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GROWTH AND CHARACTERIZATION OF INGAAS QUANTUM-WIRES

H.-H. WEHMANN, T. SCHRIMPF, P. BÖNSCH, D. WÜLLNER, D. PIESTER, A. SCHLACHETZKI
Institut für Halbleitertechnik, Technische Universität Braunschweig, Postfach 3329, D-38023 Braunschweig, Germany, IHT@TU-BS.DE
R. LACMANN
Institut für Physikalische und Theoretische Chemie, Technische Universität Braunschweig, Postfach 3329, D-38023 Braunschweig, Germany

1. Introduction

Low-dimensional semiconductor structures are expected to have superior properties for laser applications namely reduced threshold current and temperature dependence, low emission line-width, and improved dynamic behaviour [1]. These improvements are enhanced for quantum confinement of charge carriers in more than one dimension [2]. Thus, zero-dimensional quantum-dot structures (QD) are intensely investigated. However, most of these experiments are carried out with self-organized QDs which form at lattice-mismatched epitaxial growth and are thus statistically distributed in size and area. This leads to broadened emission lines and increased threshold currents. In order to circumvent these problems we focus our work on quantum wires (QWR) which are formed by well-controlled epitaxial growth on patterned substrates.

Based on anisotropically etched V-shaped grooves wire structures can be epitaxially grown in one step which are completely buried in a wide-gap semiconductor without the need of nano-structuring techniques. With such a concept QWR lasers were fabricated in AlGaAs/GaAs, however, by employing demanding fabrication techniques [3]. This material system is generally preferred for such applications since the lattice-mismatch between AlAs and GaAs is small enough to cause no problems with dislocation formation. In addition the large anisotropy of growth rates of GaAs leads to a quasi-stable radius of curvature at the tip of V-grooves such that several QWRs can easily be stacked. This is supported by the resharpening of the tips by growing Al-containing compounds. However, the most promising material system for long-distance optical links is InGaAs(P)/InP. Due to the stronger dependence of its lattice constant on the composition its growth on patterned substrates is more difficult because of different mobilities of the growth species on the crystal surface. This leads to increased In-contents in QWRs grown into V-grooves which entails compressive strain [4].

In this paper we investigate the lattice-matched growth of InGaAs with nominally 53% In on patterned (100) InP substrates by metal-organic vapour-phase epitaxy (MOVPE). In particular we examine the influence of the etching process and the initial InP buffer-layer on the properties of the following quantum structures (QS). For characterization we use photoluminescence (PL), including polarization-dependent PL, and atomic-force microscopy (AFM). We compare the results with calculated transition energies.

2. Experimental

In Fig. 1 the QS is schematically shown in cross-section. It consists of 3 µm wide V-grooves etched into

the (100)InP substrate and a layer stack consisting of an InP buffer-layer, the InGaAs active layer which forms single quantum wells (SQW) on the surface planes and the QWR in the V-groove's tip, and finally an InP cap-layer in order to reduce surface effects.

2.1. SAMPLE PREPARATION

At first the V-grooves were wet-chemically etched through a Ti-mask [5] in two steps. HBr (37%) was employed for 20 sec, followed by saturated $K_2Cr_2O_7$ (aq) : HBr (37%) (3 : 1) for 5 sec. The resulting tip radii were below 8 nm. The arithmetic average roughness of the {111} planes was 0.4 nm. Both values were obtained by AFM which was specifically calibrated for the characterization of QWR structures [6]. The Ti-mask which was formed with a conventional lift-off process was removed after etching the V-grooves in buffered HF for 30 sec. As expected, the growth process is sensitive to residuals of photoresist and Ti on the surface. Therefore, we examined several cleaning procedures which effectively remove residuals while not affecting the tip radius. We judged their effectiveness by PL-characterization. An example is shown in Fig. 2. As optimum we found a 10 sec oxygen-plasma stripping followed by 5 sec in HF (5%). After thorough rinsing in deionized water, the patterned substrates were finally etched in H_2SO_4 : H_2O (5 : 1) for 1 min. This procedure has no effect on the tip radius.

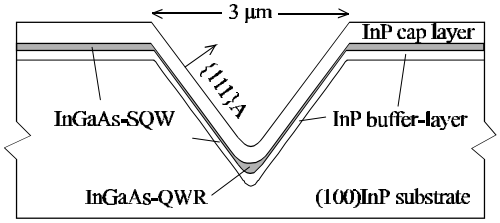

Figure 1. Schematic cross-section of quantum structure.

2.2. MOVPE GROWTH

After cleaning, the samples were directly loaded into the horizontal IR-heated MOVPE-reactor. The growth started with an InP buffer-layer, the thickness of which was varied. Subsequently, the nominally lattice-matched InGaAs layer with a thickness of 5 nm on planar (100) substrates was grown (shown shaded in Fig. 1). The layer stack was completed by a 100 nm thick InP cap-layer. All layers were nominally undoped grown at 600 °C at a reactor pressure of 100 hPa. The V/III-ratio during the growth of InP and InGaAs in the gasphase was 113 and 73, respectively. These parameters were optimized in order to produce a growth anisotropy as small as possible for the InP layers and as high as possible for the InGaAs layer without changing the temperature and the total pressure [7]. This was done because the InP should cover all open crystallographic faces most homogenously before and after the growth of the active layer, which on the other hand in the ideal case should only grow in the tip of the V-groove. In our concept of a QWR we deliberately avoided Al-containing compounds which lead to a reduced lifetime of lasers fabricated with such layers. InAlAs shows a resharpening effect also on InP which was utilized to realize stacked InGaAs QWRs [8].

3. Characterization and Results

For characterization of the QSs we employed mainly PL at 13 K with normal incidence on the (100) surface. The spot diameter of the 10 mW HeNe laser, used for illumination, was about 250 µm exciting a total of about 40 V-grooves. A Peltier-cooled Ge detector and a monochromator with a focal length of 640 mm were used. After optimizing the growth parameters [7] we focussed on the buffer-layer thickness and its influence on the layer quality, since it is well known that the quality of InGaAs layers directly grown on InP substrates is low. Fig. 2 shows the respective maximum PL intensities of the as-grown QS for two different spacings between the 3 µm V-grooves (3 and 12 µm). Although the main part of the PL originates from the SQW on the (100) plane (cf. Fig. 1) we assume that the quality of the QWR shows a similar dependence. Clearly visible is the improvement for thicker buffers saturating near 100 nm. Comparing samples which were not stripped in an oxygen plasma (open symbols) with treated samples

(solid symbols) clearly shows an improvement of the treated samples. Again, for buffer layers thicker than 100 nm the differences are marginal because all disturb ances caused by the etched surface are buried by these buffers.

Unfortunately, the growth of thicker buffers increases the tip radius and consequently the width of the crescent-shaped QWR. The schematic cross-section of our QWRs is sketched as inset of Fig. 3, which shows the increasing QWR width as well as its simultaneously decreasing thickness. However, the latter value saturates beyond 50 nm buffer thickness at 5 to 6 nm, which roughly corresponds to the desired 5 nm InGaAs thickness. Both geometrical values of the QWR were determined by AFM on $[0\bar{1}1]$ cleavage planes which were selectively etched in citric acid : H_2O_2 (7 : 1). To retrieve the accurate dimensions of the quantum wire a specialized interpretation and calibration process was developed [6]. As a compromise between layer quality and QWR width we focus on 5 and 50 nm thick buffers.

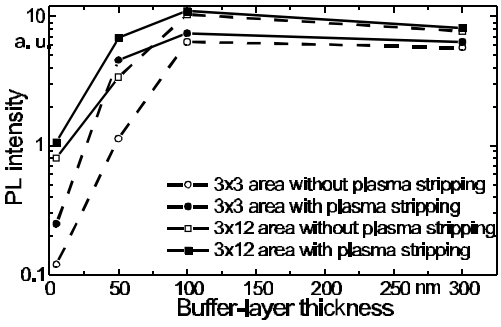

Figure 2. PL peak-intensity of the as- grown QS versus buffer-layer thickness.

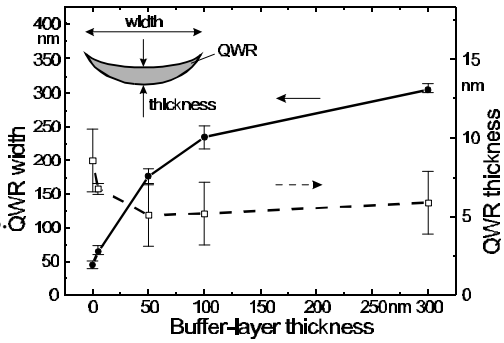

Figure 3. Width and thickness of QWRs in dependence on buffer-layer thickness.

In order to prove the one-dimensional carrier confinement within the QWR, we took PL spectra of the QS. They are dominated by a high-intensity peak which originates from the (100)SQWs (cf. Fig. 1) together with the respective peak of the (111)SQWs. For a better resolution we covered the (100) surface and parts of the (111) planes by evaporating Ti onto the surface under an angle of 70° taking advantage of the self-aligned shadowing of the V-groove tip. By this procedure we enhanced the QWR signal relative to the SQW peaks. Since the Ti film was not completely covering the SQWs we found three to four peaks. In order to obtain a clear relation between the peaks and their origin, we employed polarized excitation of the QS, since the PL intensity of QWRs is expected to decrease to about 60% when the electric field-vector of the exciting light is perpendicular to the wires as compared to parallel excitation [9].

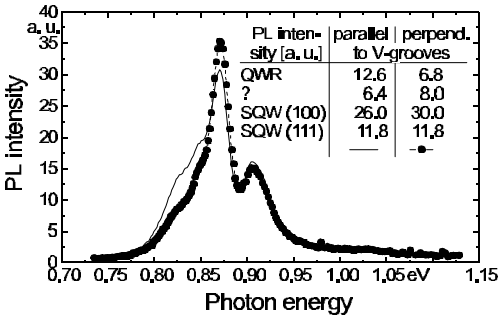

Figure 4. Measured PL spectra with polarized excitation (solid line: parallel, dash-dotted line perpendicular to QWR). Inset shows fitted peak intensities.

Fig. 4 shows two PL spectra of a QS grown with a 50 nm thick buffer. The spectra could be well fitted by four peaks, the maximum intensities of which are given in the table. We attribute the central peak to the (100) SQW which was measured to be 5 nm thick. Although, there should not be any dependence on the polarization we found a decrease by 13% for parallel excitation. Presumably it is caused by residual strain of the SQWs. Since the {111} SQWs have a thickness of only 1.5 nm the respective transition energy is highest. This peak shows no polarization dependence. The lowest energy peak decreases in intensity to 54% for perpendicular excitation relative to the parallel case. This agrees well with the results reported in [9] and thus is an indication of one-dimensional carrier confinement of the QWR.

The fourth peak (marked by a question mark in Fig. 4) shows a similar polarization dependence as the (100) SQW related peak (20% decrease). We attribute it to regions of increased edge growth in the vicinity of the V-grooves. We observed 10 to 20% higher growth rates near the edges which corresponds well to the energy shift of 20 meV.

In order to obtain information on the composition of the QWR we calculated the transition energies

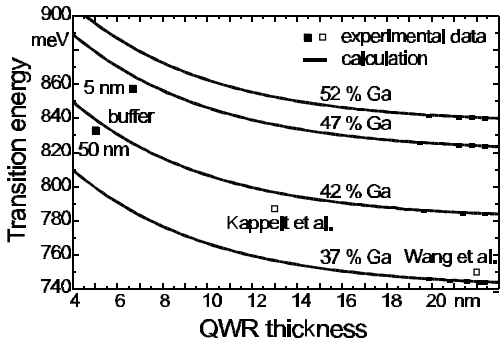

Figure 5. Calculated and measured transition energies in QWRs of different thicknesses.

by solving the two-dimensional Schrödinger equation by a finite-element program. A result is shown in Fig. 5 where we calculated the transition energy of the ground state for a 60 nm wide QWR varying its thickness. We used commonly accepted values for band-edge discontinuities and effective masses. The parameter is the Ga-content which is 47% for lattice match. Also shown are experimental data points taken from the literature [4,10] and our own findings. As expected, all QWRs are In-rich due to its increased surface mobility on the {111} planes. However, we found a slight dependence on the buffer thickness which might reflect the improved {111} surfaces with increasing buffer thickness.

4. Conclusion

We fabricated InGaAs QWRs by MOVPE growth on V-groove patterned InP substrates. Although the tip radius of the etched V-grooves increases by mass transport and buffer-layer thickness, at least 5 nm of InP are necessary to improve the PL peak intensity. By employing polarization-dependent low-temperature PL measurements we demonstrated one-dimensional confinement in our QWRs. By comparing the peak energies with calculated transition energies we found our QWRs to be In-rich.

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