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Investigation of strained InGaAs layers on GaAs substrate

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A set of $In_{0.13}Ga_{0.87}As$ layers of various thicknesses on GaAs substrate has been grown by low pressure metalorganic vapour phase epitaxy (LP MOVPE). The initial stage of relaxation process has been investigated and critical layer thickness (CLT) has been determined. The investigations were performed by applying atomic force microscopy (AFM), high resolution X-ray diffractometry (HR XRD) with conventional and synchrotron radiation. The value of CLT determined by AFM observations agrees with that obtained from diffuse scattering measurements. The value is in agreement with HR XRD results.

Keywords: low pressure metalorganic vapour phase epitaxy (LP MOVPE), strained InGaAs layer, critical layer thickness, high resolution X-ray diffractometry (HR XRD), diffuse scattering, atomic force microscopy (AFM), misfit dislocation, plastic relaxation.

1. Introduction

The growth of strained epitaxial films is of fundamental importance to the fabrication of modern electronic devices. The AlGaAs/$In_xGa_{1-x}As$/GaAs structures are the material system preferred for higher frequency and lower-noise field effect transistors over AlGaAs/GaAs system due to its band construction and superior transport properties [1, 2]. The increase in the indium content x in those structures leads to a larger conduction band discontinuity and, therefore to improved electron confinement in the channel [3]. However, the lattice mismatch between InGaAs and GaAs materials can generate defects in the strained InGaAs layer. Above the critical layer thickness, the lattice strain is not accommodated elastically and misfit dislocations are introduced at the interface [4, 5]. The knowledge of critical layer thickness and the onset of misfit dislocations generation is necessary to achieve high performance of the devices.

The onset of misfit dislocation generation varies with growth conditions, such as growth temperature and growth rate. The aim of the paper is to compare the sensitivity of AFM to HR XRD, concerning the determination of the onset of misfit dislocation generation. Our work was concentrated on the growth of $In_{0.13}Ga_{0.87}As$ layers of various thicknesses on GaAs substrate. The lattice mismatch was $\Delta a/a = 9.3\times10^{-3}$ and the calculated critical layer thickness (CLT) was $d_C = 20$ nm.

2. Experiment

The $In_{0.13}Ga_{0.87}As$/GaAs epitaxial layers of various thicknesses were grown, using low pressure metalorganic vapour phase epitaxy (LP-MOVPE) on exactly oriented GaAs(001) substrates. A horizontal quartz reactor (AIX 200) and IR heated graphite susceptor were used. Trimethylindium (TMIn) and trimethylgalium (TMGa) were used for In and Ga sources, respectively, and 100% arsine (AsH_3) and phosphine (PH_3) were applied for group V elements with palladium-purified hydrogen carrier gas. During the layer growth, the reactor pressure and temperature were maintained at 20 mbar and at 700 °C, respectively. The V/III ratio was unchanged during the growth and amounted to 87. The growth rate of $In_{0.13}Ga_{0.87}As$ layer was equal to $r = 2.7$ Å/s.

The structural properties of $In_{0.13}Ga_{0.87}As$ layers were investigated by two techniques: atomic force microscopy (AFM) and high resolution X-ray diffractometry (HR XRD) with conventional and synchrotron radiation. The investigation of sample surfaces by AFM allowed us to notice the onset of misfit dislocation generation and the type of growth. HR XRD was used to obtain information about composition, thickness and layer crystalline quality – the presence of misfit dislocation in the interface.

3. Results and discussion

The $In_{0.13}Ga_{0.87}As$ layers of various thicknesses (10, 30, 58, 80 and 100 nm) were observed under Nomarski microscope. The layer surfaces of thicknesses of 10 nm and 30 nm were flat, without any defects. Starting from the layer thickness of 58 nm, a cross-hatch pattern was visible, which resulted in the onset of misfit dislocation generation. The following figures show images of layer surfaces with thicknesses: 10 nm (Fig. 1**a**), 58 nm (Fig. 1**b**) and 80 nm (Fig. 1**c**), respectively. The surface image of 30 nm InGaAs layer (not shown in Fig. 1) is similar to the one of 10 nm and the 100 nm InGaAs surface image is like the image of 80 nm layer.

The surface morphology of these films was studied by AFM (Fig. 2). The surface of 10 nm $In_{0.13}Ga_{0.87}As$ layer shows a regularly repeated terraces finished with monolayer steps (2D growth mode) – Fig. 2**a**. The average terrace width was 550 nm and surface roughness was $R_a = 0.85$ Å. With layer thickness increasing to 30 nm, the elastic strain energy builds up to the point, where it becomes energetically favourable to form misfit dislocation at the interface. Low ridge density appeared on the 30 nm $In_{0.13}Ga_{0.87}As$ layer surface. Average geometrical parameters of these ridges are: the width – 400 nm and the height – 4.5 Å. The distance between two neighbouring ridges was 2000 nm.

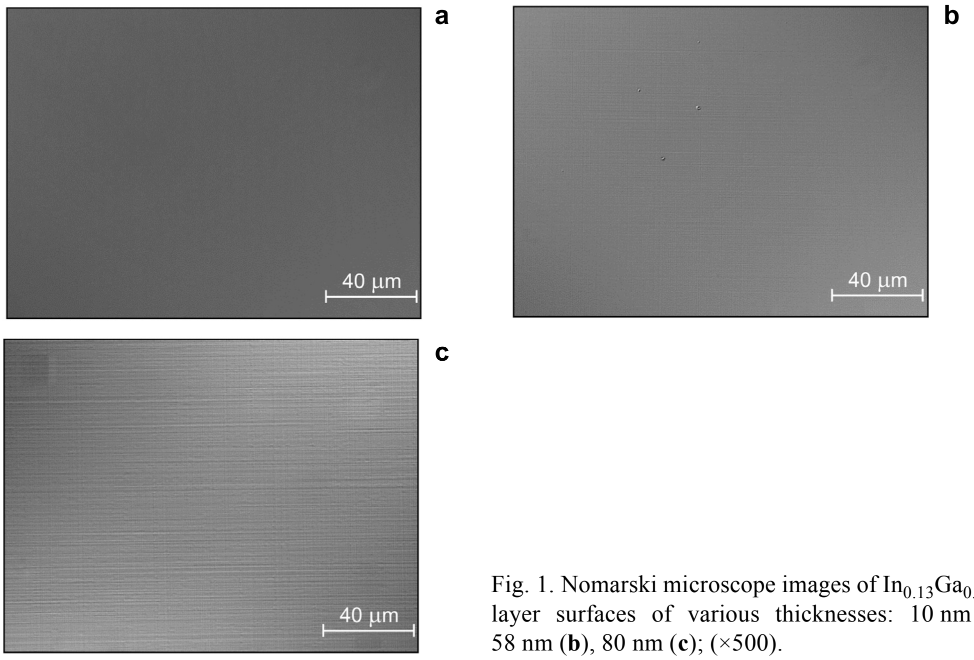

Fig. 1. Nomarski microscope images of $In_{0.13}Ga_{0.87}As$ layer surfaces of various thicknesses: 10 nm (**a**), 58 nm (**b**), 80 nm (**c**); (×500).

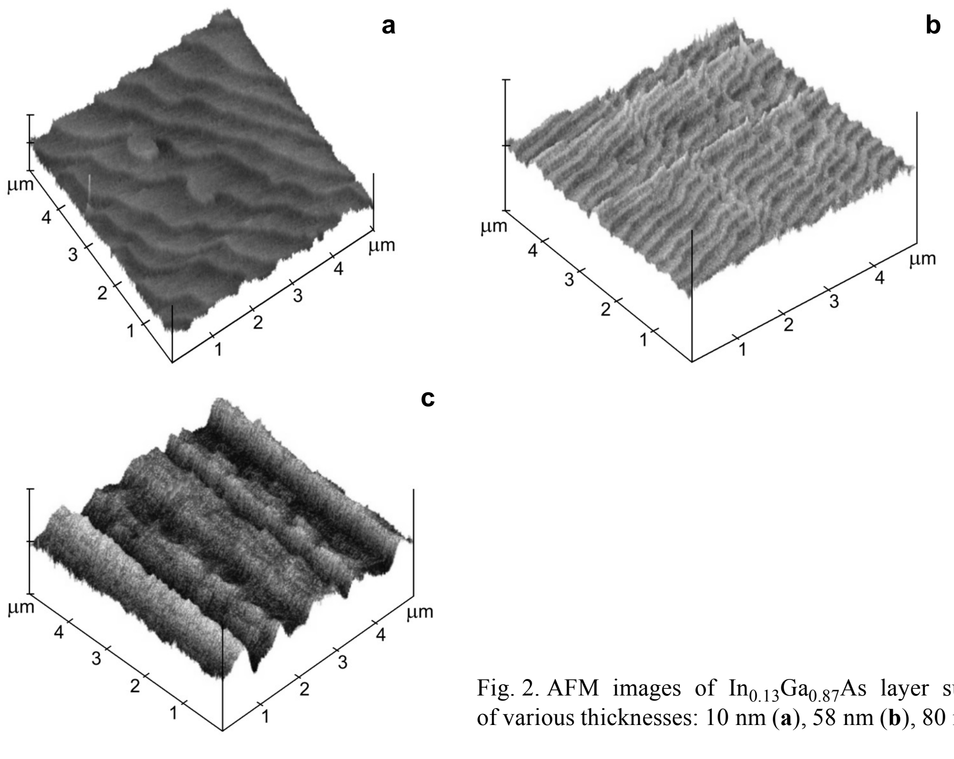

Fig. 2. AFM images of $In_{0.13}Ga_{0.87}As$ layer surfaces of various thicknesses: 10 nm (**a**), 58 nm (**b**), 80 nm (**c**).

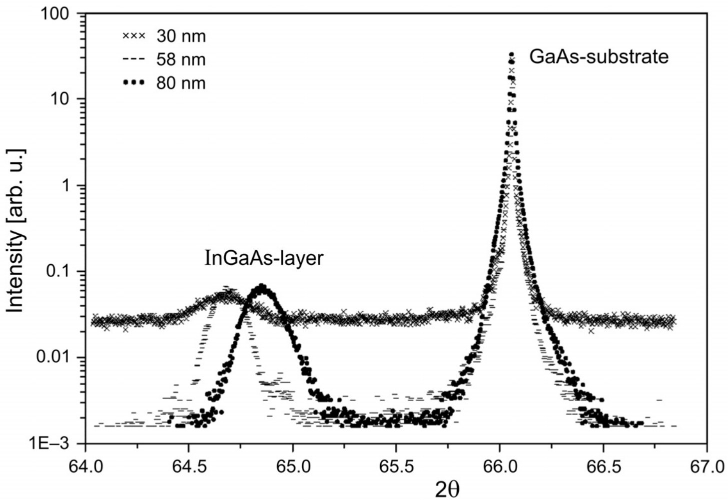

Fig. 3. HR XRD (004) rocking curves for three thickness values of $In_{0.13}Ga_{0.87}As$ layers: 30 nm, 58 nm, and 80 nm.

Two-dimensional growth mode is still maintained, which is shown in Fig. 2**b**, but the average terrace width decreases in comparison with the terrace width on 10 nm layer surface which is 281 nm. Finally, high ridge density can be seen on the surface at the layer thickness of 58 nm, as seen in Fig. 2**b**. The average distance between two neighbouring ridges is 830 nm. As the layer thickness increases further (80 nm and 100 nm), the ridges density becomes higher. The occurrence of ridges on the surface is connected to the appearance of high misfit dislocation density in the interface. Hence one can conclude that the layer thickness, when dislocations start to appear, is below 30 nm.

The $In_{0.13}Ga_{0.87}As$ layer thicknesses in the range of 10–80 nm were also investigated by HR XRD method with conventional and synchrotron radiation. The (004) rocking curves of $In_{0.13}Ga_{0.87}As$ layers for three values of thickness measured by means of conventional radiation were shown in Fig. 3.

It results from Scherrer effect that the reflection width from the layer increases when the thickness decreases. The layer reflection from InGaAs thickness of 10 nm is very wide and invisible when the conventional radiation is applied for measurements.

During the epitaxial growth, due to the lattice mismatch, the grown layers exhibit laterally compressive strain and consequently vertically tensile strain. Thus, the vertical lattice parameter is larger than the lattice constant of a strain-free $In_{0.13}Ga_{0.87}As$ layer. The strain energy accumulated in the layer increases with the increase in the layer thickness. Above the critical thickness the layer stress is released by generation of misfit dislocations. As a result, the average vertical lattice spacing is decreasing. In this state the shift between the substrate and the epilayer reflections is measurable. In Figure 3 one can see that the shift is observable for the $In_{0.13}Ga_{0.87}As$

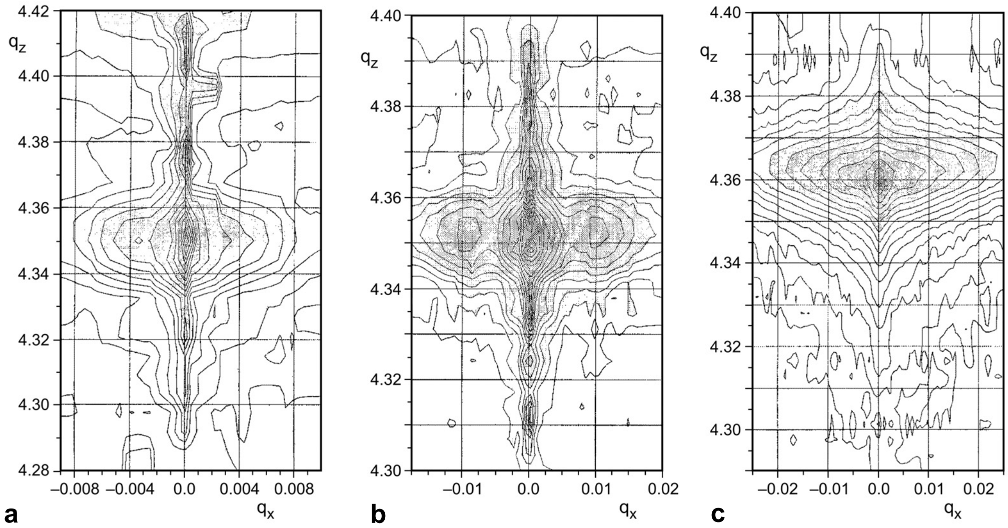

Fig. 4. Reciprocal lattice maps of $In_{0.13}Ga_{0.87}As$ layers: 30 nm (**a**), 58 nm (**b**), and 80 nm (**c**).

layer thickness of 80 nm and that it is equal to 0.6016 in the 2θ scale. Up to the layer thickness of 58 nm the shift was not observed. Hence, at which the lattice relaxation starts to appear for the epilayer thickness above 58 nm.

From the literature [4] it is known that the diffuse scattering is connected to misfit dislocations present in the interface. In order to confirm dislocation presence, we investigated the distribution of the intensity around the reciprocal lattice points 004 for layer thicknesses of 30, 58 and 80 nm, respectively. Reciprocal lattice maps 004 of epitaxial layers measured by means of synchrotron radiation were shown in Fig. 4.

Diffuse scattering distributed on both sides of vertical band is visible besides of the vertical band with interferential maximums. This diffuse scattering is connected to misfit dislocations (Figs. 4**a** and 4**b**). Figure 4**c** presents the distribution of scattered X-rays in the vicinity of 004 RLP for the 80 nm thick layer. In this case the diffuse component of the scattering which comes from the huge density of dislocations located in interface is dominant. The coherent strains of the layer are relaxated by dislocations which strongly contribute to the diffuse scattering. The strain relaxation causes the shift of the layer peak in the $\theta/2\theta$ scan in Fig. 3.

Examining of the distribution of the diffuse scattering intensity allows to state that the low misfit dislocation density is present even in the 30 nm layer. Thus, the misfit dislocations at the 30 nm layer heterointerface exist, but the shift between the substrate and epilayer is too small to be observed ($\Delta a/a = 1\times10^{-5}$).

The layer surface observed under Nomarski microscope has no cross-hatch at the small layer thickness (30 nm) when the linear density of misfit dislocation is low. About 100 of misfit dislocation ($\approx 100\,b_r$, where b_r – normal component of the Burger vectors) is needed to see one dislocation jog on the surface.

Stress relaxation process is advanced for $In_{0.13}Ga_{0.87}As$ layer of 80 nm thickness and the shift between this layer and 58 nm one is visible when we analyze of rocking curves (Fig. 3). Dislocations density was calculated on the basis of the shift value in the map and it is 1×10^{-2} Å^{-1} [6]. Indium content x in $In_xGa_{1-x}As$ layer was determined from rocking curves of strained layers with thicknesses of 30 nm and 58 nm.

On the basis of these investigations, the generation dislocations point was assessed to be lower than 30 nm and to equal the one obtained from AFM observations.

4. Conclusions

We have examined the onset of dislocations generation in the $In_{0.13}Ga_{0.87}As$ layers grown by LP MOVPE. The investigated layers thickness was in the range from 10 to 100 nm. Investigations were performed, applying two techniques: AFM, HR XRD with conventional and synchrotron radiation. The value of the layer thickness, when the misfit dislocations generation process starts (determined by AFM observations), is in agreement with the one measured by HR XRD with synchrotron radiation. This confirms high precision of AFM method. However, the main relaxation process, which should be considered as far as the layer structural quality is concerned, is related to the shift of the epilayer reflection.

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