Perpendicular magnetic anisotropic characteristics of amorphous (CoSIB/Pt)(N) multilayers

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The perpendicular magnetic anisotropic properties of amorphous multilayers of [CoSiB/Pt]_N are investigated as functions of the thickness of magnetic layers (t_{CoSiB} = 4 and 6 Å) and the number of repeated bilayers (N = 3 ~ 20). Even though the magnetization reversal process is dominated by the wall motion of magnetic domains rather than the nucleation for all the values of t_{CoSiB} and N in our experiment, the changes of magnetic properties are strongly dependent on the t_{CoSiB} and N values. The effective anisotropy constant for the 6 Å sample is K_1^{eff} = 1.2 × 10^4 erg/cm^2, which is a factor of 6 larger than that for the 4 Å sample. The coercivity variations as a function of N are explained by the Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling between the magnetic layers considering the balance of domain wall energy and magnetostatic energy.

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The growing use of electronics demands an increasing effort in obtaining faster, smaller, more reliable, and sustainable electronic memories. Since the discovery of the giant magnetoresistance effect (GMR), it has been observed that the resistance of magnetic multilayers depends on the spin alignment of magnetic materials sandwiched by not only metallic spacers but also insulating spacers. This feature is useful for producing magneto-electronic devices such as magnetic random access memory and race track memory. To obtain reliable and stable performance of magneto-electronic devices, the magnetic anisotropy of magnetic layers is of great importance. With high magnetic anisotropic materials, the magnetization is less sensitive to external magnetic field and temperature fluctuations, which is preferable in memory devices. Also to overcome the possible superparamagnetic limitation of nano-sized devices, high anisotropic materials are required.

In magnetic thin films, in-plane magnetic anisotropy (IMA) is commonly observed. As a result of the broken symmetry of surface atoms, however, surface anisotropy can result in a perpendicular magnetic anisotropy (PMA). The PMA property arises when the thin film is thin enough to ignore the bulk anisotropy, and the surface anisotropy becomes dominant in total. It has been shown that PMA materials have a larger magnetic anisotropy than commonly known IMA materials. Other advantages of PMA materials are theoretically proposed to have lower switching current density and higher thermal stability in spin transfer torque (STT) magnetic random access memory (MRAM) devices.

A large variety of PMA materials have been investigated to obtain a better understanding of PMA properties. Crystalline PMA materials, for example, Co- and Fe-based superlattice systems such as Co/Pd, Co/Pt, and Fe/Au, are actively investigated. Compared to the crystalline PMA materials, amorphous PMA materials have major advantages in two aspects. First, there are less grain boundaries, which act as domain wall pinning sites during the magnetization reversal process. Because the grain boundary leads to irregular switching, the amorphous system guarantees better switching characteristics. Second, the roughness of amorphous system is generally lower than that of crystalline systems. The interface roughness is important in multilayer films so that it can be decreased considerably.

One promising PMA material is amorphous multilayers of [CoSiB/Pt]_N, where N is the number of repeated bilayers. In this study, we report the magnetic anisotropy by measuring the high-field magnetization curves of amorphous [CoSiB(t_{CoSiB}/Pt(14 Å))_L]_N multilayers with the thickness of magnetic layer (t_{CoSiB} = 4 and 6 Å) by changing the number of repeated bilayers (N = 2 ~ 20). It is found that the perpendicular magnetic anisotropy is well preserved for all the samples, although the coercive field and the anisotropy constant are strongly dependent on the t_{CoSiB} and N values. Also the magneto-optical Kerr (MOKE) effect images demonstrate that the magnetization direction is reversed by the domain wall motion.

The samples used in this study are prepared with a dc magnetron sputtering system at room temperature: [CoSiB(4 Å)/Pt(14 Å)]_L multilayers with N = 3, 6, 9, 12, 15, 18, 20 and [CoSiB(6 Å)/Pt(14 Å)]_L multilayers with L = 2, 3, 4, 5, 6, 7, 9, 12, 15, 18, 20, where N and L are the number of repeated bilayers for each sample. We fixed the thickness of Pt layer (t_Pt) because the ferromagnetic coupling between CoSiB layers is strong when t_Pt = 14 Å. Note that the ferromagnetic coupling is weakened with increasing t_Pt up to 22 Å, where an antiferromagnetic coupling appears, which is not mentioned in this paper. For our samples, a 30 Å Pt-layer is used as a buffer layer and a 50 Å Ta capping layer is used to prevent oxidation in air. To determine the magnetic anisotropy of the 4 Å and 6 Å samples, the magnetization versus magnetic field curves are measured.

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are measured using a superconducting quantum interference device-vibrating sample magnetometer. The applied magnetic field is swept between $-70$ kOe and 70 kOe, which is at least a factor of 5 larger than the anisotropy field (the applied field in the hard-axis direction at which the magnetization saturates) and a factor of 350 larger than the coercive field (the applied field in the easy-axis direction at which the magnetization is zero) of the samples. Thus, complete saturation of the magnetization $M_s$ is assumed. To compare the magnetization curves of the different samples, the normalized magnetizations are considered. The measurements are performed at room temperature. The MOKE images are taken with our own lab-made equipments of polar geometry. The MOKE measurements are carried out by sweeping magnetic fields.

The obtained representative magnetization curves for the 4Å and 6Å samples are shown in Figs. 1(a) and 1(b), respectively. The red (circles) curves are obtained by applying the magnetic field perpendicular to the sample plane (easy axis), and the black (squares) curves are obtained by applying the magnetic field parallel to the sample plane (hard axis). It is clearly seen from these magnetization curves that the preferential direction for magnetization is perpendicular to the sample plane. So these samples are PMA materials. A noticeable feature observed in the 6Å samples is the change of hysteresis loops from a square loop at low number of repeated bilayers to a slanted loop at high number of repeated bilayers. In the 4Å samples, the hysteresis loops are never really square, but they are more slanted with increasing the number of repeated bilayers. This feature of CoSiB/Pt multilayers has been also observed in the previous report.18

Now, we assume that a small number of repeated bilayers behave as a single domain structure. When some spots in the sample are nucleated, the domain wall moves quickly across the entire sample, resulting in a sharp switching of the hysteresis loop. However, with increasing the number of repeated bilayers, the switching becomes gradual. Around zero applied field, there is a region where some of the spins are already switched and some are not, which is a multi-domain structure. There are two possibilities for this gradual switching: (1) the reversal is wall-motion dominant and due to domain wall pinning the motion is not quick enough to switch the magnetization or (2) the reversal is nucleation dominant and due to locally different coercivity there is a gradual transition. To find out which of these processes is dominant in these samples, MOKE images are obtained during the switching process. The typical MOKE images are shown in Fig. 2 for the 6 Å sample with $N = 7$. The other samples show a similar behavior. During the field sweep from 0 to +700 Oe reversely after complete saturation at negative field, the images are taken. The initial image at 0 Oe shows that the sample is fully saturated. At 120 Oe, some nucleation spots are observed. When the field is further increased, the nucleation spots grow to form larger domains.

![Normalized magnetization curves](image)
By comparing the images taken just after nucleation with the images taken at larger fields, we find that no new nucleation spots are created. This means that the magnetization reversal process is governed by domain wall motion. Therefore, it can be concluded that the gradual switching observed for the samples with a large number of repeated bilayers is caused by the decrease of domain wall motion due to domain wall pinning. This change in domain wall speed is also observed in Co/Pt multilayers.

Even though the mechanism of magnetic reversal process is similar with regard to the thickness of magnetic layer and the number of repeated bilayers, the trend of coercive field $H_c$ is differently found. In Figs. 3(a) and 3(b), the $H_c$ values are plotted as a function of the number of repeated bilayers for the 4 Å and 6 Å samples. In both samples, $H_c$ shows an increasing trend with increasing the number of repeated bilayers. However, for the 6 Å samples, $H_c$ starts to decrease at $N = 6$. When a magnetic layer is placed on top of a non-magnetic layer and this bilayer structure is repeated, the Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling comes in between the two magnetic layers via the nonmagnetic layer. It has been found that in Co/Pt multilayers, a ferromagnetic RKKY coupling between the Co layers is present. In our system, this RKKY coupling also exists between the CoSiB layers similar to the Co layers. So, when forming a stable nucleation spot, the spins at the same position in the other layers need to reverse the spin directions due to the RKKY coupling. This also changes the energy contributions. The increase of domain wall energy scales with the number of layers, in other words $\Delta E_{dw} \sim C_{dw} n$, where $\Delta E_{dw}$ is the change of domain wall energy due to the formation of magnetic domains, $C_{dw}$ is a constant, and $n$ is the number of repeated bilayers. On the other hand, the decrease of magnetostatic energy scales with the number of layers squared, in other words $\Delta E_{ms} \sim -C_{ms} n^2$, because it is due to an interaction between layers like dipoles. $\Delta E_{ms}$ is the change of magnetostatic energy due to the formation of magnetic domains and $C_{ms}$ is a constant. Therefore, the total energy needed to form a stable nucleation spot is given by $\Delta E = \Delta E_{dw} + \Delta E_{ms} \sim C_{dw} n - C_{ms} n^2$. Here, an important factor in determining the domain wall energy is the exchange energy. In general, the exchange energy opposes the formation of magnetic domains and its energy density is much larger than the magnetostatic energy density, so $C_{dw} \gg C_{ms}$. When the number of repeated bilayers is low, the domain wall energy term is dominant so that the total energy needed to form stable nucleation spots increases. However, at a certain larger number of repeated bilayers, the quadratic term of the magnetostatic energy becomes dominant despite $C_{dw} \gg C_{ms}$. Then, the total energy decreases with increasing the number of repeated bilayers because the magnetostatic interaction favors the formation of magnetic domains. Therefore, at a low number of repeated bilayers, $H_c$ increases due to the dominating domain wall energy term which scales with $n$. At a certain larger number of repeated bilayers, $H_c$ starts to decrease due to the dominating magnetostatic energy term which scales with $-n^2$. On the other hand, for the 4 Å samples, $H_c$ shows monotonic increase with increasing the number of repeated bilayers. This can be understood by the above explanation when the number of repeated bilayers is low. In a thinner magnetic layer, higher energy is required to form stable nucleation spots, and consequently the domain wall energy term becomes dominant, leading to the increase of $H_c$. In order to overcome the dominant domain wall energy, we may need higher number of repeated bilayers in the 4 Å samples.

In this sense, we may expect the different trend of magnetic anisotropy for the 4 Å and 6 Å samples by changing the number of repeated bilayers. From the measured magnetization curves, the anisotropy constants can be obtained by fitting the non-normalized hard-axis data with the GST equation. To use this equation, the $M_s$ values are needed. The measured $M_s$ values as a function of the number of repeated bilayers (which are not shown here) are found to be fluctuating. The fluctuations of $M_s$ are more significant for thinner magnetic layers and lower number of repeated layers. These fluctuations in $M_s$ can be explained by fluctuations in the topological sample geometries such as roughness and patchiness of thin magnetic layers, often inherent to the deposition techniques used. The average $M_s$ values are about 550 and 850 emu/cm³ for the 4 Å and 6 Å samples, respectively, with an average deviation about 50 emu/cm³. This difference may be caused by a magnetic dead layer. At the interface of magnetic and nonmagnetic layers, the exchange coupling may contribute less to the spin alignments, resulting in a dead layer in magnetic materials. So, if considering the thinner magnetic layer of the 4 Å sample, the real volume fraction of magnetic material will be smaller, and therefore, the $M_s$ values for the 4 Å sample will be larger.

As stated before, we obtain the effective first-order and second-order anisotropy constants of $K_1^{\text{eff}}$ and $K_2$ by using the generalized Sucksmith-Thompson (GST) method in the range with a smallest average error. The obtained anisotropy constants of $K_1^{\text{eff}}$ and $K_2$ as a function of the number of
repeated bilayers for the 4 Å and 6 Å samples are plotted in Figs. 3(c) and 3(d). It is seen that the $K_1^{\text{eff}}$ and $K_2$ values are not strongly dependent on the number of repeated bilayers but dependent on the thickness of magnetic layer. The average $K_1^{\text{eff}}$ value of the 6 Å sample is $1.2 \times 10^6$ erg/cm$^3$, which is a factor of 6 larger than that for the 4 Å sample, and it is comparable to the values observed in crystalline Co/Pt-Pd multilayers. The reduced magnetic anisotropy in the 4 Å sample is attributed to the magnetic dead layer, as mentioned in the $M_s$ variations. The anisotropy constants as a function of the number of repeated bilayers are also fluctuating around a constant value. The fluctuations decrease for higher numbers of repeated bilayers, because the effects of topological geometries such as sample roughness and patchiness are averaged out and the additional bilayer gives no big influence on the total anisotropy. When comparing the fluctuations between $K$ and $M_s$, it is clear that both are almost same over a large extent.

The obtained magnetization curves for the 4 Å and 6 Å samples with different number of repeated bilayers show a preferential direction of magnetization perpendicular to the sample plane, resulting in the typical PMA class. With MOKE images, it is found that the domain wall motion process is dominating the magnetization reversal process. Even though the mechanism of magnetic reversal process is similar, the PMA properties are differently found with the thickness of magnetic layer and the number of repeated bilayers. The hysteresis loops are gradually changed from a square loop at low number of repeated bilayers to a slanted loop at high number of repeated bilayers. This gradual change in the hysteresis loops is due to a slowing down of the domain wall motion when going to a higher number of repeated bilayers.

In the $H_c$ plots as a function of the number of repeated bilayers, the $H_c$ values monotonically increase for the 4 Å samples, while for the 6 Å samples, they increase followed by a maximum with increasing the number of repeated
bilayers. This trend is explained by assuming RKKY coupling between the magnetic layers considering the balance of domain wall energy and magnetostatic energy. The $K$ values are observed to be larger for the 6 Å samples than for the 4 Å samples, because the topological sample geometry and/or the magnetic dead layer significantly affect the magnetic anisotropy in thinner samples. In conclusion, it is able to tune or optimize the anisotropy constant and the coercive field in PMA materials just by adjusting the thickness of amorphous magnetic CoSiB layer and the number of repeated CoSiB/Pt layers even though the mechanism of magnetic reversal process is similar. This makes it possible to create new spintronics device for a specific PMA-based application.

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