Periodic elastic domains of coexisting phases in epitaxial MnAs films on GaAs

T. Plake,[a] M. Ramsteiner, V. M. Kaganer, B. Jenichen, M. Kästner, L. Däweritz, and K. H. Ploog
Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, D-10117 Berlin, Germany

(Received 20 September 2001; accepted for publication 5 February 2002)

The surface topography of epitaxial MnAs films on GaAs(001) is studied by scanning probe microscopy. We provide direct experimental evidence for temperature-dependent elastic domains of the coexisting ferromagnetic αMnAs and paramagnetic βMnAs phases. The results agree well with a theoretical model for the elastic equilibrium of periodic domains. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1467699]

Hybrid semiconductor-ferromagnet structures are of considerable contemporary interest because of their relevance for spintronic semiconductor applications that rely on spin injection from a ferromagnet into a semiconductor.[1] In this context, MnAs is a promising magnetic material because of the high ferromagnetic transition temperature ($T_C \approx 40\,^\circ$C), the relatively small coercive field (50 Oe), and the applicability of molecular-beam epitaxy for the growth of hybrid structures with semiconductors.[2,3]

Bulk MnAs crystals occur in three different phases: The ferromagnetic hexagonal phase αMnAs at temperatures $T < T_C$, the paramagnetic orthorhombic phase βMnAs in the range $T_C < T < 125\,^\circ$C, and the paramagnetic hexagonal phase γMnAs for $T > 125\,^\circ$C.[4] The structural phase transition at T_C is of first order. In contrast, for epitaxial MnAs films, a qualitatively different phase transition has been found recently by x-ray diffraction.[5] Instead of an abrupt transition, the coexistence of two structurally distinct phases, hexagonal αMnAs and orthorhombic βMnAs, occurs in a range from the bulk phase transition temperature T_C to as much as 20 °C below it. The two phases manifest themselves in two clearly distinguishable x-ray diffraction peaks, which leads to the conclusion that the domains of the two phases are of widths considerably larger than film thickness. The difference of the lattice parameters of both phases gives rise to a different thickness for each domain resulting in a height difference at the surface of about 1% film thickness. From that we expect a temperature dependent characteristic deformation of the sample surface, which can be measured by scanning probe microscopy.

In this letter, we present direct experimental evidence for the formation of elastic domains in epitaxial MnAs layers. We observe a periodic temperature-dependent corrugation of the MnAs surface and the spatial distribution of the coexisting phases.

The MnAs films were grown on GaAs(001) substrates on top of a 100-nm-thick GaAs buffer layer by using standard solid-source molecular-beam epitaxy at a temperature of about 250 °C and a growth rate of 20 nm/h.[3] The epitaxial orientation of MnAs with respect to the substrate has been determined to be MnAs$(\bar{1}100)\|$GaAs(001) and MnAs$[0001]\|$GaAs$[1\bar{1}0]$.[6] MnAs films of two different thicknesses, 100 and 180 nm, were studied by temperature-dependent scanning probe microscopy (SPM). The SPM experiments were carried out in a microscope designed for low-temperature scanning near-field optical microscopy using a scanning stage based on an OMICRON LT-STM (low-temperature scanning tunneling microscope). The temperature of the sample and the scanning stage was controlled by a CRYOVAC continuous-flow He cryostat. The topography of the sample surface was measured using bare tapered optical fiber tips, and the tip-sample distance control was achieved using a piezoelectric tuning-fork shear-force sensor.[7] The obtained images are comparable to those measured by dynamic atomic force microscopy at room temperature.

SPM images of the surface topography for the 180-nm-thick MnAs film at different temperatures are shown in Fig. 1. The sample was gradually cooled from 50 °C down to 5 °C. For sample temperatures of $T < 12\,^\circ$C and $T > 40\,^\circ$C, the SPM images reveal a surface morphology characterized by an array of mound-like features, which are strongly elongated in MnAs$[11\bar{2}0]$ direction and 200 nm wide along the perpendicular MnAs$[0001]$ direction. These topographic features, with a height of the order of 1 nm, are assigned to a vicinal MnAs$(1\bar{1}00)$ surface with monolayer steps running preferentially along $[\bar{1}1\bar{2}0]$ and leading to symmetrically inclined $(h\bar{h}0l)$ or $(hh0\bar{l})$ facets or bunches.[8]

At intermediate temperatures this shallow topography is superimposed by a predominating surface corrugation of the MnAs film with stripe-like features oriented along the MnAs$[0001]$ direction [cf. Figs. 1(b)–1(e)]. When cooling down the sample from T_C, small ridges start to form. In this early stage the ridges are of limited length and not ordered, although well oriented in the MnAs$[0001]$ direction. With further decrease in temperature, the ridges develop into long stripes and form a regular corrugation. The width of the stripes increases with decreasing sample temperature, and finally the stripes merge at about 10 °C. In the following, we prove that the observed surface corrugation is a consequence of the phase coexistence in the MnAs film.

Figures 2(a) and 2(b) show temperature dependencies of the αMnAs phase fraction determined from the surface topography measurements. The surface area was divided into

[a]Electronic mail: plake@pdi-berlin.de

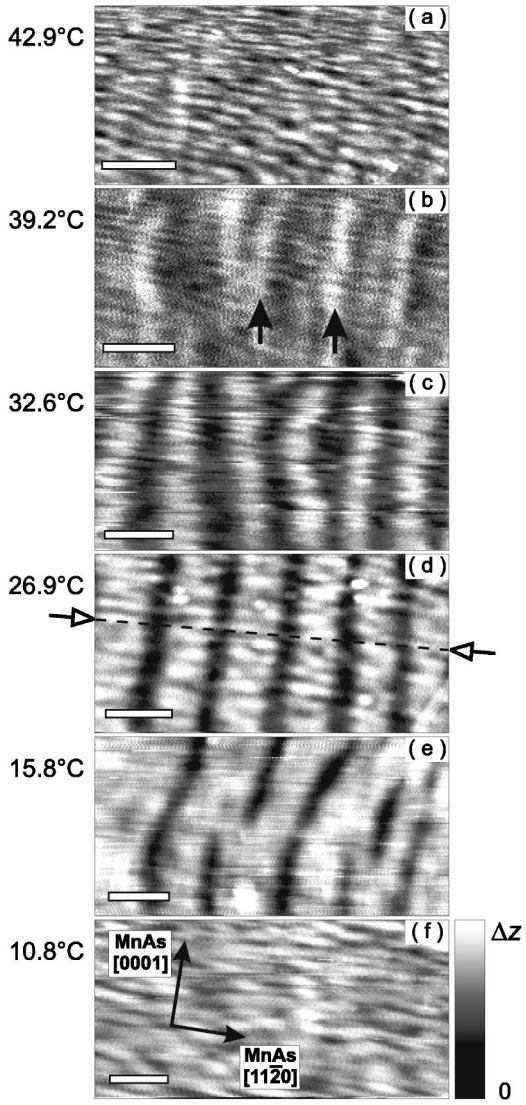

FIG. 1. Surface topography of a 180-nm-thick MnAs film at different sample temperatures. The height ranges Δz are (a) 4.0, (b) 2.8, (c) 3.2, (d) 4.7, (e) 3.4, and (f) 3.8 nm, respectively. In (b) some of the ridges are indicated by arrows. The dashed line in (d) is a line scan taken for Fig. 2. The length of the scale bars is 1 μm.

grooves and ridges, whereas the area fraction of the ridges was interpreted as the fraction of the αMnAs phase. Thereby, grooves (ridges) are defined as areas with the surface height below (above) the mean value for the whole area scan. Figures 2(c) and 2(d) present the phase fraction obtained from the relative intensities of the x-ray diffraction peaks.[5] The fraction of αMnAs phase increases almost linearly on cooling and decreases on heating, with a phase coexistence range of about 35 °C and a temperature hysteresis of 5 °C. We find a quantitative agreement between the surface topography and the x-ray diffraction data for the 180-nm-thick sample. For the 100-nm-thick sample, the surface topography measurements reveal a larger temperature hysteresis compared to the one observed by x-ray diffraction. The generally unexpected hysteresis behavior may be caused by the initially irregular distribution of ridges (grooves) which we observe in early stages of the formation of the second phase. From the comparison with x-ray data, we can clearly identify the ridges (grooves) in the topographical images to belong to αMnAs (βMnAs).

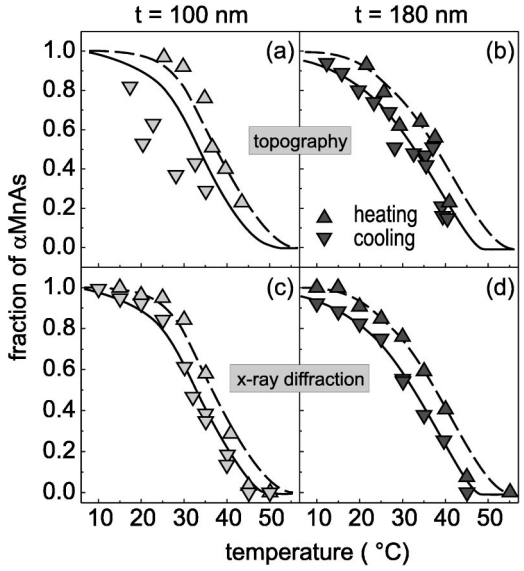

FIG. 2. Fraction of αMnAs as a function of sample temperature for a 100-nm-thick (left) and a 180-nm-thick (right) MnAs film as determined from the ridge area fraction of the corrugated MnAs surface (a, b) and by x-ray diffraction (c, d) for heating (triangles up) and cooling (triangles down) of the samples. The solid lines in (c, d) are guides for the eye. For comparison, the same lines are repeated in (a, b).

Figure 3(a) shows the surface height variation along the line indicated in Fig. 1(d). As stated above, the ridges correspond to domains of the αMnAs phase possessing the larger lattice spacing, and the grooves to the βMnAs phase domains. From this line scan, we determine the period of the domain structure to be 1.25 μm and the fraction of the αMnAs phase to be 0.69.

The problem of elastic equilibrium of periodic domains of two phases can be solved analytically. We expand the periodic variation of lattice spacings in the film from the domain of one phase to the other into Fourier series, solve the elastic equilibrium problem for each sinusoidal term separately in the film and in the substrate, and require continuity of displacements and tractions at the film-substrate interface. Details of the calculation are presented elsewhere.[9] The surface profile obtained from this solution is shown in Fig. 3(b). The calculation is performed for the domain period and the phase fraction obtained from the experimental curve [cf. Fig. 3(a)] without any fit. The good agreement in the amplitude of the height modulation and in the surface shape

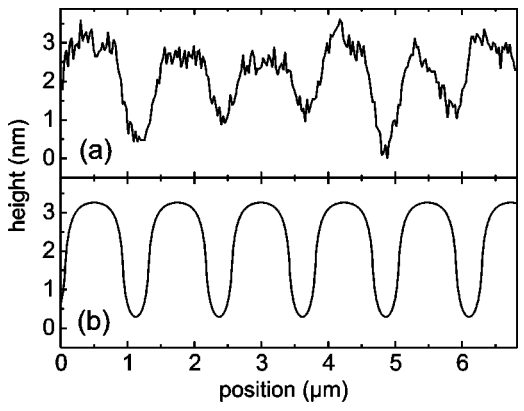

FIG. 3. (a) Surface height along the line indicated in Fig. 1(d) calculated by solving the elastic equilibrium problem.

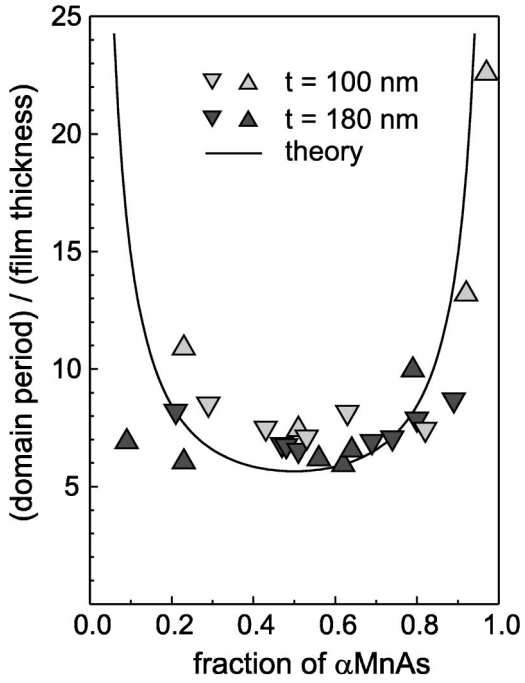

FIG. 4. Surface corrugation period normalized to film thickness as a function of the αMnAs fraction for both heating (triangles up) and cooling (triangles down) of the samples. The curve is the domain period which minimizes the elastic energy for a given phase fraction.

confirms our interpretation of the surface corrugations as domains of the two phases.

Figure 4 presents the surface corrugation period as a function of the phase fraction. The experimental data are compared with the domain period which corresponds to the elastic energy minimum for a given phase fraction.[9] The domain period normalized by the film thickness falls on a universal curve. The period reaches a minimum at equal fractions of the phases and increases when the fraction of either phase decreases. The good agreement between the measurements and the calculations proves that the corrugation period corresponds to the elastic energy minimum and hence the film is at equilibrium in the whole temperature range.

In conclusion, we have observed a temperature-dependent surface corrugation of epitaxial MnAs films on GaAs. Our results provide direct experimental evidence for the formation of periodic elastic domains as a signature of the coexistence of two structural MnAs phases. Good agreement is found with a theoretical model calculating the equilibrium state of MnAs films with periodic elastic domains.

The authors thank P. Voigt for his contribution to the data analysis, H. Kostial for the assistance with producing the fiber probes, and H. T. Grahn for helpful discussions.

[1] G. A. Prinz, Phys. Today **48**, 58 (1995).
[2] M. Tanaka, J. P. Harbison, T. Sands, T. L. Cheeks, V. G. Keramidas, and G. M. Rothberg, J. Vac. Sci. Technol. B **12**, 1091 (1994); M. Tanaka, K. Saito, and T. Nishinaga, Appl. Phys. Lett. **74**, 64 (1999).
[3] F. Schippan, A. Trampert, L. Däweritz, and K. H. Ploog, J. Vac. Sci. Technol. B **17**, 1716 (1999); A. Trampert, F. Schippan, L. Däweritz, and K. H. Ploog, Appl. Phys. Lett. **78**, 2461 (2001).
[4] H. Okamoto, Bull. Alloy Phase Diagrams **10**, 549 (1989).
[5] V. M. Kaganer, B. Jenichen, F. Schippan, W. Braun, L. Däweritz, and K. H. Ploog, Phys. Rev. Lett. **85**, 341 (2000).
[6] F. Schippan, G. Behme, L. Däweritz, K. H. Ploog, B. Dennis, K. U. Neumann, and K. R. A. Ziebeck, J. Appl. Phys. **88**, 2766 (2000).
[7] K. Karrai and R. D. Grober, Appl. Phys. Lett. **66**, 1842 (1995).
[8] L. Däweritz, F. Schippan, M. Kästner, B. Jenichen, V. M. Kaganer, and K. H. Ploog, *Proc. of the 28th Int. Symp. Comp. Semicond.* (IOP, Bristol, 2002), in press.
[9] V. M. Kaganer, B. Jenichen, F. Schippan, W. Braun, L. Däweritz, and K. H. Ploog (unpublished).