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PREPARATION AND CHARACTERIZATION OF InGaAs QUANTUM WIRES ON V-GROOVE PATTERNED InP

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Abstract

We report on the characterization of InGaAs quantum wells (QWL) and wires (QWR) on V-groove patterned InP substrates. The quality of the QWL on the (100)-surface between the grooves is discussed concerning different sample preparation methods. The material composition and the thickness of these QWL is determined. The geometrical shape of the QWR in the tip of the V-grooves is measured by atomic-force microscopy (AFM) and compared with transmission-electron microscopy (TEM). The dependence of the QWR photoluminescence (PL) on sample temperature is studied.

I Introduction

Low-dimensional semiconductor structures promise improved properties in optoelectronic devices like quantum wire (QWR) lasers, e.g. reduced and less temperature-sensitive threshold currents. In several semiconductor systems QWR lasers were already realized, particularly in AlGaAs/(In)GaAs. However, this system is not compatible with glass-fibre based optical communication. On the other hand, InGaAs/InP offers this potential and beyond this it promises better longterm stability because it is free of Al [1]. Unfortunately, in this system the epitaxial growth on patterned substrates is more difficult because of InP mass-transport and the lack of inherent lattice-match.

II Experimental

We succeeded in fabricating single QWRs on InP. This is demonstrated by transmission-electron microscopy (TEM), atomic-force microscopy (AFM) and by low-temperature photoluminescence (PL) at 13 K. The fabrication process starts with the etching of a V-groove into the (100)-InP substrate through a lift-off Ti mask [2]. After etching the mask is removed in buffered HF. Photoresist residues on the (100)-planes between the V-grooves are removed by descumming, improving the crystal quality on these planes as shown later. Immediately prior to the metal-organic vapour-phase epitaxy (MOVPE) growth the samples are etched in 5% HF (10 s) and 80% H_2SO_4 (60 s) without affecting the V-groove shape. The V-grooves are typically 3 µm wide with a pitch of 6 µm (3+3) or 15 µm (3+12), respectively. The parameters for the

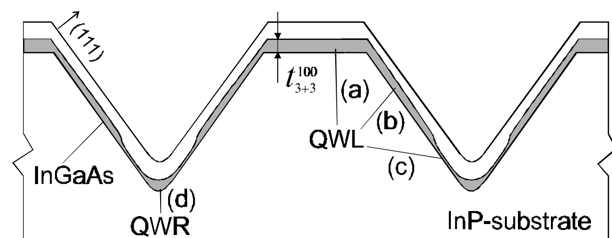

Fig. 1 InGaAs quantum structures on V-groove patterned InP substrate.

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MOVPE growth are described elsewhere [3].

The MOVPE growth starts with a thin InP buffer layer followed by nominally 5 nm thick InGaAs well material which is covered by 100 nm InP. Fig. 1 shows the schematic cross-section after growth with the InGaAs QWR (d) in the tip of the V-groove and additional single quantum wells on the (100)-surface (a) and on the {111}-facets (b), (c) where due to mass-transport into the tip the lower part (c) is somewhat thinner. Due to diffusion processes of the growth species the thicknesses and material compositions of the respective $In_{1-x}Ga_xAs$ quantum structures differ [4]. Furthermore these quantities depend on the sample geometry, especially the pitch of the V-grooves.

In conventional PL, signals of all quantum structures are superimposed and it is crucial to understand where the peaks originate from and what is the geometry and material composition of the quantum structures. In the following we discuss how to improve the crystal quality of the top QWL (a) and how to determine the composition and geometry.

III Top quantum wells

Fig. 2 shows the PL spectra of three as-grown samples with 5 nm InGaAs well material but different sample preparation steps and buffer layer thicknesses. The dotted spectrum was taken from a sample with 5 nm InP buffer layer. Only one pronounced but asymmetric peak at 920 meV dominates the spectrum. This peak originates from the upper part of the {111}-QWL (b). A second smaller peak at about 1000 meV originates from the lower part of the {111}-QWL (c) due to its reduced layer thickness. Because of the poor crystal quality the (100)-QWL (a) leads only to a low energy shoulder.

The dashed curve was taken with a sample of the same layer structure but with a descumming step prior to the growth. This preparation step removes photoresist residues from the (100)-plane before growth and increases the quality of the (100)-QWL (a). This is reflected by the PL peak near 880 meV with approximately the same intensity as the {111}-QWL peak (b). This trend could be strengthened by increasing the buffer thickness to nominal 50 nm (cf. solid curve). In this case the (100)-QWL related peak intensity increased by a factor of 10, thus dominating the normalized PL spectrum.

In order to determine the material composition of the top QWL we performed PL measurements with

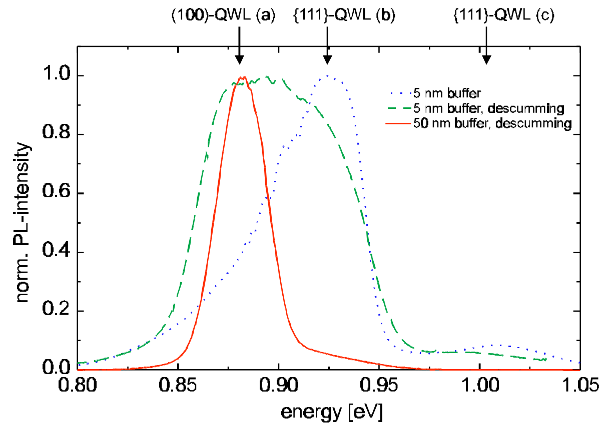

Fig. 2 PL spectra of three V-groove samples (3+3) with nominal 5 nm InGaAs layer.

100 nm thick InGaAs layers on a V-grooved substrate thus eliminating quantum size effects, i. e. the PL peak is shifted into the vicinity of 800 meV. We compared PL spectra of planar and patterned parts of the sample. Their PL energy now depends only on the $In_{1-x}Ga_xAs$ material composition. All spectra are dominated by the signal from the (100)-surface. We found an increased PL peak energy for the patterned parts with respect to the planar part corresponding to a higher Ga-content x. Table I summarizes the measured transition energies and corresponding Ga-contents for the $In_{1-x}Ga_xAs$ of the top surface. Calculated values of the Ga-content enhancement on patterned (100)-planes after the method described in [4] are listed in the last row of the table.

Table I PL energy and Ga-content x of a 100 nm InGaAs layer on planar and patterned (100)-planes.

	planar	(3+12)	(3+3)
E_{PL} [meV]	799	803	815
x [%]	46.7	47.2	50.8
calculation after [4]		47.2	48.1

The Ga-content on the (100)-plane increases from 46.7% by up to 4% for the (3+3) part. We suppose that the composition of the 100 nm thick InGaAs is the same as that of the thin QWL (5 nm). However, in addition to the pattern effect on the composition of the (100)-QWL its thickness is also influenced by the pattern. This is demonstrated in Fig. 3 where three PL spectra of the same sample are shown as given as solid line in Fig. 2, i. e. 50 nm buffer and 5 nm InGaAs. In

this case the spectra are dominated solely by the (100)-QWL. The peak energy decreases from the planar through the (3+12) to the (3+3) field of the sample although due to the increase in the Ga-content (cf. Table I) the opposite effect should be expected. However, this is overcompensated by an increase in the QWL thickness.

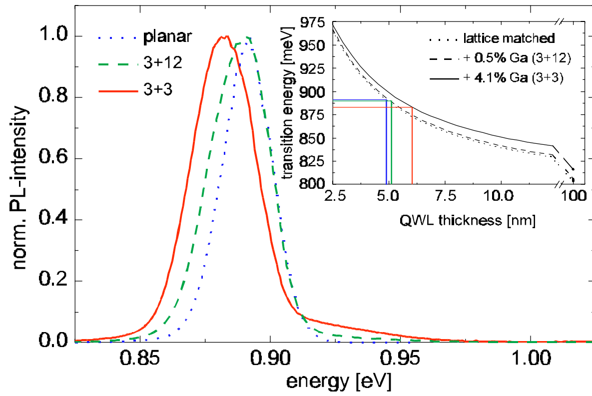

Fig. 3 PL spectra of a 5 nm InGaAs layer on planar and patterned parts of a V-groove sample.

Since we know the transition energies as well as the Ga-content of the respective (100)-QWL we can calculate its thickness. As inset of Fig. 3 the calculated thickness dependence of the transition energy of InGaAs QWL with the three compositions given in Table I is shown. From the measured PL peak-energies this yields a thickness of 4.9 nm on the planar field which slightly increases to 5.1 nm on the (3+12) field. On the (3+3) field the (100)-QWL must be 6 nm thick in order to give an 880 meV transition energy for x = 0.51. The results are summarized in Table II. The

Table II Thickness of the (100)-QWL on planar and patterned parts of a sample.

	planar	(3+12)	(3+3)
t^{100}[nm]	4.9	5.1	6
factor	x 1	x 1.04	x 1.23
calculation after [4]	x 1	x 1.1	x 1.31

last row of Table II shows calculated values of the growth rate enhancement on patterned substrates after the method described in [4]. Both effects, the increase in Ga-content and in thickness t^{100} of the (100)-QWL when moving from the planar field to the (3+3) field, can be explained by a reduced growth rate on the {111}-planes as compared to (100) and an In-rich composition [4]. The resulting gradient in the concentration of growth species leads to diffusion processes which are more pronounced with the small structure.

IV Quantum wires

In the tip of the V-groove an InGaAs QWR is deposited ((d) in Fig. 1). Its shape and dimensions vary with the InP buffer-layer thickness. A thinner buffer layer leads to a smaller QWR. This effect is due to InP mass-transport into the V-groove tip. Fig. 4a) shows a TEM image of a QWR on a 50 nm InP buffer. Fig. 4b)

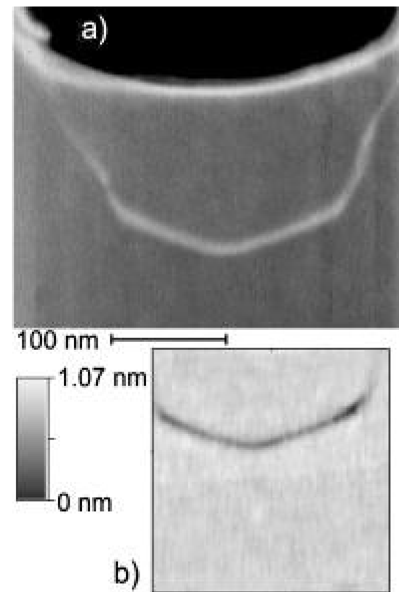

Fig. 4 Cross-section of a nominally 5 nm thick InGaAs QWR on a 50 nm InP buffer: a) TEM picture, b) AFM topograph.

shows an AFM topograph of the same sample after selectively etching the cleavage plane. Both pictures show good agreement. In order to determine the exact dimensions of the QWR the AFM and the preparation method were specially calibrated [5]. The width and thickness in the center of the QWR is found as 180 nm and 5 nm ± 2 nm, respectively.

The PL of the QWR is studied in the (3+3) part of the sample. In the PL spectrum of the as-grown structure the QWR peak cannot be identified because it is superimposed by the peaks of the other quantum structures. In order to separate the QWR peak we prepared the sample with a self aligning masking

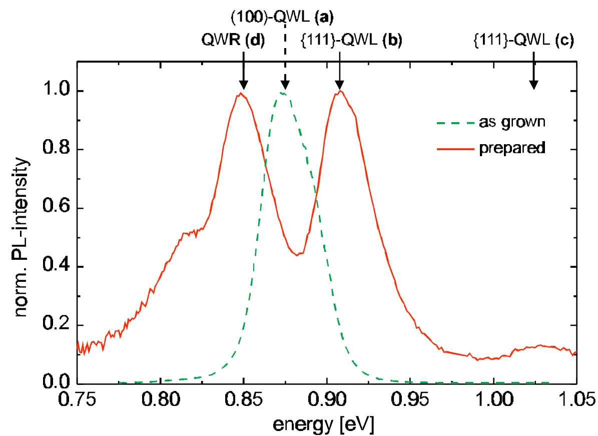

Fig. 5 PL spectra of the (3+3) part of a QWR-sample; as grown (dashed line) and prepared (solid line).

process. The sample is partially concealed by titanium. The mask covers the (100)-surface and parts of the {111}-planes. Hence the laser cannot excite these regions. Fig. 5 shows the normalized PL spectra of the as grown-sample (dashed line) with the dominant peak of the (100)-QWL (a). The solid line is the spectrum taken with the partially covered sample. It is formed by three peaks, two pronounced peaks at 850 meV (d) and 920 meV (b) and one small peak at 1025 meV (c). The peak of the (100)-QWL at 875 meV is removed by the preparation step. As discussed in the QWL section the two higher energetic peaks (b) and (c) originate from the {111}-plane. Peak (d) is the signal of the QWR in the tip of the V-groove.

Now we are able to study the QWR luminescence. Therefore we performed temperature resolved PL experiments from 13 K up to room temperature. Fig. 6 shows the absolute PL-intensities of the V-

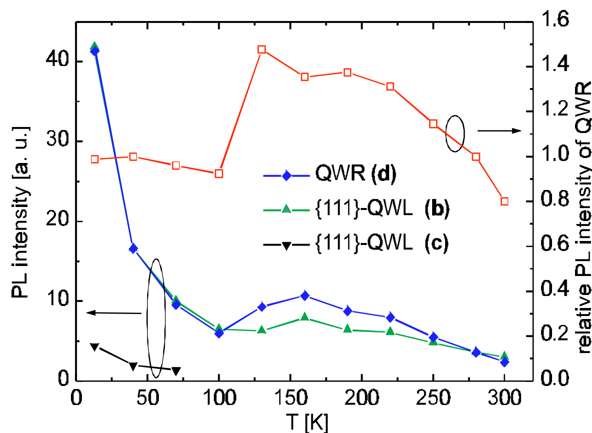

Fig. 6 PL-intensity of the V-groove quantum structures in dependence on sample temperature.

groove quantum structures (b), (c) and (d) plotted versus the sample temperature. For low temperatures up to 100 K the intensity of all structures decreases steadily. At 100 K peak (c) vanishes and especially the QWR peak starts to increase with a maximum at 150 K. Peak (b) increases slightly. From 150 K up to room temperature both peaks decrease again and the QWR peak falls below the {111}-QWL intensity. The relative intensity of the QWR, i. e. the quotient of peak intensities (d) and (b), is plotted as open symbols in Fig. 6. At low temperature the relative intensity has a flat characteristic. At 100 K the relative intensity makes a step of a factor of 1.5 and decreases below 1 at room temperature.

This effect of increasing QWR luminescence with increasing temperature was observed for QWR in the material system GaAs/AlGaAs, too [6] and can be explained by carrier diffusion along the surrounding QWL and thermalization of the photo-excited carriers in the low potential of the QWR. It is possible that the narrow {111}-QWL (c) at the edge of the QWR plays an important role in the temperature dependence of this diffusion and carrier capture process.

[1] J. Diaz, H. J. Yi, M. Razeghi, G. T. Burnham: Long-term reliability of Al-free InGaAsP/GaAs (λ=808 nm) lasers at high-power high-temperature operation; Appl. Phys. Lett. 71 (1997) 3042

[2] P. Bönsch, D. Wüllner, T. Schrimpf, A. Schlachetzki, R. Lacmann: Ultrasmooth V-grooves in InP by two-step wet chemical etching; J. Electrochem. Soc. 145 (1998) 1273

[3] P. Bönsch, D. Wüllner, T. Schrimpf, H.-H. Wehmann, A. Schlachetzki: Growth of InGaAs/InP quantum wires on patterned substrates, 7th European Workshop on Metal-Organic Vapour Phase Epitaxy and Related Growth Techniques (EW MOVPE VII) (1997)

[4] D. Wüllner, M. Chahoud, T. Schrimpf, P. Bönsch, H.-H. Wehmann, A. Schlachetzki: Diffusion during metalorganic vapor-phase epitaxy on V-groove patterned substrates, J. Appl. Phys. 85 (1998) 249

[5] D. Wüllner, A. Schlachetzki, P. Bönsch, H.-H. Wehmann, T. Schrimpf, R. Lacmann, S. Kipp, Characterization of quantum structures by atomic-force microscopy, Mater. Sci. Eng., B 51 (1998) 178

[6] M. Walther, E. Kapon, J. Christen, D. M. Hwang, R. Bath: Carrier capture and quantum confinement in GaAs/AlGaAs quantum wire lasers grown on V-grooved substrates, Appl. Phys. Lett. 60 (1992) 521