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Superluminescent diodes of the 770 – 790-nm range based on semiconductor nanostructures with narrow quantum wells

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Abstract. **Comparative experimental study of superluminescent diodes (SLDs) with active layers containing one, two, or three 5.0-nm-wide quantum wells symmetrically positioned in the waveguide layer is performed. It is shown that an increase in the number of quantum wells leads to narrowing of the superluminescence spectrum and weakens the dependence of its width on the pump level. Simultaneously, the degree of polarisation of the output radiation noticeably increases. For example, rather reliable high-power narrow-band SLDs with a spectral halfwidth smaller than 8 nm and polarisation ratio TE/TM exceeding 20 dB are developed.**

Keywords: *semiconductor nanoheterostructure, quantum-well superluminescent diode.*

1. Introduction

Commercially available nearest-IR (750 – 800 nm) superluminescent diodes (SLDs) have a cw output optical power up to 50 mW at spectral FWHM $\Delta\lambda$ = 15 – 50 nm; the power is limited by thermal saturation or degradation processes, while the spectral halfwidth is determined by the composition and geometry of the used semiconductor heterostructure and by the configuration of the active channel. Double-barrier separate confinement heterostructures (DBSCHs) with a bulk active layer or, vice versa, with a single quantum well (SQW) layer a few nanometers thick make it possible to produce SLDs with a Gaussian spectrum and $\Delta\lambda$ = 15 – 30 nm. In the case of a quantum well about 10 nm wide, the spectra have a double-peak shape with $\Delta\lambda$ up to 50 nm [1], which is determined by quantum transitions from the ground and excited subbands of the energy spectrum. These SLDs are rather widely used as light sources for optical coherence tomography (OCT) both alone and in the composition of BroadLighter combined light sources [2, 3].

Recently, SLDs of the mentioned spectral region have found metrology applications, for which the spectral width of available devices is excessive and the radiation spectral density (maximum 3 – 4 mW nm^{-1}) is insufficient.

In the present work, we have performed comparative experimental study of SLDs whose active layers consist of one (SQW diodes, type I), two (DQW diodes, type II), or three (TQW diodes, type III) quantum wells about 5.0 nm wide of identical $Ga_{0.93}Al_{0.07}As$ composition, which are symmetrically positioned in the waveguide layer. We measured the dependences of the power, spectral, and polarisation characteristics of these devices on the active layer configuration, pump level, and working temperature. In particular, we developed rather reliable narrow-band SLDs with an output spectral density exceeding 12 mW nm^{-1}.

2. Experimental samples

Figure 1 schematically shows the band diagrams of the used nanoheterostructures grown by MOCVD. The growth technology is briefly described in [4]. In contrast to [4], in which the width and chemical composition of the active layer of the SQW structure were varied, the width and composition of quantum wells and barrier layers in the present work remained unchanged. Only the number of quantum wells was varied.

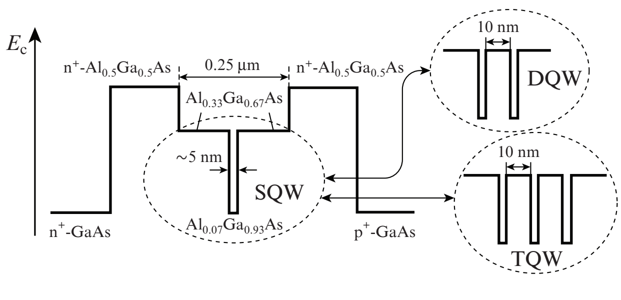

Figure 1. Band diagrams of the used nanoheterostructures.

The SLD structure was traditional for spatially single-mode devices. The active channel was a ridge waveguide about 0.25 μm thick and 4 μm wide with the axis inclined by 7° to the antireflection-coated faces of the crystal. The active channel length L_a varied within the range from 600 to 1800 μm. The measurements were performed in a continuous injection regime with thermal stabilisation of the SLD.

3. Experimental results

The spectra of all studied samples had a bell-like shape (close to Gaussian) in a wide range of injection currents. The spec-

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tral half-width $\Delta\lambda$ considerably depends on the active channel length L_a. Figure 2 shows the spectra of SLDs of types I–III with different lengths L_a measured at room temperature and identical injection currents I. These curves clearly demonstrate narrowing of the spectra with increasing length of the active channel and increasing number of quantum wells in the active layer.

The main characteristics of the studied SLDs under the same working conditions are presented in Table 1. One can see not only narrowing of the spectra in the sequence of samples of types I, II, and III but also a noticeable increase in the differential quantum efficiency and in the polarisation degree of radiation. The latter is valuable for some practical applications of SLDs because this makes it possible to use them without external polarisers.

The light–current characteristics (Fig. 3) and dependences $\Delta\lambda(I)$ (Fig. 4) show that the output optical power may vary within wide limits depending on the pump current and, for long SLDs of types II and III, exceed 100 mW, which corresponds to a spectral density higher than 12 mW nm^{-1}. As far as we know, it is record value for spatially single-mode SLDs. At the same time, $\Delta\lambda$ slightly changes with current and depends mainly on the active channel length.

Figure 5 shows the dependences of polarisation ratio TE/ TM on the injection current for long SLDs (L_a = 1500 μm). These dependences for samples of type I significantly differ from the dependences for types II and III. In the first case, the TE/TM ratio reaches its maximum (about 11) as superluminescence begins and then slowly decreases with a further increase in the pump current. For samples of type II, the maxi-

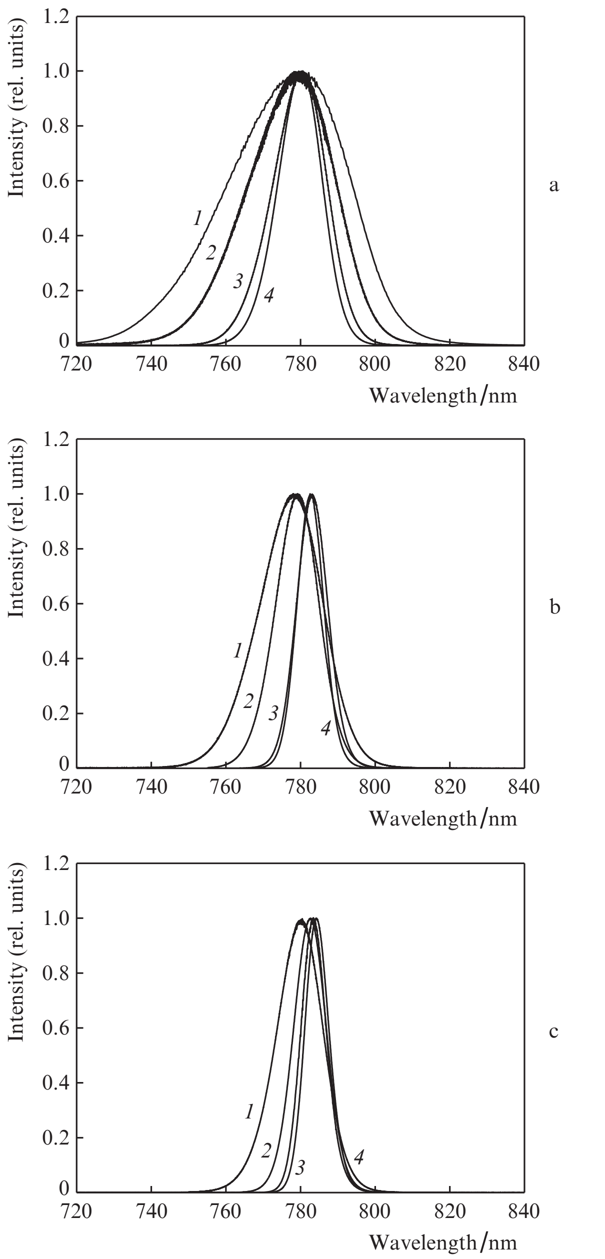

Figure 2. Emission spectra of SLDs of types (a) I, (b) II, and (c) III at an injection current of 170 nm, temperature T = 25 °C, and active channel lengths L_a = (*1*) 600, (*2*) 900, (*3*) 1500, and (*4*) 1800 μm.

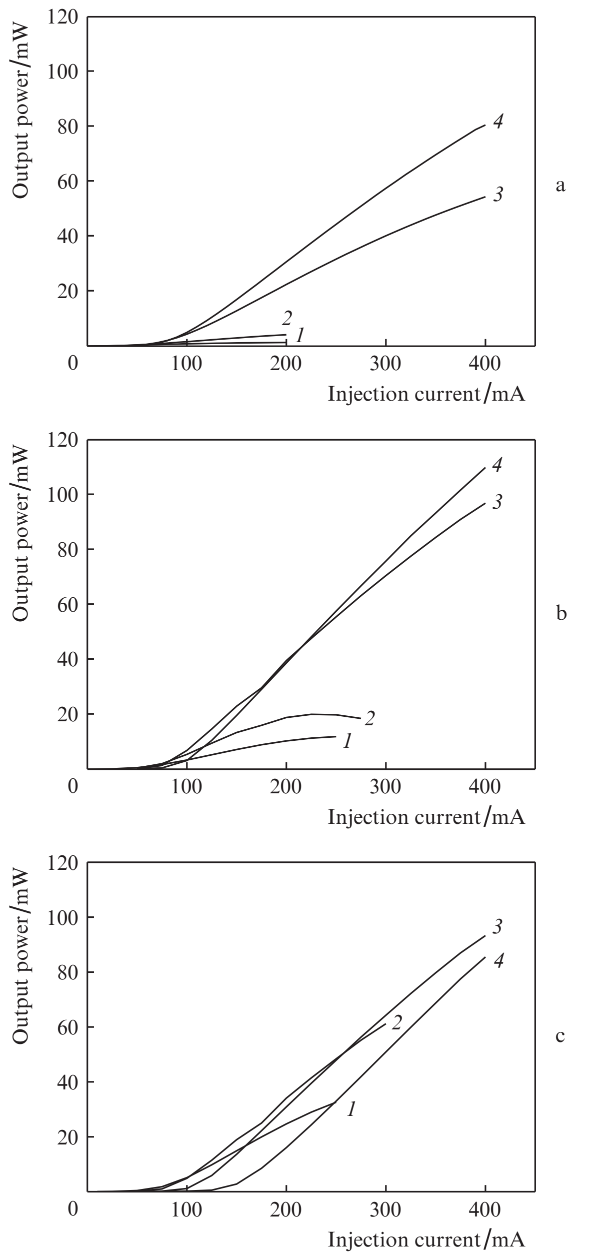

Figure 3. Light–current characteristics of SLDs of types (a) I, (b) II, and (c) III with lengths L_a = (*1*) 600, (*2*) 900, (*3*) 1500, and (*4*) 1800 μm at T = 25 °C.

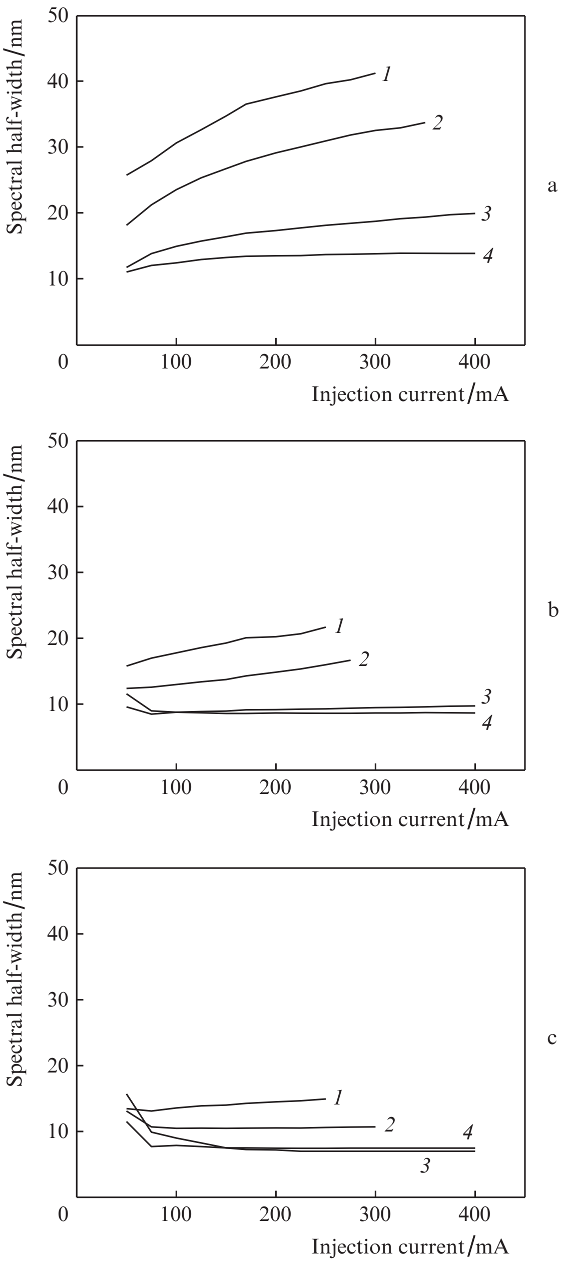

Figure 4. Dependences of $\Delta\lambda$ on the injection current for SLDs of types (a) I, (b) II, and (c) III with lengths L_a = (*1*) 600, (*2*) 900, (*3*) 1500, and (*4*) 1800 μm at $T = 25\,°C$.

Table 1. Characteristics of SLDs with a quantum well width of about 5.0 nm at an injection current of 170 mA.

Active layer type	L_a/μm	I/mA	J /kA cm^{-2}	P_{FS} /mW	P_{SM} /mW	λ_m /nm	$\Delta\lambda$ /nm	TE/TM
I	600	170	7.1	1.3	0.35	774	37	2.1
(SQW)	900	170	4.7	3.5	1.2	775	27	3.5
	1500	170	2.8	15	7	778	17	10.5
	1800	170	2.4	23	13	779	14	13.2
II	600	170	7.1	8.5	4.5	777	20	10
(DQW)	900	170	4.7	24	13	779	13.5	26.5
	1500	170	2.8	32	22	782	9	101
	1800	170	2.4	28	11	782	8.5	116
III	600	170	7.1	17	10.5	779	14	22
(TQW)	900	170	4.7	24	15	782	10.5	51
	1500	170	2.8	25	16	784	7.0	85
	1800	170	2.4	17	12	785	7.0	80

Note: L_a is the active channel length; I is the injection current; J is the injection current density; P_{FS} is the output power in free space; P_{SM} is the output power coupled out through a single-mode fibre (SMF); λ_m is the median wavelength; $\Delta\lambda$ is the spectral half-width; and TE/TM is the polarisation ratio.

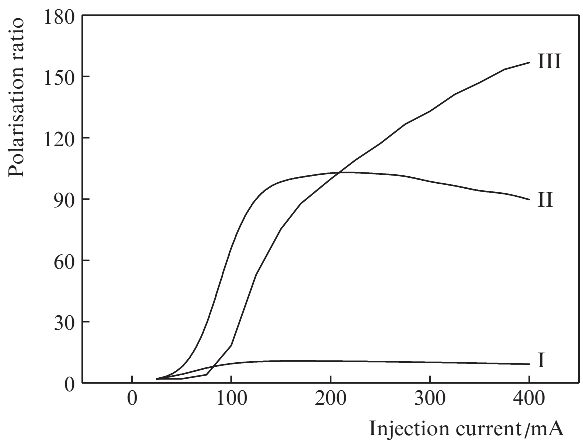

Figure 5. Dependences of the polarisation ratio TE/TM on the injection current for SLDs of types I, II, and III with L_a = 1500 μm at $T = 25\,°C$.

mum value of this ratio (about 105) is observed at a rather high superluminescence power. Finally, the TE/TM ratio for samples of type III at injection current I = 400 mA, which is close to the optical breakdown threshold, is about 160, which corresponds to a polarisation degree of 99%, and continues to increase with increasing current I.

The increase in the output optical power and in the polarisation degree, as well as narrowing of the radiation spectrum, with increasing L_a at a fixed injection current density are well-known effects for SLDs with a bell-like spectrum. Similar experimentally observed dependences on the number of narrow quantum wells in the active layer indicate an increase in the optical gain, narrowing of its spectrum, and an increase in the difference between the gains of the TE and TM waveguide modes. To describe these processes in detail, it is necessary to perform further experimental and theoretical studies.

The temperature dependences of the output SLD characteristics have been experimentally studied in the range of 10–100 °C. As was expected, the median emission wavelength λ_m at a fixed injection current linearly shifts to longer wavelengths with increasing temperature (0.3 nm deg^{-1}) due to a change in the band gap of the active semiconductor layer. The spectral half-width $\Delta\lambda$ changes very slightly, with a rate lower than 0.06 nm deg^{-1}. The polarisation ratio of the emission of SLD samples of type II with L_a = 1800 μm decreases approximately by 1.5 times as temperature increases from 25 to 55 °C (Fig. 6). A parameter that is most sensitive to the working temperature is the output optical power. At a fixed I, an increase in temperature from 10 to 70 °C leads to a decrease in P_{FS} by more than an order of magnitude even for long SLDs. This means that thermal stabilisation of the active element is necessary for most practical applications of light-emitting modules based the studied SLDs.

Preliminary life tests of SLDs for 1000 h at room temperature demonstrated their high reliability. The service lifetime

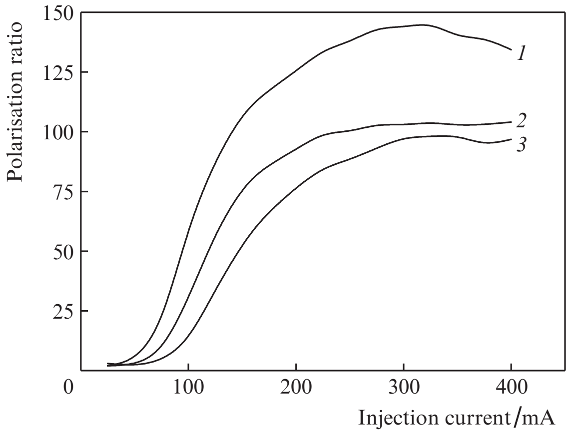

Figure 6. Dependences of polarisation ratio TE/TM on the injection current at T = (*1*) 25, (*2*) 40, and (*3*) 55 °C for an SLD of type III with L_a = 1800 μm.

even of samples with a 100-mW cw output optical power exceeds 10000 h.

4. Conclusions

The comparative experimental study of quantum-well SLDs of the 770–790-nm spectral range with active layers containing one, two, or three symmetrically positioned thin quantum wells showed that, when passing from single-layer to multilayer nanostructures, the differential quantum efficiency increases, the superluminescence spectrum sharply narrows, the dependence of the superluminescence spectral width on the pump level becomes weaker, and the polarisation degree of the output radiation considerably increases. In particular, we have demonstrated rather reliable spatially single-mode SLDs with record spectral density (exceeding 12 mW nm^{-1}) and polarisation density (99 %).

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References

1. Il'chenko S.N., Kostin Yu.O., Kukushkin I.A., Ladugin M.A., Lapin P.I., Lobintsov A.A., Marmalyuk A.A., Yakubovich S.D. *Quantum Electron.*, **41** (8), 677 (2011) [*Kvantovaya Elektron.*, **41** (8), 677 (2011)].
2. Ko T.H., Adler D.C., Fujimoto J.G., Mamedov D., Prokhorov V., Shidlovski V., Yakubovich S. *Opt. Express*, **12** (10), 2112 (2004).
3. Wojtkowski M., Lapin P.I., Mamedov D.S., Fujimoto J.G., Yakubovich S.D. *Quantum Electron.*, **35** (7), 667 (2005) [*Kvantovaya Elektron.*, **35** (7), 667 (2005)].
4. Andreeva E.V., Il'chenko S.N., Kostin Yu.O., Ladugin M.A., Lapin P.I., Marmalyuk A.A., Yakubovich S.D. *Quantum Electron.*, **43** (8), 751 (2013) [*Kvantovaya Elektron.*, **43** (8), 751 (2013)].