Study of Magnetization Reversal by Minor Loops in IrMn/CoFe Exchange-Biased Bilayers

L. Wang1, 2, S. G. Wang1, *, Q. H. Qin1, and X. F. Han1

1 State Key Laboratory of Magnetism, Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Science, Beijing 100190, China
2 School of Physics and Materials Science, Anhui University, Hefei 230039, China

We report a detailed investigation of the magnetization reversal by minor loops in Co75Fe25 (t) single layer and Ir22Mn78(10 nm)/CoFe(t) exchange-biased bilayers with different CoFe thicknesses. With increasing CoFe layer thickness in IrMn/CoFe bilayers, the magnetization reversal process shows a transition from the coherent rotation to the domain-wall motion, which is attributed to the competition among the antiferromagnetic domain wall energy, ferromagnetic domain wall energy, and the interface coupling between antiferromagnetic and ferromagnetic layers.

Keywords: Spin Valve, Hysteresis Loop, Magnetization Reversal, Domain-Wall Motion, Interface Coupling.

1. INTRODUCTION

The exchange coupling between a ferromagnetic (FM) layer and an adjacent antiferromagnetic (AFM) layer1 is a key issue in spintronic devices, such as hard disk drives, magnetic sensors, and magnetic random access memories (MRAM).2–3 For example, two ferromagnetic layers separated by a nonmagnetic barrier such as MgO in magnetic tunnel junctions could form parallel and antiparallel configuration by applying external magnetic field, where one FM layer is free to switch and the other is pinned by adjacent AFM layer due to exchange bias coupling.4, 5 The unidirectional anisotropy from exchange coupling gives rise to a shift of the hysteresis loop together with an enhanced coercivity compared with the corresponding single FM layer. Recent models for exchange bias are based on the formation of domain walls at the FM/AFM interface, either during cooling in the presence of the magnetized FM layer or as a result of a magnetic field applied during growth.6–11 Although considerable progress12–14 has been achieved, the nature of exchange bias and its microscopic origin are still debated.7, 10

The exchange bias field ($H_{ex}$) is reversely proportional to the FM layer thickness.15 Therefore, the models established for exchange bias should take the FM layer thickness into account. Unfortunately, very little research has been done to investigate the magnetization reversal as a function of the FM layer thickness in exchange-biased FM/AFM bilayers. The magnetization reversal process depends on various interactions or energies and on their competition. In general, the coherent rotation and domain wall motion play a critical role in the magnetization reversal. For a single FM layer, the reversal is usually achieved through the nucleation and propagation of the domain wall. In the exchange-biased system, the interface interaction and domain wall energies of the AFM layer should affect reversal process. Furthermore, the domain structures both in the AFM and FM layers play a crucial role in exchange-biased system. The reversal mainly occurs in the vicinity of the coercive field, so the minor loops near coercivity contain essential information of reversal process. The detailed study of magnetization reversal process would greatly enhance the understanding of the mechanisms of the enhanced coercivity and the exchange bias field. In this work, we propose a rather simple and straight-forward method to investigate the magnetization reversal process: measuring hysteretic minor loops as a function of the FM layer thickness. By changing the FM layer thickness, we can tune the relative energies between the domain energy of the FM layer and the interface coupling energy, and thus can investigate the detailed magnetization reversal. The transition of the reversal process from the coherent rotation to the domain wall nucleation has been observed with increasing the FM layer thickness.

*Author to whom correspondence should be addressed.
thickness, which can be well explained by the competition among these energies.

2. EXPERIMENTAL DETAILS

Two series of samples were grown with core structure of Ta(5)/IrMn(10)/CoFe(t)/Ta(5) and Ta(5)/CoFe(t)/Ta(5) (thicknesses in nm) by an ULVAC magnetron sputtering under a base pressure of $1 \times 10^{-6}$ Pa. A magnetic field of 170 Oe was applied parallel to the film plane during deposition to induce the easy magnetization direction. Instead of growing a lot of separate bilayers with different FM layer thickness, the CoFe layer is a wedge with thickness ranging from 0 to 20 nm in length of 50 mm in order to avoid sample-to-sample variation. Then the wedge sample was cut into equal sized pieces along the wedge direction. Magnetic properties were measured by the vibrating sample magnetometer (VSM) at room temperature. The experimental details were published elsewhere.15

3. RESULTS AND DISCUSSION

For a single CoFe layer, the coercivity ($H_C$) is nearly independent of the thickness as it is above critical value (such as 3 nm). In this work, the CoFe thickness is more than the critical value. With respect to IrMn/CoFe bilayers, both $H_C$ and $H_{EB}$ decrease monotonically as the thickness of CoFe layer increases. To investigate the magnetization reversal process in vicinity of the coercivity, the following measurement of minor loops is carried out. The sample is first saturated in a large enough negative (positive) magnetic field. Next, the field is gradually increased (decreased) to the pre-assigned value (called $H_A$ here). Then the magnetic field is decreased (increased) back to the large negative (positive) field. Repeating this procedure for various values of $H_A$, a series of minor loops are obtained.

Figure 1 shows the minor loops of a 5 nm thick CoFe single layer for both increasing (a, b, c, d) and decreasing (e, f, g, h) branches, respectively. For increasing branch shown on left, the measurement was started from a saturated negative field, then increasing field to positive $H_A$, where the data are shown by open squares. Then the magnetic field is reversed, and decreased from $H_A$ to negative direction, where the data are shown by open points. For decreasing branch shown on right, the measurement was started from a negative to a positive saturated field, then decreasing field to the negative $H_A$, where the data are shown by open squares. Then the magnetic field is reversed, and increased from $H_A$ to positive direction, where the data are shown by open points. From Figures 1(b) and (c), it is clear that the CoFe layer is saturated as the external field reaches to 50 Oe. From Figures 1(e) and (f), it shows obviously that the nucleation field is about 46 Oe with a sharp magnetization switch, indicating that the domain wall motion is dominant for the magnetization reversal here. In this case the nucleation and domain wall motion take place at a very narrow range (from 46 to 50 Oe). The magnetization reversal is symmetric with respect to the zero field, showing that the reversal behavior is identical for the increasing and decreasing branch.

For the IrMn(10 nm)/CoFe(5 nm) bilayers, the values of $H_A = -80, -60, -40$ and $-20$ Oe are chosen for increasing branch, respectively, as shown in Figures 2(a, b, c and d). The values of $H_A = -180, -220, -220$ and $-260$ Oe are chosen for decreasing branch, respectively, as shown in Figures 2(e, f, g and h). Firstly, the results show an asymmetric loop and an enhanced coercivity, indicating a strong exchange bias in IrMn/CoFe bilayers, as reported previously. Secondly, the shape of minor loops is completely different with that of single CoFe layer shown in Figure 1. For example, the magnetization reversal is

![Minor loops for IrMn(10 nm)/CoFe(5 nm) bilayers for both increasing (a, b, c, d) and decreasing (e, f, g, h) branches, respectively. The round shape indicates that the coherent rotation plays a dominate role in magnetization reversal.](image)
much sharper for single CoFe layer, but more round in IrMn/CoFe bilayers, which indicates that the domain wall motion is dominant for CoFe single layer and a more complicated magnetization reversal takes place in bilayers. Furthermore, the range of $H_A$ is much larger than that of the single layer, indicating clearly that the coherent rotation originates from the presence of the IrMn layer. Another noticeable result is that the shape of minor loops changes with different values of $H_A$. For example, when $H_A = -180$ Oe, there is no hysteresis at fields ranging from $-180$ to $100$ Oe, showing a completely reversible magnetization reversal, as shown in Figure 2(e). The driving force of magnetization reversal from $-180$ Oe to 0 Oe comes from the anisotropy energy and magnetoelastic energy of the AFM layer. Furthermore, when the value of $H_A$ is increased from $-180$ Oe to $-260$ Oe, the hysteresis becomes more and more remarkable, as shown in Figures 2(f, g, and h), showing that more AFM irreversible spin rotation are involved in the process. Similar behavior can also be observed for increasing branch of the minor loops, as shown in Figures 2(a, b, c and d). Based on the above discussion, it is reasonable to conclude that the enhanced coercivity in CoFe/IrMn bilayers can be well explained as a result of AFM irreversible spin rotation.

Above results have also been found in other AFM/FM bilayers experimentally, such as Ni$_81$Fe$_{19}$/Fe$_{50}$Mn$_{50}$ and Co$_{50}$Fe$_{50}$/Fe$_{50}$Mn$_{50}$ (not shown here), suggesting that it is an intrinsic behavior in exchange-biased systems.

Generally, the magnetization reversal in AFM layer adjacent with an FM layer includes reversible and irreversible parts, where the reversible rotation plays a critical role in the amplitude of the exchange bias field, while the irreversible one provides a major contribution to the enhanced coercivity. The asymmetric magnetization reversal process together with the hysteresis loop is considered as an intrinsic characteristic in exchange-biased system.$^{16-21}$ Since the driving force in decreasing and increasing branches comes from the external field and the AFM layer anisotropy energy respectively, the origin of the asymmetric loop can be attributed to the different mechanisms. It is well known that both the coercivity and exchange bias field in AFM/FM bilayers decrease with the increasing of the FM layer thickness.$^{10}$ In order to get a deep insight into the relationship between the coercivity and FM layer thickness, the minor loops with the different CoFe thickness for the IrMn(10 nm)/CoFe($t$) bilayers were investigated, as shown in Figure 3. It is interesting to find that the magnetization reversal process changes with the thickness of CoFe layer. When $t < 10$ nm, shown in Figures 3(a), (b), and (c), the magnetization reversal is dominated by coherent rotation with a round transition. With increasing $t$, the transition becomes sharp gradually till 20 nm, in which the shape of two branches is similar to that of single CoFe layer with domain wall motion mechanism shown in Figure 1. In Figure 4, the minor loops with different values of $H_A$ in the increasing and decreasing branches for the IrMn(10 nm)/CoFe(18.1 nm) bilayers are shown, respectively. The complete M-H loop is presented in Figure 4(a), with a shifted and square shape showing an exchange bias. The shape of minor loops shown in Figure 4 is very similar to that from CoFe layer shown in Figure 1 except that the loop is shifted with exchange bias.

The dependence of magnetization reversal process on the FM layer thickness for IrMn(10)/CoFe($t$) bilayers can be explained by taking into account the domain wall energy of the AFM layer. In the case of single CoFe layer, the nucleation and domain wall motion are dominant in the magnetization reversal, while in the AFM/FM bilayers, there are domains inside the AFM layer due to the interface coupling with the domains in the FM layer.$^{22, 23}$ There is frustration between the FM and AFM layers at the interface during the magnetization reversal in the FM
layer. Both domain walls in the FM and AFM layers are assumed to be perpendicular to the interface, the total AFM domains wall energy is expressed as followings:  

\[ \delta_{AF} = 4\sqrt{A_{AF}K_{AF}}S_{AF} \]  

(1)

where \( \delta_{AF} \) is the AFM domain wall energy, \( A_{AF} \) and \( K_{AF} \) are the AFM layer exchange stiffness and crystalline anisotropy parameters, and \( S_{AF} \) is the cross-section area of the thin film. \( S_{AF} = L \times t_{AF}^2 \), where \( L \) refers to the thin film length and \( t_{AF}^2 \) is the AFM layer domain wall thickness. If we assume \( t_{AF}^2 \) is independent on the FM layer thickness, the amplitude of \( \delta_{AF} \) is only determined by intrinsic properties of the AFM materials. Apparently, \( \delta_{AF} \) is a constant when an AFM material is selected. 

With respect to a single FM layer, the domain wall energy is expressed as:  

\[ \delta_F = 4\sqrt{A_FK_FS_F} \]  

(2)

where \( S_F = L \times t_F^2 \) is the cross-section area of the FM layer and \( t_F^2 \) is the FM layer domain wall thickness. As the FM layer domain wall energy is larger than that of the AFM layer, it is energetically favorable to form domains inside the FM layer during magnetization reversal. That is to say, the magnetization reversal is single-FM-like, in which the domain wall propagation is dominant during magnetization reversal. Otherwise, the FM layer cannot overcome the AFM layer anisotropy energy, and the nucleation and domain formation is hindered by the AFM layer. In this case, the magnetization reversal shows an AFM-reversal-like behavior, in which the coherent rotation plays a dominant role with a round shape of the minor loops. Because the FM layer domain wall energy \( \delta_F \) is proportional to the FM layer thickness, the domain wall energy increases as \( t \) increases and finally becomes larger than that of the AFM layer. Thus, the magnetization reversal will change from coherent rotation to domain wall motion, as shown in Figure 3. From the above discussions, the magnetization reversal behavior due to exchange coupling in AFM/FM exchange-biased bilayers should change with the FM layer thickness, and can be explained by the competition between the \( \delta_F \) and \( \delta_{AF} \). Therefore, a detailed theoretic model to describe the exchange bias effect must take the magnetization reversal mechanism at different FM layer thickness into account. 

4. CONCLUSION

In summary, the magnetization reversal processes of both CoFe layer thickness in IrMn(10)/CoFe(t) bilayer. Our direct experimental evidence provides a clear physics picture for the dependence of the magnetization reversal process on the FM layer thickness: for thinner and thicker FM layer, the magnetic reversal process is dominant by coherent rotation and domain wall motion, respectively. Since the exchange bias and coercivity mechanism is strongly related to the magnetization reversal process, this work offers a strong suggestion that the FM layer thickness should be taken into account to describe the exchange bias effect in AFM/FM bilayers. 

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References and Notes


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