Investigation of *InGaAs* based double - quantum well heterostructures near the critical thickness transition

N.V.Vostokov[*] , D.M.Gaponova, V.M.Daniltsev, Yu.N.Drozdov, A.V.Murel,
O.I. Khrykin, V.I.Shashkin, I.Yu.Shuleshova
Institute for Physics of Microstructures RAS,
GSP-105, Nizhny Novgorod, 6003600 Russia

It is well known that relaxation of a strained *InGaAs* thick layer is accompanied by appearance of cross-hatch patterns on the layer surface. Such patterns are caused by misfit dislocations and can be clearly seen with an atomic force microscope (AFM). But a thin layer with a high indium content, which is grown at low temperature, may have a qualitatively different relaxation behaviour.

We report the investigation of a double *InGaAs* quantum-well structure transition from the pseudomorphic to relaxed state when the layer thickness exceeds the critical value. Comparison of the AFM data and the x-ray diffraction, photoluminescence and photocurrent results confirms that AFM analysis of the surface relief makes it possible to establish the critical layer transition in the inner thin layers of structure. If the cross-hatch patterns are absent a sharp increase in surface roughness may be used as the criterion of transition. In the region below the critical thickness the roughness value correlates with a lager amount of point defects[**].

1. Introduction

An atomic force microscope (AFM) is widely used now for a surface morphology control of semiconductor device structures. At the same time, surface roughening originates partly from the defects in the inner layers and, therefore, the AFM may be used as a sensitive technique for a layer structure transition analysis.

When a strained *InGaAs* thick layer begins to relax, cross-hatch patterns appear in the AFM image, as shown in Fig. 1a for example. Such an image is formed due to

[*] E-mail: vostokov@ipm.sci-nnov.ru
[**] Investigation was supported by RFBR grants 00-02-16141, 00-02-16486, 99-02-18037 and by the program "Physics of solid state nanostructures".

misfit dislocations [1-3]. But a thin layer with a high indium content, grown at low temperature, may have a qualitatively different relaxation behaviour, see Fig. 1b. It seems interesting to investigate the specific features of the AFM image for this case.

In this paper, we report the investigation of a double quantum-well structure transition from the pseudomorphic to relaxed state, when the layer exceeds critical thickness. The transition leads to stress relaxation and for this reason it is energetically favourable [1]. The structure was constructed with two identical $In_xGa_{1-x}As$ quantum wells (x ≈ 0,3), separated by a *GaAs* thin layer and capped by a *GaAs* layer. Another feature was a reduced growth temperature in our experiment. It is known that the *In* content in the layer may be increased without structure relaxation, if the growth temperature is decreased [1,2]. An indium enriched layer is usually desirable but the problem is the quality of the structure obtained by this way. Therefore, AFM, x-ray diffraction (XRD), photoluminescence (PL) and photocurrent (PC) techniques have been applied for a complex structure investigation in our work.

2. Experimental procedure

Epilayers were grown in a vertical metal-organic vapour phase epitaxy (MOVPE) reactor at atmospheric pressure with $In(CH_3)_3$, $Ga(CH_3)_3$, AsH_3 sources and hydrogen as a carrier gas. *GaAs* (001) +3° wafers were used as substrates. The temperature of substrate was maintained at 480°C by an inductive heater. The structures #1 - #5 were constructed of $GaAs/In_xGa_{1-x}As/GaAs/\ In_xGa_{1-x}As\ /GaAs$ layer sequence (x ≈ 0.3). We varied the only growth time of two identical layers of $In_xGa_{1-x}As$, which resulted in layer thickness variation from 4 to 15 nm. The intermediate and capping GaAs layers were of 14 nm thickness.

Surface morphology was measured with a *Solver-P4* atomic force microscope (NT-MDT, Russia), operating in air. We use the following definition of roughness: $R=\Sigma|h_i-h_{mid}|/N$, where N is the total number of pixels in the AFM image, h_i the AFM reading for the *i*th pixel and h_{mid} the averaged h_i. An x-ray *DRON-4* diffractometer was used for rocking curve registration with a *Ge*(400) monochromator and $CuK\alpha_1$ radiation. The PL spectra were measured at 77 K with an *Ar* laser (λ = 514 nm) as the light source. PC data were obtained for Schottkey barrier structures formed by metal Al 0.5 mm diameter contact on the sample surface. A back side illumination was used for excitation of electrical carriers with a variable monochromatic line isolated from halogen lamp light.

3. Results and discussion

Either method does, actually, detect the critical layer thickness transition. The AFM images show a sharp increase in the roughness of surface #4 (R = 0.5 nm) in comparison with about 0.2 nm for #1 - #3. There are no clearly seen cross-hatch patterns on the relaxed surfaces, which are generally used as a sure sign of a relaxed layer in case of misfit dislocations. Fig. 1 shows a typical image of such cross-hatch patterns for single 0.2 μm thick 70%-relaxed layer $In_{0.12}Ga_{0.88}As$ and the image of #4 for comparison in the same scale. Such a behaviour may be explained by a strain induced island formation for the case of high *In* content in a thin layer.

The x-ray diffraction spectra show a clearly visible transition from two coherent smooth layers in #1,2,3 to the incoherent ones in #4, #5, see Fig. 2b.

The peak in the luminescence spectra shifts to a long wave region due to an increase in the quantum well width, but the peak intensity decreases from #2, see Fig. 2c. In #4 and #5 spectra the quantum well peak is absent at all. The photocurrent spectra clearly change between #3 and #4. Two distinct peaks corresponding to quantum levels become blurred here, see Fig. 2d.

Fig. 2a displays a quantitative comparison of the data. A set of structure quality estimates versus a single layer thickness is presented here. The quality parameters are inverse roughness (30/R), PL peak intensity, XRD interlayer interference contrast (I_{max}/I_{min}). The inverse roughness (flatness) corresponds to surface quality and it seems to be preferable in this case. Fig. 2a shows a good agreement between the data in the first approximation. It is clearly seen that the quality degrades near the 10 nm thickness. This value is near to 9 nm reported for single $In_{0.3}Ga_{0.7}As$ layer [1-3], although our structure has two such layers. The result supports the AFM capability to register transitions in the inner layers of a structure. In addition, Fig. 2c shows that PL intensity decreases from the #2, i.e. far below the critical thickness. It may be explained by a high sensitivity of PL to point defects which form nonradiative recombination centres. The AFM surface roughness also increases in this region, which proves that AFM is sensitive to point defects enhancing in the structure before the dislocations are formed. The XRD interference remains good here, so it is insensitive to point defects.

4. Conclusions

A critical layer thickness for an $In_{0.3}Ga_{0.7}As$ layer inside a double quantum well structure is found to be near 10 nm when the growth temperature is 480° C.

A low temperature growth really permits to enlarge the critical layer thickness, but the luminescence degrades before the transition, possibly due to nonradiative recombination with point defects.

The results confirm that AFM analysis of surface makes it possible to establish the critical layer transition in the inner thin layers of a structure. In the absence of cross-hatch patterns a sharp increase in surface roughness may be used as the criterion of transition. In the region below the critical thickness the roughness value correlates with enhancing of point defects.

[1] D.J. Dunstan, J. of Mater. Science: Materials in Electronics, 8 (1997) 337

[2] X.G. Xu, S. McLaughlin, J. Hu, S.P. Watkins, C.R. Bolognesi, J. of Crystal Growth., 195 (1998) 687.

[3] K. Kim, Y.H. Lee, Appl. Phys. Lett., 67 (1995) 2212.

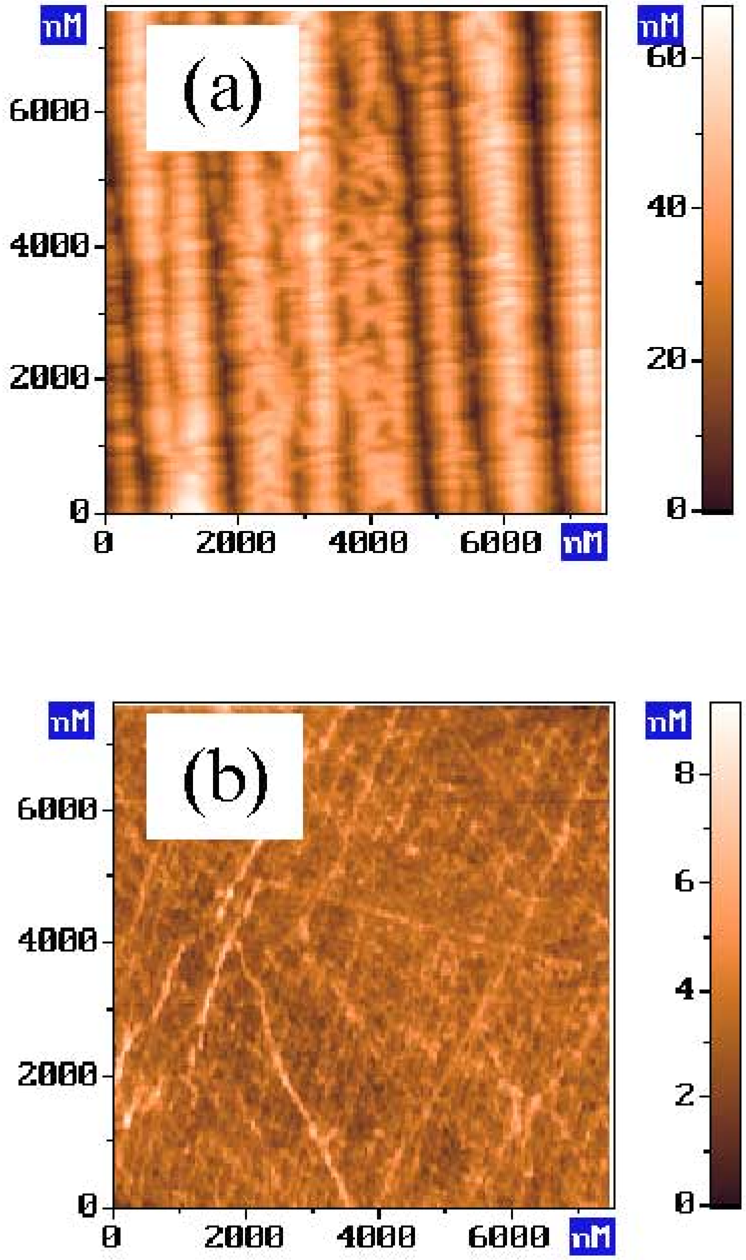

Fig.1. Typical AFM image of cross-hatch patterns for single 0.2 μm thick 70%-relaxed layer $In_{0.12}Ga_{0.88}As$ (a); and the image of #4 without such patterns for comparison (b).

Fig2. Combined structure investigation:

(a) Set of quantitative structure quality estimates vs a single layer thickness;

(b) X-ray diffraction curves;

(c) Photoluminescence data;

(d) Photocurrent data.