Functional Materials 15, No.1 (2008)

On the nature of asymmetry of nucleation centers activity in ultrathin Co films and Co/Pt multilayers

Yu.L.Iunin, Yu.P.Kabanov, V.I.Nikitenko**,
X.M.Cheng**, A.J.Shapiro*, C.L.Chien**, R.D.Shull*****

Institute of Solid State Physics, Russian Academy of Sciences,
Chernogolovka, 142432, Russia
*The Johns Hopkins University, Baltimore, Maryland 21218, USA
**National Institute of Standards and Technology, Gaithersburg,
Maryland 20899, USA

Received October 20, 2007

Magnetization reversal in ultrathin Pt(10 nm)/Co(0.6 nm)/Pt(3 nm) magnetic films and Pt(10 nm)/[Co(d)/Pt(1 nm)]$_n$/ Pt(2 nm) (d = 0.4, 0.6, 0.8 nm, n = 2, 4) multilayers with perpendicular anisotropy has been studied using Kerr microscopy. These materials demonstrate unusual effects of activity asymmetry of nucleation centers and domain wall motion. The field dependences of these effects have been studied and the asymmetry of the domain wall nucleation has been found to be suppressed by application of a magnetic field much stronger than the sample coercivity. The asymmetry comes back after several reversals at a lower field magnitude. The asymmetry of domain wall velocity decreases abruptly and vanishes as the reversal field increases in low coercivity ultrathin Co films. The effect recovers as in the reversal field value decreases. A role of the Co/Pt interface defects and nonlinear spin excitations in these phenomena is discussed.

Методом Керр-микроскопии исследовано перемагничивание ультратонких магнитных плёнок Pt(10 нм)/Co(0.6 нм)/Pt(3нм) и многослойных структур Pt(10 нм)/[Co(d)/Pt(1 нм)]$_n$/ Pt(2 нм) (d = 0,4, 0,6, 0,8 нм, n = 2, 4) с перпендикулярной анизотропией, проявляющих эффекты асимметрии активности центров зарождения и движения доменных стенок. Исследована полевая зависимость этих эффектов. Обнаружено, что приложение достаточно большого насыщающего поля (существенно превышающего коэрцитивность образца) подавляет активность асимметричных центров зарождения. Перемагничивание в полях меньшей величины приводит к восстановлению асимметрии. В ультратонких плёнках Co с малой коэрцитивностью асимметрия скоростей доменных стенок резко уменьшается и исчезает с увеличением поля, восстанавливаясь с его уменьшением. Обсуждается роль структуры межфазной границы Co/Pt и нелинейных возбуждений спиновой подсистемы в формировании этих эффектов.

The artificial ultrathin magnetic films and multilayers composed of ferromagnetic layers separated by nonmagnetic spacers represent a new type of quasi-two-dimensional structures with physical properties of a great interest. The lowering of the system dimensionality results usually in new and qualitatively different physical properties. In particular, as the thickness of magnetic layers decreases (becoming less than a few atomic layers), these structures change abruptly the easy magnetization axis from the in-plane to the out-of-plane, revealing a strong perpendicular magnetic anisotropy (PMA). Investigations of magnetization reversal of ultrathin ferromagnetic films and

multilayers with PMA have shown that some remagnetization features are similar to those of bulk materials. In particular, the reversal in ultrathin films occurs, as in the bulk materials, by the nucleation and spreading of domain walls [1–3]. The motion of domain walls was found to be either thermally activated or viscous, depending upon the magnetic field strength [2].

However, our recent study of ultrathin Pt/$[Co/Pt]_n$/Pt multilayers (n = 1, 2, 4) has revealed some quite unusual features in their magnetization reversal behavior [4] those can not be understood in the frameworks of a perfect interface structure. In addition to the usual symmetrical nucleation centers, hitherto unknown asymmetrical magnetic domain nucleation centers were found in ultrathin $[Co/Pt]_n$ structures with n = 1, 2, and 4, where the reversal begins for one direction of the field only. The new domains nucleate at different positions for magnetization **M** pointing up or down. A pronounced asymmetry in the mobility of domain walls in single Co films with low coercivity was also reported, which is in sharp contrast to the expected symmetry of magnetic reversal in general in the homogeneous bulk ferromagnets.

In this work, we have studied in detail the elementary re-magnetization events in the out-of-plane magnetized ultrathin $[Co/Pt]_n$ (n = 1, 2, 4) multilayers as a function of the saturation field and number of layers. We have studied the manner by which the asymmetrical domain nucleation activity depends on the saturation field magnitude. The dependence of the domain wall velocity asymmetry on the applied field was also investigated.

The samples to study were the Pt(10 nm)/Co(0.6 nm)/ Pt(3 nm) films and Pt(10 nm)/$[Co(d)/$ Pt(1 nm)$]_n$/Pt(2 nm) multilayers (n = 2, 4; d = 0.4, 0.6 nm) grown by DC magnetron sputtering onto Si(111) substrates at room temperature. The domain structure evolution was investigated *in situ* by magneto-optical Kerr effect (MOKE) microscopy at various magnetic fields, applied perpendicular to the film plane. The average magnetization as a function of the applied magnetic field H was determined by Hall resistance measurements at H perpendicular to the film plane. Since the extraordinary Hall resistance R_H in multilayers with PMA is proportional to M, the field dependence of R_H yields the curve $M(H)$. The $[Co/Pt]_n$ samples with n = 1, 2, and 4 show square hysteresis loops (e.g., see Fig. 1),

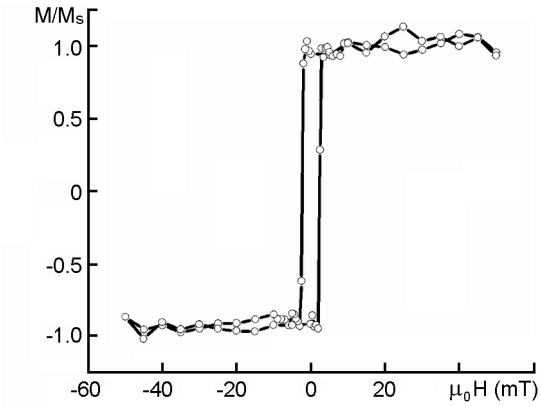

Fig. 1. Hysteresis loop for the ultrathin Co (0.6 nm) film.

their coercivity H_c increases with the number of Co layers. To study the nucleation and evolution of domains, the field was gradually reduced from the saturation field H_s to a reversed field exceeding the sample coercivity till the domain nucleation occurs and then was kept constant.

In the earlier work [4], we have shown an example of the domain structure evolution in the $[Co/Pt]_2$ structure. In this work, we illustrate the evolution of domains in the ultrathin Co(0.6 nm) film (Fig. 2). A magnetic field of $\mu_0 H = -1.4$ mT (Fig. 2a, 2b, 2c) and $\mu_0 H = +1.4$ mT (Fig. 2d, 2e, 2f) was applied after the gradual decrease from the saturating fields of $\mu_0 H_s = +60$ mT and -60 mT, respectively. The magnetization reversal in single Co ultrathin films is seen to occur through the nucleation and growth of bubble domains like in $[Co/Pt]_2$ multilayers. Similar to the bulk materials and thin films, there are "symmetric" domain walls nucleating at the same positions in the fields with opposite directions. However, as well as in $[Co/Pt]_2$, we observed not only usual symmetrical, but also the unusual asymmetrical nucleation centers in single Co layers. Such "asymmetrical" types of nucleation centers produce domains of a single magnetization direction only, either downward or upward, but not both. The domain nucleated at the field directed upward only is shown in Figs. 2e and 2f by arrows.

The difference manifests itself also in the fact that the magnetic field reversing before the "symmetrical" domain wall reached the sample boundaries (or other domains) results not only in the shrinking of a domain, but also in the formation of a ring structure due to nucleation of a new domain at the same nucleation center [3, 4].

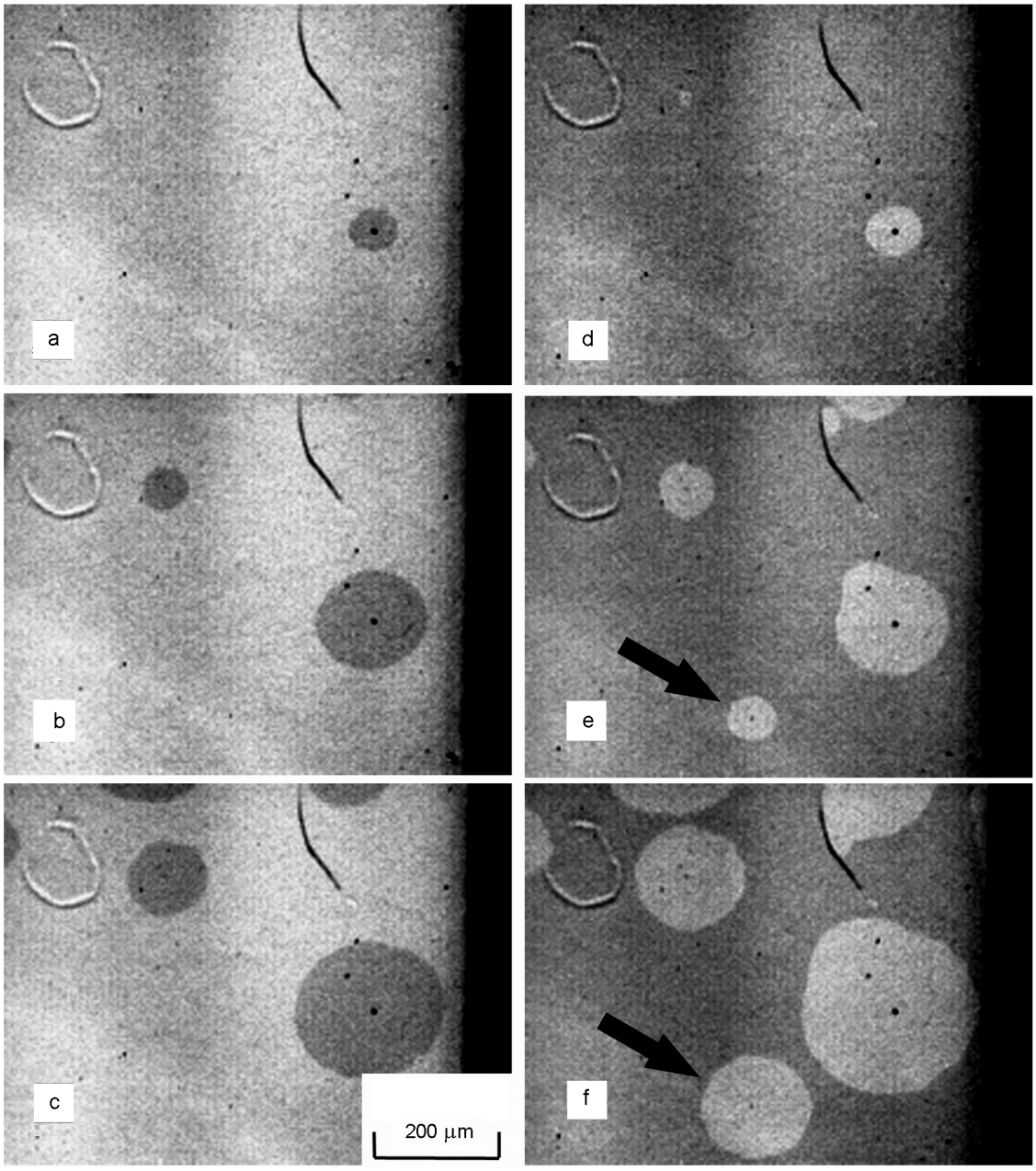

Fig. 2. MOKE images of the evolution of a domain structure in the ultrathin Co (0.6 nm) film under application of magnetic fields $\mu_0 H = -1.4$ mT (a, b, c) and $\mu_0 H = +1.4$ mT (d, e, f), respectively; arrows show the domains produced by "asymmetric" centers.

However, due to the asymmetry in nucleation activity, the shrinking of an "asymmetrical" domain is observed only, without formation of a ring structure.

We have studied in detail the existence conditions of this effect. Our experiments have revealed that the asymmetric nucleation in the single layer Co films and $[Co/Pt]_n$ multilayers ($n = 2$, 4) is observed at low saturating fields. It is suppressed by the ramping up to high saturating field, by an order or two higher than the macroscopic sample coercivity (measured by the hysteresis loop). The asymmetry suppression in the domain nucleation by application of a high field has been revealed in all of the $[Co/Pt]_n$ ($n = 1$, 2, 4) samples studied in this work. The field value at which the nucleation asymmetry is suppressed varies for various samples. We have found also that the asymmetric nucleation reappeared after several reversal cycles proceeding from a field lower that the saturating one.

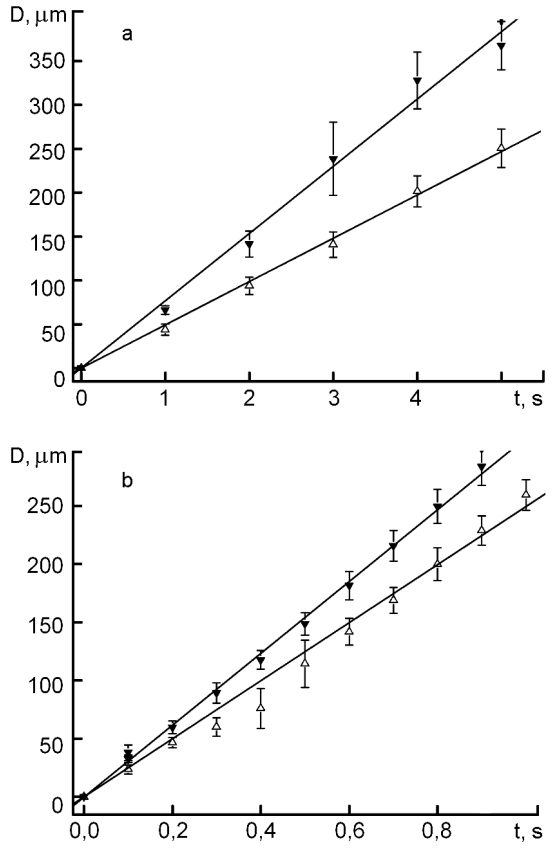

Fig. 3. Forward (open symbols) and backward (filled symbols) displacements of the "asymmetric" domain wall in the ultrathin single Co(0.6 nm) film with the coercivity $\mu_0 H_c$ = 2.3 mT as a function of time under applied magnetic fields (a) $\mu_0 H = \pm 1.26$ mT and (b) ± 1.67 mT. Solid lines are the linear fits.

This phenomenon may be due to several reasons. First, it can be defined by the defect structure peculiarities of real thin films. It is known that the adsorption of atoms on the film surface from the gas phase always occurs with formation and growth of islands. So, such elements of the interface structure as islands, steps, and pinholes are inevitable part of nanocomposites. Their role in the processes of nucleation and domain wall motion in quasi two-dimensional structures is still poorly understood.

The asymmetrical nucleation centers have been observed before, but only in the exchange coupled thin ferromagnetic/antiferromagnetic bilayers [5, 6]. Similarly, in our samples, the asymmetry may be caused by the formation of a local unidirectional anisotropy due to exchange coupling between islands with ferromagnetic and antiferromagnetic ordering. The antiferromagnetic ordering may occur either due to oxidation of some Co islands and CoO formation of [7] (if suppose that the Neel temperature for the CoO nanoislands is higher than that for the bulk oxide), or at the interfacial steps [8], or at the Co surface as previously observed in an Fe/W(001) ultrathin film [9]. Moreover, the asymmetry may be due to defects in the interface structure such as islands with very high coercivity and opposite magnetization direction [10]. Another reason for the asymmetric nucleation may be related to the existence of an unusual spin configuration known as a skyrmion [11, 12]. If skyrmions remain stable against collapse to the atomic scale, the down domains shrink to a small but finite radius in an upward field and reappear when the field is reversed.

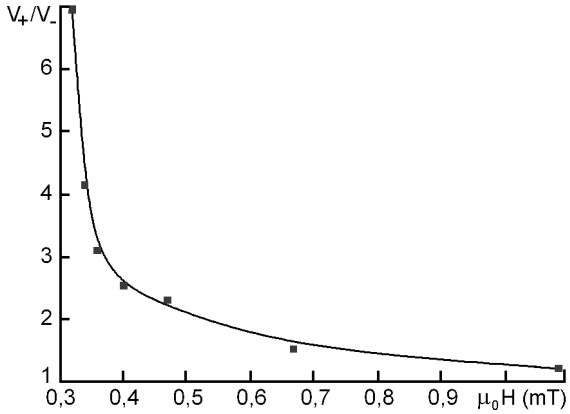

Fig. 4. Ratio of the forward and backward velocities of "asymmetric" domain walls in the Co(0.6 nm) film as a function of applied magnetic field. Solid line guides for eyes.

We have also studied the asymmetry existence conditions in the velocity of the domain walls. To measure the domain wall velocities, the magnetic field was kept constant after nucleation of domains and the domain wall displacement was measured as a function of time. The displacements are linear in time, with a well-defined velocity (Fig. 3). Unlike the "symmetrical" domains, the domain walls nucleated at "asymmetrical" centers in single Co films have backward velocities significantly larger than that of domain wall growth in a field of the same strength but opposite direction. Figure 3 shows the forward and backward "asymmetrical" domain wall displacements in the single ultrathin Co film, measured at two different applied magnetic fields, as a function of time. One can see that the

larger the magnetic field, the less the ratio of backward and forward velocities.

Figure 4 shows the field dependence of the domain wall velocity asymmetry (ratio of the backward to the forward velocity) obtained with one more ultrathin Co film. One can see that the asymmetry of domain wall mobility vanishes completely at larger magnetic fields. This effect is observed in the single Co films with low coercivity only ($\mu_0 H_c$~2 mT); it does not appear both in the single layer Co film with a larger coercivity ($\mu_0 H_c$ = 8.0 mT) and in the $[Co/Pt]_2$ sample ($\mu_0 H_c$ = 19 mT), where domain walls do not move in fields $\mu_0 H \leq 2$ mT. This asymmetrical phenomenon has never been predicted, and its origin remains unclear. Domain walls nucleated at "symmetrical" and "asymmetrical" centers overcome similar barriers during their motion but display different backward velocities. Consequently, one may suspect different types of centers form different domain wall structures.

In conclusion, we have studied in detail features of the magnetization reversal of sputtered ultrathin Co films and $[Co/Pt]_n$ (n = 2, 4) multilayers with perpendicular magnetic anisotropy. The asymmetrical activity of the domain nucleation centers is suppressed reversibly by the application of large magnetic fields in all of the samples. The asymmetry of domain wall velocity, being revealed only in the ultrathin Co films with low coercivity, decreases and disappears completely at larger magnetic fields.

This work was supported in part by Basic Research Program of the RAS Presidium P-03 "Quantum Macrophysics".

References

1. J.Pommier, P.Meyer, G.Penissard et al., *Phys. Rev. Lett.*, **65**, 2054 (1990).
2. A.Kirilyuk, J.Ferre, V.Grolier et al., *J. Magn. Magn. Mater.*, **171**, 45 (1997).
3. M.Kisielewski, A.Maziewski, M.Tekielak et al., *J. Magn. Magn. Mater.*, **260**, 231 (2003).
4. Y.L.Iunin, Y.P.Kabanov, V.I.Nikitenko et al., *Phys. Rev. Lett.*, **98**, 117204 (2007).
5. V.I.Nikitenko, V.S.Gornakov, L.M.Dedukh et al., *Phys. Rev. B*, **57**, R8111 (1998).
6. V.I.Nikitenko, V.S.Gornakov, A.J.Shapiro et al., *Phys. Rev. Lett.*, **84**, 765 (2000).
7. W.H.Meiklejohn, C.P.Bean, *Phys. Rev.*, **102**, 1413 (1956).
8. R.Skomski, H.P.Oepen, J.Kirschner, *Phys. Rev. B*, **58**, 11138 (1998).
9. A.Kubetzka, P.Ferriani, M.Bode et al., *Phys. Rev. Lett.*, **94**, 087204 (2005).
10. O.Pietzsch, A.Kubetzka, M.Bode et al., *Phys. Rev. Lett.*, **92**, 057202 (2004).
11. A.Abanov, V.L.Pokrovsky, *Phys. Rev. B*, **58**, R8889 (1998).
12. A.S.Kirakosyan, V.L.Pokrovsky, *J. Magn. Magn. Mater.*, **305**, 413 (2006).

Про природу асиметрії активності центрів зародження в ультратонких плівках Co та багатошарових структурах Co/Pt

Ю.Л.Іунін, Ю.П.Кабанов, В.І.Нікітенко, Ц.М.Чень, А.Дж.Шапіро, С.Л.Чієн, Р.Д.Шалл

Методом Керр-мікроскопії досліджено перемагнічування ультратонких магнітних плівок Pt(10 нм)/Co(0.6 нм)/ Pt(3 нм) та багатошарових структур Pt(10 нм)/ [Co(d)/Pt (1 нм)]$_n$/Pt(2 нм) (d = 0.4, 0.6, 0.8 нм, n = 2, 4) з перпендикулярною анізотропією, які виявляють ефекти асиметрії активності центрів зародження та руху доменних стінок. Досліджено польову залежність цих ефектів. З'ясовано, що прикладання досить сильного насичувального поля (яке істотно перевищує коерцитивність зразка) пригнічує активність асиметричних центрів зародження. Перемагнічування в полях меншої величини приводить до відновлення асиметрії. В ультратонких плівках Co з малою коерцитивністю асиметрія швидкостей доменних стінок різко зменшується та зникає при збільшенні поля, відновлюючись при його зменшенні. Обговорюється роль структури міжфазної межі Co/Pt та нелінійних збуджень спінової підсистеми у формуванні цих ефектів.