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Thermal properties of broad-contact single-heterostructure laser diodes

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The thermal conduction equation has been solved analytically for the broad-contact single-heterostructure GaAs-(AlGa)As laser diode. The space transformation reducing the nonhomogeneous structure of the laser diode into homogeneous one has been used. The nonradiative recombination, the reabsorption of radiation, the Joule heating as well as the radiative transfer of the spontaneous radiation through the wide-gap passive P-(AlGa)As layer have been considered. The relative participation of the above mentioned heat sources has been discussed. The temperature dependence of the GaAs thermal conductivity has been taken into account.

The influence of the internal quantum efficiency of the spontaneous radiation as well as the thicknesses and the resistivities of the individual layers on the thermal resistance of the SH laser diode has been discussed. The possible thermal optimization of SH laser diode construction has been explained.

1. Introduction

In the recent years a rapid development has been achieved in the construction of stripe-geometry laser diodes. This development has been stimulated by a very promising application of these laser diodes, namely the optical telecommunication utilizing fibre waveguides [1-4].

The broad-contact laser diodes are, however, still produced as efficient sources of electromagnetic radiation. They are especially useful in the case when their multi-filament radiation pattern is much less important than their high output.

Of the contemporary laser diode structures, the broad-contact single-heterostructure laser diodes are the simplest and cheepest ones [5-7]. They are obtained by means of only one-step liquid-phase epitaxy and their mass production may be set up relatively easily. Because of their relatively high threshold current density they are usually supplied with a pulse current. A rapid development of the laser diode technology (achieved recently) allows us to expect that this threshold current may be considerably lowered in the nearest future and consequently the broad-contact single-heterostructure laser diodes will be commonly used for the continuous wave operation.

This paper is devoted to the description of the thermal properties of the above mentioned devices under the steady-state condition. It enables also the thermal optimization of the single-heterostructure (SH) laser diodes for the transient-state operation.

The basic assumptions are presented in Section 2. The space transformation, which reduces the nonhomogeneous structure of the laser diode into homogeneous one is introduced in Section 3. InS ection 4, the heat sources distribution in the SH laser diode is discussed. The analytical solution of the considered problem is given in Section 5. In Sections 6 and 7, the main results and the discussion are presented, respectively. The paper is a continuation of the previously published works [8–16] devoted to the statical and dynamical thermal properties of the broad-contact laser diodes.

2. Assumptions

The standard structure of the broad-contact single-heterostructure GaAs-(AlGa)As laser diode is shown in Fig. 1. The thermal conductivities are taken from [17–19]. The values of the structural and supply parameters used in calculations are listed in Table 1.

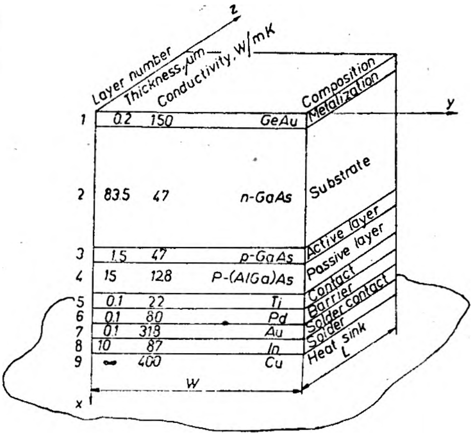

Fig. 1. Standard structure of the broad-contact single-heterostructure GaAs-(AlGa)As laser diode. Thicknesses, thermal conductivities and compositions of the individual layers are shown. W and L – width and length of the laser resonator

Table 1. The parameters of the standard GaAs-(AlGa)As broad-contact single-heterostructure laser diode and of its power supply

Parameter	Value	Unit	Parameter	Value	Unit
W	200	μm	η^{sp}	0.55	—
L	400	μm	η_{ext}	0.3	—
j	8000	A/cm^2	η_i	1	—
j_{th}	5000	A/cm^2	ϱ_2	$1.22\cdot10^{-5}$	Ωm
U	1.7	V	ϱ_4	$6.4\cdot10^{-5}$	Ωm

The thermal conduction equation is the following:

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

where λ, T and g are the thermal conductivity, temperature and the density of heat sources power, respectively.

Due to a relatively high efficiency of the heat extraction from the active layer through the contact to the heat sink if compared with both the thermal radiation and the thermal energy taken over by air particles from the laser crystal surface the following boundary conditions can be written

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = \left.\frac{\partial T}{\partial y}\right|_{y=0} = \left.\frac{\partial T}{\partial y}\right|_{y=W} = \left.\frac{\partial T}{\partial z}\right|_{z=0} = \left.\frac{\partial T}{\partial z}\right|_{r=L} = 0 \tag{2}$$

where W and L are width and length of the laser resonator, respectively.

The last four equalities reduce the thermal conduction equation (1) to a one-dimensional form:

$$\frac{d}{dx}\left(\lambda(x)\frac{dT}{dx}\right) = -g(x). \tag{3}$$

Because of much larger sizes of the heat sink than that of the laser crystal, the infinite heat capacity of the heat sink is assumed, hence we get the last boundary condition

$$T(x = x_{\mathrm{HS}}) = T_A \tag{4}$$

where T_A is the ambient temperature, the points of the external surface of the heat sink being denoted symbolically by x_{HS}.

3. Transformation

The space transformations reducing the broad-contact heterostructure laser diode to the homostructure one of the same thermal properties has been proposed in paper [20]. In the transformation, each i-th layer of thickness t_i and conductivity λ_i is replaced with the thermally equivalent GaAs layer of thickness t_i' and conductivity λ. The space transformation coefficient $f_{s,i}$ is equal to

$$f_{s,i} = \frac{t_i'}{t_i} = \frac{\lambda}{\lambda_i}, \quad i = 1, 2, 3, \ldots, 8. \tag{5}$$

The correctness of the transformation for the one-dimensional heat spreading is confirmed in paper [21] for two basic cases:

i) heat flux flowing into a transformed layer,

ii) heat generated in a transformed layer.

The transformation is carried out not only for the semiconductor layers but for the contact layers and the heat sink as well. The inverse transformation is, of course, necessary to produce the results.

In the calculations of the thermally equivalent heat sink layer, the formula of TORREY and WHITMER [22] in transformed form is used

$$t_9' = \frac{W}{2\pi} \ln\left(\frac{4L}{W}\right) \frac{\lambda}{\lambda_9} \tag{6}$$

where λ_9 – thermal conductivity of copper.

All thicknesses of the layers before and after the transformation are listed in Table 2.

Table 2. Layer thicknesses of the standard GaAs-(AlGa)As single-heterostructure laser diode before and after the transformation

Layer number	Transformation coefficient	Thickness, μm before	Thickness, μm after
		transformation	
1	0.31	0.2	0.062
2	1	83.5	83.500
3	1	1.5	1.500
4	3.67	15	55.050
5	2.14	0.1	0.214
6	0.59	0.1	0.059
7	0.15	0.1	0.015
8	0.54	10	5.400
9	0.12	66.2	7.944

4. Heat sources

The main heat source in the laser diode is located in the active layer. It is principally connected with nonradiative recombination and, to some extent, with reabsorption of radiation. Its power density may be expressed as follows [23]:

$$g_A = \frac{U}{t_3}\{j_{\mathrm{th}}(1-f\eta_{\mathrm{sp}})+(j-j_{\mathrm{th}})[1-\eta_{\mathrm{ext}}-(1-\eta_i)\eta_{\mathrm{sp}}f]\} \tag{7}$$

where U is the voltage drop at the p-n junction, j and j_{th} are the supply current density and the threshold current density, respectively, t_3 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 is equal to a fraction of the spontaneous emission from the active layer which is transferred radiatively through the passive wide-gap P-(AlGs)As layer and may be calculated as follows [24]:

$$f \approx \sin^2\left[\frac{1}{2}\arcsin\left(1-0.62\,\frac{\Delta x_{\mathrm{Al}}}{n_{\mathrm{R}}}\right)\right] \tag{8}$$

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

The above mentioned spontaneous radiation is absorbed on the surface of the Ti contact layer giving rise to the new heat source with the density

$$g_{\mathrm{tr}} = U j_{\mathrm{th}} \frac{\eta_{\mathrm{sp}} f}{2\, t_5}. \tag{9}$$

It has been assumed that a uniform distribution of g_{tr} within the Ti layer is assumed because of its negligible thickness

Besides, the Joule heating is generated within each layer with the density

$$g_{J,i} = j^2 \varrho_i, \quad i = 1, 2, 3, \ldots, 9 \tag{10}$$

where ϱ_i – electrical resistivity of i-th layer.

The application of the space transformation (Sec. 3) follows the supplementary transformation of the heat power densities with the transformation coefficient

$$f_{g,i} = \frac{g_i'}{g_i} = \frac{1}{f_{s,i}}, \tag{11}$$

which has been confirmed in paper [21]. In Eq. (11), g_i and g_i are the power densities of the heat source in i-th layer before and after the transformation, respectively.

All heat sources and their densities are listed in Table 3 and their distribution is schematically (not in a scale) shown in Fig. 2. The values of g have

Table 3. The densities of the heat source power in the standard GaAs-(AlGa)As single-heterostructure laser diode before and after the transformation

Layer number	Heat source	Density, W/m^3	
		before	after
		transformation	
1	Joule heating	$5.120 \cdot 10^8$	$1.652 \cdot 10^9$
2	Joule heating	$7.808 \cdot 10^{10}$	$7.808 \cdot 10^{10}$
3	Nonradiative recombination and reabsorption of radiation	$7.081 \cdot 10^{13}$	$7.081 \cdot 10^{13}$
4	Joule heating	$4.096 \cdot 10^{11}$	$1.116 \cdot 10^{11}$
5	Joule heating	$3.520 \cdot 10^9$	$1.645 \cdot 10^9$
	Radiative transfer	$1.449 \cdot 10^{14}$	$6.772 \cdot 10^{13}$
6	Joule heating	$7.040 \cdot 10^8$	$1.193 \cdot 10^9$
7	Joule heating	$1.920 \cdot 10^8$	$1.280 \cdot 10^9$
8	Joule heating	$6.400 \cdot 10^8$	$1.186 \cdot 10^9$
9	Joule heating	$1.280 \cdot 10^8$	$1.067 \cdot 10^9$

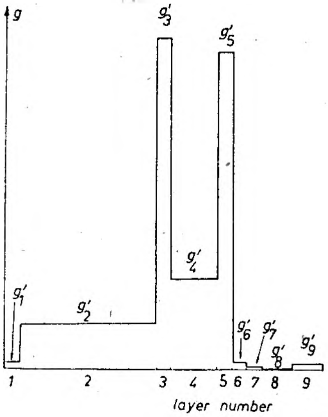

Fig. 2. The distribution of the heat power density in the SH laser diode

been calculated for the standard structure of the broad-contact SH GaAs-(AlGa)As laser diode (Fig. 1, Tab. 1). From now on, only the values after the transformation will be used and "primes" in notation of the layers thicknesses and the heat power densities will be omitted.

5. Solution

The space transformation (Sec. 3) reduces the nonlinear thermal conduction equation (3) to a form

$$\frac{d^2T(x)}{dx^2} = \frac{g(x)}{\lambda} \tag{12}$$

with the boundary conditions:

$$T(x = a_9) = T_A, \tag{13}$$

$$\left.\frac{dT}{dx}\right|_{x=0} = 0 \tag{14}$$

where $g(x)$ is equal to

$$g(x) = g_i \text{ for } a_{i=1} \leqslant x \leqslant a_i, \tag{15}$$

and a_i

$$a_0 = 0, \; a_i = \sum_{k=1}^{i} t_k, \; i = 1, 2, 3, \ldots, 9. \tag{16}$$

The values of g_i are listed in Table 3.

The solution of the above presented problem ((12)–(14)) is the following:

$$T(x) = T_A + \frac{2}{\lambda a_9} \sum_{m=1}^{\infty} \frac{\cos(K_m x)}{K_m^3} \sum_{i=1}^{9} g_i [\sin(K_m a_i) - \sin(K_m a_{i-1})] \tag{17}$$

where

$$K_m = \frac{(2m-1)\pi}{2a_9}. \tag{18}$$

It can be easily checked that the solution (17) fulfils the boundary conditions (13) and (14). Similarly, it is easy to notice that the expression (17) fulfils the equation (12). For this purpose it suffices to present the function $g(x)$ (shown in Fig. 2) in the following Fourier series form

$$g(x) = \frac{2}{a_9}\sum_{m=1}^{\infty}\frac{\cos(K_m x)}{K_m}\sum_{i=1}^{9} g_i[\sin(K_m a_i) - \sin(K_m a_{i-1})]. \tag{19}$$

6. Results

The temperature distribution, calculated for the standard structure of the broad-contact single-heterostructure GaAs-(AlGa)As laser diode (Fig. 1, Tab. 1) and the very low current density (5000 Acm^{-2}) is shown in Fig. 3. The distribution has been drawn for two cases: i) the constant thermal conductivity of GaAs: $\lambda = \lambda(T = 300\ \mathrm{K})$, and ii) the temperature-dependent thermal conductivity of GaAs: $\lambda = \lambda(T)$. For $T \geqslant 250$ K, the function $\lambda(T)$ may be approximated in the following way [25–27]:

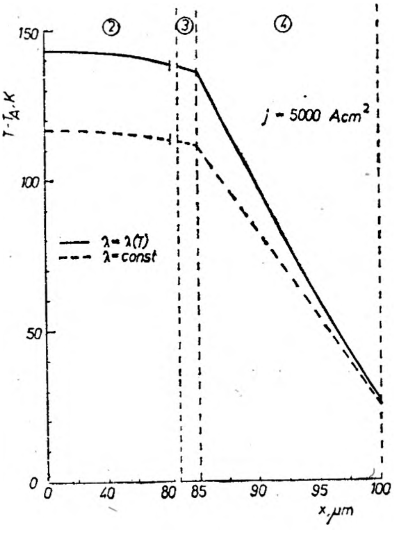

Fig. 3. The influence of the temperature dependence of the GaAs thermal conductivity on the temperature distribution in the SH laser diode supplied with a very low current density. 2, 3, 4 – numbers of layers

$$\lambda(T) = \frac{a_T}{T}, \tag{20}$$

where $a_T = 15\cdot 10^3$ W/m.

After the transformation thermal conduction equation (3) with thermal conductivity determined by (2) becomes nonlinear with respect to the temperature

$$\frac{d}{dx}\left(\frac{a_T}{T}\frac{dT}{dx}\right) = -g. \tag{21}$$

The Kirchhoff transformation shown in papers [28] and [29] enabled an easy recovery of the solution T' of the nonlinear equation (21) on the base of the analogous solution of the linear equation (12) [29]

$$T' = T_A \exp\left(\frac{T-T_A}{T_A}\right). \tag{22}$$

The above mentioned method is used in the calculations presented in this work. The results are shown in Fig. 3. It turns out that even for the very low current density (5000 Acm^{-2}), there is a considerable difference between the two curves: calculated for the constant thermal conductivity and the temperature-dependent thermal conductivity. It follows that the temperature dependence of the GaAs thermal conductivity $\lambda(T)$ cannot be neglected.

The above mentioned curves for the P-(AlGa)As layer have a different shape: the constant thermal conductivity curve is convex and that of the temperature-dependent cunductivity being concave. It is due to the temperature dependence of the thermal conductivity $\lambda(T)$ what is explained in Fig. 4.

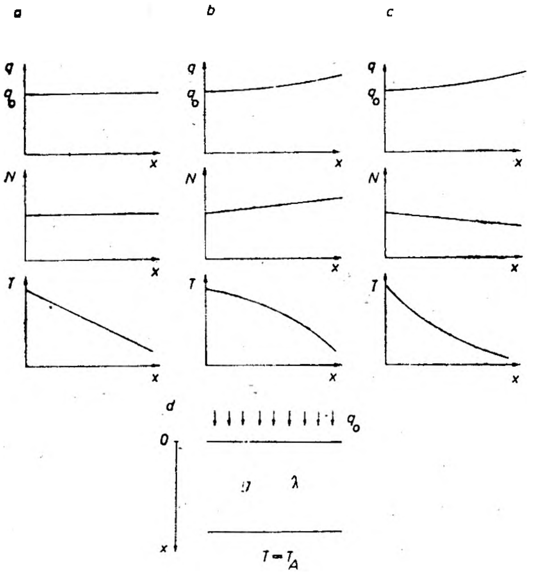

Fig. 4. Interpretation of the calculated temperature distribution in the P-(AlGa)As layer. q, N and I – density of the heat flux, slope of the temperature distribution (proportional to q/λ) and temperature, respectively; all parameters are position-dependent; g – power density of the local heat source. a – λ = const, $g = 0$, b – λ = const, $g \neq 0$, c – $\lambda = a_T/T$, $g \neq 0$, d – a simplified thermal model of the SH laser diode

From now on, only the temperature-dependent thermal conductivity curves are shown, that is why instead of "T'" the notation "T" is used.

The temperature distributions in the standard broad-contact single-heterostructure GaAs-(AlGa)As laser diodes are shown in Fig. 5 for various current densities. The above mentioned concavity of the curves for the P-(AlGa)As layer is more apparent for higher current densities. It is seen that this layer decides upon the thermal resistance of the diode because the increase of temperature taking place within it reaches at least 75 %.

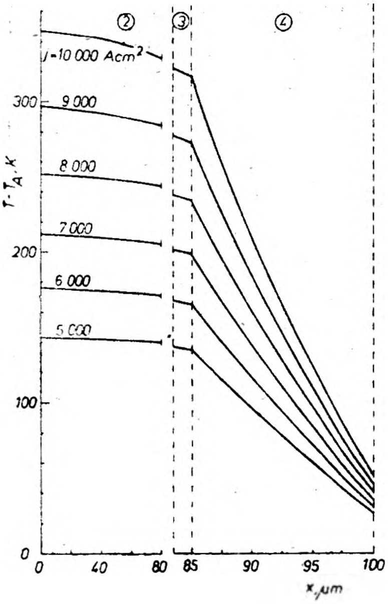

Fig. 5. The temperature distribution in the SH laser diode for various current densities

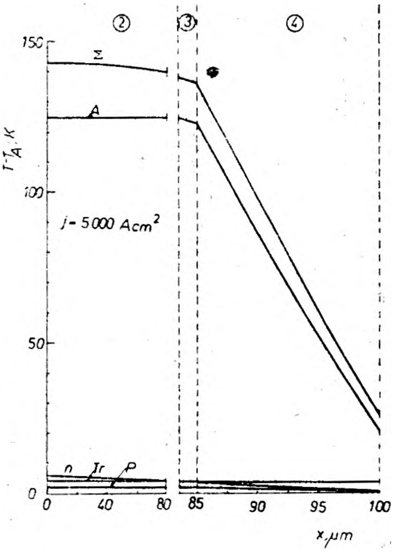

Fig. 6. Relative influence of the indvidiual heat sources on the temperature distributions in the SH laser diode supplied with very low current density. For individual curves, the following heat sources are taken into account: *Σ* – all heat sources, *A* – active layer heating, *Tr* – absorption of the transferred spontaneous radiation on the Ti layer surface, *n* and *P* – Joule heating in the substrate and P-(AlGa)As layer, respectively

The relative influence of the individual heat sources on the temperature increase is illustrated in Figs. 6 and 7 for $j = 5000$ Acm^{-2}, and $j = 10\ 000$ Acm^{-2}, respectively. The active layer heating (A) is dominant for both current densities. For higher current densities, a relative participation of the Joule heating (n and P) and that of the radiative energy transfer (Tr) becomes more and less important, respectively.

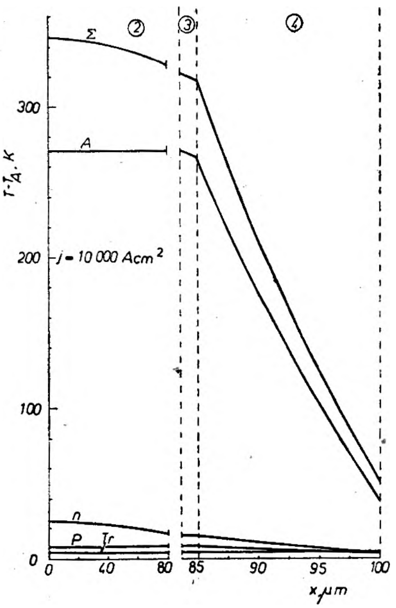

Fig. 7. Relative influence of the individual heat sources on the temperature distributions in the SH laser diode supplied with the extremely high current density

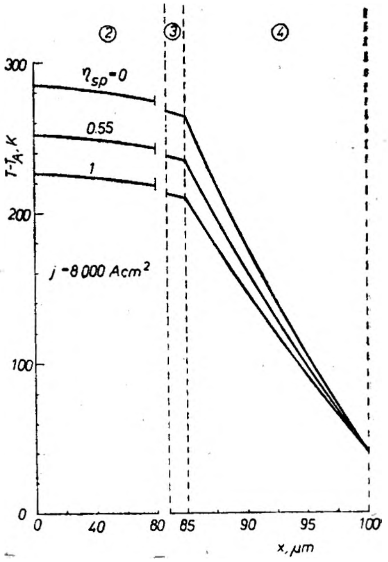

Fig. 8. Effect of the internal quantum efficiency η_{sp} of the spontaneous emission upon the temperature distribution in the SH laser diode

7. Discussion

The influence of the internal quantum efficiency η_{sp} of the spontaneous emission on the temperature distribution under consideration is illustrated in Fig. 8. It is seen that in this case the influence is relatively higher than in the double-heterostructures laser diodes [20] due to the fact that the importance of the radiative energy transfer of the spontaneous emission in the single-heterostructure (SH) laser diodes is greater than in the double-heterostructure (DH) laser diodes. In the SH laser diodes, the above mentioned transfer proceeds only towards the heat sink and hence it improves the heat extraction from the laser volume. The analogous process in the DH laser diodes takes place in both direction (towards the substrate also) and its improving influence on the heat extraction is doubtful.

The thermal resistance of the SH laser diode depends to considerable extent on the P-(AlGa)As layer thickness (Fig. 9). The temperature increase in the above mentioned layer is approximately directly proportional to its thickness. We believe that the thermal optimization of the SH laser diode should be started by the determination of the minimal P-(AlGa)As layer thickness defined by electrical and optical processes.

The influence of the active layer thickness on the temperature distribution in the SH laser diodes is illustrated in Fig. 10. The relationship between the active layer thickness and the threshold current density of the laser is taken into consideration.

The effect of the P-(AlGa)As resistivity, ϱ_4, and the substrate resistivity, ϱ_2, on the temperature distribution is shown in Figs. 11 and 12, respectively.

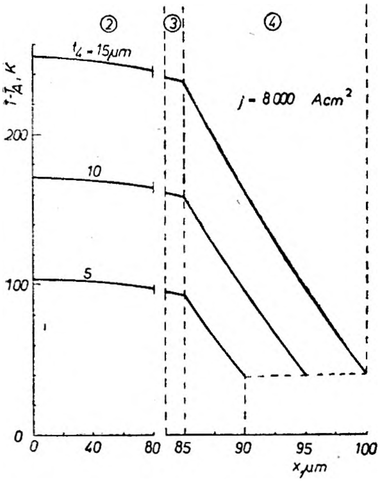

Fig. 9. Effect of the thickness t_4 of the P-(AlGa)As layer upon the temperature distribution in the SH laser diode

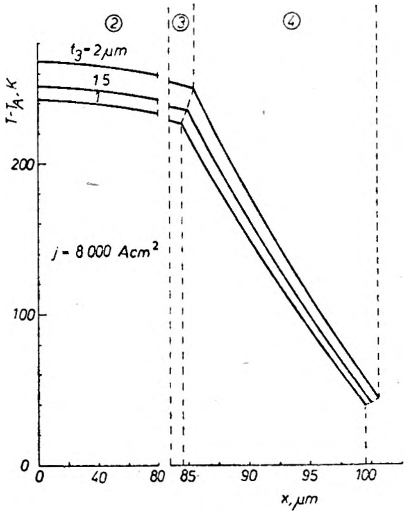

Fig. 10. Effect of the thickness t_3 of the active layer upon the temperature distribution in the SH laser diode. The dependence of threshold current density on the thickness t_3 is taken into consideration: a $- t_3 = 1\ \mu m$, $j_{th} = 4000$ Acm^{-2}, b $- t_3 = 1.5\ \mu m$, $j_{th} = 5000$ Acm^{-2}, c $- t_3 = 2\ \mu m$, $j_{th} = 7000$ Acm^{-2}

This effect is relatively small for a reasonable increase in the resistance. But in the case of the extreme increase in ϱ_4 or ϱ_2, an immense increase in the active layer temperature is observed. The influence of the resistivities of the contact layers and heat sink is negligible.

The above presented calculations have been performed for the broad-contact single heterostructure GaAs-(AlGa)As laser diodes produced at present. The temperature increases have been obviously higher than the admissible temperature for the laser diodes. However, it may be expected that the conclusions from the above discussion should preserve their validity also for the more perfect low threshold SH laser diodes produced of new quarternary materials by using more modern technologies.

The remarks referring to the optimization of the SH laser diodes in the steady-state condition remain also useful in the case of diode in the transient-state condition. It is of a particular importance, since the SH laser diodes are now widely used as cheap and efficient pulse power sources of the electromagnetic radiation.

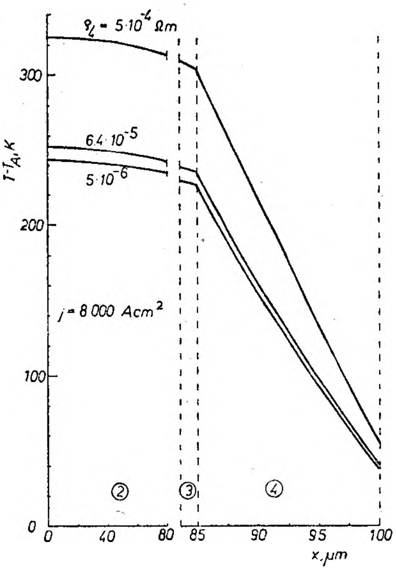

Fig. 11. Effect of the P-(AlGa)As material resistivity ϱ_1 upon the temperature distribution in the SH laser diode

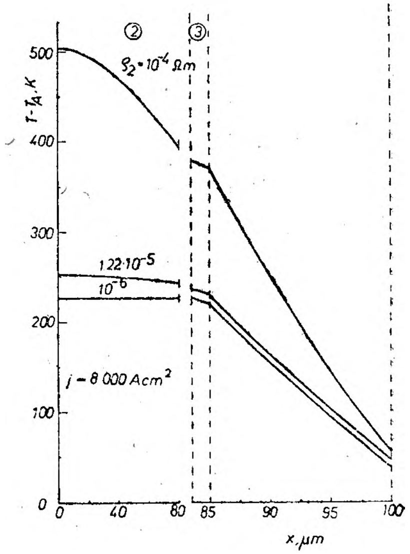

Fig. 12. Effect of the substrate resistivity ϱ_2 upon the temperature distribution in the SH laser diode

8. Conclusions

Thermal properties of the broad-contact single-heterostructure GaAs-(AlGa)As laser diode has been analysed in the paper. The nonradiative recombination, reabsorption of radiation, the Joule heating as well as the radiative transfer of the spontaneous radiation through the wide-gap passive P-(AlGa)As layer have been taken into account. The relative participation of the individual heat sources has been shown. The temperature dependence of the GaAs thermal conductivity has been taken into consideration. The influence of the internal quantum efficiency η_{sp} as well as that of the thicknesses and resistivities of the individual layers on the temperature distributions have been discussed.

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Термические свойства ширококонтактных моногетеросоединенных лазеров

В статье решено уравнение термической проводности для ширококонтактных, моногетеросоединенных лазеров GaAs-(AlGa)As. С этой целью применена трансформация пространства, редуцирующая нелинейные уравнения термической проводности к линейной форме. Учтена нелучистая рекомбинация, реабсорбция излучения, джоулево тепло, а также лучистый трансферт энергии самопроизвольного излучения широкополосной пассивной прослойки P-(AlGa)As. Обсуждена относительная доля всех вышеуказанных тепловых источников. Учтена зависимость термической проводности GaAs от температуры. Рассмотрено влияние внутреннего коэффициента полезного действия квантовой самопроизвольной эмиссии, а также толщины и внутреннего удельного сопротивления отдельных прослоек на значение термического сопротивления соединенного лазера. Объяснена возможная термическая оптимизация конструкции моногетеросоединенного лагера.

Перевела Малгожата Хейдрих