Multi QWs for laser diodes with emission wavelengths above 1100 nm

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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 fiber lasers or direct material processing without transfer of optical power to fibers or solid state lasers [1].

In comparison to AlGaAs, GaAs waveguides offer lower series resistance and higher thermal conductivity which reduces resistive heating and facilitates the removal of heat from the active region. However, a severe problem 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 a very high optical output power [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.

Experimental

Growth by metal organic vapor 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 (TMAl). For p-type doping dimethyl zinc or carbon and for n-type doping disilane diluted in hydrogen were used.

Test structures under investigation consist of $In_xGa_{1-x}As$ single or multi QWs with thicknesses of ≈ 5.6 nm each and an indium content of x = 0.35 sandwiched between 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 also of a single or multi InGaAs QW embedded in thick GaAs waveguide layers and $Al_xGa_{1-x}As$ (x = 0.25) cladding layers. On top of the p-cladding layer is a highly p-doped GaAs contact layer. The structure is designed for a small vertical far field by using very thick waveguide layers. The broad GaAs 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 low internal optical losses α_i. Therefore the use of very long cavity lengths 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 µm, 100 µm and 200 µm stripe widths and cavity lengths L 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. For testing under cw conditions the output facet of 4 mm long laser diodes was antireflection coated to 7% reflectivity and the back facet to values larger than 95%. The chips were mounted p-side down on CuW submounts with AuSn solder which were then soldered onto C-mounts.

Discussion

For a growth temperature of 530°C and an emission wavelength around 1120 nm the thickness of the QW is near and for multi QWs (MQW) it exceeds the theoretical critical thickness for 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 5.6 nm thick single or double $In_{0.35}Ga_{0.65}As$ 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 the strain energy does not exceed the critical one for defect formation. Only by the insertion of additional three QWs, a fivefold QW with barriers of 11 nm GaAs in between, first dislocation lines are obtained.

To reduce or avoid the accumulation of strain due to the larger number of QWs the effect of increasing thickness of the barriers was investigated. For finding clear dependencies 3 eightfold QWs were grown. Characterization by HRXRD shows no differences in thickness and composition for all three MQWs. 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 (fig. 2). 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 $GaAs_{0.79}P_{0.21}$ layer sandwiched between 15 nm GaAs, so that the whole 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. The PL shows only a slight shoulder on the low energy side.

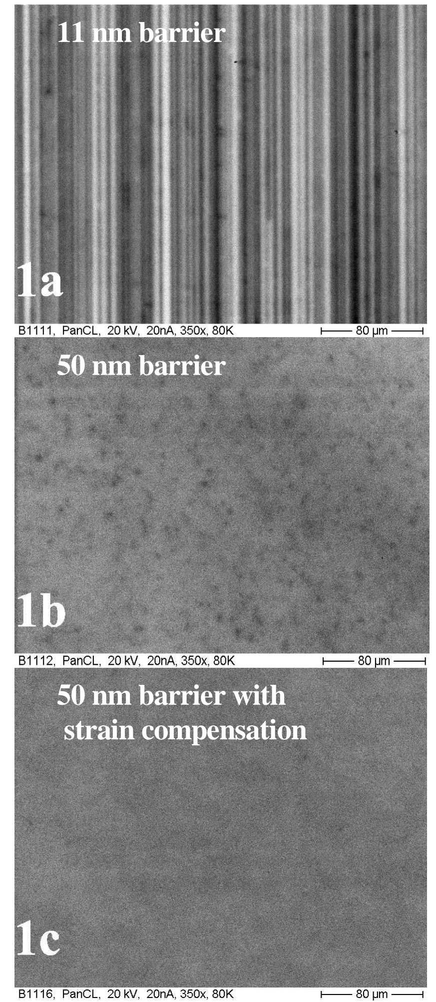

Fig. 1 CL images of eightfold QWs with different barriers

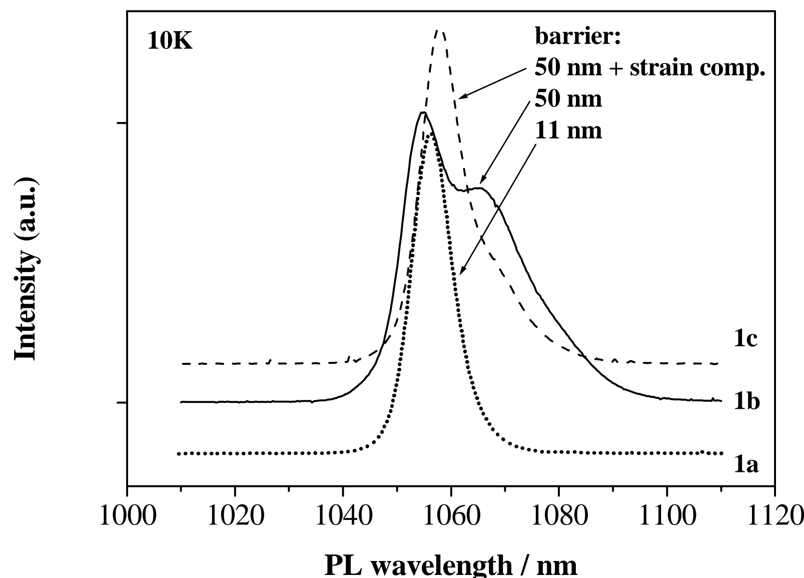

Fig. 2 Photoluminescence spectra of samples 1a, 1b, 1c

Laser diodes with AlGaAs cladding and GaAs waveguide layers, designed for a small vertical far field (half width $\leq$ 20°), 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 α_i and an increased value of η_i.

type	λ (nm)	j_{th} (A/cm^2)	η_D (%)	j_{tr} (A/cm^2)	ΓG_0 (cm^{-1})	η_i (%)	T_0 (K)
SQW	1099	953	36	60	6.7	73	
DQW	1118	310	82	131	12.7	85	76
TQW	1101	338	85	173	18.2	92	101
QQW	1118	357	86	213	25.2	96	119

Table 1 Properties of unmounted and uncoated broad area laser diodes for structures with different numbers of QWs in pulsed operation (λ emission wavelength, j_{th} threshold current density, η_D differential efficiency, j_{tr} transparency current density, ΓG_0 - modal gain coefficient, η_i - internal efficiency, T_0 characteristic temperature)

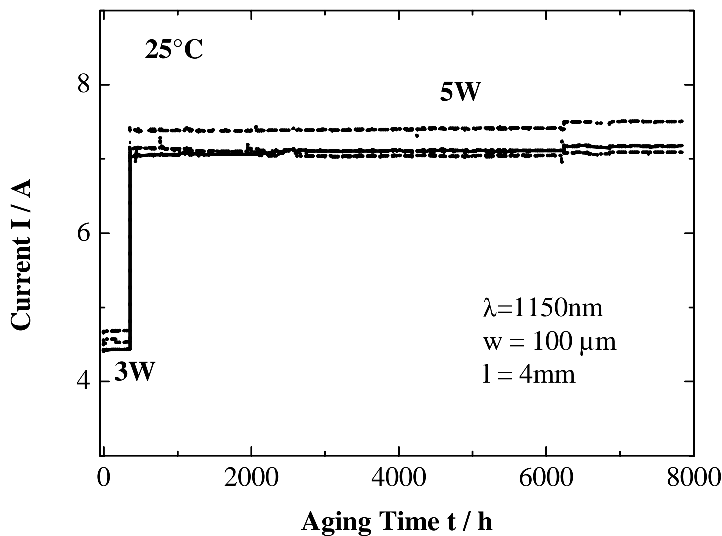

Fig. 3 Aging behaviour of laser diodes at a constant optical output power of 5 W at 25°C

Structures with one and up to 4 QWs were grown and processed into BA laser diodes. The results for laser diodes with a resonator length of 1000 µm and a stripe width of 100 µm 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 a very high threshold current density is obtained for the 1 mm long device. For this reason the characteristic temperature T_0 could not be measured. The additional QWs drastically improve the laser performance at the expense of only a slightly broader width of the vertical far field.

To investigate the potential of these laser diodes a structure with a DQW was processed for CW characterization. The resonator length was chosen to 4 mm. Despite the lower differential efficiency in comparison to TQWs and QQWs the wall plug efficiency rises to more than 50%. The maximum output power was more than 12 W from a 100 µm wide broad area laser which was limited by thermal roll over. No indication of catastrophic optical mirror damage (COMD) was found.

Lifetime test were performed for laser diodes with a double QW emitting at 1150 nm with 100 µm stripe width at 5 W optical output power. After more than 8000 h there was no noticeable degradation (fig. 3).

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 such structures show very high output powers and a very high reliability.

References

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