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Influence of Pt spacer thickness on the domain nucleation in ultrathin Co/Pt/Co trilayers

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The effect of varying the interlayer coupling between two 0.6 nm thick Co layers with perpendicular anisotropy on their magnetic ground state and the domain nucleation processes during a field reversal was studied. A transition from out-of-plane to in-plane anisotropy was revealed as the Pt spacer thickness decreased below 1.6 nm. For Pt thicknesses in the range of 1.6–5.4 nm, domain nucleation occurred in both Co layers in a correlated manner, and subsequent motion of the domain walls proceeded as though bound together. A transition to uncorrelated domain nucleation and independent wall motion was observed at Pt thicknesses above 5.4 nm. Both conventional and "asymmetrical" domain nucleation centers were observed in the whole range of platinum spacer thicknesses. © *2013 American Institute of Physics*.
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INTRODUCTION

In recent years, a number of features of the domain nucleation and motion processes have been revealed in ultrathin magnetic films with perpendicular anisotropy.[1–5] In particular, in addition to conventional "symmetric" nucleation centers, "asymmetric" domain nucleation centers were also found, where the reversal domains nucleate at different locations for magnetization pointing up and down.[2,3,5]

Multilayers composed of magnetic ultrathin layers separated by nonmagnetic spacers are particularly intriguing. The reversal properties of multilayers are determined both by the interlayer coupling through the nonmagnetic spacer and the response of the individual magnetic layers to the applied magnetic field. There are a variety of magnetization reversal features that can occur in such structures.[6–12] Some of them may be caused by the peculiarities of magnetization reversal in single films, while others are caused by the interlayer coupling. Until now, there was no detailed study of this issue. Therefore, we have performed this study observing for the first time the domain nucleation and growth in Co/Pt/Co ultrathin structures having Co layers of equal thickness and a varying Pt spacer thickness while a perpendicular magnetic field is reversed.

EXPERIMENTAL

A Pt(10 nm)/Co(0.6 nm)/Pt(t)/Co(0.6 nm)/Pt(3 nm) structure with a wedge-shaped Pt spacer was deposited by dc magnetron sputtering onto a Si substrate 50 mm long and 6 mm wide at room temperature. The platinum thickness t varied from 0 nm to 10 nm along the 50 mm sample length. After growth, the structure was cut into 10 samples of equal length (5 mm). The domain formation and evolution was studied by magneto-optical Kerr microscopy. Magnetic hysteresis loops shown in this paper of the samples were measured by a vibrating sample magnetometer (VSM) at a field sweep rate $d\mu_0 H/dt = 0.1$ mT/s. To determine the domain nucleation field, the following procedure was used. The sample was first saturated in the field perpendicular to the sample surface $\mu_0 H_{sat} = 21$ mT. Next, the field was turned-off and the field of opposite direction was gradually increased at the rate of $d\mu_0 H/dt = 0.02$ mT/s until domain nucleation and spreading occurred. Domains nucleated in the bottom and top layers can be distinguished from each other by the difference in the Kerr contrast caused by the larger light absorption from the more deeply located bottom layer.

RESULTS AND DISCUSSION

Unexpected results were obtained for the samples with Co layers separated by a very thin Pt nonmagnetic spacer. For the Pt thickness $t < 1.6$ nm, Kerr microscopy revealed only a monotonic change in the magneto-optical contrast with the variation of magnetic field magnitude. Such a change can be realized by the out-of-plane rotation of a magnetization lying in-plane in the ground state. The hysteresis loop (Fig. 1(a)) also confirmed that for this very thin spacer sample the normal to the sample surface is the hard magnetization axis. It is worth noting that a spin-reorientation transition from an out-of-plane to an in-plane magnetization has commonly been observed with an increase in the Co thickness both in single Co films grown on Pt[13] and in Co/Pt multilayers.[14] In these earlier studies, Co layers having the 0.6 nm thickness used in this work were always found to demonstrate a strong perpendicular anisotropy. In our experiments a new phenomena, not predicted by theory, has been revealed that a very thin nonmagnetic Pt spacer (up to 1.6 nm) stimulates a transition to an in-plane anisotropy in 0.6 nm thick Co layers

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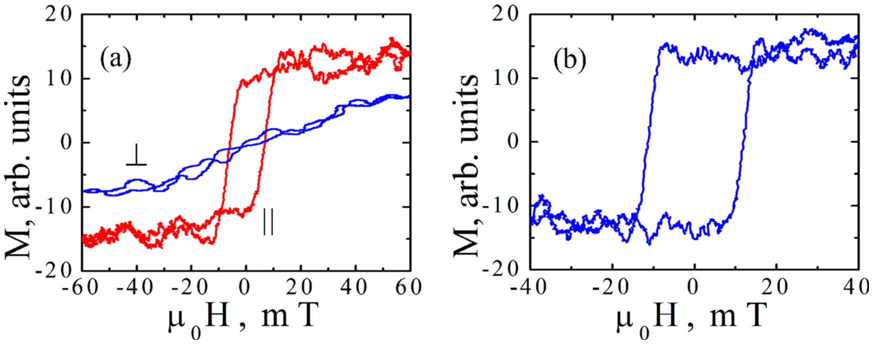

FIG. 1. Magnetization (M) vs. field (H) hysteresis loops measured in a VSM for the samples with average platinum spacer thickness (a) $t_{av} = 0.5$ nm measured in a field parallel (||) and perpendicular (⊥) to the film plane and (b) $t_{av} = 4.5$ nm with H perpendicular to the film plane.

that have a perpendicular anisotropy in the absence of this strong Co–Pt–Co interlayer coupling. The origin of the in-plane magnetization effect still needs to be determined.

For $t > 1.6$ nm, only the formation and spreading of bubble domains was observed under variation of magnetic field magnitude without any change in the magneto-optic contrast. This finding indicates the magnetization in this region is directed out of the plane of the film. The samples in this region all had square hysteresis loops (see e.g., Fig. 1(b)). We have measured the dependence of the domain nucleation field on the Pt spacer thickness for the samples with perpendicular anisotropy. The plot is represented in Fig. 2. In this plot, the nucleation field is the average of several measurements made for each data point and the error bars represent the 95% confidence level for the measurements. Where error bars are not shown, they are comparable to or smaller than the symbol size. The corresponding value of the spacer thickness was determined from the distance between the domain nucleation position and the sample edge. It is seen that in the region of small platinum thickness the nucleation field decreases sharply with the spacer thickness, but not monotonically; there is also a minimum nucleation field for the sample having a spacer thickness near 2.6 nm and a peak nucleation field for a sample having a spacer thickness near 3.5 nm. This phenomenon is similar to that described in Ref. 7, where the variation in coercivity with Pt layer thickness t was observed in macroscopic magnetometry measurements for $[\mathrm{Co}(0.4\,\mathrm{nm})/\mathrm{Pt}]_n$ (where $n = 5$–30 is the number of Co/Pt repeats) multilayers. Our results show that oscillatory interlayer coupling can also be revealed in the system of two separated Co layers by measuring their domain nucleation fields using Kerr microscopy. The dependence in Fig. 2, perhaps, as well as that obtained in Ref. 7, could be explained by a competition between the oscillatory interlayer exchange coupling and the magnetostatic interaction between layers.[15]

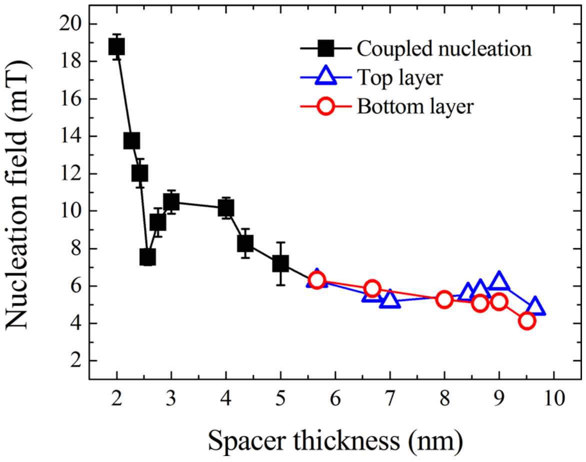

FIG. 2. Domain nucleation field dependence on the Pt spacer thickness.

The Kerr microscopy also revealed that in a wide range of Pt spacer thicknesses (1.6–5.4 nm) as the field was gradually increased the nucleation of bubble domains in the two Co layers always occurred in a correlated manner: at the same field strength (simultaneously in both Co layers) and at the same position (one domain wall above the other). Domain walls in the two layers moved as a unit, i.e., bound together, and with the same velocity, as was observed previously in a Pt(4.5 nm)/Co(0.5 nm)/Pt(3 nm)/Co(0.8 nm)/Pt(3.5 nm) structure having a constant Pt thickness.[11]

Further increase in the Pt spacer thickness above $t > 5.4$ nm resulted in an abrupt change in the domain nucleation mode from being laterally correlated to uncorrelated, and the domain wall motion in each layer became independent of the other layer. The domain nucleation field values measured in each layer in the samples with laterally uncorrelated nucleation, at the larger spacer thicknesses, were plotted separately using different symbols (Fig. 2). At $t = 5.7$–8.0 nm, the domain nucleation field values in the two Co layers were very close to each other, so their respective symbols in Fig. 2 plot overlapped. With the increase in Pt spacer thickness above $t = 8.5$ nm, the nucleation field values in the layers began to differ significantly and the domain nucleation occurred not only at different positions, but also at different field values in this spacer thickness region. This difference reached about 1.0 mT at $t = 9$ nm and was observed up to the maximum t value of our samples. Quite surprisingly, the earlier formation of domains in the bottom layer and their significantly faster spreading resulted in the formation of regions with *antiparallel* magnetization between the Co layers of the same thickness at $t > 8.0$ nm, and that situation would remain stable if one turned off the external magnetic field after reversal of the bottom layer.

The difference in the domain nucleation field values may be dictated by the difference in defect structures of the layers formed during growth of the layers. To explain the stability of the antiparallel magnetization between the Co layers, two possible explanations may be suggested. The first

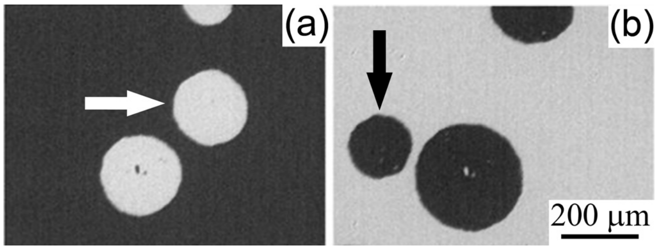

FIG. 3. Kerr images of domain structure formed at the Pt layer thickness of 5 nm for a field of (a) +14 mT and (b) −14 mT after first saturating the sample at −40 mT and +40 mT, respectively. The "asymmetric" domain nucleation centers are indicated by the arrows.

one is the change in the interlayer coupling from ferromagnetic to antiferromagnetic. Then the reversal of the bottom layer prevents the reversal of the top one. The other possibility is a decrease in the effective magnetic field caused by a weakening of the ferromagnetic interlayer coupling at large spacer thickness, so that it becomes insufficient to cause a reversal of the layers' magnetization.

In our experiments, both the composite double-layer domains in the Pt thickness range $t < 5.4$ nm and laterally uncorrelated domains in each Co layer at $t > 5.4$ nm, like those observed previously in a single Co film,[2] also demonstrated an asymmetry with respect to the sign of the reversal magnetic field in the activity of some of its domain nucleation centers, i.e., the lack of a correlation between the locations of the domain nucleation places under application of magnetic fields of opposite sign (compare Figs. 3(a) and 3(b)). This asymmetry was observed for the whole range of Pt spacer thicknesses investigated. Like in single films,[3] this asymmetry was also suppressed with the saturation of the sample by a field amplitude an order of magnitude larger than the sample's macroscopic coercivity determined from its measured hysteresis loop, but also returned during the subsequent cycling at lower fields. It should also be noted that domains nucleated both at the "symmetric" and "asymmetric" centers had the same nucleation fields at the same Pt spacer thickness and fitted on a single curve (Fig. 2).

The asymmetry in the domain nucleation center activity in the Co/Pt/Co trilayer may be the result of an inhomogeneity of the perpendicular anisotropy of single Co layers or of the interlayer exchange and orange peel coupling (which depends strongly on the nonmagnetic layer thickness). Our investigation has shown that both the variation of the Co/Pt interface structure and the interlayer coupling with increasing thickness of the nonmagnetic interlayer up to 10 nm does not result in the disappearance of the asymmetry.

CONCLUSION

In conclusion, using magneto-optical Kerr microscopy, we have investigated the magnetic ground state and sequence of remagnetization events of a Co/Pt/Co structure, having Co layers of equal thickness (0.6 nm) and an intermediate wedge-shaped Pt spacer (0–10 nm). It was revealed for very thin nonmagnetic spacer thickness (less than 1.6 nm) that the ultrathin Co layers had not an out-of-plane, but in-plane, magnetization. In the Pt thickness range for perpendicular magnetization, an unexpected magnetization behavior of two exchange-coupled Co layers was also discovered: an abrupt transition from laterally correlated to independent domain wall nucleation and motion for Pt thickness above 5.4 nm. The present observations revealed the difference in the domain nucleation field values between the top and bottom Co layers with further Pt spacer increase above 8.5 nm.

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