Asymmetric magnetic reversal of perpendicular exchange biased $(Co/Pt)_5$/IrMn probed by magnetoresistance and magnetic force microscopy

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Magnetic reversal of $(Co/Pt)_5$/IrMn multilayers with perpendicular exchange bias has been studied by magnetoresistance and magnetic force microscopy (MFM). It has been found that as a function of perpendicular external field, the resistance decreases with field above saturation and has sharp maxima at the reversal fields due to the domain wall resistance effect. The latter contribution has been found to be asymmetric, suggesting a corresponding asymmetry in the domain state in the two branches of the hysteresis loop. This asymmetry correlates with the fractal dimension of the domain wall projection deduced from MFM images, which is larger on the descending branch of the hysteresis loop than along the ascending branch. This in turn can be explained as due to the different intensities of domain wall nucleation in the two branches. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2710227]

Exchange bias (EB) effect is defined as the unidirectional pinning of magnetization in a ferromagnetic (FM) layer by an adjacent antiferromagnet (AFM), manifested in the shifting of the hysteresis loop.[1] Among many other interesting phenomena, the asymmetric magnetic reversal process of EB systems has been investigated both experimentally and theoretically.[2,3] Various methods such as neutron reflectivity and photoemission electron microscopy (PEEM) have been used to study the asymmetric reversal mechanism in the in-plane exchange bias systems. Reversal due to moment rotation and domain nucleation has been observed along the two field branches of the hysteresis loop.[4–6]

Recently, the reversal mechanisms in $(Co/Pt)_5$/AFM system with perpendicular EB have also been studied by magnetic x-ray small angle scattering and time-resolved Kerr microscopy.[7,8] In contrast to the in-plane EB systems, the only observed difference in the reversal mechanism on the ascending and descending branches of the magnetization curve in the $(Co/Pt)_5$/AFM perpendicular EB system is in the domain nucleation density, which is higher on the descending branch, when the field sweeps from parallel to antiparallel with respect to the bias direction. This asymmetry has been attributed to the nonuniformity of nucleation barriers due to the defects in FM or inhomogeneities in the AFM layer.[8]

In this study, we used a combination of magnetoresistance (MR) and magnetic force microscopy (MFM) measurements in a varying external magnetic field to investigate the magnetic reversal in perpendicular exchange biased $(Co/Pt)_5$/IrMn multilayers. For the measurement geometry, the anisotropic magnetoresistance contribution can be neglected and the observed maxima of magnetoresistance are attributed to the variation of the domain wall resistance. The asymmetry in domain nucleation along two different magnetic reversal branches is confirmed by both methods.

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Multilayers of $[Co(6\ Å)/Pt(20\ Å)]_5$/IrMn(80 Å) were deposited by ion beam sputtering on insulating Si(001) substrates at room temperature through thin Hall bar-shaped shadow masks. The chamber base pressure was 9×10^{-9} Torr and the Ar pressure during deposition was 1.2×10^{-4} Torr An external magnetic field of 400 Oe was applied perpendicular to the thin film plane during the growth, using a permanent magnet to introduce exchange bias.[9] Magnetotransport measurements were performed in a Quantum Design MPMS–5M system at temperatures in the range of 5–300 K at a current of 1 mA. The magnetic field was applied in a direction perpendicular to the plane of the film. The hysteresis loops were deduced from the extraordinary Hall effect (EHE),[10,11] and MR as a function of magnetic field was measured simultaneously with the Hall resistance.[12] Evolution of the domain structures under a varying perpendicular field was imaged on the same sample using the MFM

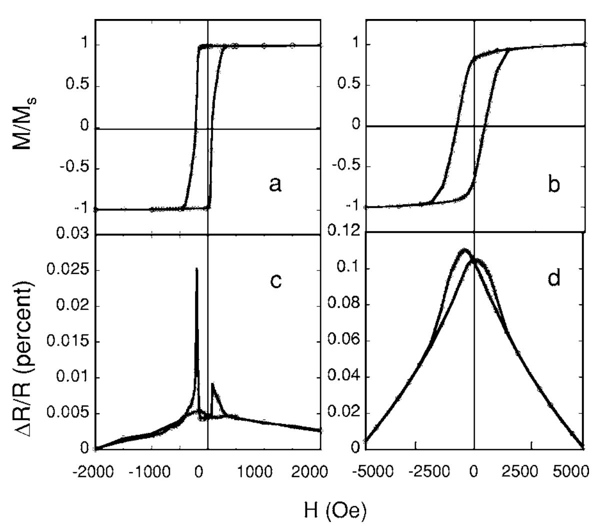

FIG. 1. Perpendicular EHE hysteresis loops at (a) 300 K and (b) 5 K, and magnetoresistance as function of external field at (c) 300 K and (d) 5 K of the perpendicular exchange biased $(Co/Pt)_5$/IrMn multilayer.

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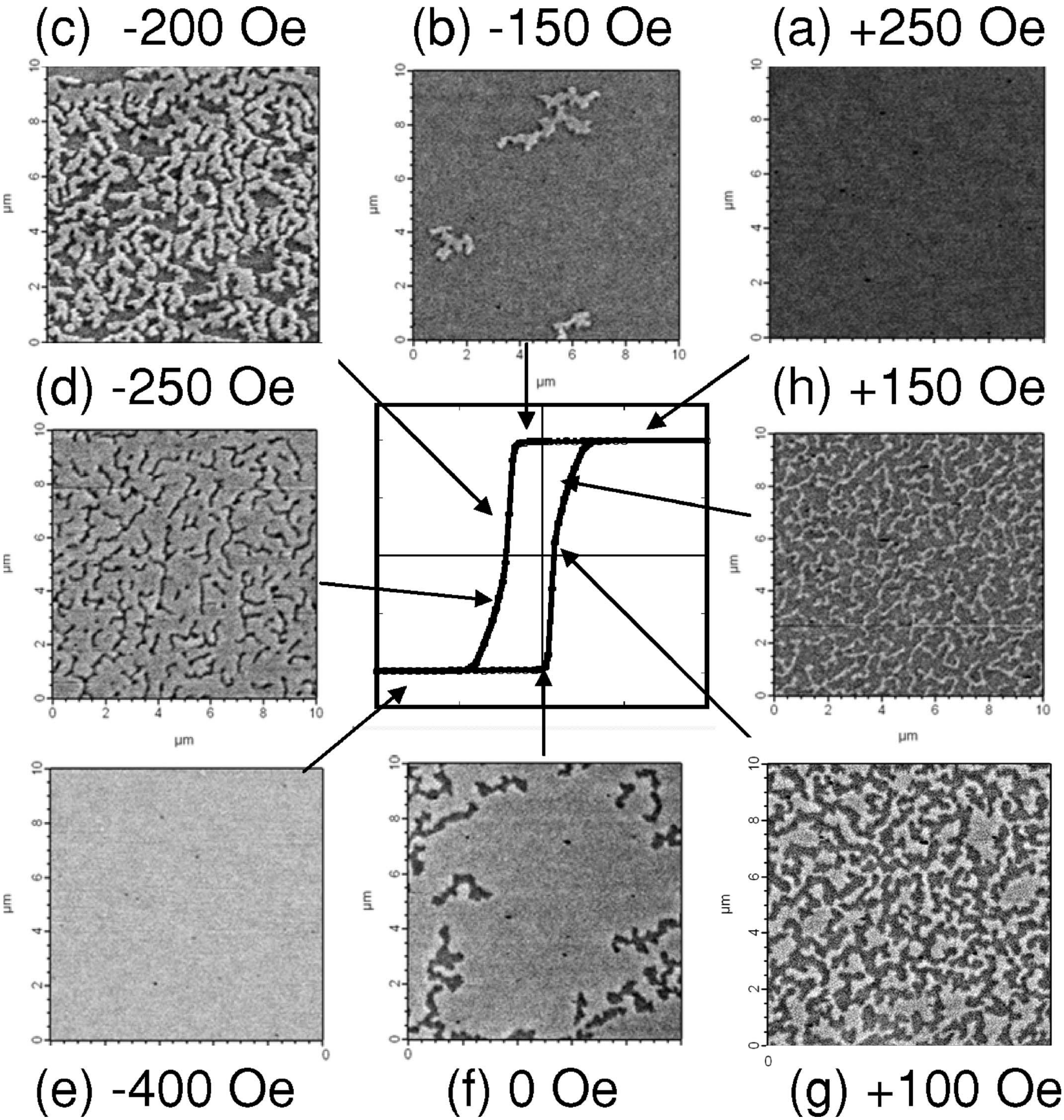

FIG. 2. Magnetic force microscope images under various external fields along the hysteresis loop of the perpendicular exchange biased $(Co/Pt)_5/IrMn$ multilayer.

mode of an Asylum MFP-3D scanning probe microscope.

Figures 1(a) and 1(b) show the hysteresis loops measured by EHE at 300 and 5 K. The bias fields are about 75 and 205 Oe, respectively. The MR defined as $\Delta R/R=[R(H)\text{-}R(H_{max})]/R(H_{max})$, where H_{max} is the maximum measurement field, is plotted as a function of field in Figs. 1(c) and 1(d). The MR decreases with the field in large fields, and has two sharp maxima at the reversal fields, with the relative variation at the reversal around 0.02% at room temperature. The irreversible small-field behavior can originate from anisotropic magnetoresistance (AMR), domain wall resistance, or their combination. The former is caused by the variation of the angle between the magnetic moment and current directions, expressed as $\rho=\rho_0-\Delta\rho\sin^2\theta$, where θ is the angle between the current and local magnetic moment, $\Delta\rho$ is the resistivity difference between the parallel and transverse configurations, and ρ_0 is the resistivity at $\theta=0$.[12] However, this contribution can be ruled out in our case since both the magnetic anisotropy and the applied field are nominally perpendicular to the current. The domain wall resistance

comes from spin dependent scattering of transport electrons when they pass across the domain walls.[13,14] This contribution will be a maximum during the reversal if the reversal is due to the domain wall nucleation and evolution. The MFM experiments (see below) support the argument in favor of this mechanism to explain the peaks in the MR measurements.

Multilayers with perpendicular anisotropy are ideal for MFM studies, since MFM is sensitive to the perpendicular magnetic field gradient.[15] MFM imaging of the perpendicular exchange biased multilayers, as a function of applied field, clearly elucidated the related domain nucleation and domain wall motion. Figure 2 shows selected MFM domain images of $(Co/Pt)_5/IrMn$ multilayers at various magnetic fields starting from the positive saturation field (a) to the negative saturation field (e), then back to the positive saturation field in symmetric field positions with respect to the loop center. The scan area is $10\times10\ \mu m^2$. Image (a) shows a single domain state. With decreasing field, around −150 Oe, nucleation of domains with opposite magnetization starts. With further decrease in field, an abrupt domain density increase is observed around −200 Oe, followed by the domain growth until the complete reversal. The images taken on the ascending branch of the hysteresis loop show qualitatively similar behavior. Though the domain wall nucleation is apparently lower on the ascending branch of the loop, images with apparently similar domain wall densities can be found on both sides of the loop [compare (c) and (g)].

For quantitative evaluation of the effective domain wall density at the reversal, we calculated the fractal dimension of the domain wall projection on the film plane D_f, representing the static jaggedness of domain geometry and hence the effective domain wall (DW) area, and intensity of the DW scattering. D_f has also been found before to correlate with domain nucleation and evolution dynamics.[16] D_f tends to increase as the reversal behavior becomes nucleation dominant, since nucleation produces long range roughness. D_f of the $(Co/Pt)_5/IrMn$ multilayer from MFM images in Fig. 2 are calculated using the ruler method, with the scale of 300 nm to 1 μm.[17,18] The D_f along the descending branch is about 1.23, which is larger than the D_f along the ascending branch of the hysteresis loop (around 1.16). It indicates that the DWs on the descending branch have larger jaggedness and effective area. According to Ref. 16, it also means that the domain nucleation is more pronounced on the descending branch.

It was found that the MR curves (Fig. 1) are asymmetric. The peak corresponding to the descending branch of the hysteresis loop is higher than that on the ascending branch. For example, at 300 K, the peak amplitude is ~0.02% on the descending branch, four times larger than that on the ascending branch. This difference reflects the difference between the domain states in the two reversal branches. From comparison with the analyses of the MFM images, higher MR peak an the descending branch correlates with higher effective domain wall density. However, we notice that the difference in the values of fractal dimension D_f is relatively small and can explain the asymmetry of magnetoresistance only qualitatively. Additional considerations need to be considered to fully describe this effect.

These results are different from the MR in the in-plane exchange bias systems, where higher MR on ascending branches than on the descending branches has been observed.[19,20] It was explained by the moment rotation mode along ascending branches versus the domain nucleation mode along descending branches. The former one results in a larger AMR effect. It is clear that although the magnetic reversal is asymmetric in both the in-plane and perpendicular anisotropy cases, the reasons for asymmetry are different.

In summary, asymmetric magnetic reversal of perpendicular exchange biased $(Co/Pt)_5/IrMn$ multilayers has been observed by both MR and MFM methods. The domain wall resistance is asymmetric along the ascending and descending branches of the hysteresis loops, which can be explained by the difference in domain wall density in the two reversal branches. This conclusion follows from the analyses of the MFM images and fractal geometry of the domain walls. Both the MR and MFM data are consistent with the reported data on x-ray small angle scattering and time-resolved Kerr microscope data in that the magnetic reversal is due to domain nucleation and growth in both the descending and ascending branches, in contrast to most in-plane exchange bias system.

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