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# Growth of laser diode structures with emission wavelength beyond 1100 nm for yellow–green emission by frequency conversion

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ABSTRACT

Laser structures for emission wavelengths of 1120 nm and 1180 nm, suitable for non-linear frequency conversion to yellow–green and yellow–orange, were developed. At 1120 nm emission wavelength different active regions and structures were investigated. The introduction of a GaAs spacer layer between GaAsP barriers and InGaAs QWs reduces threshold and transparency current density significantly. Lifetime measurements were done successfully over 1700 h for broad area and 10 000 h for ridge waveguide tapered lasers.

Broad area laser diodes with a partly strain-compensated 6 nm InGaAs QW, emitting at 1180 nm, show lifetimes above 1000 h at an output power of 1.5 W. The required beam quality was achieved by processing a ridge waveguide laser with an included distributed Bragg reflector. Such a laser emits up to 200 mW in single mode output power.



## 1. Introduction

Laser diodes emitting in the yellow–green range are key components for many applications, e.g. DNA sequencing, medical skin treatments, time resolved fluorescence spectroscopy and laser cooling of sodium atoms. Unfortunately, this yellow–green spectral region is currently not accessible directly with laser diodes based on the (In,Ga)N system, due to an increase of the quantum confined Stark effect, the formation of dark spots as a result of In diffusion in the InGaN quantum well (QW) or the formation of threading dislocations, all in dependence of the substrate orientation and indium content [1]. An alternative for this wavelength range are high-brilliance laser diodes based on GaAs substrates emitting in the spectral range between 1100 nm and 1200 nm and non-linear frequency conversion. There are different approaches to realize such laser diodes on GaAs substrates, namely either with InGaAs or GaInNAs quantum wells (QW) or with InGaAs quantum dots (QD) [2,3].

Using $In_xGa_{1-x}As$ QWs it is necessary to optimize the crystal growth to cope with the high strain. For emission wavelengths beyond 1100 nm the thickness of the QW is near and for MQWs it exceeds the theoretical critical thickness for the formation of dislocation lines according to Matthews–Blakeslees model for double-kink dislocations mechanisms [4]. Such defects alter the layers to be not suitable for the preparation of laser diodes. Therefore it is necessary to optimize the growth process and the design of the laser structures in order to accommodate the high strain without defect formation [5,6].

The additional incorporation of nitrogen into the InGaAs QW led to a red shift of the emission wavelength up to 1450 nm. Unfortunately, in such devices the radiative efficiency is strongly reduced due to increased nonradiative recombination which deteriorates the laser properties [7].

Laser diodes with quantum dots as active material suffer still from a relatively broad vertical far-field and low output power, which is insufficient for frequency doubling.

In this paper we investigate the growth, processing and device parameters of defect-free laser diodes emitting at wavelengths of 1120 nm and 1180 nm yielding emission wavelengths of 560 nm and 590 nm by non-linear frequency conversion.

## 2. Experimental procedure

Epitaxial growth was carried out in an Aixtron 200/4 machine at temperatures between 500 °C and 760 °C (thermocouple reading), a total gas flow of 15 slm and 150 mbar total pressure on exactly oriented (0 0 1) GaAs substrates. Precursors were pure arsine, phosphine and the trimethyl compounds of gallium (TMGa), indium (TMIn) and aluminum (TMAl). Disilane in hydrogen, carbon, intrinsically incorporated at reduced V/III ratios, and dimethylzinc (DMZn) were selected for n- and p-doping, respectively. The low

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growth temperatures of 500 °C and 520 °C have been used for the growth of the InGaAs QW with an In content above 30%, the higher temperature of 760 °C is necessary for the growth of oxygen-free AlGaAs waveguide layers.

The structures were analysed ex-situ by high-resolution X-ray diffraction (HRXRD), photoluminescence (PL) at room temperature and cathodoluminescence (CL) at 80 K. HRXRD was applied to determine layer thickness and composition of the QWs and barriers by comparing the measured rocking curves to simulated ones. From the composition the strain ε was calculated by $(a_{substrate} - a_{layer})/a_{substrate}$, where $a$ is the lattice constant.

To characterize the properties of such laser structures they were processed into broad-area (BA) laser diodes with 100 μm stripe width and different cavity lengths between 0.4 mm and 4 mm. For the BA laser diodes the absorption loss and other figures of merit were determined from the cavity length dependence of threshold current density $j_{th}$ and internal efficiency $\eta_i$ under pulse conditions with a pulse width of 500 ns and a repetition rate of 5 kHz, assuming a logarithmic dependence of the gain on current density.

For non-linear frequency conversion laser diodes with a nearly diffraction limited beam and a narrow spectral line width are necessary. It has been shown that ridge waveguide (RW) and ridge waveguide tapered lasers (RW-TPL) with an internal distributed Bragg reflector (DBR) grating are capable of providing the required spectral radiance for second harmonic generation (SHG) laser modules [8].

## 3. Results and discussion

Laser diodes emitting beyond 1100 nm need very high indium content in excess of 30% in the $In_xGa_{1-x}As$ QW. For such highly strained layers the growth and the structure have to be carefully optimized to avoid strain relaxation. The vertical design is an asymmetric super-large optical cavity (asloc) structure which is based on a previous development for 1060 nm [9]. While the basic laser structure is also suitable for the 60 nm longer wavelength, the higher indium content requires modifications of the growth process. At 1060 nm we could grow the InGaAs QW still at 650 °C, but for 1120 nm a lower temperature is necessary to increase the indium content in the QW above 30%. This requires a longer growth interruption between InGaAs and AlGaAs growth for temperature adjustment and leads to more indium diffusion effects. The asloc structure includes an active region with a double InGaAs QW (DQW) and $GaAs_{0.85}P_{0.15}$ barriers embedded into asymmetrical 4.8 μm wide $Al_{0.25}Ga_{0.75}As$ waveguide and $Al_{0.35}Ga_{0.65}As$ cladding layers. This vertical design results in the required narrow vertical far field beam divergence of 15° FWHM. A DQW was chosen on the one hand to compensate for the reduction of the overlap of the optical field with the active region which leads however on the other hand to an increased strain in the active region. For this reason two different quantum well thicknesses $w_{QW}$ of 5 nm and 7 nm were selected with different cumulative strain (see samples A and B in Table 1). The thicker QW contains less indium for the desired emission wavelength of 1120 nm and therefore lower effects of indium fluctuations at the heterojunctions on device performance are expected [10,11]. For strain compensation the highly compressively strained QWs are embedded in tensily strained GaAsP barriers. The outer barriers have a thickness of 5 nm and the GaAsP barrier in between the QWs has a thickness of 7.5 nm to suppress coupling between QWs. This results in an accumulated thickness $w_{bar,tot}$ of 17.5 nm for the GaAsP barriers. Comparing the remaining strain compensation ($|w_{QW} \bullet \varepsilon_{QW}| / |w_{bar,tot} \bullet \varepsilon_{bar}|$), where $\varepsilon_{QW}$, $\varepsilon_{bar}$ are the strain in the QW and barrier, respectively, the structures A and B feature a strain compensation of 85% and 62%, respectively (Table 1). Despite the lower indium content the thicker QW has less strain compensation. Both structures were investigated by cathodoluminescence and no defects were observed.

Table 1 also compares the electro-optical properties of different 1120 nm broad area laser diodes. In structures C, D and E additionally a 2 nm thick GaAs spacer layer was introduced between the GaAsP barrier layers like it was suggested in [12] to suppress possible intermixing between GaAsP and InGaAs. Furthermore in structure E the aluminum content was reduced to 15% in the waveguide and to 25% in the cladding layers for better thermal and electrical management. Unexpectedly, the thicker QW has the lower threshold current density and the lower transparent current density. In addition, structures without GaAs spacer and 7 nm QW thickness have higher internal efficiency. The reason for that is still unclear, but lower internal efficiencies for the thinner QWs point amongst other things to carrier escape from the active region into the waveguide or cladding layers and/or carrier loss at non-radiative defect centers within the active region [13]. The integration of GaAs spacers leads not only to a suppression of the intermixing but also to changes in the band structure around the QW, i.e. to a step graded QW. As a result a considerable decrease of threshold and transparency current densities and a slight increase of slope are obtained. On the down side, the additional heterojunctions lead to a slight increase of internal loss. Reducing the aluminum content in the layers the gain decreases and therefore threshold and transparency current densities increase. On the other hand, the forward voltage at 2 A decreases from typical 1.51 V to 1.46 V due to the better electrical conductivity.

Unfortunately, BA laser diodes are not well suited as pump sources for a second harmonic generation due to their bad beam quality. Therefore, a ridge waveguide RW tapered laser diode with a cavity length of 6 mm was processed (Fig. 1). The 2 mm long and 4 μm wide RW section contains an 1 mm long internal distributed Bragg reflector (DBR) section with a 5th order surface grating

**Table 1**
Electro-optical properties of different structures with different QW thickness. Samples A–E are DQW, samples F and G are SQW structures. Thickness and composition for samples A, B, F and G were determined by HRXRD, $\varepsilon$ was than calculated. Growth time for sample C is the same like for A, for D and E the same like at B. ($w_{QW}$—QW thickness, $x_{In}$—indium content in $In_xGa_{1-x}As$ QW, $\varepsilon_{QW}$—QW strain, $w_{bar,tot}$—total barrier thickness, $\varepsilon_{bar}$—barrier strain, $\lambda$—emission wavelength, $j_{th}$—threshold current density, $j_{tr}$—transparency current density, $\eta_I$—internal efficiency, $S$—slope, $\alpha_I$—internal loss).

| Sample | $w_{QW}$ (nm) | $x_{In}$ (%) | $w_{QW} \bullet \varepsilon_{QW}$ (nm•%) | $w_{bar,tot} \bullet \varepsilon_{bar}$ (nm•%) | $\lambda$ (nm) | $j_{th}$ (A/cm$^2$) | $j_{tr}$ (A/cm$^2$) | $\eta_i$ (%) | $S$ (A/W) | $\alpha_i$ (1/cm) |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 5 | 32.6 | –11.4 | 9.68 | 1109 | 438 | 151.4 | 56 | 0.287 | 1.0 |
| B | 7 | 30.6 | –15.5 | 9.68 | 1115 | 333 | 126.5 | 60 | 0.282 | 1.5 |
| C | 5 | | | | 1111 | 296 | 138.4 | 61 | 0.307 | 1.3 |
| D | 7 | | | | 1116 | 282 | 117.1 | 60 | 0.287 | 1.7 |
| E | 7 | | | | 1108 | 389 | 147.4 | 57 | 0.293 | 0.9 |
| F | 6 | 39.0 | –16.7 | 10.22 | 1182 | 115 | 66 | 60 | 0.282 | 1.6 |
| G | 9 | 36.5 | –22.3 | 10.22 | 1182 | 109 | 47 | 66 | 0.275 | 2.7 |