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RF magnetron sputtering induced the perpendicular magnetic anisotropy modification in Pt/Co based multilayers*

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We demonstrate that radio frequency (RF) magnetron sputtering technique can modify the perpendicular magnetic anisotropy (PMA) of Pt/Co/normal metal (NM) thin films. Influence of ion irradiation during RF magnetron sputtering should not be neglected and it can weaken PMA of the deposited magnetic films. The magnitude of this influence can be controlled by tuning RF magnetron sputtering deposition conditions and the upper NM layer thickness. According to the stopping and range of ions in matter (SRIM) simulation results, defects such as displacement atoms and vacancies in the deposited film will increase after the RF magnetron sputtering, which can account for the weakness of PMA. The amplitude changes of the Hall resistance and the threshold current intensity of spin orbit torque (SOT) induced magnetization switching also can be modified. Our study could be useful for controlling magnetic properties of PMA films and designing new type of SOT-based spintronic devices.

Keywords: perpendicular magnetic anisotropy, RF magnetron sputtering, ion irradiation, spin orbit torque

PACS: 85.70.–w, 75.70.–i, 79.20.–m **DOI:** 10.1088/1674-1056/abcf9d

1. Introduction

Current induced magnetization switching of perpendicular magnetic anisotropy (PMA) materials by spin orbit torque is promising for the next generation magnetoresistive random access memory (MRAM).[1–4] In the heavy metal/ferromagnetic metal (HM/FM) bilayer system, the PMA is sensitive to the HM/FM interface and FM can be switched by the spin current injected from the HM layer.[5–7] The critical switching current density and charge-to-spin conversion efficiency are dependent on the PMA in the HM/FM system.[8,9] PMA of thin films can be affected by various techniques: thermal annealing, ion irradiation, or oxidation.[10–17] In the previous works, these methods all need an additional process after the thin films growth to modify PMA. Therefore, it is essential to develop new effective ways to modify PMA of thin films.

Magnetron sputtering is a widely used method in thin films growth. Metals are generally deposited by direct current (DC) sputtering. However, for insulating target materials such as oxides and ceramics, there is a charge building up on the surface of the target with DC signal, which hinders the sputtering to proceed. By using a radio frequency (RF) source, the electrostatic charge can be discharged in each cycle, which allows the deposition of quality insulators such as AlO_x and MgO. During RF magnetron sputtering, the deposited film is grounded and the target is connected to a RF power (13.56 MHz). The insulator target acts as a conductor for the RF alternating current field but also acts as an isolate for a self-induced DC field. When the target is anode, the deposited film will be irradiated by the positive ions in ignited plasma. Plasma during RF magnetron sputtering is mainly restrained near the target, thus the positive ion density on the target surface is higher than that on the deposited film surface. Even so, the magnetic properties of the deposited film can be affected by this ion irradiation. To our knowledge, few works have taken this effect into consideration.[18,19]

In this work, we investigate how the magnetic properties could be engineered by the RF magnetron sputtering. We firstly demonstrated that the influence of ion irradiation during RF magnetron sputtering should not be neglected and PMA of the deposited film could be tailored. AlO_x is widely used in the spintronic research,[1,2] so we chose AlO_x as the insulator target to investigate the RF magnetron sputtering effect. Then we studied the underlying physical mechanisms of the PMA changes by SRIM simulation. Finally, the influences of RF magnetron sputtering on SOT induced magnetization switching were investigated.

2. Method

To investigate the influences of RF magnetron sputtering on the deposited magnetic film, we firstly deposited

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Ta(1)/Pt(4)/Co(0.8)/Ru(2) (the numbers are layer thicknesses in nm) thin films on thermally oxidized silicon substrates using a DC magnetron sputtering system. The AlO_x layer was subsequently deposited on these films in different RF magnetron sputtering time t_{RF} (1–10 min) with RF power P_{RF} = 100 W. The base pressure of the sputtering system was less than 5×10^{-8} Torr. The DC sputtering conditions for all the metallic layers were: Ar gas pressure of 0.8 mTorr and DC power of 30 W with the deposition rates between 0.01 nm/s and 0.02 nm/s. The Ar gas pressure of 2 mTorr and RF power of 100 W were used to deposit AlO_x layer with the deposition rate of 0.2 nm/min. Thus we can use the RF magnetron sputtering time t_{RF} to represent the deposited AlO_x layer thickness. The samples were then patterned into Hall bars with the width of 10 μm and the length of 50 μm by standard photo lithography and Ar^+ ion milling, as shown in Fig. 1(a). The Hall bar structure allows us to probe the ferromagnetic state of the devices by measuring the anomalous Hall effect (AHE). A small current of 100 μA was used to detect the ferromagnetic states while minimizing the heating effect.

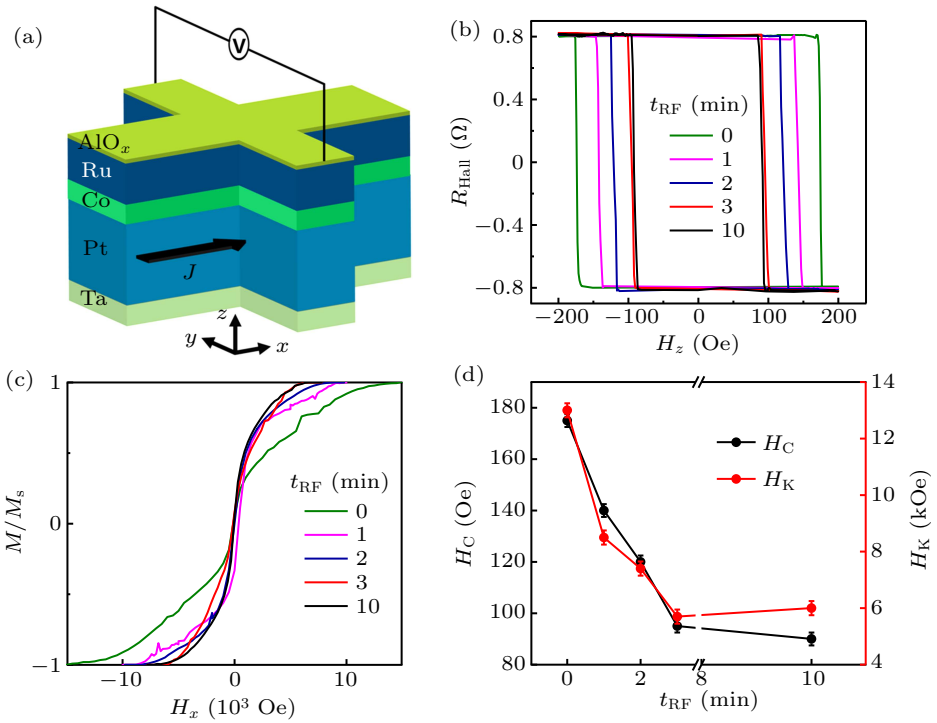


Fig. 1. (a) Schematic of the studied magnetic multilayer system and the experimental measurements set-up for the Hall bar devices with the definition of *x*–*y*–*z* coordinates. (b) Out-of-plane magnetization hysteresis loops measured by AHE for devices deposited AlO_x layer with t_{RF} = 0, 1, 2, 3, 10 min, respectively, at fixed P_{RF} = 100 W. (c) In-plane magnetization hysteresis loops measured by VSM. (d) Magnetic coercive field H_C and anisotropy field H_K obtained from (b) and (c) respectively as functions of t_{RF}.

3. Result and discussion

Typical magnetic parameters (coercive and anisotropy fields) were deduced from the hysteresis loops to characterize PMA. Figure 1(b) shows the AHE hysteresis loops under the out-of-plane magnetic field. Clear square magnetic hysteresis loops were obtained for all the samples, indicating that all the films exhibit good perpendicular magnetic anisotropy even after RF magnetron sputtering. The same magnitude of the AHE resistance suggests the magnetization of all the samples can be fully reversed by the vertical magnetic field continuously. However, the coercive field H_C of the devices decreases from 175 Oe to 95 Oe with increasing t_{RF} from 0 to 3 min, which is shown in Fig. 1(d). For devices with t_{RF} further increasing up to 10 min, the H_C is almost unchanged. Similar results in PMA Ta/Pt/Co/Pt and Ta/Pt/Co/Ti structures were also observed (details see supplementary Fig. S1). Anisotropy field H_K is defined as the required minimum external magnetic field to fully align the magnetization along the hard axis. For Ta(1)/Pt(4)/Co(0.8)/Ru(2) structure, to obtain the relation between the magnetic anisotropy field H_K and the variation of t_{RF}, the magnetic hysteresis loops with the in-plane magnetic field swept between +15000 Oe and −15000 Oe for different samples were measured via a vibrating-sample magnetometer (VSM) at room temperature. The results are shown in Fig. 1(c). Similar with H_C, the determined H_K decreases dramatically initially and reduces to the half value of the sample without RF magnetron sputtering, which indicates the reduced PMA with increasing RF magnetron sputtering time. The H_K then keeps almost unchanged with t_{RF} further increasing, as shown in Fig. 1(d). The almost unchanged H_K and H_C for the samples with $t_{RF} > 3$ min suggest that the impacts on the magnetic properties with further RF magnetron sputtering gradually diminish.

To identify the reason for this phenomenon, several experiments were performed. Firstly, we excluded the oxidation of Co atoms after deposition of the AlO_x, x-ray photoelectron spectroscopy (XPS) spectra of the Co layer was measured for the deposited magnetic samples. No obvious difference is observed before and after the deposition of the AlO_x (details see supplementary Fig. S2), which indicates that 2 nm thick Ru layer is sufficiently thick to prevent oxidation of the Co atoms. Secondly, we removed the upper AlO_x layer on the samples by the chemical etching technique and the hysteresis loops were subsequently measured again. The influences of the RF magnetron sputtering remained, thus the effect of interfacial stress was ruled out. Finally, the measured hysteresis loops for the structure of Ta/Pt/Co/Ru with different Ru thickness t_{Ru} were shown in supplementary Fig. S3. The magnetic properties almost keep the same between the $t_{Ru} = 6$ nm and $t_{Ru} = 2$ nm samples, indicating that it is not the thickness of the top layer that modifies the PMA of the deposited film. Considering that these above factors were all excluded and ion irradiation induced PMA weakness has been observed in other works,[11,20] we believe that ion irradiation induced by RF magnetron sputtering is the main reason for the PMA modification in our experiments.

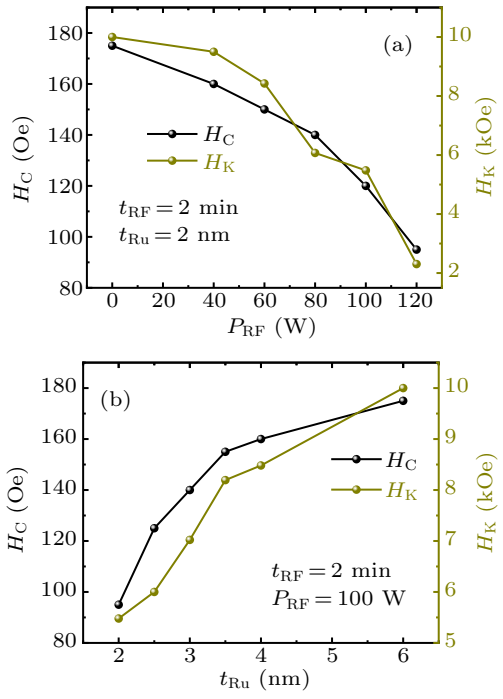


Fig. 2. (a) The magnetic coercive field H_C and anisotropy field H_K against RF magnetron sputtering power P_{RF}, with $t_{RF} = 2$ min and $t_{Ru} = 2$ nm. (b) H_C and H_K as functions of Ru layer thickness t_{Ru}, with $t_{RF} = 2$ min and $P_{RF} = 100$ W.

The irradiation energy of Ar^+ ions in plasma is related to the RF power. We expect a more significant reduction of the H_C and H_K when a higher RF magnetron sputtering power is used. Besides, a thicker Ru layer t_{Ru} can screen the irradiation effect more effectively. To verify our predictions, the AlO_x layer was deposited on Ta(1)/Pt(4)/Co(0.8)/Ru(2) magnetic thin films with different power intensities P_{RF} (40–120 W) for 2 min. The DC self-bias potential is 160 V when $P_{RF} = 40$ W and linearly increases to 300 V when $P_{RF} = 120$ W. As presented in Fig. 2(a), compared with the sample without AlO_x capping layer, the H_C is reduced by 15 Oe and 80 Oe with $P_{RF} = 40$ W and 120 W, respectively. In Fig. 2, the H_K was measured by AHE and the detailed calculation process was shown in supplementary Fig. S4. Figure 2(a) shows that the H_K also decreases with the increasing P_{RF}. When $P_{RF} = 120$ W, the H_K reduces to 25% of the initial H_K value. Then, the AlO_x was deposited with the fixed $P_{RF} = 100$ W and $t_{RF} = 2$ min on Ta(1)/Pt(4)/Co(0.8)/Ru(t_{Ru}) thin films with varying Ru layer thickness from 2 nm to 6 nm. As shown in Fig. 2(b), with the increase of t_{Ru}, the reduction of H_C and H_K induced by RF magnetron sputtering decreases, indicating that the Ar^+ ions irradiation effect is gradually screened by the thicker Ru layer.

To understand the underlying physical mechanisms of the PMA changes in our experiments, the ion irradiation in the RF magnetron sputtering process was modeled by Monte Carlo simulation programs (SRIM).[21,22] We used the grown Ta(1)/Pt(5)/Co(0.8)/Ru(2) structure for simulation. The damages in the deposited film caused by ion irradiation have two major terms: (I) displacement atoms, the atoms which are knocked off from their original normal lattice positions by an energetic Ar^+ ion; (II) vacancies, empty lattice sites caused by atoms' displacement. The DC self-bias potential was 300 V when $P_{RF} = 120$ W, thus ion irradiation energy $E_{Ar+} = 300$ eV was set in the SRIM simulation. Although the fluence of Ar^+ ion irradiation on the target is much higher than that on the deposited film, we can estimate the ion fluence at the deposited film F_S by the ion fluence at the target F_T according to their relation. The RF source is a sinusoidal alternating current signal. If we ignore the influence of the transverse electromagnetic wave, F_T can be approximately calculated by the equation $F_T \approx 4P_{RF}t_{RF}/\pi V_{RF}eA$, where V_{RF} is the DC self-bias potential, e is the charge of electron, and A is the area of the target. The shape of the plasma acting on the target surface is approximately a sphere, thus F_S can be estimated by the equation $F_S \approx (R_T/R_S)^2 \times F_T$, where the distance between the plasma and the deposited film R_S is 45 cm and the radius of the plasma sphere R_T is 5 cm. The deposited AlO_x layer will make the ion irradiation have less influence on the Pt/Co/Ru structure. This can be equivalent to the shorter of the ion irradiation time, so we used a shorter simulation irradiation time compared to the time in the actual experiments. With the Ar^+ ion irradiation energy $E_{Ar+} = 300$ eV and ion fluence $F_S = 5.9 \times 10^{16}$ ions/cm^2, the simulation results are shown in Fig. 3. Figure 3(a) shows the distribution of the displacement Ru and Co atoms and figure 3(b) shows the spatial

distribution of the vacancies in the Co layer. There are two mechanisms accounting for the PMA modification in our experiments. Firstly, some Ru atoms are driven into the Co layer by the irradiation process and the penetrated Ru atoms can subsequently bombard the Co atoms. As shown in Fig. 3(a), although most Co atoms keep stay in the Co layer, part of the Co atoms can be bombarded into the Pt layer. The PMA of Pt/Co/Ru is strongly dependent on the Pt/Co interface quality, thus atoms intermixing at the Pt/Co interface can result in a weaker PMA.[23] Secondly, the magnetic properties of Pt/Co films depend on not only the Pt/Co interface, but also the structure of the Co layer as well. Defects such as interstitial atoms and vacancies in the Co layer will change the magnetic domain structure of the Co layer.[24–26] At the places irradiated, the magnetic domains would be more easily switched by the external magnetic field, which has been confirmed in previous study of the Pt/Co/Pt films.[11] Therefore, the weakened PMA of Pt/Co/Ru multilayers can be explained by the atoms intermixing at the Pt/Co interface and the change of the magnetic domain structure in the Co layer. Considering that the PMA of the Pt/Co based thin films can be affected by RF magnetron sputtering, the SOT induced magnetization switching should be influenced as well.

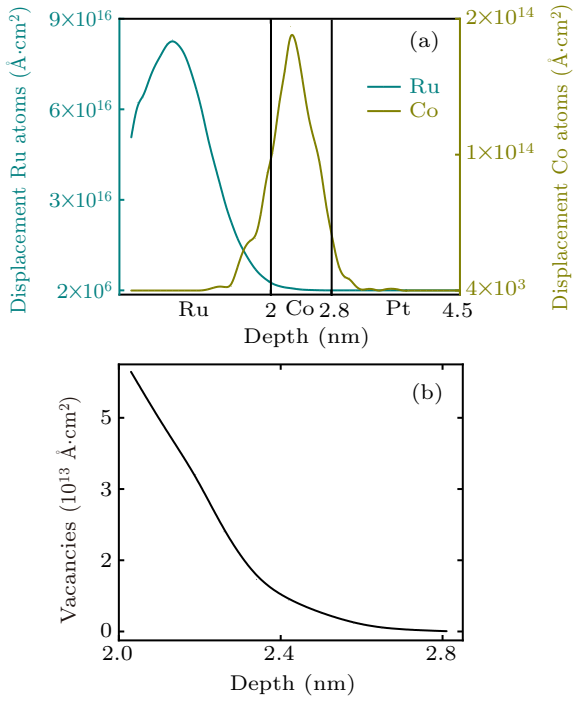


Fig. 3. The simulated results of SRIM. (a) Displacement Ru and Co atoms distribution after Ar^+ ion irradiation with ion irradiation energy $E_{Ar+} = 300$ eV and ion fluence $F = 5.9 \times 10^{16}$ ions/cm^2. (b) Vacancy number distribution in Co layer after Ar^+ ion irradiation.

As shown in Fig. 4(a), current pulse induced magnetization switching for devices Ta(1)/Pt(4)/Co(0.8)/Ru(2)/AlO_x(t_{RF}) was investigated. Every 2 seconds, a pulse current I_{pulse} with duration of 15 ms was injected to the devices. R_{Hall} was measured by a low current of 100 μA after each pulse to probe the magnetization state. Because of the spin Hall effect (SHE) in the Pt layer, the charge current in the x direction gives rise to a spin current in the out-of-plane direction, with the spin orientation along the y direction. The spin current is absorbed by the adjacent Co layer, resulting in both a damping-like torque $\tau_{\parallel} \sim m \times y \times m$ and a field-like torque $\tau_{\perp} \sim m \times y$, where m is the unit vector that denotes the magnetization direction. Neither torque possesses an up- or down-direction preference. But if an external magnetic field is applied collinearly to the current, the symmetry in the response to the SHE torque is broken and the magnetization can be deterministically switched.[4] For our devices, an external magnetic field $H_X = -300$ Oe is applied along the $-x$ direction, thus positive currents favor a positive magnetization (resulting in a positive Hall resistance), while negative currents favor a negative magnetization.

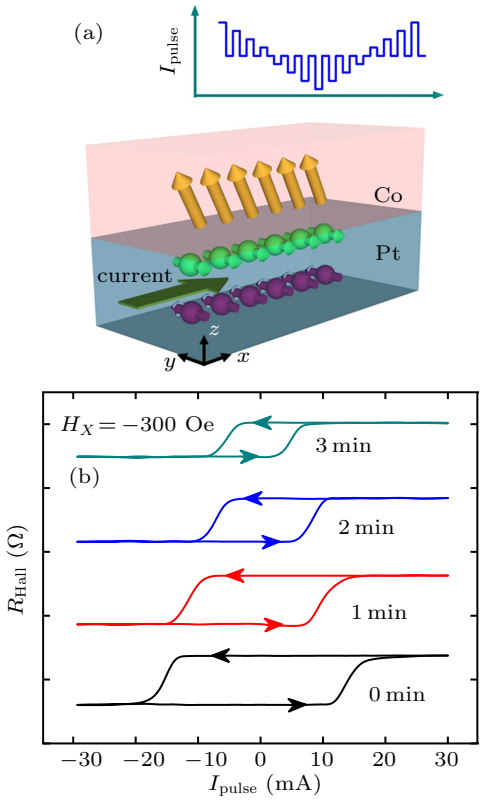


Fig. 4. (a) Illustration of the spin Hall effect in the Pt layer with an external magnetic field of $H_X = -300$ Oe. (b) Current pulse induced magnetization switching for the devices with $t_{RF} = 0$, 1, 2, 3 min.

The current induced magnetization switching loops for the devices with $t_{RF} = 0$, 1, 2, 3 min are shown in Fig. 4(b). The threshold current intensity I_{th} decreases with increasing t_{RF}, which is consistent with the fact that PMA of the thin films is weakened after RF magnetron sputtering. However, the magnitude of the maximum anomalous Hall resistance becomes smaller with $t_{RF} \geq 2$ min, which is different from the constant maximum anomalous Hall resistance reversed by the vertical magnetic field. In our experiments, the samples exhibit a multi-domain structure, thus the magnetization reversal process is dominated by magnetic domain propagation.[27,28]

Considering there is spatial inhomogeneity, the domain walls would be easily nucleated in the more seriously irradiated area. On the other hand, after RF magnetron sputtering, defects in the Co layer and degradation of the Pt/Co and Co/Ru interfaces can act as pinning centers. When $t_{RF} = 1$ min, the influence of these pinning centers was not strong. The critical switching current density decreased and a full SOT induced magnetization switching could be achieved. For more serious irradiated devices with $t_{RF} = 2$, 3 min, SOT cannot induce a full magnetization switching. The reason might be that the pinning centers hinder parts of the magnetic domains to be switched by SOT, which results in the smaller Hall resistance. We have also investigated the difference in magnetic domains switching process after RF magnetron sputtering by polar magneto-optical Kerr effect (MOKE) measurement technique. The experiment results are shown in Fig. S5 in supplementary materials, which suggests that the magnetic domains in the irradiated area become more easily to be nucleated and reversed, which is in good agreement with the current induced magnetization switching.

4. Conclusions

In summary, AlO_x was deposited on Pt/Co/NM type structures by RF magnetron sputtering technique. We found that ion irradiation during RF magnetron sputtering can weaken the PMA of the deposited films. Using a smaller RF magnetron sputtering power and increasing the thickness of the NM layer can reduce the impacts of this ion irradiation. The simulation results of SRIM indicate that the degradation of the Pt/Co interfaces and the increasing defects in the Co layer can account for the PMA weakness. In the SOT induced magnetization switching process, both the Hall resistance and the threshold switching current density decreased after RF magnetron sputtering. Our results will attract the attention of the RF magnetron sputtering and may lead to innovative spintronic applications.

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