechanism in IrMn/CoFe exchange-coupled films with different IrMn AFM layer thickness (d_{AFM}) using Lorentz transmission electron microscopy (LTEM) and magnetometry. LTEM gives local information about the magnetization reversal mechanism and vibrating sample magnetometry (VSM) gives bulk information about the reversal.

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II. Experimental Details

The //seed(5 nm)/Cu(1 nm)/$Ir_{30}Mn_{70}$(x nm)/$Co_{90}Fe_{10}$ (10 nm)/Ta(5 nm) exchange-coupled films with $x = 10$, 7 and 5 (referred as S10, S7, and S5, respectively) were deposited by magnetron sputtering on Si wafer substrates. Substrates for LTEM had an electron transparent Si_3N_4 membrane covering a window in the Si. The films were deposited, and post-annealed at 250 °C for 2 h, in a magnetic field. No remarkable differences were detected between the microstructure of films with different AFM layer thickness.

The magnetization reversal of the exchange-coupled films was followed in real-time using the Fresnel mode of LTEM in a JEOL 4000EX TEM operated at 400 kV and modified by using a low-field objective lens in which the specimen sits in a field-free region. A variable in-plane magnetic field between ±400 Oe was applied *in-situ* in the TEM parallel or antiparallel to the unidirectional easy axis (UEA), which coincides with the direction of the field applied during the film growth and annealing. This implies that there is little or no spin flop coupling between the AFM and FM moments at the interface. The magnetic measurements were made using a vibrating sample magnetometer. In the waiting time experiment a cumulative procedure was used and the films were held at negative saturation of the FM layer for various period of time t_{ns}. In the experiments on the sweep rate dependence, the time spent at positive or negative saturation is reasonably short (few seconds) in order to avoid possible thermal activation happening at these stages. We change the sweep rate by changing the time at each field step or by changing the field step size itself.

III. Results and Disscussion

Fig. 1 shows the effect on the forward and recoil reversals of cycling the film several times around the hysteresis loop in quick succession. A training effect (i.e., shift of the loop with successive cycles) is observed, either on the forward reversal [Fig. 1(a)] if $t_{ns} = 0$, or on the recoil reversal for $t_{ns} > 0$ [Fig. 1(b)].

The effect of waiting at negative saturation of the CoFe layer for different t_{ns} was also studied using LTEM. Before following each loop the field has been cycled three to five times in order to remove the training effect. As t_{ns} was increased the entire hysteresis loop shifted along the $\mathbf{H_a}$-axis, resulting in a decrease

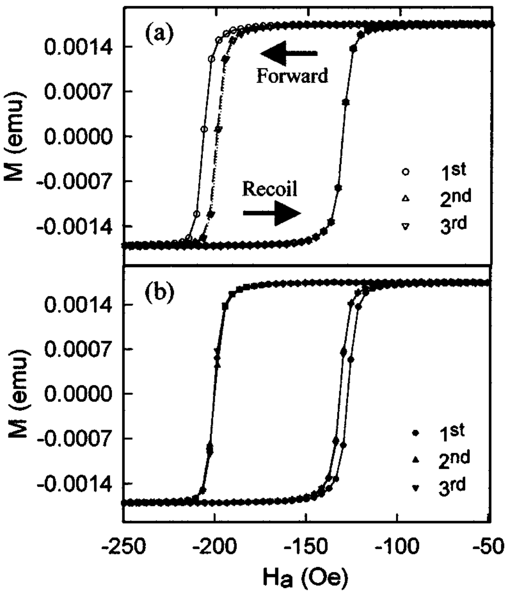

Fig. 1. VSM hysteresis loops of IrMn(10 nm)/CoFe(10 nm). The sequentially recorded loops are numbered and show a training effect. (a) $t_{ns} = 0$ and (b) $t_{ns} = 900$ s.

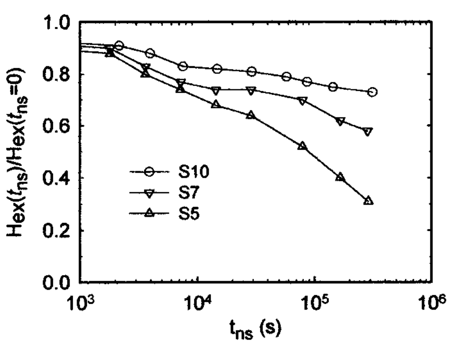

Fig. 2. $H_{ex}(t_{ns})/H_{ex}(t_{ns} = 0)$ as functions of t_{ns} for the IrMn/CoFe system from Lorentz TEM data. The solid lines are guide for eyes.

in the offset of the loop with respect to zero field. Fig. 2 shows the reduction of exchange field as t_{ns} increases. It should be noted, however, that the coercivity of the pinned CoFe layer and the mechanism by which the forward and recoil reversals occurs remained identical to those for zero wait time, for values of t_{ns} up to 84 h.

In order to determine the influence of thermal activation on domain growth, the domain dynamics were investigated by waiting at a field part way along the forward branch of the hysteresis loop. Reversal of the FM layer continued to occur even when the field was kept constant, as shown in the Fresnel mode LTEM images of a region of film S10 seen in Fig. 3.

We have also measured the sweep rate dependence of H_{c1} and H_{c2} (field at which the magnetization equals zero on the forward and recoil branches of the loop, respectively). As shown in Fig. 4, a linear relation between H_{c1} or H_{c2} and Log_{10}(sweep rate) is present, but two different slopes appear for the sweep rate range studied.

The training effect is believed to be a result of thermal activation with a *small* time constant. For the case where the film has not been held at negative saturation [Fig. 1(a)], before starting

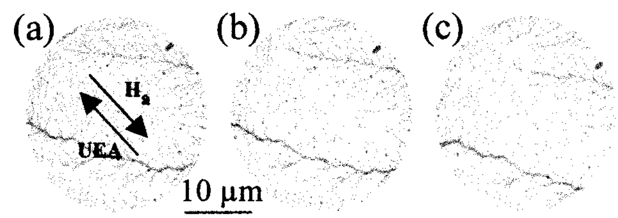

Fig. 3. Series of images of IrMn(10 nm)/CoFe(10 nm) (S10) recorded at constant field part way along the forward branch of the loop for (a) 0 s, (b) 30 s, and (c) 80 s.

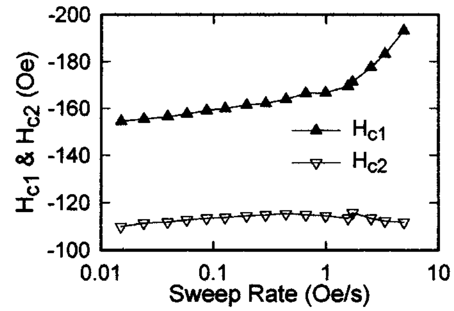

Fig. 4. Sweep rate dependence of coercivity for IrMn(5 nm)/CoFe(10 nm). The solid lines are guide for eyes.

the loop, all the AFM regions are initially aligned along the positive direction. The exchange field induced by the FM layer during the forward reversal and whilst at negative saturation results in some proportion of the AFM layer reversing its magnetization direction and the UEA anisotropy decreases. As the number of magnetization cycles increases this reversed proportion approaches equilibrium so that the difference between one loop and the next becomes smaller. As shown in Fig. 1(b), the recoil branch of the shifted loop (i.e., after waiting for t_{ns} at negative saturation of the FM layer) also shows a training effect. This effect has also observed in the LTEM experiments. We believe that holding the film at negative saturation for extended periods increases the proportion of reversal in the AFM layer driven by thermal activation (with a small time constant) above the equilibrium value and field cycling brings the film back toward equilibrium.

An asymmetry in the domain wall nucleation and annihilation sites is also observed. These sites are different for the two branches of the same loop. This asymmetry has also been observed in several other experiments [5], [12] and is believed to arise from a similar origin to the training effect, namely thermally activated reversal of the AFM layer with a small time constant as the FM layer stays for a short time at negative saturation or during reversal of the FM layer along the forward branch of the loop. There is an energy barrier distribution which changes at negative saturation of the FM layer so that along the recoil reversal the sites with lowest or highest energy barrier do not coincide with those along the forward branch of the loop. In addition to the thermally activated reversal we believe there to be pinning of the FM layer by the AFM layer at random sites across the interface, possibly associated with the roughness of the interface or other microstructure features [6].

The waiting time effect is believed to be a result of the reversal of regions of magnetization in the AFM layer driven by thermal activation with a *large* time constant, which occurs as the film is held at negative saturation. As t_{ns} increases, the exchange coupling between the FM and AFM layers causes more of the AFM layer magnetization to rotate or reverse antiparallel to the UEA. This reduces the original UEA, resulting in a shift of the recoil loop toward UEA. The shift of the forward loop toward zero is a result of the same effect—more of the AFM moment is exchange-coupling the CoFe moment antiparallel to the original UEA, thus lowering the energy barrier to reversal of the CoFe layer along the forward loop. As t_{ns} increases, the degree of AFM moment rotation or reversal increases and the loop shift increases.

The fact that as t_{ns} increases no change in the reversal *mechanism* is seen can be explained as follows: the domain structure and therefore the magnetization reversal process along the forward loop is dominated by the CoFe film rather than by the AFM layer and therefore does not change. It is suggested that no change to 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, and their effect is thus not easily visible in the LTEM images.

There is another point one should note, which is that as d_{AFM} decreases the degree of asymmetry and, for a given value of t_{ns}, the shift of the hysteresis loop toward zero field, increase. It is difficult to explain this through microstructure and UEA orientation which are similar for all the films studied here. It is also impossible to attribute this to the grain size distribution, which is found to be a normal distribution with very similar mean value and standard deviation for all samples. One possible reason is that, as d_{AFM} decreases, the energy barrier for AFM reversal driven both by small-time-constant thermal activation and by large-time-constant thermal activation decreases and so the changes in the AFM layer become more significant per unit time, resulting in greater effect on the reversal of the FM layer.

The dynamics of domain growth as seen for example in Fig. 3 indicate a thermally activated contribution (with both small and large time constants) to reversal along the forward branch of the loop. The sweep rate dependence of the hysteresis loop may give some information on thermal activation which could be used to confirm the two energy barrier assumption outlined above. It is believed that the slope of a linear relation between coercivity and Log(sweep rate) corresponds to the energy barrier distribution for the system [13], [14]. Fig. 4 shows the sweep rate dependence of S5 and similar dependence has been found on S7 and S10. The fact that two slopes appear on the sweep-rate dependence of H_{c1} and H_{c2} is thus in agreement with the assumption that two energy barrier distributions with different time constants coexist.

IV. Conclusion

We believe that, in the IrMn/CoFe system, two energy barrier distributions with different time constants coexist. The large-time-constant thermally activated reversal of the AFM layer contributes to a increasing shift of the entire hysteresis loop toward zero field with increased period of time spent at negative saturation of the FM layer. The small-time-constant thermal activation contributes to an asymmetry in domain nucleation and annihilation sites and to training effects. As the thickness of the AFM layer decreases, the energy barriers for thermally activated reversal of the AFM layer decrease so the changes in the AFM layer thus become more significant, resulting in greater effect on the reversal of the FM layer.

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