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Influence of magnetic field sweep rate on the hysteresis loops of $Ni_{0.8}Fe_{0.2}/Fe_{0.5}Mn_{0.5}$ exchange bias bilayer

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The influence of the magnetic field sweep rate on the hysteresis loops of exchange bias $Ni_{0.8}Fe_{0.2}/Fe_{0.5}Mn_{0.5}$ bilayers has been investigated with a vibrating sample magnetometer. It was found that the sweep rate of 13.6 kA/4πms is high enough to bring about obvious changes in the hysteresis loops of the exchange bias bilayer. High sweep rate in the magnetization reversal stage enlarges the coercivity of the sample, while high sweep rate in the saturation state reduces the coercivity. The above phenomena were attributed to magnetic viscosity in the ferromagnetic layer enhanced by the interface exchange interaction and domain magnetization reversals assisted by thermal fluctuation in the antiferromagnetic layer respectively.

Keywords: exchange bias, coercivity, sweep rate, magnetic viscosity, Fulcomer–Charap model
PACC: 7550E, 7560L, 7570C

1. Introduction

After a ferromagnet (FM) in contact with an antiferromagnet (AFM) is cooled through the Néel temperature of the AFM in an external magnetic field, the exchange interaction at the FM/AFM interface can shift the hysteresis loop of the ferromagnet along the axis of external field. This phenomenon is named exchange bias. Exchange bias was first found by Meiklejohn and Bean in partially oxidized cobalt particles as early as 1956,[1] however a satisfactory theoretical explanation of it is still lacking. In 1991, Dieny *et al* fabricated spin-valve structure by combining an exchange bias bilayer with a giant magneto-resistance (GMR) sandwich layer.[2] This structure can utilize the GMR effect in high performance magnetic read heads, which promoted the magnetic storage industry dramatically. The industrial need for high performance spin-valve devices has re-activated the interest in studies on exchange bias.[3−5]

With increasing read/write speed of magnetic storage devices, the influence of dynamic magnetic properties of the devices on their performance becomes more and more significant. The knowledge on the dynamic magnetic properties of exchange bias systems will help us to understand and optimize the behaviours of the spin-valve-based magnetic head. On the other hand, the studies on dynamic magnetic properties of the exchange bias system can provide clues for a more satisfactory theory of exchange bias. Several studies have been devoted to magnetic responses of exchange bias systems in dynamic magnetic fields in recent years.[6−8] In this paper, we report the influence of different magnetic field sweep rates on the hysteresis loops of NiFe/FeMn exchange bias bilayer. In Section 2, the experimental method is described. Results and discussion are presented in Section 3, and finally a summary is given in Section 4.

2. Experimental methods

The samples used in this experiment are typical exchange bias systems (glass substrate / Ta (4 nm) / $Ni_{0.8}Fe_{0.2}$ (12 nm) / $Fe_{0.5}Mn_{0.5}$ (X nm) / Ta (3 nm)) which are prepared by dc magnetron sputtering. The base pressure in the sample preparation cham-

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ber was lower than 2×10^{-5} Pa. The pressure of Ar gas was kept at 4.5×10^{-1} Pa during growth. The hysteresis loops were measured with a vibrating sample magnetometer (VSM). In measurements, the external magnetic field was kept at a constant sweep rate, either 1.1 kA/4πms or 13.6 kA/4πms, unless we change the sweep rate manually. It means that we acquired the magnetization signals without stopping field sweep. Since in VSM measurements, magnetization signals have to be processed by a lock-in amplifier first before acquired, the measurement mode may lead to the lag of the magnetization signals behind the external field signals, resulting in a distortion of the measured loops if the field sweep rate is too high. In order to eliminate this measurement effect, we have reduced the time constant of the lock-in amplifier until no obvious distortion can be observed, at the same time we measure several of the samples collectively to keep sufficiently large signal-noise-ratio. Figure 1 shows the hysteresis loop of a 12 nm NiFe sample obtained with the same measurement parameters in the following normal experimental data. We can find that the loop measured at 13.6 kA/4πms shows nearly no difference from that obtained at 1.1 kA/4πms. To avoid the influence of training effect,[3] before the normal measurements, the samples are swept in a field with a sweep rate of 1.1 kA/4πms for several cycles until the change in coercivity and exchange bias field is smaller than 0.1 kA/4πm.

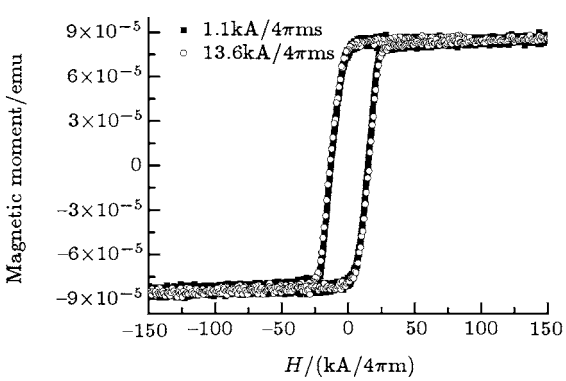


Fig.1. The hysteresis loops of the sample (glass substrate / Ta (5 nm) / $Ni_{0.8}Fe_{0.2}$ (12 nm) / Ta (5 nm)) at different field sweep rates.

3. Results and discussion

Significant and complicated changes with switching of the field sweep rate between 1.1 and 13.6 kA/4πms have been observed in the hysteresis loops of the exchange bias bilayers. We use the sample with the FeMn thickness of 3.5 nm as an example to describe the changes systemically since we have observed that the phenomena are more remarkable at this thickness. We change the field sweep rate only when the field sweeps the midpoint of the loop, i.e. the exchange bias field, because this point just separates the magnetization process into two different stages: magnetization saturation and magnetization reversal, so that the possible difference of the two stages can be distinguished easily. The stable hysteresis loop at 1.1 kA/4πms is plotted as solid squares in Fig.2 as a reference loop. This loop is shifted to the positive axis. The exchange bias field is about 5 kA/4πm. For convenience, we name it loop A. We switch the sweep rate to 13.6 kA/4πms when the field passes by the exchange bias field in the increasing-field branch, i.e. the S_1 point in Fig.2(a), and the first loop after switching is named loop B, which is plotted in empty triangles as shown in Fig.2(a). We can find that the first half of loop B has a larger coercivity than loop A. However, the coercivity of the second half loop has little difference from that of the corresponding part of loop A. With further sweeping at a faster rate, both of the two halves of the loop show nearly the same coercivity with loop A, and would not change with repeated field sweeps at this rate. We name the stable loop at 13.6 kA/4πms loop C (see Fig.2(b)). When the external field passes by the S_1 point, we switch the sweep rate back to 1.1kA/4πms. The first loop after switching is plotted in empty circles in Fig.2(c) which is named loop D. We can observe that the first half of loop D shows a smaller coercivity than loop A. Further sweeping at 1.1 kA/4πms would make the loop resume loop A.

In the above experiment, we change the sweep rate only when the external field sweeps in positive direction, i.e. in the increasing-field branch. We have also tried to change the field sweep rate in the deceasing-field branch, i.e. at the S_2 point indicated in Fig.2(a). The results are basically similar.

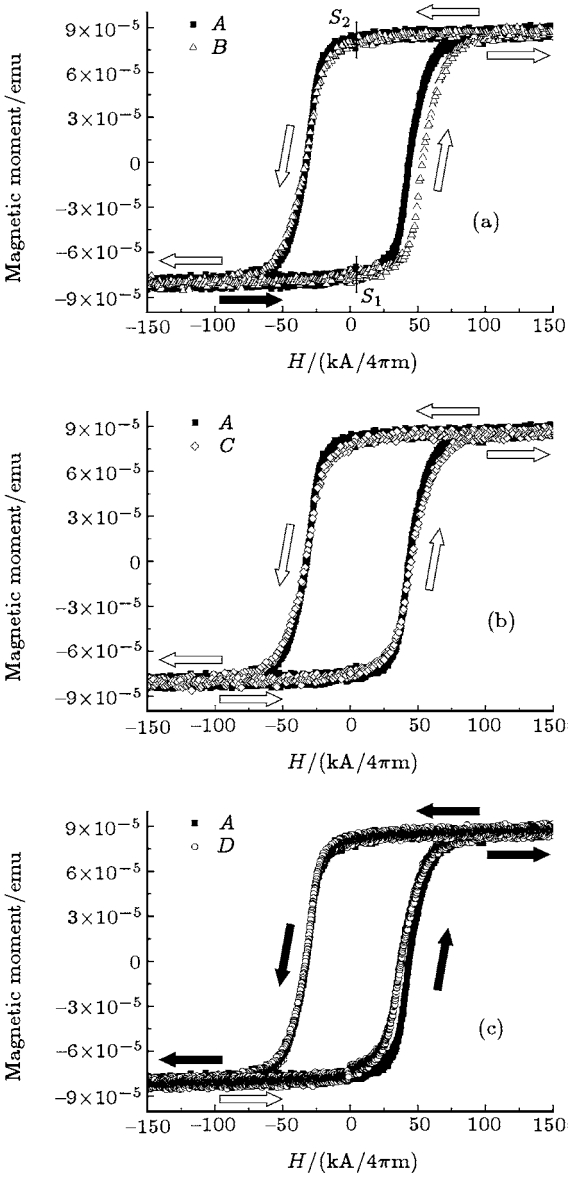


Fig.2. The hysteresis loops of the sample (glass substrate / Ta(4 nm) / $Ni_{0.8}Fe_{0.2}$(12 nm) / $Fe_{0.5}Mn_{0.5}$(3.5 nm) / Ta(3 nm)) obtained in the magnetic field of different sweep rates. The arrows are drawn to indicate the sweep direction and sweep rate of the field. Solid arrows represent the sweep at 1.1 kA/4πms. Empty arrows represent the sweep at 13.6 kA/4πms.

From the results obtained above, we can observe that apparent changes in coercivity appear only at the magnetization process where we change the field sweep rate. If the sweep rate is kept at constant 13.6 kA/4πms like in loop C and the decreasing-field branch of loop B, the coercivity changes little. It suggests that different responses to sweep rates in the saturation state and in the magnetization reversal process cooperatively lead to the results, since sweep rate switching means making different sweep rates at the two stages. Comparing the increasing-field branches of loops A and B, we can find that they have the same sweep rate at the magnetization saturation stage. So the larger coercivity of loop B in this branch can only be attributed to the higher sweep rate in loop B at the magnetization reversal stage. On the contrary, the increasing-field branch of loop D has a higher sweep rate than that of loop A at the magnetization saturation stage, but the same sweep rate at the magnetization reversal stage. So the smaller coercivity of loop D must be due to the higher sweep rate at the saturation stage. The decreasing-field branch of loop B and both the two branches of loop C have a higher sweep rate in both the saturation state and the magnetization reversal process, so the observed little change in coercivity can be attributed to the counteraction of the above two effects. Therefore, we can conclude from the data, that the faster field sweep in the saturation state leads to a smaller coercivity, while the faster field sweep in the magnetization reversal process leads to a larger coercivity.

It is known that a single atom spin responses an external magnetic field by a damping precession motion relative to the field direction instead of reversing to the direction directly.[9] It would make the hysteresis loop obtained in an alternating field different from that measured in a quasi-stable field. However, a frequency of at least several thousand Hz is needed to produce detectable changes in this case. The frequencies of about 0.01Hz used in this experiment are much smaller. So our results cannot be dominated by this mechanism.

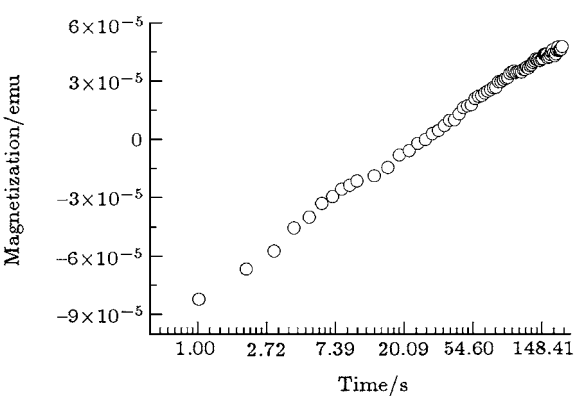


Fig.3. The time evolution of the magnetization of the sample (glass substrate / Ta(4 nm) / $Ni_{0.8}Fe_{0.2}$(12 nm) / $Fe_{0.5}Mn_{0.5}$(3.5 nm) / Ta(3 nm)) after the external magnetic field stops sweeping at 25 kA/4πm.

Street and Wooley[10] found the magnetic viscosity effect in AlNiCo alloy in 1949. Magnetic viscosity means that when the external field stops sweeping at coercivity, the magnetization will not stop changing

immediately. Instead, it will increase with time as

$$M(t) = M_0 + S\ln(t), \tag{1}$$

where M_0 is the initial magnetization when the field just stops and S is termed magnetic viscosity parameter. Néel[11] demonstrated that magnetic viscosity is the result of magnetization reversals activated by thermal fluctuation. Since a higher field sweep rate means less assistance from thermal fluctuation in magnetization reversals, the external magnetic field needed to reverse the magnetization will be higher, which leads to a larger coercivity in a higher sweep rate. This effect can be observed in low-frequency regime, so it is possible that the larger coercivity of loop B in our experiment may result from magnetic viscosity.

The influence of thermal fluctuation can be described by a fluctuation field $H_{\rm f} = S/\chi_{\rm irr}$, where S is the magnetic viscosity parameter and $\chi_{\rm irr}$ is the irreversible susceptibility. Based on Eq. (1), the magnetic viscosity parameter can be obtained by measuring the time dependence of magnetization. Figure 3 shows the time evolution of the measured magnetic moment after the external magnetic field stops sweeping at 25 kA/4πm. A nearly linear relation between the magnetization and the logarithm of the time can be observed. From the slope, we can obtain the magnetic viscosity parameter to be 2.4×10^{-5} emu/V, where V is the volume of the NiFe layer. In a soft magnetic material the irreversible susceptibility nearly equals the total susceptibility. We can obtain the total susceptibility by measuring the maximum slope of the hysteresis loop, about 0.6×10^{-5} (4πmemu/kA)/V. So the thermal fluctuation field can be calculated to be about 4 kA/4πm. It is found that in a magnetic viscosity system, the coercivity increases with the sweep rate according to the relation $\Delta H = H_{\rm f}\ln({\rm d}H/{\rm d}t)$.[12] From this we can deduce that the difference of coercivity between fast and slow field sweeps is about 10 kA/4πm. It is well consistent with the observed value. Thus we can make sure that the increase of coercivity is caused by magnetic viscosity.

Magnetic viscosity parameters of magnetic materials are inversely proportional to their average activation volumes, since relative small units are easier to be influenced by thermal fluctuation. Activation volume is the actual particle volume for an isolated single-domain particle and is the effective volume of the material covered by a single jump between pinning centres in a domain-wall motion process.[13] Therefore, magnetic viscosity is more obvious in groups of small magnetic particles and hard magnetic materials which have relative small domain size in the magnetization reversal processes.[14] Soft magnetic materials have much larger magnetic domains in the reversal processes, hence magnetic viscosity can hardly be observed in them. In a pure NiFe layer, no change can be observed; the observed magnetic viscosity should be the result of coupling between the ferromagnetic and antiferromagnetic layers. The studies of magneto-optical Kerr effect microscopy revealed that the magnetization reversal of exchange bias bilayers starts with a wide spread nucleation of reversal domains of 1–10μm[15] which is much smaller than that in the pure soft magnetic film that develops one domain extending to the entire film in the reversal process. Therefore, the average domain wall width in the exchange biased FM film is much smaller than that of the unbiased one and easier to be influenced by thermal fluctuations.

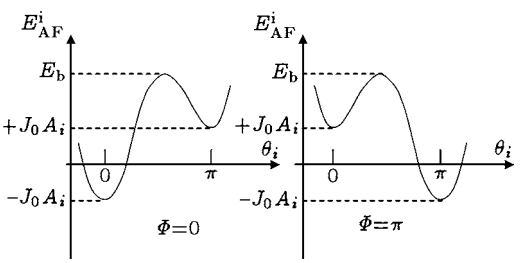


Fig.4. A scheme of the energy of an AFM grain versus the angle between the net moment of the AFM grain and the easy magnetization axis.

We have also observed the reduction of coercivity resulting from higher sweep rates at saturation. Similar phenomena have been reported in many exchange bias systems.[5–8] Stamps presented a theoretic explanation to the effect based on the exchange bias model made by Fulcomer and Charap.[16] In this model, an AFM layer is considered to be composed of many grains. Each grain has a uniform spin arrangement, while the interactions between the grains are neglected. So, every AFM grain interacts with the FM layer separately. In other words, the AFM layer is a group of AFM single domain particles.[11] We simplify the model by assuming that every AFM grain has the same easy axis as the FM layer, thus the energy of AFM grains and the FM layer can be expressed as[16]

$$E^{\rm i}_{\rm AF} = K_{\rm a}V_i\sin^2\theta_i - J_0A_i\cos(\theta_i - \Phi), \tag{2}$$

where $K_{\rm a}$ represents the magnetic anisotropy constant of an AFM grain, J_0 is the exchange parameter of the coupling between AFM grains and the

FM layer, θ_i is the angle between the net moment of the AFM grain and the easy axis. V_i and A_i are the volume and lateral area of the AFM grain respectively. Φ is the angle between the magnetization of FM layer and the easy axis. We only consider the case in which FM layer is in its magnetization saturation states, i.e., $\Phi = 0$ and $\Phi = \pi$. So Eq.(2) becomes $E^i_{\rm AF} = K_{\rm a}V_i \sin^2\theta_i \pm J_0 A_i \cos\theta_i$, where "+" is for $\Phi = \pi$ and "− " is for $\Phi = 0$. We can find that when $K_{\rm a}V_i > J_0A_i/2$, there will be two minima in E-θ curve (see Fig.4). They correspond to the states of net moments of AFM grains being parallel and antiparallel to the magnetization of FM layer respectively. The antiparallel state is metastable, and to reach the parallel configuration the AFM grain must overcome a reversal barrier. The longer time the system is kept in saturation, the more AFM grains will reach the parallel states by thermal fluctuations. Since the number of AFM grains in parallel states determines the coercivities of next loops,[5] a longer dwelling time in a saturation state could result in a larger coercivity in the next reversal process. In this experiment, a higher field sweep rate means a shorter time in saturation, which could lead to the reduction of the coercivity.

The relax time τ of the AFM grains from metastable states to stable states can be written as[8]

$$1/\tau = \nu_0\{\exp[-(E_{\rm b} - J_0A_i)/k_{\rm B}T] + \exp[-(E_{\rm b} + J_0A_i)/k_{\rm B}T]\}, \qquad (3)$$

where $E_{\rm b} = K_{\rm a}V_i[1 + (J_0A_i/2K_{\rm a}V_i)^2]$. ν_0 has an order of 10^9 $\rm s^{-1}$. The magnetic anisotropy of FeMn is about $2.0\times$ 10^6 $\rm erg/cm^3$.[17] J_0 of NiFe/FeMn interface is about 0.15 $\rm erg/cm^2$.[18] So the lateral size of the grains that could contribute to the effect can be estimated to be around 10 nm. It is close to the grain sizes of NiFe/FeMn systems grown on Ta buffer layers observed in previous works.[19−21] So it is reasonable that the thermal activated reversals of AFM grains can influence the hysteresis loop during the whole experiment.

4. Conclusion

In summary, we have investigated the influence of sweep rates of external magnetic fields on the hysteresis loops of NiFe/FeMn exchange bias bilayer. We found that a faster sweep field in magnetization reversal process leads to a larger coercivity, while a faster sweep field in the saturation states leads to a smaller coercivity. The phenomena are ascribed to the thermal-fluctuation-activated magnetization reversals in the FM layer and AFM layer respectively.

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