Temperature-dependent magnetic force microscopy investigation of epitaxial MnAs films on GaAs(001)

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(Received 9 September 2002; accepted 11 February 2003)

We present variable-temperature magnetic force microscopy (VT-MFM) studies of epitaxially grown MnAs films on GaAs(001). Around a critical temperature of $T_c = 40\,°C$, the MnAs film undergoes a first order structural phase transition. Due to the strain involved, ferromagnetic α-MnAs and paramagnetic β-MnAs phases coexist as stripes along MnAs[0001]. The dimensions of the α-phase change from isolated dots at higher temperatures to well ordered stripes at lower temperatures. VT-MFM allows a close look at the evolution of domain patterns of MnAs micromagnets. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1564642]

Hybrid semiconductor ferromagnet structures, like the MnAs/GaAs system, are promising for future spin electronics.[1–3] Great progress has been made in the epitaxial growth of this material system by molecular beam epitaxy (MBE).[4,5] Systematic in-plane and out-of-plane magnetization measurements combined with magnetic force microscopy (MFM) imaging shed light onto the magnetic structure of the films.[6] Recently, it turned out that the phase transition between orthorhombic paramagnetic β-MnAs and hexagonal ferromagnetic α-MnAs at about 40 °C is of great importance for the structural and magnetic properties of the films.[7–9] In strained films, the two phases coexist over a certain temperature range. In combining x-ray diffraction, atomic force microscopy (AFM), and MFM measurements, a strong correlation between the phase composition, topography, and magnetic structure of the films became evident at room temperature.[9] A self-organization mechanism was discovered that separates the coexisting phases into a periodic array of stripes along the MnAs[0001] direction, leading to characteristic surface corrugation.[7–9] The periodicity of the stripes increases linearly with the MnAs film thickness and ranges from roughly 300 nm for 50 nm thick films to 800 nm for 140 nm thick films.[10] The ridge-groove structure corresponds to α- and β-MnAs, respectively. Temperature-dependent scanning probe microscopy measurements gave direct evidence of the formation of elastic domains at the phase transition.[11] Recently, a combined low energy electron microscopy and magnetic circular dichroism photoemission electron microscopy study gave detailed insight into the structural and magnetic phase transition.[12]

In this letter, we present variable-temperature MFM (VT-MFM) measurements of MnAs films on GaAs(001) grown by MBE. VT-MFM allows the measurement of topography and magnetic contrast of the same spot on the sample as a function of the temperature and gives an insight into the interplay of micromagnetic and structural features.

MnAs layers (130 nm thick) were grown on GaAs(001) substrates employing standard solid-source MBE. The growth conditions lead to unique epitaxial *A* orientation with MnAs$(\bar{1}100)\|$GaAs(001) and MnAs$[0001]\|$GaAs$[1\bar{1}0]$.[4] The surface topography and microscopic magnetic structure were studied by MFM.[6] MFM is based on noncontact force microscopy that employs ferromagnetic probes usually magnetized along the tip axis, and delivers the topography or magnetic contrast depending on the working conditions (setpoint and amplitude). Because the forces that act on the magnetic tip show linear dependence on the magnetic field gradient in the vertical direction, the MFM is primarily sensitive to out-of-plane magnetization components. In order to study the phase transition of MnAs on GaAs, we added a temperature-controlled stage to the MFM (VT-MFM). The stage allows sample temperatures ranging from 80 to 580 K in a controlled atmosphere and very little thermal drift.[13]

The image of the topography [Fig. 1(a)] shows alternating ridges and grooves oriented along the MnAs[0001] direction. This is due to the strain-mediated coexistence of two structural phases of MnAs, namely, α-MnAs, a ferromagnetic hexagonal material, and β-MnAs, a paramagnetic material with an orthorhombic unit cell.[7] The lattice constants of the two MnAs phases in the hexagonal plane differ by 1.2%, thereby inducing the contrast in topography. A finer structure, oriented in the MnAs$[11\bar{2}0]$ direction, is superimposed and corresponds to a vicinal $[1\bar{1}00]$ surface with monolayer steps running preferentially along $[11\bar{2}0]$.[9,10]

The magnetization of the films was measured on a macroscopic scale using a superconducting quantum interference device (SQUID) magnetometer. On GaAs[001], MnAs exhibits strong uniaxial in-plane anisotropy with the $[11\bar{2}0]$ axis being an easy axis, $[\bar{1}100]$ a middle hard axis (out-of-plane direction), and [0001] a hard axis of magnetization (in plane along the stripes).[6] The MFM pictures [Figs. 1(b) and 1(c)] show a complex magnetic domain structure on the ferromagnetic ridges [cf. with Fig. 1(a)], while the paramagnetic grooves show no significant magnetic contrast. Two predominant domain structures are visible at room temperature: (I) meander-like structures and (II) elongated structures. The contrast in the meander is due to domains of opposite magnetization in the direction of the easy axis. The lower sketch in Fig. 1(c) illustrates this configuration. Alternating bright and dark areas (parallel to [0001]), due to the stray field of the antiparallel magnetized bar magnets, are visible

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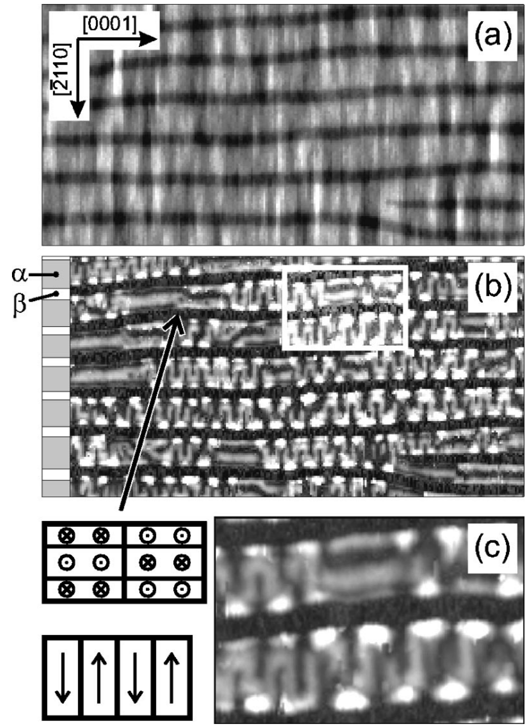

FIG. 1. $10\times 5\ \mu m^2$ scans of a 130 nm thick MnAs film at room temperature (21 °C) in (a) noncontact mode that delivers topographical contrast and (b) MFM mode at zero magnetic field. The α and β stripes are marked. (c) Details of the domain structure [indicated in (b)] along with a schematic picture of the two predominant domain patterns ($2.5\times 1.7\ \mu m^2$ scan).

at the ends of the domains. Between the domains, that is, along the domain walls, bright and dark features are visible which are due to out-of-plane moments of opposite sign. Since the out-of-plane direaction is a medium axis of magnetization, the rotation of the magnetic moment inbetween two neighboring domains of opposite magnetization takes place via out-of-plane rotation (180° domain walls of the Bloch type). On the other hand, wide domains are visible that extend in the MnAs[0001] direction over a few type (I) domain periods. These elongated domains [type (II)] show three stripes (bright-dark-bright or dark-bright-dark) and are more or less symmetric with respect to the [0001] domain axis. The boundary of two type (II) domains of opposite sign is indicated by the arrow in Fig. 1(b). In general, the appearance of type (II) domains can be linked to narrow ridges [cf. Fig. 1(a)]. The magnetic contrast is due to effective out-of-plane moments in the film, as seen in Fig. 1(c). Their origin is not yet understood and could be due to out-of-plane domains in the direction of the middle hard axis [$1\bar{1}00$] or a domain configuration involving the [$\bar{2}110$] and [$\bar{1}\bar{1}20$] directions. Also, local crystallographic misorientations of MnAs could lead to such a magnetic contrast. Another possible configuration could be the breakup of a type (I) domain into two smaller antiparallel type (I) domains, where the fine structure can no longer be resolved with MFM.

To study the temperature evolution of the structural and micromagnetic properties of the film, we performed variable-temperature MFM measurements. The measurements directly show the coexistence of the ferromagnetic and the paramagnetic phases of MnAs over a wide temperature range (≈30 °C) below the phase transition temperature. The structural composition in the coexistence region, as well as the micromagnetic properties, exhibit temperature hysteresis. Thus, to prepare identical starting conditions for the temperature cycling experiments, we heated the sample to ≈50 °C in order to eliminate ferromagnetism and then cooled it down to room temperature. No difference was found when the heating and cooling steps were performed at different rates (with the temperature stage employed).[13]

In general, for temperatures around room temperature and below, primarily type (I) domains (meander like) are found. The width of the domains (in the [0001] direction) is 190 nm independent of temperature. With a decrease in β-MnAs content, i.e., vanishing grooves interaction of the domains across the ridges increases and the bar magnets align in dipolar fashion. Above room temperature, i.e., when the ferromagnetic ridges are becoming narrow, the number of type (I) domains decreases and type (II) (elongated) domains dominate. Above ≈32 °C, another elongated domain type completely takes over, one that condenses into ferromagnetic dots which finally disappear several degrees above T_c. Upon subsequent cooling, a large number of the ferromagnetic seeds reappear at the same spot, however, the local structural and magnetic properties are not strongly correlated with this initial distribution of α-phase seeds.

VT-MFM scans of a cooling sequence are shown in Fig. 2 ($10\times 10\ \mu m^2$). From above T_c, the temperature was lowered in successive 2 °C steps. At 41 °C, i.e., above T_c of the bulk, the MFM image shows small dot-like regions of magnetic contrast, presumably ferromagnetic "condensation seeds" (see the upper right-hand side arrow). Slightly below T_c, at 39 °C, the number of ferromagnetic dots increases and forms chains elongated in the MnAs[0001] direction (see, e.g., the dot aggregation close to the upper right-hand side arrow). According to the phase transformation model for MnAs given by Bean and Rodbell,[14] the exchange energy and thus T_c are a function of strain, where T_c increases with tensile strain and vice versa. Since the phase transformation from β- to α-MnAs starts at particular spots in the film and expand the material 1.2% (see Fig. 2, 41 °C), the surrounding material gets compressed and the local T_c is lowered. Between 39 and 37 °C, the chains transform into ferromagnetic stripes with average length of 5 μm. Another effect of the strain dependence of T_c is the temperature hysteresis of the film as a whole. The difference in temperature between the disappearance of the ferromagnetic stripes upon heating and their reappearance upon cooling was determined to be 2 °C. At 37 °C, a domain structure very similar to the type (II) domain pattern at room temperature is dominant. These type (III) domains consist of two instead of three stripes and effective out-of-plane magnetization. The width of these domains increases as the ridges grow together upon further cooling (upper left-hand side arrow). However, type (II) domains start forming at around 31 °C, ending type (III) growth (lower left-hand side arrow).

The striped structure that starts forming around 37 °C is remarkably regular at lower temperatures. First, well ordered areas appear that stretch over a few stripes. With further cooling these ordered areas begin to interpenetrate in the MnAs[0001] direction. The two arrows pointing toward each other indicate this kind of ordered stripe boundary. At 33 °C many pairs of interpenetrating stripes have grown together

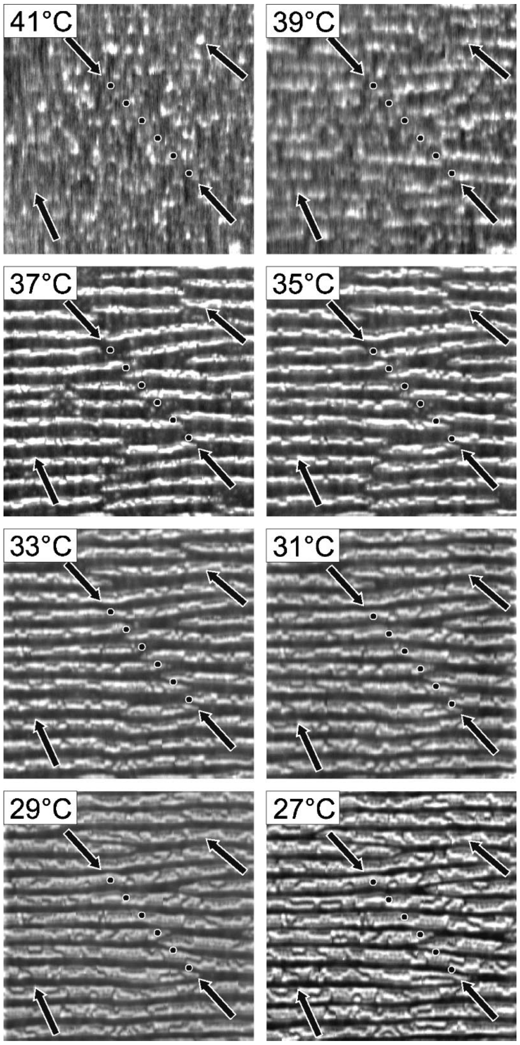

FIG. 2. $10\times10\ \mu m^2$ scan series of MFM images at various temperatures ranging from above $T_c\approx40$ down to 27 °C. The arrows and dots mark fixed positions on the sample in order to better visualize changes to the micromagnetic pattern.

and formed larger connected stripes. Supernumeral stripes terminate and form ''edge dislocations'' in the ordered stripe pattern (see lower right-hand side arrow in Fig. 2 at lower temperatures).

In summary, we have studied the temperature dependence of the micromagnetic properties of epitaxially grown MnAs films on GaAs(001) by MFM. These films exhibit elastic domains of coexisting ferromagnetic α-MnAs and paramagnetic β-MnAs phases, resulting in periodic surface corrugation. Temperature-dependent MFM gave insight into the evolution of the structural and magnetic domains as the sample was cooled from above $T_c\approx40\,°C$. Initial domain condensation took place at localized spots, developed into chains and finally extended into ferromagnetic stripes. The stripes merged together and attained a well-ordered periodic state at room temperature. Mainly three different domain types were found and they governed defined temperature ranges.

The authors thank M. Ramsteiner and A. Ney for valuable discussions.

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