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Ferromagnetic domain structure and hysteresis of exchange bias in NiFe/NiMn bilayers

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Magnetization reversal in NiFe/NiMn bilayers was studied by measuring anisotropic magnetoresistance and pseudo-Hall effect simultaneously. Since the single domain state of the ferromagnetic layer could be well traced in such measurements, we were able to distinguish hysteresis of exchange bias from inhomogeneous magnetization. The exchange bias was found to have two components during the single domain reversal process. Domain breaking in given fields took place when the biasing field became more random.

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I. INTRODUCTION

In a ferromagnetic (FM)/antiferromagnetic (AFM) bilayer, the FM layer can have an effective unidirectional magnetic field, biasing, under proper conditions. The so-called exchange bias comes from the exchange coupling between FM and AFM layers.[1] Since exchange bias found important applications in spin-polarized transport, much attention has been given to the FM/AFM system.[2]

The nature of the exchange coupling in a FM/AFM bilayer is determined by the properties of the FM layer, the AFM layer, and their interface. Many theoretical models have been already developed to understand exchange bias.[3–7] These theories captured some essential features of the AFM layer and/or the interface, but assuming that the FM layer is in a single domain state. However, the single domain state was not shown clearly in previous experimental studies on biasing field. One can expect a single domain FM layer in zero applied magnetic field, but domain breaking would be very natural in conventional hysteresis loop measurements, from which biasing fields were usually obtained.

Besides exchange bias, another important feature of the exchange coupling is the increased coercivity. Theoretical explanations of coercivity have taken into account interfacial spin-flop coupling,[6] small domains in the FM layer,[8] and the instability of AFM grains.[9] In order to clarify which mechanism dominates, revealing domain structures in the FM layer would be crucial.

Very recently, there was a lot of interest to understand the asymmetrical magnetization reversal in exchange biased bilayers,[10–12] Different FM magnetic structures in the reversal process were discussed. In these works, the applied magnetic field was parallel (or antiparallel) to the biasing direction. It would be interesting to study the reversal process in a magnetic field whose direction can vary in the film plane because more information about the exchange coupling could be obtained in such comprehensive measurements.

In this paper, from the comprehensive magnetization reversal measurements, we have clearly shown that there were two kinds of magnetization hysteresis. One came from the magnetic instability of the AFM layer, the other due to the breaking of FM single domain. In addition, we observed that domain breaking and merging in the FM layer were closely related to the hysteresis in exchange bias.

II. EXPERIMENTS

Clear identification of the domain breaking is a key progress in this work. This is usually difficult because most methods, e.g., magnetometry or susceptibility, measure only a projection of net sample magnetization in the direction of applied field. In order to measure the vector of magnetization, polarized neutron reflectometry was used.[11] Actually a much simpler and powerful method is available. One can measure anisotropic magnetoresistance (AMR) and pseudo-Hall effect (PHE) simultaneously.

In a FM metallic film, magnetoresistance is anisotropic due to the anisotropic scattering of conduction electrons. For a single domain film, the electric fields are given by,[13]

$$E_x = j\rho_\perp + j(\rho_\parallel - \rho_\perp)\cos^2\theta, \tag{1}$$

$$E_y = j(\rho_\parallel - \rho_\perp)\sin\theta\cos\theta, \tag{2}$$

where the current density j is assumed along the x-axis direction, the magnetization of the single domain is at angle θ with respect to j, and $\rho_\parallel$ and $\rho_\perp$ are the resistivities parallel and perpendicular to the magnetization, respectively. Equation (1) is for AMR, while Eq. (2) is for PHE.

Previously, both AMR and PHE have been used to study the exchange coupling in FM/AFM bilayers,[14,15] however, they were used separately. In these studies, biasing fields were obtained by fitting the experimental data with a single domain model, which was expected to be applicable in general discussions. It would be very interesting to have evidence of single domain state before doing quantitative analysis, especially when hysteresis appeared.[15]

In order to trace the domain breaking and merging, we can rewrite Eqs. (1) and (2) as follows

$$E_x - \frac{j(\rho_\parallel + \rho_\perp)}{2} = \frac{j(\rho_\parallel - \rho_\perp)}{2}\cos 2\theta, \tag{3}$$

$$E_y = \frac{j(\rho_\parallel - \rho_\perp)}{2}\sin 2\theta. \tag{4}$$

It is easy to see that E_x vs E_y plot should be a circle if the single domain model is valid (Fig. 1). Any domain breaking will result in moving the data points towards the origin of the circle for two reasons. First, if magnetizations in the adjacent

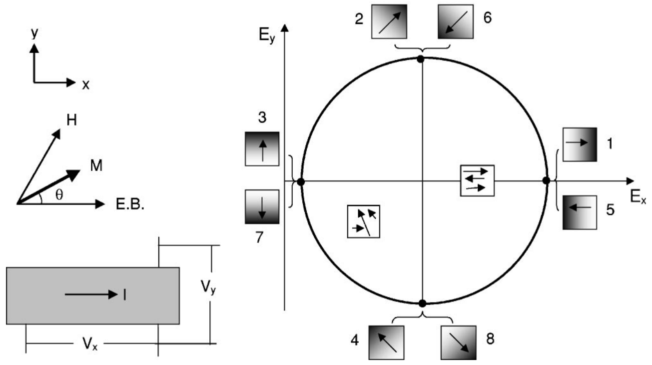

FIG. 1. Left: Experimental setup for AMR and PHE measurements. The sample film plane was defined as the $x-y$ plane. Magnetization of the magnetic film M was rotated in the film plane due to competition of in-plane applied magnetic field H and exchange bias (EB). The latter was parallel to the x-axis in zero field. By using an excitation current I flowing along x-axis, AMR and PHE were measured as V_x and V_y, respectively. Right: Monitoring the single domain state by AMR and PHE. The sample was shown as the squares, in which arrows showed the directions of magnetization. When the sample was in the single domain state, $1 \sim 8$, the electric fields E_x and E_y, which were calculated from V_x and V_y directly, run on a circle according to Eqs. (3) and (4). A single point on the circle represented two antiparallel magnetic states, for example 2 and 6. Breaking of the single domain state resulted in multidomains with random directions or domain walls. Both of them dragged the points from the circle to its origin, as illustrated by the two squares in the circle.

domains are not antiparallel, the anisotropy of the system will be obviously averaged out according to Eqs. (3) and (4). Second, if magnetizations in the adjacent domains are antiparallel, the presence of domain walls will also reduce the anisotropy. Therefore, using both AMR and PHE, we can monitor the magnetic structure in a magnetic film.

Samples used in this study are NiFe (26 nm)/NiMn (50 nm) bilayers coated with Ta deposited on glass substrates. The films were annealed at different temperatures for 5 h in magnetic fields. Details of the sample preparation have been published elsewhere.[16] The experimental setup, shown in Fig. 1, was used in our previous studies.[17,15] We have already reported PHE study of the samples.[15] It was shown that uniaxial anisotropy, which was induced by spin-flop coupling,[6] is not present in NiFe/NiMn bilayers. The absence of spin-flop coupling was also reported in NiFe/FeMn system.[18] This seems to be a common feature for FM/AFM coupling with a Mn alloyed AFM layer. Hysteresis was observed in the PHE measurements, and in some cases one branch of the PHE data followed the single domain prediction with a fixed biasing field. This observation might be related to the asymmetry of the magnetization reported recently.[11,12] The hysteresis should contain important information about the exchange coupling. But convincing conclusions cannot be drawn without the knowledge of domain structure in the samples. Fortunately, as shown above, this could be done by considering both AMR and PHE.

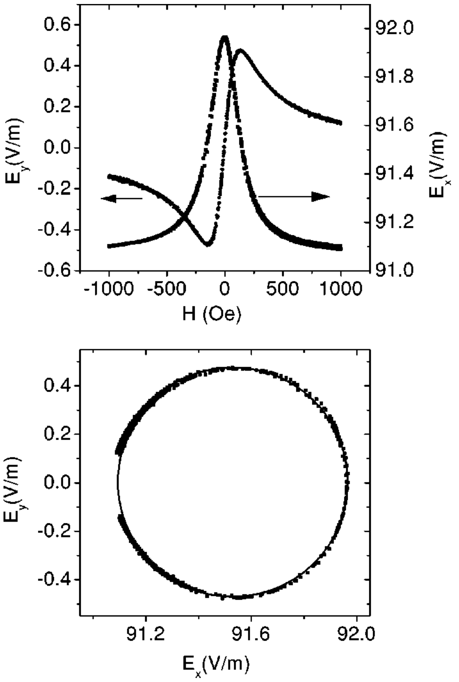

FIG. 2. AMR and PHE electric fields, E_x and E_y, showed no detectable hysteresis during the magnetization reversal when the magnetic fields were applied perpendicular to the biasing direction in the film plane. The trace of AMR and PHE fields proved that the FM layer was in a single domain state.

III. RESULTS AND DISCUSSION

It was assumed that the FM layer should be in a single domain state when its magnetization rotated within a small angle relative to the biasing direction.[14,15] This assumption can be checked in Fig. 2, where magnetic fields were applied perpendicular to the biasing direction in the film plane. The magnetization rotated between $-90°$ and $90°$ when the magnetic field swept up and down. A trace similar to that in Fig. 1 was seen when we plotted E_x vs E_y. Such a trace is a strong evidence of a single domain state as discussed in the preceding section. This check is general because it is independent of specific forces on the FM layer during the magnetization reversal. A more careful examination of the trace revealed that it was actually an ellipsoid instead of a circle. The axis along PHE is 8% longer than that along AMR. This is not very surprising considering the presence of Ta and NiMn layers. However, to our knowledge, there is no detailed study on how a nonmagnetic or antiferromagnetic metal layer influences the AMR and the PHE of a magnetic film. Clearly, this deserves further investigation. In this paper, since we are more interested in the magnetization reversal and exchange coupling, we simply accepted the fact and assumed that the ellipsoid comes from renormalization of coefficients in Eqs. (3) and (4), which was applied to the fittings below. Anyway, the ellipsoid was still very useful to monitor domain structures of the FM layer as discussed before.

In Fig. 3, a magnetic field was applied at 30° with respect to the biasing direction so that the magnetization of the FM layer could rotate more when the sign of the magnetic field

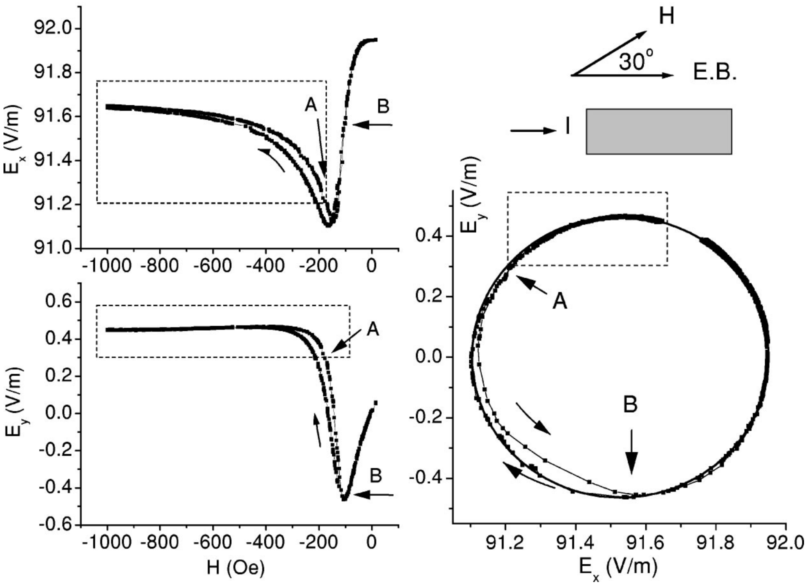

FIG. 3. Hysteresis and domain breaking. The magnetic fields were applied along 30° with respect to the exchange bias (EB). The fields swept up and down between -1000 Oe and $+1000$ Oe. Only negative sides were shown in the field dependence of E_x (AMR) and E_y (PHE), while the whole data were shown in the E_x vs E_y plot. The FM layer continued to be a single domain when the magnetic field swept from 1000 Oe to -1000 Oe. From -1000 Oe to 1000 Oe, hysteresis before point A was due to the AFM instability, after that the single domain was broken. Merging of the broken domains and restoring of the original exchange bias took place at point B. (see text).

was reversed. A striking feature immediately appeared when we plotted E_x vs E_y. It is obvious that in one branch of the loop the FM layer kept a single domain form while in the other one domain breaking took place. This feature justified our previous PHE analysis.[15] With this single domain check we can go further to see the nature of hysteresis of PHE and AMR.

It is interesting to see what happened in the windows of Fig. 3. These windows show the same magnetization reversal process. There is a large hysteresis in both PHE and AMR signals. The hysteresis could come from domain nucleation in the FM layer or from the hysteresis of exchange coupling due to magnetic instability in the AFM layer. However, *no hysteresis* is observed in the trace of E_x vs E_y, which runs along the ellipsoid. As discussed above, the data points (E_x, E_y) fit into the ellipsoid only if the FM layer is in a single domain state, any breaking of the state will drag the points to the origin of the ellipsoid. So the behavior of E_x vs E_y in the window proves that the FM layer continued to be a single domain state in the reversal process. Thus the hysteresis in PHE and AMR has to come from that of exchange bias due to instability in the AFM layer.

Following the hysteresis of exchange bias, the single FM domain started to break at point A, where the magnetization was at about $-110°$ relative to the original biasing direction in this case. It was surprising that with the increase in the magnetic fields the broken domains merged very quickly [at about $-45°$ (point B)], and with the merging of the FM domains the original biasing field was also recovered, i.e., hysteresis in the three plots disappeared simultaneously. Such breaking and merging processes strongly suggest that there is a close relation between the instabilities in the AFM layer and the FM layer.

Now that we have clear evidence that the FM layer was a single domain in the magnetization reversal process shown in the windows of Fig. 3, we can safely go ahead to see in detail what happened there.

The experimental data of E_x in the single domain process shown in Fig. 3 were replotted as symbols in the lower panel of Fig. 4. The solid line in the panel was calculated theoretically with a biasing field of 143 Oe, which had been obtained from fitting the data in branch a with magnetic fields higher than -200 Oe. The 143 Oe biasing field deduced here using AMR is consistent with that using PHE.[15] It can been seen that the data in branch a were lower than the theoretical

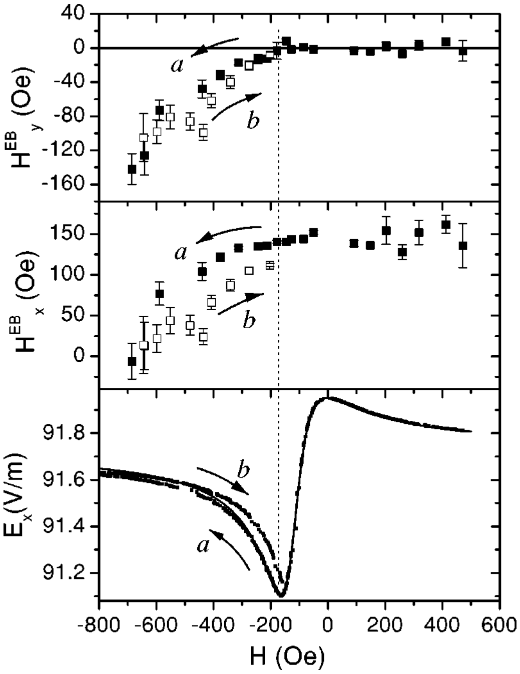

FIG. 4. Lower: Hysteresis of the AMR signal E_x during the single domain reversal process. The solid line is a theoretical prediction with a biasing field of 143 Oe. Upper and center: Two components of biasing fields H_x^{EB} and H_y^{EB}. They were obtained by fitting $E_x(H)$ locally, i.e., using data near a given magnetic field. The vertical dashed line marks the point beyond which H_y^{EB} developed and disappeared.

prediction when the magnetic fields were lower than -300 Oe, which means that the magnetization of the FM layer rotated less than expected. Lesser rotations of the magnetization would require an increase in the biasing field if its direction was fixed during the reversal process. But such an increase seems impossible. In fact, it is not necessary to assume a fixed biasing direction. In order to see how the exchange bias varied during the magnetization reversal, we divided the magnetic fields into a number of small ranges and within each range of the fields we fitted the data with two free parameters, i.e., two components of the exchange bias, H_x^{EB} and H_y^{EB}. The results were shown in the upper and center panels of Fig. 4. The large errors in high fields came from the weak dependence of E_x on H, especially because the change in the magnetization direction was very small in high fields (both positive and negative). Despite the errors, two features are apparent from the figure. First, H_x^{EB} began to decrease when the magnetization rotated more than 90° with respect to the original biasing direction, and surprisingly, a transverse biasing field H_y^{EB} developed in the meantime. At -650 Oe, H_x^{EB} was almost zero and the biasing became transverse. Fitting in fields lower than -650 Oe was prohibited by the extremely large errors because the relative rotation of magnetization of the FM layer was too small. Second, H_y^{EB} disappeared with the increase in the magnetic field in branch *b*, while H_x^{EB} reappeared but reached a lower value, which was mostly responsible for the hysteresis between branches *a* and *b*. The behavior of E_y^{EB} suggests that some elastic energy could be stored in the AFM layer, however, it is puzzling that the elastic deformation only occurred when the magnetization rotated more than 90°. The absence of hysteresis in Fig. 2 also supports that there is a critical angle. One possible explanation for this behavior is that the interactions between AFM grains might be a barrier to the changes in the magnetic structure within individual AFM grains. When the magnetization of the FM layer rotates far enough from the original biasing direction, the increased energy at AFM/FM interface overcomes the interaction energy so that magnetizations of the AFM grains could rotate. Small rotations in the AFM grains lead to occurrence of H_y^{EB}, while large rotations cause the hysteresis in H_x^{EB} since one can expect uniaxial anisotropy in the AFM grains.

Finally, we discuss the domain breaking and merging processes. The magnetic structure of the FM layer is determined by exchange coupling with the AFM layer, domain-wall energy within the FM layer, and the applied magnetic fields. Random field in the FM/AFM interface could drive the FM layer into small domains in the zero field if the domain-wall energy is small.[8] It can be seen from Fig. 3 that the broken domains merged before the applied field reversed its sign, as marked by point *B* in the figure, so domain-wall energy should be larger than the random field in our samples. But the single domain could still be broken by an applied magnetic field, provided the frustration in exchange coupling is not very weak. Thus we have the following understanding of the reversal process. In branch *a* of Fig. 4, the random field was small and so the FM layer could keep its single domain. After the hysteresis of exchange bias, the frustration became stronger, and the applied field could help to break the domain (point *A* in Fig. 3); with the increase in the field the broken domain merged due to the large domain-wall energy. Furthermore, when the field was applied near antiparallel to the exchange bias, field assisted breaking could take place for a smaller randomness of the biasing field. In fact, in these cases domain breaking processes dominated the magnetization reversal so that it was difficult to analyze the exchange coupling using a single domain model.

IV. CONCLUSIONS

In summary, we traced the single domain state of the FM layer in FM/AFM bilayers by measuring AMR and PHE simultaneously. The evolution of the exchange coupling during the magnetization reversal was demonstrated. The breaking of the FM single domain in applied magnetic fields could be triggered by the hysteresis of exchange coupling.

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