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Interdiffusion in highly strained InGaAs-QWs for high power laser diode applications

F. Bugge*, U. Zeimer, H. Wenzel, G. Erbert, M. Weyers

Ferdinand-Braun-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Str. 4, D-12489 Berlin, Germany

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Abstract

With the aim of realizing laser diodes on GaAs with an emission wavelength above 1120 nm, we have studied the indium incorporation behavior into highly strained pseudomorphic InGaAs-QWs grown by metalorganic vapor-phase epitaxy (MOVPE). To obtain such long wavelengths the $In_xGa_{1-x}As$ ($x > 0.3$) quantum wells were grown at much lower temperature (530 °C) than the AlGaAs cladding layers. The indium diffusion and the resulting emission wavelength shift during growth of the upper cladding layers and their dependence on growth parameters like strain compensation, quantum well composition and V/III-ratio has been studied.

Laser diodes with very small far field angles were processed into broad area devices (50–200 μm × 1000–4000 μm). Such devices show thermally limited output cw powers above 10 W.

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Keywords: A3. Metalorganic vapor-phase epitaxy; A3. Quantum wells; B1. InGaAs; B3. Laser diodes

1. Introduction

GaAs-based laser diodes in the wavelength range at and beyond 1100 nm due to their high output power potential are interesting as sources for Raman amplifiers in telecommunication systems, for pumping up-conversion fiber lasers or direct material processing without transfer of optical power to fiber or solid state lasers.

For several applications it is necessary to adjust the emission wavelength exactly to obtain high efficiencies of the whole system, for other applications additionally a high output power is necessary. Laser diodes emitting beyond 1100 nm need a high indium content in the InGaAs quantum well (QW). Decreasing the growth temperature T_g the critical layer thickness for relaxation as well as for the transition from two-dimensional growth to

*Corresponding author. Tel.: +49 30 63922672; fax: +49 30 63922685.
E-mail address: bugge@fbh-berlin.de (F. Bugge).

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three-dimensional growth can be increased and longer wavelengths can be achieved [1]. On the other hand, the growth of AlGaAs layers at such low temperatures results in an increased oxygen incorporation and point defect formation, which results in a degradation of the performance of laser diodes [2,3]. Thus, highly strained QWs typically are grown at lower temperatures than the surrounding (Al)GaAs waveguide and cladding layers [4,5]. Several authors have shown, that a post-growth annealing of InGaAs QWs results in a blue shift of the emission wavelength [6,7].

In this paper we discuss the effect of growth temperature variations and post growth annealing steps on the emission wavelength of InGaAs single and double QWs.

2. Experimental procedure

Growth was carried out in an Aixtron 200/4 machine on exactly oriented (0 0 1) 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.

To study the indium interdiffusion behavior, single and double QWs sandwiched between (Al)GaAs cladding layers were grown. In all cases the InGaAs QWs were grown at 530 °C, while the (Al)GaAs cladding layers were grown at temperatures between 530 and 770 °C. To adjust the necessary growth temperature the growth was interrupted between spacer layers surrounding the QW and the cladding layers. Several samples, completely grown at 530 °C, were subjected to post growth annealing steps to compare the “in-situ” and “ex-situ” diffusion behavior of the InGaAs QWs.

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 was used to estimate changes in the QW after annealing. For investigation of the density of non-radiative defects within the QW cathodoluminescence (CL) images were taken at 110 K.

Using these results, complete laser structures with AlGaAs cladding, moderately doped between $5\times10^{17}\,cm^{-3}$ and $10^{18}\,cm^{-3}$, and GaAs waveguide layers, undoped and low doped between $1–5\times10^{17}\,cm^{-3}$, were grown and processed into broad-area (BA) laser diodes. The lasers were characterized under pulsed and cw conditions.

3. Results

While low growth temperatures are preferable for the growth of InGaAs QWs they can result in higher oxygen incorporation and higher point defect densities in the waveguide and cladding layers and thus deteriorated layer properties. Fig. 1 shows the oxygen concentration dependence on growth temperature for a 1 μm thick $Al_{0.7}Ga_{0.3}As$ layer. During the growth T_g was lowered from 770 °C down to 600 °C linearly. While there is no dependence of the growth rate on T_g in this temperature range a correlation between oxygen concentration and depth and thus growth temperature from a SIMS profile is observed. While

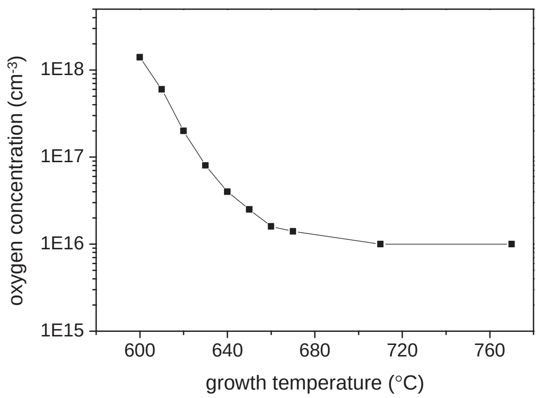

Fig. 1. Dependence of oxygen concentration in an $Al_{0.7}Ga_{0.3}As$ layer on growth temperature ($10^{16}\,cm^{-3}$ is the background level).

above 660 °C the oxygen concentration is at or below the detection limit it remarkably increases for lower temperatures. Although for lasers emitting beyond 1100 nm lower aluminium concentrations are sufficient, low growth temperatures thus should be avoided. Therefore a temperature gradient during the growth process is necessary. The temperature used for the upper waveguide structure results in a blue shift of the emission wavelength of the InGaAs QW compared to QWs grown without temperature change. The knowledge of this shift is essential for adjusting the emission wavelengths of laser diodes. Fig. 2 shows the PL peak wavelength of three structures consisting of an InGaAs QW sandwiched between 10 nm thick GaAs spacer layers, all grown at 530 °C, and 700 nm thick $Al_{0.1}Ga_{0.9}As$ cladding layers grown between 530 and 770 °C. For the structure completely grown at 530 °C the simulation of the rocking curve results in a 5.8 nm thick $In_{0.346}Ga_{0.644}As$ QW. The room temperature peak wavelength shifts from 1129 to 1092 nm for samples with AlGaAs cladding layers grown at 530 and 770 °C, respectively. Additionally, we obtained a reduction of the FWHM of the PL signal from 26.3 to 19.5 nm. This can be explained by a smoothing of the interfaces by diffusion during the growth at higher temperatures.

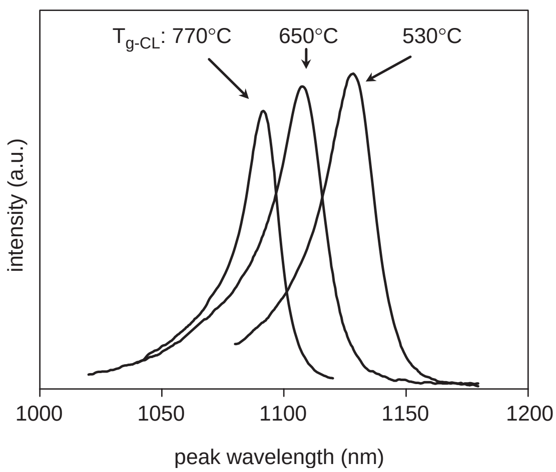

Fig. 2. PL spectra at room temperature of samples with InGaAs QW grown at 530 °C and cladding layer grown at different temperatures.

In literature, the indium diffusion behavior was usually investigated by rapid thermal annealing (RTA) after growth at temperatures above the usual growth temperature in MOVPE and with times drastically lower than necessary for layer growth. Taylor et al. [6] found a blue shift of 40 nm for an $In_{0.18}Ga_{0.82}As$ QW annealed at 950 °C. Bürkner et al. [7] annealed an $In_{0.35}Ga_{0.65}As$ QW for 15 s at 950 °C and obtained even a shift of 70 nm, two times higher than what we obtained for the "in-situ" annealing. To compare the "in-situ" with post growth annealing structures InGaAs QWs sandwiched between 300 nm thick GaAs layers grown at 530 °C were annealed in the same MOVPE reactor under arsine between 600 and 770 °C. The annealing time of 10 min was chosen similar to the growth time for the upper AlGaAs cladding layers. The results are shown in Table 1 and Fig. 3. The wavelength shift and the reduction of the FWHM of the PL signal from the as-grown state after annealing at 770 °C is comparable to that of the structure where the upper cladding layer was grown at 770 °C. Therefore, results from

Table 1
Photoluminescence peak wavelength in dependence on annealing temperature

PL (nm)	x_s	w_{QW} (nm)	Annealing temperature (°C)
1128	0.347	5.8	As-grown
1116	*0.347*	*5.8*	600
1108	*0.347*	*5.8*	650
1085	*0.307*	*6.5*	770
with GaAsP spacers			
1116	0.345	6	As-grown
1103			600
1099	*0.345*	*6*	650
1072	*0.305*	*6*	770
with GaInP spacers			
1135	0.36	6.2	As-grown
1126			650
1109			770

Solid state composition x_s and QW width w_{QW} are given for the as-grown structure. The data for annealed samples (in italic) are extracted from simulations assuming a rectangular QW. Only for annealing at 770 °C a structural change in the QW can be seen in the rocking curves.

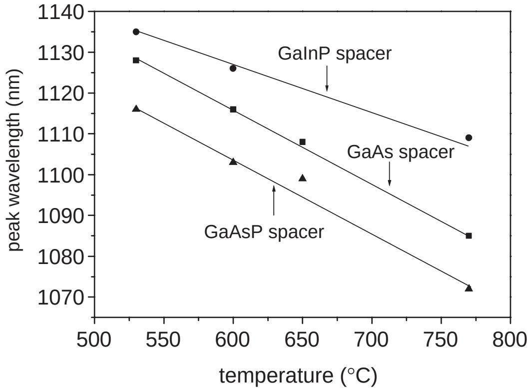

Fig. 3. PL peak wavelength of InGaAs QWs as a function of annealing temperature for samples with different spacers.

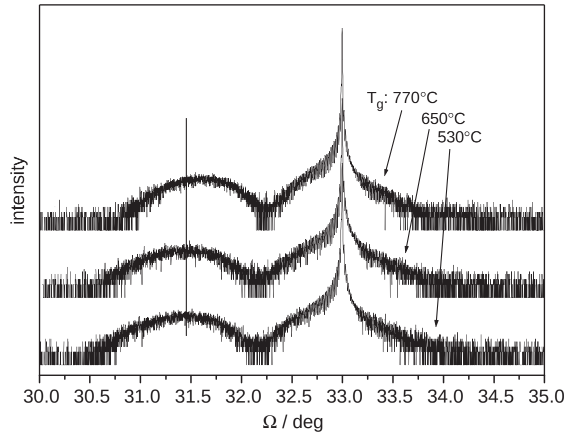

Fig. 4. Rocking curves for as-grown (530 °C) and annealed (650 °C, 770 °C) samples. The line is a guide for the eye showing that the peak related to the InGaAs QW does only shift for $T_a = 770\,°C$.

a more detailed characterization of annealed samples should also be comparable.

The samples were characterized by HRXRD and for the as-grown one thickness and composition of the QW was estimated. A comparison of all rocking curves shows that only for samples annealed at 770 °C a measurable deviation from the as-grown rocking curve is found (Fig. 4) although already at a lower annealing temperature of 650 °C a PL shift of 20 nm is obtained (Table 1). The indium diffusion during annealing, results in graded interfaces. At lower annealing temperatures this grading causes already a shift in the PL emission but leaves the rocking curves nearly unchanged. The data of x_s and w_{QW} of annealed samples (in italic) give only a hint for changes in the rocking curves. The degraded interfaces were not taken into account in the simulation.

Fig. 5 shows CL images of an as-grown (a), and a structure annealed at 770 °C (b). The as-grown structure has a homogeneous luminescence without dark spots. After annealing the luminescence becomes inhomogeneous, probably due to diffusion processes in both lateral and vertical directions which then result in lateral composition inhomogeneities. This is not in contradiction to the finding of lower FWHM of the PL signal for structures grown or annealed at 770 °C. The CL image is a result of the "bulk" QW material, whereas the FWHM is more affected by the quality of heterointerfaces. Additionally, an accumulation of point defects results in dark spots also. Dark spots and composition inhomogeneities deteriorate the epitaxial layer performance and, therefore, can shorten the lifetime of devices based on such structures.

The effect of different indium content on the blue shift is shown in Fig. 6. A sample with two different QWs with comparable thickness but different indium content separated by a 100 nm GaAs barrier was grown. In the as-grown state the lower QW emits at 1191.5 nm, the upper at 1112 nm. After annealing at 770 °C a blue shift of 46 and 29.5 nm, respectively, is observed. The reason for the larger shift of the QW with the longer wavelength is most probably a combination of the higher indium concentration gradient and the higher strain. Structures with 11 nm thick $GaAs_{0.84}P_{0.16}$ strain-compensating spacer layers with a shorter emission wavelength caused by the higher barriers but comparable indium content in the QW show shifts of the emission wavelength comparable to those with GaAs spacer layers (Table 1, Fig. 3). If the reduced strain results in a reduced indium diffusion, then an additional interdiffusion of arsenic and phosphorus seems to cancel this effect.

To suppress an indium outdiffusion from the QW a diffusion stop layer or indium containing layers are necessary. Kawai et al. [8] have shown that an AlAs interlayer suppresses the indium

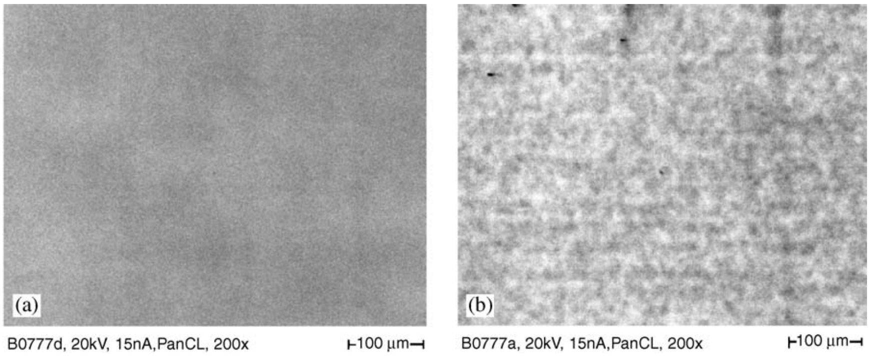

Fig. 5. Panchromatic CL images of InGaAs QWs as-grown (a) and annealed at 770 °C (b).

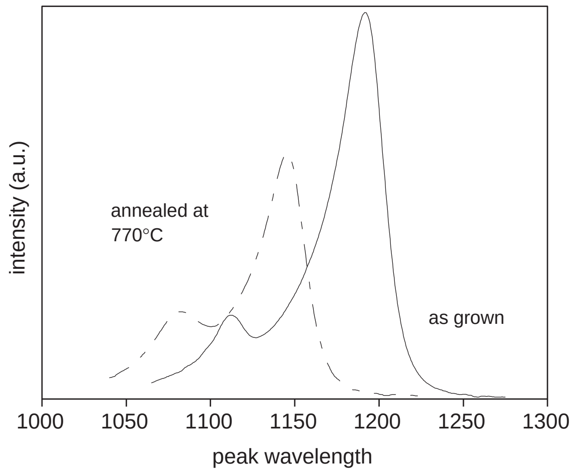

Fig. 6. PL spectra of a DQW with different indium concentrations, as-grown and annealed at 770 °C. The peak wavelength of the higher strained QW shifts by 46 nm, the lower strained by 32 nm after annealing.

diffusion effectively. However, such a layer will adversely affect laser properties since it results in a very high barrier. Thus, we investigated the effect of 10 nm thick GaInP spacer layers on the interdiffusion. The results are also shown in Table 1 and Fig. 3. The blue shift of the emission wavelength was reduced by a factor of 2. Lattice-matched $Ga_{0.52}In_{0.48}P$ has a higher indium concentration in the group III sublattice than the $In_{0.35}Ga_{0.65}As$ QW and therefore there is an indium concentration gradient into the QW. Nevertheless, an emission wavelength shift was obtained, which is most probably due to the additional interdiffusion of phosphorus and arsenic.

The findings on the diffusion behavior favor a low growth temperature for waveguide and cladding layers for devices, where a blue shift of the emission wavelength is unwanted. This is the case when the wavelength of GaAs-based InGaAs QWs is to be pushed to its long wavelength limits. Against that are the inferior AlGaAs layer properties at lower T_g.

To evaluate the device properties, broad area lasers with stripe widths of 60, 100 and 200 µm were processed. The QWs were grown at $T_g = 530\,°C$. 3.4 µm GaAs as waveguide and 0.8 µm $Al_{0.25}Ga_{0.75}As$ as cladding layer were used. The waveguide core is intentionally undoped, which results in very low absorption losses and allows resonator lengths of 4 mm. Waveguide and cladding layer were grown at 770 or 600 °C.

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 internal efficiency η_i 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. The results for 2 mm long devices are shown in Table 2. SQW and DQW laser diodes with growth temperature of waveguide and cladding layers $T_{g-WL+CL} = 770\,°C$ have similar threshold current densities of 180–200 A/cm^2, but the slope efficiency is higher for the DQW. For the structure of type C the p-doped waveguide and cladding layers were grown at 600 °C. The transparency current density

Table 2
Threshold current density (j_{th}) for a broad area device with 100 μm width and a cavity length of 2 mm, transparency current density and slope efficiency (η_D) for different structures in pulsed operation. $T_{g-WL+CL}$ is the growth temperature for the p-doped waveguide and cladding layers

Type	λ (nm)	j_{th} (A/cm^2)	j_{tr} (A/cm^2)	η_D (%)	$T_{g-WL+CL}$ (°C)	Remarks
A	1118	181	63	65	770	SQW
B	1135	203	128	72	770	DQW
C	1153	274	120	63	600	DQW

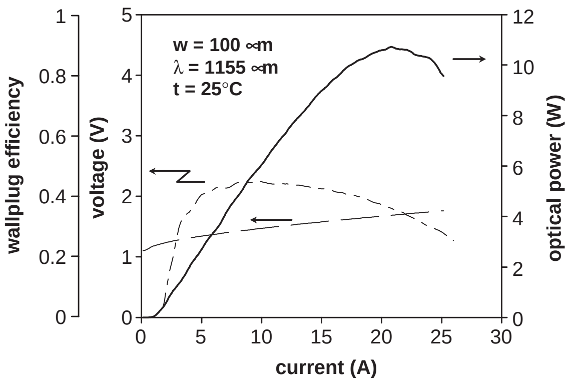

Fig. 7. CW optical output power, forward voltage and wall plug efficiency vs. current for a laser diode with emission wavelength of 1155 nm.

is comparable to type B but the threshold current density is about 35% higher. Leakage currents are a possible explanation due to a higher concentration of point defects and/or oxygen incorporation at low T_g. This explanation is supported by the low characteristic temperature T_0 of 57 K for C in comparison to 81 K for structure B. An additional factor for increasing j_{th} is a slightly reduced far field angle, which points to a lower difference in the refractive index between waveguide and cladding layers. The layer properties, grown at 600 and 770 °C, respectively, are still not fully comparable.

To reach extremely high optical output powers a structure of type B was then processed for CW characterization due to its higher wall-plug efficiency in comparison to structure C. The resonator length was chosen to be 4 mm. The facets were antireflection and high reflection coated. The chips were mounted p-side down on copper–tungsten submounts with AuSn solder and on C-mounts finally. In Fig. 7 the optical power and wall plug efficiency are shown against the operating current. The maximum of wall plug efficiency is slightly below 50%. In CW operation we tried to test the catastrophic optical mirror damage (COMD) level. We achieved a power of nearly 11 W from a 100 μm stripe which was limited by thermal roll over and no indication of COMD was found. To the best of our knowledge this is amongst the highest CW powers for 100 μm stripe lasers ever published. The very small far-field angle of 20° of this structure makes it especially suitable for a beam collimation and coupling.

4. Conclusion

The effect of temperature treatment during growth and in subsequent annealing steps on the emission wavelength of highly strained InGaAs QWs was investigated. During growth or annealing at 770 °C over the time scale necessary for the growth of cladding layers of laser diodes, a blue shift of more than 40 nm was obtained.

Broad area laser diodes with waveguide and cladding layers grown at different temperatures were realized with very good device characteristics. A very high cw output power up to 11 W at a lasing wavelength of 1150 nm was achieved from a 100 μm wide and 4000 μm long device with a very small half width of the far-field angle of 20°. Lifetime tests at 5 W for a 60 μm wide and 4 mm long stripe show no degradation after 1000 h and therefore the high potential for high-power applications.

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