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Variation of domain formation in a 15 nm NiFe layer exchange coupled with NiO layers of different thicknesses

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The correlation between ferromagnetic domain formation and exchange bias in a series of NiFe/NiO samples with varying NiO thicknesses has been investigated using the magneto-optic Kerr effect and magnetic force microscopy. Below a critical thickness (15 nm) of NiO, the exchange bias H_E is zero and ripple domains exist in the NiFe layer. Above this critical thickness, cross-tie type domain walls appear concurrently with the appearance of exchange bias. Both the number of cross-tie domain walls and the exchange bias increase with an increase in NiO thickness, reaching a maximum at 35 nm NiO, after which both show a gradual decrease. This variation of domain wall formation in the NiFe layer with the NiO thickness possibly reflects the variation of the domain structure in the NiO layer through interfacial exchange coupling. [DOI: 10.1063/1.1564639]

The hysteresis loop of a ferromagnetic (FM)/antiferromagnetic (AF) bilayer cooled in an applied field to below the AF Néel temperature (or, alternatively, grown in an applied field) is shifted from its origin by an amount known as the exchange field H_E.[1,2] The magnitude of the exchange coupling (two orders of magnitude lower than expected for uncompensated interfaces) and the fact that exchange coupling exists for both compensated and uncompensated AF interfaces suggest that AF domain formation plays an important role. Many experimental and theoretical studies have shown that the existence of domains in the AF layer is necessary for the appearance of exchange bias in FM/AF bilayers.[3–17] Theoretical models have suggested both parallel and perpendicular domain walls. Mauri *et al.*[3] suggested that a domain wall forms in the AF layer parallel to the interface while the magnetization of the FM layer rotates. In models by Malozemoff[4] and by Nowak *et al.*,[5] the AF layer broke up into lateral domains with domain walls perpendicular to the interface when the sample was field cooled to below the Néel temperature. The exchange bias H_E is attributed to the energy stored in AF domain walls. Hence, H_E is proportional to the AF domain wall energy $4\sqrt{A_{AF}K_{AF}}$, where A_{AF} and K_{AF} are the exchange stiffness and anisotropy constant of the AF layer, respectively. The presence of exchange coupling at the FM/AF interface ensures that the AF domains have an effect on domain wall formation in the FM layer.[16] Direct observation of AF domains is difficult, but the observation of FM domains coupled to the AF provides indirect evidence of their existence.[6,16] Nikitenko *et al.*[18] have investigated the asymmetric magnetization reversal process in the epitaxial NiO/NiFe system using the magneto-optic indicator film technique to observe domain formation.

In this letter, we have used magnetic force microscopy (MFM) to investigate the variation in domain wall formation in a 15 nm $Ni_{81}Fe_{19}$ layer exchange biased with NiO layers of a series of thicknesses. Exchange-biased systems play an important role in magnetic read heads and possibly in magnetic random access memory (MRAM) applications and the effects of domain formation in these materials play an important role in determining the ultimate size.

The NiO/NiFe (15 nm) bilayers with different NiO thicknesses were prepared on Si(100) substrates by rf and dc magnetron sputtering from separate NiO and NiFe targets at deposition rates of 0.38 and 0.26 Å/s for NiO and NiFe, respectively. Our sputtering system can accommodate up to 12 substrates, so all samples were grown in a single run under the same conditions. The Ar pressure was 3 mTorr and the base pressure was 4×10^{-7} Torr. No external fields were applied; however, there was an in-plane stray field of ~8 Oe from the gun. The x-ray results show the polycrystalline structure of NiO with a mixture of (111) and (200) orientations and the highly (111) textured NiFe. Hysteresis loops were obtained by the magneto-optic Kerr effect (MOKE) with the magnetic field applied in plane and parallel to the incident plane of light. Domain patterns were obtained at zero field by MFM imaging.

Figure 1(a) shows typical MOKE loops along the unidirectional axis for the as-grown NiFe (15 nm)/NiO bilayers with several different NiO thicknesses. For 10 nm NiO, the loop is square with no shifting of the loop but has enhanced coercivity (in contrast to the coercive field of 5 Oe for the bare 15 nm NiFe film). Increasing the NiO thickness changes the shape of the loop and at a critical thickness of 15 nm shifting of the loop is seen. Because H_E is affected by the field in which it was prepared, the critical thickness of the AF layer for the appearance of H_E depends on that field. Our observed NiO critical thickness of 15 nm is related to the stray field (~8 Oe) from the sputtering gun. A critical thickness for the appearance of exchange bias is a usual feature of the dependence of exchange bias on the AF thickness. The variation of H_E with the NiO thickness is shown in Fig. 1(b). At more than 15 nm, H_E increases quickly to a maximum at 35 nm and then decreases monotonically as the NiO thickness increases further.

MFM images of the as-grown states at zero field for the

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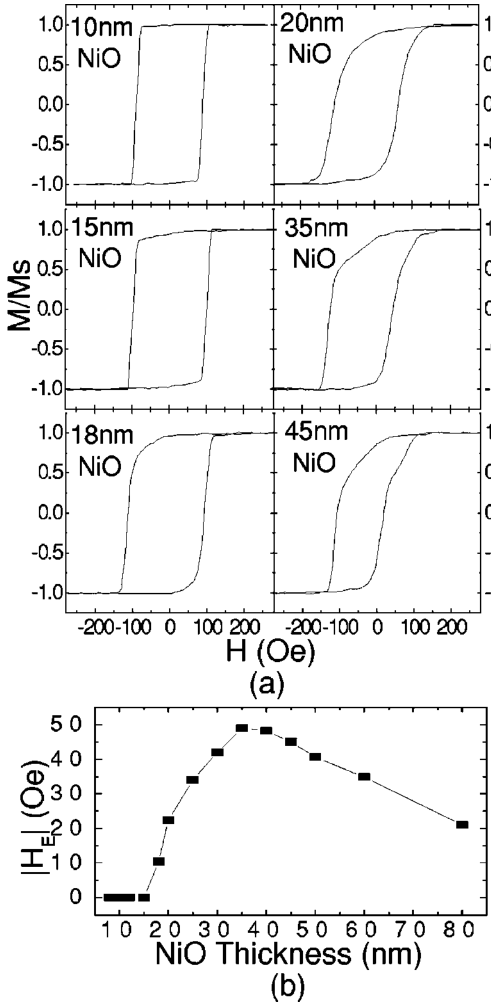

FIG. 1. (a) Longitudinal MOKE loops of the first cycle for fields along the unidirectional axis for as-grown NiFe/NiO bilayers with differing NiO thicknesses; (b) exchange bias field as a function of the NiO thickness.

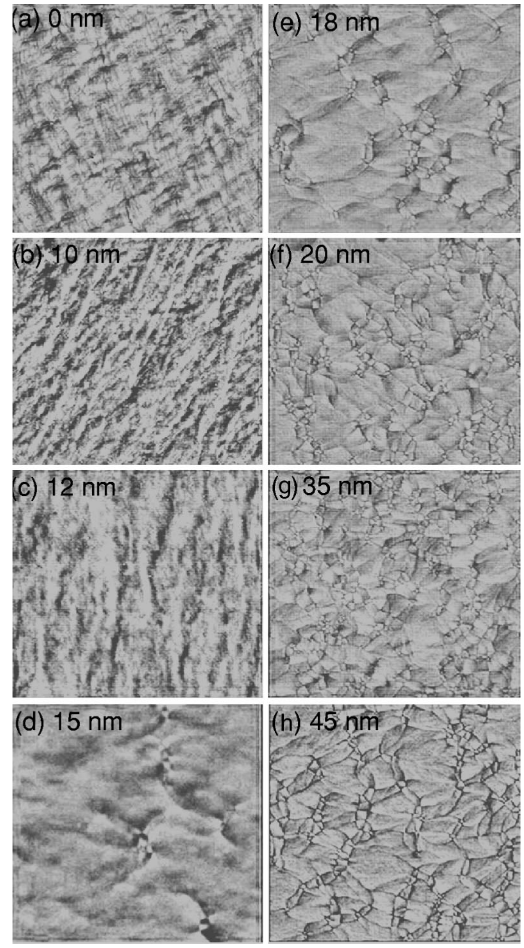

FIG. 2. MFM images of as-grown NiFe (15 nm)/NiO bilayers as a function of the NiO thickness. All measurements were taken at zero field. The scanning area is $20\times 20\ \mu m^2$. The numbers in the image represent thicknesses of NiO layer.

pure 15 nm NiFe film and the NiFe/NiO bilayers with several typical NiO thicknesses are shown in Fig. 2. The pure NiFe film shows ripple domains. For the NiFe/NiO bilayers with NiO thickness less than 15 nm, the domain patterns, although different from those of the pure film, are still ripple shaped. At thickness of 15 nm, the ripple domain pattern disappears and cross-tie domain walls appear. With an increase in NiO thickness, Figs. 2(d)–2(g) clearly indicate that the number of cross-tie domain walls increases and reaches a maximum at NiO thickness of 35 nm, at which the exchange bias is at a maximum. With a further increase of the NiO thickness, the number of cross-tie domain walls decreases as shown in Fig. 2(h). The direct correspondence between the density of cross-tie domain walls in the NiFe layer and the exchange bias field possibly provides indirect evidence that domains exist in the NiO layer and affect domain wall formation in the NiFe layer through interfacial exchanging coupling (discussed in the following).

The variation of H_E with the AF thickness is well known and can be explained by competition between the interfacial exchange energy and the anisotropy energy.[7,17] According to the domain state (DS) model of Nowak *et al.*,[5] cooling in the presence of an interface field that stems from magnetized FM leads to a metastable domain state in the AF layer which carries surplus magnetization at the FM/AF interface. The domain walls are perpendicular to the interface and extend throughout the thickness of the AF layer. The exchange bias is then determined by the competition between the interfacial coupling energy and the magnetic anisotropy energy of the AF layer given by $K_{AF}t_{AF}$. When the NiO thickness is less than the critical thickness, the anisotropy energy is small and the AF magnetization at the interface can be dragged and rotate with the FM magnetization, leading to enhanced coercivity but no shifting of the loop. Above the critical thickness, the anisotropy energy overcomes the interfacial exchange energy and stabilizes the net AF magnetization at the interface, leading to the appearance of exchange bias. The thickness dependence of H_E arises from the fact that, at small AF thickness, disorder at the interface dominates, thereby making it energetically favorable for domain wall formation in the NiO layer. As the NiO thickness increases to more than 15 nm, the increase in the number of domain walls in the NiO layer leads to an increase in exchange bias H_E. As the NiO thickness becomes too large, however, the cost in energy associated with forming a domain wall through the AF layer increases and it becomes more energy efficient to form larger fewer domains. The reduction in the number of domain walls in the NiO layer by the formation of larger domains results in a decrease of exchange bias with an increase in NiO thickness to more than 35 nm. Due to exchange coupling across the interface, variation of the domain

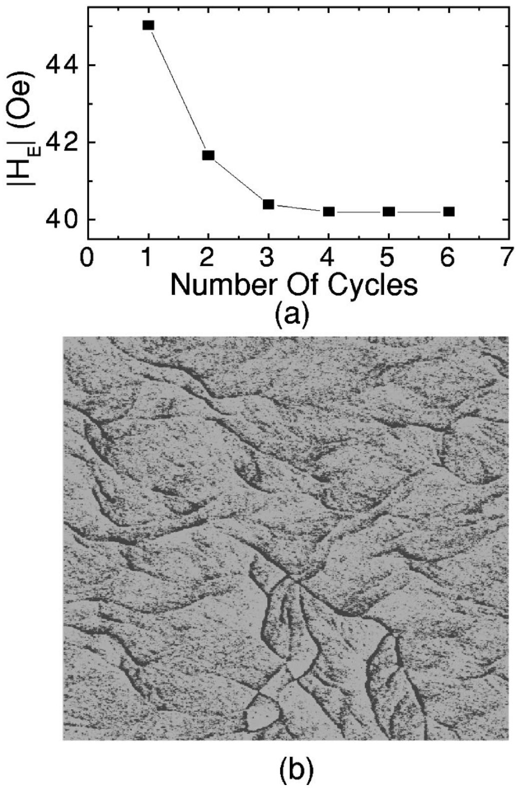

FIG. 3. (a) Training effect in the NiFe (15 nm)/NiO (45 nm) bilayer. H_E drops by only 5 Oe; (b) MFM image of the NiFe (15 nm)/NiO (45 nm) bilayer in the remanent state (zero field) after six hysteresis loop cycles. The scanning area is $20\times 20\ \mu\mathrm{m}^2$.

configuration in the NiO layer possibly affects domain wall formation in the NiFe layer, and induces dependence of the domain wall density in the NiFe layer on the NiO thickness. This is precisely the behavior we see: the domain wall density in the NiFe layer increases until a NiO thickness of 35 nm is reached, after which it decreases. Our data indicate that one can obtain useful information about the thickness dependence of domain wall formation in the AF layer by observing the variation of domain patterns in the FM layer.

In order to test the correlation between domain wall number and exchange bias field, we cycled the NiFe (15 nm)/NiO (45 nm) bilayer. Figure 3(a) shows the variation in exchange bias according to the number of hysteresis loop cycles. The training effect is small, with the exchange bias dropping ~5 Oe after six cycles of hysteresis. Figure 3(b) shows the domain pattern in the remanent state (zero field) after six cycles. In contrast to the domain pattern in the as-grown state shown in Fig. 2(h), there are few cross-tie domain walls after cycling. The domain walls in the NiFe layer become longer, and their number decreases by the formation of larger domains. In the DS model, the exchange bias is related to the net AF magnetization at the interface, which is metastable. During field cycling, rearrangement of the AF domain structure occurs, which leads to a drop in NiO domain density, which in turn leads to a drop in exchange bias field. Due to exchange coupling across the interface, rearrangement of the domain structure in the NiO layer possibly leads to rearrangement of the domain configuration in the NiFe layer, that is, it decreases the number of domain walls in the NiFe layer by forming larger domains.

In summary, we observed a strong correlation between the density of domain walls in a FM layer exchange coupled with an AF layer and the exchange bias field. At a critical NiO thickness of 15 nm, cross-tie domain walls appear in the NiFe layer, along with a finite value of H_E. With an increase in NiO thickness, both the number of cross-tie domain walls and H_E increase and reach a maximum at a NiO thickness of 35 nm. Upon a further increase of the NiO thickness, both H_E and the number of cross-tie domain walls in the NiFe layer decrease. This behavior of domain wall formation in the FM layer possibly reflects the variation in domain configuration in the NiO layer according to the NiO thickness through interfacial exchange coupling.

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