Temperature performance of InGaAs/InGaAlAs laser diodes with δ-doping active region

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Abstract. The optical gain performance of 1530-1565 nm laser diodes with active regions containing p-doped barrier layers has been investigated. We have studied the threshold current density and differential quantum efficiency in wide temperature range and compared modal gain behaviour of laser diodes made of heterostructure with delta-doped barrier layers by carbon at level of $10^{12}$ cm$^{-2}$ and heterostructure with undoped barrier layers.

1. Introduction

One of the main approaches to create the 1300-1550 nm range vertical cavity surface emitting laser (VCSEL) is a wafer fusion. The wafer fusion belongs to the hybrid method of VCSELs production. It allows integrating the active region made of InGaAlAs/InP heterostructure and distributed Bragg reflectors (DBR) based on AlGaAs/GaAs layers in one heterostructure [1]. An essential characteristic affecting on semiconductor lasers modulation speed is a differential optical gain [2]. High differential gain can be achieved using elastically strained InGa(Al)As quantum wells (QW) in active region.

Besides elastically strained QWs, the heavy holes’ dispersion effects on the differential gain and can be controlled by changing the lattice mismatch parameter between QWs and InP substrate. Although the rise of strain in QWs leads to the growth of differential gain in an active region [3], which increases VCSEL modulation frequency, the use of this approach is limited. It is impossible to fabricate heterostructures with multiple QWs and the lattice mismatch parameter between InGa(Al)As QWs and InP substrate more than 2-2.5% [4]. Thus, for further increasing of modulation frequency it is necessary to combine this approach with others. Selective doping of the active region near QWs is one of promising approaches to increase the VCSEL modulation speed [5].

In our case, we assume δ-doping of a thin layer in the InGa(Al)As barrier between QWs by carbon, i.e. acceptor impurity. As a result, the charge state of QWs, the charge carriers distribution between p-i-n emitters of the VCSEL’s structure, electron and hole fluxes change. The raise of resonance frequency $f_r$ determined by:

$$ f_r \propto \left( \frac{\Gamma G_{diff} S}{S_0} \right)^{1/2} $$

(1)
where \( \Gamma \) – is the rate confinement factor, \( S \) – is the number of photons, \( G_{\text{diff}} \) – is the differential gain. The increase of differential gain leads to the limiting resonance frequency of the laser due to charge neutrality in QWs, taking into account the different density in energy of the charge carriers distribution [6].

2. Heterostructures

Two types of strained InGaAlAs/InGaAs heterostructures have been grown on InP substrate by molecular beam epitaxy (MBE). Active region of both types of heterostructures consisted of 7 In\(_{0.74}\)Ga\(_{0.26}\)As QWs sandwiched between In\(_{0.53}\)Al\(_{0.20}\)Ga\(_{0.27}\)As barrier layers. First type of heterostructure (S1) contained active region with barrier layers doped by carbon with doping level of \( 1 \times 10^{12} \) cm\(^{-2} \) in the centre of InAlGaAs barrier layer (Fig.1). Second type of heterostructure (S2) contained active region with undoped InAlGaAs barrier layers.

Figure 1. Schematic band diagram of the \( \delta \)-doping barriers for S1 heterostructure’s In\(_{0.74}\)Ga\(_{0.26}\)As/In\(_{0.53}\)Al\(_{0.20}\)Ga\(_{0.27}\)As heterojunction.

Dependences of the integrated emission intensity on the excitation power for both heterostructures are shown in the figure 2a. The intensity is higher for doped heterostructure, comparing with undoped heterostructure, at excitation powers below 9 mW. At the higher excitation level, the integrated emission intensities for both heterostructures become similar and practically indistinguishable. The analysis of the full width at half maximum (FWHM) of PL spectra as a function of the excitation level is shown in the figure 2b. The values of FWHM lies approximately in the range of 60-100 meV and increases with a pumping level up for the S2 structure. The S1 heterostructure’s change of FWHM is very weak and FWHM lies in the range of 78-90 meV. This relates to a fact that in doped heterostructure holes states are always occupied due to holes from \( \delta \)-doped layers. Captured by QWs electrons always can find holes for effective radiative recombination [7].

3. Experiment

Temperature stability of laser characteristics is one of the main issues for InP based laser diodes. InGaAs/InGaAlAs heterostructures can enhance temperature performance of 1300-1550 nm range lasers due to higher conduction band offset in comparison with InGaAsP heterostructures [8]. The active regions similar to S1 and S2 heterostructures were grown by MBE for laser heterostructures. The active region was placed between two In\(_{0.52}\)Al\(_{0.48}\)As cladding layers, top cladding layer was 1.5 um thick and bottom cladding layer was 1 um thick. P-doped InGaAs layers used as a p-contact. The 100-um wide stripe laser diodes with various cavity lengths were fabricated using the standard post-growth process. No coatings were deposited on the laser diodes facets. Measurements of threshold current density and light-current characteristics of the laser diodes were performed in pulse laser operation. Temperature was controlled by thermal electric cooler.
Threshold current density ($J_{th}$) and differential quantum efficiency ($\eta_{diff}$) for the laser diodes with cavity lengths of 0.5, 1.0 and 2.0 mm were measured in the temperature range from 16 to 70 °C. Using equation (2) characteristic temperatures $T_0$ and $T_1$ were estimated as:

$$ J_{th}(\Delta T) = J_{th}(0) \exp\left(\frac{\Delta T}{T_0}\right), \eta_{diff}(\Delta T) = \eta_{diff}(0) \exp\left(-\frac{\Delta T}{T_1}\right) $$

(2)

where $\Delta T$ – temperature range, $T_0$ – characteristic temperature of threshold current density and $T_1$ – characteristic temperature of differential quantum efficiency. Obtained results are shown in figure 3(a) and in figure 3(b).

Figure 3(b) shows the values of $T_0$ and $T_1$ extracted from the analysis of the temperature dependences of the threshold current and the differential quantum efficiency. With temperature higher than 50 °C threshold current density $J_{th}$ and differential quantum efficiency $\eta_{diff}$ in lasers with strained QWs and doped barriers are close to the values in lasers with undoped barriers. Laser diodes with δ-doped active region are characterised by $T_0$ in a 77-99 K range and $T_1$ in a 102-110 K range. The S2 heterostructure demonstrates 51-71 K and 53-73 K for $T_0$ and $T_1$ respectively.
The modal gain dependence ($g_{mod}$) on the injection current can be obtained using the fact the modal gain is equal to the total laser losses at the threshold:

$$\frac{g_{mod}}{\eta_{int}} = \frac{\alpha_{out} + \alpha_{in}}{\eta_{int}} = \frac{(\alpha_{out} + \alpha_{in}) \cdot \alpha_{out}}{\eta_{diff}}$$

where $\alpha_{out}$ - output optical losses, $\alpha_{in}$ - internal optical losses, $\eta_{diff}$ - differential quantum efficiency.

Figure 4 shows the threshold modal gain dependence on temperature for both structures and different cavity lengths, plotted using the equation (3), and temperature dependence of $\eta_{diff}$. The maximum obtained value of the effective modal gain (i.e. $g_{mod}/\eta_{int}$) exceeded the 140 cm$^{-1}$.

**Figure 4.** Modal gain depending on temperature for different cavity lengths: S1(closed symbols) and S2(open symbols).

**4. Conclusion**

The laser diodes of the spectral range about 1.55 um made of InGaAs/InGaAlAs heterostructures grown by MBE were investigated. Structures with an undoped active region are characterized by a strong temperature sensitivity of both the threshold current and the differential quantum efficiency ($T_0 \sim T_1 \sim 50-70$ K). Doping of barriers with carbon at the level of $1 \times 10^{12}$ cm$^{-2}$ per quantum well increases $T_0$ to 77-99 K and $T_1$ to 102-110 K while simultaneously increasing the threshold current and reducing the differential efficiency near room temperature. With temperatures $>50$ °C the effect of modulated doping disappears. The obtained results can be used for design and optimization of semiconductor laser active regions.

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