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Thermal properties of stripe-geometry laser diodes

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In this work thermal properties of stripe-geometry double-heterostructure GaAs–(AlGa)As laser diodes have been analyzed. The space transformation reducing the nonlinear thermal conduction equation to the linear one has been used. The transformation has replaced the nonhomogeneous GaAs–(AlGa)As double-heterostructure of the laser diode for the homogeneous, GaAs or (AlGa)As homostructure.

In calculations of the heat sources distribution, nonradiative recombination, reabsorption of radiation, Joule heating, the radiative transfer of the spontaneous radiation through the passive layers as well as the current spreading effect have been taken into account.

1. Introduction

In recent years an intense effort has been devoted to the development of laser diodes, the simplest and most compact lasing devices. Most of them utilize a stripe-geometry. This development has been stimulated by the optical telecommunication where a stripe-geometry laser diode [1–8] is used as a carrier wave generator assuring an efficient coupling with a fiber lightguide [9–11].

Due to the operation of the laser diode the temperature increases within its volume. This is induced mainly by nonradiative recombination as well as reabsorption of radiation and the Joule heating. This rise of temperature deteriorates the laser diode performance causing an increase in the threshold current density, a decrease in the output power and the external quantum efficiency, as well as a shift of the whole spontaneous radiation spectrum and the mode peaks on spectral characteristics. In the case of the stripe-geometry laser diodes without a built-in waveguide, the temperature distribution in the *p-n* junction plane improves the stabilization of the radiation filament.

Because of all the above mentioned effects, the operational characteristics of laser diodes are influenced by their thermal properties which have been investigated by many authors. The one-dimensional heat extraction in the oxide-insulated stripe laser diodes was described by GAREL-JONES and DYMENT [12]. The two-dimensional case for the stripe-geometry laser diodes without oxide barriers (e.g., proton bombardment stripe laser diodes or planar stripe laser diodes) was analysed by JOYCE and DIXON [13]. Subsequent papers devoted to this subject added some improvements to the work of Joyce and Dixon. NEWMAN et al. [14] took into consideration the radiative energy transfer of the spontaneous radiation. DUDA et al. [15] investigated the relative influence of various heat sources (including the Joule heating) on the temperature distribution in the laser diodes. BUUS [16, 17] took account of the current spreading effect. ITO and KIMURA [18] considered the heat extraction from the top surface of the laser crystal (thermal radiation and conduction through a bonding wire). STEVENTON et al. [19] and YANO et al. [20] adapted this model to the InGaAsP stripe laser diodes.

The solution given by Joyce and Dixon has the form of an infinite series with unknown coefficients. These coefficients can be determined by solving a great number of equations for the continuity of temperature and heat flux on each boundary between layers. This is the main disadvantage of the above method. In this paper, the approximate, analytical solution of the thermal conduction equation in the active layer of the stripe-geometry laser diode is presented. In this case, the expansion coefficients depend only on the laser construction parameters and the energy source.

The basic assumptions of the model are presented in Sec. 2; the space transformation which reduces the nonhomogeneous medium of the laser diode to homogeneous one is the subject of Sec. 3; the distribution of the heat sources is discussed in Sec. 4. The solution and results are presented in Sec. 5 and Sec. 6, respectively.

The present work is a continuation of our previous papers devoted to the thermal properties of broad contact laser diodes in the steady-state condition [21–23] and in the transient-state condition [24–29] as well as to the thermal properties of stripe-geometry laser diodes [30].

2. Assumptions

The standard construction of the stripe-geometry double-heterostructure GaAs–(AlGa)As laser diode without oxide barriers is shown in Fig. 1, where

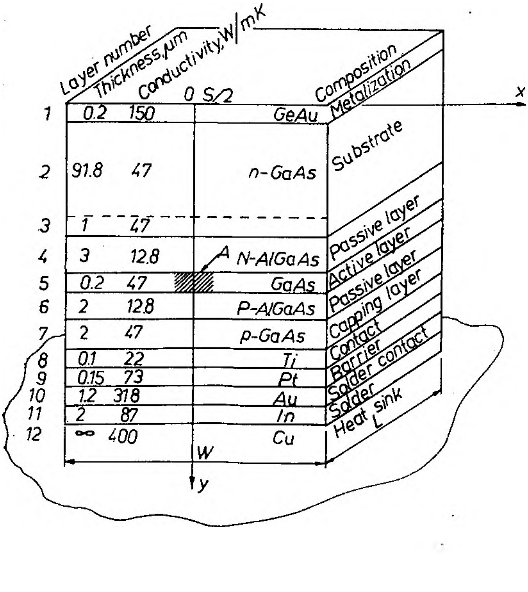

Fig. 1. Standard construction of stripe-geometry, double-heterostructure GaAs–(AlGa)As laser diode without oxide barriers (A – the active region)

the thermal conductivities are taken from papers [31–33]. Standard parameters of the laser used in calculations are given in Table 1.

Table 1. The parameters of standard stripe-geometry double-heterostructure GaAs–(AlGa)As laser diode

Parameter	Value	Unit	Parameter	Value	Unit
W	300	μm	η_{sp}	0.55	—
S	15	μm	η_{ext}	0.3	—
L	400	μm	η_i	1	—
I	150	mA	ϱ_4	$4.26\cdot10^{-4}$	Ωm
I_{th}	100	mA	ϱ_6	$7.00\cdot10^{-5}$	Ωm
U	1.7	V	ϱ_7	$1.40\cdot10^{-4}$	Ωm

In this case, because of the position dependence of the thermal conductivity λ, the thermal conduction equation is nonlinear:

$$\nabla(\lambda\nabla T) = -g \tag{1}$$

where T is temperature and g is power density of heat sources.

The boundary conditions may be formulated by assuming:

i) a negligible heat extraction from the top and side walls

$$\left.\frac{\partial T}{\partial x}\right|_{x=\pm W/2} = 0, \tag{2}$$

$$\left.\frac{\partial T}{\partial y}\right|_{y=0} = 0, \tag{3}$$

ii) a symmetry of the construction according to the y-axis

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0, \tag{4}$$

iii) an infinite thermal capacity of the heat sink

$$T(y = y_{HS}) = T_A \tag{5}$$

where y_{HS} denotes points on the external surface of the heat sink and T_A is ambient temperature.

The main heat source in the active layer is placed very close to the heat sink. High efficiency of the heat extraction process in the laser diode seemingly enables us to formulate the boundary conditions (2) and (3) in a simpler form: $T\big(x = \pm(W/2)\big) = T(y = 0) = 0$. The measurements [34–36] of the temperature distributions on the mirror facet have, however, proved the inadequacy of the above mentioned assumption.

3. Transformation

The space transformation presented in papers [37] enables, for the one-dimensional case, the substitution of the thermally equivalent GaAs homostructure for the GaAs–(AlGa)As double-heterostructure. In this way, the thermal conduction equation (2) becomes linear:

$$\nabla^2 T(x, y) = -\frac{g(x, y)}{\lambda}. \tag{6}$$

The transformation reduces the multi-layer, nonhomogeneous structure of the double-heterostructure (*DH*) GaAs–(AlGa)As laser diode to the homostructure GaAs laser diode replacing each i-th layer of thickness t_i and thermally conductivity λ_i with the thermal equivalent GaAs layer of thickness t_i' and thermal conductivity

$$\frac{t_i'}{t_i} = \frac{\lambda}{\lambda_i} = f_{s,i} \tag{7}$$

where $f_{s,i}$ is the space transformation coefficient of i-th layer.

Similar transformation for the two-dimensional case under consideration involves an alteration of the lateral spreading of the heat flux. In this way, the transformation into the GaAs homostructure lowers the temperature in the active region in comparison with the real distribution, and the analogous transformation into the (AlGa)As homostructure raises this temperature. In the next Sections we shall try to compare the real temperature distribution in the p-n junction plane with the arithmetic mean of the results of both the transformations.

The transformation is performed for all the layers. In the case of the heat sink, the method proposed by LAFF et al. [38] is used

$$S_1 = \frac{P}{L\lambda_t}\left(\frac{\partial T_{\mathrm{av}}}{\partial(\Delta t)}\right)^{-1} \tag{8}$$

where S_1 – effective width of the heat flux flowing into the heat sink, P – dissipated power, L – length of the laser resonator, T_{av} – averaged temperature of the active region, and Δt – thickness of a hypothetic layer of thermal conductivity λ_t inserted between the laser chip and the heat sink. The thermal resistance Q_{HS} of the copper heat sink is then equal to

$$Q_{HS} = \frac{1}{2\pi\lambda_{12}L}\ln\left(\frac{4L}{S_1}\right) \tag{9}$$

where λ_{12} – thermal conductivity of copper.

The increase in temperature in the heat sink may be presented as follows:

$$\Delta T_{HS} = Q_{HS} q_t S_1 L = \frac{q_t}{\lambda_{12}} t_{12} \tag{10}$$

where the averaged density q_t of the total heat flux flowing into the heat sink is

$$q_t = \frac{P}{S_1 L} \tag{11}$$

and t_{12} is the thickness of the copper layer of the thermal resistance Q_{HS}. Then the thickness t_{12} of the thermally-equivalent GaAs layer will be

$$t'_{12} = \frac{S_1}{2} \ln\left(\frac{4L}{S_1}\right) \frac{\lambda}{\lambda_{12}} \tag{12}$$

All thicknesses of the layer before and after the transformation into GaAs, as well as the transformation into (AlGa)As are listed in Table 2.

Table 2. The space transformation coefficients and the thicknesses of layers of the standard stripe-geometry laser diode before and after the transformation

Layer number	Space transformation coefficient	Thickness [μm] before transformation	Thickness [μm] after transformation
1	0.0853	0.2	0.02
2	0.272	91.8	24.97
3	0.272	1	0.27
4	1	3	3
5	0.272	0.2	0.05
6	1	2	2
7	0.272	2	0.54
8	0.582	0.1	0.06
9	0.175	0.15	0.03
10	0.0403	1.2	0.05
11	0.147	2	0.29
12	0.032	∞	0.99

4. Heat sources

In the laser diode volume there exist three sorts of the heat sources:

i) The main heat source is placed in the active region and results from non-radiative recombination and reabsorption of the generated radiation. Its power density is [35]

$$g_A = \frac{U}{t_5} \{j_{\mathrm{th}}(1-f\eta_{\mathrm{sp}}) + (j-j_{\mathrm{th}})[1-\eta_{\mathrm{ext}}-(1-\eta_i)\eta_{\mathrm{sp}}f]\} \tag{13}$$

where U is the voltage drop at the p-n junction, j and j_{th} are the supply current density and threshold current density, respectively, and t_5 is the thickness of the active layer, η_{sp}, η_{ext} and η_i are the internal quantum efficiency of the spontaneous emission, the external differential quantum efficiency of the lasing and the internal quantum efficiency of the lasing , respectively. Coefficient f describes the radiative transfer of the spontaneous radiation generated in the active region through the wide-gap, passive (AlGa)As layers. It may be calculated in the following way [39]:

$$f \approx 2\sin^2\left[\frac{1}{2}\arcsin\left(1-0.62\,\frac{\Delta x_{AL}}{n_R}\right)\right] \tag{14}$$

where n_R – refractive index of the active region material and Δx_{AL} – difference in AlAs content between passive and active layers.

ii) In the GaAs capping layer and in the top layer of the substrate (layer 3 in Fig. 1) there exist the additional heat sources that are connected with the absorption of the spontaneous radiation transferred radiatively through the passive layers. Assuming the homogeneous distribution of the power density in both layers, they may be represented as follows:

$$g_{Tr,7} = Uj_{\text{th}}\frac{\eta_{sp}f}{2t_7}, \tag{15}$$

$$g_{Tr,3} = Uj_{\text{th}}\frac{\eta_{sp}f}{2t_3}. \tag{16}$$

iii) A supplementary influence is exercised by the Joule heating generated in each layer with a density

$$g_{J,i} = j^2\varrho_i, \quad i = 1, 2, 3, \ldots, 12 \tag{17}$$

where ϱ_i – electrical resistivity of i-th layer material.

In all the formulae given in this Section, the current spreading has not been taken into consideration. These formulae are adequate for laser diodes with a good current confinement. A more general example will be shown in Section 6.

The space transformation should be also performed for the power densities. This is due to the changes of the layer thicknesses. The transformation coefficient of the heat power densities is therefore the following:

$$f_{g,i} = \frac{g_i'}{g_i} = \frac{1}{f_{s,i}}, \quad i = 1, 2, 3, \ldots, 12. \tag{18}$$

All the heat power densities, before and after the space transformations, are listed in Table 3. In the next Sections the primes will be omitted because only the values after the transformation will be considered.

Table 3. Heat power densities before and after the transformation

Heat source	Localization		Density [Wm^{-3}] before transformation	Density [Wm^{-3}] after transformation	Notation for calculations
Nonradiative recombination and reabsorption of radiation in the active layer	Active layer	g_5	$1.398 \cdot 10^{14}$	$5.141 \cdot 10^{14}$	g_5
Absorption of spontaneous radiation transferred radiatively through passive layers	p-GaAs	$g_{7,Tr}$	$2.577 \cdot 10^{12}$	$9.453 \cdot 10^{12}$	$g_7 = g_{7,Tr} + g_{7,J}$
	n-GaAs (Tr)	g_3	$5.153 \cdot 10^{12}$	$1.891 \cdot 10^{13}$	g_3
Joule heating	n-GaAs	g_2	$3.3 \cdot 10^7$	*	*
	N-(AlGa) As	g_4	$2.66 \cdot 10^{11}$	$2.66 \cdot 10^{11}$	g_4
	P-(AlGa) As	g_6	$8.75 \cdot 10^{10}$	$8.75 \cdot 10^{10}$	g_6
	p-GaAs	$g_{7,J}$	$4.38 \cdot 10^{10}$	$1.61 \cdot 10^{11}$	$g_7 = g_{7,Tr} + g_{7,J}$
	Ti	g_8	$1.4 \cdot 10^9$	*	*
	Pt	g_9	$2.9 \cdot 10^8$	*	*
	Au	g_{10}	$8 \cdot 10^7$	*	*
	In	g_{11}	$2 \cdot 6 \cdot 10^8$	*	*
	Heat sink	g_{12}	$5 \cdot 10^7$	*	*

* means that this heat source with a density $< 10^{10}$ Wm^{-3} will not be taken into further account

5. Solution

The problem considered reduces now to the solution of the linear thermal conduction equation

$$\nabla^2 T(x,y) = -\frac{g(x,y)}{\lambda} \tag{19}$$

with the boundary conditions:

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0, \tag{20}$$

$$\left.\frac{\partial T}{\partial x}\right|_{x=W/2} = 0, \tag{21}$$

$$\left.\frac{\partial T}{\partial y}\right|_{y=0} = 0 \tag{22}$$

$$T(x = a_{12}) = T_A \tag{23}$$

where

$$g(x,y) = \begin{cases} g_i & \text{for } |x| \leqslant S/2 \quad \text{and } y \in \langle a_{i-1}, a_i \rangle \\ 0 & \text{elsewhere} \end{cases} \tag{24}$$

$$a_i = \sum_{k=1}^{i} t_k, \quad i = 1, 2, 3, \ldots, 12 \tag{25}$$

and g_i are given in Table 3.

The solution of this problem is the following:

$$T(x,y) = T_A + \frac{4}{\lambda W a_{12}} \sum_{m=1}^{\infty} \left\{ \frac{G_m \cos(L_m y)}{L_m} \left[\sum_{n=0}^{\infty} \frac{\sin(K_n(S/2))}{K_n(K_n^2 + L_m^2)} \times \cos(K_n x) + \sum_{n=1}^{\infty} \frac{\sin(K_n(S/2))}{K_n(K_n^2 + L_m^2)} \cos(K_n x) \right] \right\}, \tag{26}$$

with

$$K_n = \frac{2n\pi}{W}, \tag{27}$$

$$L_m = \frac{(2m-1)\pi}{2a_{12}}, \tag{28}$$

$$G_m = \sum_{i=1}^{12} g_i [\sin(L_m a_i) - \sin(L_m a_{i-1})]. \tag{29}$$

6. Results

Let us consider the arithmetic mean of both the solutions obtained with the aid of the transformations into GaAs (T_1) and (AlGa)As (T_2) as a result of our calculations:

$$T = \frac{1}{2}(T_1+T_2). \tag{30}$$

For the standard stripe-geometry double-heterostructure GaAs–(AlGa)As laser diode (Fig. 1, Tab. 1) the new obtained solution (N) is compared with the exact solution (*JD*) of Joyce and Dixon in Fig. 2. It is evident that the observed discrepancy of both curves is insignificant.

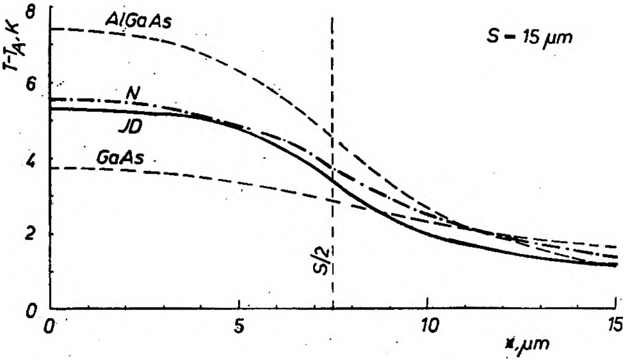

Fig. 2. Temperature distributions in the *p-n* junction plane of stripe-geometry *DH* laser diode with $S = 15$ μm. *JD* – solution of Joyce and Dixon, N–new approximated solution, GaAs and AlGaAs – solutions for the transformations into GaAs and (AlGa)As, respectively

In order to check this method, we perform an analogical comparison for the extremely different conditions:

i) $S = 15$ μm, but the thicknesses of the passive layers are $t_4 = 2$ μm and $t_6 = 3$ μm,

ii) $S = 10$ μm,

iii) $S = 5$ μm.

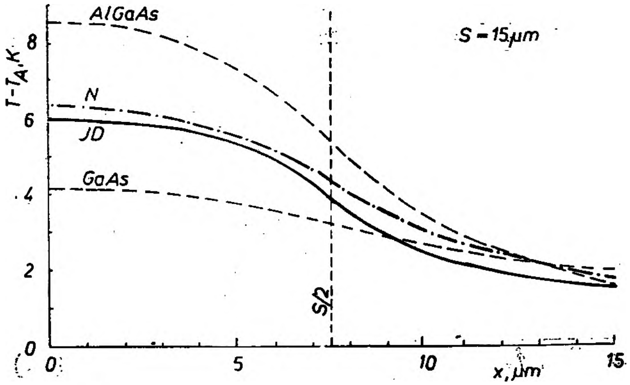

Fig. 3. Temperature distributions in the *p-n* junction plane of stripe-geometry *DH* laser diode with $S = 15$ μm and the changed values of the layer thicknesses: $t_4 = 2$ μm and $t_6 = 3$ μm

The results are shown in Figs. 3–5, respectively. It turned out that the proposed method is relatively insensitive to the reasonable changes of the laser diode structure. The method may be used for the approximate determination of the temperature distribution in the p-n junction plane of the stripe-geometry laser diode.

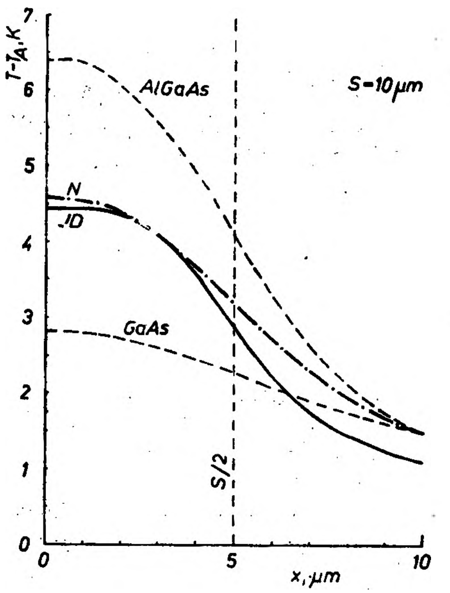

Fig. 4. Temperature distributions in the p-n junction plane of stripe-geometry DH laser diode with $S = 10\ \mu$

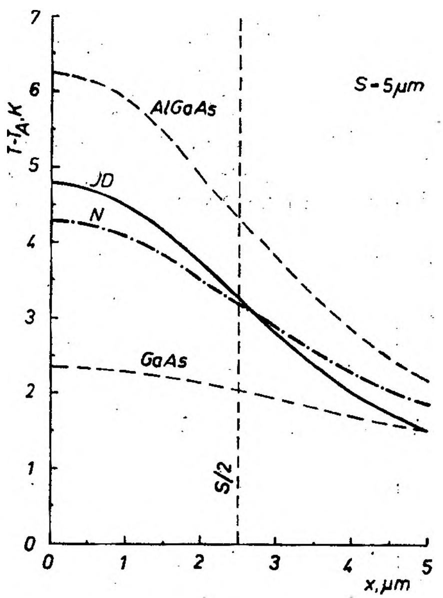

Fig. 5. Temperature distributions in the p-n junction plane of stripe-geometry DH laser diode with $S = 5\ \mu$m

In the case of stripe-geometry laser diodes without the effective confinement of the current path between the contact and the active regions (e.g., oxide insulated, proton bombarded and planar stripe lasers), the current spreading effect should be taken into consideration. This effect results from the finite electrical resistance of the p-layer and P-layer, and may be usually described in the following way [40–41]:

$$j(y) = \begin{cases} j_1 & \text{for } |y| \leqslant S/2 \\ \dfrac{j_1}{\left(1+\dfrac{|y|-S/2}{l_0}\right)^2} & \text{for } |y| \geqslant S/2 \end{cases}, \tag{31}$$

where

$$j_1 = 1+2(B/S)^2-2(B/S)\sqrt{(B/S)^2+j}, \tag{32}$$

$$l_0 = Bj_1^{-1/2}, \tag{33}$$

$$B = \left(\frac{2}{R_\square}\frac{n_c kT}{e}\right)^{1/2}, \tag{34}$$

$$R_\square = \frac{\varrho_6}{t_6}+\frac{\varrho_7}{t_7}, \tag{35}$$

$$j = I/LS, \tag{36}$$

with I – supply current, k – Boltzman constant, e – unit charge, n_c – constant (for the *DH* GaAs–(AlGa)As laser diode: $n_c \approx 2$, [43]).

For the heat power densities, we assume the same relative lateral distribution as for the current density

$j(y)$:

$$g(x,y) = \begin{cases} g_i \dfrac{j(y)}{j} & \text{for } x \in \langle a_{i-1}, a_i\rangle, \quad i = 3,4,5,6,7, \\ 0 & \text{elsewhere} \end{cases} \tag{37}$$

The solution of the thermal conduction equation (19) with $g(x,y)$ given by (37) and the boundary conditions (20)–(23), is the following

$$T(x,y) = T_A + \frac{4}{\lambda W a_{12}}\sum_{m=1}^{\infty}\left\{\frac{G_m\cos(L_m y)}{L_m}\left[\sum_{n=0}^{\infty}\frac{a_n\cos K_n x}{K_n^2+L_m^2} + \sum_{n=1}^{\infty}\frac{a_n\cos(K_n x)}{K_n^2+L_m^2}\right]\right\} \tag{38}$$

where [17]:

$$a_n = \frac{j_1}{j}\left\{\frac{\sin\big(K_n(S/2)\big)}{K_n} + l_0\cos\big(K_n(S/2)\big) + K_n l_0^2\left[\cos\big(K_n(S/2)\big)F(K_n l_0) + \sin\big(K_n(S/2)\big)G(K_n l_0)\right]\right\}, \tag{39}$$

$$F(K_n l_0) = \cos(K_n l_0)\,\mathrm{si}(K_n l_0) - \sin(K_n l_0)\,\mathrm{Ci}(K_n l_0) \tag{40}$$

$$G(K_n l_0) = \cos(K_n l_0)\,\mathrm{Ci}(K_n l_0) + \sin(K_n l_0)\,\mathrm{si}(K_n l_0) \tag{41}$$

where integral sine and cosine are used

$$\mathrm{si}(x) = -\int_x^\infty \frac{\sin t}{t}\,dt = -\frac{\pi}{2} + \int_0^x \frac{\sin t}{t}\,dt = -\frac{\pi}{2} + \mathrm{Si}(x) \tag{42}$$

$$\mathrm{Ci}(x) = -\int_x^\infty \frac{\cos t}{t}\,dt.$$

The influence of the current spreading effect on the temperature distribution in the DH stripe-geometry laser diodes for $S = 15$ μm and $S = 10$ μm is illustrated in Figs. 6 and 7, respectively. It is apparent that the temperature-induced waveguiding in the DH stripe-geometry laser diodes depends strongly on the efficiency of the current confinement, i.e., on the value of the composite sheet resistance $R_{\square}$.

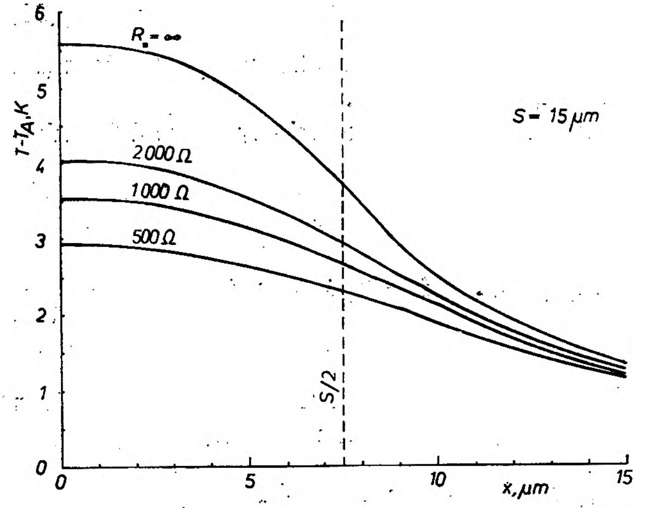

Fig. 6. Temperature distributions in the p-n junction plane of stripe-geometry DH laser diode with $S = 15$ μm and various values of sheet resistance $R_{\square}$

BUUS [16] has adapted the Joyce-Dixon model to the stripe-geometry DH laser with the current spreading effect. He obtained analogical results, but for points outside the active region the temperature distributions depend-

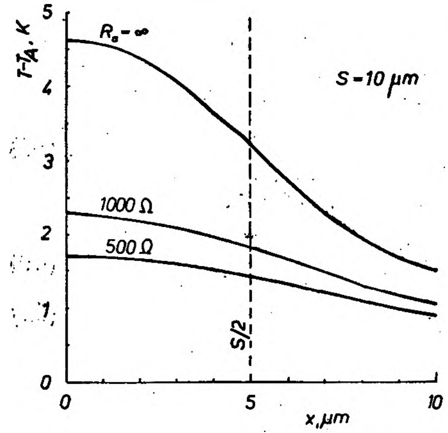

Fig. 7. Temperature distributions in the p-n junction plane of stripe-geometry DH laser diode with $S = 10$ μm and various value of sheet resistance $R_{\square}$

ed much more strongly on the sheet resistance $R_{\square}$. This means that for this region the method described here is less exact. As far, however, as the electrical and optical properties of the laser diode are concerned, the temperature distribution outside the active region is much less important.

7. Conclusions

The approximate, analytical solution of the thermal conduction equation was obtained for the stripe-geometry double-heterostructure GaAs–(AlGa)As laser diode. The space transformation reducing the nonhomogeneous medium of the laser diode to the homogeneous one was used. The results were compared with the exact, semi-analytical solution of Joyce and Dixon. The current spreading effect was taken into consideration.

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Термические свойства ленточных лазеров

В настоящей работе произведен анализ термических свойств бигетеромуфтовых ленточных лазеров GaAs-(AlGa)As. С этой целью применена трансформация пространства, редуцирующая нелинейное уравнение термической проводности к линейной форме. Эта трансформация заменяет неоднородную бигетероструктуру GaAs-(AlGa)As муфтового лазера однородной гомоструктурой GaAs или (AlGa)As.

В расчетах распределения источников тепла учтены нелучистая рекомбинация, реабсорбция излучения, джоулево тепло, лучистый трансферт спонтанного излучения через пассивные слои, а также эффект токораспределения.

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