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Measurement of the Energy Barrier Distribution in the Antiferromagnetic Layer of Exchange-Biased Materials

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***Abstract*—The value of exchange field of two FeMn–NiFeCo-based spin valves with varying thickness of the pinned ferromagnetic layer has been determined as a function of temperature. The complexities caused by thermal activation of the antiferromagnet during measurement have been overcome by the development of a measurement protocol. The values of the exchange field obtained provide a measure of the degree of order in the antiferromagnet. Thus it is possible to determine the distribution of energy barriers to reversal for the system. We find that for a 110-Å-thick pinned NiFeCo layer a broad distribution exists, whereas for an 80-Å layer, the distribution is bimodal and has a component subject to thermal activation at temperatures down to 260 K.**

***Index Terms*—Exchange bias, exchange interactions.**

I. Introduction

EXCHANGE couples and spin valve systems have attracted much attention of late due to their technological importance [1], [2]. An exchange-biased system consists of an antiferromagnetic (AFM) layer exchange-coupled to a ferromagnetic (FM) thin film. In this configuration, the FM acquires a unidirectional anisotropy generally referred to as the exchange anisotropy $(H_{\rm ex})$ [3]. While a number of theories have been proposed, there is yet to emerge a unifying explanation of the effect. One fact that is becoming increasingly clear is that the magnetization of the FM has an effect on the AFM through the exchange interaction between the layers. For example, there has been recent work done where changes in the bulk magnetization of the FM layer were seen to have an effect on $H_{\rm ex}$ [4]. In two similar studies, the value of $H_{\rm ex}$ was varied by field cooling i.e., lowering the temperature of the sample from above the Neél temperature to a lower temperature so as to "set" the AFM, with the pinned FM layer in different magnetization states. For the CoO–Py system, it was found that the system maintained a "memory" of the state in which it was cooled [5]. Similarly, in the CoO–Co system, it was found to be possible to set $H_{\rm ex}$ to a wide range of values dependent upon the FM remanent state during field cooling [6].

The switching of FMs is controlled by a distribution of energy barriers to reversal. Magnetic viscosity measurements on MnF_2–Fe exchange-coupled samples, which do not display memory effects [7], show an asymmetric reversal via an energy barrier distribution with contributions from the FM and AFM layers. In our previous work, changes in the AFM layer were induced by holding the FM layer in reverse saturation for varying periods of time [8]. Thus, we were able to show that the distribution is changed by a thermally assisted relaxation process in the AFM layer. At a fixed temperature, the reversal follows logarithmic behavior, and hence time alone can not be used to map the distribution in detail. This current work aims to develop an experimental technique to determine the energy barrier distribution of the AFM layer. The reversal of the AFM has been investigated for two FeMn–NiFeCo–Cu–NiFeCo spin valves with different thicknesses of the pinned FM layer. $H_{\rm ex}$ is determined as a function of temperature at which the sample is held in reverse saturation for a fixed time. The values of $H_{\rm ex}$ subsequently obtained when the sample is cooled to low temperature have been used to map out a plot of the energy barriers $f(\Delta E)$ in the AFM.

II. Experimental

Two full spin valves incorporating FeMn as an AFM are used for this experiment. The sample structure is glass/Ta (100 Å)/NiFeCo (100 Å)/Cu (24 Å)/NiFeCo (x Å)/FeMn (150 Å)/Ta (50 Å), where $x =$ 80 Å and 110 Å. The samples were grown using sputter deposition and have been well characterized in the past [9]. Hysteresis loops were measured using a vibrating sample magnetometer with a noise base of 5×10^{-6} emu. The sample temperature was varied using an Oxford Instruments CF1200 cryostat.

As we have reported previously, the values of $H_{\rm ex}$ are highly dependent upon the previous history of the sample [8]. We have developed a procedure by which it is possible to reproducibly and reliably measure $H_{\rm ex}$ and, thus, be able to form conclusions about the interactions taking place between the pinned FM and AFM layers. To "reset" any previous thermal activation of the AFM layer, the sample is held at 373 K in a field of $H = +300$ Oe for 45 min. We have established by experiment that in this condition we can completely reverse the order in the AFM within a 15-min period. Hence, holding the sample in positive field for three times this period ensures that the AFM is in a fully ordered state. Also, the magnitude of the field used is such as to ensure that the FM layer is saturated in the positive direction $(H > H_{\rm sat\ pinned})$. After reset, the sample temperature is ramped to the temperature used to activate the AFM layer $(T_{\rm act})$ and a field of $H = -300$ Oe $(H > -H_{\rm sat\ pinned})$ is applied for 15 min. After activation, the sample is quenched to

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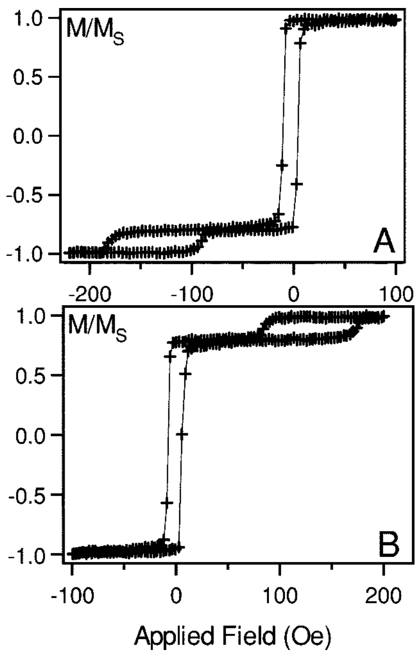

Fig. 1. Hysteresis loops of the 80-Å sample held in reverse bias at temperatures of (A) $T_{\mathrm{act}} = 275$ K and (B) $T_{\mathrm{act}} = 390$ K.

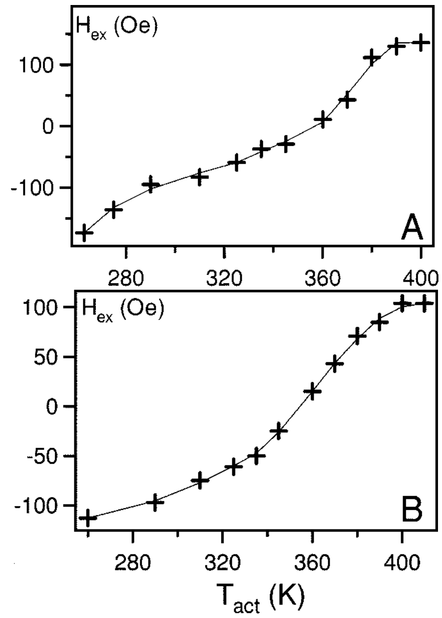

Fig. 2. Exchange field H_{ex} as a function of temperature used to activate the sample T_{act}. (A) 80-Å pinned layer. (B) 100-Å pinned layer. Solid lines are guides to the eye.

$T = 263$ K followed by the measurement of a hysteresis loop. The aim of cooling the sample is to eliminate as much as possible thermal activation during the measurement of the loop. It should be noted that thermal activation during the measurement would have an effect on the shape of the derived energy barrier distribution. This procedure is repeated for each of the different temperatures used to activate the sample. The time interval of 15 min has been chosen because on a logarithmic scale over which thermal activation of a distributed energy barrier system occurs, significant further changes in the degree of order of the AFM will not occur.

III. Results and Discussion

Hysteresis loops for the sample with an 80-Å pinned layer are shown in Fig. 1. The loops shown demonstrate the effect that the two extreme states of order of the AFM layer have on the pinned FM layer. In Fig. 1(a), the sample has been held in reverse saturation at $T_{\mathrm{act}} = 275$ K for 15 min. Here the pinned FM layer has a negative magnetization in the direction of the original exchange bias. On the other hand, Fig. 1(b) shows the hysteresis loop for $T_{\mathrm{act}} = 390$ K. In this case, the layer has a positive magnetization in the opposite direction to the original bias. Over the range of T_{act} at which the sample was measured, H_{ex} of the pinned FM layer was observed to shift uniformly along the field axis.

Fig. 2(a) and (b) shows the variation of the exchange field measured at 260 K as a function of the temperature at which the thermal activation of the AFM layer was undertaken. The data in Fig. 2(a) for the sample with an 80-Å pinned NiFeCo layer shows a form characteristic of a bimodal energy barrier distribution. This impression is confirmed by the data in Fig. 3(a), which shows the differential of the data. Here it is clear that the distribution is bimodal with the main part at 360 K, and the

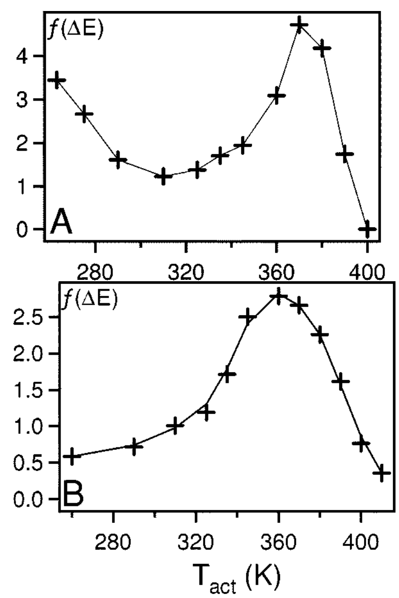

Fig. 3. Differentials of H_{ex} with respect to T_{act}. This gives a measure of the barriers to reversal $f(\Delta E)$ in the AFM. (A) 80-Å pinned layer. (B) 100-Å pinned layer. Solid lines are guides to the eye.

system remains thermally activated to temperatures below our chosen measurement temperature.

For the sample with a 110-Å pinned NiFeCo layer, the data in Fig. 2(b) show monomodal behavior confirmed by the differentiated data in Fig. 3(b). Interestingly, the data for this sample show a broad distribution centered at about 360 K coincident with the high temperature peak for the 80-Å sample. The distribution appears not to be lognormal in form but extends to low temperature covering the range of the low-temperature peak of the 80-Å sample. Thus, it appears that there is a complex dependence of the energy barrier on the thickness of the pinned layer.

From this data, it is also clear that the usual measurement of the distribution of blocking temperatures by measurement of the variation of H_{ex} with temperature is inappropriate because thermal activation of the AFM will be ongoing at a logarithmic rate during the measurements. Also, these measurements may give a zero value for the exchange field because equal portions of the AFM are in ordered states in opposite senses and not fully thermally activated.

Analysis of changes in an AFM material are complex, as no measurements of the actual magnetic state of the AFM layer can be made on short timescales. In terms of magnetic measurements, all that can be inferred is the approximate state of the AFM layer from the resulting effect on the pinned layer. Changes in the AFM layer are to a good approximation driven only by the exchange coupling (or exchange field) from the FM layer acting upon it. Other work has shown that changes in the state of the AFM layer are thermally activated [8].

In terms of the observed hysteresis loop of the FM, the work reported here shows that the degree of order in the AFM is reflected directly in the macroscopic shift in the loop, which can be characterized by H_{ex}. For a system where the FM has a square hysteresis loop or where a reasonably fast sweep rate is used, the exchange field acting on the AFM layer is effectively plus or minus some constant value. Hence, the position of the loop of the FM on the field axis is in effect a measure of the magnetization of the AFM layer. Conversely, for a measurement made using control of time, the magnetization of the FM layer represents the "field" applied to the AFM. For an experiment such as this, where the time for which the AFM is exposed to the negative exchange field is constant, the variation of temperature allows the energy barrier distribution $f(\Delta E)$ to be mapped.

IV. Conclusion

We have developed a measurement protocol for the determination of the energy barrier distribution in the AFM layer of exchange-biased systems. The procedure ensures that the measurement is not affected by thermal activation during the measurement of the FM layer. From our preliminary data, we have observed a dependence of the energy barrier distribution on the thickness of the pinned FM layer.

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