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Domain structure formation and evolution in epitaxial exchange-biased NiFe films with dislocation slip planes

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The effect of dislocations on formation the magnetic structure and the elementary events of magnetization reversal processes in epitaxial thin exchange-biased NiFe(100 Å)/NiO(500 Å) bilayers with [110] or [100] unidirectional anisotropy have been investigated using the magneto-optic indicator film technique. The dislocations have been revealed to induce an inhomogeneous distribution of the magnetization vectors on their slip planes. The dislocation slip planes act as domain nucleation and domain wall pinning centers. The dislocations produce a strong local magnetic anisotropy along one of the <010> directions independent of the orientation of the unidirectional anisotropy induced during the film deposition in the rest (dislocation-free) sample area. Taking into account that the NiFe ferromagnetic film has almost zero magnetostriction, the observed effects could be attributed to stresses or/and uncompensated spins near to the dislocations in the antiferromagnetic layer.

С использованием метода магнитооптической индикаторной пленки исследовано влияние дислокаций на формирование доменной структуры и элементарных актов процесса перемагничивания в тонких эпитаксиальных обменно-смещенных NiFe(100 Å)/NiO (500 Å) двухслойных пленках с ориентацией однонаправленной анизотропии вдоль [110] или [100]. Установлено, что краевые дислокации обусловливают неоднородное распределение векторов намагниченности вдоль их плоскостей скольжения. Дислокационные плоскости скольжения действуют как центры зарождения новых доменов и центры пиннинга для движения доменных стенок. Дислокации индуцируют сильную локальную магнитную анизотропию вдоль одного из направлений <010>, которая не зависит от ориентации однонаправленной анизотропии, наведенной в процессе осаждения пленок в остальной (бездислокационной) части каждого образца. Принимая во внимание то, что ферромагнитные пленки NiFe имеют почти нулевую магнитострикцию, наблюдаемые эффекты могут быть обусловлены напряжениями или/и нескомпенсированными спинами вблизи дислокаций в антиферромагнитном слое.

1. Introduction

The promising use of exchange coupled ferromagnetic (FM)/antiferromagnetic (AFM) bilayers in multilayer systems with giant magnetoresistance effect such as magnetic sensors, read heads, and random access memory, has initiated intensive investigations of their properties [1–3]. The FM/AFM bilayer is an important component of spin-valves and tunnel magnetic junctions showing high magnetoresistance values. Though the unique properties of such bilayer structures were discovered by Meiklejohn and Bean [4] half a century ago, the fundamental problems such as the origin of the unidirectional anisotropy field H_{EX} [5–8] and enhanced coercivity H_C [8–11] of these artificial nanocomposite materials, are not yet well understood [2, 12–14]. In order to explain the discrepancy between the theoretical and experimental values of H_{EX} and H_C in exchange-biased films, most attention has been focused on crystal and magnetic structures of both AFM and FM layers [15, 16] as well as on roughness [2, 15, 17–20] and inhomogeneities [21, 22] of the interface. The influence of various crystal lattice defects on the exchange coupling between FM and AFM films and their magnetization reversal was demonstrated in [8, 11–13]. However, the role of such important defects as dislocations in a domain structure formation and the magnetization reversal behavior of exchange coupled magnetic bilayers was not studied enough.

On the other hand, it is well known that the magnetization curve characteristics of traditional bulk ferromagnetic single crystals are defined to a great extent by the change of the relativistic and exchange interactions under the influence of spatially inhomogeneous internal stresses. The most important sources of these stresses are dislocations. Those produce a slowly-decreasing long-range stress fields. To explain the effect of dislocations on the processes of magnetization rotation and domain wall (DW) motion in ferromagnets, a theory [23] was developed and the influence of individual dislocations on these processes was studied directly in experiment [24]. The dislocations have been shown to cause an inhomogeneous distribution of the magnetization vectors around them, influencing the kinetics of the spin reorientation phase transformations and acting as both new domain nucleation and domain wall pinning centers. However, until now, there are essentially no direct studies of the dislocation influence on the properties of magnetic nanostructured heterophase materials and especially of exchange coupled FM/AFM bilayers.

The understanding of the exchange bias phenomenon in FM/AFM heterostructures and the central issue of the AFM spin structure influence thereon can be attained through the study of the reversal processes in a FM layer exchange coupled to the AFM one. To determine conditions of the magnetic domain structure formation and possible switching modes associated with the formation of a specific spin configuration near dislocations in epitaxial exchange coupled FM/AFM bilayers containing dislocations, we have investigated in this work in detail the distribution and evolution of the net magnetic moments in such heterostructures.

2. Experimental

The NiFe (100 Å)/NiO (500 Å) epitaxial bilayers were grown by ion beam sputtering onto single crystal (001) MgO substrate [25]. The unidirectional anisotropy of bilayers was induced during deposition by means of permanent magnets producing a uniform bias field $H = 300$ Oe in the substrate plane along either its <110> or <100> crystallographic direction. The macroscopic features of the films were determined from the hysteresis loops measured with a vibrating sample magnetometer. The photoelasticity method [26] was used to reveal the crystal lattice defects in the films. To study the domain structure transformation and DW propagation under the magnetization reversal, we used the magneto-optical indicator film (MOIF) technique [8, 27] with digital image processing. In this technique, a transparent Bi-doped yttrium iron garnet indicator film with an Al mirror bottom surface is placed on the sample to image the stray magnetic fields around the film edges, domain walls, and other magnetic defects. In the absence of a magnetic field, the garnet magnetization is oriented in-plane, but it is deflected out of plane by perpendicular components of the stray field $H_\perp$ around the sample. Using a polarizing microscope, the magneto-optical (MO) images of the sample magnetic structures are obtained in the reflected light due to the double Faraday effect in the indicator film (using polarizer and analyser slightly uncrossed at a small angle β). The magnetic fields at the the sample edges and at DWs permit to estimate both the orientation and magnitude of the average magnetization, **M**, in the registered heterostructure region [28]. The black and white colours of the MO image correspond to opposite signs of $H_\perp$. All experiments were made at room temperature.

The magnetometric measurements and the MOIF imaging have been performed with the magnetic field **H** applied along the unidirectional anisotropy axis coincident with the direction of the magnetic field applied during the bilayer growth. The hysteresis loops for both samples are shifted to the negative field from **H** = 0. They exhibit the exchange shifts $H_{EX} = 35$ Oe and 20 Oe and enhanced coercive fields $H_C = 40$ Oe and 26 Oe for [110] and [010] samples, respectively. In all the MOIF experiments, the

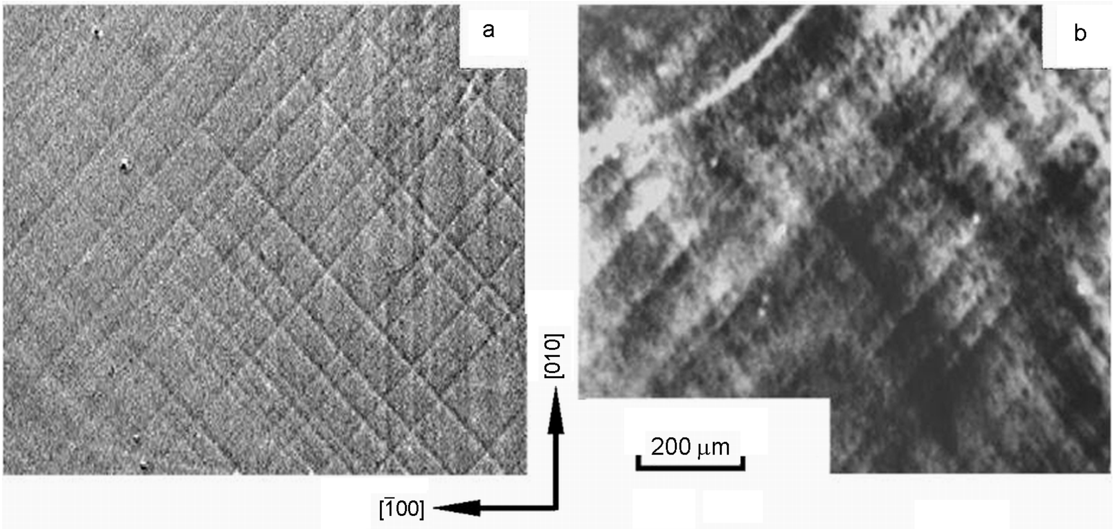

Fig. 1. (a) MOIF image of the domain structure in a NiFe/NiO bilayer; (b) microstress fields caused by the slip planes of edge dislocations revealed by an optical birefringence.

net magnetization direction was estimated from the maximal magneto-optical intensities measured along the profile lines at two perpendicular edges (as it was demonstrated in [28]) of a sample corner during preliminary measurements. The MO images presented below show small rectangular sample areas inside the samples. These areas comprise slip planes of both edge and screw dislocations.

3. Results and discussion

First, the samples were magnetized along the unidirectional anisotropy to a saturation state in the field $H = 240$ Oe. In this case, one a strong MO contrast was observed at the sample edges that is due to the stray field, and practically no contrast inside the bilayers (imaging area in the Figures). In some cases, when the field was decreased to zero, the MO white-black contrast has appeared along the lines of the <110> orientation (Fig. 1a). Using birefringence pictures of the same or similar area (Fig. 1b), we have found that these lines are caused by edge dislocations aligned in (110) and $(1\bar{1}0)$ slip planes. These dislocations induce effective internal microstresses. Both screw and edge dislocations were introduced into the MgO substrate during cleaving the substrate prior to the bilayer deposition. Figures 2 and 4 display the domain structure behavior in the [110] and [010] NiO/NiFe bilayers, respectively, during the magnetization reversal. White arrows mark the vector **M** along the unidirectional anisotropy axis obtained by the method mentioned above.

The NiFe hysteresis loop measured along the [110] direction parallel to magnetic field direction applied during the bilayer growth is shown in Fig. 2a. Figs. 2b–2f exhibit the sample remagnetization from the ground state. In the saturated state under field of +240 Oe, the MO contrast was practically invisible. After decreasing of the applied field (Fig. 2b), the black-white MO contrast has appeared near the vertical lines. The further field decreasing resulted in inhomogeneous magnetization rotation in the homogeneous (between edge dislocation slip planes) regions (Fig. 2c) and in consecutive formation of numerous microdomains (Fig. 2d), which grew (Fig. 2e) and coalesced (Fig. 2f). Those regions were saturated by field $H \approx -80$ Oe.

At this stage of the magnetization reversal, new stripe domains near dislocation slip planes perpendicular to the previous ones were formed (Fig. 2d). Magnetization of these domains was switched from section to section (Figs. 2e and 2f) and MO contrast of those regions (not shown here) practically disappeared, whereas the MO contrast near parallel $(\bar{1}10)$ slip planes, it did not disappear but only changed its sign. The complete reversal of the latter occurs under field $H \approx -70$ Oe. In this case, the polarity reversal of the [110] "dislocation" domains proceeds by nucleation and growth of small size domains (Fig. 2d–2f).

Then the sample was magnetized to the saturation state opposite to the unidirectional anisotropy by the negative field $H = -240$ Oe. Like in the previous stage, no MO contrast was observed inside the sam-

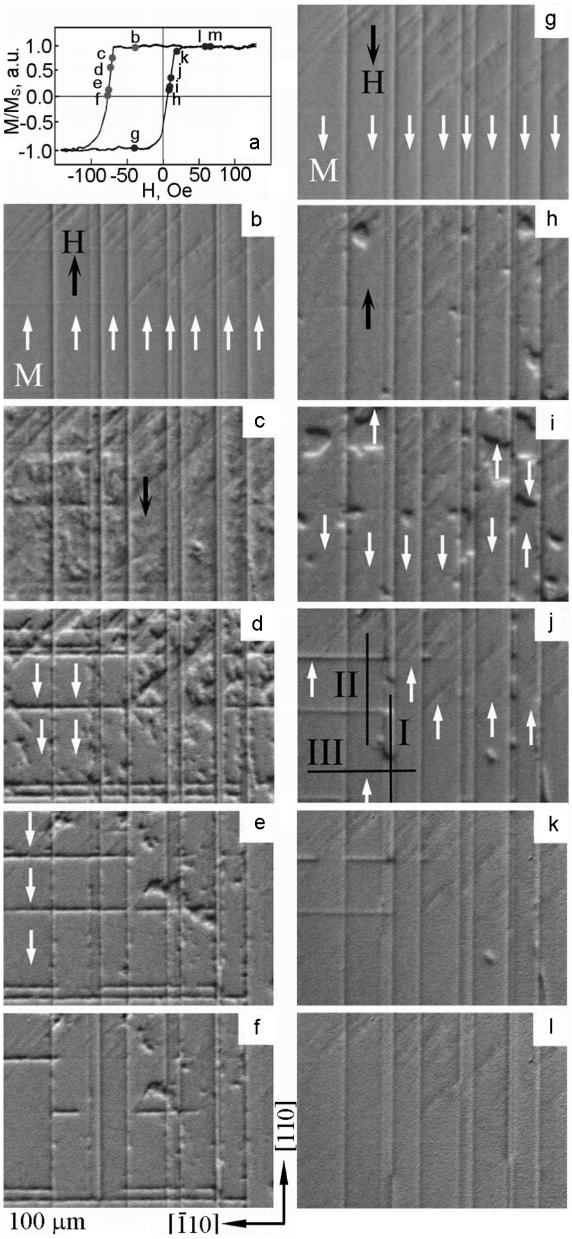

Fig. 2. Magnetic hysteresis loop (a) and MOIF images of domain structure taken during the unidirectional-axis magnetization reversal of a [110] NiFe/NiO bilayer. (b)–(l) correspond to the conditions indicated by the circles labeled by the same letters on the hysteresis loop in (a). White arrows indicate local magnetization directions in domains.

ple. When the field was increased, the white-black contrast has appeared along the (1$\bar{1}$0) dislocation slip planes (Fig. 2g). In case of the remagnetization to the ground state, the reversal of spins localized in the homogeneous regions (between the slip planes) has another scenario. As the field increases to $H = +13.8$ Oe (Fig. 2h), new domains with the opposite magnetization direction appeared practically near the lines with inhomogeneous magnetization distribution. These domains grew with increase of magnetic field (Fig. 2i) and practically saturated all the areas between the dislocation slip planes (Fig. 2j). It is important to note that the domain walls moved only between these lines and never across them. However, in the latter state, a great MO white-black contrast appeared near new lines, which were perpendicular to the initial ones and coincided with the (110) edge dislocation slip planes. The main feature of these lines is consecutive switching of the line segments (Fig. 2k) and finally of all ones (Fig. 2l) during the field increasing. Some small MO contrast is observed at the location of these lines after this process. This fact indicates that specific domains with magnetization not oriented along the unidirectional anisotropy axis are formed along those dislocation slip planes.

A quite other situation with magnetization distribution during magnetization reversal occurs near edge dislocation slip planes oriented along unidirectional anisotropy axis (vertical lines). As is seen in Fig. 2, the MO contrast near these planes is always visible during magnetization reversal. Analysis of the contrast shows that **M** is not oriented along the unidirectional anisotropy axis as well. Moreover, Figs. 2j–2l show that remagnetization of these unusual linear domains proceeds due to switching **M** to the opposite direction either in some sections (for example, third left line in Figs. 2j and 2k) or in a whole line (for example, first left line in Figs. 2k and 2l). The complete reversal of these domains occurs under field $H \approx 70$ Oe, i.e. under approximately same absolute values of the applied field as those upon the remagnetization from the ground state.

Thus, the results show that (i) orientation and behavior of spins localized near the dislocation slip planes is different from those ones of spins localized inside the homogeneous regions; (ii) unlike the homogeneous regions, the inhomogeneous ones with local [110] dislocation domains have an enlarged but unshifted hysteresis loops; (iii) as the magnetostriction value of free NiFe layers is negligible [8], the local spin distribution and coercivity extension of the NiFe layer near dislocation slip planes is caused by exchange coupling to deformed structure of the antiferromagnetic NiO layer along these slip planes.

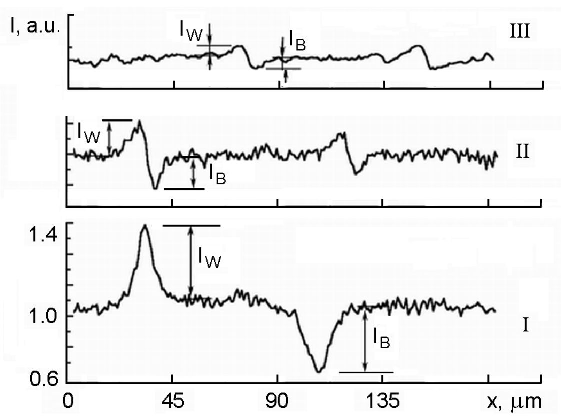

Fig. 3. Intensity of the MO signals along the photometry lines delineated in the Fig. 2j across the white and black domain walls (I) and quasi-one-dimensional domains localized near perpendicular (II) and parallel (III) dislocation slip planes.

The **M** orientation can be estimated by analysing the variations of MO intensity, I, near any magnetic defect (sample edge, domain wall, etc). Photometric measurements of the MO signal intensities along the profile lines indicated in Fig. 2j are shown in Fig. 3. The plots show the intensity distribution across both (I) a domain with white and black walls inside the homogeneous region and magnetized linear domains (II) perpendicular and (III) parallel to [110] direction. Deviations of the MO signal from the mean intensity level (the gray background) to white and black colors are $I_W = I_0[\sin^2(\beta + \varphi) - \sin^2\beta]$ and $I_B = I_0[\sin^2\beta - \sin^2(\beta - \varphi)]$, where I_0 and φ are the intensity of the incident linearly polarized light and the Faraday rotation angle, respectively. For small β and φ the average intensity $I_A = (I_W + I_B)/2 \sim \varphi \sim H_\perp \sim M_n = M\cos(\alpha)$, where M_n is a local magnetization component perpendicular to the magnetic defect, and α is the angle between the magnetization vector **M** and the vector **n** normal to that defect. Because the field $H_\perp$ at any boundary is formed by local magnetic moments localized in both adjacent domains, the intensity $I_A = k[M\cos(\alpha_1) + M\cos(\alpha_2)]$, where α_1 and α_2 are angles between **M** and **n** at opposite sides of this boundary in homogeneous and inhomogeneous regions, respectively, and k is a constant depending on the indicator film properties, distance between the indicator and the sample, and the size of adjacent domains. So, because α_1 is equal to 0° and 90° for $(1\bar{1}0)$ and (110) slip planes, respectively, the I_A value characterizes the orientation of a net magnetization in inhomogeneous magnetic regions. Analysis of the MO signal variations across the dislocation slip planes shows that the estimated angles α_2 in these regions have values between 30° and 60°.

A more exact orientation of **M** on the dislocation slip planes was obtained in bilayers with the <100> unidirectional anisotropy. The NiFe/NiO hysteresis loop measured along the [010] direction parallel to the magnetic field direction applied during the bilayer growth is shown in Fig. 4a. First, the sample was magnetized along the unidirectional anisotropy to a saturation state by field $H = +240$ Oe. Unlike the reversal of the [110] sample, when the field was decreased to zero, no white-black contrast has appeared along the lines of <110> orientation. The MO signal along these lines appeared only when new domains are formed (Fig. 4b) and extended (Fig. 4c–4d). It is important to note that after saturation of the bilayer opposite to the unidirectional anisotropy, the MO black-white contrast along dislocation slip planes was maintained (Fig. 4e).

When the field was increased to $H \cong +5$ Oe, new domains with the opposite magnetization direction have essentially appeared (Fig. 4f) near the elongated regions with inhomogeneous magnetization distribution, and extended (Fig.4g–4i) in homogeneous regions. However, the main feature of these lines is the MO contrast disappearance after the domain walls are moved therealong (Fig. 4i). This fact indicates that a local magnetization along those dislocation slip planes is oriented away from the unidirectional anisotropy axis. Moreover, the magnetization vector in the center of these domains is perpendicular to the unidirectional anisotropy axis along the [010] direction, because the angle between this axis and edge dislocation slip planes is 45° and, consequently, only in this case M_n in both the homogeneous regions and the dislocation domains should be the same, i.e. no magnetic charges producing the stray fields $H_\perp$ are formed.

Fig. 4j shows the NiFe surface steps revealed in reflected light on the NiO/NiFe bilayer epitaxially grown onto MgO (001). Those are formed by the intersection of screw dislocation slip planes with the upper NiFe surface. It is seen (comparing with MOIF imaging in Figs. 2 and 4) that these steps practically do not influence the FM/AFM bilayers magnetization reversal.

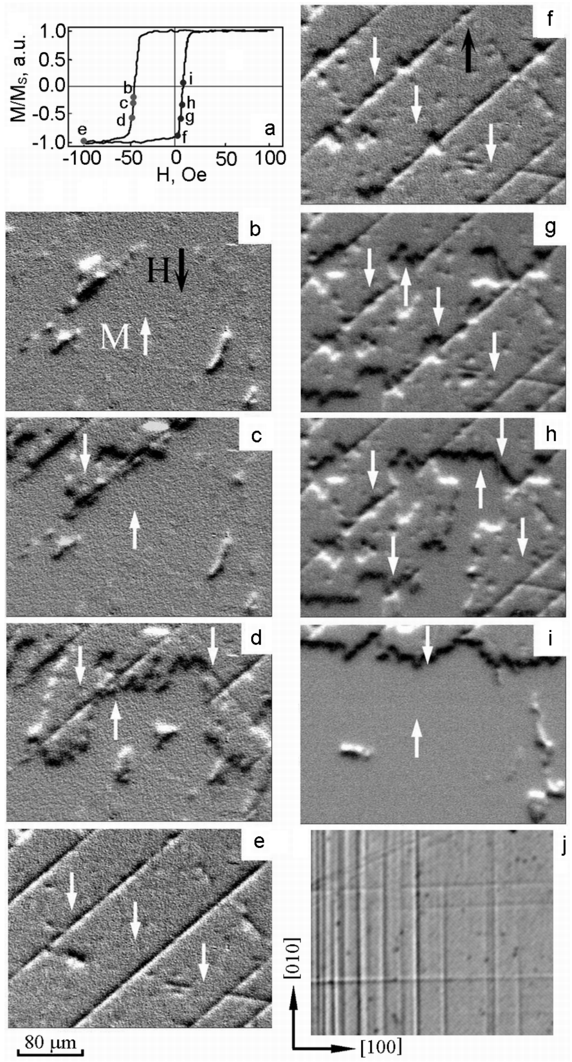

Fig. 4. Magnetic hysteresis loop (a) and MOIF images of domain structure taken during the unidirectional-axis magnetization reversal of a [010] NiFe/NiO bilayer. (b)–(i) correspond to the conditions indicated by the circles labeled by the same letters on the hysteresis loop in (a). White arrows indicate local magnetization directions in domains. (j) is a picture of surface steps associated with screw dislocation slip planes revealed in reflected light at the NiFe surface.

Thus, it is clear that one of the significant features of the magnetization reversal process in the both NiO/NiFe bilayer types is a complex domain structure resulting from the strong influence of edge dislocations on domain nucleation and domain boundary motion. It should be emphasized that unlike the screw dislocations, the edge ones induce inhomogeneous internal stresses. It was supposed that the induced inhomogeneous magnetic anisotropy due to magneto-elastic interactions plays an important role in the bilayer remagnetization. However, the free NiFe layers (grown on MgO (001) without a NiO buffer) with a similar dislocation structure have shown no strong dislocation influence on the domain structure. The magnetization reversal process proceeds by the growth of domains over the whole sample due to an almost zero magnetostriction in NiFe [29]. Such a difference between the domain structure behavior in the free ferromagnetic film and that in the exchange-biased one indicates that dislocations in the NiFe/NiO bilayer influence primarily the spin configurations in the antiferromagnetic layer. As it was shown in [30], some local ferromagnetic structures near an edge dislocation in antiferromagnet can be formed, and this can affect the behavior of spins in the ferromagnetic layer due to exchange coupling at the interface.

4. Conclusions

The magneto-optical indicator film technique has been used to investigate in detail the dislocation effect on the magnetic domain structure formation and elementary events of magnetization reversal processes in epitaxial exchange coupled NiO/NiFe bilayers. We have revealed that the dislocations induce an inhomogeneous distribution of the magnetization vectors in the FM layer along their slip planes and acts as new domain nucleation and/or domain wall motion pinning centers. It was found that the magnetization vector orientations in domains localized near edge dislocations do not depend on the axes orientation of the induced unidirectional anisotropy ([100] or [110]) and spatially inhomogeneous internal stresses. It was established that, despite almost zero magnetostriction of NiFe, the edge dislocations influence significantly the domain structures in these exchange biased ferromagnetic films. One can conclude that the disturbed spin structure in AFM layer near edge dislocation slip planes defines the distribution and behavior of spins in the adjacent part of the ferromagnetic layer due to the exchange coupling at the interface. These results allow to understand better the exchange biasing of a ferromagnet by its interaction with an antiferromagnet and the role of such crystal defects as dislocations in the formation of spin structures in FM and AFM layers and their interfaces.

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Формування та еволюція доменної структури в епітаксіальних обмінно-зміщених плівках NiFe з дислокаційними площинами ковзання

В.С.Горнаков, В.І.Нікітенко, Ч.Г.Лі

З застосуванням магнітооптичної індикаторної плівки досліджено вплив дислокацій на формуванння доменної структури та елементарних актів процесу перемагнічування у тонких епітаксіальних обмінно-зміщених NiFe (100 Å)/NiO (500 Å) двошарових плівках з орієнтацією однонаправленої анізотропії вздовж [110] або [100]. Встановлено, що крайові дислокації обумовлюють неоднорідне розподілення векторів намагніченості вздовж їхніх площин ковзання. Дислокаційні площини ковзання діють як центри зародження нових доменів та центри пінінгу для руху доменних стінок. Дислокації індукують сильну локальну магнітну анізотропію вздовж одного з напрямів <010>, яка не залежить від орієнтації однонаправленої анізотропії, наведеної у процесі осадження плівок у всій іншій (бездислокаційній) частині кожного зразка. Беручи до уваги те, що феромагнітні плівки NiFe мають майже нульову магнітострикцію, ефекти, що спостерігаються, можуть бути обумовлені напругами або/та нескомпенсованими спінами поблизу дислокацій в антиферомагнітному шарі.