Magnetic structure of epitaxially grown MnAs on GaAs(001)

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We investigate in detail the occurrence of magnetic domains in epitaxially grown MnAs films on GaAs(001) by magnetic force microscopy (MFM). MnAs layers exhibit in their demagnetized state a very complex magnetic domain structure. High resolution MFM images reveal detailed information on the domain wall. Additionally, we imaged magnetic domains in the dependence on the applied magnetic field. This detailed investigation gives new insight into the correlation between film topography and magnetic domain structures. Systematic magnetization measurements in-plane and out-of-plane have shown high anisotropy in our films. The out-of-plane magnetization determined as a function of the applied field reveals that the direction of the magnetic moments in the domain walls are out-of-plane, thus the domain walls are determined as 180° Bloch type. [S0021-8979(00)07617-9]

I. INTRODUCTION

Thin magnetic layers on semiconductor substrates represent new challenges in material science and open up novel device concepts. In general these two material classes are very dissimilar in terms of crystal structure, chemical, and physical properties. Therefore their monolithic integration would appear to be difficult. However, high quality MnAs can be epitaxially grown on GaAs(001) substrates using molecular beam epitaxy (MBE).[1,2] Even in the form of thin films of nanometer thickness, MnAs is ferromagnetic with a Curie temperature close to the bulk value of $T_C = 318$ K.[3] Its magnetization exhibits a strong in-plane uniaxial anisotropy with the axis of easy magnetization lying in-plane, parallel to MnAs$[11\bar{2}0]$. To date, the structure of magnetic domains in MnAs layers has not been investigated. Here we present a systematic study of magnetic domains in MnAs films on GaAs(001) and their dependence on the applied magnetic field. The orientation of domain walls, which have been identified as being 180° Bloch type, is determined by magnetization measurements along various crystallographic directions.

II. EXPERIMENT

Ferromagnetic MnAs layers were grown on GaAs(001) substrates by using standard solid-source MBE. In order to ensure a clean surface a 100 nm thick GaAs buffer layer was first grown. During growth of the buffer the substrate temperature was fixed at $T_s = 550\,°C$ and the As_4/Ga beam equivalent pressure (BEP) ratio at 10. After the buffer growth the sample was cooled down to $T_s = 250\,°C$ within 20 min, leading to the GaAs(001)-$c(4\times4)$ surface reconstruction. On this As-rich template MnAs was grown with a growth rate of 20 nm h^{-1} at $T_s = 250\,°C$ and with an As_4/Mn BEP ratio of 90. Magnetization measurements on a macroscopic scale were carried out using a superconducting quantum interference device magnetometer (Quantum Design MPMS). The microscopic magnetic structure of the MnAs films was investigated at room temperature by employing the magnetic force microscopy (MFM) technique. This method is established and widely employed for studying domain formation in magnetic materials, especially in thin films.[4] The MFM contrast formation indicating the variation in magnetization is qualitatively well understood, whereas a quantitative analysis is more complicated.[5] A first order approximation for the additional force acting on a magnetized tip delivers a linear dependence of the force on the magnetic field gradient in the vertical direction. The z derivative of this force can be seen as an additional contribution to the cantilever spring constant and shifts its resonance frequency.[4] Thus a change of contrast indicates a change of magnetization, e.g., in a domain wall where the magnetization vector changes its direction. The microscope employed in this work was a commercial multimode AFM system (Park Scientific Instruments M5) operated in noncontact (NC) mode. The magnetic contrast is achieved by the use of Co coated, hard magnetic cantilevers (Park MFM Ultralever), which were magnetized perpendicular to the sample surface. The tip was mechanically excited close to its free resonance frequency (typically between 80 and 100 kHz). Due to the interaction of the tip with a magnetic sample a shift of the resonance frequency occurs, leading to a decrease of the oscillation amplitude. This is directly translated into contrast by the NC-AFM feedback loop. It is necessary to distinguish between the influence of the topography of the surface and the image contrast generated by the magnetic interaction. In our experiments the surface topography was investigated by using a nonmagnetic tip. Using the magnetized tip, magnetic images were obtained for different tip–sample separations (typically

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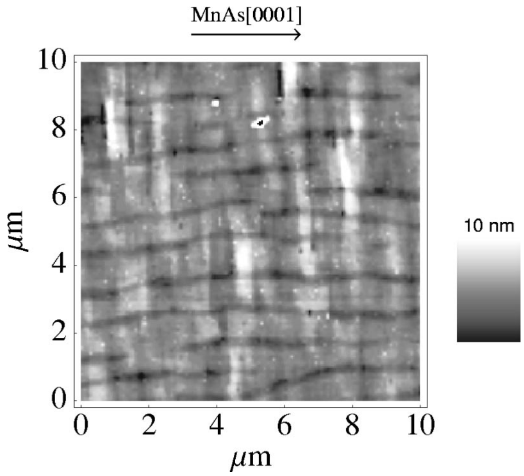

FIG. 1. Topography imaged by AFM of a 100 nm thick MnAs film grown on GaAs(001). Regular arranged furrows, indicated by dark lines, are visible along MnAs[0001].

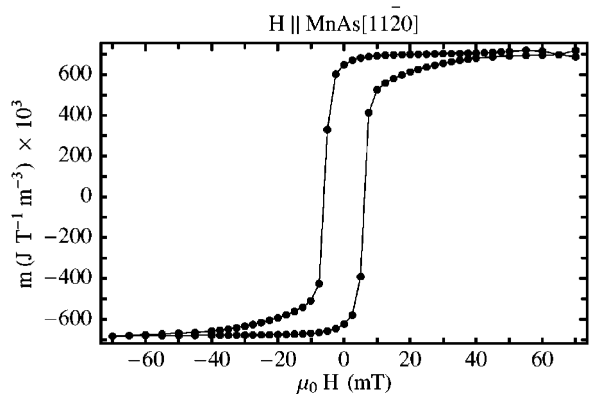

FIG. 2. Magnetization M measured as a function of the applied magnetic field ($\mu_0 H$) along MnAs[11$\bar{2}$0] of a 100 nm thick MnAs film.

20–50 nm). The observed modulation depth for the magnetic signal is approximately one order of magnitude higher than that for the topography study and amounts to 80 nm. This is taken to indicate a strong magnetic signal originating from the sample. By comparing the different interaction lengths the separation between topography and magnetic contrast becomes clear. Van der Waals forces, leading to topography contrast, have to be taken into account below a length of 10 nm, whereas the magnetic interaction length is one order of magnitude higher.[4] This ensures that at larger tip–sample distances only the magnetic signal is detected. In order to achieve a higher stability of the feedback loop a small bias voltage was applied between tip and sample (typically −1 to 5 V). This biasing keeps the net force on the cantilever always positive so that the feedback loop can keep it constant.

III. RESULTS AND DISCUSSION

A. Structural properties

The epitaxial orientation of MnAs with respect to the substrate has been determined by reflection high-energy electron diffraction during growth and by postgrowth transmission electron microscopy studies. These investigations showed the orientation to be MnAs($\bar{1}$100) || GaAs(001) and MnAs[0001] || GaAs[1$\bar{1}$0] (type A orientation[6–8]). The surface topography of a 100 nm thick MnAs film imaged by AFM is shown in Fig. 1. Broad regular arranged furrows are visible along the MnAs[0001] direction. The furrows are characterized by a depth of 4–7 nm and by a width of 100–200 nm, respectively. The large difference between depth and width of these flat furrows ensures a small roughness. The determined root-mean-square roughness of this 10 μm ×10 μm scan amounts to 1.04 nm, a reasonable value for epitaxial growth.

B. Magnetization measurements

The measurements reported here were all performed at room temperature. All signals were corrected for the diamagnetic contribution of the GaAs substrate. The magnetization of several substrates was determined in separate experiments. The diamagnetism of GaAs is five orders of magnitude weaker compared to the ferromagnetism of MnAs. However, the volume ratio between film and substrate ($\sim 10^{-4}$) compensates for the strong ferromagnetic signal of the film at high fields. Several measurements were conducted in which the magnetic field was applied along different crystallographic axes of the films. Thus the direction dependence of magnetic moments was obtained leading to the following results.

First, a nearly perfect square hysteresis loop is observed by applying the magnetic field in-plane along MnAs[11$\bar{2}$0] the easy axis of magnetization, as shown in Fig. 2. The saturation magnetic moment at 60 mT has been determined as 2.58 μ_B/Mn atom. This value compares favorably with the magnetization reported for bulk MnAs at room temperature namely 2.44 μ_B/Mn atom.[3] The small difference between the two values is probably attributed to the improved crystal quality of our single-crystalline epitaxial films compared to the polycrystalline bulk material.

Second, applying the field in-plane but parallel to the hard axis of magnetization along MnAs[0001] leads to completely different magnetic behavior. An approximately 100 times stronger field of 2 T is required to align all moments along the external magnetic field direction. This demonstrates the high structural purity, concerning crystalline phases and epitaxial orientation, of our MnAs films. The results are presented in Fig. 3 and are labeled as ''⊥.'' The curve labeled ''raw data'' represents the as-measured data without the correction for the diamagnetic contribution of GaAs. In addition to the low field measurement shown in Fig. 2 with $H||$ MnAs[11$\bar{2}$0] a measurement at high fields has been performed, labeled by ''||.'' Both measurements, ranging from −3 T to 3 T along the hard and easy axis of magnetization, allow the determination of the effective anisotropy constant K_{eff} of the film according to

$$K_{\mathrm{eff}} = \int_0^{m_s} \mu_0 H \, dm. \qquad (1)$$

Solving the integral graphically, as denoted by the gray area in Fig. 3, yields $K_{\mathrm{eff}} \approx (740 \pm 20) \times 10^3$ J/m^3.

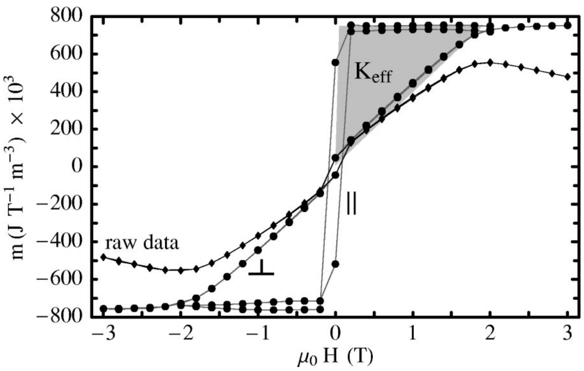

FIG. 3. In-plane magnetization with the magnetic field parallel (||) and perpendicular (⊥) to $[11\bar{2}0]$ at high magnetic fields. The width of the curve around zero field with the magnetic field parallel to the easy axis of magnetization (||) arises from the large step size used for these measurements (compare to Fig. 2).

Third, an out-of-plane measurement with the magnetic field perpendicular to the MnAs$(\bar{1}100)$ growth plane is shown in Fig. 4. Due to geometric limitations of the magnetometer a much smaller sample volume had to be used. For this setup the demagnetization factor perpendicular to MnAs $(\bar{1}100)$, $\mathcal{N}_c$, and the sample stray field has to be taken into account.[9] Due to the ratio between length and thickness $(\sim 10^4)$ the value for $\mathcal{N}_c$ amounts to one. At approximately $H = 1.5$ T the diamagnetic contribution of GaAs compensates the ferromagnetic signal of MnAs and the combined measured signal is close to zero. In this field region the tiny magnetic signal causes an increase in the relative error as seen in the raw data set (thin curve) in Fig. 4. However, it can be clearly seen that the film is magnetically saturated at about 1 T.

C. MFM investigations

We have imaged the magnetic structure of MnAs layers in its demagnetized state by using MFM. The demagnetized state has been attained by heating the film to a temperature well above the bulk Curie temperature of 318 K.[3] Subsequently the film was cooled to room temperature in zero field to ensure that on a macroscopic scale no preferred magnetic moment direction existed in the sample. The resulting scans carried out first along the *x* and subsequently along the *y* directions are shown in Figs. 5(a) and 5(b). Their similarity verifies that there is effectively no influence of the magnetic tip on the film. In its demagnetized state MnAs forms a very complex magnetic structure. Areas with a homogeneous magnetization are imaged gray, whereas bright contrast indicates a change of the magnetic moment orientation.[4] There are two types of contrast features. The first type is characterized by bright contrast along the topographical furrows (Fig. 1). These contrast features are induced by crystallography. Within a furrow the magnetic moments are not parallel to each other, resulting in gradients that are detected by the MFM. The other type of contrast features are along the $[11\bar{2}0]$ direction. This direction is the easy axis of magneti-

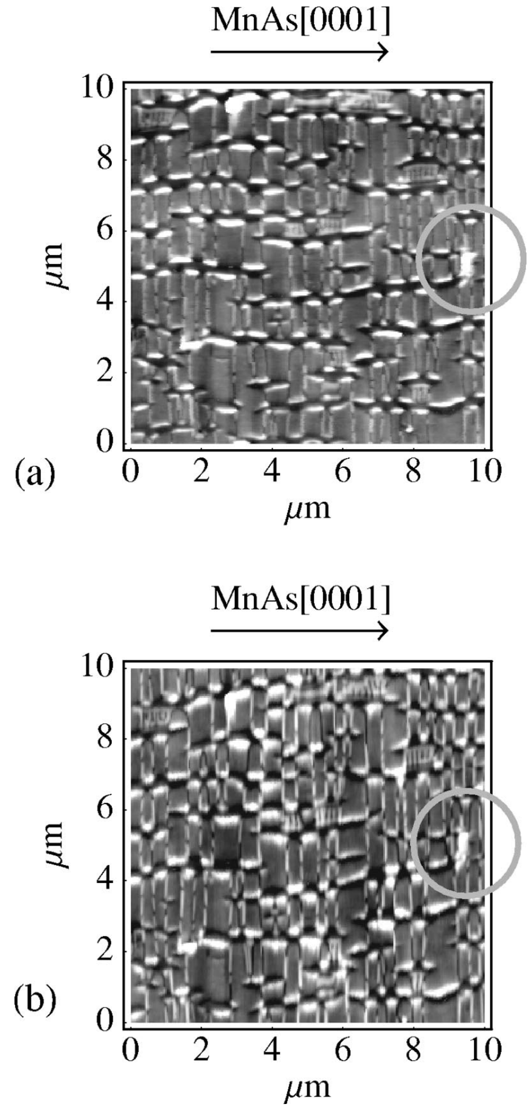

FIG. 5. Magnetic domains in a 100 nm MnAs film grown on GaAs(001) imaged by MFM at room temperature. Two different scans in *x* (a) and *y* direction (b) have been performed and the similarity of both scans shows that there is negligible interaction between the hard magnetic tip and the magnetic film. For a convenient comparison two gray circles in *x* and *y* scans surround a characteristic feature.

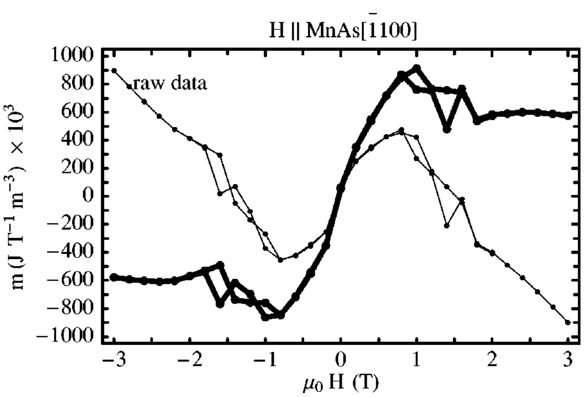

FIG. 4. Magnetization measurement of a 100 nm MnAs film with the magnetic field out-of-plane, parallel to MnAs$[\bar{1}100]$. The curve labeled with ''raw data'' presents the as-measured data. They include the diamagnetic contribution of the GaAs substrate and the demagnetization factor, which has to be taken into account for the out-of-plane setup. The correction with respect to these two contributions leads to the thick curve.

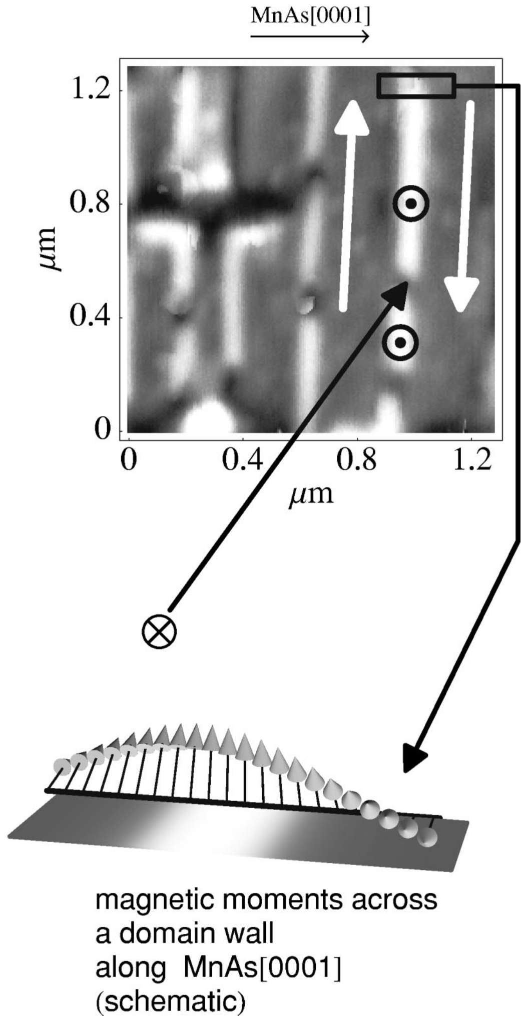

FIG. 6. MFM measurement of a domain boundary. The orientation of two neighbored domains is indicated by white arrows. The direction of the magnetic moments in the domain wall is shown by in-plane (⊗) and out-of-plane (⊙) pointers, respectively. The pointers are schematically emphasized on the right hand side, representing a cross section of the wall.

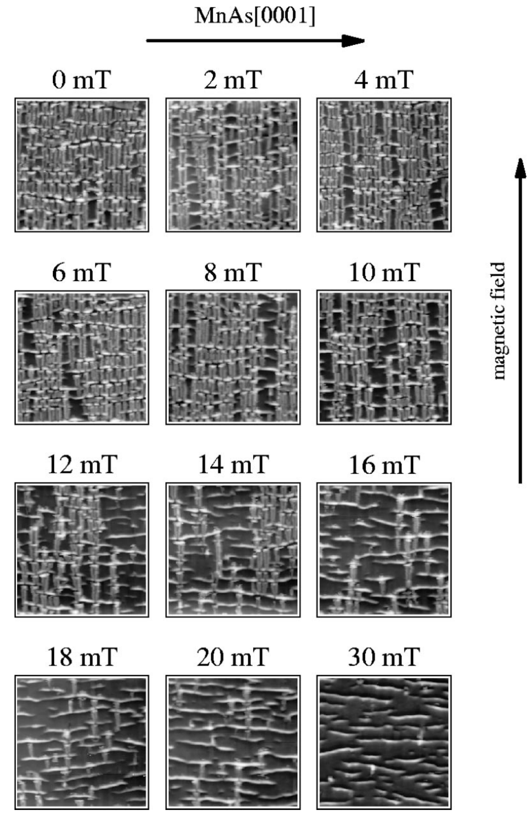

FIG. 7. MFM images of the MnAs($\bar{1}100$) surface taken over a scan area of 10 μm × 10 μm. The images have been obtained after applying a magnetic field outside of the MFM instrument with different field strengths parallel to MnAs[$11\bar{2}0$]. The field strength used to magnetize the sample is indicated in every image.

zation, in which the moments lie in zero field. In the demagnetized state the average domain size amounts to 0.5 μm× 1.5 μm. In order to analyze the contrast more precisely a high resolution MFM image has been taken (Fig. 6). In this figure two neighboring domains are indicated by white arrows. The magnetic moments are oriented opposite to each other with a relative direction as indicated in Fig. 6. The magnetic moment in the center of a domain wall is oriented perpendicular to the surface as revealed in the following. Magnetization measurements in Figs. 3 and 4 have shown that the alignment of magnetic moments along MnAs[0001] is energetically most unfavorable. If the 180° rotation of magnetic moments between two neighboring domains were in-plane, then the moments would be parallel to MnAs[0001]. The other possibility of a 180° rotation can be realized by an out-of-plane rotation, as schematically shown at the right hand side of Fig. 6. This possibility is energetically more favorable as the in-plane rotation of magnetic moments, as already shown by the direction dependence of the magnetization in Figs. 3 and 4. The moment alignment along MnAs[0001] requires a field of 2 T, whereas the alignment out-of-plane needs only half this value (Figs. 3 and 4). The rotation of magnetic moments out-of-plane results in a significant magnetization contribution perpendicular to the film as detected by the MFM. The corresponding change of direction within the domain wall is schematically shown on the right hand side of Fig. 6 for the out-of-plane component. This high resolution image, which is close to the resolution limit of the instrument, shows further details of the domain wall. The measurements reveal an internal structure within the domain wall. The direction of magnetization changes along MnAs[$11\bar{2}0$] as indicated by the in (⊗) and out (⊙) arrows in Fig. 6. Similar observations of such internal reconstructed domains walls were found for different materials, e.g., permalloy or Fe films.[9] Explanations for internal domain walls structures are based on the maximum stray field reduction within a domain in which the walls are involved.[9]

MFM investigations of a 10 μm×10 μm scan area have been performed in order to image the domain dependence on applied magnetic field at room temperature. In this systematic investigation we measured a 100 nm thick MnAs film by using MFM for different magnetization states. At first, the sample has been measured in its demagnetized state and was taken out of the instrument for magnetization. Placing the sample within a long solenoid having a winding number of $N=130$ the magnetic field was generated by passing a current I, ranging from 0 to 30 A corresponding to 0–30 mT. The orientation of the sample was such that the magnetic field was applied parallel to the easy axis of magnetization, i.e., along MnAs$[11\bar{2}0]$. After slowly reducing the current to zero the sample was removed out of the coil and replaced in the instrument for investigation. This procedure was repeated for every applied field. The magnetic field was increased from zero field to 20 mT in steps of 2 mT. Finally, one image has been taken after applying a field of 30 mT. The MFM image series is shown in Fig. 7. A stepwise reduction of domain walls along MnAs$[11\bar{2}0]$ is observed. The reduction in the density of domain walls along MnAs$[11\bar{2}0]$ in Fig. 7 can be seen between 8 and 16 mT. The interplay between the topographical furrows and the magnetic contrast becomes more evident. In the fully magnetized state at 30 mT in Fig. 7 bright contrast appears at the furrows. This fact is explained as follows: in the fully magnetized sample all domain walls are vanished because they aligned along the direction of the applied field, except for the moments in a furrow. The surface across a furrow is not perfectly flat and vertical component of magnetization occurs, imaged by MFM contrast. This shows the influence of topographic features on the microscopic magnetic properties. Additional AFM measurements are strongly required in order to understand the as-measured MFM contrast in more detail. In our case the furrows seem to provide a ''natural confinement'' for the magnetic domains in the demagnetized state of MnAs. But in the magnetically saturated case the furrows induce contrast due to the structural deviation of magnetic moments from the easy axis of magnetization.

IV. CONCLUSION

We have investigated the directional dependence of the magnetization in epitaxially grown MnAs films on GaAs(001). Three different measurements combining with MFM images have shown that the magnetization in a domain wall is perpendicular to the surface. Thus the domain walls are of the 180° Bloch type as shown by high resolution MFM measurements. The application of an external magnetic field results in a completely different magnetic structure of the MnAs film. The process of the removal of magnetic domain walls has been observed in detailed MFM studies. Such changes in the domain structure take place on a length scale of $\sim 1\ \mu$m. The magnetization pattern reveals the mutual influence of magnetic and structural topography. Our systematic MFM investigations, presented here, allow a new insight into the complicated context of domain and domain wall formation governed by topography in single crystalline MnAs films.

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