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Magnetization and coercivity in Co/Pt multilayers with constant total Co layer thickness

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Abstract: Co/Pt multilayers with perpendicular anisotropy were deposited using a dc magnetron sputtering system under high vacuum. Magnetization process was investigated by the measurement of magnetic components parallel and perpendicular to the applied field. A dependence of the coercivity of Co/Pt multilayers on the Co layer thickness was reported, in which the total thickness of Co layers kept constant. It is observed that the coercivity increases with the increment of Co layer thickness. For the samples with the same Co layer thickness while different total Co layer thickness, the coercivity first increases and then decreases with the increase of the total thickness of Co layers. This effect could be attributed to the competition between the reduction of H_C related to incoherent reversal and the step-up of H_C contributed by the magnetic polarization of Pt atoms at the interface of Co and Pt layers during magnetization reversal. The results show that the change of the coercivity is strongly related to the Co layer thickness, but not the total thickness of Co layers. The dependence of the coercivity on the angle between an applied field and the easy axis shows that the nucleation mode is dominant in magnetization reversal process of the samples.

Key words: Co/Pt multilayers; perpendicular magnetic anisotropy; coercivity

1 Introduction

The magnetization and coercivity are important topics in magnetic material research. The development of the magnetic information storage technique continually refreshes the record density of data. Higher density can be achieved by means of perpendicular recording due to the lower superparamagnetic limit and larger anisotropy in magnetic media with perpendicular magnetic anisotropy (PMA). So, the research on the material with PMA is always highly regarded. As well known, Co/Pt is a representative sample of PMA system, which has attracted much attention in the last twenty years for both fundamental researches and magnetic information storage applications[1−5]. PMA can be phenomenologically described as an interfacial magetocystalline anisotropy due to the symmetry breaking at the interfaces. It is known that the anisotropy of the orbital magnetic moment at the interface between ferromagnetic and non-magnetic layers contributes to the perpendicular magnetic anisotropy due to the spin−orbit interaction. The interesting behavior in Co/Pt multilayer is always a hot topic because of its PMA[6−8]. As well known, the PMA of the Co/Pt multilayers originates from the dominating interfacial anisotropy when the ferromagnetic (FM) layer is very thin[9]. The individual ultra-thin Co layers are coupled together, further, by Pt spacers and behave as a single ferromagnet.

The coercivity, H_C, plays an important role in the recording process. There are many reports on the dependence of H_C on both depositing gas pressure of Co/Pt multilayer[10−11] and temperature[12]. Also, KNEPPER and YANG[13] thought that the Co/Pt multilayer with PMA exhibits Ruderman-Kittel-Kasuya-Yosida (RKKY) oscillatory interlayer coupling as the thickness of the Pt spacer increases, leading to the oscillation of H_C when the thickness of the Pt spacer is changed.

In fact, H_C is very sensitive to the Co layer thickness and less dependent on the Pt layer thickness. Most studies focused either on changing Pt layer

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thickness[13] or the total thickness of Co/Pt multilayer[14], but less investigation on changing the Co layer thickness with constant total thickness of Co layers in Co/Pt multilayer. In this work, we report a study of coercivity when total thickness of Co layers in Co/Pt multilayer is constant. We divided the samples into five groups, and every group is composed of the samples with the same total thickness of Co layers and different Co layer thickness. The total thickness of Co layers is not same for different groups. In this case, the dependence of H_C on the Co layer thickness and the total thickness of the Co layers can be compared. It would be beneficial to exploring the mechanism of coercivity in Co/Pt multilayers with PMA. Magnetization process was investigated by the measurement of magnetic components parallel and perpendicular to the applied field direction.

2 Experimental

All samples of Co/Pt multilayer were deposited onto a 10 nm Pt buffer layer on the Si(100) wafer at room temperature (RT) using a dc magnetron sputtering system under high vacuum. The base pressure of the sputtering system was around 1.0×10^{-5} Pa, and the Ar pressure during sputtering was about 0.3 Pa. The Co/Pt multilayer sample was prepared with the layer structure [Co(t_x nm)/Pt(1.25 nm)]$_n$/Co(t_y nm)/Pt(t_{Pt} nm) to keep the total thickness of the Co layers, t_{Co} ($t_{Co}=nt_x+t_y$), constant. Five series of samples were prepared with various total thicknesses of Co layers, t_{Co}=1.26, 1.8, 2.16, 2.7, and 3.42 nm, labeled as Ⅰ, Ⅱ, Ⅲ, Ⅳ and Ⅴ, respectively. In each series, t_x, Co layer thickness in the Co/Pt multilayers, was changed as 0.27, 0.36, 0.45, 0.54, and 0.63 nm, labeled as 1, 2, 3, 4, and 5, respectively. Therefore, the samples were labeled as Sample *PQ*, in which *P* denoted Ⅰ, Ⅱ, Ⅲ, Ⅳ, or Ⅴ, and *Q* denoted 1, 2, 3, 4, or 5, respectively. For the expression of the sample, it should be noted that t_{Pt}=0.75 nm when t_y is zero, otherwise t_{Pt}=2 nm, in order to keep that the thickness of the Pt spacer between two adjacent Co layers is 1.25 nm and the thickness of top Pt layer is 2 nm, respectively, in each sample.

Magnetic measurements were performed in a vibrating sample magnetometer with vector pickup coils. As shown in Fig.1, the direction of the applied field *H* is denoted as the *x* axis, and easy axis is along the normal direction of the sample plane. The angle θ between the *H* direction and the normal direction of the sample plane can be changed by rotating the sample. The hysteresis loops of the sample were measured at room temperature from the saturated states in a positive field, and the magnetization components parallel (M_x) and perpendicular (M_y) to the applied field direction were recorded.

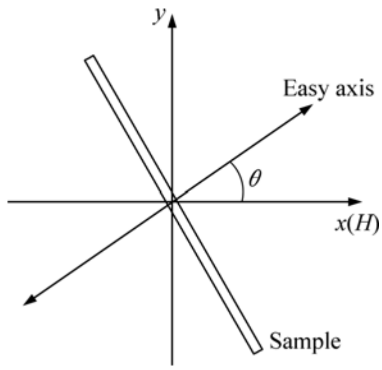

Fig.1 Scheme showing direction of applied field *H* defined as *x* axis and easy axis (solid line with arrow) along normal direction of film plane (θ: angle between direction of positive applied field and easy axis)

3 Results and discussion

Fig.2 shows the small angle XRD patterns of [Pt(40 Å)/Co(2.7 Å)]$_{10}$Pt(40 Å) and [Pt(30 Å)/Co(6.3 Å)]$_{10}$ Pt(30 Å). It is shown that a periodic structure appears for Co/Pt multilayers prepared by magnetron sputtering. Here, the Co layer thicknesses shown in Figs.2(a) and (b) are the minimum and the maximum in the periodic structure of all 25 samples mentioned above, respectively. But, the Pt layer thickness is larger than that in 25 samples. Because the minimum thickness of Pt layer is 12.5 Å in 25 samples, it is still large enough so that Pt layer exhibits the layered structure. Only the state of Co layer is detected by XRD. So, the Pt layer thickness is decided by XRD measurement precision rather than the Pt layer thickness in 25 samples. The XRD pattern confirms the layered structure of Co layer sputtered. It is obvious that the sample bears good artificial structure. The film thickness of multilayers calculated by XRD pattern corresponds well with the result calculated by sputtering rate.

Fig.3 shows the hysteresis loops of M_x measured at θ=0° for the sample Ⅰ1, Ⅰ2, Ⅰ3, Ⅰ4, Ⅰ5, in which t_{Co} is 1.26 nm, with good squareness. And M_y loop is near flat along the horizontal axis. M_y loop is not shown here for reasons of clarity. When θ=0, M_x is the magnetization, *M*, of the sample. It is obvious that PMA has been established in the five samples. One can see that H_C changes a lot even if t_{Co} of each sample is the same. The inset shows the dependence of coercivity H_C on the Co layer thickness, t_x, for samples of t_{Co}=1.26 nm. The minimum H_C is 27/(4π) kA/m in the sample Ⅰ1, where t_x=0.27 nm. The maximum H_C is 256/(4π) kA/m in the sample Ⅰ5, where t_x=0.63 nm. This indicates that the thicker the Co layer is, the larger the H_C for the Co/Pt multilayer with PMA.

The dependence of the coercivity on t_{Co} for all the

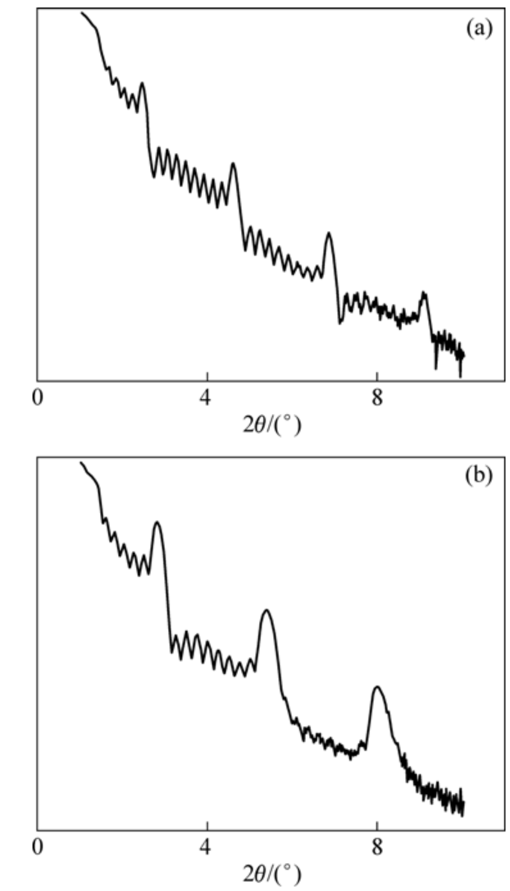

Fig.2 Small angle XRD patterns of $[Pt(40\ Å)/Co(2.7\ Å)]_{10}$ Pt(40 Å) (a) and $[Pt(30\ Å)/Co(6.3\ Å)]_{10}Pt(30\ Å)$ (b)

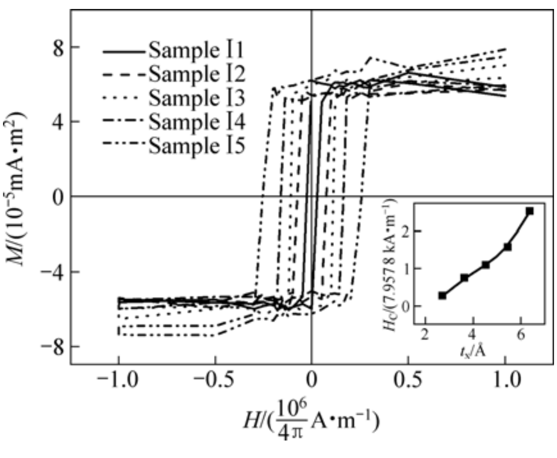

Fig.3 Hysteresis loops of sample with t_{Co}=1.26 nm (Inset: dependence of H_C on Co layer thickness, t_x, for samples with t_{Co}=1.26 nm)

25 samples is shown in Fig. 4. Each curve corresponds to the same t_x, but different t_{Co}. Firstly, the H_C is enhanced with the increase of t_x when they are of the same t_{Co}. Secondly, the H_C is various for the samples with the same t_x but different t_{Co}, which indicates an influence of t_{Co} on the H_C. One could find that the influence of t_{Co} on H_C when t_x is the same is weaker than that of t_x when t_{Co} is the same, indicating that the H_C of the Co/Pt multilayers is dominated by the thickness of the Co layer, t_x. Meanwhile, the behavior of H_C is similar for the four series samples except Q=5, as shown in Fig.4. The H_C first increases and then decreases with the increase of t_{Co} for the same t_x, in which the increase of t_{Co} means that the number of repetitions (n) increases, i.e. both Pt layer number and Co layer number increase. As well known, the Pt atoms in the vicinity of a FM layer could be polarized and contribute a little bit of magnetic moments[13, 15−16]. And the magnetic polarization of Pt atoms could extend into the Pt layer at room temperature[13, 17]. Thus, the polarized Pt layers could not only act as an effective FM layers, but also enhance the coupling of the adjacent Co layers. When n increases, the number of magnetically polarized Pt atoms in the vicinity of Co layer increases, and then the coupling of Co layers becomes stronger, leading to the increase of the H_C. With the further increase of t_{Co}, the H_C no longer increases, whereas decreases with the increase of t_{Co}, which could be attributed to the existence of incoherent reversal during magnetization reversal.

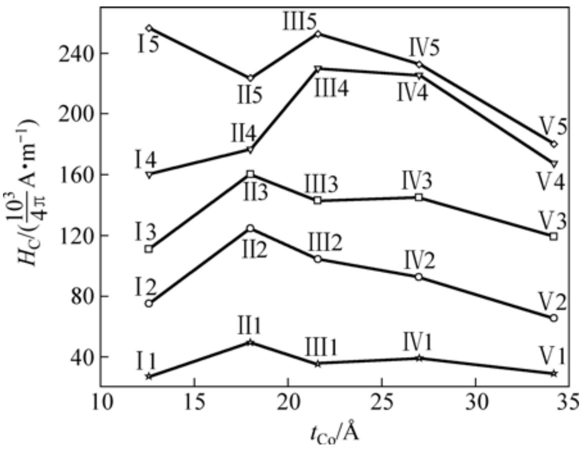

Fig.4 Dependence of coercivity on t_{Co} for samples with different t_x

Fig.5 shows the hysteresis loops of the samples Ⅰ1, Ⅳ1 and Ⅴ1 measured at θ=0°, in which t_x of the samples is 0.27 nm with t_{Co} of 1.26, 2.7 and 3.42 nm, respectively. It is noted that the coercivity for these three samples displays little difference, which is consistent with the discussion above that the coercivity of the Co/Pt multilayers is dominated by t_x, not t_{Co}. In this case, Co layer number, n, varies with different t_{Co}, and thus, it is easy to understand that the effect of n on the coercivity of the Co/Pt multilayers is weak. However, the shape of the corresponding hysteresis loops (shown in Fig.5) is distinct from each other as t_{Co} and n increase. The squareness of hysteresis loops of the sample Ⅳ1 and Ⅴ1 is less than that of the sample Ⅰ1. In fact, magnetization reversal for sample Ⅰ1 is coherent due to

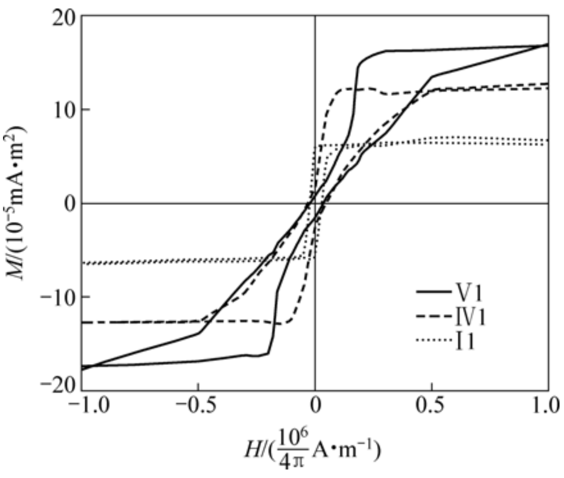

Fig.5 Hysteresis loops of samples Ⅰ1, Ⅳ1, and Ⅴ1

the FM coupling of Co layers through the Pt spacer. But, magnetization reversal for samples Ⅳ1 and Ⅴ1 is fully different from that of Ⅰ1. For samples Ⅳ1 and Ⅴ1, the magnetization switching takes place when the applied field $H>0$ during magnetization reversal from positive to negative field applied, displaying the typical incoherent reversal which means that magnetic moments of each Co layer is not reversed synchronously. The switching behavior is determined by the competition of magnetostatic energy and domain-wall energy in an applied magnetic field. According to Ref.[18], it is favorable to form a single domain state for the multilayers with small n and multiple domain state for multilayers with large n at remanence. For samples with the same t_x, when t_{Co} increases, that is, n is large, magnetization reversal is incoherent due to the formation of multiple domain. During incoherent reversal, the magnetic moment direction of each domain is different. The magnetic moment of different domains partly countervails each other so that net magnetic moment is easy to be zero in a low applied field, i.e. low coercivity. In other words, the H_C falls down with the increase of t_{Co} due to incoherent reversal. As it is mentioned above, the H_C goes up with the increase of t_{Co} by the magnetic polarization of Pt atoms at the interface between Co and Pt in the multilayer during magnetization reversal. Thus, when t_{Co} increases, the tendency of the H_C of the multilayers with the same t_x is determined by competition of the two effects. When t_{Co} is small, the effect of the magnetic polarization of Pt atoms is dominant, so the H_C goes up with the increase of t_{Co}. As t_{Co} becomes large, the effect of incoherent reversal is more obvious, leading to the decrease of H_C as further increasing the t_{Co}, as seen in the later part of the curves in Fig.4.

It is noted that H_C first increases and then decreases, with t_{Co} except the series Q=5, as shown in Fig.4. However, the critical t_{Co}, at which H_C reaches its peak on a curve, is different for various t_x. The critical t_{Co} is 1.8 nm for the samples with t_x=0.27, 0.36, and 0.45 nm, and 2.16 nm for the samples with t_x=0.54 nm, respectively. It is interesting that the n falls in the range of 4−5 for these t_x values. The results show that H_C decreases with increase of t_{Co} when $n>5$, indicating that the reduction of H_C caused by incoherent reversal overpasses the step-up of H_C contributed by the magnetic polarization of Pt atoms in the procedure of magnetization reversal. For the samples of t_x=0.63 nm, the tendency of H_C with t_{Co} (shown in Fig.4) is different from that of samples with other t_x values because of the effect of the top Co layer, t_y. When t_x=0.63 nm, t_y is 0, 0.54, 0.27, 0.18 and 0.27 nm for different t_{Co} values, respectively. According to the discussion above, the H_C increases with the increase of the Co layer thickness. Because t_y is always smaller than t_x, the role of the top Co layer does not favor H_C. Although the effect of the top Co layer on H_C is usually weak, the effect of the top Co layer could not be ignored for small n. For sample Ⅰ5, in which t_x is 0.63 nm with t_{Co} of 1.26 nm, n=2 and t_y=0, the H_C is dominated only by the Co layer, t_x, without the effect of the top Co layer. Therefore, its H_C gets the maximum. As t_{Co} of the sample with t_x of 0.63 nm increases, t_y of the top Co layer is larger than 0, and H_C becomes small.

Fig.6 shows the hysteresis loops of the sample Ⅲ5 measured at θ=45°. One can see from Fig.6 that with decreasing the applied field from a positive maximum value (descending branch), M_y increases to the positive, and falls to the negative, then approaches to zero for large negative field. With increasing the applied field from a negative maximum value (ascending branch), M_y decreases to the negative, and then raises to the positive, finally approaches to zero for large positive field. While M_x increases to the positive maximum value when the applied field is at maximum positive value, and M_x decreases to the negative maximum value when the applied field is at the maximum negative value. So, we can deduce the pathway of the magnetization rotation. For the descending branch, the magnetization first rotates counterclockwise toward one direction of the easy axis from the direction of positive applied field. Next, irreversible reversal process takes place when the applied field reaches the critical field. Finally, the magnetization rotates clockwise to the direction of negative field applied. For the ascending branch, the magnetization first rotates counterclockwise toward another direction of the easy axis from the direction of negative field applied, and after the irreversible reversal process, the magnetization rotates clockwise to the direction of positive field applied. The angle between the magnetization and x axis varies nearly 180° during the irreversible reversal process. We measure hysteresis loops of all samples in different angles. Other hysteresis loops are not shown here. The pathway of the magnetization mentioned above is similar for all samples.

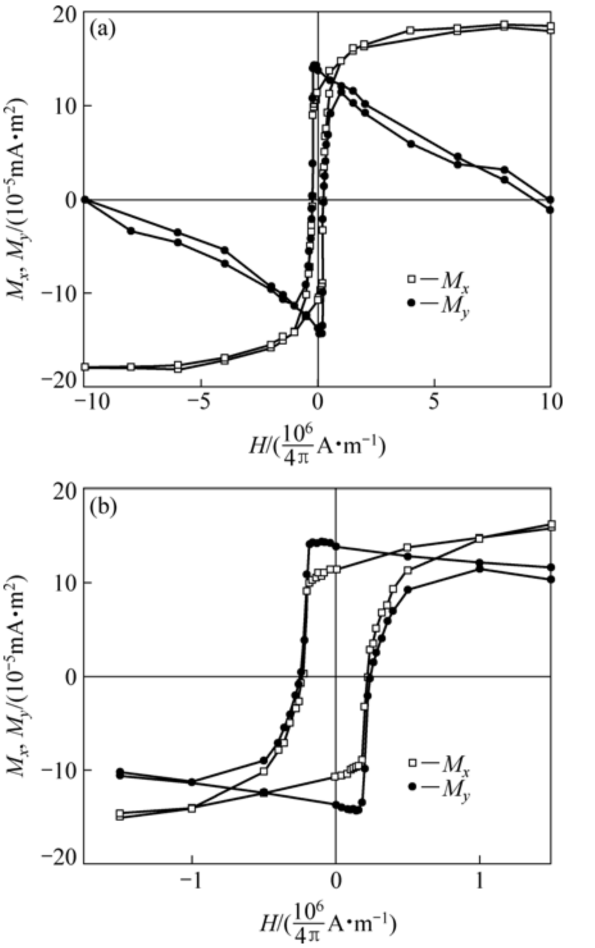

Fig.6 Hysteresis loops of sample Ⅲ5 measured at θ=45°: (a) Whole hysteresis loops; (b) Low field part

Fig.7 shows the behavior of the angular dependence of the coercivity, H_C, for the sample Ⅲ5. The angle θ between the applied magnetic field and the normal direction of the sample plane (easy axis) can be changed by rotating the sample during magnetic measurement. H_C increases as the θ increases from 0 to about 75° and then decreases sharply with further increment of θ. The maximal H_C is located at around 75°. It is inferred that the magnetization reversal of this sample seems to be dominated by magnetic domain wall motion from the behavior of H_C on angle θ[19]. But, the deviation between $H_C(\theta)$ and $H_C(0)/\cos\theta$ increases with the increase of angle θ, where $H_C(\theta)$ and $H_C(0)$ correspond to angle of θ and 0°, respectively. This indicates that angular dependence of H_C does not obey Kondorsky relation[20], which suggests that the nucleation mode is dominant in magnetization reversal process of the samples. It is consistent with the result mentioned above that the angle between the magnetization and x axis varies nearly 180° during the irreversible reversal process. The mechanism of coercivity is of nucleation type. The same results are obtained in all samples. In other words, the mechanism of coercivity is irrelevant with Co layer thickness and the total thickness of Co layer in all samples.

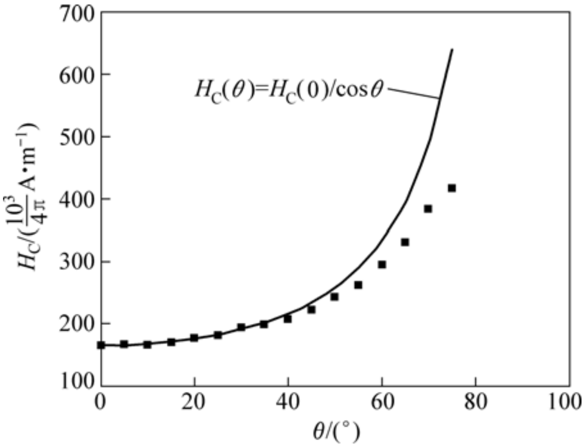

Fig.7 Angular dependence of H_C for sample Ⅲ5

4 Conclusions

1) The coercivity of Co/Pt multilayers increases with the increase of Co layer thickness, t_x, when the total thickness of Co, t_{Co}, keeps constant.

2) When the Co layer thickness, t_x, is the same, the coercivity first increases and then decreases with the increment of the total thickness of Co layer, t_{Co}. This could be attributed to the competition between the reduction of H_C related to incoherent reversal and the step-up of H_C contributed by the magnetic polarization of Pt atoms at the interface between Co and Pt layers during magnetization reversal.

3) The effect of the total thickness of Co layer, t_{Co}, is weaker than that of the Co layer thickness, t_x, on coercivity in the Co/Pt multilayers.

4) The angle between the magnetization and x axis varies nearly 180° during the irreversible reversal process. The nucleation mode is dominant in magnetization reversal process of the samples.

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