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Effect of deposition technique of Ni on the perpendicular magnetic anisotropy in Co/Ni multilayers

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ABSTRACT

The perpendicular magnetic anisotropy (PMA) of Si/Pt 3.5/(Co 0.3/Ni 0.6)$_n$ /Co 0.3/ Pt 3 (all thicknesses are nm) multilayers were investigated for two different sample sets by using ferromagnetic resonance (FMR) and magnetooptic Kerr effect (MOKE) techniques. In the first sample set all layers (buffer, cap, Co and Ni) were grown by magnetron sputtering technique while in the second sample set Ni sub-layers were grown by molecular beam epitaxy (MBE) at high vacuum. Apart from deposition technique of Ni, all other parameters like thicknesses and growth rates of each layers are same for both sample sets. Multilayers in these two sample sets display PMA in the as grown state until a certain value of bilayer repetition (n) and the strength of PMA decreases with increasing n. Magnetic easy axis's of the multilayered samples switched from film normal to the film plane when n is 9 and 5 for the first and second sample sets, respectively. The reason for that, PMA was decreased due to increasing roughness with increasing n. This was confirmed by X Ray Reflectivity (XRR) measurements for both sample sets. Moreover, in the first sample set coercive field values are smaller than the second sample set, which means magnetic anisotropy is lower than the latter one. This stronger PMA is arising due to existence of stronger Pt (111) and Co/Ni (111) textures in the second sample set.

1. Introduction

Spin transfer torque (STT) effect is one of the alternative ways to induce magnetization reversal in magnetic thin films by using spin polarized current instead of using long range fields [1,2]. However there are some challenges for integration STT based technologies into the practical devices. One of them is to reduce magnetization switching currents while maintaining the thermal stability. Magnetic thin films with high PMA are required to overcome these challenge. PMA in magnetic thin films can be originated from interface anisotropy like Co/X (X=Pt, Pd, Ni) multilayered systems where Co and X layers have only a few atomic layer thickness [3–5], and/or volume anisotropy such as FeCo thin films epitaxially grown on Rh, Ir or Pd [6–9]. Among these multilayers Co/Ni system does not include non-magnetic layers, therefore does not suffer from low spin polarization. Moreover since the atomic number of Ni is smaller than Pt and Pd, Co/Ni multilayers can be expected to have smaller Gilbert damping constant values than Co/Pt and Co/Pd multilayers. From these points of views Co/Ni multilayers are very good candidates to be employed in spintronics applications especially in STT.

In order to obtain desirable magnetic properties in magnetic thin films, it is significant to determine suitable growth conditions. Previously some growth parameters such as number of repetition of Co/Ni bilayers [10–12], growth rates [5] and thicknesses [13] of Co and Ni layers, type of buffer layers [12] and annealing [14,15] have been reported to be effective on magnetic properties of Co/Ni multilayers. The deposition technique was also reported to be effective on magnetic properties of Co/Ni multilayered films [16,17]. For instance, if both of the Co and Ni layers were deposited by MBE instead of sputtering, stronger PMA was obtained [18,19]. However, to our knowledge, the effect of deposition method of Co or Ni single layers was not studied on magnetic anisotropy of Co/Ni multilayers. In the present work magnetic anisotropy of Co/Ni multilayers with varying number of repetitions were studied for two different sample sets. The difference between sample sets is deposition technique of Ni sub-layers. In the first sample set, all layers were grown by magnetron sputtering deposition technique; however in the second sample set Ni sub-layers were grown by MBE technique at ultra-high vacuum environment (10^{-9} mbar). The orientation of magnetic easy axis and magnitudes of the anisotropies were investigated dependent on number of repetition for both sample sets. The deposition type of Ni sub-layers strongly

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affected the switching thickness of magnetic easy axis and magnitudes of the anisotropies.

2. Experiments

For both sample sets, our sample system can be summarized as Si/Pt 3.5/(Co 0.3/Ni 0.6)$_n$ /Co 0.3/ Pt 3 where all thicknesses are given in nm. Here n denotes number of repetition of Co/Ni bilayers. The Co/Ni multilayers were grown on Si (100) substrate at room temperature. Before deposition Si substrate was annealed at 900 K in 30 min. At the bottom of the multilayer system Pt buffer layer was grown with a thickness of 35 Å in order to induce 111 texture. Moreover the multilayer system was covered with 30 Å Pt cap layer against to the oxidation. Pt cap layer was also proven to be indispensable to observe PMA in Co/Ni multilayers [15]. As mentioned before in the first sample set (SS1) all layers were grown by magnetron sputtering. The base pressure of the sputter chamber is 2×10^{-9} mbar and during the deposition Argon (Ar) pressure was 5×10^{-3} mbar. Pt layers were grown by DC generator while Co and Ni layers were grown by RF generators. The deposition rates for Pt, Co and Ni layers were 8.75, 0.44, 3.27 Å/min, respectively. In the second sample set (SS2), except Ni, again all layers were grown by magnetron sputtering. The growth rates and thicknesses of the layers and also the used Ar pressure and generator type were the same. Only Ni layers were deposited by thermal evaporation in an MBE chamber with a base pressure of 1×10^{-10} mbar. The thickness and growth rate of Ni were kept 6 Å and 3.27 Å/min like in SS1. During the deposition of Ni layers, the pressure in the MBE chamber was 1×10^{-9} mbar. The reason for keeping very low deposition rate was to get as smooth as possible surfaces and interfaces in grown films. One can expect much rough surfaces in the case of higher growth rates and the magnetic behaviors can be very different. The samples were transferred behind the chambers at ultra-high vacuum (UHV) conditions. All samples were investigated at as grown state, no annealing procedure was applied.

Magnetic properties of the films were investigated by ferromagnetic resonance (FMR) and magneto optic Kerr effect (MOKE) techniques. The FMR measurements were carried out at room temperature with a microwave frequency of 9.8 GHz with a JEOL ESR spectrometer (JES FA300). We have performed FMR measurements for out of plane geometry where the films were rotated from sample plane to sample normal with respect to the applied DC magnetic field. The MOKE measurements were done at room temperature for the polar MOKE geometry with a Nanosan Instruments MOKE magnetometer (SmartMOKE Magnetometry System). Moreover we have calculated saturation magnetization (Ms) of films with a Quantum Design vibrating sample magnetometer (VSM). X Ray Diffraction (XRD) and X Ray Reflectivity (XRR) measurements were registered on the multilayered films by a Rigaku Thin film X Ray Diffractometer.

3. Results and discussion

Fig. 1a and b show polar MOKE hysteresis loops of as grown Si/Pt 3.5/(Co 0.3/Ni 0.6)$_n$ /Co 0.3/ Pt 3 multilayer system which are included in SS1 and SS2, respectively. For multilayers included in SS1 we have measured MOKE hysteresis loops of films for odd values of n from 3 to 9. For $n=3$ and 5 rectangular hysteresis loops were obtained that indicate PMA. For $n=7$ a bow-tie shape hysteresis loop were registered in polar MOKE geometry while the magnetic easy direction is still perpendicular to film plane. Hard axis loop was obtained in polar MOKE geometry for $n=9$ (not shown in the figure). On the other hand we have measured polar MOKE hysteresis loops of films for every values of n from 2 to 6 for multilayers included in SS2. For this sample set we have obtained rectangular hysteresis loops for $n=2$, 3 and 4, while for $n=5$ and 6 we have obtained hard axis loops in polar MOKE geometry (not shown in the figure). As it is clearly seen, in SS2, for $n=2$ there is a slight deviation from rectangular geometry when compared to the loops for $n=3$ and 4. That implies the strength of PMA for $n=2$ is smaller than for $n=3$ and 4. That is also proven from analysis of angular dependence of FMR spectra and will be mentioned. Nevertheless since the perpendicular saturation field for $n=2$ is smaller than demagnetizing field, only 100 Oe, there is no doubt for this sample to have PMA. When hysteresis loops for SS1 and SS2 are evaluated together, multilayers in SS1 display PMA for greater values of n. In SS1 even for $n=7$ it is possible to obtain PMA, while it is possible to obtain PMA only until $n=4$ in SS2. A second difference is observed in the switching characteristic of magnetic easy axis from perpendicular to film plane geometry to parallel to film plane geometry with increasing n between SS1 and SS2. In SS1, after the rectangular loop of $n=5$, when $n=7$, a bow-tie shape hysteresis appears. This kind of a hysteresis was reported previously in both Co/Pd [20] and Co/Ni [14] multilayers and discussed as a result of multi-domain structure forming in order to reduce the magneto static energy. For $n=9$ the bow-tie shape hysteresis loop disappears and a typical hard axis loop is obtained. In SS2 no bow-tie shape hysteresis appears and just after perfect rectangular hysteresis loop of $n=4$ we have obtained hard axis loop in polar MOKE geometry for $n=5$. Namely, the switching is gradually in SS1 while it is sudden in SS2. The intensity of a MOKE hysteresis loop is proportional with the magnetically alive thickness of the sample. In both Fig. 1a and b the intensities of the loops were not normalized and they increase directly proportional with n, as it is expected.

Fig. 2a and b show angular dependence of resonance fields of Co/Ni multilayers included in SS1 and SS2, respectively. Both the experimental data and theoretical calculations are present in the figures. Experimental data and theoretical calculations are represented by the symbols and solid lines respectively. The following magnetic energy density is used to evaluate the experimental resonance field values,

$$E = -M.H\left[\sin\theta_H\sin\theta\cos\left(\varphi_H-\varphi\right)+\cos\theta_H\cos\theta\right]+2\pi M^2\cos^2\theta - K_p\cos^2\theta \qquad (1)$$

where the first term represents Zeeman energy, the second and third terms indicate demagnetization anisotropy and perpendicular anisotropy energy, respectively. θ and θ_H are polar angles, φ and φ_H are azimuth angles for magnetization vector M and external DC field vector H with respect to the reference axis; K_p is perpendicular anisotropy constant. The resonance field is obtained from the classical FMR equation:

$$\frac{w}{\gamma} = \frac{1}{M\sin\theta}\left(E_{\theta\theta}E_{\varphi\varphi} - E_{\theta\varphi}{}^2\right)^{1/2} \qquad (2)$$

In Eq. (2), γ is the gyromagnetic ratio, ω is the precession frequency of M. $E_{\theta\theta}$, $E_{\varphi\varphi}$ and $E_{\theta\varphi}$ are second derivatives of E with respect to θ and φ.

FMR data in Fig. 2a confirms the obtained results from MOKE data about the direction of easy magnetization axis for multilayers in SS1. It is clearly interpreted that for $n=5$ and 7, the easy magnetization direction is perpendicular to film plane. As the number of repetitions increased, for $n=9$, the easy magnetization direction is switched parallel to film plane. FMR data in Fig. 2b also confirms the obtained results from MOKE data for multilayers in SS2. For $n=2$, 3 and 4 magnetic easy axis is perpendicular to film plane whereas for $n=5$ and 6 magnetic easy axis is parallel to film plane.