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Highly strained very high-power laser diodes with InGaAs QWs

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Abstract

With the aim of realizing laser diodes in the wavelength range beyond 1100 nm on GaAs, we have studied the indium incorporation behaviour into pseudomorphic InGaAs-quantum wells with extremely high indium content grown by metalorganic vapour phase epitaxy. A wide growth temperature range between 490°C and 770°C as well as the dependence on V/III-ratio and strain compensation has been studied. At the maximum In-content of 41%, a photoluminescence wavelength of 1238 nm at room temperature is obtained. Laser diodes with an emission wavelength up to 1206 nm were processed. Structures with a slightly reduced In-content, emitting at 1120 nm, were processed to broad-area devices (100 μm × 1000 μm) and show output powers up to 12 W, which corresponds to a record high internal power density of 23 MW/cm^2, with a good reliability. LOC structures with a reduced far field below 30° and a higher indium content emit 8.5 W at 1170 nm.

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1. Introduction

Laser diodes in the wavelength range at and beyond 1100 nm are interesting for pumping up-conversion fibre lasers or as sources for Raman amplifiers in telecommunication systems. Laser diodes grown on GaAs substrates also have been attracting much interest from the viewpoint of application to long-wavelength vertical cavity surface emitting lasers. There are different approaches to realize such laser diodes, namely either with InGaAs or GaInNAs quantum wells (QWs) or with InGaAs quantum dots (QDs).

It is necessary to optimize the crystal growth in order to accommodate the highly strained InGaAs QWs without defect formation. Shoji et al. [1] used a ternary $In_{0.21}Ga_{0.79}As$ substrate and were able to increase the indium content up to 38% in the QW. Schlenker et al. [2] and Takeuchi et al. [3] used the alternative group-V precursor tertiarybutylarsine, reduced the growth temperature (T_g) down to 530°C and optimized the V/III ratio to achieve QWs with an indium content of 41% and high crystalline perfection. Bugge et al. [4] have shown,

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that, using arsine as precursor, structures with good performances and an indium content of 37% can also be grown at 530°C.

In this paper, we discuss the metalorganic vapour phase epitaxy (MOVPE) growth of highly strained InGaAs/GaAs QWs for high-power laser diodes applications at wavelengths beyond 1100 nm.

2. Experimental procedure

Growth was carried out down to $T_g = 530°C$ on exactly oriented (0 0 1) GaAs substrates and for $T_g < 530°C$ on substrates slightly misoriented by 2° towards (1 1 0). 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 in hydrogen were used.

To study the indium incorporation behaviour, single QWs sandwiched between GaAsP strain-compensating spacer layers and/or 100 nm thick undoped GaAs waveguide layers and 300 nm p- and n-doped $Al_{0.25}Ga_{0.75}As$ cladding layers were grown. In all cases, the AlGaAs cladding layers were grown at 770°C, but the GaAs waveguide, the GaAsP spacer layers and the InGaAs QW were all grown at different temperatures. To adjust the necessary growth temperature, the growth was interrupted between the AlGaAs and GaAs layers.

High-resolution X-ray diffraction (HRXRD) was applied to determine the relaxation, layer thickness w, indium content x_s and phosphorus content y_s in the solid phase by comparing the measured rocking curves to simulated ones. The HRXRD results were compared to the wavelength and the full-width at half-maximum (FWHM) of photoluminescence (PL) emission.

Using these results, complete laser structures with 1.5 μm thick AlGaAs cladding, moderate doped between 10^{17} and $10^{18}\,cm^{-3}$, and 100 nm thick undoped GaAs waveguide layers were grown and processed into broad-area (BA) laser diodes. The lasers were characterized under pulsed and cw conditions.

3. Results

One possibility to increase the indium incorporation in pseudomorphic InGaAs QWs is the growth at low temperature where the indium migration length on the surface is reduced and so the Stranski–Krastanov growth mode starts at a higher indium concentration on the surface. At growth temperatures below 600°C, kinetic aspects begin to dominate the epitaxial growth. Nevertheless, the optical properties of InGaAs-QWs deteriorate only slightly by reducing T_g down to 490°C. Fig. 1 compares the 300 K PL spectra of structures grown at 650°C and 510°C. The FWHM at 300 K are comparable and only at 10 K the FWHM is doubled to 8.5 meV for the lower growth temperature. A maximum PL peak wavelength of 1238 nm was obtained for $T_g = 510°C$ which corresponds to an indium content of 41%. To our knowledge, this is among the highest indium contents in pseudomorphic InGaAs/GaAs QWs.

For T_g below 600°C, it is necessary to take into account the effect of different V/III ratios, because the decomposition efficiencies reduce for all precursors in a different manner. The V/III ratio affects the migration length and the adsorption/desorption behaviour on the surface. To investigate this effect, QWs were grown at 510°C varying the V/III ratio from 113, which is a typical value for our growth conditions, to 63 keeping the TMIn

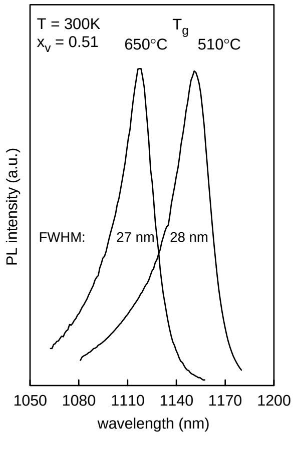

Fig. 1. PL spectra at 300 K of two InGaAs-QWs grown at 510°C and 650°C with the same vapour-phase composition.

and TMGa flow rates constant and reducing the AsH_3 flow. The room temperature PL peak wavelength shifts from 1208 to 1226 nm and the 10 K FWHM increases from 6.8 to 11.5 meV. This increase of indium incorporation at reduced V/III ratio is consistent with results from Takeuchi et al. [3]. They suggest reduced parasitic reactions between AsH_3 and TMIn as possible explanation, but certainly it is also necessary to take into account the effect of hydrogen radicals from arsine on indium desorption.

At growth temperatures between 570°C and 650°C, we studied the effect of strain-compensating GaAsP spacer layers on the indium incorporation behaviour. X-ray investigations show a slightly lower indium content in QWs with strain compensation, which corresponds also to a shorter PL peak wavelength. The smaller lattice constant of the GaAsP spacer layer results in an increasing strain barrier and reduces the indium incorporation. The FWHM of the peak from the QW is reduced by adding the GaAsP layers, but an additional PL peak at 1265 nm was observed (Fig. 2). The existence of this peak depends on the chosen T_g and vapour phase composition. We suggest that the GaAsP spacers suppress indium segregation into the following layer resulting in a sharper interface. Additionally, the nonsegregated indium can form QD-like fluctuations, which are responsible for the PL peak at 1265 nm. Opposite to the work on QD [5], the PL intensities of the QWs are higher than for the "QD" by a factor of 10. This peak disappears when lowering the growth temperature at the same composition of QW and spacer layers. When increasing the indium content, it appears again also at the lower T_g.

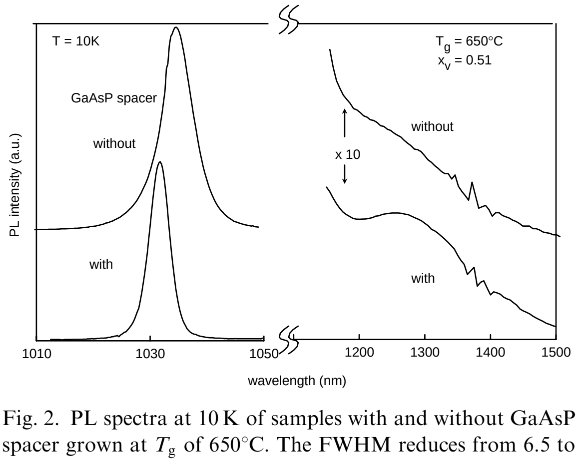

Fig. 2. PL spectra at 10 K of samples with and without GaAsP spacer grown at T_g of 650°C. The FWHM reduces from 6.5 to 4.5 nm introducing a GaAsP spacer.

Table 1
Threshold current density (j_{th}) and transparency current density (j_{tr}) in dependence of different emission wavelengths λ for broad-area devices (100 μm width and 1000 μm cavity length) in pulsed operation

λ (nm)	j_{th} (A/cm^2)	j_{tr} (A/cm^2)	$T_{g\text{-}AZ}$ (°C)	GaAsP spacer
1102	93	44	650	Yes
1120	94	37	600	Yes
1154	256	58	530	Yes
1173	126	57	530	Yes
1192	101	54	510	No
1206	183	52	510	No

To evaluate the device properties of highly strained InGaAs QWs, BA lasers with different emission wavelengths and with stripe widths of 60, 100 and 200 μm were processed (Table 1). The QWs were grown at T_g between 650°C and 510°C in order to shift the lasing wavelength as much as possible. Down to $T_g = 530$°C, the structures were grown with a GaAsP spacer layer. The transparency current density j_{tr} and other figures of merit were determined from the cavity length dependence of threshold current density and external differential efficiency under pulse conditions, assuming a logarithmic dependence of the gain on current density. Lasers with 100 μm stripe width and 1000 μm cavity length exhibit very low transparency current densities (j_{tr}). For an emission wavelength of 1120 nm, j_{tr} equals 37 A/cm^2, which is amongst the lowest transparency current densities ever reported for QW lasers. The reason is the large compressive strain due to the high indium content in the QWs which is known to lower the transparency current density due to the decrease of the in-plane heavy-hole and electron masses. For emission at longer wavelength, the higher j_{tr} is attributed to degrading interface properties, but the observed values of 52–54 A/cm^2 are to our knowledge still the lowest transparency current densities reported in this wavelength range.

The internal losses differ in these structures between 1 and 7 cm^{-1}.

Laser diodes with QW compositions where PL data give no evidence for a beginning relaxation or the appearance of QD-like fluctuations in the InGaAs layer were also characterized in cw operation. For these structures, well-resolved thickness fringes in X-ray rocking curves and a homogeneous cathodoluminescence intensity pattern also point to smooth interfaces without the formation of QD-like fluctuations.

Lasers grown at 530°C with GaAsP spacer layers and an emission wavelength of 1120 nm, a cavity length of 2 mm and facets with anti-reflection ($R \approx 1\%$) and high-reflection ($R \geqslant 90\%$) coatings were mounted epi-side down with an AuSn solder on a T-cBN heatspreader. At a temperature of 25°C, high wall-plug efficiencies of nearly 60% are achieved due to the high slope efficiency of about 90%, a low threshold current of 240 mA and a low series resistance of 0.1 Ω measured in the cw regime. A characteristic temperature of the threshold current $T_0 = 113$ K and a characteristic temperature of the external differential efficiency $T_1 = 990$ K were determined in the temperature range between 15°C and 85°C. At room temperature, we achieved a maximum output power of almost 12 W, limited by catastrophic optical mirror damage (COMD) (Fig. 3a).

Lasers emitting at 1170 nm were mounted epi-side up on c-mount. These devices have GaAsP spacer layers and a large optical cavity (LOC) structure with 1 μm wide GaAs waveguide layers and only 0.7 μm wide $Al_{0.25}Ga_{0.75}As$ cladding layer, which results in a reduced far field angle below 30°. The cavity length in this case was 4 mm. At a temperature of 25°C, we observed also high wall-plug efficiencies of nearly 60% and slope efficiencies of about 80%. The threshold current increases for this structure to 490 mA. The device emits 8.5 W limited by thermal rollover due to insufficient heat removal from the p-side up mounting (Fig. 3b).

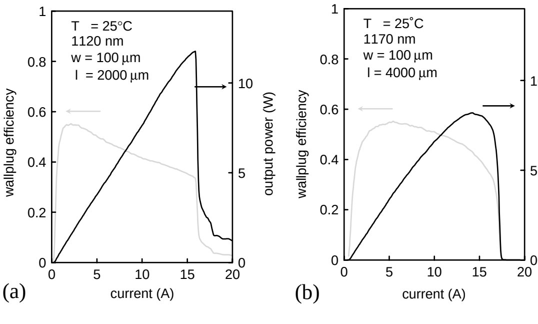

Fig. 3. Output power vs. current for an emission wavelength of 1120 nm, mounted p-side down (a) and 1170 nm, mounted p-side up (b).

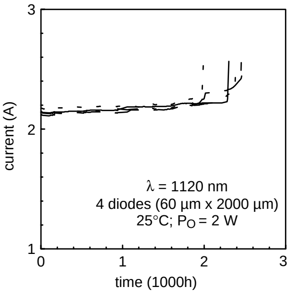

Fig. 4. Aging behaviour of BA devices.

Lasers emitting at 1206 nm were grown without GaAsP spacers and characterized up to now only under pulse conditions. The unmounted, uncoated 100 μm wide and 1000 μm long devices have a threshold current of 180 mA and emit up to 1.4 W at 3 A before thermal rollover starts.

The good crystallographic perfection of the highly strained InGaAs QW emitting at 1120 nm is reflected in the aging behaviour (Fig. 4). Lifetime tests over 2500 h yielded a very low degradation rate below $10^{-5}\,\text{h}^{-1}$ at a very high output power of 2 W for a 60 μm stripe-width device up to the end of life. The devices failed between 2000 and 2500 h due to mirror defects.

4. Conclusion

The growth of InGaAs QWs at low temperatures down to 490°C allows for structures with high strain without indications of relaxation and defect formation.

BA laser diodes with highly strained InGaAs QWs were realized with an emission wavelength up to 1206 nm with very good device characteristics. A record-high cw output power up to 12 W at a lasing wavelength of 1120 nm was achieved from a 100 μm wide and 2000 μm long device. Lifetime tests show the high potential for high-power applications.

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