Thickness-dependent magnetic domain change in epitaxial MnAs films on GaAs(001)

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The authors report the change of the magnetic domain structure, dependent on the film thickness of MnAs films epitaxially grown on GaAs(001), investigated by magnetic force microscopy. Interestingly, as the film thickness decreases, the domain structure within the ferromagnetic α-MnAs stripes changes from a head-on domain structure to a simple 180° one around a thickness of 250 nm. This result is understood by the change in the demagnetizing factor of the ferromagnetic stripes with the film thickness. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2402235]

Epitaxial MnAs film on GaAs substrate is one of the promising systems for future spintronic applications because it has ferromagnetic (FM) properties with well-ordered interfaces at room temperature in spite of the large lattice misfit.[1,2] This material has been extensively studied for the possible application to magnetic tunnel junctions, spin injection devices, etc., even though a higher Curie temperature T_C is desirable for a stable operation of the devices at room temperature.[3,4] Apart from its importance in device applications, there is also a tremendous interest in the fundamental study of this system. While the bulk MnAs shows a phase transition from the FM hexagonal α-MnAs to the paramagnetic orthorhombic β-MnAs at $T_C \sim 45$ °C,[5] the MnAs film system exhibits the coexistence of two phases (α-MnAs and β-MnAs) in the form of self-organized periodic stripes at room temperature, via strain stabilization.[6,7] Therefore, the magnetic domain study on the MnAs film becomes an important issue for its application to spin-injection devices and for the fundamental understanding of the interplay between the structural and magnetic properties.

Most of the previous studies report observations of the magnetic domain structures in epitaxial MnAs films on GaAs(001) using x-ray magnetic circular dichroism photoemission electron microscopy[8] and magnetic force microscopy[9–11] (MFM) without any analytical explanation. Recently, the MFM measurements have been carried out for constant film thicknesses of 180 and 250 nm to understand the magnetic domain structure according to the applied magnetic field.[11,12] Considering the fact that the periodic length of the two phase stripes depends strongly on the film thickness,[13] a thickness-dependent study is essential for a better understanding of the magnetic domain structure of MnAs films. In this letter, we present the observation of a systematic variation of the magnetic domain structure with thickness in the MnAs/GaAs(001) system using MFM.

For this study, a series of the MnAs films with varying thickness of 10, 25, 50, 100, 250, and 500 nm was grown on the GaAs(001) substrates at 270 °C by molecular-beam epitaxy. The detailed growth conditions are described elsewhere.[14] The epitaxial orientations of the MnAs films with respect to the GaAs (001) substrate are MnAs $(\bar{1}100)\parallel$GaAs(001), MnAs$[0001]\parallel$GaAs$[\bar{1}10]$, and MnAs$[11\bar{2}0]\parallel$GaAs[110]. The magnetic properties of the MnAs films were investigated using a superconducting quantum interface device magnetometer (SQUID). All the samples have an in-plane magnetic anisotropy with an easy axis along the MnAs $[11\bar{2}0]$ and a hard axis along the MnAs [0001] in the film plane. The out-of-plane direction MnAs $[\bar{1}100]$ is an intermediate axis. At room temperature the strain-stabilized coexistence of two phases, α-MnAs and β-MnAs, was witnessed from the x-ray diffraction experiment. An atomic force microscopic (AFM) study of the MnAs films at room temperature reveals that the α-MnAs and β-MnAs stripes are aligned along the MnAs [0001] and perpendicular to the magnetic easy axis MnAs$[11\bar{2}0]$.

The magnetic domain structure was investigated using a MFM system, which was a noncontact force microscope (PSIA, XE-100) equipped with a magnetic tip (Nanosensors). The magnetic tip is coated with cobalt alloy (40 nm thick) on the tip side and aluminum (30 nm thick) on the detector side, and the tip radius is typically less than 50 nm. The magnetic tip scans the sample in the noncontact mode to obtain the surface morphology, and then a second scan is carried out at a constant height above the surface so that the magnetic and topographic signals are well separated. In our

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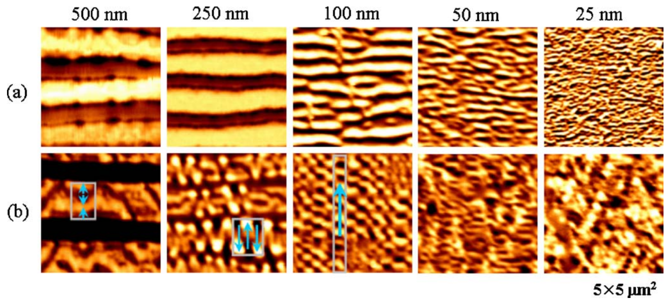

FIG. 1. (Color online) Variation of the MFM images for MnAs films with decreasing film thickness at (a) the saturated state and (b) the demagnetized state, where the observed area is 5×5 μm^2 and the easy axis is perpendicular to the FM stripe direction.

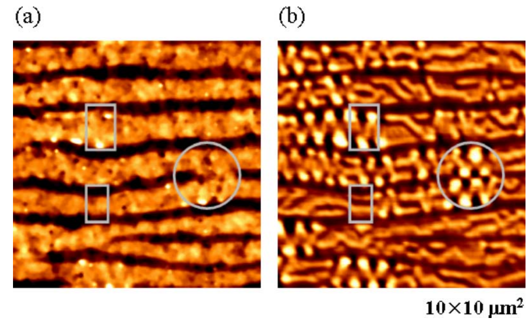

FIG. 2. (Color online) (a) AFM and (b) MFM images of 250 nm MnAs film on an area with a large fluctuation in the FM stripe width.

measurement, the MFM images were obtained using the interleave mode at a lift scan height of 50 nm. The contrast of the observed MFM images illustrates the interplay between the stray field above the film surface and the magnetic tip. Also, the MFM system is equipped with an electromagnet, which allows to investigate the evolution of the magnetic domains in an in-plane applied magnetic field (up to 600 Oe).

Figure 1 shows typical MFM images of the MnAs films with varying thickness of 25, 50, 100, 250, and 500 nm at (a) the saturated and (b) demagnetized states, where the observed area is 5×5 μm^2 and the easy axis is perpendicular to the stripe direction. The demagnetized state was obtained by heating the sample up to 80 °C, which yielded a complete transition to paramagnetic β-phase, and then cooling it down to room temperature. It should be noted that MFM contrast within the FM α stripe in our experiment is due to two contributions: the out-of-plane magnetic components within the 180° Bloch walls of the sample and the stray field from the end parts of the in-plane magnet. This is naturally expected because all MnAs samples have a uniaxial in-plane magnetic anisotropy with an easy axis perpendicular to the stripe direction, as confirmed from the SQUID measurement. As shown in Fig. 1(a), all FM stripes of each MFM image are in a single domain state, where MFM contrast within the FM α stripe is ascribed to the stray field from the boundary of two stripes. Interestingly, it is found that the periodic length and the widths of two stripes of α and β phases proportionally decrease as the thickness decreases. More significantly, the magnetic domain structures of the MnAs films at the demagnetized state reveal complex changes with decreasing film thickness, as shown in Fig. 1(b).

As seen in Fig. 1(b), the domain structure within the FM stripes at the demagnetized state for a film thickness of 500 nm can be described as head-on domains. The head-on domains are expressed as the spin configurations in which the magnetization directions of two domains meet head on, as demonstrated in the rectangular box of the MFM image of the 500 nm sample. In contrast, with decrease in the thickness to about 250 nm, the domain structure within the FM stripes contains a mixture of head-on domains and simple domains. These simple domains are defined as the spin configurations having a single spin direction along the width of the FM stripe, as demonstrated in the rectangular box of the MFM image of the 250 nm sample. The head-on domains observed in the 250 and 500 nm samples indicate the formation of closure domain configurations in depth,[11] which is expected from the fact that the domain wall length in the MnAs film is about 100 nm.[15] On the other hand, the simple domains below a film thickness of 100 nm are thought to appear because their thicknesses are lesser than the domain wall length. Especially, the sawtooth shaped domain structure in the 500 nm sample is a typical characteristic of the head-on domains. Generally, this structure is generated to reduce the magnetic charge density along the stripe direction.[16,17] The resultant shape is determined by the competition between the domain wall and dipolar energies around the domain boundary along the stripe direction.

With decrease in thickness to about 100 nm, the correlation between the spin directions in the domains of the neighborhood FM stripes becomes significant, while there seems to be no correlation at a thickness of 500 nm. The rectangular box in the MFM image corresponding to the 100 nm sample clearly shows this correlation. This change is due to the increase in the dipolar interaction with decreasing thickness, induced by the decreasing gap distance between the stripes. This interaction enables the spin directions in the neighborhood FM stripes to be aligned to the same direction. This correlation is also observed in the 250 nm sample in the regions with the narrow gap distance between the stripes, induced by the large fluctuations in the stripe width. So, the domain structures in the 100 and 50 nm samples exhibit the domain structures elongated across the FM stripes, having two domains along the easy axis and the 180° domain wall. This domain structure is similar to that in normal in-plane FM films, with an exception to the stripe patterns. On the other hand, the MFM image in the 25 nm sample contains circular spots with strong contrast, different from those in the 100 and 50 nm samples, as vividly seen in Fig. 1(b). This will be discussed later.

Strikingly, the domain structure in the 250 nm sample is found to have both domain configurations of the head-on domain and the simple domain in spite of its uniform thickness, as vividly seen in Fig. 1(b). This indicates that there may be a major origin for the change of the domain structure in the FM stripe in addition to the film thickness. For further understanding, the AFM and MFM images of the 250 nm thick MnAs film were investigated on the area with a large fluctuation in the stripe width, as in Figs. 2(a) and 2(b). We can find that two contrasting domain structures appear in spite of the uniform film thickness, explained by the difference in the demagnetizing factor, with change in the width of the FM stripe: the head-on domains appear in the narrow stripes with large demagnetizing factors, while the simple domains appear in the wide stripes with small demagnetizing factors. The demagnetizing factor can be estimated by the aspect ratio w/t of the width w to the thickness t of the FM

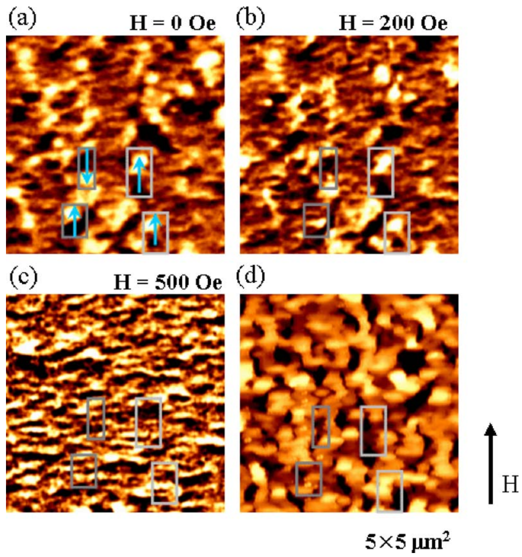

FIG. 3. (Color online) (a)–(c) Field-dependent MFM images, together with (d) AFM image (at $H=0$), of 25 nm MnAs film, where an external magnetic field is applied along the easy axis perpendicular to the FM stripe direction.

stripe. The aspect ratios w/t of the FM stripes in two rectangular boxes of Fig. 2 are estimated as 6.4 and 3.2, respectively. The increase of the aspect ratio w/t with decrease in the thickness t ranges from a value of 3.1 ± 0.1 in the 500 nm sample to a value of 5.8 ± 2.0 in the 100 nm sample. Hence, the change in domain structure from head-on domains to simple domains with decreasing thickness can be ascribed to the change in the demagnetizing factor with change in the width of the FM stripes as well as the thickness. Also, the change of the demagnetizing factor is found to be influenced by the change in the gap distance between the stripes. As seen in the circular box of Fig. 2, the effect of the decrease in the gap distance between the stripes is again the appearance of a simple domain structure despite a small value (4.0) of the aspect ratio. It must be noted here that a simple domain structure in the 250 nm sample is found to occur only at aspect ratio value greater than 4.7 ± 1.3. Therefore, the domain structure in this case is governed by the decrease in the gap width, which causes an increase in the dipolar interaction between two stripes thereby causing an increase in the demagnetizing factor of the stripes.

To understand the domain structure in the 25 nm sample, we have investigated the field-dependent behavior of the domain structure using the MFM system. Figure 3 shows the field-dependent MFM images and the AFM image (at $H=0$) on the 5×5 μm^2 area of the 25 nm sample at room temperature, where each rectangular box denoted in each figure represents exactly the same area of the sample. An external magnetic field was applied along the easy axis perpendicular to the stripe direction, as indicated by a black arrow. The field-dependent MFM images clearly show that a couple of the spots with strong contrast changes to the stripe pattern as the field increases, as witnessed in the rectangular boxes of Fig. 3. From this result, we conjecture that the spots with strong contrast are ascribed to the strong stray fields from the boundary with the head-on spin directions. That is, the domain structure in the 25 nm sample consists of many closed domains which are spreading across some FM stripes, while the domain structures in the 100 and 50 nm samples have open domains elongated across the FM stripes. Also, it is seen that the locations of the closed domains are well matched with the defects seen in the surface morphology of the film, which indicates that the domain wall gets pinned around the defects in the surface. The characteristics of the closed domains also appear in the 10 nm sample, with smaller closed domains due to an increase in defect density. As the thickness decreases, the domain structure in the MnAs film changes from open domains to closed domains from a thickness of 25 nm, induced by the increase in the surface defect of the surface.

In summary, using a MFM system we have witnessed the systematic variation of magnetic domain structure with thickness in the epitaxial MnAs/GaAs(001) system. With decreasing film thickness, the domain structure in the FM stripe was changed from head-on domains to simple ones around a thickness of 250 nm. This can be ascribed to the demagnetizing factor variation with the thickness. The domain structure in a thin sample with a thickness of 25 nm showed closed domains spreading across some FM stripes, which can be explained by an enhanced surface effect with decreasing film thickness.

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