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High-power semiconductor 0.89 – 1.06-μm lasers with a low emission divergence based on strained quantum-well InGaAs/(Al)GaAs structures

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Abstract. **Heterostructure lasers with a separate electronic and optical confinement based on strained quantum-well structures with single and double InGaAs quantum wells and different waveguide parameters are studied. The heterostructure design and technological conditions of the quantum-well growth are optimised to increase the output power and reduce the laser emission divergence. Semiconductor lasers are fabricated with a cw output power as high as 4 W and the emission divergence of less than 30° in the plane perpendicular to the $p-n$ junction plane. The pulsed output power of these lasers is limited by the catastrophycal damage of mirrors at a linear power density of 3000 W cm^{-1}.**

Keywords: *high-power quantum-well heterostructure lasers, emission divergence, MOCVD epitaxy.*

1. Introduction

A great attention has been presently paid to the development of laser diodes (LDs) based on AlGaAs/GaAs heterostructures with InGaAs ultrathin active layers (quantum wells). A variation of content of In in the active layers provides a tuning of the emission wavelength in a rather broad spectral range from 0.89 to 1.06 μm. This, in turn, makes possible the fabrication of LDs for applications in optical communications, location, medicine, material processing, and pumping of various media.

The most important technical parameters of an LD are its emission power and operating lifetime. However, the LD can be efficiently used only when the full width at half-maximum (FWHM) of its emission pattern (angular divergence) does not exceed 30° because the angular aperture of objectives is 30 – 40° in most cases.

The emission divergence in the plane of the LD active layer is determined by the localisation of the emitted light flux in optical channels, which randomly arise during pumping. In this case, the typical FWHM of the emission pattern is 10 – 15° [1]. In the plane perpendicular to the heterostructure layers, the emission divergence is caused by diffraction of the emission from the open end of the dielectric waveguide formed by the heterostructure layers. It is possible to change on purpose the LD emission divergence by choosing appropriately the composition and geometry of these layers.

In this paper, we study the optimisation of parameters of quantum-well InGaAs/(Al)GaAs heterostructures with the aim of fabricating laser diodes emitting in the spectral range of 0.89 – 1.06 μm with the enhanced power and decreased FWHM (less than 30°) of the emission pattern.

2. Simulation of the far-field emission pattern

To determine the spatial distribution of the LD emission, the equation of propagation of a TE electromagnetic wave in a plane dielectric waveguide formed by the heterostructure layers (Fig. 1) was solved numerically. The refractive indices of the heterostructure layers at the given emission wavelength λ was determined using a modified model of a single oscillator [2], which agrees well with the known experimental data for AlGaAs solid solutions [3 – 5]. The refractive index of the InGaAs active layer at the emission wavelength was taken to be equal to 3.62.

The FWHM of the emission pattern in the plane perpendicular to the plane of the active layers was calculated as a function of the thickness and composition of the optical

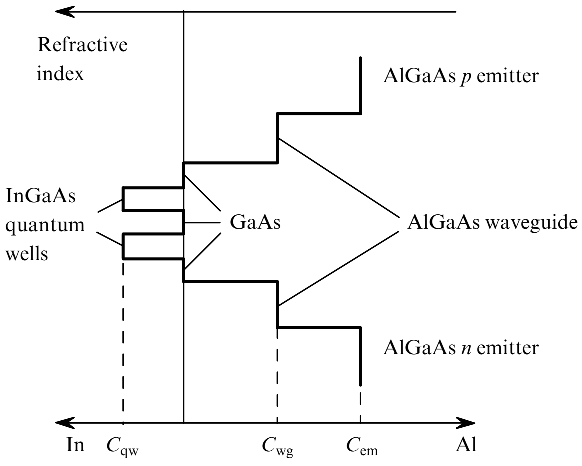

Figure 1. Design of the heterostructure for laser diodes (C_{qw}, C_{wg}, and C_{em} are concentrations of AlAs in the quantum well, waveguide layers, and emitters of the heterostructure).

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waveguide and the number of quantum wells in the active region. We found that the FWHM of the emission pattern was slightly dependent on the emission wavelength in the spectral range of 0.85 – 1.06 μm at the given thickness of the waveguide and compositions of the waveguide and emitter layers. This is explained by the fact that the refractive index of the AlGaAs solid solution decreases linearly with increasing wavelength at concentrations of AlAs $C = 0.15 - 0.45$. As a result, the difference between the refractive indices at the waveguide – emitter interface remains almost constant. The typical results of the calculations are presented in Fig. 2.

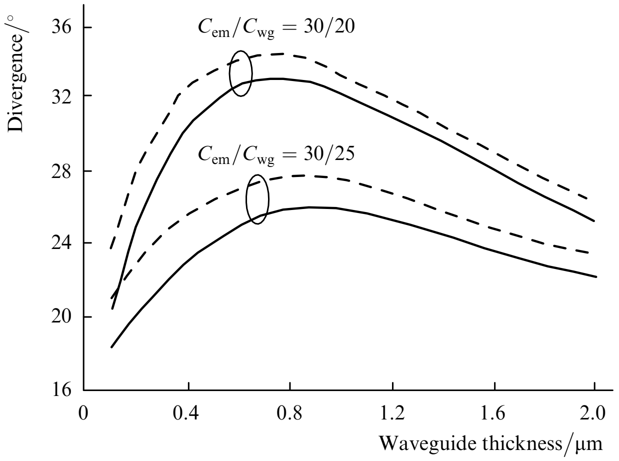

Figure 2. Dependence of the FWHM of the emission pattern on the optical waveguide thickness at different concentration of AlAs in the waveguide layers and emitters of the heterostructure for single (solid lines) and double (dashed lines) InGaAs quantum wells in the active region.

It follows from the data obtained that an increase in the number of quantum wells in the active region results in the increase in the emission divergence due to increasing the total thickness of the waveguide. However, a sufficiently narrow (less than 30°) emission pattern can be obtained for an LD with an active region containing both one and two quantum wells by choosing appropriately the composition and thickness of the heterostructure layers. In this case, no less than 70 % of the total flux of the laser emission will be concentrated within a cone with a vertex angle of 30°.

3. Experimental

The results of the calculations were used to optimise the parameters of InGaAs/GaAs/AlGaAs heterostructures designed for emission in the range of 0.89 – 1.06 μm. Symmetric laser heterostructures were grown using MOCVD epitaxy on the (100) surface of a *n*-GaAs substrate. The concentration of AlAs in the emitters of different structures (30 % – 40 %) and the thickness of waveguide layers for each heterostructures were chosen in such a way that the calculated FWHM of the LD emission pattern did not exceed 30°.

Mesa stripes with a width of 100 – 200 μm were fabricated on the grown laser heterostructure using photolithography and ion-plasma etching until the surface of the *p*-AlGaAs emitter. The stripes were regrown by a ZnSe film. Multilayer dielectric coatings with a reflectivity of $R_1 = 0.08 - 0.1$ (the output facet) and $R_2 = 0.95 - 0.98$ (the back facet) were placed on the LD mirror facets using the electronic evaporation in vacuum. LDs were mounted *p*-side down on a copper plate, which then was placed in the emitter housing.

The LD parameters were continuously monitored upon pumping by current pulses of duration 90 – 110 ns with a pulse repetition rate of 10 – 20 kHz.

4. Results and discussion

By studying the dependence of the differential efficiency and the threshold current density on the LD cavity length, we found that the internal losses in the layers of the grown heterostructures were 3 – 5 cm^{-1} and the inversion current density was $j_0 = 80 - 120$ A cm^{-2}.

The average current densities j_{th} and differential efficiencies s determined for a selection of 14 LDs which were fabricated from the same heterostructure are presented in Table 1. The experimental data on the emission divergence

Table 1.

Laser diode	Number of QWs	λ/μm	j_{th}/A cm^{-2}		s/W A^{-1}	Divergence/°	
			Experiment	Theory		Experiment	Theory
S-823	1	891	324	201	0.966	26.9 – 28.0	27.6
S-912	1	905	260	210	1.02	25.6 – 26.3	26.1
S-967	1	885	307	351	0.836	21.4 – 22.3	21.9
S-968	1	892	400	389	0.91	18 – 24	21.3
S-969	2	903	241	297	0.8	20.2 – 24.0	25.2
S-971	2	909	262	293	0.82	23 – 25.1	26.1
S-990	2	947	275	284	0.93	30.8 – 32.6	31,5
S-992	2	970	245	294	0.96	28.5 – 30.3	29.7
S-991	2	1005	290	295	0.89	28.9 – 30.1	29.1
S-1209	2	1020	280	284	0.76	30.5 – 33.0	32,1
S-818	2	1040	220	304	0.79	25.0 – 28.0	27.3
S-578	2	1055	215	363	0.88	23.0 – 26.0	24.3
S-635	2	1058	230	310	0.91	25.5 – 30.1	29.7
S-1211	2	1060	285	286	0.84	28.9 – 32.0	31.5

Note: The calculations were carried out for $j_0 = 100$ A cm^{-2}, $R_1 R_2 = 0.1$, the cavity length 800 μm, and the losses in heterostructure layers of 5 cm^{-1}.

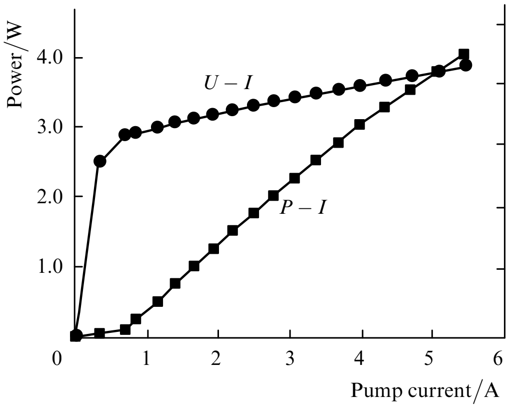

Figure 3. Typical volt – current (●) and light – current (■) characteristics of laser diodes with a 200-μm wide contact.

in the plane perpendicular to the $p-n$ junction is also presented. For comparison, j_{th} and divergences which were calculated taking into account the geometry and compositions of the heterostructure layers are presented in Table 1.

The comparison of the experimental data with the calculation results showed that the obtained values of the threshold current and emission divergence were close to the expected ones, which demonstrates the correctness of the chosen theoretical models and a good level of technology of the heterostructure growth.

We studied the dependence of the maximum power $P_{\max}$ of the emission pulse, at which a damage of the resonator mirror facet occurs, on the mesa stripe width W. We found that the linear power density at the LD mirror at the catastrophyc degradation was ~ 3000 W cm^{-1}. This corresponds to the optical flux density of 35 – 40 MW cm^{-2} which is a record large value for pulsed LDs.

The characteristic temperature T_0 of all the types of LDs was 130 – 150 K and reached 170 – 180 K for the best samples. The series resistance r of LDs was almost independent of the heterostructure type and was 0.22 – 0.28 Ω for LDs under test. Typical cut-off voltages of the volt – current characteristics of LDs were 1.4 – 1.5 V.

The rather high characteristic temperature T_0 and the differential efficiency s and comparatively low series resistance of the emitting element provided the high emission power. The emission power of an LD with a 100-μm broad contact was 2.5 W at 20 °C and the pump current of 3.2 – 3.5 A. The emission power of an LD with a 200 μm broad contact achieved 4 W at the pump current of 5.4 – 5.6 A. Typical light – current and volt – current characteristics of the LDs are presented in Fig. 3.

The service-life characteristics of LDs with a 100-μm broad contact were studied at the output cw power of 1.5 W and the ambient temperature of 50 °C. In this case, the temperature of the active element was, according to our estimations, 75 – 80 °C. A decrease in the emission power after 200 hours of the continuos operation did not exceed 0.5 % of the initial value.

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