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Magnetization processes in exchange-biased MnPd/Fe bilayers

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The magnetization processes in MnPd/Fe bilayers have been investigated using vibrating sample and torque magnetometry. An analytical model based on coherent magnetic moment rotation has been used to qualitatively explain and describe the magnetization processes. The shift of the hysteresis loop, the increased coercivity, the easy and hard axis behavior as well as the intermediate magnetic state seen in the hysteresis loops are reproduced in the model. However, the magnitude of the bias and the coercivity are not strictly in agreement with the measured values. The discrepancies are attributed to the simplified model which does not take into account the role of magnetic domains and incoherent spin rotation. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1751230]

The exchange bias effect was discovered in Co–CoO particles by Meiklejohn and Bean and has since been found in many other materials systems.[1–4] Exchange bias refers to the unidirectional magnetic anisotropy which can be seen in exchange coupled ferromagnetic/antiferromagnetic structures cooled through the Néel temperature in the presence of a magnetic field giving rise to a shift of the magnetic hysteresis loop. The shifted hysteresis loop is also accompanied by an increased coercivity which is much larger than the intrinsic value of the ferromagnet. In spite of the extensive research carried out on different exchange bias systems its microscopic origin is poorly understood.[3–5] For instance, none of the many different theoretical models that have been proposed are able to describe all the features of the exchange bias effect.[6–8] To address some of these issues we have grown MnPd/Fe bilayers of high structural quality that show exchange bias. We present a study of the magnetization processes in these MnPd/Fe bilayers. An analytical model based on coherent magnetic moment rotation qualitatively describes all the main features of the magnetization processes as a function of applied magnetic field.

The MnPd/Fe bilayers were grown on single-crystalline $MgO_{(001)}$ substrates by ion-beam sputtering at 350 °C in ultrahigh vacuum ($<10^{-8}$ Torr). A magnetic field (300 Oe) was applied along the easy axis of Fe ($Fe_{[100]}$ is the easy and $Fe_{[110]}$ is the hard) during deposition. X-ray diffraction (XRD) texture measurements show that the Fe layer, grown on the MgO substrate, is single crystalline with a (001) growth orientation, whereas the MnPd layer is *c* axis oriented with a small *a* axis component.[9,10] A low-angle XRD scan from the investigated sample was fit to a Parratt model[11] with the following result: Au(30 Å)/MnPd(450 Å)/Fe(50 Å)/MgO, and a MnPd/Fe interface roughness of 2.5 Å. The composition of the thin film MnPd alloy was determined by energy dispersive x-ray analysis to be Mn(52 at. %)–Pd(48 at. %).

Figure 1 shows hysteresis loops from the Au(30 Å)/MnPd(450 Å)/Fe(50 Å)/MgO sample measured at room temperature in a vibrating sample magnetometer (VSM). The magnetic field is applied along three different directions, 0° (a), 45° (b), and 90° (c) with respect to the bias direction. In a pure single-crystalline $Fe_{[001]}$ film the [100] and [−100] direction are equivalent, however, in the MnPd/Fe film the unidirectional anisotropy, induced by the exchange coupling between the ferromagnet (Fe) and the antiferromagnet (MnPd), breaks the symmetry between these two directions. This can be seen as a shift of the hysteresis loop when the bias direction ($Fe_{[100]}$) has a component along the field direction. The loop is shifted by −160 Oe when the applied field is parallel to the bias direction and by −125 Oe when it makes an angle of 45°. Another notable feature is the increased coercivity, approximately 110 Oe (0°) and 40 Oe (45°), which should be compared to ~10–20 Oe for an unbiased single-crystalline $Fe_{[001]}$ film. The hysteresis loop is not shifted but there is an intermediate magnetic state between the two saturated states when the magnetic field is applied perpendicular to the bias direction which is not seen in $Fe_{[001]}$ films. This step in the hysteresis loop has also been observed in other exchange bias systems when the applied magnetic field is perpendicular to the bias direction.[12] In some cases it is also seen when the field is parallel to the bias direction.[13]

All the different features seen in Fig. 1 can be quantatively explained by a simple analytical model. The total energy of a system of magnetic moments is essentially the sum of the Zeeman energy, the exchange energy, the magnetostatic energy and the magnetic anisotropy energy. However, the exchange and magnetostatic energies are constants and can be omitted if it is assumed that the magnetic moments rotate coherently in-plane and no magnetic domains are

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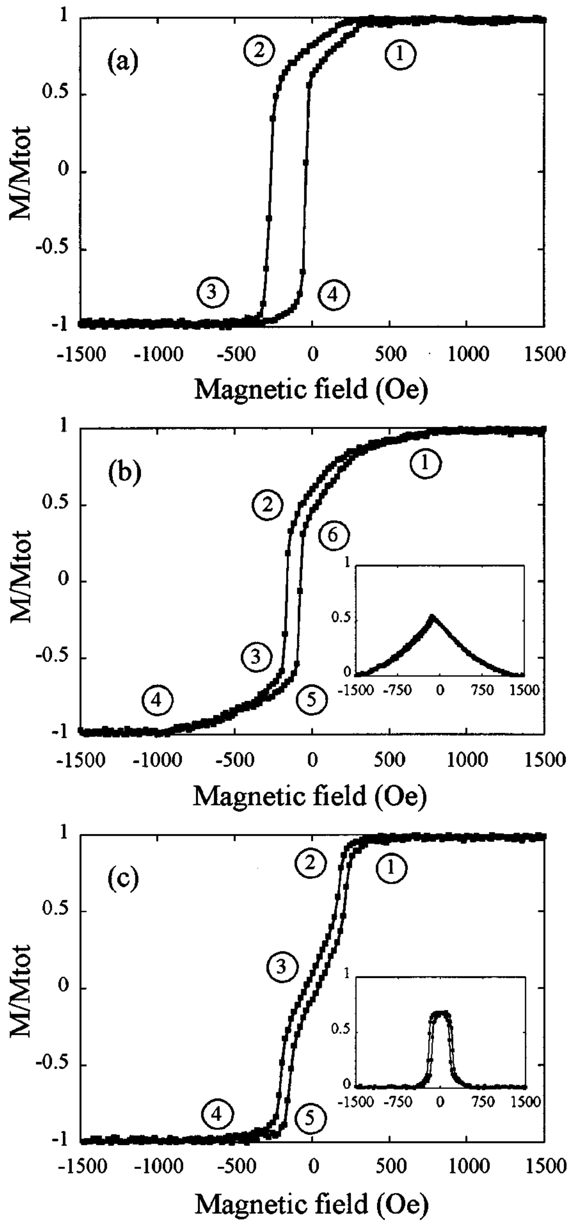

FIG. 1. Hysteresis loops from the MnPd/Fe bilayer measured at room temperature in a vibrating sample magnetometer. The magnetic field is applied: 0° (a), 45° (b), and 90° (c) with respect to the bias direction. The insets [M/M_{tot} vs H(Oe)] in (b) and (c) show the corresponding VSM measurements in the direction perpendicular to the applied magnetic field.

formed. This yields the following simplified total energy expression:

$$E = -HM\cos(\alpha-\theta) + K_1\sin^2(\theta)\cos^2(\theta) - K_2\cos(\theta) + K_3\sin^2(\theta),$$

where θ and α are the angles that the magnetization and the applied magnetic field make with the bias direction ($Fe_{[001]}$). H and M are the magnetic field and the magnetization, respectively. The total anisotropy energy has been divided into three components, a cubic (K_1), a unidirectional (K_2), and a uniaxial (K_3) term. Torque measurements (Fig. 2) were carried out at room temperature in a magnetic field of 1 kOe. Analysis of the data gives the following anisotropy constants: $K_1 = 4.6\times10^4$ J/m^3, $K_2 = 2.9\times10^4$ J/m^3, and $K_3 = 0$.

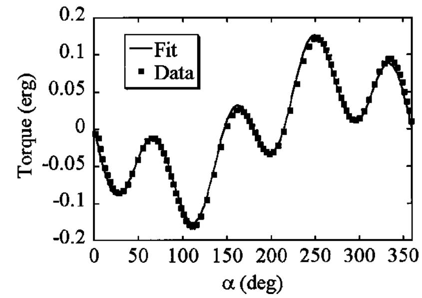

FIG. 2. Torque data from the MnPd/Fe bilayer. The measurement was performed at room temperature in a magnetic field of 1000 Oe. The cubic and the unidirectional torque components are clearly distinguishable; the short wavelength oscillations correspond to the cubic anisotropy while the long wavelength corresponds to the unidirectional.

Using higher order anisotropy terms did not improve the fit. It has been found that thin Fe films ($\leqslant$50 Å) on $MgO_{(001)}$ have a cubic anisotropy constant which is less than 50% of the bulk value (4.8×10^4 J/m^3).[14] Thus, the large values for K_1 and K_2 indicate an enhanced cubic and a large induced unidirectional anisotropy. The cubic and the unidirectional components are clearly distinguishable in the data; the short wavelength oscillations correspond to the cubic anisotropy while the long wavelength corresponds to the unidirectional. It is well known that the induced anisotropies are very sensitive to structural, chemical and magnetic disorder at the antiferromagnet/ferromagnet interface.[3,4] For example, it has been observed that the uniaxial anisotropy increases with increasing interface disorder.[12] As discussed above, the MnPd/Fe interface roughness was found to be of the order of 2.5 Å. This is less than what has been seen in other exchange-biased samples and it could explain why no uniaxial anisotropy is observed.[10,15–17]

In Fig. 3, the total energy has been plotted as a function of magnetic field and θ angle for three different applied field directions: (a) α=0°, (b) α=45°, and (c) α=90°. The paths the magnetic moments follow as a function of applied magnetic field are given by the arrows in the figures. As seen in Fig. 3(a), the magnetic moments switch abruptly between the two saturated states when the magnetic field is parallel to the bias direction. Furthermore, the two switching fields are not the same, ~−600 Oe compared to ~+400 Oe, which means that the hysteresis loop is shifted by −100 Oe and that the coercivity is very large, roughly 500 Oe. Thus, the model qualitatively reproduces both the shift of the hysteresis loop and the increased coercivity. When the field is applied at 45° with respect to the bias direction [Fig. 3(b)] and then reduced the magnetic hard axis behavior seen in Fig. 1 is reproduced: the moments rotate from the magnetic hard $Fe_{[110]}$ to the easy bias direction ($Fe_{[100]}$). The two switching fields, approximately −300 and 0 Oe, differ which implies a biased hysteresis loop (−150 Oe) with increased coercivity (150 Oe). The agreement between the experimental data and the model is quite good for the magnitude of the bias but not for the coercivity. Figure 3(c) shows the energy contours for the case where the magnetic field is applied perpendicular to the bias direction. When the magnetic field is reduced from saturation the magnetic moments rotate from perpendicular to

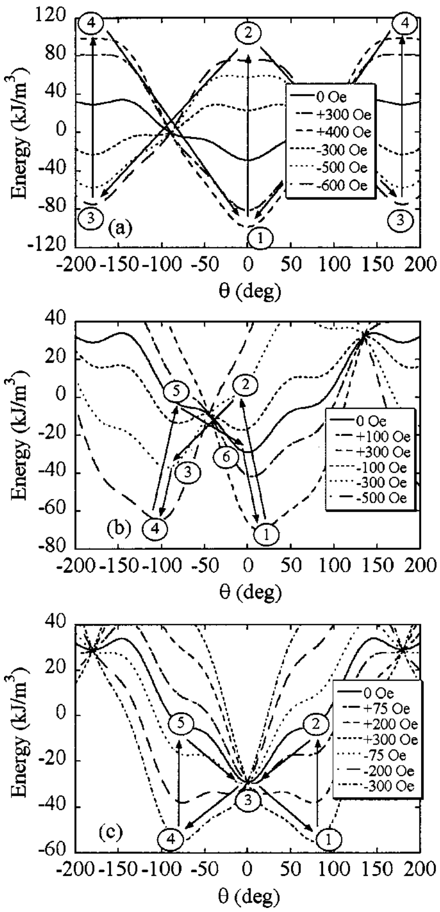

FIG. 3. Zeeman plus anisotropy energy as a function of θ-angle and magnetic field for three different α angles: 0° (a), 45° (b), and 90° (c). $\theta=0°$ corresponds to the bias direction. The numbers in the figure correspond to the numbers in Fig. 1.

the bias direction to parallel due to the induced unidirectional anisotropy. The magnetization will remain in this intermediate state until the Zeeman energy is large enough to overcome the anistropy energy. No shift of the hysteresis loop is expected for this field orientation due to the mirror symmetry of the energy landscape with respect to the bias direction.

VSM measurements in the direction perpendicular to the applied magnetic field are shown in the insets in Figs. 1(b) (45°) and 1(c) (90°). No net perpendicular magnetic moment is expected when the bias direction is parallel to the field. The measurements clearly show that the net magnetic moment of the sample rotates into the bias direction for both orientations as predicted by the model. However, the measured net magnetic moments at zero field are less than what are expected if all the magnetic moments rotate into the bias direction: $\sim 0.71 M_{\mathrm{tot}}$ (average value at zero field) (45°) and $\sim 0.68 M_{\mathrm{tot}}$ (90°), where M_{tot} is the total magnetic moment of the sample. The fact that the measured net magnetic moment is less than the total moment of the sample suggests that magnetic domains are formed when the applied field is reduced. Preliminary x-ray photoemission electron microscopy measurements on an exchange-biased Pt/Fe/MnPd/MgO sample confirm these conclusions.

Thus, the magnetization processes as described by this model are qualitatively correct. However, it should be emphasized that coherent magnetic moment rotation is an ideal case. For instance, it has been shown experimentally that when the magnetic field is applied parallel to the bias direction, the magnetization reversal proceeds by domain nucleation and growth, while the reversal occurs by incoherent moment rotation for the field perpendicular to the bias.[10,18]

In summary, we have investigated the magnetization processes in high quality exchange-biased MnPd/Fe bilayers. The shift of the hysteresis loop, the increased coercivity, the easy and hard axis behavior as well as the intermediate magnetic state are reproduced qualitatively in the model based on coherent magnetic moment rotation. However, to quantitatively describe the magnitude of the bias and coercivity one needs to take into account magnetic domains and incoherent spin rotation.

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