Magnetic force microscope study of antiferromagnet–ferromagnet exchange coupled films

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Magnetic microstructure in micron and submicron size elements made of bilayer antiferromagnet–ferromagnet (AFM/FM) (AFM: NiMn, PtMn, and IrMn; FM: NiFe and CoFe) exchange coupled polycrystalline films have been studied using a magnetic force microscope. AFM/FM elements with various thickness of FM layer (50–500 A) have been examined and compared with nonexchange biased FM elements of the same size, shape, and thickness. Micromagnetic structures observed in AFM/FM elements with thick (>200 A) FM layer indicated that, in addition to unidirectional anisotropy, the AFM layer induces uniaxial anisotropy in a FM layer. Bilayers with a NiMn or PtMn AFM layer exhibited higher induced uniaxial anisotropy than ones with IrMn. In the elements with a thin (<100 A) FM layer and NiMn or PtMn as an AFM layer, a local switching of the magnetization direction under an external applied field has been observed. The size of the "switched" areas depends on the material and thickness of the FM and AFM layers. No local switching, just slight rippling of magnetization in the FM, was observed in the samples with an IrMn AFM layer. The results can be explained using either the model of thermally activated switching of AFM grains or the model of induced uniaxial anisotropy at the AFM/FM interface suggesting local variations of induced uniaxial anisotropy. In both models, the in-plane exchange in the FM layer has to be taken into account. [DOI: 10.1063/1.1452225]

The phenomenon of exchange anisotropy, related to the exchange coupling at the interface between an antiferromagnet (AFM) and a ferromagnet (FM) was discovered by Meiklejohn and Bean over 40 years ago.[1] The technological applications stimulated extensive theoretical and experimental studies of this effect in thin films. Few theoretical models have been suggested for the explanation of the exchange anisotropy.[2–5] During the last years, a few studies of micromagnetic behavior of AFM/FM systems have been carried out which show, for instance, a difference in micromagnetic structure formed during magnetization of AFM/FM in the directions parallel and antiparallel to the exchange field.[6] Micromagnetic structure depends on the materials and thickness of AFM and FM layers. Especially complex structures can be observed in polycrystalline AFM/FM films.

In the present article, we report the results of a systematic study of magnetic microstructure with high spatial resolution (~50 nm) in micron size elements made of bilayer AFM/FM (AFM: NiMn, PtMn, and IrMn; FM: NiFe and CoFe) exchange coupled polycrystalline films with various thickness of the layers.

Samples of AFM/FM bilayer films were deposited on oxidized Si(001) substrates using dc magnetron sputtering. In most of the studied samples, the FM layer was deposited on top of the AFM layer. NiMn, PtMn, and IrMn were used as the AFM layer materials, while NiFe and CoFe were used as the FM layers. All samples in this study were annealed in a magnetic field. Anneal conditions (temperature, time, and magnetic field) were different for the samples with different AFM layer material and thickness. The conditions were chosen to maximize the exchange field for a particular sample structure.

Micromagnetic measurements were done using magnetic force microscopy (MFM) on samples patterned into small elements by means of photolithography. Patterning was done after the samples had been annealed in the field. The image of magnetic charges at the element edges allows simple determination of the average magnetization direction in the element. Elements studied in this work were elongated in the direction perpendicular to exchange induced anisotropy, making induced anisotropy compete with shape anisotropy.

Micromagnetic structures observed in studied AFM/FM elements with thick (>200 A) FM layer indicated that in addition to unidirectional anisotropy, the AFM layer induces uniaxial anisotropy in the FM layer.[7] Figure 1 shows a sequence of MFM images of a $2\times5\ \mu$m NiMn(280 A)/NiFe(200 A) element obtained under external field progressively increased in the direction opposite to the pinning field and then decreased back to zero. A seven-domain closure structure forms in the element when the applied field approximately compensates the pinning field. In this state, the magnetization in most of the element is oriented parallel to the exchange induced anisotropy axis and at 90° to the shape anisotropy axis. In the sample, the exchange induced uniaxial anisotropy energy per unit area of the film surface is about 1.5×10^{-1} erg/cm^2.[8] It overcomes the shape anisotropy of the 200 A thick $2\times5\ \mu$m NiFe element. The effect of induced uniaxial anisotropy is stronger in the samples with NiMn and PtMn AFM layers, in which structural grains are characterized by uniaxial magnetocrystalline anisotropy, than in the samples with IrMn, in which the grains, most likely, have cubic magnetocrystalline anisotropy. A four-domain Landau–Lifshitz structure forms in the $2\times5\ \mu$m NiFe(100 A)/IrMn(70 A) element when the external field compensates the pinning field (~75 Oe) [Fig. 2(c) and 2(f)]. This indicates that shape anisotropy of the 100 A thick element overcomes

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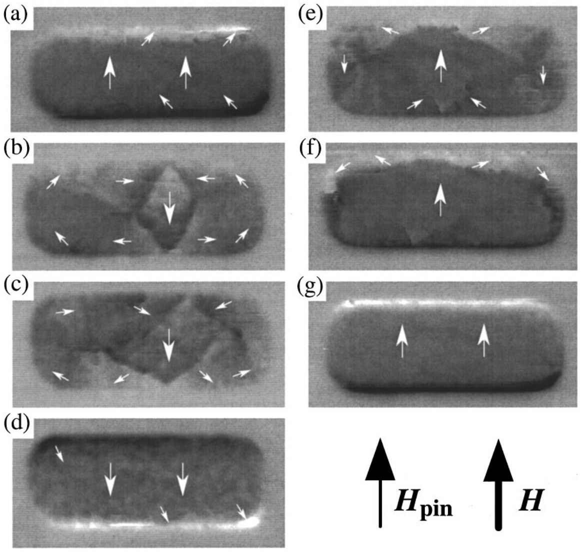

FIG. 1. MFM images of a 2×5 μm NiMn(280 A)/NiFe(200 A) element obtained under external field progressively increased in the direction opposite to pinning field and then decreased: 0 Oe (a), −50 Oe (b), −100 Oe (c), −250 Oe (d), −50 Oe (e), 0 Oe (f), and 75 Oe (g). Before patterning, the film was annealed at 270 °C for 2 h under 250 Oe field.

exchange induced uniaxial anisotropy. The induced uniaxial anisotropy manifests itself (results) in the delay of the formation of four-domain structure when the field is increased from 0 to 75 Oe or decreased from 300 Oe to 75 Oe [Figs. 2(a)–2(c) or Figs. 2(d)–2(f)]. Under the experimental condi-

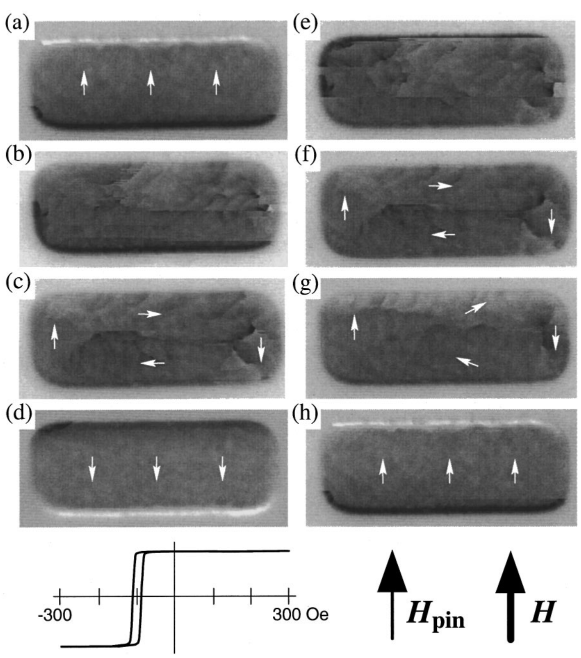

FIG. 2. MFM images of a 2×5 μm NiFe(100 A)/IrMn(70 A) element obtained under external field progressively increased in the direction opposite to pinning field and then decreased: 0 Oe (a), −75 Oe (b), −75 Oe (c), −300 Oe (d), −75 Oe (e), −75 Oe (f), −50 Oe (g), and 0 Oe (h). Image (c) was collected 20 min after the collection of image (b), (f) was collected 10 min after (e). Images (b) and (e) show unstable micromagnetic structure, which changes during the collection of the image. Before patterning, the film was annealed at 250 °C for 2 h under applied field. Inset shows hysteresis loop of the parent film before patterning.

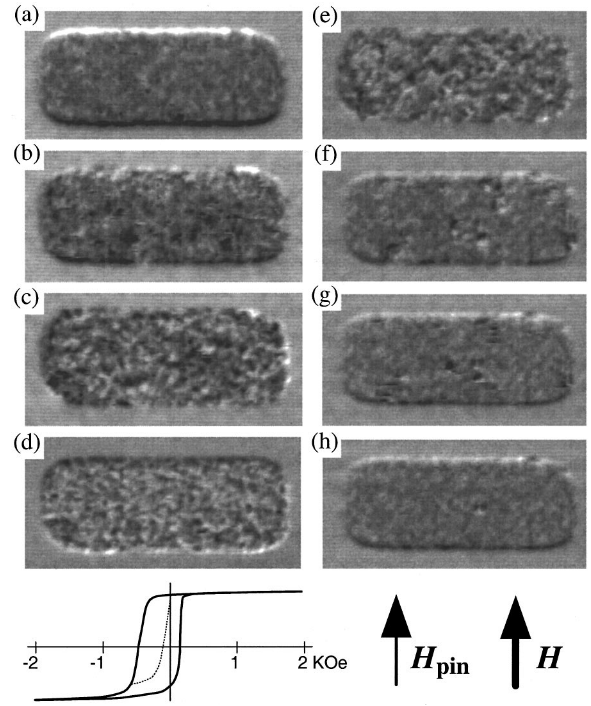

FIG. 3. MFM images of a 2×5 μm NiMn(280 A)/NiFe(100 A) element obtained under external field progressively increased in the direction opposite to pinning field and then decreased: 0 Oe (a), −200 Oe (b), −300 Oe (c), −570 Oe (d), −150 Oe (e), −50 Oe (f), 0 Oe (g), and 0 Oe (h). Image (h) was collected 10 min after the collection of image (g). Isolated areas with switched magnetization direction are clearly seen in (f). Image (g) shows reversal of magnetization in the switched areas back to pinning direction during collection of the image. Before patterning, the film was annealed at 270 °C for 2 h under the applied field. Inset shows hysteresis loop of the parent film before patterning.

tions, the element remained in a frustrated state, in which magnetization is switching between various metastable states, for tens of minutes before it comes to the stable four-domain state.

In the elements with a thin (<100 A) FM layer and NiMn or PtMn as the AFM layer a local switching of magnetization direction under external applied field has been observed. Sequences of MFM images of 2×5 μm NiMn(280 A)/NiFe(100 A) and PtMn(250 A)/NiFe(100 A) elements obtained under external field progressively increased in the direction opposite to pinning field and then decreased back to zero are presented in Figs. 3 and 4, respectively. Magnetization in the switched areas is 180° or close to 180° twisted relative to the magnetization in adjacent areas. In the MFM images, switched areas show up as closely spaced pairs of black and white spots with a direction from ''black'' to ''white'' opposite to the ''black-to-white'' direction of the image of magnetic charges at the edges of the element. Isolated switched areas are clearly seen in Fig. 3(f). A single, isolated switched area in the PtMn(250 A)/NiFe(100 A) element is also shown in Fig. 5. The size of the switched areas in the described samples is 0.1–0.2 μm, which is five to ten times greater than the size of structural grains in the films (20–30 nm). The areas switch in a viscous manner. Pairs of successive MFM images taken under constant applied field [Figs. 3(g), 3(h) and Figs. 4(f), 4(g)] show switching of the

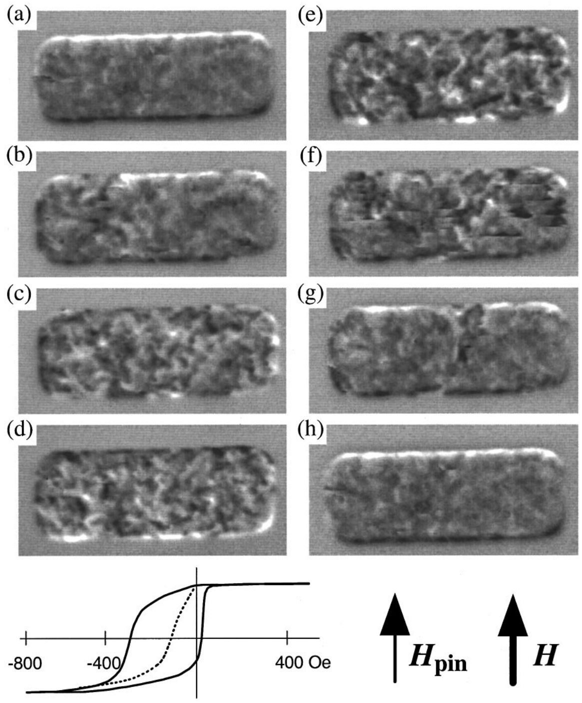

FIG. 4. MFM images of a 2×5 μm PtMn(250 A)/NiFe(100 A) element obtained under external field progressively increased in the direction opposite to pinning field and then decreased: 0 Oe (a), −200 Oe (b), −300 Oe (c), −570 Oe (d), −200 Oe (e), −100 Oe (f), −100 Oe (g), and 0 Oe (h). Image (g) was collected 20 min after the collection of image (f). Image (f) shows reversal of magnetization in the switched areas back to pinning direction during collection of the image. Before patterning, the film was annealed at 260 °C for 8 h under applied field. Inset shows the hysteresis loop of the parent film before patterning.

magnetization direction in the areas over time as a result of thermal excitation and excitation by the MFM tip field. Similar micromagnetic behavior was observed in NiMn/CoFe and PtMn/CoFe bilayers (Fig. 6). However, the size of switching areas was significantly larger. Most likely it is due to the greater in-plane exchange length in CoFe than in NiFe. No

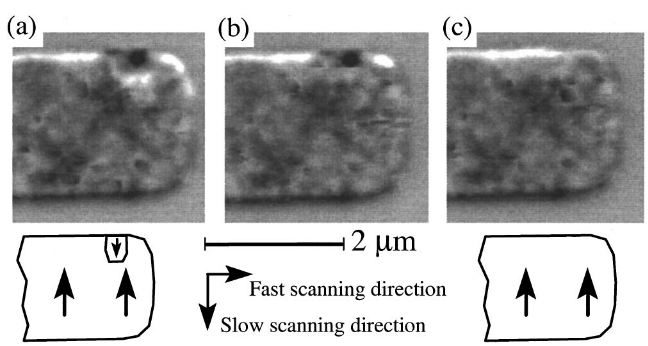

FIG. 5. MFM images of a part of a 2×5 μm PtMn (250 A)/NiFe (100 A) element. The unidirectional exchange field and induced anisotropy axis are perpendicular to the long side of the element. Images show the micromagnetic state of the element after applying a 600 Oe field opposite to the exchange field and then reducing it consequently to 50 Oe (a) and 0 Oe (b), (c) [(b)—first image taken after reducing field to zero, (c)—second taken image]. Area with magnetization opposite to the magnetization in the rest of the element is seen in the top left-hand side corner of the element. Magnetization in the area switches in the direction of exchange field during scanning of the image (b).

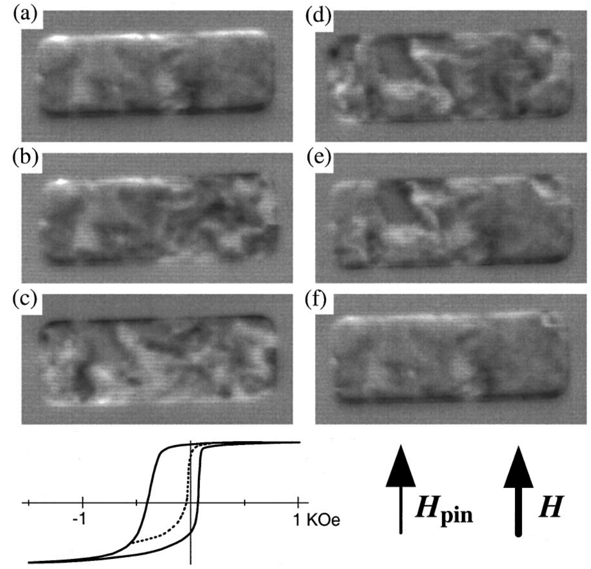

FIG. 6. MFM images of a 2×5 μm PtMn(100 A)/CoFe(100 A) element obtained under external field progressively increased in the direction opposite to pinning field and then decreased: 0 Oe (a), −300 Oe (b), −550 Oe (c), −50 Oe (d), 0 Oe (e), and 100 Oe (f). Before patterning, the film was annealed at 300 °C for 4 h under an applied field. Inset shows hysteresis loop of the parent film before patterning.

local switching was observed in the samples with IrMn AFM layer. Exchange with IrMn induces slight rippling of magnetization in the FM layer (Fig. 2). Unlike NiMn or PtMn, whose structural grains have uniaxial magnetocrystalline anisotropy, IrMn grains are likely characterized by cubic magnetocrystalline anisotropy. This is the most likely reason for the lower observed perturbation of the FM layer spin structure in the samples with an IrMn AFM layer than in the samples with NiMn or PtMn AFM.

Observed local magnetization switching can be explained using either the model of thermally activated switching of AFM grains[9,10] or the model of induced uniaxial anisotropy at the AFM/FM interface[7] suggesting local variations of induced uniaxial anisotropy. In both models, the in-plane exchange in the FM layer has to be taken into account to explain the effect of the FM layer material and thickness. An increase of the in-plane exchange in the FM layer or its thickness increases the weight of the FM exchange energy in the total energy of the system and suppresses perturbation of the FM layer spin structure caused by the exchange with the AFM layer.

[1] W. H. Meiklejohn and C. P. Bean, Phys. Rev. **102**, 1413 (1956); **105**, 904 (1957).
[2] D. Mauri, H. C. Seigmann, P. S. Bagus, and E. Kay, J. Appl. Phys. **62**, 3047 (1987).
[3] A. P. Malozemoff, J. Appl. Phys. **63**, 3874 (1988).
[4] N. C. Koon, Phys. Rev. Lett. **78**, 4865 (1997).
[5] K. Takano, R. H. Kodama, A. E. Berkowitz, W. Cao, and G. Thomas, Phys. Rev. Lett. **79**, 1130 (1997).
[6] V. I. Nikitenkio, V. S. Gornakov, L. M. Dedukh, Y. P. Kabanov, A. F. Khapikov, A. J. Shapiro, R. D. Shull, A. Chaiken, and R. P. Michel, J. Appl. Phys. **83**, 6828 (1998).
[7] T. C. Schulthess and W. H. Butler, J. Appl. Phys. **85**, 5510 (1999).
[8] T. Pokhil, S. Mao, and A. Mack, J. Appl. Phys. **85**, 4916 (1999).
[9] E. Fulcomer and S. H. Charap, J. Appl. Phys. **43**, 4190 (1972).
[10] C. Hou, H. Fujiwara, and F. Ueda, J. Magn. Magn. Mater. **198**, 450 (1999).