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Using magnetoresistance to probe reversal asymmetry in exchange biased bilayers

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We have measured the anisotropic magnetoresistance of Fe films exchange coupled to antiferromagnetic MnF_2 layers. Exchange bias and coercivity obtained from magnetoresistance are in close agreement with superconducting quantum interference device magnetometry data. In addition the magnetoresistance reveals an asymmetry in the magnetization reversal process, despite the fact that the magnetization hysteresis loops show little shape asymmetry. These results correlate well with an earlier study of magnetization reversal asymmetry by polarized neutron reflectometry. The data imply that the magnetization reverses by coherent rotation on one side of the loop and by nucleation and propagation of domain walls on the other. [S0021-8979(00)04913-6]

INTRODUCTION

Over 40 years[1] of research on exchange induced anisotropy at the interface between an antiferromagnet (AF) and a ferromagnet (F) has revealed many intriguing manifestations of this effect.[2] Despite the experimental and theoretical interest, and the importance in applications,[3] it remains a poorly understood phenomenon. Many recent experiments have focused on the exchange bias (H_E) and coercivity (H_C) of exchange shifted loops.[2] Two important phenomena associated with exchange bias have to be understood to arrive at a quantitative understanding: (a) the behavior of the exchange bias and its relation to the coercivity and (b) the reversal processes along the hysteresis loop. Asymmetry in reversal can often be observed in hysteresis loops, e.g., Refs. 4 and 5, and must be included in a full theoretical formulation.[6] Here we show that anisotropic magnetoresistance (AMR) provides useful information about the reversal process in good agreement with more direct neutron scattering measurements.

It is well established that AMR can be used as a probe of magnetization reversal and domain structure. Systems such as chains of submicrometric ferromagnetic (F) dots[7] and F nanowires,[8–11] for example, have been studied in this fashion. It is also well known that magnetoresistance measurements can be used to investigate exchange bias; magnetoresistance is useful for the determination of exchange bias in thin films[12] and submicrometric wires,[13] while the angular dependence of the in-field resistivity can be used to make reversible measurements of the exchange bias energy.[14]

In this article, we use AMR as a probe of magnetization reversal in exchange biased bilayers. Specifically, we investigate MnF_2/Fe AF/F bilayers[15] whose AMR reveals distinct reversal asymmetry while the hysteresis loops show little signature of this on either side of the loop. Polarized neutron reflectivity measurements[16] showed that the magnetization reversal mechanism is distinctly different on approach to positive or negative saturation. In fact the reversal was found to be due to magnetization rotation in one case and nucleation and propagation of domain walls in the other. We show here that the AMR measurement is sensitive to such effects and can clearly distinguish between the two reversal processes.

EXPERIMENTAL DETAILS

The growth and characterization of the exchange biased MgO (substrate)/ZnF_2 (buffer)/MnF_2 (AF, $T_N = 67.3$ K)/Fe(F)/Al(cap) layers was described in more detail elsewhere.[15] The layers are grown by electron beam evaporation and characterized by reflection high energy electron diffraction (RHEED) and x-ray diffraction at high angle and in the grazing incidence geometry. Briefly, the fluoride layers are quasiepitaxial (twinned) films with a body centered tetragonal structure and a (110) orientation, while the Fe overlayers are polycrystalline. MgO/ZnF_2/Fe/Al layers were also deposited for comparison. The AF/F sample used to obtain the data in this article has a MnF_2 thickness of 54.0 nm and an Fe thickness of 13.5 nm, as determined by grazing incidence x-ray reflectivity.

The magnetization was measured by superconducting quantum interference device (SQUID) magnetometry while the AMR was measured with standard (four terminal) dc and ac techniques in a He^4 flow cryostat equipped with a superconducting solenoid. All measurements were made with the field applied parallel to the (100) MgO direction (i.e., at 45° to both of the twin anisotropy axes) and transport data were taken with the current in plane and parallel to the field. The temperature dependence of the resistivity was measured from 4.2 to 300 K in both zero field cooled and 2 kOe field cooled conditions. The dependence was typical for an Fe film (MnF_2 is an insulator) with no anomaly present at T_N for any cooling field size or orientation. Current–voltage characteristics were measured at 10 K (stabilized to within 10 mK) from 1

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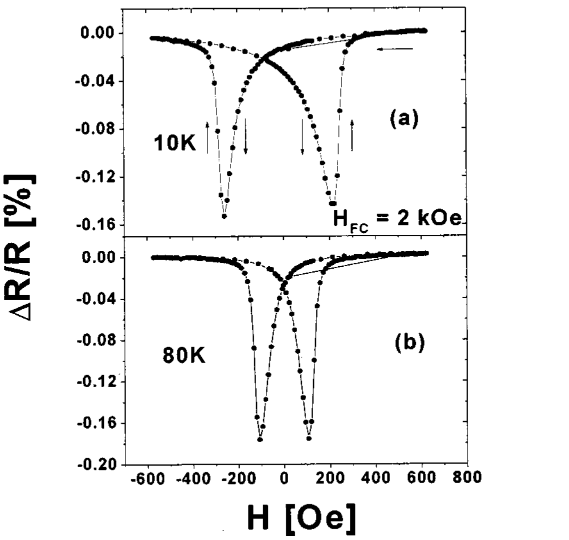

FIG. 1. Fractional MR at (a) $T=10$ and (b) 80 K. The cooling field, $H_{FC}=2$ kOe. Note that the data were taken with the current in plane and parallel to the in-plane magnetic field. The solid lines are guides to the eye. Arrows show the direction in which the field was swept.

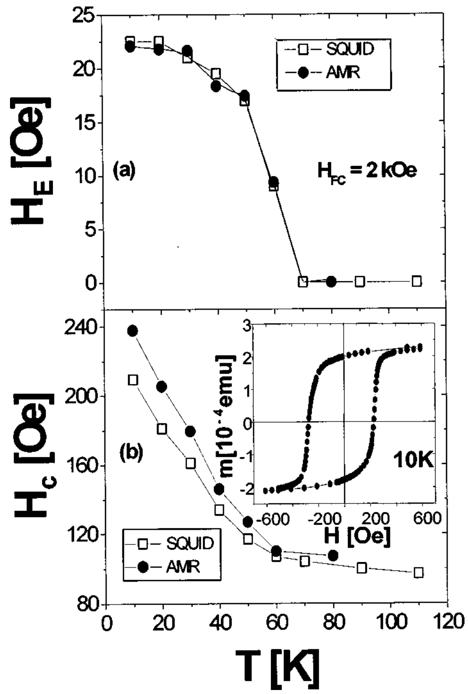

FIG. 2. The temperature dependence of the exchange bias (a) and coercivity (b) for $H_{FC}=2$ kOe. Square symbols represent data taken via SQUID magnetometry while circular symbols represent data taken via AMR measurements. Inset: SQUID hysteresis loop at $H_{FC}=2$ kOe and $T=10$ K. The solid lines are guides to the eye.

μA up to 10 mA to rule out self-heating. The remnant fields at the sample position were measured and accounted for by measuring the hysteresis loops of single (low coercivity) Fe films. These fields were significantly smaller than the H_E values reported here.

RESULTS AND DISCUSSION

Typical AMR is shown in Fig. 1 at 80 K ($T>T_N$) and at 10 K ($T<T_N$) after field cooling through T_N in 2 kOe (note that the measuring field is applied along the same axis as the cooling field, with positive measuring fields corresponding to the same direction as the cooling field). The 80 K data are symmetric about the resistance axis, while the magnitude of the AMR is in rough agreement with literature values for Fe.[17] The 10 K field cooled data display a shift along the field axis with the minima in resistivity occurring at $\sim$260 and 215 Oe in the positive and negative field directions. The value of H_E (22 Oe) determined from this data is in excellent agreement with the value obtained from the magnetization hysteresis loop (22.5 Oe), as shown in the inset of Fig. 2. Figure 2 shows the good agreement on the temperature dependence of H_E and H_C for the two techniques. The physical meaning of such temperature dependencies was discussed in a previous article.[15]

An interesting discrepancy between the two measurement techniques is evident on close examination of Fig. 1 and the inset of Fig. 2. The shape of the magnetization hysteresis loop is symmetrical with respect to a vertical axis through the geometric center of the loop whereas the shape of the AMR curve in Fig. 1(a) is not. In the AMR data the reversal on the negative field side of the loop is much sharper than the reversal on the positive field side. Note that this asymmetry is not an artifact of sample misalignment, or current direction misalignment as the asymmetry disappears when the sample is no longer exchange biased at 80 K [see Fig. 1(b)]. Further, no such effect is observed in Fe layers on nonmagnetic ZnF_2 at any temperature studied. The unidirectional anisotropy associated with the exchange bias is clearly involved. Note that data such as that in Fig. 1(b) are asymmetric with respect to a vertical axis through the resistance minima, i.e., on a given side of the loop the data near positive and negative saturation are asymmetric. This effect is clearly unrelated to the exchange anisotropy and is not discussed here.

The asymmetry in magnetization reversal is further examined in Fig. 3, where the AMR traces for increasing and decreasing field are overlapped to compare their shape. An

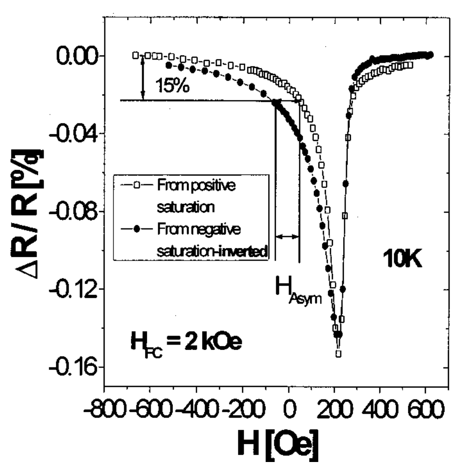

FIG. 3. The inversion and overlaying of the ''increasing field'' and ''decreasing field'' parts of the AMR trace shown in Fig. 1(a). The definition of the parameter $H_{\rm asym}$ is clearly illustrated. The solid lines are guides to the eye.

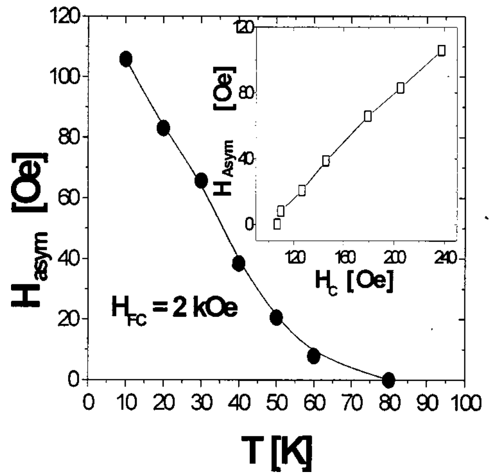

FIG. 4. The temperature dependence of H_{asym} (as defined in Fig. 3) for $H_{FC}=2$ kOe. Inset: H_{asym} vs coercivity, H_C. The solid lines are guides to the eye.

asymmetry is clearly observed. (Note that an identical procedure applied to the magnetization hysteresis loops results in only a slight asymmetry). To describe this quantitatively, we arbitrarily define the magnitude of the asymmetry (H_{asym}) as the field shift of the two curves at the point where the resistivity is reduced by 15% of the total reduction at the coercivity (as shown in Fig. 3). Figure 4 shows H_{asym} against temperature. The asymmetry appears below T_N (as expected) and increases monotonically with decreasing temperature. The similarity between the temperature dependences of H_{asym} and H_C [Fig. 2(b)] is striking and is emphasized further in a plot of H_{asym} as a function of H_C (inset of Fig. 4). Clearly the asymmetry increases linearly with the coercivity. We should stress that the conclusions drawn from Fig. 4 are independent of the exact definition of H_{asym}. Although the precise values are dependent on this arbitrary choice, the general increase of H_{asym} with H_C holds regardless.

Previous polarized neutron reflectometry on MnF_2/Fe bilayers[16] showed that the magnetization reversal on the negative field side of the loop occurs via coherent magnetization rotation, while on the positive field side it occurs via the nucleation and propagation of domain walls. This difference is a result of the twinned nature of the AF films and is described in detail in Ref. 16. The AF anisotropy axes of the two twins in the MnF_2 are oriented at 90° to each other. However, each individual twin requires that the easy axis for the magnetization of the Fe overlayer is perpendicular to its own anisotropy axis,[18] which leads to frustration. The result[16] is a situation where the easy axes of the Fe layer lie at 45° to both twin directions as a compromise. This has profound consequences for the magnetization reversal mechanisms. When the field is reduced from positive saturation the existence of an easy axis at 45° from the original field direction encourages rotation of the magnetization towards this easy axis. Hence rotation is induced on this side of the loop and eventually the magnetization vector is reversed. When the field is increased from negative saturation the situation is changed by the fact that the unidirectional anisotropy favors a situation where the magnetization vector aligns with it. This stimulates the formation of reverse domains rather than reversal by coherent rotation. To summarize, the reversal mechanism on the left and right hand side of the loops is fundamentally different.

The AMR measurements are clearly sensitive to this asymmetry, despite the fact that the magnetization hysteresis loops are not. The shape of the AMR trace in Figs. 1(a) and 3(a) shows that the *approach* to saturation on each side of the loop is apparently the same. It is the reduction of the field *from saturation* which shows asymmetry in the AMR, i.e., these measurements are sensitive to the initial stages of reversal. This process is sharper as the field is reduced from positive saturation (where the magnetization reversal occurs by rotation) than when the field is reduced from negative saturation (where nucleation and propagation is the dominant mechanism). This can be seen by looking at the resistance change between the saturation field and the geometric center of the loop; this is larger when reducing the field from negative saturation than when reducing from positive saturation. In other words, when the field is reduced from negative saturation the start of the reversal process occurs at higher negative fields (i.e., further from H_C). We suggest that the key point required to understand this is that the unidirectional anisotropy always favors the formation of the reverse domains. As a consequence the initial nucleation and expansion of the reverse domains is encouraged, resulting in a magnetoresistive response at larger negative fields, further from the coercive field. We note that this is contrary to the expectation that coherent rotation processes would result in a less sharp magnetoresistance curve. Moreover, the data in the inset of Fig. 4 show that the reversal asymmetry is more pronounced for loops with a larger coercivity, consistent with a stronger unidirectional anisotropy allowing formation of reverse domains at higher and higher negative fields, far from the coercive field.

SUMMARY AND CONCLUSIONS

In summary, we have investigated exchange biased hysteresis loops by conventional SQUID magnetometry and by measuring anisotropic magnetoresistance. The two methods are in close agreement on values for the exchange bias and coercivity. The magnetoresistance is sensitive to the asymmetry in magnetization reversal process on either side of the hysteresis loop as determined by previous measurement by polarized neutron reflectometry. We conclude that the asymmetry is related to the initial formation of reverse domains as favored by the exchange-induced unidirectional anisotropy.

ACKNOWLEDGMENTS

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