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Effect of roughness on perpendicular magnetic anisotropy in (Co$_{90}$Fe$_{10}$/Pt)$_n$ superlattices

Jinjun Qiu, Zhaoliang Meng, Yi Yang, Ji Feng Ying, Qi Jia Yap, and Guchang Han

1Data Storage Institute, A*STAR (Agency for Science Technology and Research), 2 Fusionopolis Way, #08-01 Innovis, Singapore 138634
2Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576

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Superlattice [Co$_{90}$Fe$_{10}$(0.21)/Pt(0.23)]$_n$ (unit in nm) with the repeat cycles n ranging from 3 to 30 were studied. Both effective anisotropy ($K_{\text{eff}}$) and PMA constant ($K_{\text{ff}}$) reached a maximum at n=8. When the 3 nm Pt underlayer was deposited at low energy condition, the $K_{\text{eff}}$ and $K_{\text{ff}}$ of (CoFe/Pt)$_n$ are 4.0 and 6.1 erg/cc, respectively. On the other hand, the $K_{\text{eff}}$ and $K_{\text{ff}}$ increased to 6.8 and 9.7 erg/cc, respectively, when the Pt underlayer deposited at high energy condition. As the n increases, the surface roughness monotonously increases and $d_{111}$ inside the superlattice layers increase and relax from bottom to top part. The interface roughness and relaxation in superlattice reduce the PMA considerably.

I. INTRODUCTION

Perpendicular magnetic anisotropy (PMA) films have been intensively investigated for applications in spintronic devices, such as spin-transfer-torque magnetic random access memory (STT-MRAM)\cite{1,2}, nanowire racetrack memory\cite{3}. Two essential properties determining a high density STT-MRAM application are low critical spin-torque switching current density ($J_{\text{c}}$) and high thermal stability parameter ($\Delta$) of the memory cell. PMA materials have higher $\Delta$ and lower $J_{\text{c}}$ as compared with in-plane magnetized materials\cite{4,5}. Furthermore, the reference layer (RL) can exert a large magnetic stray field on the free layer (FL) in magnetic tunnel junctions (MTJ)\cite{6}, causing a shift of the magnetic hysteresis loop and the asymmetric magnetization reversal behavior of the FL. Synthetic antiferromagnetic (SAF) structure consisting of two ferromagnetic (FM) layers separated by a nonmagnetic spacer layer\cite{7} was commonly used to reduce the stray field. However, as MTJ size decreases, the stray field from the SAF structure increases significantly due to different spatial losses of magnetostatic fields from different FM layers. Surface roughness is also a key factor of RL because the interlayer exchange coupling strength of FMs in SAF structure decays exponentially with increasing the interfacial roughness and low $J_{\text{c}}$ needs low resistance area product (RA) of smooth barrier to avoid pinhole. To further suppress the stray field, ultrathin PMA films with high PMA constant ($K_{\text{ff}}$) and small roughness are required as RL\cite{8} in STT-MRAM.

Co(Fe) based multilayers with noble metals such as Pt, Pd have been widely studied due to their relatively larger PMA\cite{9,10} and magnetic properties such as $K_a$ and magnetization ($M_s$) can be easily tuned by adjusting the number of bilayer cycles, the thickness of Co(Fe) and non-magnetic layers. Three possible mechanisms have been proposed to explain the PMA in Co(Fe)/Pt(Pd) multilayers. Firstly, the PMA can arise from interface anisotropy caused by the electron orbital hybridization between 3d electrons of Co or Fe and 4d electrons of Pd or Pt. Secondly, the magnetocrystalline anisotropy induced by the formation of Co(Fe)Pt(Pd) alloy in the multilayers play an important role in the formation of PMA. Finally, PMA may result from magnetoelastic anisotropy, which is produced from the strain and lattice mismatch between Co(Fe) and Pt(Pd) layers. It was reported that the magnetic properties of Co/Pd multilayers strongly related to its surface and interface morphology\cite{10,11}. K.
Yakushiji et al.\textsuperscript{3} reported that ultrathin [Co/Pt(Pd)]\textsubscript{3-6} multilayers with atomic scale flat interfaces showed a strong PMA and high thermal stability.

In this work, we systematically studied the roughness effect on ultrathin (Co\textsubscript{90}Fe\textsubscript{10}/Pt)\textsubscript{n} superlattices with n change from 3 to 30. We also aimed to grow the ultrathin PMA superlattices with small roughness and high K\textsubscript{U} as RL in STT-MRAM.

II. EXPERIMENTAL AND DISCUSSION

Ultrathin (Co\textsubscript{90}Fe\textsubscript{10}/Pt)\textsubscript{n} multilayer films consisting of alternative CoFe (t\textsubscript{CoFe} = 0.21 nm) and Pt (t\textsubscript{Pt} = 0.23 nm) monolayers with the (CoFe/Pt) bilayer repeat cycles n ranging from 3 to 30 were deposited on Si(100) substrates with 1 µm-thick thermal-oxide by using magnetron sputtering system. Ta(3)/Pt(3) was deposited as the underlayer. Except the 3 nm Ta deposited at a power 200 W and a pressure of 0.1 Pa, the CoFe and Pt layers were deposited at low energy condition as previously reported.\textsuperscript{12} Alternating gradient force magnetometer (AGFM) with a maximum field of 2 Tesla and a superconducting quantum interference device magnetometer (SQUID) were used to measure magnetization vs magnetic field (M-H) curves with field applied perpendicular to the plane (OP) or in plane (IP). The film microstructure and thickness were identified by transmission electron microscopy (TEM). The surface morphology was analyzed by atomic force microscopy (AFM). All characterization was done at room temperature.

[CoFe0.21/Pt0.23]\textsubscript{n} superlattices with different (CoFe/Pt) bilayer repeat cycles n ranging from 3 to 30 were deposited. PMA existed in all superlattices with n ≥3. Figure 1(a) shows the AGFM measured out of plane M-H curves. The dependence of out of plane coercivity (H\textsubscript{Cop}), effective anisotropy (K\textsubscript{eff}), PMA constant (K\textsubscript{U}) and average surface roughness (R\textsubscript{a}) on (CoFe/Pt) bilayer repeats n were shown in 1(b), 1(c) and 1(d), respectively. The effective anisotropy (K\textsubscript{eff}) could be roughly estimated by K\textsubscript{eff} = M\textsubscript{S}H\textsubscript{S}/2, where H\textsubscript{S} is the saturation field obtained from the in-plane M-H curve. The PMA constant K\textsubscript{U} is determined as K\textsubscript{U} = M\textsubscript{S}H\textsubscript{K}/2 = M\textsubscript{S}(H\textsubscript{S} + 4πM\textsubscript{S})/2, where 4πM\textsubscript{S} is the demagnetization field. The value of M\textsubscript{S} was obtained through dividing magnetic moment (m) by the total volume of the CoFe/Pt multilayers. Perfect square out of plane M-H curves were obtained for superlattices with n from 3 to 11 whereas the M-H curves consist of a sharp

![Image](https://example.com/image.png)
reversal transition followed by a long, high-field tail when \( n \geq 15 \). The percentage of sharp reversal transition part to saturation of superlattices decreases as the \( n \) increases. They are about 80\%, 45\% and 30\% when \( n \) are 15, 20 and 30, respectively. The sharp transition is attributed to relatively smooth CoFe/Pt bilayers which are first deposited on the Ta/Pt underlayer. After a few bilayers are formed, the further CoFe/Pt bilayers become increasingly rough, giving rise to the tail.\(^{13}\) The AFM result shown in figure 1(d) confirmed the average surface roughness is increased with increasing \( n \).\(^{14}\) It is natural that thicker films exhibit larger roughness, since the local structural disorder such as atomic misfits, defects, dislocations, and crystalline misorientations are accumulated during the film deposition.

It is noted that \( K_u \), \( K_{\text{eff}} \) and \( H_{\text{Cop}} \) gradually increase to their respective maximum values as \( n \) increases from 3 to 8 and decrease with further increasing \( n \). The increase in \( K_{\text{eff}} \) and \( K_u \) for \( n \) ranging from 3 to 8 can be ascribed to the increase in the number of CoFe/Pt interfaces and thus promote the superlattice-like structure. When \( n=8 \), \( K_u \) and \( K_{\text{eff}} \) are 6.1 and 4.0 Merg/cc, respectively. This PMA variation in CoFe/Pt superlattices with \( n \) is attributed to the combined effects of the number of CoFe/Pt interfaces and the elastic strain induced by magneto-elastic interface anisotropy. As \( n \) increases, the randomly distributed ad-atoms will accumulate and the roughness will increase, resulting in a relaxation state and the destruction of the superlattice structure. The random nature of such fluctuations induced roughness is expected to lower the strength of PMA.\(^{15}\) Meanwhile as the roughness increases, CoFe and Pt atoms at the fluctuating interface will induce the augmentation of in-plane magnetization components, which would decrease the sharp reversal transition part and raise the rail part in OP M-H curve as shown in figure 1(a).

TEM was used to investigate the relaxation state in the sample (CoFe/Pt)\(_{30}\) as the CoFe/Pt bilayer repeats \( n \) increased. Figure 2 shows the TEM cross sectional image and selected area electron diffraction (SAED) patterns. Although TEM could not give quantitative information on the roughness information of Pt/CoFe interfaces, the cross sectional image in figure 2 shows an interface roughness larger than one atomic layer thickness. The d-spacing of (11\(\bar{1}\)) \((d_{11\bar{1}})\) in the 3 nm Pt underlayer obtained from SAED is 0.229 nm. The \( d_{11\bar{1}} \) inside the superlattice at bottom(c), middle (b) and top part (a) are 0.217, 0.220 and 0.222 nm, respectively. The \( d_{11\bar{1}} \) increased and relaxed from bottom to top in the superlattice, which means the strain between CoFe and Pt sublayers decreased from bottom to top. It is reported that the strain induced magnetoelastic anisotropy can promote the PMA with increasing strain.\(^{16}\) Therefore, as the repeat number \( n \) increases, the smaller strain in the upper CoFe/Pt bilayers results in smaller \( K_{\text{eff}} \) in whole superlattice.

A (CoFe/Pt)\(_8\) superlattice deposited at the same conditions as above-mentioned (CoFe/Pt)\(_{30}\) was also analyzed by TEM. Figure 3(a) shows its cross sectional TEM image and SAED patterns. The roughness can be obviously seen in both cross sectional TEM images shown in figure 2 and

![FIG. 2. Cross sectional TEM images and SAED patterns of superlattices (CoFe/Pt)\(_{30}\).](image-url)
FIG. 3. Cross sectional TEM images and SAED patterns of superlattices (CoFe/Pt)$_8$ with Pt underlayer deposited at low (a) and high energy (b) conditions.

Figure 3(a). It mainly arises from the bottom underlayer. The AFM measured average roughness (Ra) of the Ta3/Pt3 film sample is 0.18 nm. To further suppress the roughness of underlayer, a high energy deposition condition with a power of 50 W and an Ar pressure of 0.1 Pa was used to deposit the 3 nm Pt underlayer. The Ra of the Ta3/Pt3 film decreases to 0.14 nm. Figure 3 shows the cross sectional TEM images and selected electron diffraction patterns of two (CoFe/Pt)$_8$ superlattices deposited on these two kinds of underlayers deposited at low energy (a) and high energy mode (b). Comparing the two cross sectional TEM images, the superlattice grown on flatter underlayer shows atomically flat highly crystallized sublayers (Fig. 3(b)). The $d_{11ar{1}}$ inside two Pt underlayer obtained from SAED patterns are very close whereas the $d_{11ar{1}}$ inside the rougher (a) and flatter superlattice (b) layers are 0.222 and 0.218 nm, respectively. The difference of $d_{11ar{1}}$ between Pt underlayer and superlattice layers in b is larger than a, which means the strain between the CoFe and Pt sublayers in flatter superlattice b is larger than that in rougher a.

Figure 4 shows the SQUID measured in-plane and out of plane M-H curves of two superlattices (CoFe/Pt)$_8$ with 3 nm Pt underlayer deposited at low (a) and high (b) energy conditions, the inserts are their enlarged OP M-H curves. The square OP M-H curves exhibited sharp magnetization reversals, while the in plane curves showed perfect linearity below the saturation field. Comparing the M-H curves, the $M$, $H_s$ and $H_{C_{op}}$ of rougher superlattice a are smaller than those of flatter b. The $K_u$ and $K_{eff}$ of superlattice a are 6.1 and 4.0 Merg/cc, respectively. Nevertheless, the $K_{eff}$ and $K_1$ of superlattice b are 6.8 and 9.7 Merg/cc, respectively. Since the 8 repeats CoFe/Pt bilayers in two superlattices were deposited under the same conditions, it is the rougher Pt underlayer results in CoFe/Pt interfaces in above superlattice having larger interfacial roughness and smaller strain-induced magnetic anisotropy, which reduces the PMA considerably.\textsuperscript{17}

FIG. 4. SQUID measured IP and OP M-H curves of superlattices (CoFe/Pt)$_8$ with Pt underlayer deposited at low (a) and high energy (b) condition, the inserts are enlarged OP M-H curves.
III. CONCLUSION

[Co$_{90}$Fe$_{10}$/(0.21)/Pt(0.23)]$_n$ superlattices were deposited on Si wafers with thermo-oxide by magnetron sputtering at room temperature. The effect of roughness ($R_u$) on the properties of superlattice [CoFe/Pt]$_n$ with the repeat bilayer cycles $n$ ranging from 3 to 30 were studied. Both $K_{\text{eff}}$ and $K_u$ reached a maximum at $n$=8. When the 3 nm Pt underlayer was deposited at low energy, the $K_{\text{eff}}$ and $K_u$ of [CoFe/Pt]$_n$ are 4.0 and 6.1 Merg/cc, respectively. On the other hand, the $K_{\text{eff}}$ and $K_u$ increased to 6.8 and 9.7 Merg/cc, respectively, when the Pt underlayer deposited at high energy. As the $n$ increases, the surface roughness monotonously increases and $d_{111}$ inside the superlattice layers increase and relax from bottom to top part. The interface roughness and relaxation in superlattice reduce the PMA considerably. The highly crystallized [CoFe/Pt]$_n$ superlattice with atomically flat sublayers and high PMA can be used as reference layer in STT-MRAM.


