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Change of Magnetic Domain Structures of MnAs Thin Film on GaAs(001)

Hiromi Kuramochi, Jun Okabayashi*, Takashi Manago** and Hiroyuki Akinaga**
Research Consortium for Synthetic Nano-Function Materials Project (SYNAF): Seiko Instruments Inc., 1-1-1 Higashi, Tsukuba, Ibaraki 305-8562, Japan
Fax: 81-298-61-2777, e-mail: hiromi.kuramochi@aist.go.jp
*SYNAF: The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
**SYNAF: National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Higashi, Tsukuba, Ibaraki 305-8562, Japan

Ferromagnetic materials generally form magnetic domain structures to reduce their magnetostatic energy. The shape of magnetic domain walls is directly identified from magnetic force microscope (MFM) images. We observed in-plane uniaxial anisotropy of magnetic domain structures of MnAs/GaAs(001) films at RT. Different magnetic domain structures were obtained after magnetization along [1-10] and [110] GaAs directions in consistent with magnetic hysteresis characteristics. Temperature effects for the structure were also studied between RT-400 K. Sharp structure changes due to phase transition were observed at around 318 K and magnetic domain structures disappeared above 323 K.
Key Words: MnAs, MFM, In-plane anisotropy, phase transition

1. INTRODUCTION

The combination of magnetic metal and semiconductor has been studied intensively to explore new devices based on the coupling of spin and mobile charge carriers in the past decade. Epitaxial thin-film growth of magnetic manganese compounds on semiconductor substrates, *e.g.*, Mn_2Sb/GaAs(001), has received much attention since the manganese compounds have various magnetic properties [1-3]. There has been also increasing interest in highly spin-polarized ferromagnets since these materials have potential technological applications in spin-polarized electron transport devices. As a new attempt, noble material for spintronics was designed by *ab initio* calculations, highly spin-polarized zinc-blende CrAs was successfully grown on a GaAs substrate by molecular-beam epitaxy [4].

Ferromagnetic materials generally form magnetic domain structures to reduce their magnetostatic energy. The shape of magnetic domain walls is directly identified from magnetic force microscope (MFM) images. MnAs can be epitaxially grown on GaAs(001) substrate by Molecular Beam Epitaxy (MBE) as ferromagnetic-metal/semiconductor hybrid films. MnAs shows a 1st-order ferromagnetic-nonmagnetic transition together with the crystallographic transition from NiAs to MnP type crystal structure at a Curie temperature of 318 K [5]. It is known that the magnetization easy axis is along the *a*-axis of the hexagonal NiAs structure. We observed a difference of magnetic domain structures of MnAs/GaAs(001) after magnetization along the easy magnetization axis and perpendicular to that. Phase transitions due to temperature change between RT-400 K are also reported in this paper.

2. EXPERIMENT

MnAs layers were grown on n^+-GaAs (001) substrates by MBE. After growing a 20 nm GaAs buffer layer at 853 K, the substrate temperature was cooled to 473 K to grow the MnAs film. GaAs surface reconstruction changed from 2x4 to c(4x4) which was checked by RHEED pattern. During the growth of MnAs, the flux ratio of As/Mn was set at about 100. The thickness of MnAs film is designed to be 30 nm. After the growth, sample was annealed at 623 K under the As flux. From the x-ray diffraction and magnetization measurement, MnAs film is epitaxially grown as [-1101] orientation [6]. The *a*-axis of the hexagonal NiAs crystal structure, namely the magnetization easy axis of the thin film, is parallel to the [1-10] GaAs direction in the (001) plane.

Atomic Force Microscope (AFM) and MFM measurements were performed with an environmental control AFM/MFM unit (SII, SPA-300HV) in vacuum ($<5x10^{-2}$ Pa). It based on the optical lever system [7] to measure the deflection of the cantilever. The cantilever with a microfabricated Si tip is coated with Al/Co alloy. The nominal spring constant is 42 N/m. Noncontact mode is used for MFM observation, the tip is kept 0-30 nm above the sample surface. Operation in vacuum without air resistance gains larger Q factor and makes high-sensitive observation possible [8]. MFM observations were carried out in zero field after magnetization of samples. In-plane magnetization of the sample was done using an electromagnet up to H=1.5 T, which is enough for saturation, at room temperature. Sample temperature was varied from 298 K to 400 K with a rate of 1 K/min under 1×10^{-1} Pa. To observe the same area during phase transition, AFM and MFM images were taken simultaneously and defects in AFM images were used as position makers.

3. RESULTS AND DISCUSSIONS

Magnetization measurements were performed to investigate the magnetic properties of the present MnAs/GaAs (001) thin film. The magnetic field was applied in-plane along different directions during magnetic hysteresis characteristics measurements at room temperature. Square hysteresis loop was observed by applying the magnetic field in-plane along GaAs[1-10] as shown in fig. 1. The remnant magnetization is 322 emu/cm^3 and the coercive field is 25 mT. Completely different hysteresis characteristics was observed when the magnetic field was applied along GaAs[110], the remnant is 17 emu/cm^3, which is about one 20th of the former. Fig. 1 clearly shows the uniaxial anisotropy of the present sample and the easy axis of magnetization is in-plane, parallel to GaAs[1-10].

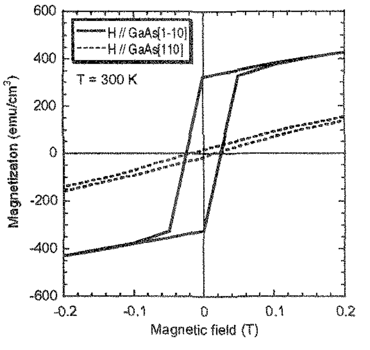

Fig. 1 Anisotropic magnetic hysteresis characteristics with the magnetic field parallel to GaAs[1-10] and[110].

Figs. 2 (a) and (b) show topographic images of MnAs/GaAs(001) surface (5x5 μm^2). Characteristic rectangular defects along GaAs[110] direction were observed randomly on the surface. They are 300-800 nm in length and 15-40 nm in depth. Roughness of this surface is about 2 nm and white dots (~4 nm in height) covered the surface. Figs. 1 (c) and (d) are MFM images corresponding to figs. 1 (a) and (b), respectively. They show remnant magnetic state after magnetization along different orientations. Produced

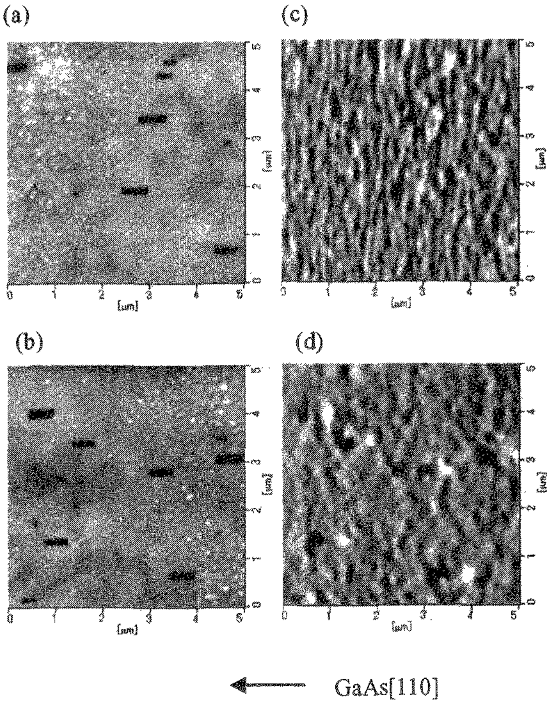

Fig. 2 Topographic images and Magnetic domain structure of MnAs/GaAs(001) thin film. (a) and (b) Topographic images of 5x5 μm^2 area. (c) MFM image of the same area as (a) after magnetization along GaAs[1-10]. (d) MFM image corresponding to (b) after magnetization along GaAs[110]. All images were taken at 298 K.

stripe magnetic domains along GaAs [1-10] direction were observed after magnetization parallel to [1-10] direction, easy magnetization axis, as shown in fig. 1 (c). The domain structure was not affected by the magnetic tip, because it did not change according to scan direction. When the sample was magnetized parallel to GaAs[110], rotating the sample 90 degree in the electromagnet, less directional weak domain walls were observed. Pairs of black and white spots were also observed in fig. 1 (d). They are observed inverted using an MFM tip with opposite magnetization orientation. So that they are magnetic poles with outward (white) and inward-plane (black) magnetic moments. Comparing the MFM image [fig. 1 (d)] to the topographic image [fig. 1 (b)], it is found that these poles are located at the edges of rectangular defects. On the other hand, it is rather difficult to find pair of poles in fig. 1(c). It is consistent with the M-H characteristics, conspicuous domain walls due to the larger remnant obscure the poles in the case of magnetization parallel to the easy magnetization axis. The difference between two MFM images obviously shows the in-plane anisotropy of the MnAs thin film in conformity to the M-H characteristics. It is an example of magnetic structural change controlled by applying magnetic field.

The domain structure could be governed by topography as with the previous work [9], it depends on the structural properties of the thin film, *i.e.*, the surface orientation, thickness and defects. In the case of the present sample, the characteristic fair rectangular defects make local nonmagnetic areas on the surface. Figs. 3 show the relation between the position of rectangular defects and pairs of magnetic poles. Relative scan direction to the surface orientation is the same. When the positions of defects are marked in the corresponding MFM image, it is found that the edges of rectangular defects are exactly located in the black or white poles. It means that a magnetic circuit is formed at a rectangular defect. The orientations of magnetic circuits are in one direction, along GaAs [110] from right to left in fig. 2 (d). It is independent of magnetization direction as shown in figs. 3. It denoted that the magnetic circuits at the edge of rectangular defects are stable. Repetition of change of magnetization direction did not affect the orientation of magnetic circuits. It indicates the pinning of poles at the edge of rectangular defects.

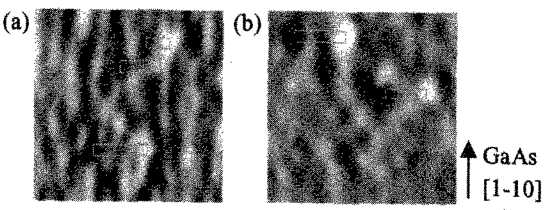

Fig. 3 Relation between the position of rectangle defects and magnetic poles. Images (2x2 μm^2) were taken at room temperature. (a) Magnetization parallel to GaAs[1-10]. (b) Magnetization parallel to GaAs[110].

Next, the change of magnetic domain structure was observed during the phase transition. After magnetization at room temperature, the sample temperature was increased up to 400 K and the same area (5x5 μm^2) of the surface was monitored every 3-5 K by AFM/MFM. AFM images did not change during phase transition. It suggests that the spatial changes were too small, viz. atomic level, to detect under such large area observation. Figs. 4 show series of MFM images from 308 K to 323 K with respect to each 5 K. The contrast of MFM images are emphasised to clarify the movement of the magnetic domain structure, only domain walls are viewable in these images. The orientation of magnetization was parallel to GaAs[110]. The magnetic domain structures up to 308 K did not present large difference at a glance, it became slightly fragmentary. The evident changes come out with the sample temperature of 313 K. The magnetic domain walls got fuzzy and noises increased. The scratch noises in the SPM images are generally known as moving objects and/or as an evidence of transformation in progress. The magnetic domain structure lost the directionality at 318 K as shown in fig. 4 (c). These MFM images proof that the Curie temperature of the present sample is around 318 K. Above the Curie temperature, the magnetic domains disappeared. The phase transition occurred sharply in a narrow temperature range (< 10 K). The magnetic domain structure changes every second drastically according to the temperature increase between 313 K and 323 K, so that real-time observation of behaviour of the magnetic domains during demagnetization is possible if the temperature increase slowly. It is an example of the magnetic structural change controlled by temperature.

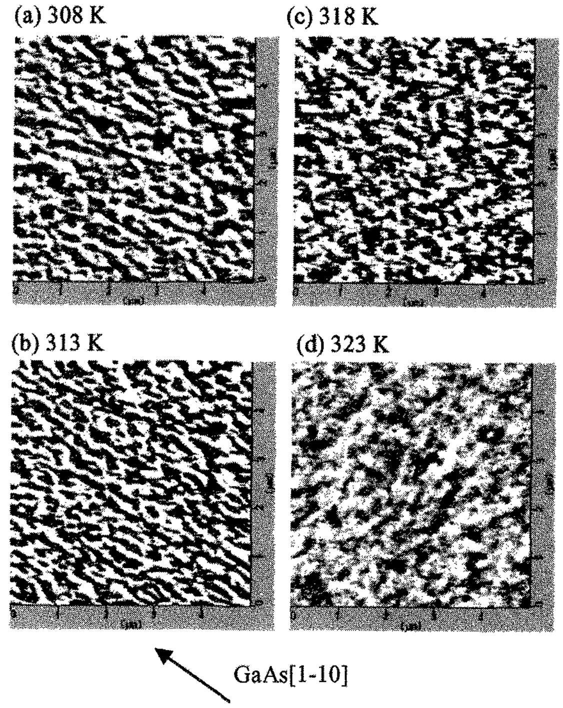

Fig. 4 MFM images of magnetic domain structure in the same area during phase transition of MnAs/GaAs(001) thin film. *Magnetization parallel to [110].* Images are taken at denoted temperature.

The pinning of magnetic poles at the edges of rectangular defects also avails on the transition of domain structures. Figs. 5 show MFM images of the same area around the same rectangular defect at 298 K and 308 K, respectively. Small differences are seen between these two images. There are two poles, black and white, and only one magnetic domain within the rectangular indicator at room temperature [fig. 5 (a)]. As shown in fig. 5 (b), a narrow magnetic domain appeared in the middle of the rectangular indicator. There are four poles within the same area at 308 K. It means that two nodes appeared in the magnetic moments wave inside the rectangular defect. It is due to the pinning of magnetic poles at the edges of the

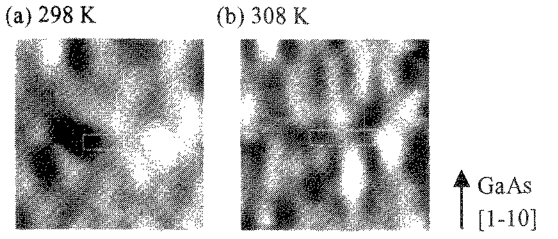

Fig. 5 Detail MFM images (1x1 μ m^2) around the same rectangular defect during phase transition. Rectangles in the images indicate the exact place and size of a defect. Magnetization direction is parallel to GaAs[1-10].

rectangular defect, original magnetic circuit was kept without change. Instead of changing the stable magnetic circuit, a new magnetic circuit appeared inside the original one. Therefore, only even-number magnetic poles are able to exist within a rectangular defect area. The original magnetic circuits are stable until the Curie temperature.

4. SUMMARY

We have investigated the changes in domain structure of an epitaxially grown MnAs thin film on GaAs(001) by variable temperature AFM/MFM in vacuum. The magnetic domain structure of the present sample shows a uniaxial anisotropy along GaAs[1-10] and [110]. The easy axis of magnetization is parallel to the GaAs [1-10]. The visible ferromagnetic-nonmagnetic phase transition occurred in a narrow temperature range between 313 K and 323 K. Local transitions due to the pinning of magnetic poles are observed on the present MnAs thin film with rectangular defects.

5. ACKNOWLEDGEMENT

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REFERENCES

[1] S. Miyanishi, H. Akinaga, W. Van Roy and R. Tanaka, Appl. Phys. Lett. **70**, 2046 (1997).

[2] H. Akinaga, S. Miyanishi, W. Van Roy, J. De Boeck and G. Borghs, Appl. Phys. Lett. **73**, 3285 (1998).

[3] H. Akinaga, M. Mizuguchi, T. Manago, T. Sato, H. Kuramochi, K. Ono, H. Ofuchi and M. Oshima, Physica **E10**, 447 (2001).

[4] H. Akinaga, T. Manago and M. Shirai, Jpn. J. Appl. Phys. **39**, L1118 (2000).

[5] C. Kittel, "Introduction to Solid State Physics", Wiley, New York (1976) pp. 439.

[6] M. Tanaka, J. P. Harbison, M. C. Park, Y. S. Park, T. Shin, G. M. Rothberg, Appl. Phys. Lett. **65**, 1964 (1994).

[7] G. Mayer and N. M. Amer, Appl. Phys. Lett. **53**, 1045 (1988).

[8] M. Yasutake, T. Yamaoka and Y. Nagatani, Jpn. J. Appl. Phys. **35**, 3783 (1996).

[9] F. Schippan, B. Hehme, L. Daweritz, K. H. Ploog, B. Dennis, K. U. Neumann and K. R. A. Ziebeck, J. Appl. Phys. **88**, 2766 (2000).

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