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High-power single-mode laser diodes based on carbon-doped quantum-well InGaAs/AlGaAs heterostructures

E.I. Davydova, M.A. Ladugin, A.A. Marmalyuk, A.A. Padalitsa,
A.V. Petrovskii, A.V. Sukharev, M.B. Uspenskii, V.A. Shishkin

Abstract. **Emission parameters of single-mode laser diodes based on InGaAs/GaAs/AlGaAs heterostructures doped with carbon and grown by using the metallorganic vapour phase epitaxy (MOVPE) technique are studied. The obtained results show that maintaining a certain doping profile ensuring optimisation of series resistance and internal optical losses during all fabrication stages of the active element of a diode laser, provides for enhancement of the laser efficiency. Based on laser heterostructures studied in this paper, highly efficient single-transverse-mode laser diodes emitting 300 mW at 980 nm have been manufactured.**

Keywords: *single-mode diode laser, output power, doping, carbon tetrachloride, MOVPE.*

1. Introduction

The increasing requirements to the output power and operating life of single-mode laser diodes (LDs) emitting in the range from 900 to 1000 nm necessitate continuous improvement of the fabrication technology and design of epitaxial heterostructures [1, 2].

The results of papers [3, 4] have shown that during the fabrication of a laser heterostructure, particular attention should be paid to the p-emitter doping profile in the immediate vicinity of the heterostructure interface between the p-emitter and the waveguide. When a traditional dopant (zinc) is used, the nominal doping profile is spread, resulting in the increase in internal optical losses and possible deterioration of LD electrical parameters.

In this paper, we discuss a possible solution to this problem by using another dopant, whose profile is distorted much less both during the epitaxial growth and the subsequent technological processing of the heterostructure. It is shown that the suggested optimisation significantly influences the parameters of single-mode LDs.

E.I. Davydova, M.A. Ladugin, A.A. Marmalyuk, A.A. Padalitsa, A.V. Petrovskii, A.V. Sukharev, M.B. Uspenskii, V.A. Shishkin
M.F. Stel'makh Polyus Research and Development Institute,
ul. Vvedenskogo 3, 117342 Moscow, Russia;
e-mail: M.Ladugin@siplus.ru

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2. Experimental

The quantum-well laser InGaAs/GaAs/AlGaAs heterostructures were grown using the MOVPE technique at a reduced pressure in a horizontal quartz reactor on the SIGMOS-130 setup with a rotating graphite substrate holder. Triethylgallium (TEGa), trimethylaluminum (TMAl) and trimethylindium (TMIn) were used as the sources of the 3rd group elements, while 100 % arsine (AsH_3) was used as a source of the 5th group elements. We used silane (SiH_4) as an n-dopant source, carbon tetrachloride (CCl_4) and diethylzinc (DEZn) as p-dopant sources. Hydrogen purified by diffusion through a palladium filter heated up to $T = 450\,^{\circ}\mathrm{C}$ and having the dew point no higher than $-100\,^{\circ}\mathrm{C}$ was used as a carrier gas.

We studied two laser heterostructures of the same design [1], while differing in the type of the p-emitter dopant. As a p-type dopant, we used zinc in the first heterostructure and carbon in the second heterostructure. The composition of the active area of the laser heterostructure provided for the electroluminescence wavelength of 960 – 965 nm. The details of the heterostructure design and those of the active element of a single-mode ridge LD are described in [2]. Figure 1 shows the design of a ridge LD. The resonator length of the LDs under study was 1000 μm, the reflection coefficients of the front and back mirrors were 0.03 and 0.98, respectively. The laser crystals at the p-contact side were soldered on a copper heatsink by means of the indium solder. To measure the electrical and optical parameters of the LDs, they were fixed in holders with a pressure contact.

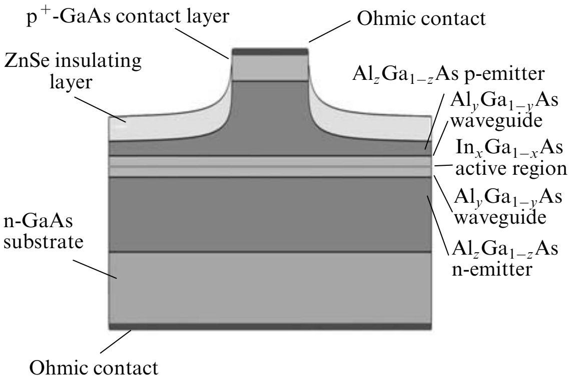

Figure 1. Scheme of a ridge laser diode.

3. Results and discussion

At present, zinc is used as a p-type dopant for (Al)GaAs epitaxial layers [1 – 4]. A characteristic feature of this dopant is its high diffusion rate, which results in the redistribution of zinc atoms during the epitaxial growth and subsequent technological processing of the heterostructure. In addition, the growth is accompanied by the adsorption of zinc reagents on internal surfaces of the growth chamber and gas lines, resulting in the 'memory effect' [5]. All of the above impede the formation of the doping profile with a controlled change in the dopant concentration when using zinc.

It is known that a low doping level of the p-emitter near the p-emitter – waveguide heterostructure interface causes an additional voltage drop across this heterostructure region when applying a bias voltage and increases the differential serial resistance of the LD [3]. As a result, the LD efficiency substantially decreases and the heat release in the active region increases, which negatively affects both the maximum attainable power and the laser lifetime. At the same time, an increase in the doping level of the p-emitter layer results in the increase in both the absorption level on free carriers in the emitter and optical losses [3]. In this case, both the slope efficiency and the LD efficiency decrease. Thus, when fabricating laser heterostructures, the doping profile of the emitter layers should be precisely controlled during the growth process and deviate as little as possible from the optimal distribution.

This problem can be solved by using an acceptor dopant with a low diffusion coefficient. We chose carbon as such a dopant [6]. Besides, carbon doping provides for high concentration levels of p-type dopants, which is necessary for fabricating low-resistance emitter and contact layers. This dopant lacks 'the memory effect' and has a low activation energy [6, 7].

In this paper, we used carbon tetrachloride (CCl_4) as a p-type dopant, which ensures, when using the MOVPE, the possibility of obtaining controlled doping levels of high-quality AlGaAs epitaxial layers in a wide range of concentrations of holes with abrupt doping profiles [7].

As a result of using carbon as an acceptor dopant during the doping of the laser heterostructures, the stability of the output power P_{SM} of a single-mode laser has been significantly increased. For a single-mode LD based on a Zn-doped heterostructure, P_{SM} was 170 – 190 mW, while its maximum value was 210 mW [2]. For an LD based on a C-doped heterostructure, typical values of P_{SM} were 240 – 280 mW and the maximum power in the single-mode regime exceeded 300 mW.

Figure 2 presents typical diagrams of radiation divergence in a C-doped heterostructure LD in the planes perpendicular ($\Theta_{\perp}$) and parallel ($\Theta_{\parallel}$) to the p – n junction. The intensity distributions can be well approximated by Gaussians. The position of the distribution maximum hardly changes with changing the pump current (the measurement error is within 0.5°). The full width at half maximum of the distribution in the parallel plane increases insignificantly with increasing the current (no more than by 1°). The width was 7 – 8° in the parallel plane and 28 – 30° in the perpendicular plane.

Note that the maximum pump current (i.e. before the moment of catastrophic optical degradation) has increased. Figure 3 shows a typical light – current characteristic of this heterostructure LD. The threshold pump current was 40 – 45 mA, the slope efficiency in single-mode regime was 1.04 – 1.05 W A^{-1}. When the multimode lasing regime is used, the light – current characteristic becomes nonlinear. A further increase in the pump current leads to recovery of the slope efficiency and to an increase in the power up to 480 – 490 mW, after which the catastrophic optical degradation occurs. In similar tests, the LDs made of Zn-doped heterostructures were destroyed at pump currents not exceeding 240 – 280 mA.

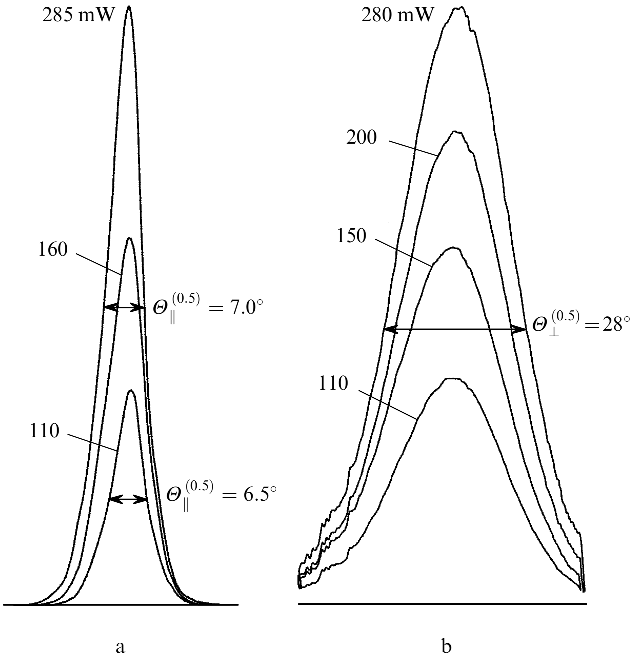

Figure 2. Typical divergence diagrams of the LD made of carbon-doped heterostructure in the planes parallel (a) and perpendicular (b) to the p – n junction.

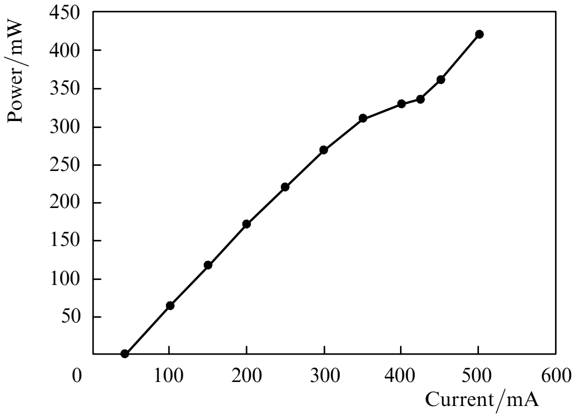

Figure 3. Typical light – current characteristics of an LD made of a carbon-doped heterostructure.

The result obtained in this paper emphasises the need to control the dopant distribution in the emitter layers located in the immediate vicinity of the waveguide in laser heterostructures. Besides, the possibility to substantially increase the output power of a laser diode indicates that the given carbon-doping profile is preserved during all stages of laser fabrication.

4. Conclusions

The results obtained in this work show that conservation of the given profile, ensuring optimisation of both serial resistance and internal optical losses at all stages of laser element fabrication, leads to an increased efficiency of the LD performance.

The studied laser InGaAs/AlGaAs heterostructures doped with carbon and grown by means of the MOVPE have ensured the possibility to produce highly efficient single-mode LDs emitting 300 mW at 980 nm in the single-mode regime.

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