DYNAMICS OF 180° NÉEL WALLS IN TWO-DIMENSIONAL PERMALLOY PARTICLES OBSERVED VIA PICOSECOND TIME-RESOLVED PHOTOEMISSION ELECTRON MICROSCOPY

A. KRASYUK[1], F. WEGELIN[1], S.A. NEPIJKO[1,2], H.J. ELMERS[1], G. SCHÖNHENSE[1], I. MÖNCH[3], H. VINZELBERG[3], C.M. SCHNEIDER[4]

UDC 537.611.3

[1]**Institute of Physics, University Mainz**
(7, Staudingerweg, Mainz 55099, Germany),

[2]**Institute of Physics, Nat. Acad. of Sci. of Ukraine**
(46, Prosp. Nauky, Kyiv 03028, Ukraine),

[3]**Institute of Solid State and Material Research Dresden**
(20, Helmholtzstr., Dresden 01069, Germany),

[4]**Institute of Solid State Research IFF-6, Electronic Properties, Research Centre Jülich**
(52425, Jülich, Germany)

Stroboscopic pump-probe measurements (a time-resolution of about 10 ps) have been conducted on a photoemission electron microscope by using the synchrotron radiation source UE46-PGM beamline at BESSY-II (Berlin) with low alpha bunch option (a photon pulse was characterized by the root mean square of 3 ps, and the repetition rate was 0.5 GHz). This technique was applied to studying the dynamics of 180° Néel walls between domains in rectangular permalloy ($Ni_{81}Fe_{19}$) particles (their lateral sizes comprised 16 μm × 32 μm, the thickness amounted to 10 nm) due to the action of an external magnetic field being a sum of pulse and constant magnetic fields directed oppositely. The velocity of 180° Néel walls comprises $\sim 10^3$ m/s, when the rate of change (increase) of a magnetic field is $1.2 \cdot 10^6$ T/s. The remagnetization fundamental frequency is estimated to be ~ 1.25 GHz.

1. Introduction

Studies of the magnetization dynamics are of importance for the achievement of a higher operational speed of magnetic memory elements. Such investigations have been performed using synchrotron radiation with a time resolution of 125 ps [1] (15 ps [2]) by using the stroboscopic technique on a photoemission electron microscopy (PEEM). X-ray magnetic circular dichroism (XMCD) was used in these experiments to visualize magnetic domains. XMCD is realized by a subtracting PEEM image at the illumination by left σ^- and right σ^+ circularly polarized radiation. In practice, to perform the normalization, an asymmetric image is used. The asymmetry is the normalized difference $[I_i(\sigma^-) - I_i(\sigma^+)]/[I_i(\sigma^-) + I_i(\sigma^+)]$ at each point i of this image.

The time-resolved PEEM investigation of the visualization and propagation of spin waves in rectangular permalloy particles (their lateral sizes comprised tens of microns at a thickness of several tens of nanometers) has been performed in [2,3]. Under the influence of an oscillatory field along the short side of the sample, the Néel wall in the initial classical Landau–Lifshits pattern shifts away from the center, corresponding to an induced magnetic moment perpendicular to the exciting field.

The present work is devoted to the more detailed studies of both the propagation of spin waves and the dynamics of 180° Néel walls movement during the magnetization.

2. Experiment

The measurements were performed on a photoemission electron microscope (FOCUS IS-PEEM [4,5]) by using the UE46-PGM beamline at the BESSY-II (Berlin) synchrotron radiation source with a low alpha bunch option (a photon pulse had the root mean square width of 3 ps, and the repetition rate was 0.5 GHz). Two-dimensional permalloy particles on a copper microstrip line (Fig. 1,*a*) were investigated. An external magnetic field acted on the particles was formed by the current through the microstrip line (Fig. 1,*b*). To produce such specimens, a continuous copper (Cu) film was firstly deposited on a silicon substrate by magnetron sputtering, then a continuous permalloy ($Fe_{19}Ni_{81}$) film was deposited. The two-dimensional permalloy particles were prepared on the copper microstrip line from such a system with the help of photolithography. The microstrip line of 50 μm in width was characterized by

 ISSN 2071-0194. Ukr. J. Phys. 2009. V. 54, N 1-2

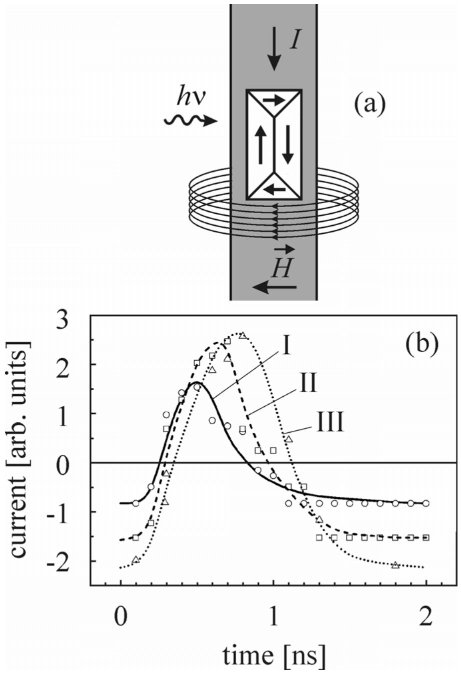

Fig. 1. (a) Scheme of a two-dimensional rectangular permalloy particle on a copper microstrip line. Directions of the projection of synchrotron radiation in the particle plane $h\nu$, the current passing through the microstrip line I, and the magnetic field H created by it are shown. (b) Current profiles reconstructed from a change of the linear size of PEEM images of the particle being studied under the current passage through the microstrip line. The period of pulses is equal to 2 ns

a wave impedance matched with the rest of the circuit (50 Ω) through which a current pulse passed. The process of preparation of permalloy particles on the copper microstrip line is described in [6, 7] in more details.

3. Results and Discussion

In some cases, the visualization of the walls between magnetic domains is more informative than that of the magnetic domains themselves. For this purpose, the studies of 180° Néel walls was performed under the illumination by circularly polarized radiation perpendicular to the wall direction (Fig. 1,a). Figure 2 shows static XMCD-PEEM images of rectangular particles of 10 nm thick with a lateral size of 16 μm along the horizontal direction and the aspect ratio of 1:4 (a), 1:2 (b), 3:4 (c), 1:1 (d), 2:1 (e), and 4:1 (f). The wavy arrow indicates the illumination direction projected in

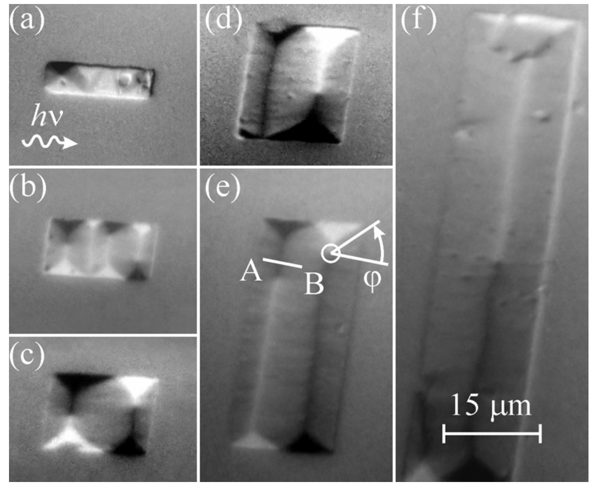

Fig. 2. Static XMCD-PEEM images of the domain structure in the magnetic-field-free state of permalloy rectangular particles 10 nm thick with a lateral size of 16 μm along the horizontal and the aspect ratio of 1:4 (a), 1:2 (b), 3:4 (c), 1:1 (d), 2:1 (e), and 4:1 (f). The magnetic contrast is due to XMCD at the Ni L_3 edge ($h\nu$= 853 eV). Other designations are given in the text

the image plane (from left to right). A rather high lateral resolution (down to 20 nm) enables the magnetic structure of domain walls to be well seen. 1) A turn of the domain magnetization direction occurs in the plane of a permalloy particle clockwise and anticlockwise for light and dark domain walls between them, respectively. These 180° Néel domain walls have the magnetization direction identical with that of the closing domains which they adjoin. 2) The region where 180° Néel domain walls with opposite magnetization directions converge (marked by the circle in Fig. 2,e) has a vortex magnetic structure. A deviation from this structure is observed for the region with the radius which only slightly exceeds the width of the domain wall. 3) The profile of a 180° Néel domain wall, for instance, along line AB in Fig. 2,e has a 1.8-μm full width at half maximum (FWHM), that is almost an order of magnitude more than that for bulk permalloy [8]. This is caused by the ripple structures of domains of the particle under study.

The domain structure of rectangular permalloy particles in Fig. 2,a–f is known [9]. It is caused by the fact that there was an external magnetic field during their preparation. This field existed in the plane of these particles and was directed perpendicularly to their side with a fixed length of 16 μm. In this case, a good closure of the magnetic flux within ferromagnetic particles (small stray fields) was provided. A particle of

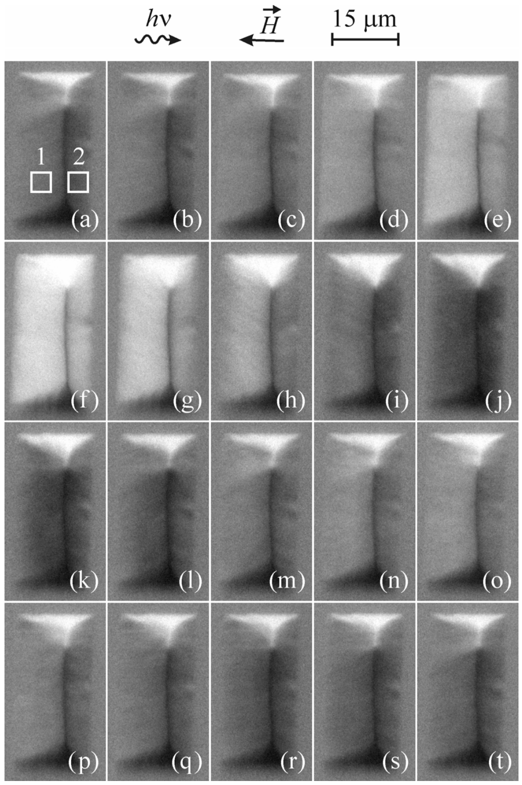

Fig. 3. XMCD-PEEM images of the particle being studied under the action of external magnetic field I at time $t = 0$ (*a*), 100 (*b*), 200 (*c*), 300 (*d*), 400 (*e*), 500 (*f*), 600 (*g*), 700 (*h*), 800 (*i*), 900 (*j*), 1000 (*k*), 1100 (*l*), 1200 (*m*), 1300 (*n*), 1400 (*o*), 1500 (*p*), 1600 (*q*), 1700 (*r*), 1800 (*s*), and 1900 ps (*t*). Designations used here are identical to those in Fig. 1,*a*

16×32 μm^2 in size (see Fig. 2,*e*) was chosen to investigate the dynamics of the action of an external magnetic field on it. The field was a sum of pulse and constant magnetic fields directed oppositely. Current pulses I, II and III with FWHM of 100, 300, and 600 ps and the relation of intensities of their maxima of 1:1.5:2, respectively, were applied at the microstrip line input. Their shapes shown in Fig. 1,*b* by curves drawn across round, square, and triangular experimental points were reconstructed from a change of the linear sizes of the PEEM image of the particle being investigated under the passage of a current pulse through the microstrip line. The latter fact is caused by a change of the magnification of a photoemission electron microscope during the variation of the voltage between an object and an extractor. The real pulses had FWHM of 430 (I), 520 (II), and 750 ps (III). The magnetic fields existing directly at the bottom of a pulse and at its maximum amounted to –0.08 and +0.17 mT (I), –0.16 and +0.22 mT (II), and –0.21 and +0.27 mT (III). In all these cases, the rate of increase of the external magnetic field was the same and comprised 1.2×10^6 T/s (maximum slope).

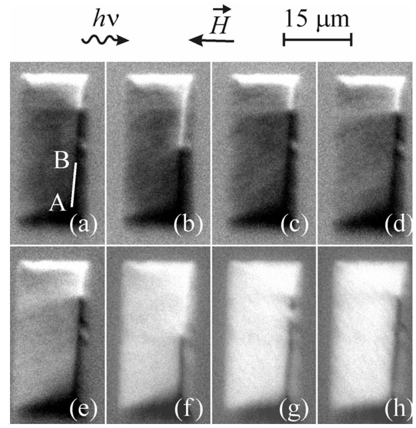

Fig. 4. XMCD-PEEM images of the particle being studied under the action of external magnetic field II at time $t = 0$ (*a*), 100 (*b*), 200 (*c*), 300 (*d*), 400 (*e*), 500 (*f*), 600 (*g*), and 700 ps (*h*). Designations used here are identical to those in Fig. 1,*a*

The magnetic field pulse acts on the magnetization within a ferromagnetic particle resulting in the formation of a spin wave. Its attenuation time is longer than the time between two pulses (the magnetic field pulses are synchronized with the photon pulses and come in all 2 ns). In addition, there is a constant component of the magnetic field. Therefore, at the moment of the arrival of every next pulse ($t = 0$ ps), the magnetic structure of the permalloy particle under study differs from the initial one (cf. Figs. 3,*a* and 2,*e*). It consists of two domains being already separated by a 180° Néel wall with the magnetization direction parallel to the long particle side and two closing domains (the domain magnetization directions are shown in Fig. 1,*a*).

As is visible in Fig. 3,*a*, at the moment of the pulse arrival t= 0, the domains situated on both sides of a 180° Néel wall have different sizes (they are wider on the left than on the right). This effect manifests itself stronger with increase in the magnetic field (i.e. higher current pulses through the strip line) (cf. Figs. 3,*a* and 4,*a*). The series of PEEM images shown in Figs. 3 and 4 correspond to the cases of the action of external magnetic fields I and II, respectively. In the case of external magnetic field III, at the moment of the pulse arrival $t = 0$, a 180° Néel wall is already situated near the right edge of the permalloy particle under study (see Fig. 4 in [2]). This phenomenon is explained by the self-trapping effect of the dominating spin-wave mode when the system is excited just below the resonance frequency. In this case under the influence of the oscillatory field, the Néel wall in the initial classical Landau pattern shifts away from the center, corresponding to an induced magnetic moment perpendicular to the exciting field [2].

Figure 3,*a*–*t* shows a series of PEEM images of the particle being studied with the steps Δt= 100 ps during the action of external magnetic field I (the current described by curve I in Fig. 1,*b* passes through the microstrip line). If the external magnetic field becomes stronger, the contrast becomes brighter, but then it darkens as the field becomes weaker. When the magnetic field pulse is over, a further change of the contrast is observed. It is wave-like and is caused by the change of the domain magnetization direction by the angle φ (the angle φ is counted from the illumination direction anticlockwise). The dependence $\varphi(t)$ was calculated from a change of the gray level in region 1 (see Fig. 3,*a*) for the series of PEEM images in Fig. 3,*a*–*t*. It is shown by curve I in Fig. 5,*a*, upper panel. Curve I in Fig. 5,*a*, lower panel, shows the similar dependence for region 2 (see Fig. 3,*a*).

Experimental curves II and III given in Fig. 5,*a* correspond to the action of external magnetic fields II and III (currents through the microstrip line are shown by curves II and III in Fig. 1,*b*). As is seen from Fig. 5,*a*, the action of a magnetic field results in a rotation of the magnetization directions. In domains separated by a 180° Néel wall, they turn in the opposite directions (in this case, a better closure of the magnetic flux is provided, i.e. the stray fields are minimal). In addition, the viscosity of the system provides a phase lag of the rotation of the magnetization direction. Thus, a change of the magnetization direction proceeds to increase even when the external magnetic field has reached its maximum. The comparison of Figs. 5,*a* and 1,*b* shows that the maxima of the dependences $\varphi(t)$ and the external magnetic field (current through the microstrip line) are separated by a time lag of 150 (I), 100 (II), and 50 ps (III). The stronger the external magnetic field, the greater is the angular change of the magnetization direction, and the longer is the time required for its relaxation after the pulse action is over. The spin wave is characterized by a frequency which is greater, when the external magnetic field is stronger. The spin wave frequency can be estimated in the region, where the external magnetic field is constant. It is maximum (about 1 ns) for the case of magnetic field I (it begins in 1 ns after the start of a pulse and lasts till the next pulse comes). In this interval for curve I in Fig. 5,*a*, upper panel (see also Fig. 5*a*, lower panel) the period comprises T= 800 ps, i.e. the spin wave frequency is $f_{\rm I} = T^{-1}$= 1.25 GHz. In a similar manner, the spin wave frequencies $f_{\rm II}$ and $f_{\rm III}$ can be determined from curves II and III. The close values of $f_{\rm I}$, $f_{\rm II}$, and $f_{\rm III}$ show that, in the performed experiment, the magnetic field only weakly influences the spin wave frequency. This means that its fundamental frequency f is always close to $f_{\rm I}$= 1.25 GHz. The fundamental frequency of spin wave is determined by the extrapolation to the case without external magnetic field, i.e. $f_{\rm III} > f_{\rm II} > f_{\rm I} \approx f$. Let us notice such an important result that it exceeds the excitation frequency equal to 0.5 GHz. The system is excited with a significant oscillating Fourier component of 1 GHz, i.e., just below the resonance frequency of the free-running system.

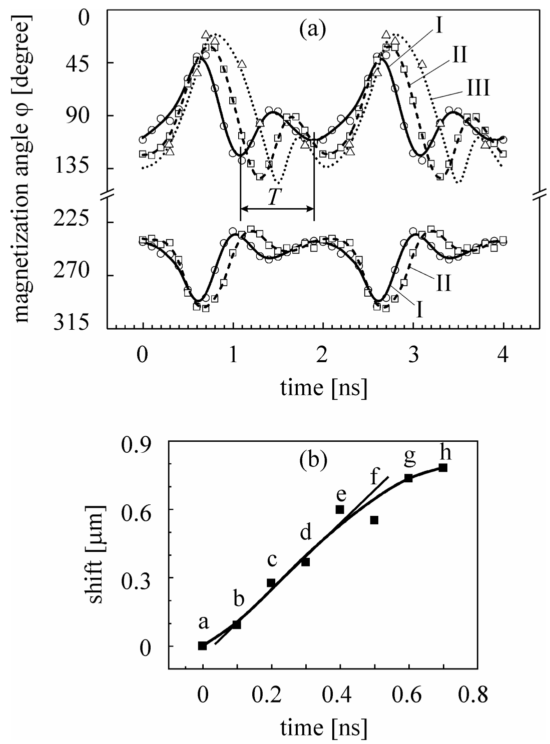

Fig. 5. (*a*) Time dependences of the angle of the magnetization direction in the region marked by a white small square to the left (to the right) of 180° Néel wall in Fig. 3,*a* under the action of external magnetic fields I, II, and III are shown in upper (lower) panel. (*b*) Time dependence of the shift of a 180° Néel wall designated by AB in Fig. 4,*a*. Points *a*–*h* correspond to images (*a*–*h*) in Fig. 4

The movement of a 180° Néel domain wall is observed during the action of an external magnetic field. Figure 4,*a*–*h* shows a series of XMCD-PEEM images

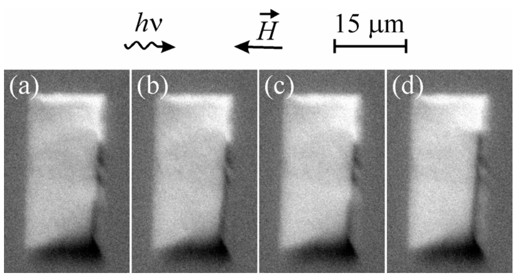

Fig. 6. XMCD-PEEM images of the particle being studied under the action of external magnetic field II at time t = 640 (a), 650 (b), 660 (c), and 670 ps (d). Designations used here are identical to those in Fig. 1,a

under the action of magnetic field II with the step Δt = 100 ps in the region $0 \leq t \leq 700$ ps. This region corresponds to the pulse leading edge, i.e. to an increase of the magnetic field. As the field becomes stronger, the fragment AB of the 180° Néel domain wall (its designation is given in Fig. 4,a) shifts to the right. Figure 5,b illustrates the time dependence of this shift, $S(t)$. Designations of the points in Fig. 5,b correspond to those in Fig. 4,a-h. The tangent to the dependence $S(t)$ in Fig. 5,b shows that the velocity of movement of the 180° Néel domain wall does not exceed $\sim 10^3$ m/s, which corresponds to the literature data [2].

Similary, the movement of a 180° Néel domain wall was studied under the action of external magnetic field II. This shift was greater than that under the action of external magnetic field I. When employing external magnetic field III, the absolute value of the shift is still more, but its relative shift is already smaller. In the latter case, as was already noted, at the moment of the arrival of a next pulse, the 180° Néel domain wall is already situated near the right edge of the permalloy particle, and its further shift to the right under the action of the next pulse is small (its movement is restricted by the particle right edge).

A series of XMCD-PEEM images of the particle under study (Fig. 6,a–d) illustrates the dynamics of the 180° Néel domain wall in more detail (with the step Δt= 10 ps) near the maximum of external field II (640 ps $\leq t \leq$ 670 ps).

The results of a computer simulation confirm the proper understanding of the observed processes. It was performed for a permalloy rectangular particle with a lateral size of 16×32 μm^2 and 10 nm thick. The external magnetic field was applied along its short side. This corresponded to the case of external magnetic field I. The computer simulation was performed with the help of a modified OOMMF simulation code [10] (see also [11]), the cell size (an elementary region with uniform magnetization) amounted to 10 nm. It was shown that the results of the computer simulation did not depend (i) on the linear size of a cell if this size did not exceed 10 nm and (ii) on the number of pulses in a series if this number was greater than 30. The spin waves excited by magnetic pulses were analyzed by frequencies. The computer simulation is an evidence in favor of the experimental result that the fundamental frequency of spin waves in the particle being considered is close to 1.25 GHz. However, there are more high-frequency modes as well. They are characterized by different localizations within the particle. The results of the computer simulation will be published in more details later on.

4. Conclusions

In conclusion, we note the following results. In the present work, the magnetic structure of 180° Néel domain walls was first visualized with the help of the XMCD contrast on a photoemission electron microscope. Earlier, they were determined only as boundaries between domains. This study enabled changes in their magnetic structure under the action of sufficiently high external magnetic fields to be directly observed. The dynamics of these domain walls was investigated during the influence of pulses of the external magnetic field. If its temporal gradient comprises 1.2×10^6 T/s, the velocity of movement of the 180° Néel domain walls amounts to 1×10^3 m/s. The spin waves were visualized, and the peculiarities of their propagation within the permalloy particles with lateral sizes of tens of microns and 10 nm thick were studied under excitation by magnetic field pulses at the 0.5-GHz repetition rate. In such a particle, the fundamental frequency of a spin wave was equal to 1.25 GHz.

The authors thank all members of BESSY (Berlin, Germany) for their help during the beamtimes.

1. C.M. Schneider, A. Kuksov, A. Krasyuk, A. Oelsner, D. Neeb, S.A. Nepijko, G. Schönhense, I. Mönch, R. Kaltofen, J. Morais, C. de Nadaï, and N.B. Brookes, Appl. Phys. Lett. **85**, 2562 (2004).

2. A. Krasyuk, F. Wegelin, S.A. Nepijko, H.J. Elmers, G. Schönhense, M. Bolte, and C.M. Schneider, Phys. Rev. Lett. **95**, 207201 (2005).

3. G. Schönhense and H.J. Elmers, Surf. Interface Analysis **38**, 1578 (2006).

4. http:// www.focus-gmbh.com

5. C.M. Schneider and G. Schönhense, Rep. Progr. Phys. **65**, R1785 (2002).

6. A. Krasyuk, A. Oelsner, S.A. Nepijko, N.N.Sedov, A. Kuksov, C.M. Schneider, and G. Schönhense, Appl. Phys. A **79**, 1925 (2004).

7. A. Oelsner, A. Krasyuk, D. Neeb, S.A. Nepijko, A. Kuksov, C.M. Schneider, and G. Schönhense, J. Electr. Spectr. Relat. Phenom. **137-140**, 751 (2004).

8. A. Hubert and R. Schäfer, *Magnetic Domain. The Analysis of Magnetic Microstructures* (Springer, Berlin, 1998).

9. S.A. Nepijko, M. Klais, G. Schönhense, N. Cramer, Z. Celinski, C.M. Schneider, S. Zennaro, N. Zema, and N.N. Sedov, Appl. Phys. A **76** 809 (2003).

10. M. Bolte, R. Eiselt, T. Eimüller, P. Fischer, and G. Meiner, J. Magn. Magn. Mater. **290-291**, 723 (2005).

11. M.J. Donahue and D.G. Porter, *OOMMF User's Guide Version 1.2 Interagency Report NISTER 6376* (National Institute of Standards and Technology, Gaithersburg, MD, Sept. 1999).

ДОСЛІДЖЕННЯ ДИНАМІКИ 180° НЕЄЛІВСЬКИХ СТІНОК У ДВОВИМІРНИХ ПЕРМАЛОЄВИХ ЧАСТИНКАХ ЗА ДОПОМОГОЮ ПІКОСЕКУНДНОЇ ФОТОЕМІСІЙНОЇ ЕЛЕКТРОННОЇ МІКРОСКОПІЇ

О. Красюк, Ф. Вегелін, С.О. Непийко, Х.Й. Ельмерс, Г. Шонхензе, І. Мьонх, Х. Вінцелберг, К.М. Шнайдер

Р е з ю м е

Стробоскопічні вимірювання (часова роздільна здатність близько 10 пс) були виконані у фотоемісійному електронному мікроскопі з синхротронним збудженням. З цією метою використовувався канал UE46-PGM синхротронного накопичувального кільця BESSY-II (Берлін), що працює в режимі "low alpha bunch" (фотонний імпульс характеризується протяжністю переднього фронту 3 пс і частотою повторення 0,5 ГГц). Така техніка дозволила дослідити динаміку 180° неєлівських стінок між доменами в прямокутних пермалоєвих частинках (їх латеральні розміри 16×32 мкм^2 і товщина – 10 нм) під дією зовнішнього магнітного поля, яке являло собою суперпозицію протилежних по знаку імпульсного та постійного магнітних полів. Швидкість руху 180° неєлівських стінок становила $\sim 10^3$ м/с при зміні (збільшенні) швидкості магнітного поля $1{,}2 \cdot 10^6$ м/с. Власна частота перемагнічування становила $\sim$1,25 ГГц.