Laser structures with InGaAs-QWs and n-AlGaAs/p-GaInP cladding layers for emission wavelength beyond 1100 nm

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Introduction

High power diode lasers operating in the wavelength range beyond 1100 nm are of significant interest as pump sources for Raman amplifiers in telecommunication. Additionally, high power lasers will open applications in material processing systems without transfer of optical power to fiber or solid-state lasers.

Standard laser diodes consist mainly of $Al_xGa_{1-x}As$ which is used both for the waveguide (WL) and cladding layers (CL) and is typically grown at temperatures above 700°C. Reasons for this high growth temperature are reduced oxygen incorporation and better layer performance [1]. Unfortunately, $In_xGa_{1-x}As$-QWs for wavelengths beyond 1100 nm need an indium content above x = 0.3. Such high In-content can be incorporated into the QW only at significantly lower growth temperatures [2]. Thus structures have to be grown at different temperatures for the QW and the surrounding waveguide and cladding layers which leads to indium diffusion during the growth of the upper p-doped layers of the laser structure and a blue shift of the emission wavelength. An alternative is the use of p-GaInP instead of AlGaAs as cladding layer. GaInP can be grown at lower growth temperatures without a deterioration of the layer performance. Low growth temperatures are even preferred since below 670°C ordering and decomposition effects decrease [3].

Experimental

Growth by metal organic vapour phase epitaxy (MOVPE) was carried out in an Aixtron 200/4 reactor on exactly oriented (001) GaAs substrates. Precursors were pure arsine, phosphine and the trimethyl compounds of gallium (TMGa), indium (TMIn) and aluminium (TMAl). For p-type doping dimethyl zinc and for n-type doping disilane diluted in hydrogen were used.

Test structures for this study consist of $In_xGa_{1-x}As$ single QWs with thicknesses of ≈ 6 nm and an indium content of x = 0.35 sandwiched between 300 nm thick GaAs layers, which yield an emission wavelength around 1120 nm. All layers for the test structures were grown at 530°C, except for the buffer layer. The laser structure consists of a double InGaAs QW embedded in thick GaAs waveguide layers and $Al_{0.25}Ga_{0.75}As$ cladding layers. On top of the p-cladding layer is a highly p-doped GaAs contact layer. The structure is designed for a narrow vertical far field by using very thick GaAs waveguide layers. These broad waveguide layers are undoped in the inner part and lowly doped ($< 5\cdot10^{17}$ cm^{-3}) towards the cladding layers. This results in low free carrier absorption and hence low internal optical losses α_i. Therefore the use of very long cavities is possible, which again improves the heat removal.

For laser structures the InGaAs QWs were grown at 530°C, while the GaAs waveguide and AlGaAs cladding layers were grown at temperatures between 570°C and 770°C. To adjust the necessary growth temperature the growth was interrupted between the spacer layers surrounding the QW and the waveguide layers.

High-resolution X-ray diffraction (HRXRD) was applied to determine layer thickness w and indium content x_s in the solid phase by comparing the measured rocking curves to simulated ones. Simulation of the rocking curves was done in a first approximation assuming rectangular QWs, although due to the diffusion processes during annealing graded interfaces are expected. However, graded interfaces in our HRXRD analysis can only be seen if they extend over more than 2 nm. Photoluminescence at room temperature and at 10 K was used to estimate changes in the QW after annealing.

The structures were processed into broad-area (BA) laser diodes with 60 µm, 100 µm and 200 µm stripe widths and cavity lengths from 1 mm to 4 mm. The transparency current density j_{tr} and other figures of merit were determined from the cavity length dependence of threshold current density j_{th} and differential efficiency η_d under pulse conditions with a pulse width of 400 ns and a duty cycle of 1:400, assuming a logarithmic dependence of the gain on current density.

Results

The effect of different growth temperatures for the p-doped side of laser diodes was investigated on simple test structures. These test structures, grown at 530°C, were annealed for a time of 10 minutes, corresponding to the growth time of the p-side of laser diodes, at 600°C, 650°C and 770°C. The results of PL characterization at 10 K of a 6 nm thick $In_{0.35}Ga_{0.65}As$ QW are shown in Fig. 1. With increasing annealing temperature the PL peak wavelength shifts to shorter wavelengths by up to 42 nm. The rocking curves of these samples do not show a significant difference. Only in the case of an annealing temperature of 770°C a slight difference in comparison to the as grown sample can be seen. The simulation of the rocking curves results in an increase of the InGaAs QW thickness by ≈ 0.75 nm to 6.5 nm and a reduction of the indium content by ≈ 4 % to 31 %. Therefore, it is necessary to adjust the composition of the InGaAs QW for comparable laser emission wavelength in dependence of the growth temperature and growth time of the subsequent layers. Hereby it is also necessary to take into account that for a growth temperature of 530°C and an emission wavelength above 1100 nm the thickness of the single QW is near and for multi QWs exceeds the theoretical critical thickness for strain relaxation, which results in the formation of point defects and dislocation lines. Such defects render the layers not suitable for the preparation of laser diodes. For these reasons a lower growth temperature for the upper part of laser structure seems to be advantageous.

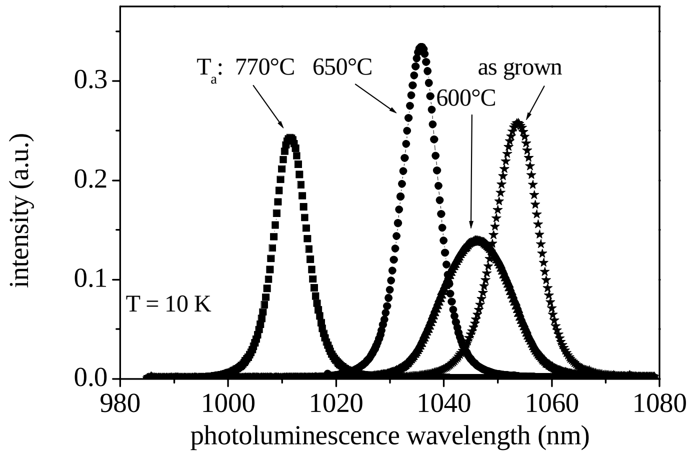

Fig. 1 PL spectra at 10 K of InGaAs QWs as a function of annealing temperature.

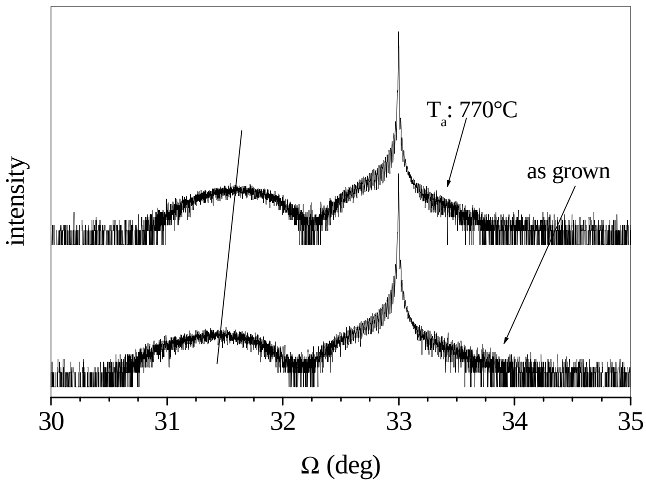

Fig. 2: Rocking curves for as-grown (530°C) and annealed (770°C) samples. The line is a guide for the eye.

The laser structure was chosen with a very high thickness of the waveguide layer and a relatively low difference in refractive index between waveguide and cladding layers. This leads to a half width of the far field angle between 19 and 20 degrees, which means that 95 % of the output power is included in the central emission lobe with a divergence of 34.5 degrees. This very narrow far field makes such structures especially suitable for beam collimation and coupling. But in such structures the gain per QW is very low and for this reason double QW structures were used. An additional advantage of such a structure is the low aluminium content in the layers. Firstly a lower aluminium content results in a lower affinity to oxygen and therefore an expected lower oxygen incorporation during the growth and secondly with increasing aluminium content the thermal resistance increases to a maximum for $x_{Al} = 0.5$. A high thermal resistance leads to reduced output power due to less efficient heat removal.

Laser structures with 350 nm thick $Al_{0.25}Ga_{0.75}As$ cladding layers and 1.7 µm GaAs waveguide layers were grown by MOVPE with a double InGaAs QW on (100) GaAs substrates at different temperatures for the p-side (structures A, B, C). The layers were characterized and processed into laser diodes. The results of unmounted and uncoated broad area laser diodes with a stripe width of 100 µm, measured under pulsed excitation, are shown in table 1. Wavelength, threshold current density and slope efficiency are estimated for a resonator length of 1 mm. For comparable emission wavelengths the indium content in the vapour phase has to be reduced slightly in dependence on the lower growth temperature.

The laser results show, that despite the low aluminium content the growth of AlGaAs containing layers at temperatures below 700°C leads to inferior laser performance with increasing threshold current density and decreasing efficiency (structures A,B in comparison to C). The measurement of the oxygen concentration in an $Al_{0.7}Ga_{0.3}As$ layer, grown in a wide temperature range between 600°C and 770°C, shows an increase of the oxygen concentration at growth temperatures below 700°C. The increase of the oxygen concentration corresponds with the increase of threshold current density [4]. This together with the formation of point defects at reduced growth temperatures leads to the degradation of the laser performance.

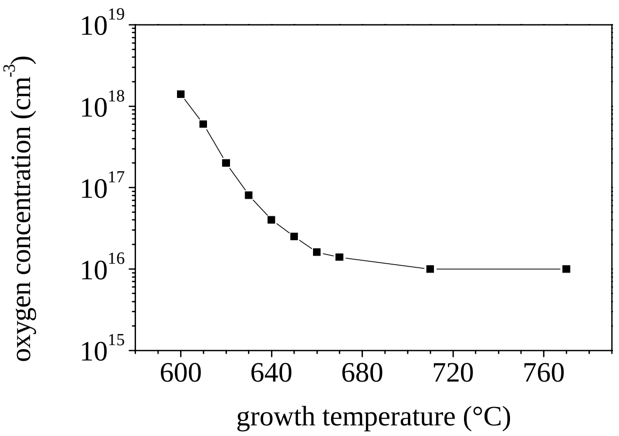

Fig. 3 Dependence of oxygen concentration in an $Al_{0.7}Ga_{0.3}As$ layer on growth temperature.

An alternative to AlGaAs cladding layers is the substitution by a GaInP cladding. A disadvantage of GaInP is the possibility of ordering and spinodal-like decomposition effects which can affect the growth of subsequent layers. Therefore, for the n-cladding layer AlGaAs was chosen and only the p-side was substituted by GaInP. The results are also shown in Tab. 1. In sample D the p-GaAs waveguide layer was still grown at 770°C, comparable to the best structure with p-AlGaAs cladding, and only the p-GaInP layer was grown at a typical growth temperature for GaInP of 600°C. In this case the laser diode properties are nearly identical for AlGaAs or GaInP cladding layer. Due to the distinctly thicker GaAs waveguide layer, grown at 770°C, in comparison to the GaInP cladding, the effect of reduced indium diffusion and, respectively, reduced red shift of the emission wavelength could be not obtained. For a reduced indium diffusion behaviour the GaAs waveguide and the GaInP cladding layers were grown at 570°C (structure E). This structure shows only slightly inferior laser properties in comparison to the best ones, but a longer emission wavelenth at a lower TMIn concentration in the vapour phase during growth. The red shift of the emission wavelength due to indium diffusion effects thus was significantly reduced.

structure	x_v	p-cladding layer	T_{g-WL}	T_{g-CL}	λ	j_{th}	s	η_i
			°C	°C	nm	A/cm^2	W/A	%
A-B0784	0.5225	$Al_{0.25}Ga_{0.75}As$	550	600	1117	520	0.327	65
B-B0980	0.5253	$Al_{0.25}Ga_{0.75}As$	650	650	1112	391	0.424	76
C-B0844	0.5281	$Al_{0.25}Ga_{0.75}As$	770	770	1118	310	0.455	85
D-B0852	0.5281	GaInP	770	600	1121	310	0.453	85
E-B0947	0.5253	GaInP	570	570	1125	323	0.446	86
F-B1131	0.5382	GaInP	570	570	1213	312	0.347	80

Tab. 1 Growth parameters and laser data of different laser structures (x_v – composition of the vapour phase TMIn/(TMIn+TMGa), T_g –growth temperature of waveguide and cladding layer, respectively, λ - emission wavelength, j_{th} – threshold current density, s – slope efficiency, η_i – internal efficiency)

For these reasons this structure is the favoured one for wavelengths around 1200 nm with a further increased In incorporation. The red shift due to diffusion effects increased by increasing the indium content in the quantum well (Tab. 2). In this test structure a double InGaAs QW with different indium content and a barrier of 100 nm GaAs between the QWs was embedded in 300 nm thick GaAs layers, characterized by PL, and than annealed for 10 minutes at 770°C. In the QW with the higher indium content a stronger red shift of 46 nm after annealing is obtained in comparison to 32.5 nm for the QW with lower indium content.

A laser structure emitting at 1213 nm was grown at 570°C (p-doped layers) with a threshold current density comparable to the best AlGaAs structures emitting at 1120 nm. Slope and internal efficiency are lower, probably the high indium content in the QW deteriorates the quality of the heterointerface. The internal efficiency of 80% for a laser diode with a half width of the far field angle of 20° is well suitable for most applications and can be further increased by additional QWs [5].

	x_v	PL peak wavelength at room temperature (nm)		$\Delta\lambda$ (nm)
		as grown	after annealing	
QW 1	0.5096	1116.8	1084.3	32.5
QW 2	0.5855	1193.7	1147.7	46.0

Tab. 2 PL peak wavelength before and after annealing for two different QWs

Conclusions

GaInP cladding layers as an alternative to AlGaAs can be grown at lower temperatures. Lower growth temperatures result in a smaller red shift of the emission wavelength of InGaAs QWs and, therefore, a lower TMIn content in the vapour phase is necessary for comparable wavelengths. Due to the lower indium content the strain in the QW is also reduced and a shift towards longer wavelength without formation of defects is possible.

Broad area laser diodes with GaInP p-cladding layers show laser properties comparable to structures with AlGaAs p-cladding at a lower TMIn supply. The lower growth temperature allows the extension of the emission wavelength above 1200 nm only with a slight deterioration of the laser performance.

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