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MAGNETIC PROPERTIES AND DOMAIN STRUCTURE OF CoFeB/Pd MULTILAYERS WITH PERPENDICULAR MAGNETIC ANISOTROPY

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Abstract. The magnetic properties and domain structure of $(CoFeB/Pd)_n$ (n = 2 ÷ 10) multilayers prepared by DC magnetron sputtering with perpendicular magnetic anisotropy have been investigated systematically. The study has been carried out by using vibration sample magnetometer (VSM) and magneto-optical Kerr effect (MOKE) microscope. The results show clear changes of magnetic hysteresis and domain structure when increasing the number of bilayer (n) from 2 to 10. With increasing the number of bilayers, the multilayers' hysteresis loops change from square to slanted shape while domain structures change from circular-like to maze. The magnetization reversal changes from easy to be fully reversed with small n to hard to be fully reversed with large n. The behavior is explainable in term of pinning effect.

Keywords: domain structure, Kerr effect, hysteresis loops.

Classification numbers: 2.2.1, 2.5.2.

1. INTRODUCTION

Ferromagnetic multilayers are switches composed of ferromagnetic layers (Fe, Co, Ni, or metal alloy CoFe, CoFeB, etc) and non-magnetic layers (Pt, Pd, Ag, etc). When the magnetic layer's thickness is reduced to be about few nm, the interface anisotropy becomes dominant, resulting in a perpendicular magnetic anisotropy (PMA). In these kinds of multilayers, magnetic moments align perpendicularly to the planes of the multilayers. These multilayers play a key role in spintronics devices [1-3] and high density magnetic recording media. Thus, the investigations of the PMA multilayers have been paid much attention [4-8].

Many PMA multilayers have been studied such as Co base: Co/Pt [2, 9], Co/Pd [10, 11] and CoFe/Pd [12, 13], CoPt and FePt [14, 15], CoFeB/MgO [3, 15, 16]. Among these, CoFeB/Pd multilayers are more attractive because they exhibit high spin polarization [17] and moderate saturation magnetization [16], which are essential for reducing the current density required for spin switching.

The huge PMA was studied and proved to exist in CoFeB/Pd multilayers in 2010 [18]. The anisotropy depends on the thickness of magnetic and non-magnetic layers as well as the number of bilayers. In 2013, Cui's group investigated the PMA of CoFeB multilayers with different buffer layers and observed the PMA in the multilayers with MgO, W, Ta, and Ti buffer layers, in which the multilayer with MgO buffer layer showed the best result [19]. Domain structure of CoFeB/MgO was studied by Yamanouchi [20], but this study just focused on domain structure of the sample at the demagnetization state. In 2013, Burrowes's group showed a significantly low pinning field in a CoFeB thin film.

However, the above studies mostly focus on magnetic properties or domain structures at a certain state such as demagnetization state, while there has been little works directly studying the co-relation between multilayers' domain structures and hysteresis loops.

Otherwise, to enhance the efficiency, quality as well as stability of spintronic devices using nano structure magnetic multilayers, it is necessary to understand the magnetic properties especially the domain structures and the dynamic processes of the multilayers. In addition, from the thickness dependence and the number of bilayer dependence of the above issues we could find out adequate structures for the future applications.

This paper presents a systematic study of the detailed magnetization process on the observation of the magnetic domain structure in a series of amorphous CoFeB/Pd multilayers with changing the number of CoFeB/Pd bilayers by using VSM and MOKE microscope under out-of plane applied magnetic field.

2. EXPERIMENTS

The CoFeB/Pd multilayers were grown on Si wafers with a native oxide layer by using a DC magnetron sputtering system at a very low deposition rate (~ 0.01–0.02 nms^{-1}). The nominal composition of the CoFeB target was 40:40:20. Where, magnetic (CoFeB) layer's thickness was 0.4 nm and non-magnetic (Pd) layer's thickness was 1.0 nm. A top Ta layer (1.0 nm thick) was used to protect the multilayers from ambient oxidation. The details of sample preparation can be found elsewhere [21]. The number of bilayer n was varied from 2 to 10. The hysteresis loops were measured by VSM with perpendicular applied field up to 20kOe. Domain structures of the multilayers were observed by MOKE microscope, which can simultaneously produce Kerr hysteresis by analyzing domain images. The polar Kerr scheme was used to observe the domains with an out-of-plane field up to 2 kOe.

3. RESULTS AND DISCUSSION

Figure 1 presents the magnetic hysteresis (M-H) loops of the CoFeB/Pd multilayers with a variation of the number of bilayer (n = 2 to 10). The results indicate that the PMA has been established in all samples, where, the hysteresis loops are more square-like with small n (up to 6). With large numbers of n (greater than 6) the hysteresis loops show the slanted regions (circled) when reaching to the saturation field.

Form the figure, one can see that with increase of n the multilayers' coercivity increases and reaches the maximum at $n = 6$. In magnetic multilayer films, the coercivity is resulted from contributions of exchange coupling and interface anisotropy. With increasing n, the enhancement of the coercivity is proportional to the exchange coupling between the layers [22]. In addition, the interface anisotropy is a source of perpendicular magnetic anisotropy, which increases with increase of n for low number leading to the enhancement of coercivity. At the same time, the roughness and stress could increase as n increased leading to the loss of conformity between the layers. The loss of conformity causes the reduction in the anisotropy energy per interface as *n* increased [23], resulting in the reduction of the coercivity. The observed coercivity behavior is practically general for magnetic multilayer films [23, 24].

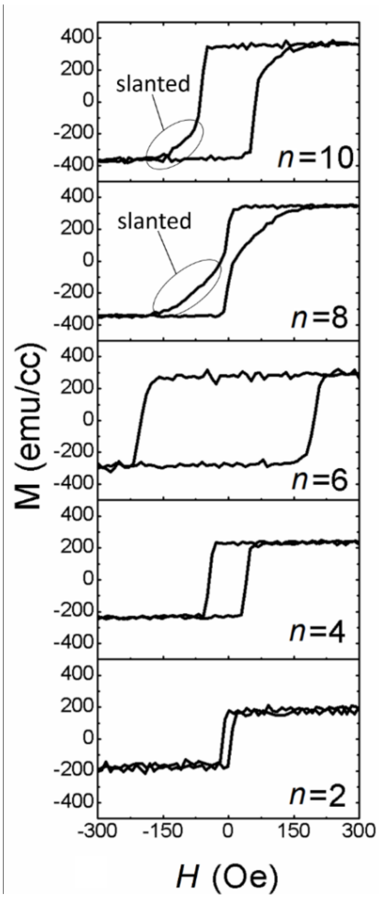

Figure 1. Hysteresis loop of CoFeB/Pd multilayers with n = 2, 4, 6, 8 and 10.

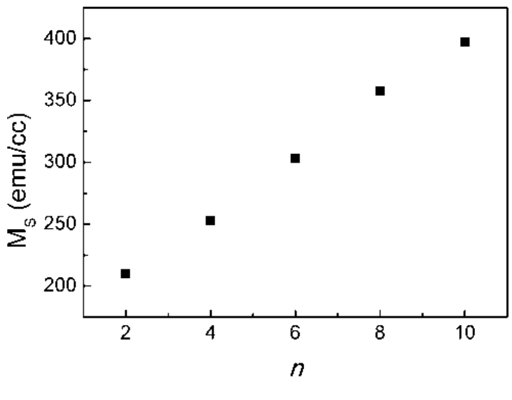

Figure 2. The variation of M_S as a function of n.

Figure 2 shows the saturation magnetization M_S as functions of n. With increasing n, M_S increases, as a linear function, from 210 emu/cc to 400 emu/cc. This result is similar to that of the reported result of PMA MgO/CoFeB/Ta/[Co/Pd]$_n$ [14]. The magnetization of a multilayer film could be considered as two terms: the volume magnetization and the surface/interface magnetization. When fixing the CoFeB and Pd thicknesses and changing the number of bilayers, the portion of magnetic layer in one unit of volume is, theoretically, unchanged. That means the volume magnetization keep constant. Otherwise, if *n* increases, usually, the roughness also does. The rough surfaces could sometime enhance surface/interface magnetization leading to the increase of the volume magnetic moment. The lowest M_S value is found in the sample with two bilayers of CoFeB/Pd. A low M_S of the spin polarizer layer is one of the key factors for reducing the spin-switching current density in spin-transfer torque devices [10].

To understand the magnetization behavior of the multilayers presented in the Figure 1, the domain observations have been carried out using polar Kerr effect microscope supplemented with hysteresis loops measurements. Two multilayers were selected, $(CoFeB/Pd)_4$ with typical square-shaped *M-H* curve and $(CoFeB/Pd)_8$ with typical slanted *M-H* curve.

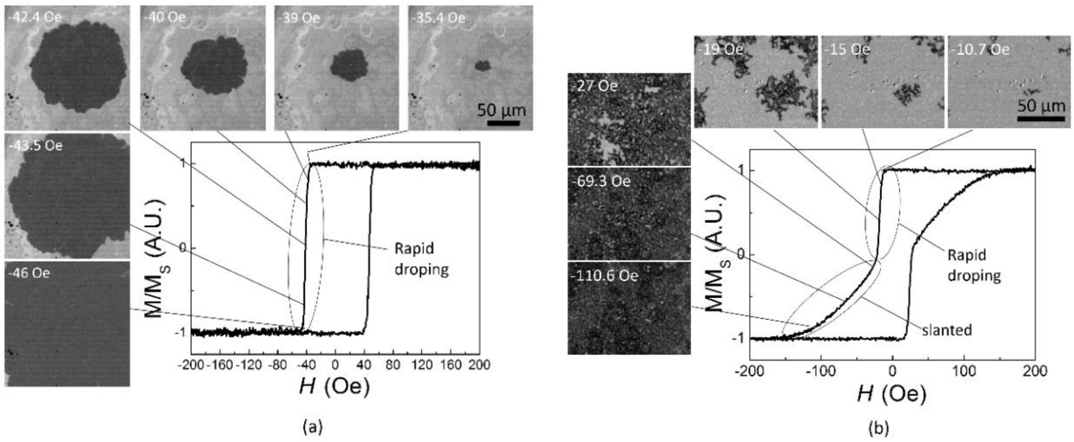

Figure 3. Magnetic domain along the *M-H* curves of multilayers with (a) $n = 4$ and (b) $n = 8$.

The result for $(CoFeB/Pd)_4$ is presented in the Figure 3(a). After magnetically saturated under a maximum positive field of 2 kOe applied perpendicularly to the multilayer's plane, the reversal started with decreasing the magnetic field from the maximum positive field to a negative minimum field of -2 kOe, and then increasing to the maximum positive field again. A square-shaped hysteresis loop was deduced from the MOKE measurement which was similar to that obtained by the VSM. Note that, near the saturation phase, almost no slanted region could be observed. The domain images captured along the *M-H* curves reveal the observed behavior. At -35.4 Oe a reversed domain with an opposite direction of magnetization denoted by dark spot on the bright background was nucleated in the observation area. With decreasing magnetic field, magnetization reversal occurred dominantly by domain wall propagation, where, the dark domain with circular-like shape expanded its boundary. Similar circular-like domain structure and reversal behavior were observed previously for other PMA Ta-CoFeB-MgO [25] and WTa-CoFeB-MgO [26] films. By careful examining the domain image, we can see the rough boundary with some tiny unreversed areas near the edge of the domain, for example the domain at -40 Oe. At -42.4 Oe, a net zero magnetization is almost obtained with the nearly same areas of the bright domain (positive direction of the magnetization) and the dark domain (negative direction of the magnetization). With further decreasing the magnetic field, the dark domain expands, becoming dominant in the observed area and the reversal process mostly completed at -46 Oe. The domain's growth and the domain walls propagation seem to be steady indicating a weak pinning effect on the propagation of the domain walls in this multilayer. This aspect is very promising regarding applications in domain-wall-controlled spin-transfer torque devices.

A different domain evolution was observed in the $(CoFeB/Pd)_8$ multilayer as presented in Figure 3(b). Even though the observation area was smaller than that of $(CoFeB/Pd)_4$ multilayer, the number of nucleation sites was larger. The number of nucleation sites is presumably increased due to the increase of the pinning sites at the interfaces of the multilayers which usually increases as *n* increases. After nucleation at -10.7 Oe, with decreasing the magnetic field, the magnetization reversal occurred by domain wall propagation down to about -27 Oe. With a close look inside the reversed domain (dark region), one can see not only no more circular-like domain but also lots of tiny unreversed area within the domain boundaries. This is so called dendritic domain, which is similar to the domain pattern of CoFeB/Pd multilayers with large numbers of bilayers (*n* = 7 and 14) [27]. With applied field strength stronger than the multilayer's coercivity (form -27 Oe to -150 Oe), the reversed domains mostly covered all the observed region but the unreversed areas could be still observable. In this multilayer, the magnetization reversal occurred, firstly, rapidly due to a domain wall propagation process and then a slow annihilation process of many tiny unreversed domains due to strong pinning effect. Upon increasing the CoFeB/Pd bilayer number, the pinning effect became stronger due to the increase of the number of pinning sites located in the interfaces leading to the existence of the tiny unreversed domain inside the domain boundaries.

To further understand the magnetic behavior of $(CoFeB/Pd)_n$ multilayers, the magnetic relaxation measurements have been performed. Firstly, each multilayer was saturated positively under a magnetic field of 2 kOe. Then the applied field was reversed to a negative field of about 80% of the multilayer's coercivity and fixed its value to record the magnetization reversal and domain evolution under the constant negative field. The results for $(CoFeB/Pd)_4$ and $(CoFeB/Pd)_8$ were presented in Figure 4.

The result for $(CoFeB/Pd)_4$ in Figure 4(a) shows that after switching applied field, the magnetization is reversed gradually from a positive saturation (+1) to a negative saturation (-1) in ~15 s. In which, it takes ~7.5 s for the magnetization to be reversed a half (this time is called half reversal time, $t_{1/2}$). Please note that, in this multilayer, the fully negative saturation could be reached after only in twice of $t_{1/2}$. Domain images shows that the magnetization reversal occurs dominantly by domain wall propagation. Domain structure is circular-like with some tiny unreversed region near the edge of the domain, which can be seen at the 9 s domain image.

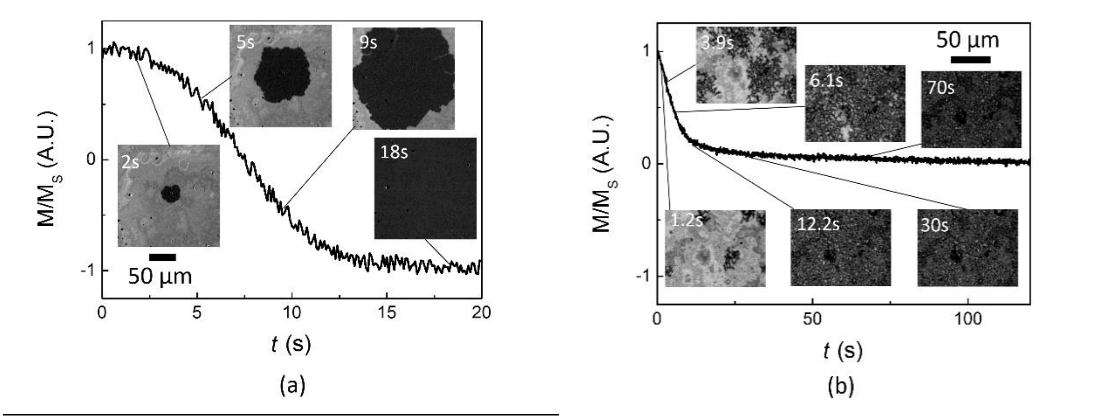

Figure 4. Relaxation curves and domain structures of multilayers with (a) *n* = 4 and (b) *n* = 8 taken along the curves.

Otherwise, Figure 4(b) shows that, in $(CoFeB/Pd)_8$ the magnetization reversal occurs, firstly, by domain wall propagation from 0 to 12 s. From 12 s, the reversed domain (dark regions) covers all the observation area, however, it takes ~120 s ($t_{1/2}$) for magnetization to be reversed a half. After 12 s, the magnetization reversal occurs dominantly by annihilation process of tremendous number of the unreversed domains. We have checked that, under the constant magnetic field (~80 % of the multilayer's coercivity), even after five times of $t_{1/2}$, the magnetization could not be reversed to a fully negative saturation. That means the relaxation in this multilayer is a long lasting process resulting from the strong pinning effect.

4. CONCLUSIONS

We have investigated magnetic properties and domain structure of $(CoFeB/Pd)_n$ multilayers with a variation of the number of bilayer *n* from 2 to 10 by using VSM and MOKE microscope under out-of plane applied magnetic field. With small *n*, the *M-H* curves were square-shaped and magnetization reversals were easy to be fully reversed. While with large *n*, the *M-H* curves were slanted near the saturation field and magnetization reversals were hard to be fully reversed. A clear physical picture and understanding of the processes associated with the observed macroscopic phenomenal of the magnetic hysteresis loop change has been figured out by direct domain observations. Where with the large *n* (> 6) the large number of pinning sites at the layers' interfaces was produced resulting in the increase of the number of nucleation sites and pinning effect.

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