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Broadband near-IR double quantum-well heterostructure superluminescent diodes

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***Abstract*. Superluminescent diodes (SLDs) based on double quantum-well (AlGa)As/GaAs heterostructures emitting between 800 and 900 nm are studied experimentally. These SLDs provide a high enough output power in the emission bandwidth more than 55 nm at much shorter active channel lengths than SLDs based on similar single quantum-well heterostructures. Despite the high injection current density, the service life of the SLDs exceeds 10000 hours.**

Keywords: *superluminescent diode, quantum-well heterostructures.*

1. Introduction

The last decade was marked by the rapid development of optical coherence tomography (OCT) [1]. This method, which is sometimes called optical biopsy, allows the contactless and almost instant *in vivo* two- and three-dimensional imaging of biological tissues. Most of the OCT systems use superluminescent diodes (SLDs) as miniature radiation sources emitting a broad enough spectral band (low coherence) with a high brightness and high efficiency. Among numerous applications in medicine and biology, OCT systems have gained the widest acceptance in ophthalmology [2]. Diagnostic Stratus OCT devices manufactured for several years by Carl Zeiss Meditec (over 6000 device have been already produced) are successfully applied at ophthalmologic clinics and medical centres worldwide. These devices use near-IR SLD modules emitting lines of width 22 – 25 nm, which provides the axial resolution ~ 10 μm. Similar devices with a better spatial resolution, which can be provided by using SLDs emitting broader lines, are being developed at many companies and laboratories. In the last year Optopol Technology, Topcon Medical Systems, and Optovue started the batch production of next-generation ophthalmologic OCT systems based on SLD-37 modules emitting lines of width 45 – 55 nm [3], which provides the twofold advantage in the spatial resolution. These SLDs are manufactured of (AlGa)As/GaAs single quantum-well heterostructures (SQWs) [4, 5]. The maximum spectral width (minimum coherence length) of radiation of such SLDs is achieved under operating conditions when the intensities of quantum transitions from the ground and first excited state become equal. In this case, the emission spectrum acquires the characteristic double-hump shape. The depth of a dip between the two spectral maxima is a critical parameter. For practical applications in OCT, this depth should not exceed, as a rule, 2.0 dB (37 %). This requirement is often very difficult to fulfil, especially for high-power SLDs.

It is known that the superluminescence spectrum can be smoothed by using multilayer QWSs. In this case, however, the total volume of the active SLD region drastically increases, and to achieve the maximum width of the emission spectrum, the injection current density should be considerably increased, which can adversely affect the reliability of devices. The aim of our study is to further improve the spectral parameters of SLD-37 devices. We investigated SLDs based on (AlGa)As/GaAs double QWs (DQWs), paying the main attention to resource tests of experimental samples.

2. Experimental samples

The (AlGa)As/GaAs semiconductor quantum-well structures were grown by the MO CVD method in a SIGMOS-130 horizontal quartz reactor with a rotating graphite substrate holder. The growth temperature was 770 °C at a pressure of 60 Torr in the reactor. As the sources of the III and V group elements, $Al(CH_3)_3$, $Ga(C_2H_5)_3$, and AsH_3 were used. $Zn(C_2H_5)_2$ and SiH_4 were used as ligatures of the p and n type conductivity and hydrogen was used as a carrier gas. The epitaxial growth was performed on n-GaAs (100) substrates.

Figure 1 presents the energy band diagram of grown heterostructures. The main difference of these double separate-confinement structures from structures described in [5] is that their active regions contained two quantum wells separated by the (AlGa)As barrier. To obtain a broad emission spectrum, the geometry of quantum wells and the barrier thickness between them were selected to provide the interaction of the electronic wave functions in adjacent wells and to achieve the splitting of energy levels. We used two types of DQWs with different quantum-well widths. This width for type I structures was larger by 25 % that that for

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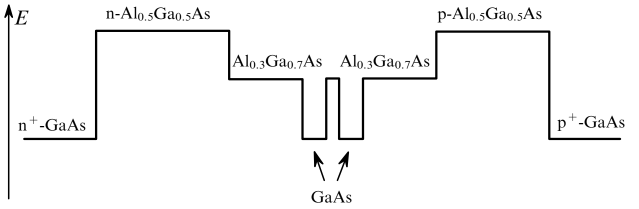

Figure 1. Schematic energy band diagram of an (AlGa)As/GaAs DQW.

type II structures. The active region was located between 0.15-μm-thick waveguide $Al_{0.3}Ga_{0.7}As$ layers and 1.5-μm-thick $Al_{0.5}Ga_{0.5}As$ emitter layers. The thickness of the upper contact p^+-GaAs layer was 0.5 μm.

The design of SLD samples was conventional. Their active channel was a straight ridge waveguide of width 4.0 μm tilted at 7° with respect to the normal to crystal end-facets on which AR coatings were deposited. The active channel length could be varied in a broad range with a step of 100 μm. All measurements were performed in the continuous injection regime at 25 °C.

3. Experimental results

Figure 2 presents typical light – current characteristics of DQW SLDs with active channel lengths L_a from 400 to 800 μm. The points on the curves indicate operation regimes corresponding to equalised spectral maxima. Superluminescent diodes with large L_a had the higher external quantum efficiency; however, their emission at any reasonable injection currents was dominated by quantum transitions from the ground state and for this reason the emission bandwidth $\Delta\lambda$ did not exceed 30 nm. We did not study these samples in this paper. One can see from Fig. 2 that the maximum emission bandwidth $\Delta\lambda$ for SLDs based on type II DQWs is achieved at higher injection current densities. This is explained by the fact that the energy gap between the ground and first excited state increases with decreasing the quantum well width.

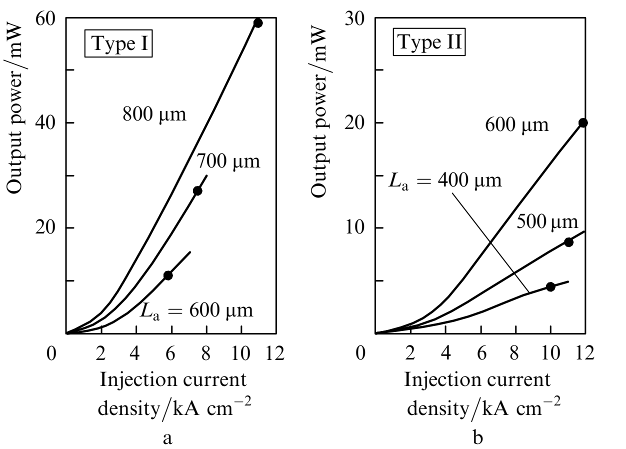

Figure 2. Light – current characteristics of SLDs based on type I (a) and II (b) DQWs with different active channel lengths.

Figure 3 shows the emission spectra and coherence functions for two SLD samples based on DQWs of different types. The noticeable broadening of the spectrum of type II samples along with a decrease in the spectral dip depth is of great practical interest. The narrowing of the central peak of the coherence function and a decrease in the height of its 'pedestal' make it possible to improve the resolution and increase the sensitivity of OCT systems.

Table 1 presents the main physical parameters of the SLD samples. For comparison, in the first line are presented the ranges of parameters of SLDs based on the above-mentioned SQW. As expected, the maximum of $\Delta\lambda$ for samples studied was achieved for the required power levels at smaller lengths L_a and higher injection current densities j. It is well known that the aging rate of semiconductor lasers during their operation can strongly depend on the value of j. We performed resource tests for four batches of SLD samples of type I with $L_a = 600$ and 700 μm and type II with $L_a = 400$ and 500 μm. The corresponding dependences are shown in Fig. 4. The tests of type I samples have been successful. The extrapolation of the time dependences of P_{fs} (Figs 4a, b) shows that the median service life of these samples exceeds 20000 hours ($L_a = 600$ μm) and 15000 hours ($L_a = 700$ μm). Unfortunately, type II samples, which have the record spectral parameters among SLDs emitting in these spectral range, revealed rapid aging and degraded (P_{fs} decreased by 50 %) during 200 hours (Figs 4c, d). Superluminescent diodes with such a short service life can be used in laboratory experiments; however, they are unsuitable for the batch production of light-emitting modules. The reasons for their rapid aging require additional investigations. It is obvious that the aging was caused by a high operating current density, although the value $j = 10^4$ A cm^{-2} itself is not too high. Modern high-power laser diodes based on similar heterostructures reliably operate in

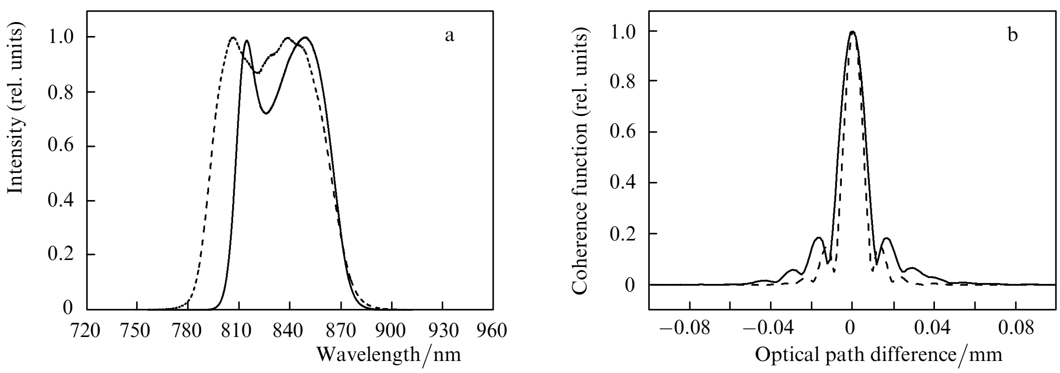

Figure 3. Spectrum (a) and central peak of the coherence function (b) for a SLD based on a DQW of type I with $L_a = 600$ μm (solid curves) and type II with $L_a = 400$ μm (dashed curves).

Table 1. Parameters of SLDs with different active channel lengths for the maximum emission bandwidth.

QWS type	$L_a/\mu m$	I/mA	$j/kA\ cm^{-2}$	P_{fs}/mW	P_{sm}/mW	$\lambda_m/\mu m$	$\Delta\lambda/nm$	$L_c/\mu m$	ΔS (%)
SQW	1200 – 1600	140 – 250	3.0 – 4.0	2.0 – 50.0	1.0 – 25.0	835 – 850	45.0-55.0	12.5 – 16.0	10.0 – 37.0
Type I DQW	600	140	5.8	11.0	5.5	838	56.0	12.5	26.0
	700	210	7.5	28.0	14.5	839	55.0	12.8	27.0
	800	350	10.9	60.0	32.0	840	54.0	13.0	28.0
Type II DQW	400	160	10.0	4.5	1.7	829	72.5	9.5	15.0
	500	220	11.0	9.0	4.0	831	70.0	9.9	18.0
	600	285	11.8	20.5	10.0	835	65.0	10.7	26.0

Note: (I) injection current; (j) injection current density; (P_{fs}) output power to the open space; (P_{sm}) output power through a single-mode fibre; (λ_m) median wavelength; (L_c) coherence length; (ΔS) spectral dip depth.

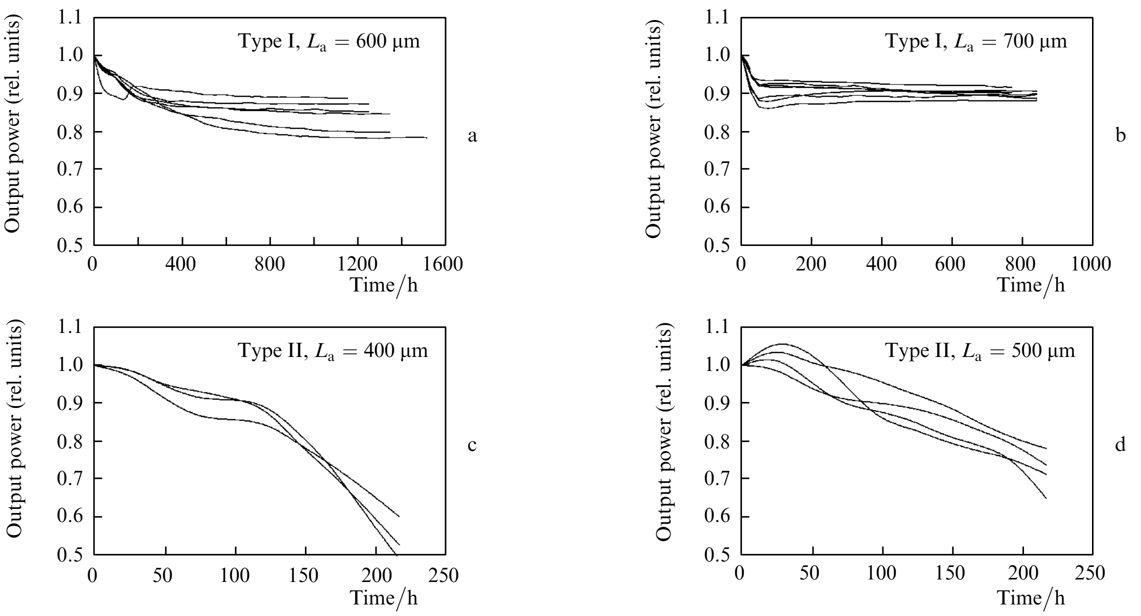

Figure 4. Chronograms of resource tests of SLDs based on DQWs of types I and II with different active channel lengths.

the cw regime even at higher current densities. In addition, radiation loads on crystal facets in laser diodes are considerably higher than these in SLDs. We can assert quite confidently that the further improvement of the growth processes and subsequent processing of epiwafers of type II will result in the manufacturing of SLDs with the output parameters demonstrated above and the acceptable service life.

Superluminescent diodes of type I with $L_a = 800$ μm have the output power that is excessive for ophthalmologic OCT systems, but they are undoubtedly of interest for some other applications. In particular, they can be efficiently used in combined BroadLighter radiation sources [6]. At present these SLDs are being subjected to preliminary resource tests.

4. Conclusions

Our investigations have shown that the use of DQWs improves the spectral parameters of broadband SLDs emitting in the 800 – 900-nm range. Despite the high injection current density, these SLDs can have the acceptable service life. The required output parameters of these SLDs can be obtained at lower active channel lengths, which noticeably increases the number of SLDs manufactured from a heteroepitaxial plate of unit area. The latter circumstance is quite important in the batch production of devices.

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