Origin of uniaxial magnetic anisotropy in epitaxial MnAs film on GaAs(001) substrate

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We investigate the origin of in-plane uniaxial magnetic anisotropy of epitaxial ferromagnetic MnAs film on GaAs(001). Interestingly, as temperature increases, the in-plane uniaxial magnetic anisotropy along the MnAs[11$\bar{2}$0] direction changes and then disappears. Direct microscopic domain observations show that the type of domain structure changes from a simple domain to a closure one with increasing temperature. From these results, the temperature-dependent change of the in-plane magnetic anisotropy is ascribed to a decrease in the shape anisotropy induced by the decrease in the width of the ferromagnetic α-stripe. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2844856]

Ferromagnetic (FM) MnAs film on GaAs substrate has attracted much attention for potential spintronic applications in spin injection,[1–3] magnetic tunneling junction,[4,5] and magnetologic device.[6] Recently, the fundamental interest on this system has grown significantly, largely motivated by the experimental observation of tunable scaling behavior, in which domain-evolution pattern during magnetization reversal is varied depending on temperature.[7,8] This variation is ascribed to the decrease of the saturation magnetization M_S with temperature,[9] induced by the magnetostructural phase transition from FM α-MnAs to non-FM β-MnAs with increasing temperature.[10–12] Thus, understanding the magnetic property on the MnAs film has been a challenging issue from fundamental and technical aspects.

In particular, the magnetic anisotropy on the MnAs film is very intriguing. The bulk MnAs shows a magnetocrystalline anisotropy with an easy plane of MnAs(0001) without any preferred magnetization direction in the easy plane.[13] On the other hand, the MnAs film is known to exhibit a well-defined in-plane uniaxial anisotropy with an easy axis of MnAs[11$\bar{2}$0] in the film plane at room temperature.[9] Recently, it has been reported that in-plane and out-of-plane magnetization components coexist in the MnAs film with increasing temperature from 20 to 45 °C,[14–16] where out-of-plane magnetization component was considered as a possible origin about the magnetologic device operation.[6] Thus, the magnetic anisotropy of the MnAs film is highly complex and its underlying physics is still unclear. In this letter, we have investigated the temperature-dependent change of the in-plane magnetic anisotropy of the MnAs films by means of a superconducting quantum interface device (SQUID) magnetometer. The origin of the change in the in-plane magnetic anisotropy could be understood from a detailed investigation of the temperature- and field-dependent domain structure using a magnetic force microscope (MFM).

For this study, the MnAs films with different thicknesses of 100, 250, and 500 nm were epitaxially grown on a GaAs(001) substrate at 270 °C by molecular-beam epitaxy. The detailed growth conditions are described elsewhere.[17] The epitaxial growths of the MnAs films on the GaAs(001) substrate exhibit MnAs($\bar{1}$100)‖GaAs(001), MnAs[0001]‖GaAs[$\bar{1}$10], and MnAs[11$\bar{2}$0]‖GaAs[110]. Vibrating sample magnetometer measurements at room temperature showed that the MnAs films have well-defined strong uniaxial magnetic anisotropy with an easy axis along the MnAs[11$\bar{2}$0], an intermediate axis along the MnAs[$\bar{1}$100], and a hard axis along the MnAs[0001]. The temperature-dependent M-H curves of the MnAs films were measured using a SQUID magnetometer. Magnetic domain structures of the MnAs films were investigated using a MFM system, equipped with a variable temperature stage and an electromagnet in order to measure the temperature- and field-dependent MFM images. The MFM system essentially consists of a noncontact force microscope (PSIA, XE-100) and a magnetic tip coated with Co alloy (Nanosensors).

In Fig. 1(a), we demonstrate the M-H curves of the MnAs film with thickness of 250 nm at various temperatures of 15, 30, and 40 °C measured using a SQUID magnetometer. The external magnetic field H is applied along MnAs[11$\bar{2}$0] in the sample plane (marked as $H_{\|}$) or MnAs[$\bar{1}$100] perpendicular to the sample plane (marked as $H_{\perp}$). It should be noted that the saturation magnetization M_S decreases as the temperature increases, which is ascribed to the decrease in the volume ratio of FM α-MnAs with increasing temperature. One can clearly see that the M-$H_{\|}$ curve of the MnAs film at T=15 °C exhibits a square loop, while the M-$H_{\perp}$ curve shows a slant one. These results reveal that the sample has uniaxial magnetic anisotropy along the MnAs[11$\bar{2}$0] in the film plane. However, note that the shape of the M-$H_{\|}$ curve is changed from a square to a slant one with increasing temperature, reflecting the disappearance of the uniaxial anisotropy along the MnAs[11$\bar{2}$0] direction.

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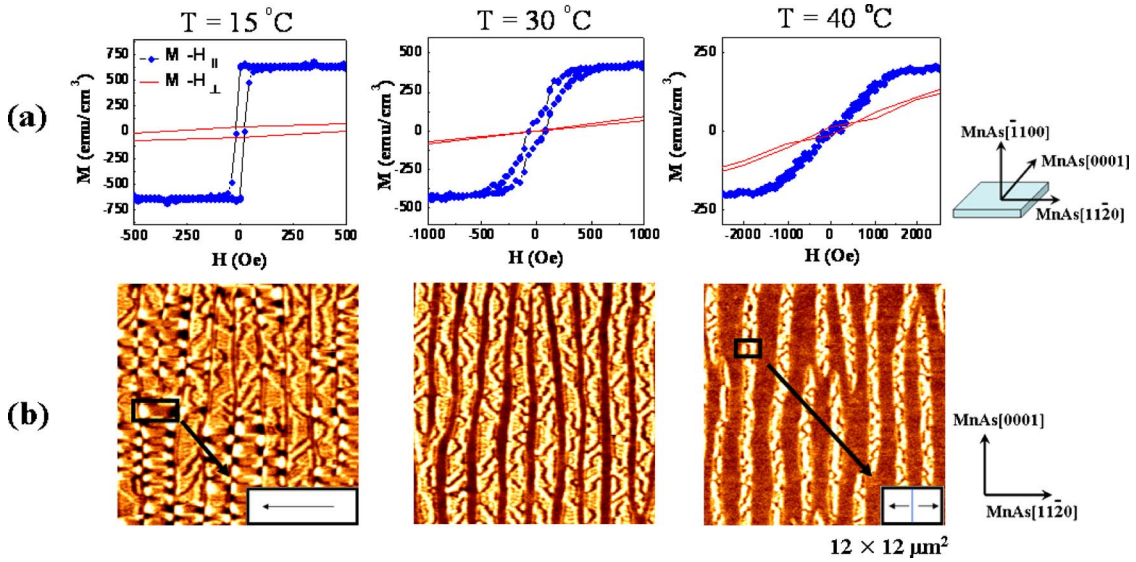

FIG. 1. (Color online) (a) The temperature-dependent M-H curves of the MnAs film, in which an external field H is applied along the MnAs[11$\bar{2}$0] (marked as $H_{\parallel}$) and along the MnAs[$\bar{1}$100] (marked as $H_{\perp}$). (b) The corresponding MFM images of the 5×5 μm^2 sample area at the demagnetized states.

Also, the experimental results on the MnAs films with different thicknesses of 100 and 500 nm were found not to be essentially different from the ones on the MnAs film with thickness of 250 nm, except that the transition temperature where the in-plane uniaxial anisotropy begins to destroy appears at lower temperature for a larger thickness.

To understand the origin about the change of the in-plane magnetic anisotropy, we have investigated the domain structures of the MnAs films with temperature using a MFM system. Figure 1(b) shows MFM images of the MnAs film with varying temperature at the demagnetized states corresponding to the M-H curves in Fig. 1(a), in which the observation area is 12×12 μm^2. The demagnetized state was obtained by heating to 80 °C and then cooling to each designated temperature. As seen in Fig. 1(b), two different magnetic structures of the FM α- and non-FM β-MnAs phases coexist with forming stripe patterns along the MnAs[0001]. Moreover, as the temperature increases, the width of the FM α-stripe decreases and that of the non-FM β-stripe increases. This causes a decrease of M_S as the temperature increases, as seen in Fig. 1(a). It should be noted that the magnetic contrast at the surface of the FM α-stripe is ascribed to stray fields from the end parts of the in-plane magnetization that originate from the two contributions of the boundaries between two different stripes and those between two head-on domains within the α-stripe. From the MFM images, two typical domain structures can be observed at the surface of the FM α-stripe: the simple domain and the head-on domain structures. The simple domain structure is defined as the domain configuration with the same magnetization direction along the width of the FM α-stripe, as schematically shown in the box of the MFM image at 15 °C. On the other hand, the head-on domain structure shows a domain configuration in which the magnetization directions of two domains meet head on, as shown in the box of the MFM image at 40 °C. However, the head-on domain structure is known to have a higher magnetic energy compared to the simple structure as it has magnetostatic energy generated from the magnetic charges around the domain boundary.[18,19]

Considering that MFM can measure only the surface domain configuration of the sample, it is uncertain whether the head-on domain structure observed at the film surface exists through the film thickness. To clarify this question, we have measured the field-dependent MFM images of the MnAs film at 42.5 °C, as shown in Fig. 2. The external magnetic field H is applied along the easy axis of the MnAs[11$\bar{2}$0], perpendicular to the stripe direction. Interestingly, as the strength of an applied field increases, the domain configuration at the surface continuously changes from a head-on domain structure to a simple structure. Moreover, it is seen that as the strength of an applied field decreases from 1200 to 0 Oe, the domain configuration again becomes an original head-on domain structure. These characteristics could not be explained if the head-on domain structure existed through the film thickness. Generally, the head-on domain structure at a demagnetized state cannot be resumed after the magnetization is saturated, because this process

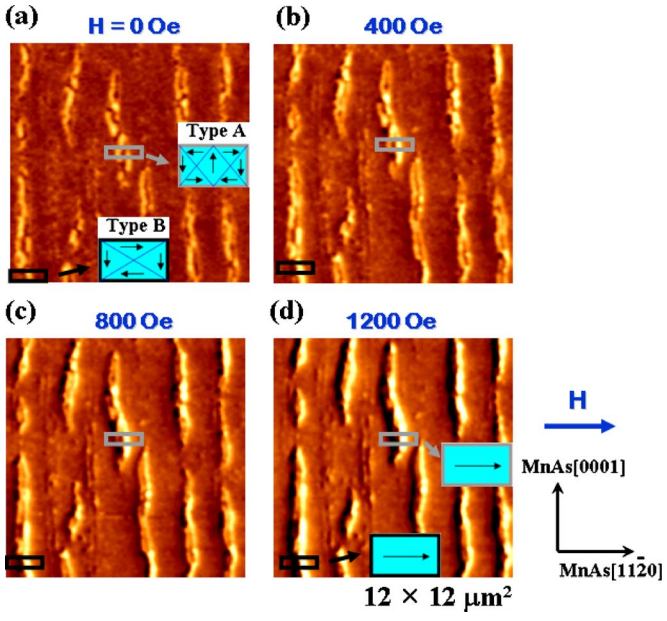

FIG. 2. (Color online) The field-dependent MFM images of the MnAs film measured at 42.5 °C. The gray and black boxes in the inset represent the closure-type domain structures A and B, respectively.

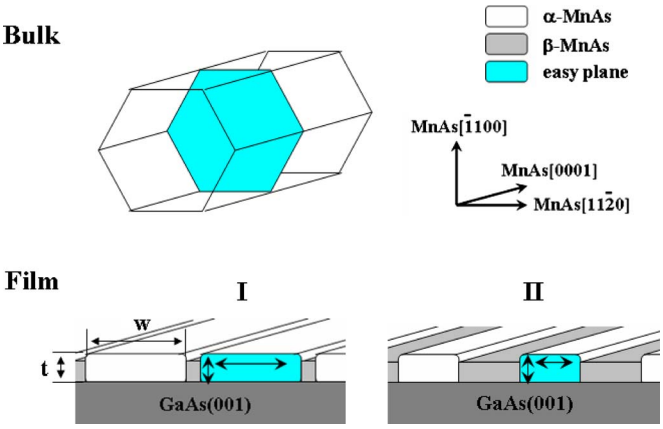

FIG. 3. (Color online) A schematic diagram for understanding the origin of the in-plane magnetic anisotropy of the MnAs film.

costs a higher magnetostatic energy due to the magnetic charges.[18,19] Therefore, the observed head-on domain structure is understood by the surface configuration of the closure-type domain structure on the cross-sectional plane of the FM α-stripe to minimize the magnetostatic energy, as schematically presented in the gray box of Fig. 2(a) (marked as type A).[20]

Another closure-domain structure was also observed in the MFM images of the MnAs films. As shown in Fig. 2, the magnetic contrast of the MFM image within the black box was found to become more apparent as the strength of an applied field increases. This implies that the size of the domain along the applied field direction on the cross-sectional plane becomes larger as the applied field increases, as schematically drawn in the black box of Fig. 2 (marked as type B). Similarly, the domain configuration of the closure-type B is resumed to its original domain configuration at $H=0$, which is similar to the closure-type A. Thus, it is concluded that the head-on domain structures observed at high temperatures represent the surface domain configurations of the closure-types A or B.[20] The return to the original demagnetized state at $H=0$ is a typical characteristic of the closure-domain structure, which is caused by its magnetostatic energy minimization process.[21,22]

An interesting feature regarding the domain structure of the MnAs films is the abrupt change from the simple domain to the closure-type structure as the temperature increases, which is found to be closely related to the change of the in-plane magnetic anisotropy. Figure 3 shows a schematic diagram to explain the origin of the in-plane magnetic anisotropy of the MnAs film. As shown in Fig. 3, it is well known that bulk MnAs has a strong magnetocrystalline anisotropy with an easy plane of MnAs(0001) and a hard axis of MnAs[0001]. However, in the case of the MnAs film, two different phases of α- and β-stripes coexist and form periodic patterns via the strain stabilization, induced by the large lattice mismatch between the film and the substrate.[10,11] As the temperature increases, the width of α-stripe decreases and that of β-stripe increases: this is schematically depicted for two representative cases of I and II in Fig. 3. In the case I, the simple domain structure is caused by the in-plane shape anisotropy due to the large demagnetizing factor w/t, given by the aspect ratio of the width w and the thickness t in the α-stripe, as depicted in Fig. 3. On the other hand, the in-plane shape anisotropy is reduced in the case II due to a small w/t, which results in the closure-type domain structure, as the domain alignment along the thickness direction cannot be negligible. Hence, the change of the in-plane magnetic anisotropy as well as the change of the domain structure can be ascribed to a decrease in the shape anisotropy, induced by a decrease in the width of the FM α-stripe.

In summary, the origin of the in-plane uniaxial magnetic anisotropy in the epitaxial FM MnAs film on GaAs(001) was investigated by studying the temperature- and field-dependent domain structure. Interestingly enough, the in-plane uniaxial magnetic anisotropy in this system was found to change as temperature increases. From microscopic domain observations, it can be seen that the domain structure changes from a simple domain to a closure-type structure as the temperature increases. This reveals that the change of the domain structure according to the temperature is ascribed to the decrease in the in-plane shape anisotropy induced by the decrease in the width of the FM α-stripe. Thus, we conclude that the origin of the in-plane uniaxial magnetic anisotropy is the shape anisotropy resulting from the structure of the FM α-stripe.

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