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Defect Structure of High-Temperature-Grown GaMnSb/GaSb

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GaMnSb/GaSb(100) layers with embedded MnSb inclusions have been grown at 720 K using MBE technique. This paper presents the investigation of the defect structure of $Ga_{1-x}Mn_xSb$ layers with different content of manganese (up to $x = 0.07$). X-ray diffraction method using conventional and synchrotron radiation was applied. Dimensions and shapes of inclusions were detected by scanning electron microscopy. Depth profiles of elements were measured using secondary ion mass spectroscopy technique.

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1. Introduction

GaMnSb is considered as one of new materials from the diluted magnetic semiconductor group (DMS) potentially useful for spintronics [1–4]. DMSs exhibit unique, valuable magnetic properties due to exchange interaction between carrier spins and localized spins. One of other methods for creating ferromagnetic semiconductor is introducing ferromagnetic nanoinclusions into semiconductor matrix. In order to obtain materials with desired magnetic properties it is reasonable to start with inclusions with the Curie temperature exceeding the room temperature. It was shown that high-temperature growth of GaMnSb induces the formation of MnSb inclusions in GaSb matrix, whereas low-temperature growth inhibits the formation of MnSb inclusions [3].

In order to find the best technological conditions for the formation of ferromagnetic nanoinclusions embedded in semiconductor matrix, the structural characteristics of these materials is needed. Therefore, the major purpose of this work is to determine the defect structure of high-temperature molecular beam epitaxy (MBE) grown $Ga_{1-x}Mn_xSb$ layers, in dependence on different concentration of manganese (up to $x = 0.07$).

2. Experimental

$Ga_{1-x}Mn_xSb$ layers were grown on the GaSb(100) substrate, using the MBE technology. To achieve the creation of ferromagnetic precipitates, epitaxial growth was performed at high temperature equal to 720 K. The thickness of $Ga_{1-x}Mn_xSb$ layers was equal to 0.63 μm. Three types of samples, with different Mn concentration ($Ga_{0.99}Mn_{0.01}Sb$, $Ga_{0.97}Mn_{0.03}Sb$ and $Ga_{0.93}Mn_{0.07}Sb$) were investigated.

Strain state and the lattice parameters of $Ga_{1-x}Mn_xSb$ layers were studied using high-resolution PHILIPS-MRD diffractometer in double- and triple-axis configuration (Cu K_{α_1} radiation was used). Reciprocal space maps (RCMs) for 004 symmetrical and 224 asymmetrical reflection, as well as the rocking curves and $2\theta/\omega$ diffraction patterns were registered.

Polycrystalline phase was investigated using monochromatic synchrotron X-ray beam ($\lambda = 1.54056$ Å) at W1 station at HASYLAB-DESY in Hamburg, applying the glancing incidence diffraction method (coplanar 2θ scan). In this mode the rotational axis of the sample (ω axis) has been aligned exactly with the sample surface and then the sample was rotated about this axis by a very small angle (here equal to 1°). During measurement the angular position of the sample with respect to the incident X-ray beam was fixed while the detector was rotated in the wide range of 2θ angles in the plane perpendicular to the sample surface. The coplanar 2θ scans technique is very sensitive to very thin polycrystalline layers.

To examine the depth profiles of Ga, Sb and Mn elements, secondary ion mass spectrometry (SIMS) measurements were performed. Also scanning electron microscopy (SEM) was used for probing the sample surface.

3. Results and discussion

The SEM studies reveal the presence of isolated MnSb inclusions of various shapes (Fig. 1). Typical lateral dimensions depend on the Mn concentration value, and for the studied samples the maximum size of inclusions was about 200, 300 and 600 nm, for $Ga_{1-x}Mn_xSb$ with $x = 0.01$, 0.03 and 0.07, respectively. Rocking curve diffraction measurements (ω scans) showed that the MnSb inclusions have block structure with the misorientation angle between blocks equal to about 1°.

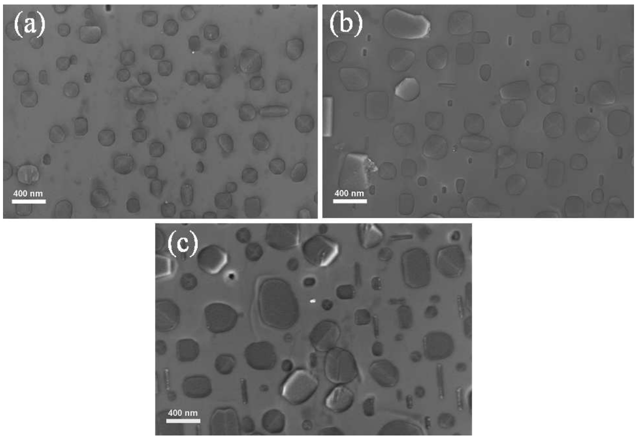

Fig. 1. SEM images of $Ga_{1-x}Mn_xSb$ ($x = 0.01$ (a), 0.03 (b), 0.07 (c)) layers grown on GaSb(100) substrates.

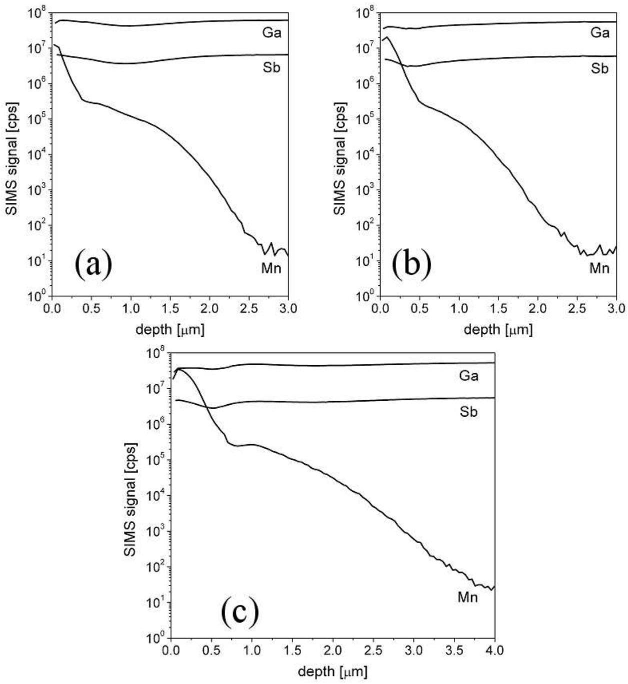

Fig. 2. SIMS depth profiles of Mn, Ga and Sb in $Ga_{1-x}Mn_xSb$/GaSb(100) samples ($x = 0.01$ (a), 0.03 (b), 0.07 (c)).

The SIMS studies indicate strong Mn diffusion to the GaSb substrate (Fig. 2). This process is due to the high temperature used during the MBE growth.

The polycrystalline fraction of hexagonal MnSb was detected by using the glancing incidence diffraction method and synchrotron radiation (Fig. 3). The different intensity may be related to the various Mn content in GaMnSb layers and also with preferred orientation of crystallites. In this measurement mode, the reflections 10.2, 20.1, 22.3 and 30.0 coming from MnSb phase are visible for all three types of samples. Also for $Ga_{1-x}Mn_xSb$ with $x = 0.01$ the reflections 20.0 and 21.2 MnSb are observed as well as for $Ga_{1-x}Mn_xSb$ with $x = 0.03$ the peaks coming from 10.1 and 11.1 MnSb reflections are visible (Fig. 3).

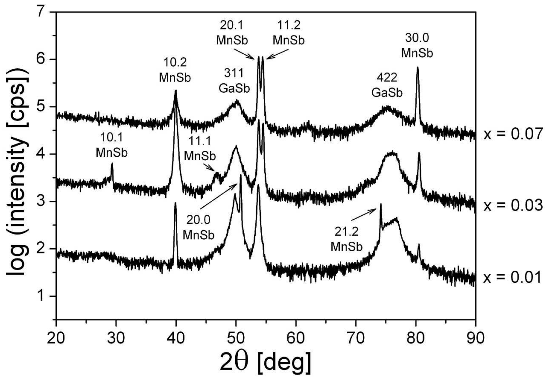

Fig. 3. Coplanar 2θ scans measured using glancing incidence diffraction geometry and X-ray synchrotron radiation source, for $Ga_{1-x}Mn_xSb$/GaSb(100) samples ($x = 0.01$, 0.03, 0.07, respectively).

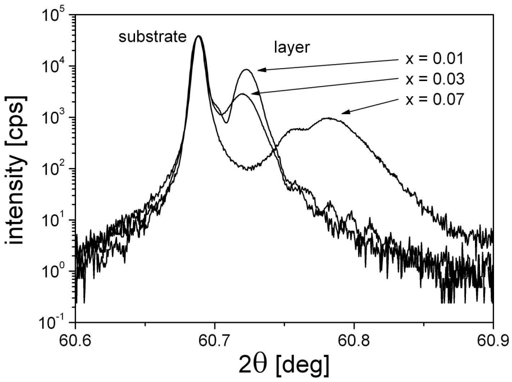

Fig. 4. $2\theta/\omega$ diffraction patterns (004 reflection) for $Ga_{1-x}Mn_xSb$/GaSb(100) samples ($x = 0.01$, 0.03, 0.07, respectively); high-resolution diffraction and conventional X-ray source were used.

The $2\theta/\omega$ diffraction patterns as well as the reciprocal space maps for symmetrical reflection indicate the lattice parameter dispersion within the layers (Figs. 4 and 5). Simultaneously, pronounced diffuse scattering related to defect structure was observed for $Ga_{1-x}Mn_xSb$ with $x = 0.07$. Figure 5 shows also that the lattice planes of the GaMnSb layer are parallel to the GaSb substrate planes. Reciprocal space maps for the asymmetrical reflection reveal that the investigated GaMnSb layers are

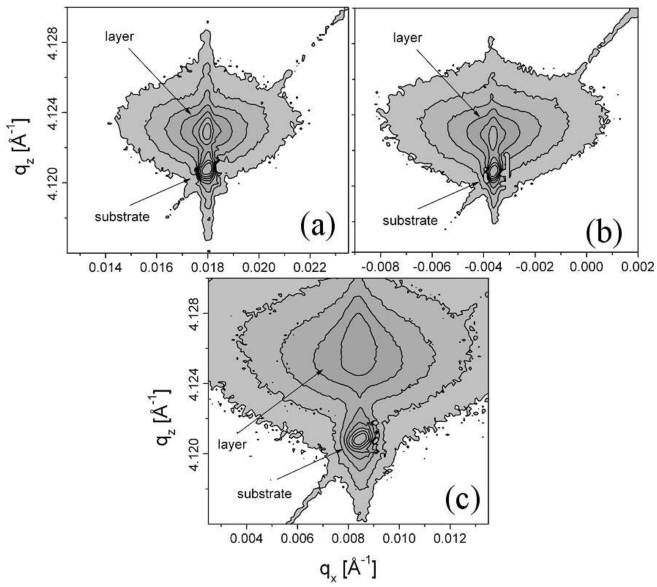

Fig. 5. Reciprocal space maps around 004 reflection for $Ga_{1-x}Mn_xSb$/GaSb(100) samples ($x = 0.01$ (a), 0.03 (b), 0.07 (c)); high-resolution diffraction and conventional X-ray source were used.

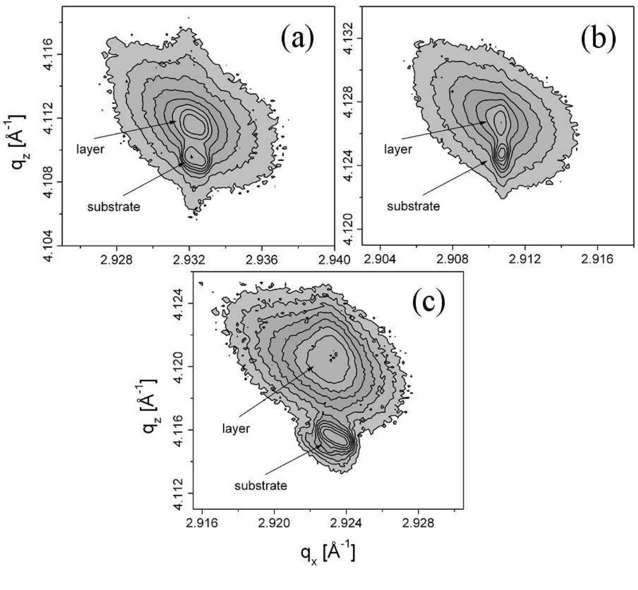

Fig. 6. Reciprocal space maps around 224 reflection for $Ga_{1-x}Mn_xSb$/GaSb(100) samples ($x = 0.01$ (a), 0.03 (b), 0.07 (c)); high-resolution diffraction and conventional X-ray source were used.

fully strained in respect of the GaSb substrate (Fig. 6) because the in-plane lattice parameter of the GaMnSb layer is equal to the GaSb lattice parameter. The out-of-plane lattice parameters for the $Ga_{0.99}Mn_{0.01}Sb$, $Ga_{0.97}Mn_{0.03}Sb$ and $Ga_{0.93}Mn_{0.07}Sb$ layers are equal to 6.0922, 6.0924 and 6.0869 (±0.0001) Å, respectively. From the results we can infer that only part of Mn atoms form MnSb hexagonal inclusions, remaining fraction of Mn atoms, substitute the Ga atoms in GaSb layer. Due to the smaller ionic radius of Mn than that of Ga, a decrease of the lattice parameter was detected for $Ga_{1-x}Mn_xSb$ with $x = 0.07$ (Fig. 4). For $Ga_{1-x}Mn_xSb$ with $x = 0.01$ and 0.03, this effect was not observed.

4. Summary

The defect structure of the high-temperature MBE--grown epitaxial $Ga_{1-x}Mn_xSb$ layers on GaSb(100) substrate was examined. The SEM studies as well as diffraction measurements revealed the presence of hexagonal MnSb inclusions of different sizes related to Mn concentration. The lattice parameter values were calculated and lattice parameter dispersion was showed. The fully strained GaMnSb layers were observed. Strong Mn diffusion to the GaSb substrate was detected. For $Ga_{1-x}Mn_xSb$ with $x = 0.07$ only a part of Mn atoms introduced to the GaSb layer forms the hexagonal MnSb inclusions.

Acknowledgments

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