Growth and shape directionality of domains in exchange-coupled ferromagnet/antiferromagnet bilayers

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Abstract. Real time domain wall (DW) propagation processes were observed using the magneto-optic indicator film technique (MOIF) in both single crystal and polycrystalline epitaxial exchange-coupled ferromagnet/antiferromagnet (FM/AFM) bilayers. In both cases a new phenomenon of preferable directions of a DW’s expansion under a canted magnetic field was found. Upon application of a magnetic field oriented slightly (4°–10°) off the unidirectional anisotropy axis clockwise or counterclockwise, unlike along this axis, during remagnetization from the ground state the domain growth occurred in that same direction at an angle of (14°–45°). During remagnetization to the ground state upon field reduction, but no inversion, the preferred domain growth direction was at the angle with reversed sign, however in case the field reduction to zero or inversion, the preferred DW growth direction disappeared or was at the original angle, respectively. It was revealed the angle of the domain wall orientation in canted field does not depend on the value of field angle.

1. Introduction
Generated interest in the magnetic, magnetotransport, structural, and thermal stability properties of exchange coupled FM/AFM bilayers is determined by important practical applications [1-3]. The resultant striking exchange-bias phenomena such as FM hysteresis loop shifting away from the origin by the magnitude of the exchange bias field $H_E$ and enhanced coercivity $H_C$ [2-5] are attracting a considerable scientific interest. It has been established that the real crystal [6] and domain [7] structures are crucial for the understanding of the exchange coupling in FM/AFM systems. Recent investigations [7-9] have shown that in general one has to deal with different modes of reversal for the forward and backward branches of the hysteresis loop. These modes define $H_E$ and $H_C$. The spin structure and dynamics at the interface are probably very important in determining the overall magnetic switching behaviour during reversal. However a role of a domain structure transformation and domain wall propagation in the hysteresis behavior of the FM does not begin to be clear enough.

To determine the conditions and the origin of possible switching modes associated with the domain wall formation and correlation between domain structure transformation and hysteretic properties, we have studied magnetization reversal processes in both single crystal and polycrystalline bilayers under applied fields near the left and right coercive fields, which characterize the reversal of these bilayers from and to the ground states, respectively. In this work, we report on the observation of an acute asymmetry in the orientation of the FM domain walls during reversal.
2. Experimental

In order to study domain structure transformation and DW propagation during the magnetization reversal processes in epitaxial single-crystal and polycrystalline exchange coupled bilayers we used the MOIF technique [10] 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 top of the sample to image the stray magnetic fields around the film edges and domain walls. 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 polarized light microscope, 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. The magnetic poles on the edges and on DWs permit an estimation of both the orientation and magnitude of the average magnetization, \( M \), of the surrounding region. The black and white colors of the MO image correspond to opposite signs of \( H_\perp \).

In experiments both single-crystal bilayers of Ni\(_{81}\)Fe\(_{19}\) (10nm)/NiO(50nm) grown by ion beam sputtering onto a (001) MgO substrates [8, 11] and polycrystalline ones of Ni\(_{81}\)Fe\(_{19}\) (16nm)/Fe\(_{50}\)Mn\(_{50}\) (30nm) and Co(10nm)/Ir\(_{20}\)Mn\(_{80}\) (10nm) deposited by dc magnetron sputtering onto oxidized Si substrates were used. Unidirectional anisotropy was created during deposition in the FM layers by means of a 300 Oe uniform permanent magnet field in the plane of the substrate. The anisotropy fields of NiFe/NiO, NiFe/FeMn, and Co/IrMn bilayers, which were determined from a shift of the hysteresis loops, were equal about 35, 11.7, and 87 Oe, respectively. The kinetics of the magnetization reversal for the Co/Ir–Mn bilayer films have been measured after annealing procedure at temperature 400°C for 30 min, which has made its shifted hysteresis loop wider with negative and positive switching fields [10]. Hysteresis loops of bilayers were measured with a vibrating sample magnetometer. Domain structures observation and hysteresis loop measuring were made at room temperature.

3. Results and discussion

The magnetometric measurements and the MOIF imaging were performed with the magnetic field, \( H \), applied either along the unidirectional anisotropy axis, which coincides with the direction of the magnetic field applied during the bilayer growth, or away from this one by small angle \( \phi \) clockwise (CW) or counterclockwise (CCW). The hysteresis loop and MOIF images of the NiFe/FeMn bilayer during magnetization are shown in figure 1. The loop measured along the direction, which coincides with the direction of a magnetic field applied during the bilayer growth, exhibits an exchange shift and negative values of both forward and backward branches. Here and in the following experiments the letters on the MOIF pictures correspond to the conditions indicated by the circles labeled by the same

![Figure 1](image-url)

**Figure 1.** Hysteresis loop and MOIF images of the NiFe/FeMn bilayer during initial field application (a)–(c) and reduction (d),(e) along (top row) and at an angle ~4° CCW (middle) and CW (bottom) from the unidirectional anisotropy axis. The field direction is indicated by the white arrow while the black arrows indicate the magnetization directions in the various domains.
letters on the corresponding hysteresis loops. It should also be stated that hysteresis loops and MO portraits of the samples in the saturated state did not practically depend on the small angle $\varphi$ of applied field deviation from a unidirectional anisotropy axis. So everywhere in the figures we have shown only one loop and one MO portrait of saturation magnetization of each sample.

Upon application of $H$ along the unidirectional anisotropy (figure 1, top row), at a magnetic field close to the coercive field, new domains of reversed magnetization nucleated in the sample and their growth encompassed the whole sample within a small field range of $H$. The white vertical left-hand band perpendicular to the unidirectional axis at the figure 1 (a) is the edge of the saturated bilayer, revealed due to magnetic stray fields. DWs are visualized as white and black lines depending on $M$ orientation in domains. In both cases of the remagnetization process from the ground state [figure 1 (a) - (c)] and to the ground state [figure 1 (d), (e)] DWs did not essentially have preferable orientation.

Figure 1, middle and bottom rows, illustrates domain structure during magnetization reversal after application of a magnetic field oriented at the angle $4^\circ$ to anisotropy axis CCW and CW, respectively. Dark circles at the images (c) and (d) indicate locations of DW cusps in the captured frames during DW’s moving. It is clearly seen that in both cases these cusps, which are the most mobile part of the walls, move in a direct trajectory at an angle $\alpha$ from unidirectional axis. Apparently, it determines the preferable of DW’s orientation. One can see the sign of $\alpha$ is same as the sign of $\varphi$ during switching of $M$ from the ground state and it is changed when $M$ is switched to the ground state. It is important to note that $\varphi$ and the $H$ polarity have not changed in these two cases. However, the change of the sign of $\varphi$ leads to the change of the sign of $\alpha$ during switching both from and to the ground state. The values of the angle $\alpha$ estimated from the figure 1 were $22^\circ\pm2^\circ$ in the case of the CCW remagnetization from the ground state and of the CW remagnetization to the ground state and $14^\circ\pm2^\circ$ in the case of the CW remagnetization from the ground state and of the CCW remagnetization to the ground state. These values of $\alpha$ did not practically depend on the value of tilt angle $\varphi$ of the applied field. A comparison between the unidirectional-axis (top row in figure 1) and canted (middle and bottom) magnetization reversal of NiFe/FeMn bilayer lets us conclude that a perpendicular to unidirectional anisotropy axis component of the field plays a significant role. In order to check up this suggestion we have study samples with zero (NiFe/NiO) and positive (Co/IrMn) values of the switching to the ground state field. Figures 2 and 3 demonstrate the hysteresis loops and MOIF images of the NiFe/NiO and Co/IrMn bilayer, respectively, during magnetization reversal. As in previous case both the remagnetization along unidirectional axis from the ground state [figures 2 (b) and 3 (b), top row] and to the ground state [figures 2 (c) and 3 (c), top row] the domain walls did not essentially have preferable orientation.

**Figure 2.** Hysteresis loop and MOIF images of the NiFe/NiO bilayer during initial field application (a), (b) and reduction (c) along (top row) and at an angle $\sim8^\circ$ CCW (middle) and CW (bottom) from the unidirectional anisotropy axis.

**Figure 3.** Hysteresis loop and MOIF images of the Co/IrMn bilayer during initial field application (a), (b) and reduction (c) along (top row) and at an angle $\sim10^\circ$ CCW (middle) and CW (bottom) from the unidirectional anisotropy axis.
These two bilayers demonstrate the same feature during the remagnetization process from the ground state [figures 2 (b) and 3 (b), middle and bottom rows]; the sign of \( \alpha \approx 45^\circ \) is same as the sign of \( \varphi \) during switching of \( M \). However, unlike the previous experiment, these ones reveal new behavior of NiFe/NiO and Co/IrMn samples during the remagnetization process to the ground state. Figures 2 (c) show the MO portraits of a domain structure of the single-crystal NiFe/NiO bilayer during switching \( M \) to the ground state upon application field at an angle \( \sim 8^\circ \) CCW (middle row) and CW (bottom row) from the unidirectional anisotropy axis. It is clearly seen that in this case there is no preferable DW’s orientation. Figures 3 (c) show the small size domain structures of the Co/IrMn bilayer during switching \( M \) to the ground state upon application field at an angle \( \sim 10^\circ \) CCW (middle row) and CW (bottom row) as well. Unlike the previous cases in this one there is clear distinguished DW’s orientation at an angle of \( \sim 45^\circ \), with a sing, which is same as the sign of the field angle. Notice that the revealed phenomenon was not observed in the similar single NiFe and Co thin films [12].

Analysis of application \( H \) oriented slightly off the unidirectional axis shows that the component of the field perpendicular to this axis plays a crucial role. Our experiments show the magnetization reversal of bilayers is determined by processes of new domains nucleation and 180° DWs motion. These DWs are assumed to consist of FM and AFM parts due to exchanged coupling at the interface. In super thin films, the FM part of such hybrid DW has the Neel structure, which is characterized by left or right sense of in-plane spin rotation from one domain to the other. A choice between these two senses during magnetization reversal is determined by sign of an external field component, which is normal to the anisotropy axis. Due to exchange coupling at the interface, AFM spins of DW will be involved in the reversal [5, 6] creating an antiferromagnetic twist. Taking into account a magnetocrystalline or (and) surface anisotropy, it is quite within reason to suggest that AFM spins try to find energetically more favorable extension direction rotating together with FM spins. It determines the preferable direction of the motion of leading part of DWs and, consequently, their orientation. Different mechanisms of twisting and untwisting of AFM spins during magnetization reversal from and to ground state [5, 7, 8] are probably causing the observed changes of sign of DWs orientation.

In summary, the MOIF pictures reveal that application of a magnetic field oriented at the small angle (4°–10°) to the unidirectional anisotropy axis, both counterclockwise and clockwise, leads to nucleation domains of reversed magnetization with domain walls, which are quasi-periodic and have preferable orientation of some angle (~14°–45° for various bilayers). The orientation of DWs doesn’t depend on the value and deviation angle of the applied field. The revealed effect is an intrinsic property of the exchange coupled FM/AFM heterostructures.

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