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First-order reversal curve investigated magnetization switching in Pd/Co/Pd wedge film*

Yan Li(李岩)[1,2], Wei He(何为)[1,†], Rui Sun(孙瑞)[1,2], Zi-Zhao Gong(弓子召)[1,2], Na Li(李娜)[1,2], Qeemat Gul[1,2], Xiang-Qun Zhang(张向群)[1], and Zhao-Hua Cheng(成昭华)[1,2,‡]

[1] *State Key Laboratory of Magnetism and Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing* 100190, *China*

[2] *School of Physical Sciences, University of Chinese Academy of Sciences, Beijing* 100049, *China*

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The magnetization switching plays an essential role in spintronic devices. In this study, a Pd(3 nm)/Co(0.14–1.68 nm)/Pd(5 nm) wedge film is deposited on an MgO (111) substrate by molecular beam epitaxy. We investigate the polar magneto-optical Kerr effect (MOKE) and carry out the first-order reversal curve (FORC) measurements. For the wedge system, it is observed that the Co thickness could drive the spin reorientation transition (SRT) from out-of-plane to in-plane. Meanwhile, we find the different types of magnetization switchings in the continuous SRT process, which can originate from the formation of different magnetic compositions. Our work provides the possibility of tuning the interfacial effect, and paves the way to analyzing magnetization switching.

Keywords: wedge film, MOKE, FORC, magnetization switching

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1. Introduction

The interfacial effects are of great significance in magnetism. In recent years, numerous phenomena have emerged at interfaces due to the symmetry breaking and the spin-orbit coupling, such as the spin memory loss, the Rashba effect and the Dzyaloshinskii–Moriya interaction.[1–3] The Co/Pd or Co/Pt multilayers with strong perpendicular magnetic anisotropy (PMA) are considered as a viable candidate for interfacial studies. Generally, it is believed that the PMA of Co/Pd or Co/Pt multilayers is caused by the interfacial hybridization of electronic states, and especially the thickness of Co layer plays a crucial role in the electronic states of interfaces.[4,5] There are also quite a few studies showing that interfacial discontinuity is related to the PMA.[6] Nevertheless, thin Co layers often combine with Pd or Pt atoms to form interfacial alloys or clusters with a range of compositions, which causes complicated magnetization to switch, such as the bimodal feature.[7–11] Thus, magnetization switching requires a complete understanding of the interfacial systems. It remains challenging to develop a simple technique to characterize the complicated interfacial system, especially in industry. Nevertheless, the first-order reversal curves (FORC), originating from rock magnetism, provide an insight into exploring subtle magnetization processes and characterizing magnetic particle systems.[12–15]

Here, we deposit a single period Pd/Co/Pd wedge film on an MgO (111) substrate. A wedge film has the advantage of much smaller experimental error. Compared with Co/Pd multilayer, our sample provides the possibility of manipulating the interfacial effect in the system with only two interfaces. Our experiments show Co thickness-driven spin reorientation transition (SRT) and different types of magnetization switchings in a single period sample. We perform the first order reversal curve (FORC) method to analyze the magnetic reversal process.

2. Experimental detail

The MgO (111) substrate was annealed at 700 °C for 2 h in the molecular beam epitaxial chamber.[16] A Pd layer with a thickness of 5 nm was evaporated as a buffer layer at a pressure of 5×10^{-9} mbar (1 bar = 10^5 Pa). At a pressure below 2×10^{-10} mbar, the Co stepped-wedge sample with thickness ranging from 0.14 nm to 1.68 nm in steps of 0.5 mm was deposited via a motor driven shutter. Finally, the sample was covered by a 3-nm-thick Pd film. The polar magneto-optical Kerr effect (p-MOKE) measurement was carried out, where the laser was focused into a $\sim$ 0.2-mm diameter spot on the sample surface. To further explore the magnetization switching, we measured the first-order reversal curve (FORC) based on the p-MOKE. After saturating the film, the FORC was measured by reducing an applied magnetic field to a reversal field H_r, then increasing gradually the field back to a saturation

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†Corresponding author. E-mail: hewei@iphy.ac.cn

‡Corresponding author. E-mail: zhcheng@iphy.ac.cn

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level again, thereby the magnetization M was measured as a function of the increasing field $H(H > H_r)$, and thus a curve $M(H_r, H)$ was obtained. A series of curves $M(H_r, H)$ was measured by repeating the above process at different values of reversal field H_r. The FORC distribution is calculated as a mixed second order,

$$\rho(H_r, H) = -\frac{1}{2M_s}\frac{\partial^2 M(H_r, H)}{\partial H_r \partial H},$$

where M_s is the saturation magnetization. The detail of FORC measurement has been described in previous research.[13–15] On a micro-displacement platform, the wedge film was scanned to obtain hysteresis loops or FORC distributions at various Co thickness values. All depositions and measurements were performed at room temperature.

3. Results and discussion

An SRT observed from out-of-plane to in-plane is presented in Fig. 1(a), which is derived from the competition between the interfacial magnetic anisotropy and the shape anisotropy.[6] Furthermore, we obtain a characteristic change in the shape of the hysteresis loop with increasing Co thickness. Figure 1(a) shows a typical rectangular hysteresis loop with a switching field of 40 Oe (1 Oe = 79.5775 A·m^{-1}) for a Co thickness of 0.56 nm. When increasing the Co layer thickness up to 0.7 nm, the switching actually emerges with a two-jump loop as shown in Fig. 1(b). The two jumps occur at 40 Oe and 90 Oe, respectively. Notably, the two loops of 0.56-nm- and 0.7-nm-thick Co layers have almost the same jumps at 40 Oe. The hysteresis loop of 0.84-nm Co gives rise to three-jump magnetization switching, corresponding to jumps at 40 Oe, 90 Oe, and 140 Oe, where it should be noted that the jumps at 40 Oe and 90 Oe occur again. The gray dashed lines in Fig. 1(b) show a guidance of partially overlapped jumps. In the case of a 1.54-nm Co layer, the magnetization orients parallel to the film plane as shown in Fig. 1(a).

Here, two different mechanisms can be thought of as dominating the reversal process: nucleation and domain wall motion. Which of these mechanisms dominates a reversal process depends on the interaction forces between domains with different magnetic orientations.[17] Generally, a two-successive or two-separate 90 °C domain wall motion could result in multi-jump switching in an epitaxial film.[16,18] However, in the case of a layer with a few Co atoms, the diffusions of Co and Pd atoms could form a mixed alloy or clusters, and thus causing a short range order. Consequently, it is not possible that the two-successive or two-separate 90 °C domain wall motion brings about multi-jump switching due to the absence of long rang order. To gain more insights, the polar Kerr intensity is extracted at a magnetic field of 300 Oe and different wedge locations for the same MOKE geometry as shown in Fig. 2. It is evident that the thickness- dependent polar Kerr intensity is divided into three regions. The intensity rapidly increases linearly with Co thickness till a thickness of 0.56 nm (region I), and then decreases linearly from 0.56 nm to 0.84 nm (region II), and finally decreases slowly with Co thickness till the thickness reaches more than 0.84 nm (region III). According to Refs. [19] and [20], the Kerr intensity keeps a linear dependence on thickness if the magnetization is thickness independent for an ultrathin ferromagnetic film. Therefore, we speculate that the thickness dependence of the Kerr intensity means different magnetic compositions related to switching processes in the transition procedure. Referring to the overlapped switching field in Fig. 1(b), we prefer to attribute multi-jump loops to the networks of Co–Pd alloys with various compositions or Co–Co clusters in region II, which act as pinning centers of the domain wall. Above a certain Co thickness (region III), the distribution of inhomogeneity falls with the increase of Co thickness, and the number of jumps should decrease. Briefly, the fluctuations of magnetic compositions result in multi-jump loops. The explanation is supported by previous studies, which have given bimodal features in multilayers.[7–9] Our experiments show multi-jump features in a single period Pd/Co/Pd film. As a result, our system also excludes interlayer exchange coupling between different periods. Although we do not currently have the experiment to determine magnetic compositions, we could correlate FORC distributions with microscopic magnetic information.

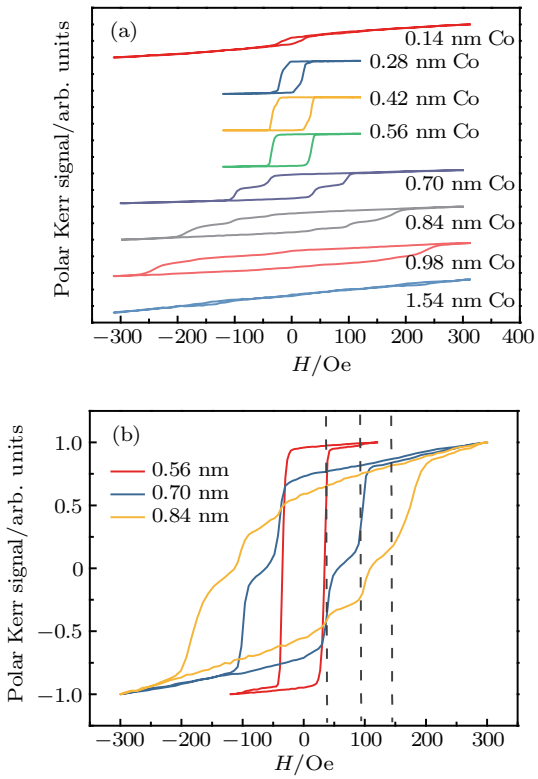


Fig. 1. (color online) (a) Hysteresis loops of Kerr rotation at different wedge locations. (b) Multi-jump loops corresponding to Co thickness values of 0.56 nm, 0.7 nm, and 0.84 nm, respectively. Gray dashed lines represent guidance of partially overlapped jumps.

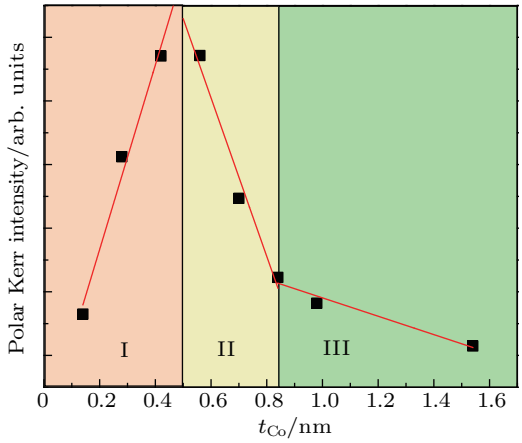


Fig. 2. (color online) Polar Kerr intensity versus Co thickness, showing piecewise linear fit (red curve).

To further confirm our speculation, we explore the details of the magnetic regions using FORC. The FORC distribution,

$$\rho(H_r, H) = -\frac{1}{2M_s}\frac{\partial^2 M(H_r, H)}{\partial H_r \partial H},$$

eliminates the reversible components of magnetization switching, and maps out the irreversible processes. In order to adapt for the Preisach model, we rotate the coordinates, $H_c = (H - H_r)/2$, $H_u = (H + H_r)/2$, where H_u corresponds to the distribution of interparticle interaction field, and H_c indicates the distribution of local coercivity.[13–15] As shown in Figs. 3(a) and 3(b), the distributions with 0.28 nm and 0.56-nm Co layers display only one single nucleation process. The strip coercivity distribution of the 0.28-nm Co layer has the characteristics of single domain particles, and exhibits a larger spread of local domain pinning.[15] By contrast, the distribution of the 0.56-nm Co layer shows a more stable magnetic configuration. Besides, the distribution of the 0.28-nm Co layer has larger vertical spread than the 0.56-nm Co layer (see inset in Fig. 3). The vertical spread increases with increasing the concentration of particles, indicating that magnetic dipolar interaction exists between particles.[21] As a consequence, Co atoms should be randomly located at Pd layers, and form a discontinuous film in region I. The distribution of 0.7-nm Co layer consists of two peaks in Fig. 3(c), and exhibits the increased number of pinning sites. The first peak, having a character similar to those in Figs. 3(a) and 3(b), is loosely coupled with the second one. The coexistence of different magnetic compositions contributes to the two nucleation processes. In contrast, it seems to be different peaks merging together in Fig. 3(d), which are tightly coupled with each other. That is, when Co atoms gradually form a continuous Co film, different magnetic compositions appear in the transitional region II. Thus the FORC distributions display different nucleation processes, and coercivity H_c shifts to a higher field. Accordingly, the interfacial discontinuity influences the PMA. With Co film becoming continuous, the different compositions are tightly coupled with each other, the shape anisotropy $-(1/2)\mu_0 M_s^2$ is enhanced, and the magnetization is rotated near to the film plane.

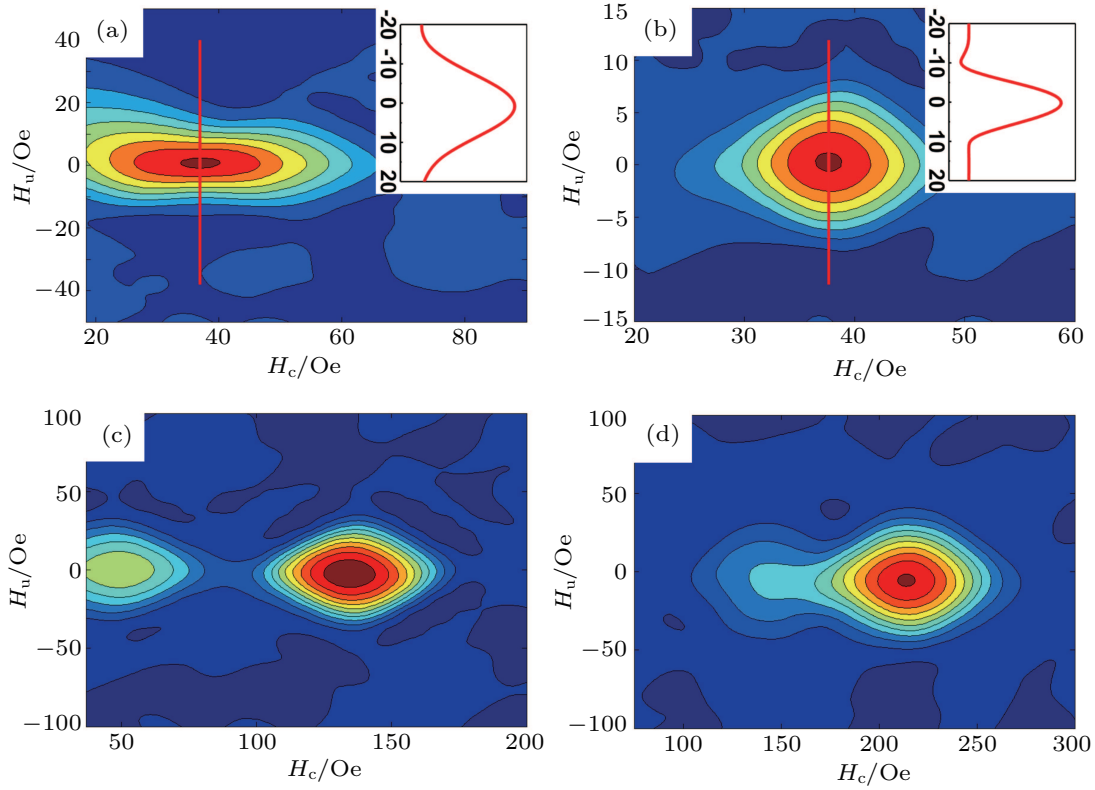


Fig. 3. (color online) FORC distributions with Co layer thickness values of (a) 0.28 nm, (b) 0.56 nm, (c) 0.7 nm, and (d) 0.98 nm. Inset: the vertical projection of FORC distributions in panels (a) and (b).

It is significant to quantitatively distinguish reversible and irreversible switching in industrial applications. The irreversible components can be estimated by the integration,[12,13] $I_{\mathrm{Irrev}} = \int \rho(H_{\mathrm{r}}, H)\,\mathrm{d}H_{\mathrm{r}}\,\mathrm{d}H = \int \rho(H_{\mathrm{u}}, H_{\mathrm{c}})\,\mathrm{d}H_{\mathrm{u}}\,\mathrm{d}H_{\mathrm{c}}$ as shown in Fig. 4. The irreversibility reaches a maximum value for the 0.56-nm Co layer. Beyond the critical thickness, the switching is gradually dominated by the reversible process.

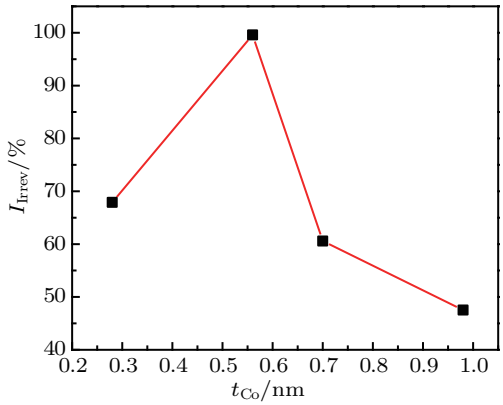


Fig. 4. (color online) Irreversible switching component versus Co layer thickness, obtained from FORC. The red line is a guide for the eyes.

4. Conclusions

We have investigated Co thickness-dependent magnetization switching modes in a single period Pd/Co/Pd wedge film via scan detections of MOKE and FORC. We observe a Co thickness-induced SRT and different types of magnetization switchings in the single sample. The SRT is derived from the competition between the interfacial magnetic anisotropy and the shape anisotropy. The networks of different magnetic compositions are detected by p-MOKE by using the laser with a 0.2-mm diameter spot, resulting in multi-jump hysteresis loops. The FORC distributions depict images of nucleation processes and quantitatively evaluate irreversible switchings at different Co-wedge locations. Our work raises the possibility of manipulating the interfacial effect, and offers a method to analyze magnetization switching systematically.

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