Interface roughness effects on the surface anisotropy in Co/Pt multilayer films

Jin-Hong Kim and Sung-Chul Shin
Department of Physics, Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea

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We have investigated the effects of interfacial roughness on the surface anisotropy in Co/Pt multilayer films prepared by sputtering. Degree of interfacial roughness was varied by changing the Ar sputtering gas pressure from 2 to 20 mTorr in the sample preparation. The surface anisotropy was found to be increasing with decreasing interface roughness. We have observed that the surface anisotropy energy for the multilayer films prepared at various Ar pressures was logarithmically dependent on the integrated low-angle x-ray intensity. © 1996 American Institute of Physics.

Co/Pt multilayer films have been attracting wide attention because of their novel properties and potential technical applications.1,2 Recently, there have been rapidly increasing interests in the magnetic anisotropy of Co/Pt multilayer films, which exhibit an easy axis perpendicular to the film plane.3–5 The fundamental origin of the magnetic anisotropy of such multilayer films still remains not clear. However, the first principle explanation of the strong perpendicular anisotropy has generally been ascribed to Néel’s surface anisotropy which is a consequence of the reduced symmetry in the surroundings of surface or interfacial atoms.6

It is generally known that the surface anisotropy is strongly dependent on the interfacial morphologies in Co-based multilayer films.7 Thus, the surface anisotropy as well as other magnetic properties of multilayer films is very sensitive to the preparation methods and deposition conditions.7–12 Much more energetic atoms are generally involved in sputtering with Ar gas than in vapor deposition. These energetic atoms are expected to modify the microstructure of the films. It is reported that films prepared by vapor deposition exhibit a larger surface anisotropy than those prepared by sputtering with Ar gas.3,8 However, no systematic studies have been reported yet to correlate the surface anisotropy with the interfacial roughness. In this communication, we manipulate the interfacial morphology by varying sputtering Ar gas pressure and report a logarithmic dependence of the surface anisotropy on the low-angle x-ray intensity.

Co/Pt multilayers were prepared by dc magnetron sputtering from 2-in. diam Co and Pt targets onto Corning 7059 glass substrates using a rotatable substrate table. The dwelling time, which the substrates spend above each target, was controlled by a programmable timer interfaced to a stepping motor which drives the substrate table. Sputtering Ar gas pressure was varied from 2 to 20 mTorr to manipulate the interfacial morphology. At each Ar gas pressure, a series of samples having different Co sublayer thicknesses, but a constant Pt sublayer thickness was prepared with maintaining the same total number of 23 bilayers. The thickness of Pt sublayers at each Ar pressure is listed in Table I. The structural properties of the multilayer films were examined by low-angle x-ray diffractometry. Magnetization was measured using a vibrating sample magnetometer (VSM). The magnetic anisotropy was measured by a torque magnetometer at an applied field of 15 kOe. The surface morphology was investigated using an atomic force microscope (AFM).

The effective magnetic anisotropy, $K_{eff}$, per unit Co volume of Co/Pt multilayer film might be phenomenologically described as the sum of volume and surface terms

$$K_{eff} = K_v t_C o + 2K_s,$$

where $t_C o$ is Co sublayer thickness, $K_v$ is a Néel-type surface contribution, and $K_s$ is a volume term consisting of magnetocrystalline, magnetoelastic, and shape anisotropy.8 Hence, for a multilayer system being described by Eq. (1), $K_v$ as well as $K_s$ could be experimentally determined from a plot of $K_{eff} t_C o$ vs $t_C o$. The dependence of $K_{eff} t_C o$ on $t_C o$ is shown in Fig. 1 for the multilayers prepared at 2, 5, 10, and 20 mTorr Ar pressures. As seen in the figure, the behavior of the sample prepared at each Ar pressure is well fitted by Eq. (1). Hence, $K_v$ and $K_s$ can be determined as half of the numerical value of the intercept at $t_C o = 0$ and the slope, respectively. The obtained values of $K_v$ and $K_s$ at each Ar pressure are listed in Table I. The largest $K_s$ is observed for the multilayer film prepared at 5-mTorr Ar pressure, while $K_v$ is more than fourfold enhancement in comparison to the sample prepared at 20-mTorr Ar pressure. The variation of the surface anisotropy is believed to be ascribed to the change of interfacial microstructure, which is due to different Ar pressures used in the sample preparation. It is known that the bombardment of energetic Ar atoms reflected from the target smear out the interfaces of the constituents in the low sputtering Ar gas pressure. In order to improve the magnetic properties by enhancing the interfacial sharpness in Co/Pt multilayers, Garcia et al.13 have tried heavy sputtering gas such as Kr or Xe to reduce the damaging effects of energetic bombardments. Columnar structure and rough surfaces can be observed in the samples prepared at high Ar pressure because of the bombardment of Ar atoms and the kinetic energy of sputtered atoms having been reduced by collisions. In our results, it has been observed that 5 mTorr is an optimum sputtering Ar pressure to get the larger $K_s$ with the smoother surface than other pressures. Samples with rough (smooth) interfaces are expected to show a rough (smooth) surface morphology. The surface morphologies of the samples prepared at different Ar pressures were investigated.
to correlate with $K_s$. Figure 2 shows the AFM images of the surface morphologies of 1000-Å-thick Co/Pt multilayer films prepared at (a) 5 mTorr and (b) 20 mTorr. A smooth and dense surface morphology can be seen for the samples prepared at 5-mTorr Ar pressure, while a rough and coarse surface morphology for samples prepared at 20-mTorr Ar pressure. The interfaces of the latter sample are speculated to be not well-defined in comparison with those of the former one. The root-mean-square (rms) surface roughness measured by AFM for the samples prepared at different Ar pressures are listed in Table I. It is interesting to point out from Table I, that $K_s$ increases with decreasing rms surface roughness. Later, we will discuss these properties in conjunction with low-angle x-ray diffraction results.

The negative slope in Fig. 1 indicates a negative $K_v$ favoring in-plane magnetization. The numerical value of $K_v$ for the multilayer films prepared at 2 and 5 mTorr are large in negative and gradually increases with increasing sputtering Ar gas pressure. A change in the shape anisotropy, due to the variation of the magnetization depending on sputtering Ar gas pressure as shown in Fig. 3, seems to be a major cause for the variation of the volume anisotropy. In Fig. 3 the saturation magnetization, $M_s$, for Co/Pt multilayers prepared at 2, 5, 10, and 20 mTorr is plotted against $t_{Co}$. The values of $M_s$ were obtained by dividing the magnetization of the multilayer with only Co volume. $M_s$ values for the multilayers prepared at 2 and 5 mTorr are similar and gradually decreases with increasing sputtering Ar pressure. As pointed out by Shin et al., the density of the film decreases with increasing Ar pressure which reflects an increase of porous region due to the fact that less energetic atoms are associated with increasing pressure. This reduction of $M_s$ might also be ascribed to an increased interface roughness, since a fraction of the Co buried into the valley of the Pt sublayer results in the decrease of the Curie temperature and reduces $M_s$ value as indicated by Bertero et al. It is seen that the $M_s$ value exceeds the bulk value of Co (1422 emu/cm$^3$) in a sample except for those prepared at 20 mTorr. Enhanced magnetization is believed to be caused by the polarization of Pt atoms.

<table>
<thead>
<tr>
<th>$P_Ar$ (mTorr)</th>
<th>Pt sublayer thickness ($\AA$)</th>
<th>$K_s$ (erg/cm$^2$)</th>
<th>$K_v$ (erg/cm$^3$)</th>
<th>rms surface roughness ($\AA$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>11.0</td>
<td>0.27</td>
<td>$-1.3 \times 10^5$</td>
<td>4.7</td>
</tr>
<tr>
<td>5</td>
<td>12.2</td>
<td>0.34</td>
<td>$-1.4 \times 10^5$</td>
<td>2.2</td>
</tr>
<tr>
<td>10</td>
<td>9.5</td>
<td>0.14</td>
<td>$-9.0 \times 10^4$</td>
<td>6.1</td>
</tr>
<tr>
<td>20</td>
<td>11.2</td>
<td>0.08</td>
<td>$-4.6 \times 10^6$</td>
<td>18.0</td>
</tr>
</tbody>
</table>
near the Co sublayer as already reported by several investigators.\textsuperscript{14,15} The fact that $M_s$ decreases monotonically with increasing $t_{Co}$ is understood by considering a corresponding reduction in the effective number of polarized Pt atoms per unit Co volume.

Low-angle x-ray diffraction intensity reflects the degree of the interfacial ‘‘sharpness’’ or ‘‘roughness’’ in a multilayer; a larger diffraction intensity is expected for a multilayer with a sharper interface, as reported in many systems.\textsuperscript{16,17} In Co/Pt multilayer films we have observed that the low-angle x-ray diffraction intensity of the sample was sensitively dependent on the sputtering Ar pressure and the largest diffraction intensity was obtained for the sample prepared at 5-mTorr Ar pressure, which was consistent with AFM results. Interestingly enough, we have found that the surface anisotropy energy was logarithmically dependent on the integrated low-angle x-ray intensity, as demonstrated in Fig. 4. The bilayer thicknesses of the examined samples prepared at 2, 5, 10, and 20 mTorr Ar pressure are 14.7, 16.6, 13.7, and 15.6 Å, respectively, and the samples have ~4-Å-thick Co sublayers. The number of 23 bilayers are the same for all samples. The close correlation between the surface anisotropy energy and the low-angle x-ray diffraction intensity might be ascribed to the interfacial microstructure of the multilayers. It should be mentioned that the logarithmic relationship was consistently observed not only for different bilayer thicknesses but also for a different system such as Co/Pd multilayer films.

In conclusion, we have studied the effects on the structural and magnetic properties of Co/Pt multilayer films when the Ar pressure was varied from 2 to 20 mTorr. It was observed that the sensitive dependence of the microstructure of the multilayer on the Ar pressure has influenced the magnetic properties. The surface anisotropy was found to be logarithmically dependent on the integrated low-angle x-ray intensity, which might be ascribed to the variation of interfacial microstructure.