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PHYSICS OF SEMICONDUCTOR DEVICES

Temperature Dependence of the Threshold Current Density and External Differential Quantum Efficiency of Semiconductor Lasers (λ = 900–920 nm)

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Abstract—The temperature dependences of the emission characteristics of semiconductor lasers based on asymmetric separate-confinement heterostructures with a broadened waveguide fabricated by metalorganic chemical vapor deposition (radiation wavelength λ = 900–920 nm) have been investigated. It is found that an increase in the energy depth and number of quantum wells (QWs) in the active region makes it possible to increase the temperature stability of the threshold current density and the differential quantum efficiency of semiconductor lasers on the basis of these structures. A temperature stability of threshold current density with a characteristic parameter T_0 = 290 K has been obtained in lasers based on a heterostructure with four QWs. It is experimentally shown that the laser parameters are stabilized due to the decrease in the threshold current density and threshold carrier density in the QWs of the active region. It is also demonstrated that, when the carrier concentration in these QWs reaches a certain value, the temperature stability of the threshold current density and differential quantum efficiency sharply decreases.

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1. INTRODUCTION

The temperature stability of laser characteristics is one of the most important criteria in fabricating laser heterostructures for laser bars and arrays. Such a parameter as the maximum power emitted by a single active element is not of primary importance when a laser bar or array are designed. Since laser bars are mounted on a heat sink with a high density, a single active element is so strongly heated in the CW or quasi-CW lasing modes that the maximum radiation power is most often limited by a level of 2–4 W. This limitation is especially important when it is necessary to increase the emission intensity in an array where the distance between the laser bars is less than 0.5 mm. In this design heat is removed along a thin heat-conducting layer of the heat sink and the temperature stability of the threshold current density and differential quantum efficiency are of primary importance.

In our previous paper [1] we reported the results of investigating the effect of thickness of a quantum-confined strained active region on the characteristics of a semiconductor laser based on an asymmetric separate-confinement laser heterostructure.

The purpose of this study was to analyze the temperature dependence of the threshold current density and differential quantum efficiency in semiconductor lasers based on asymmetric separate-confinement heterostructures with different number and different energy depth of quantum wells (QWs) in the active region, fabricated by metalorganic chemical vapor deposition (MOCVD).

The investigation of the temperature dependence of the threshold current density $J_{th}(T)$, began almost simultaneously with the studies of semiconductor lasers. A generally accepted description of this dependence is the empirical exponential function in the form [2]

$$J_{th}(T) = J_{th}(T_1)\exp\left(\frac{T-T_1}{T_0}\right), \qquad (1)$$

where T and T_1 are the highest and lowest temperatures of the laser diode within the approximation range, $J_{th}(T_1)$ is the threshold current density at the temperature T_1, and T_0 is a characteristic parameter.

The exponential temperature dependence of the threshold current density is most often related to the exponential temperature distribution of carriers over energy states in the active region. The characteristic parameter T_0 is determined experimentally, and it depends on a great number of factors: properties of the semiconductor materials forming the heterostructure, type and energy parameters of the laser heterostructure, and the geometrical sizes of the epitaxial layers forming the heterostructure. Nevertheless, the charac-

Table 1. Parameters of layers in laser heterostructures

Structure type	Layer	Layer composition	Layer thickness	Number of layers	Doping
1	*p*-Type emitter	$Al_{0.5}Ga_{1-x}As$	1.92 μm		Zn: 10^{18} cm^{-3}
	Waveguide	$Al_{0.31}Ga_{1-x}As$	0.76 μm		Undoped
	Spacer	GaAs	70 Å		″
	Active region	$In_xGa_{1-x}As$	100 Å	1	″
	Spacer	GaAs	70 Å		″
	Waveguide	$Al_{0.31}Ga_{1-x}As$	1.25 μm		″
	n-Type emitter	$Al_{0.5}Ga_{1-x}As$	1.87 μm		Si: 10^{18} cm^{-3}
2	*p*-Type emitter	$Al_{0.5}Ga_{1-x}As$	1.58 μm		C: 10^{18} cm^{-3}
	Waveguide	$Al_{0.31}Ga_{1-x}As$	0.48 μm		Undoped
	Active region	$In_xGa_{1-x}As$	50 Å	1	″
	Waveguide	$Al_{0.31}Ga_{1-x}As$	0.89 μm		″
	n-Type emitter	$Al_{0.5}Ga_{1-x}As$	1.64 μm		Si: 10^{18} cm^{-3}
3	*p*-Type emitter	$Al_{0.5}Ga_{1-x}As$	1.61 μm		C: 10^{18} cm^{-3}
	Waveguide	$Al_{0.31}Ga_{1-x}As$	0.47 μm		Undoped
	Active region	$In_xGa_{1-x}As$	50 Å	4	″
	Barrier	$Al_{0.31}Ga_{1-x}As$	300 Å	3	″
	Waveguide	$Al_{0.31}Ga_{1-x}As$	0.88 μm		″
	n-Type emitter	$Al_{0.5}Ga_{1-x}As$	1.68 μm		Si: 10^{18} cm^{-3}

teristic parameter T_0, which makes it possible to describe the temperature dependence of the threshold density using expression (1) [3], can be chosen for any interval in the temperature range of 10–400 K.

To increase the temperature stability of lasers based on separate-confinement heterostructures, one has to increase the Fabry–Perot cavity length, as a result of which the threshold current density decreases [4]. In asymmetric separate-confinement laser structures with a broadened waveguide, the stability of the threshold current density is improved by increasing the thickness of the quantum-sized active region, which reduces the threshold current density due to the increase in the optical confinement factor [1]. In this study we tried to increase the stability of threshold current density by varying different parameters of the active region in an asymmetric separate-confinement laser heterostructure.

2. EXPERIMENTAL SAMPLES

The investigations were performed on three types of asymmetric separate-confinement laser heterostructures based on solid solutions of the AlGaAs/InGaAs system. In the laser heterostructure of type 1 the active region is located between intermediate GaAs layers (spacers), in the heterostructure of type 2 the active region is directly between the AlGaAs waveguide layers, and in the heterostructure of type 3 the number of active regions (between the waveguide layers) is increased to four. The characteristic thicknesses and compositions of the epitaxial layers forming the asymmetric separate-confinement laser heterostructures of different types are listed in Table 1. These heterostructures were fabricated by MOCVD; the growth temperature was in the range of 720–770°C and the pressure in the reactor was maintained at a level of 60–80 Torr. The sources of the group-III elements were trimethylaluminum, triethylgallium, and trimethylindium, and 100% arsine was the source of arsenic. A mixture of silane with hydrogen was used as a ligature to grow *n*-type structures, and diethylzinc and the carbon tetrachloride were used as a ligature for *p*-type structures. High-purity hydrogen served as a carrier gas. The growth was performed on *n*-GaAs(100) substrates.

Mesastripe lasers with an emission aperture of 100 μm and different cavity lengths were fabricated from laser heterostructures using the standard technique. The temperature dependences of the threshold, spectral, and power characteristics of the experimental laser samples were investigated after their mounting on the heat sink.

3. OVERHEATING OF THE SEMICONDUCTOR LASER ACTIVE REGION IN THE CW LASING MODE

The overheating of the semiconductor laser active region with respect to the heat sink significantly affects the lasing characteristics. In high-power semiconductor lasers operating in the CW mode, the heterostruc-

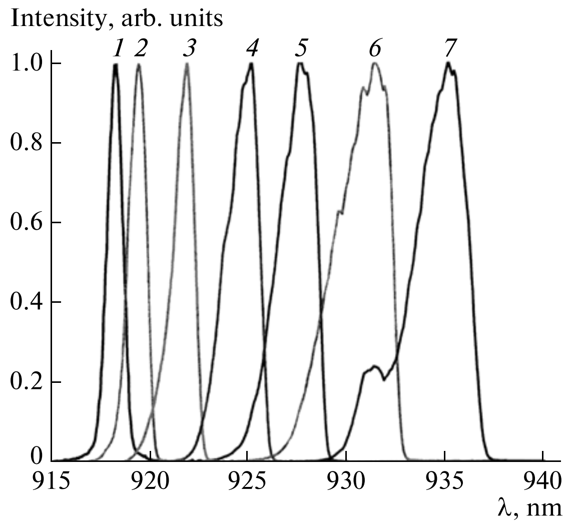

Fig. 1. CW lasing spectra of a semiconductor laser based on the heterostructure of type 3 at pump currents of (*1*) 1.45, (*2*) 2, (*3*) 3, (*4*) 4, (*5*) 5, (*6*) 6, and (*7*) 7 A.

ture layers are overheated with respect to the heat sink by several tens of kelvins. Overheating of the active region in a laser heterostructure can be detected by the shift of the long-wavelength edge of the lasing spectrum (Fig. 1). To this end, the temperature of the laser heat sink is maintained constant (20°C) and the lasing spectrum is recorded as a function of the pump current. If the long-wavelength edge shift and its temperature coefficient are known, one can determine the overheating with respect to the heat sink of the CW laser active region.

The temperature coefficient of the long-wavelength edge shift was determined using the following technique. Pulsed lasing spectra of semiconductor lasers based on heterostructures of three types were measured. The chosen parameters of the pump current pulses, width $\tau = 0.5$–1 μs and frequency $f =$ 1 kHz, allowed us to exclude the effect of active-region overheating with respect to the heat sink at pump currents up to 1–1.5 A. In our experiment the heat sink temperature corresponded to that of the active region, which made it possible to detect simultaneously the active-region temperature and the long-wavelength edge position in the lasing spectrum. The shift coefficient for the long-wavelength edge of the lasing spectrum was found from the experimental data to be 3.3 Å/°C; this value is in good agreement with the reference data [5].

Thus, using the experimentally determined long-wavelength edge shift (Fig. 1) and its temperature coefficient (3.3 Å/°C), we found the overheating of the laser active region with respect to the heat sink: 30–50°C.

The active-region overheating depends not only on the pump current but also on the laser efficiency and the thermal resistance (determined by the quality of metallization and heat sink mounting). The efficiency and thermal resistance of the semiconductor lasers under study cannot be significantly affected by changing the geometric parameters of the active region of the laser heterostructures of all three types. The maximum efficiency of the lasers studied reaches 50–60%, and their thermal resistance is 4–5 K/W. The effect of these factors cannot be excluded completely; nevertheless, it must be reduced. The active-region overheating with respect to the heat sink can be reduced by increasing the temperature stability of the main laser characteristics: threshold current and external differential quantum efficiency. Therefore, the study of the temperature dependence of the threshold current density and external differential quantum efficiency in order to find the design of laser heterostructure with a high temperature stability is of great interest.

4. TEMPERATURE DEPENDENCE OF THRESHOLD CURRENT DENSITY AND DIFFERENTIAL QUANTUM EFFICIENCY

The temperature dependence of the threshold current density J_{th} was investigated for lasers based on heterostructures of three types operating in the pulsed mode ($\tau = 0.5$–1 μs, $f = 1$ kHz) at temperatures from 20 to 140°C. The Fabry–Perot cavity length was varied from 600 to 3500 μm. The temperature of the copper heat sink was stabilized using a high-power Peltier element with a water-cooled heat sink and additional electric furnace mounted directly on the copper holder of the heat sink. The heat sink temperature was measured by a temperature-sensitive element in the immediate vicinity of the laser crystal. The temperature dependences of the threshold current density for the lasers based on the heterostructures of three types under consideration are shown in Fig. 2. The threshold current density is presented for one 50-Å-thick QW; thus, this dependence can be used to estimate the threshold concentration in the active region. The calculated threshold carrier concentration in the QW active region for the laser structures of three types is shown in Fig. 3. The calculation was performed using the well-known expression [6]

$$J_{th} = qd_{QW}NBn_{QW}^2, \quad (2)$$

where q is the elementary charge, d_{QW} is the QW thickness, N is the number of QWs, B is the radiative recombination coefficient, and n_{QW} is the threshold electron concentration in the active region.

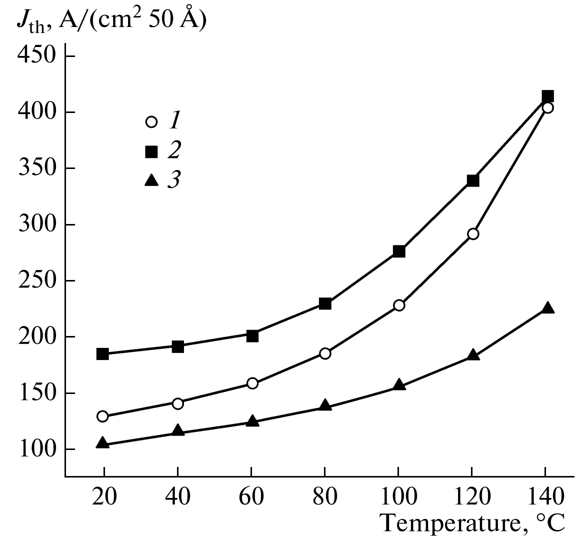

Fig. 2. Temperature dependences of the threshold current density, reduced to an active region of 5 nm, for semiconductor lasers based on heterostructures of types 1, 2, and 3.

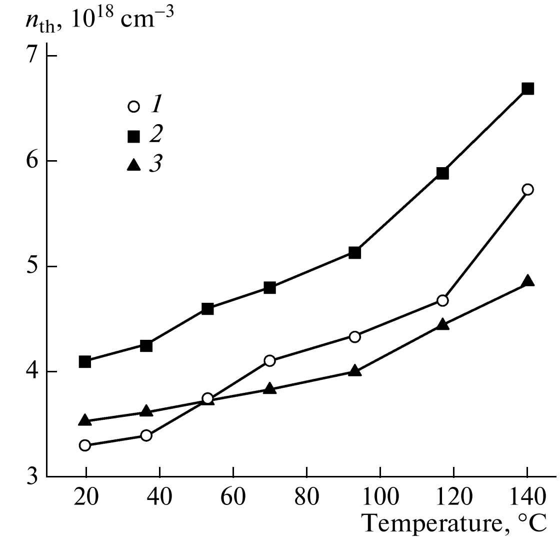

Fig. 3. Temperature dependences of the threshold carrier concentration (n_{th}) in the active region of semiconductor lasers based on heterostructures of types 1, 2, and 3.

Two portions can be selected in the temperature dependences of the threshold current density and threshold carrier concentration for the lasers based on the three heterostructures under study. The first portion, corresponding to low temperatures, is characterized by a weak temperature dependence of the parameters, whereas in the second (high-temperature) portion the parameters depend strongly on temperature. The temperature behavior changes at threshold current densities of 240–250 A/cm^2 in single-QW structures and 150 A/cm^2 in the structure with four QWs, which corresponds to approximately the same threshold concentration (~4.5×10^{18} cm^{-3}) but at different temperatures. For the samples based on the heterostructure of type 3, the change in the temperature behavior occurs at the maximum temperature. The maximum temperature of the "kink" was observed in lasers with a maximum cavity length and minimum threshold current density.

Table 2 contains the values of the characteristic temperature parameter T_0 for the two portions of the temperature dependences of the threshold current density for the lasers based on the heterostructures of different types. The characteristic parameter T_0 was calculated from formula (1). The lasers based on the third-type structure, where the active region consists of four QWs without GaAs spacers, have the highest temperature stability. The dependences obtained suggest the following: when the carrier concentration in the active region of asymmetric separate-confinement laser heterostructure reaches a certain value, the temperature stability of the threshold current sharply decreases, thus deteriorating all emission properties (Figs. 2, 4). The external differential quantum efficiency also decreases with an increase in temperature. The temperature dependences of the external differential quantum efficiency for semiconductor lasers based on the laser heterostructures of three types are shown in Fig. 4. A dramatic decrease in the external differential quantum efficiency to 20% with an increase in temperature is observed for the lasers based on the type-1 structure. A decrease in the external differential quantum efficiency to 40% is observed for the lasers on heterostructures of types 1 and 2. A sharp decrease occurs when the temperature reaches some critical temperature near 100°C. The lasers based on heterostructures of types 1 and 2 differ by the lengths of the Fabry–Perot cavities, which provide a high external differential quantum efficiency at low temperatures. In lasers with one QW in the active region the optimal cavity length reached 2.5–3.5 mm, in contrast to 0.6–1.0 mm for the lasers with an active region containing four QWs. The choice of the optimal cavity length is important when designing laser arrays, where short cavities are preferred, because they make it possible to efficiently remove heat.

Table 2. Characteristic parameter T_0 for laser heterostructures of three types

Heterostructure type	T_0, K	
	low-temperature range	high-temperature range
1	130–150	40–96
2	160–240	90–120
3	210–290	90–120

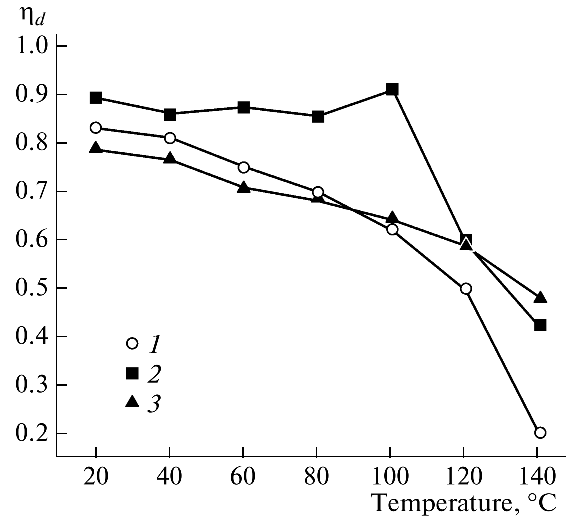

Fig. 4. Temperature dependences of the differential quantum efficiency η_d of the semiconductor lasers based on heterostructures of types 1, 2, and 3.

5. CONCLUSIONS

In asymmetric separate-confinement laser heterostructures, an increase in the energy depth and number of QWs in the active region makes it possible to significantly increase the temperature stability of the threshold current and external differential quantum efficiency. The laser characteristics are stabilized due to the decrease in the threshold current density and threshold carrier concentration in the QWs of the active region. Independently of the design features of the laser structures of all three types, when the carrier concentration in the QWs reaches a certain value, the temperature stability of the threshold current density and differential quantum efficiency sharply decrease. In the lasers based on the heterostructure with four QWs without spacers the critical concentration is obtained at maximum temperatures: 100–110°C.

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