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Measurements of lattice-matched antiferromagnetic/ferromagnetic films which are ideal layered systems to study exchange bias are reported. Epitaxial films of $FePt_3$ have two kinds of antiferromagnetic ordering. The spin ordering phase with wave vector $Q_1=(\frac{1}{2}\ \frac{1}{2}\ 0)$ has a Néel temperature $T_N=160$ K and that with wave vector $Q_2=(\frac{1}{2}\ 0\ 0)$ has $T_N=100$ K. Neutron diffraction confirmed the presence of $Q_2=(\frac{1}{2}\ 0\ 0)$ antiferromagnetic ordering in 200 nm $Fe_{25}Pt_{75}$ grown on MgO(100). The loop shift and coercivity of a trilayer film of $CoPt_3/FePt_3/CoPt_3$ decrease with increasing temperature, consistent with the observed Néel temperature of $FePt_3$. The x-ray diffraction rocking curve widths of films grown on MgO(100) and $Al_2O_3(11\underline{2}0)$ are compared and related to the loop shifts that are observed in the films with lattice-matched antiferromagnetic/ferromagnetic interfaces. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2177347]

INTRODUCTION

Exchange bias or the unidirectional shift of the hysteresis loop is routinely used to "pin" the direction of the ferromagnetic layer in a spin valve giant magnetoresistive (GMR) head. However, the phenomenon of exchange bias in antiferromagnetic/ferromagnetic (AF/F) systems has not been comprehensively explained since the crystallographic and magnetic structure of interfaces are often not well understood. Current models emphasize the structure of the antiferromagnet and the interface structure of the AF/F in describing exchange bias for most systems that are polycrystalline.[1] Epitaxial systems offer a way to obtain additional insights into the phenomena of exchange bias, since the magnitude of the effect is determined by the defect structure of the antiferromagnet and interface. Numerical models often suffer from the lack of idealized systems to prove/disprove them and systems described in this study have unique properties in which it may be possible to obtain a detailed understanding of the relationship between structure and magnetism.

Bilayers of antiferromagnetic $FePt_3$ with ferromagnetic transition metals ($FePt_3$/Co and $FePt_3$/Fe) grown on MgO(110) exhibit the exchange bias effect.[2] The low Néel temperature of $FePt_3$ (160 K) makes it possible to perform experiments where the sample is field cooled through the Néel temperature while avoiding temperatures where structural changes may occur at the interface due to atomic diffusion. Nevertheless, the large amount of epitaxial strain at the AF/F interface in these systems produces an additional magnetic anisotropy. If Fe is replaced with Co in $FePt_3$, it results in a highly ordered $L1_2$ $CoPt_3$ that is ferromagnetic with the magnetic easy axis in plane. In $CoPt_3$, the ordered phase occurs when films are grown between 550 and 700 °C with the maximum amount of order produced at 630 °C.[3] The lattice constant of $CoPt_3$ is 3.85 Å and is only 0.5% smaller than the lattice constant of $FePt_3$ (3.87 Å). Therefore, epitaxial $CoPt_3$ ferromagnetic films with the same crystal structure as $FePt_3$ antiferromagnetic films and a good lattice match between the two alloys offer a way to study exchange bias in strain-free interfaces.

The structure of the antiferromagnetic $FePt_3$ is strongly dependent on the composition and temperature and plays an important role in describing exchange bias in these systems. The antiferromagnetic properties of Fe_xPt_{100-x} ($23 \leqslant x \leqslant 29$) alloys in bulk form have been studied extensively with neutron diffraction.[4] Fe moments in nearly stoichiometric $FePt_3$ are ordered as alternating ferromagnetic sheets in the (110) planes and have a very high moment ($3.3\mu_B$). Bulk ordered $FePt_3$ exhibits an antiferromagnetic spin structure with a wave vector $Q_1=2\pi/a(\frac{1}{2}\ \frac{1}{2}\ 0)$ below $T_{N1}\sim 160$ K. In Fe-rich alloys ($x>0.26$) a spin structure transition to a second antiferromagnetic phase $Q_2=2\pi/a(\frac{1}{2}\ 0\ 0)$ occurs below $T_{N2}\sim 100$ K. Antiferromagnetism in epitaxial Fe_xPt_{1-x} thin films ($x=0.26-0.30$) grown on MgO(110), MgO(111), and $Al_2O_3(11\underline{2}0)$ substrates have been studied using elastic neutron scattering.[5] The current study involves the fabrication and characterization of lattice matched $CoPt_3/FePt_3$ multilayers on MgO(100) and $Al_2O_3(11\underline{2}0)$.

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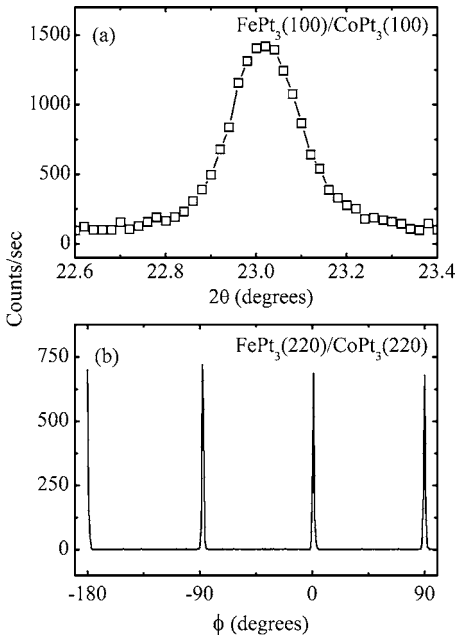

FIG. 1. (a) X-ray scan showing the presence of ordering in $CoPt_3$(10 nm)/$FePt_3$(50 nm)/$CoPt_3$(10 nm) trilayer (b) Phi scan of the (220) reflection revealing the epitaxial nature of the trilayer film.

RESULTS AND DISCUSSION

The films in this study were grown in a sputtering chamber with a base pressure lower than 2×10^{-8} mbar. The films have a 1 nm Fe seed layer along with a buffer layer of $CrPt_3$(2 nm) and were capped with 2 nm of Pt to prevent oxidation. The stoichiometry was controlled by adjusting the sputter rates of individual targets (calibrated with a quartz crystal microbalance). In the current study, a trilayer of $CoPt_3$(10 nm)/$FePt_3$(50 nm)/$CoPt_3$(10 nm) was cosputtered on a MgO(100) substrate at a deposition temperature of 650 °C. The epitaxial nature and the presence of chemical ordering in these films was confirmed using x-ray diffraction. In XPt_3 (Fe and Co) alloys with ordered $L1_2$ structure, Pt atoms occupy the corners of a cubic lattice while the X atoms occupy the face centers. The ordered phase can be imagined as being composed of two cubic lattices of Pt and Fe or Co, respectively. The (100) reflection is structure factor forbidden in a fcc lattice. The presence of the (100) reflection in an XPt_3 (Fe and Co) lattice indicates that the alloy is chemically ordered. Figure 1(a) shows the ordered $FePt_3/CoPt_3$(100) peak that corresponds to an out of plane lattice parameter of $a=3.86$ Å, very close to the value in bulk $FePt_3$ (3.87 Å). The phi scan of the (220) reflection, shown in Fig. 1(b), was performed at $\psi=45°$ and confirmed the epitaxial nature of the trilayer. Furthermore, in order to determine the presence of antiferromagnetic ordering, neutron diffraction studies were performed on a single layer of 200 nm thick $Fe_{25}Pt_{75}$ grown on MgO(100) with similar procedures as outlined above. Elastic neutron scattering was performed using the HB1a triple axis spectrometer of the High Flux Isotope Reactor at the Oak ridge National Laboratory. The HB1a is a fixed-initial-energy spectrometer with $E_i=14.61$ meV that corresponds to a neutron wavelength of 2.37 Å. Scans of the reciprocal unit vector h around the $(\frac{1}{2}\ 0\ 0)$ reflection were performed at various temperatures. The temperature dependence of the $(\frac{1}{2}\ 0\ 0)$ antiferromagnetic peak is shown in Fig. 2. The antiferromagnetic ordering decreases with increasing temperature and vanishes completely at $T=180$ K. It was important to make this confirmation since the $Q_2=(\frac{1}{2}\ 0\ 0)$ antiferromagnetic phase was previously found to occur only in $Fe_{25}Pt_{75}$ films grown on $Al_2O_3(11\bar{2}0)$ and not for $Fe_{25}Pt_{75}$ films grown on MgO(110) and MgO(111).[5,6]

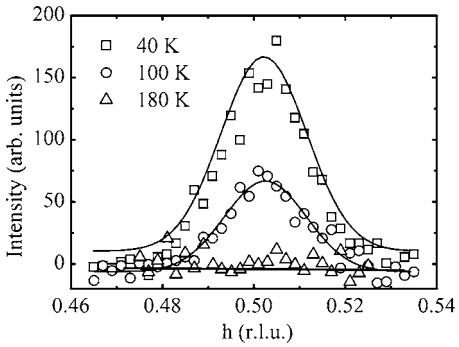

FIG. 2. Neutron diffraction of 200 nm $FePt_3$ grown on MgO(100) showing the variation of antiferromagnetic $(\frac{1}{2}\ 0\ 0)$ spin ordering with temperature.

The low temperature magnetization measurements were performed in an Oxford vibrating-sample magnetometer (VSM) by field cooling in a 2 T field to a temperature of 40 K. A trilayer of $CoPt_3$(10 nm)/$FePt_3$(50 nm)/$CoPt_3$ (10 nm) grown on MgO(100) showed a measurable loop shift in a direction opposite to the direction of the cooling field and decreased with increasing temperature. The coercivity of the trilayer film showed a decreasing trend with an increase in temperature as shown in Fig. 3(a). In comparison, a $CoPt_3$(20 nm) film exhibited a small positive loop shift ($\leqslant$4 Oe) that is within the experimental uncertainty as shown in Fig. 3(b). Also the rate of decrease of coercivity is lower for the purely ferromagnetic $CoPt_3$ film. The higher coerciv-

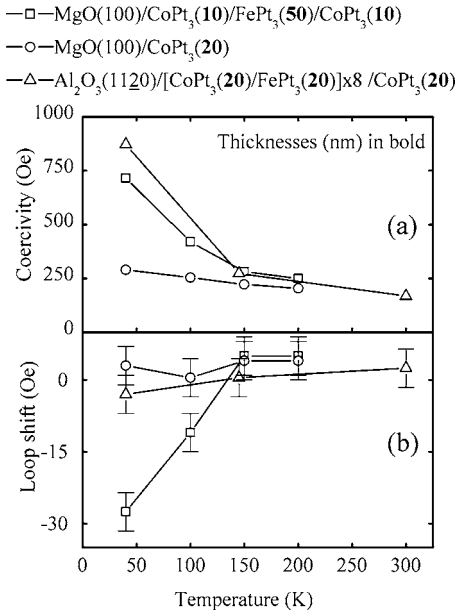

FIG. 3. Temperature dependence of (a) coercivity (b) loop shift in $CoPt_3/FePt_3/CoPt_3$ and $CoPt_3$ grown on $Al_2O_3(11\bar{2}0)$ and MgO(100). The lines are just guides to the eyes.

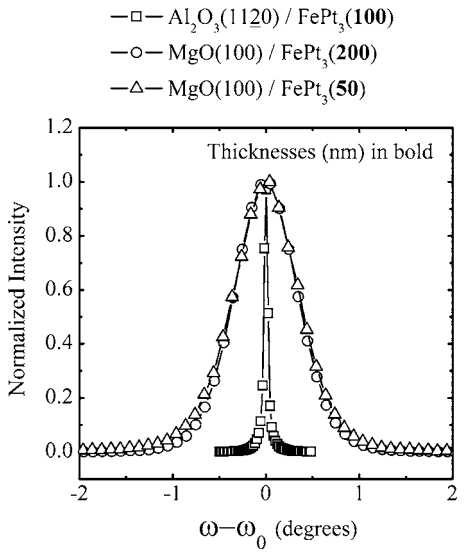

FIG. 4. Comparison of rocking curve widths of $FePt_3$ grown on $Al_2O_3(11\underline{2}0)$ and MgO(100).

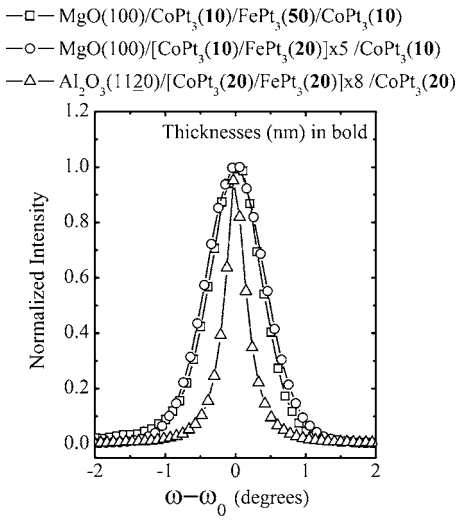

FIG. 5. Rocking curves of multilayers of $FePt_3/CoPt_3$ grown on $Al_2O_3(11\underline{2}0)$ and MgO(100).

ity of the trilayer film can be attributed to the antiferromagnetic pinning present in these films. In addition, bilayers and multilayers of $FePt_3$ were grown on $Al_2O_3(11\underline{2}0)$ using similar procedures as outlined above. The $FePt_3$ films grown on $Al_2O_3(11\underline{2}0)$ have a (111) texture and rocking curve widths of less than 0.1°. The films grown on MgO(100) display rocking curve widths in the range of 0.6° and 1.0° as shown in Fig. 4. This trend is apparent in the rocking curves of $CoPt_3/FePt_3$ multilayers shown in Fig. 5. The measured lattice constants (in angstroms) are MgO(111)=2.43, MgO(1$\underline{1}$0)=2.98, $Al_2O_3(11\underline{2}0)$=2.38, $Al_2O_3(1\underline{1}00)$=2.75, $FePt_3(2\underline{11})$=2.37, $FePt_3(1\underline{1}0)$=2.74, and $FePt_3(111)$=2.22. The lattice mismatches of films grown on $Al_2O_3(11\underline{2}0)$ are 0.4% and 8.6% along the [1$\underline{1}$0] and [2$\underline{11}$] directions of $FePt_3$, respectively. But in the case of films grown on MgO(100), the mismatch is 8.6% for both directions. Also, previous experimental studies have shown the presence of significant in-plane strains in films grown on MgO(110).[5] In comparison, the films grown on $Al_2O_3(11\underline{2}0)$ with the same seed and buffer layers are bulklike and essentially strain-free. It is expected that the AF/F interface of films grown on MgO will have more defects when compared to films on $Al_2O_3(11\underline{2}0)$. However, $FePt_3/CoPt_3$ multilayers grown on $Al_2O_3(11\underline{2}0)$ exhibited no exchange bias [Fig. 3(b)] within the experimental uncertainty while the films grown on MgO(100) showed a temperature dependent loop shift ranging from 0 to −28 Oe. The differences in behavior of the $FePt_3$ films grown on MgO(100) compared to those grown on $Al_2O_3(11\underline{2}0)$ can be attributed to higher strain and defect densities in the former. It appears that the imperfect nature of the $FePt_3/CoPt_3$ interface grown on MgO(100) promotes the exchange pinning effects.

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