MBE growth and characterization of ferromagnetic MnAs layers on CaF_2:Si(111)

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Studies of epitaxial growth and properties of ferromagnetic thin films on semiconductors are very attractive because of possibility to integrate magnetic with semiconductor in the same electronic device [1]. The integration is expected to lead to quite new element base for opto- and microelectronics. Among known ferromagnetics, MnAs is the one that complies reasonably with the requirements which should be met for such kind of applications. Although investigations of polycrystalline MnAs magnetic films deposited on amorphous substrates were started a long ago, epitaxial MnAs layers on Si(100) and GaAs(100) were grown quite recently [2,3]. In these studies, it was found that conditions of formation of ferromagnetic / semiconductor interface influence greatly to structural and magnetic properties of grown layers.

In this paper, we investigate growth, crystalline structure and magnetic properties of epitaxial MnAs films on heteroepitaxial CaF_2/Si(111) substrates, that have been thoroughly studied before [4,5] , as well as on As-Si(111) substrates. It is demonstrated that by means of molecular beam epitaxy (MBE) such ferromagnetic films may be grown with high crystalline quality and well pronounced magnetic properties.

All the heterostructures were grown in a small research MBE system at Physico - Technical Institute. After conventional chemical treatment, Si substrates were loaded into the growth chamber where they were annealed at 1250°C to evaporate silicon oxide. This procedure allows to obtain atomically clean Si(111) surface with 7x7 superstructure. Crystalline quality of substrate as well as growth of both buffer layer and ferromagnetic film were monitored *in situ* by reflection high energy electron diffraction (RHEED) at electron energy 15keV. The RHEED patterns for $[1\bar{1}0]$ and $[11\bar{2}]$ azimuths showed streaks indicating the corresponding layer to be a single crystalline with surface being smooth in atomic scale. A profilometer was used to measure film thickness. For #702, #703, #717 structures (See Table 1) , MnAs was deposited at 300°C on a ~10 nm thick pseudomorphic CaF_2 buffer layer. The buffer layer was grown by two-step technique [5]. In other structures As-Si(111) surface was prepared following the method described in Ref. 2. In order to protect the grown layers from possible ambient contamination, MnAs film was covered with a few monolayers of CaF_2.

Table 1 Structural and magnetic parameters of the MnAs films.

Sample	Thickness, nm	$t_{\perp}$, nm	Strain $\varepsilon, 10^{-3}$	Tilt $\omega, 10^{-3}$ rad	c, Å base phase	H_C, Oe	M_S, emu/cc	M_R, emu/cc
702	750	15	0.4	2.3	5.71 (2)	30	700	130
703	400	40	1.2	2.7	α-MnAs (000L)	60	1100	750
717	380	>60	1.3	4.0		-	-	-
718	150	40	2.6	9.7	5.714(2)	-	–	–
722	160	45	1.6	5.0	α-MnAs(000L)	-	–	–
714	90	40	2.8	7.0	5.62(1) β-MnAs(001)	700	450	240

The samples were studied in single crystal geometry on High brilliance D/max P.C system (Rigaku Corp) X-ray diffractometer with copper target. The primary beam divergence was less than 5 arc. min. To determine both film crystallinity and its phase content, X-ray rocking curves were taken in wide angle range.

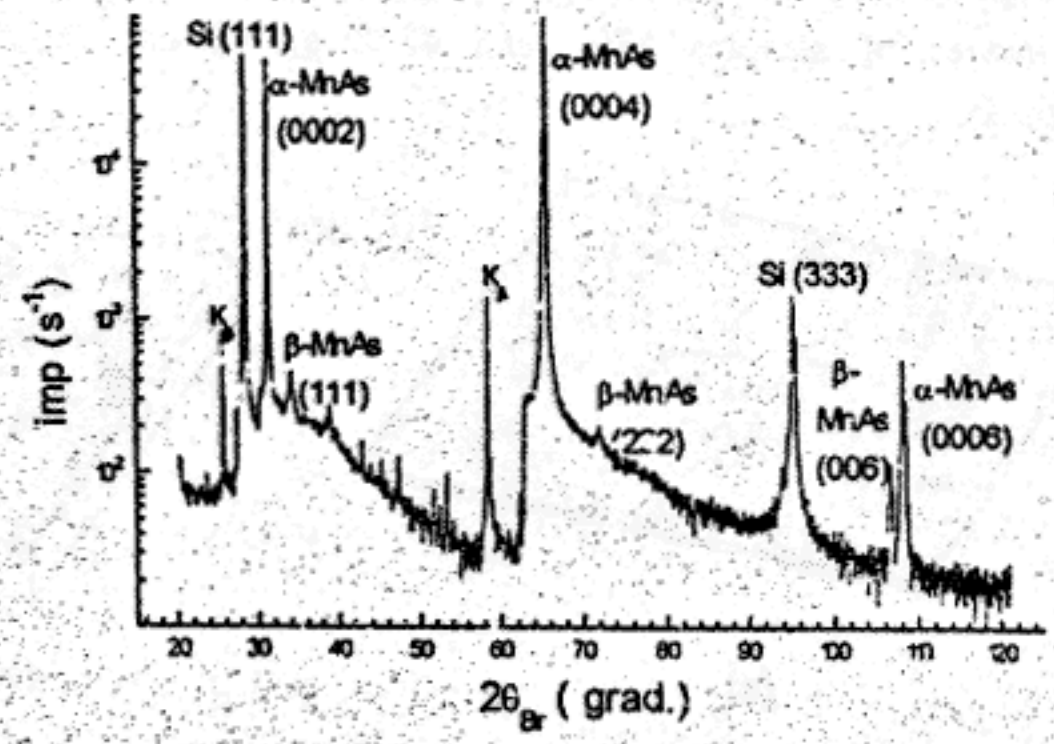

Fig.1 X-ray diffraction curve obtained from MnAs film on CaF_2/Si(111) substrate (sample #717).

Fig.1 presents a typical X-ray rocking curve obtained from a MnAs/CaF_2/Si(111) heterostructure (sample #717). Presence of (0002), (0004) and (0006) peaks on the curve shows that a single crystalline MnAs film was obtained with a hexagonal structure and (000L) growth direction. Pairs of peaks in several diffraction orders indicate that two phases are present in the film. Positions of main diffraction peaks give for the lattice parameter c value of 5.714±0.002Å that is the same as in α-MnAs. Smaller peaks on the tails of the main peaks correspond to

orthorhomboedral structure of β-MnAs which is close to that of α-MnAs [2]. The observed peaks originate from diffraction on (111) and (001) planes of paramagnetic phase. The distinctive features in rocking curves are also present for other samples where α-MnAs with hexagonal structure and (000L) growth direction seems to be the dominant phase while the β -MnAs phase proportion is less than 10%. The sole exception is provided by sample #714 where the β-MnAs phase dominates with lattice parameter c=5.62Å and prevailing growth of grains along (001) direction. The (000L) oriented α-MnAs phase and (111) oriented β-MnAs phase grains could be also observed in a small proportion.

For more detailed study of film structural quality, ω and (ω,2ω) rocking curves were measured in the vicinity of diffraction peaks of the dominant phase. The results were treated in mosaic-block crystal model. Grain size along the direction normal to substrate ($t_\perp$), microstrain existing in grains (ε), and grain misorientation (ω) were estimated and listed in Table 1. One can see that films grown on a CaF_2 buffer layer have better crystalline quality evaluated by smaller values of microstrain inside the grains and less misorientation of the latter. It is worth noting that grains of the second phase are two times smaller and have less perfect structure.

The surface morphology of the grown films was measured with an atomic force microscope (AFM) P4-SPM-MDT-16 operating in contact topography mode. Fig.2 presents AFM images of samples #702 and #722 grown on CaF_2/Si(111)(a) and As-Si(111)(b) respectively.

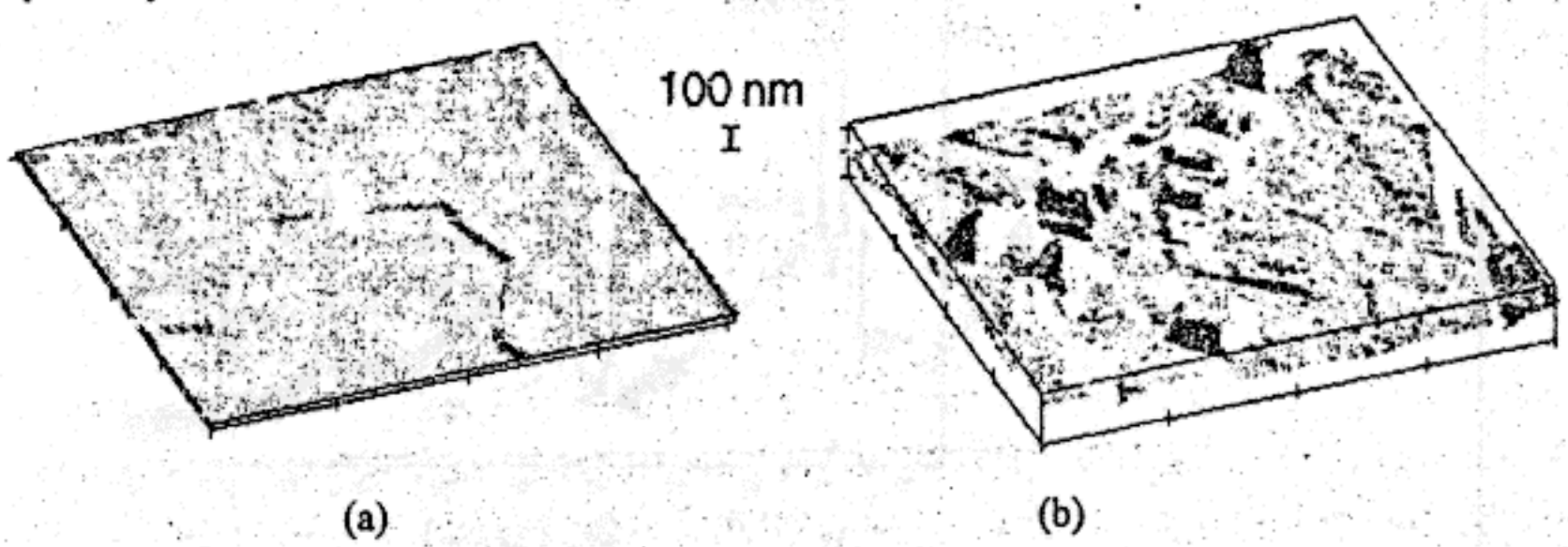

Fig.2 AFM images of samples #702 (a) and #722 (b). Scanned area 4 μ × 4 μ. Maximum height deviations are 30nm for (a) and 250nm for (b). Note for (a) typical height deviation is only 10nm.

Characteristic six-fold faceting observed on the images confirms the X-ray results described above. One can see the film grown on CaF_2 buffer layer is much smoother with typical deviation of the height only 10 nm. Besides it was found that 4° misorientation of substrate surface with respect to Si(111) plane for sample #714 leads to formation of phase with a distorted pseudo-cubic structure. This is in agreement with X-ray diffraction measurements indicating that β-MnAs (001)-oriented phase prevails in the sample.

The magnetization of 3x1x0.3 mm size pieces of the studied samples was measured at room temperature with an alternating gradient force magnetometer in the same way as was described in Ref. 2. Fig.3 shows the (M-H) curves for samples #702 and #714 in the geometry of $\overline{H}$ being parallel to [11$\bar{2}$] direction. The #702 film appeared to be isotropic in the plane of substrate as opposed to the #714 sample whose magnetic properties in the same plane were found to be quite anisotropic. The parameters of (M-H) magnetization curves for several samples are presented in the Table 1. Here, H_c stands for coercive field, M_r and M_s - for remnant and saturation magnetization respectively. It is seen that the value of H_c for #702 is twice less than that of #703 and almost an order of magnitude less than H_c for #714. It is also small comparing with the values obtained in Ref. 2. It is worth to mention that small value of H_c is known to indicate high structural quality of the material. The saturation magnetization M_s of #702 sample appears to be higher than that of #714 which can be due to the presence of β-phase in the latter sample.

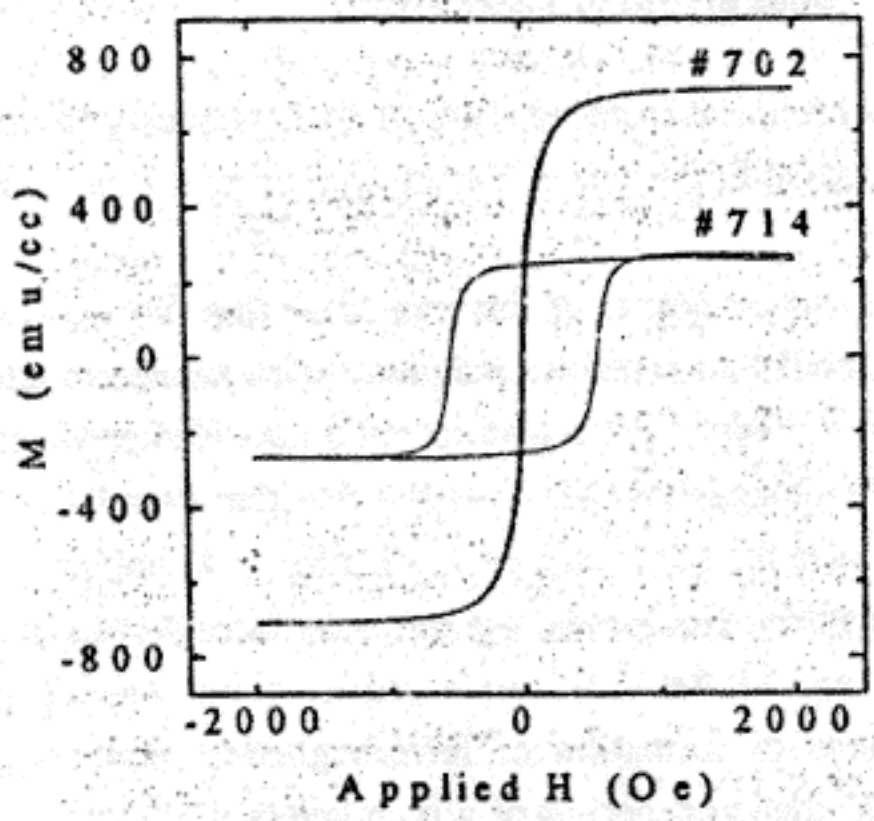

Fig.3 Magnetization as a function of applied field

Thus comparing structural and magnetic properties of epitaxial MnAs films grown on CaF_2/Si(111) and As-Si(111) substrates, we conclude that those properties strongly depend on the nature of buffer layer and are considerably better for the films grown on CaF_2.

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