

## Laser diodes with highly strained InGaAs MQWs and very narrow vertical far fields

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The effect of variation of the number of highly strained InGaAs quantum wells embedded in GaAs layers on the crystal quality of the epitaxial layers and AlGaAs/GaAs laser diodes was investigated. With four quantum wells and very thick waveguide layers, reasonable efficient laser diodes emitting above 1100 nm with a narrow vertical far field (FWHM = 15 °) were obtained. Broad area laser diodes with 200 µm stripe width and an optimised doping profile emit nearly 20 W cw output power.

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### 1 Introduction

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

In comparison to Al<sub>0.5</sub>Ga<sub>0.5</sub>As waveguides, GaAs waveguides offer lower series resistance due to the higher carrier mobilities and four times higher thermal conductivity, which reduces resistive heating and facilitates the removal of heat from the active region. However, a drawback is the low effective electron barrier between InGaAs quantum well (QW) and GaAs waveguides which leads to low internal efficiency. An increase of the number of QWs should result in an increased internal efficiency. Therefore, such structures have the potential for very high optical output power [1, 2].

AlGaAs/GaAs test and laser structures with highly strained InGaAs QWs were grown and the effect of different numbers of QWs on layer properties and laser performance was investigated.

### 2 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 aluminum (TMAI). 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<sub>x</sub>Ga<sub>1-x</sub>As single or multi QWs with thicknesses of ≈ 6 nm each 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

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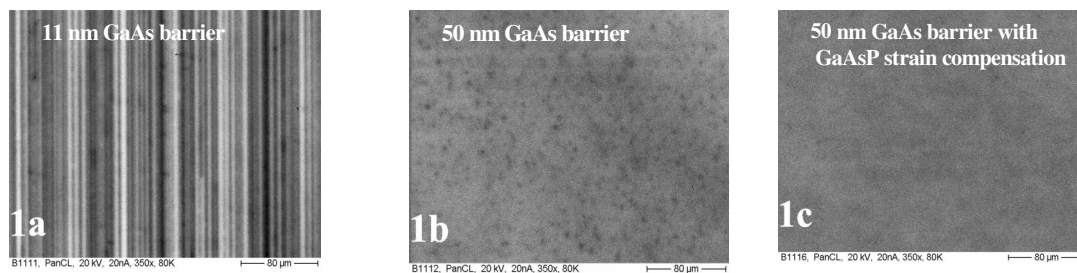
the buffer layer. The laser structure consists also of a single or of multi InGaAs QW embedded in thick GaAs waveguide layers and  $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$  cladding layers. On top of the p-cladding layer is a highly p-doped GaAs contact layer. The structure is designed for a narrow vertical far field by using very thick GaAs waveguide layers. These broad waveguide layers are undoped in the inner part and lowly doped ( $< 5 \cdot 10^{17} \text{ cm}^{-3}$ ) towards the cladding layers. This results in low free carrier absorption and hence low internal optical losses  $\alpha_i$ . 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.

The structures were processed into broad-area (BA) laser diodes with 60  $\mu\text{m}$ , 100  $\mu\text{m}$  and 200  $\mu\text{m}$  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  $\eta_d$  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. For testing under cw conditions the front facet of 4 mm long laser diodes was low reflection coated to 7% reflectivity and the back facet to 95% reflectivity. The chips were mounted p-side down on passively cooled heatsinks (CCP), which allow a better heat transfer and easier current supply in comparison to standard C-mounts.

### 3 Results and discussion

For a growth temperature of 530 °C and an emission wavelength around 1120 nm the thickness of the single QW is near and for multi QWs (MQW) it exceeds the theoretical critical thickness for strain relaxation resulting in the formation of point defects and dislocation lines. Such defects render the layers not suitable for the preparation of laser diodes. In the case of  $\approx 6$  nm thick single or double  $\text{In}_{0.35}\text{Ga}_{0.65}\text{As}$  QWs cathodoluminescence (CL) images show no hints for the formation of defects. Also high resolution X-ray investigations (HRXRD) show no indications for strain relaxation in the QWs. At this low growth temperature apparently the strain energy does not yet exceed the critical one for defect formation.



**Fig. 1** CL images of eightfold QWs with different barriers.

To investigate the accumulation of strain due to a larger number of QWs the effects of an increase of the thickness of the barriers and of strain compensation were investigated. For finding distinct dependencies three eightfold QWs were grown. Characterization by HRXRD shows no differences in thickness and composition for all three different MQW structures. The CL images are shown in Fig. 1. The first 8QW structure with 11 nm barriers shows a high density of dislocation lines. With a barrier thickness of 50 nm in the second 8QW only dark spots can be seen (1b). However, with wider barriers an additional photoluminescence (PL) peak at the lower energy side is observed. While in structure 1a the strain energy was accumulated and resulted in the formation of dislocation lines, in structure 1b apparently the

stress was reduced by the transition from the 2-dimensional to the 3-dimensional growth mode and the formation of indium rich quantum dots. These dots result in the additional PL peak.

The effect of an introduction of strain compensating barriers is shown in Fig. 1c. These barriers are formed by including a 21 nm thick GaAs<sub>0.79</sub>P<sub>0.21</sub> layer sandwiched between 15 nm GaAs, so that the total barrier thickness of 50 nm is comparable to structure 1b. Strain and thickness of the GaAsP layer are calculated for a strain compensation of 100%. Such barriers reduce the overlap of strain fields and should suppress the transition from the 2-dimensional to the 3-dimensional growth mode.

In the CL image (Fig. 1c) no dislocation lines and no dark spots are obtained and the PL shows only a slight shoulder on the low energy side.

Super large optical cavity (SLOC) laser diodes [3] with 350 nm thick AlGaAs cladding and 1.7  $\mu\text{m}$  thick GaAs waveguide layers, designed for a narrow vertical far field (full width at half maximum  $\Theta_L \leq 20^\circ$ ), were grown with different numbers of QWs. The small effective electron barrier of about 160 meV between the InGaAs QW and the GaAs waveguide layer leads to a correspondingly large excess electron density in the waveguide at and above threshold. An increase of the number of QWs decreases the excess electron density in the waveguide due to the reduced threshold carrier density in the QWs. Therefore, the absorption by excess carriers and the recombination rate of electrons and holes in the waveguide is diminished which results in a decreased value of  $\alpha_i$  and an increased value of  $\eta_i$ .

Structures with one and up to 4 QWs were processed into BA laser diodes up to now. All structures were grown without GaAsP strain compensation, because no indications of defects or strain relaxation in the quadruple QW (QQW) were obtained. The results for laser diodes with resonator lengths  $L$  between 0.2 mm and 4 mm and a stripe width of 100  $\mu\text{m}$  are shown in Table 1. As expected, transparent current density and the modal gain increase with the number of QWs. The internal efficiency increases from 73% for a single QW to 96% for a fourfold QW. In the structure with a SQW a very low gain and therefore a very high threshold current density is obtained for the 1 mm long device. The additional QWs drastically improve the laser performance at the expense of only a slight increase of the threshold current density and a slightly broader width of the vertical far field.

**Table 1** Properties of unmounted and uncoated broad area laser diodes for structures with single, double, triple and quadruple QW in pulsed operation ( $\lambda$  emission wavelength,  $j_{th}$  threshold current density,  $\eta_D$  differential efficiency,  $\Gamma G_0$  - modal gain coefficient,  $\eta_i$  - internal efficiency,  $\Theta_L$  full width at half maximum of the vertical far field).  
\*  $L = 1$  mm

type	$\lambda^*$ (nm)	$j_{th}^*$ (A/cm <sup>2</sup> )	$\eta_D^*$ (%)	$\Gamma G_0$ (cm <sup>-1</sup> )	$\eta_i$ (%)	$\alpha_i$ (cm <sup>-1</sup> )	$\Theta_L^*$ ( $^\circ$ )
SQW	1099	953	36	6.7	73	1.8	18
DQW	1118	310	82	12.7	85	0.9	19
TQW	1101	338	85	18.2	92	0.8	19
QQW	1118	357	86	25.2	96	0.9	19

The very high efficiency of the QQW structure allows a further reduction of the vertical far field without a strong decrease of the laser diode performance. For this reason the thickness of the GaAs waveguide layer was increased from 1.7  $\mu\text{m}$  to 2.2  $\mu\text{m}$  on both sides. Table 2 shows the results for BA laser diodes in dependence on the thickness of the waveguide layer.

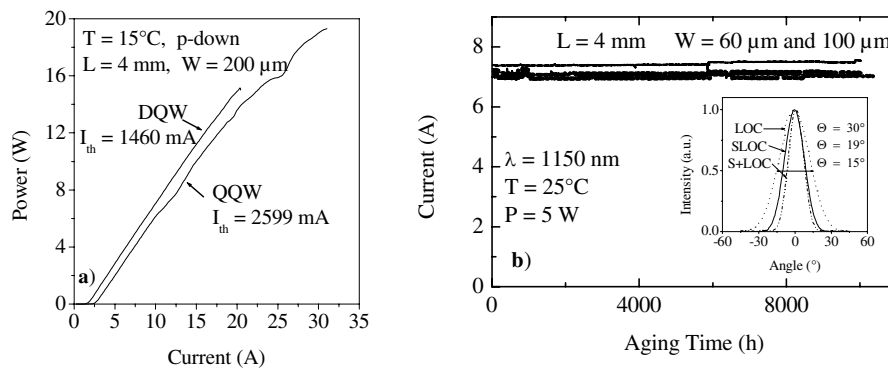
**Table 2** Properties of broad area laser diodes for structures with reduced (SQW-LOC), standard (QQW-SLOC) and increased (QQW-S+LOC) thickness of the waveguide layers.

type	$d_{WL}$ ( $\mu\text{m}$ )	$\lambda^*$ (nm)	$j_{th}^*$ (A/cm <sup>2</sup> )	$\eta_D^*$ (%)	$\Gamma G_0$ (cm <sup>-1</sup> )	$\eta_i$ (%)	$\Theta_L^*$ ( $^\circ$ )
SQW-LOC	2 x 1	1109	312	55	9.9	89	30
QQW-SLOC	2 x 1.7	1118	357	86	25.2	96	19
QQW-S+LOC	2 x 2.2	1128	381	80	22.5	86	15

An increase of the waveguide thickness from 1  $\mu\text{m}$  to 2.2  $\mu\text{m}$  on both sides reduces the half width of the far field to  $15^\circ$ , which results in a more circular beam at a reasonable efficiency. The insert in Fig. 2b shows the reduction of  $\theta_{\perp}$  by increasing the waveguide thickness.

The occurrence of higher order modes by increasing the thickness of the waveguide layers was suppressed by reducing the thickness of the cladding layers. For a cladding thickness of 0.3  $\mu\text{m}$  and below the propagation loss of the fundamental mode remains on the level of the absorption loss, whereas the propagation loss of the higher order modes drastically increases.

Laser diodes with 4 mm cavity length and 200  $\mu\text{m}$  stripe width were mounted p-side down on CCP heatsinks. The power current characteristics are given in Fig. 2a. For the DQW structure nearly 15 W and for the QQW structure nearly 20 W were obtained and no indication of catastrophic optical mirror damage was found. The kinks in the QQW structure are possibly due to the formation of ring modes. The output power is comparable to the 16 W for a SQW obtained by [1], but with a clearly lower  $\theta_{\perp}$  of  $19^\circ$  in comparison to  $31^\circ$  in [1].



**Fig. 2** Power current characteristic for a DQW and QQW laser structure (a) and aging behaviour for a DQW structure. The insert in Fig. 2b shows the vertical far field for structures with different waveguide thickness.

First lifetime tests were performed for 4 mm long laser diodes emitting at 1150 nm with 60  $\mu\text{m}$  (1 diode) and 100  $\mu\text{m}$  (3 diodes) stripe width at 5 W optical output power (Fig. 2b). After 10,000 h there was no noticeable degradation, indicating the excellent crystallographic perfection of the highly strained InGaAs quantum wells used in these devices. Based on this excellent aging behaviour additionally laser diodes were tested at 8 W (100  $\mu\text{m}$  x 4 mm device) and 15 W (200  $\mu\text{m}$  x 4 mm device). Also no noticeable degradation was obtained after 2,000 h.

## 4 Conclusion

Thickness and composition of the barriers in highly strained InGaAs MQWs affect the formation of defects in such structures. A strain compensation by introduction of GaAsP layers can shift the onset of defect formation to higher indium contents. Laser diodes processed from MQW structures allow a drastic reduction of the vertical far field due to the high internal efficiency and show very high output powers of 20 W from 200  $\mu\text{m}$  aperture with no noticeable degradation during 10,000 h aging time at 5 W from 100  $\mu\text{m}$  aperture.

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