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THERMAL OPTIMIZATION OF A CONSTRUCTION OF A DOUBLE-HETEROSTRUCTURE GaAs/(AlGa)As DIODE LASER

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Analytical as well as computer aided thermal optimization of a construction of a stripe-geometry double-heterostructure GaAs/(AlGa)As diode laser were performed in the present work. The influence of various construction parameters of the laser on its thermal resistance is shown.

As a rule of thumb, the mean-time-to-failure (MTTF) of an electronic device (e. g. a diode laser) is reduced by a factor of two as the operating temperature, i. e. the temperature of its active area, increases by 10 K [1, 2]. Heading toward this direction, it is obvious that the heat must be dissipated effectively in a device to achieve a high performance.

The aim of this work is to perform a thermal optimization of a construction of a stripe-geometry double-heterostructure GaAs/(AlGa)As diode laser without oxide barriers from a point of view of a minimal increase in its active area temperature. The calculations have been carried out for room temperature (T_O = 300 K).

Assumption

The schematic representation of a diode laser under consideration is shown in Fig. 1. Its typical construction parameters (let us say: nominal set of the parameters) are presented in Table 1, whereas values of thermal conductivities of the materials used are listed in Table 2.

Construction parameters, whose values are optimized to achieve a minimal temperature increase in an active area, are presented in Table 3 with

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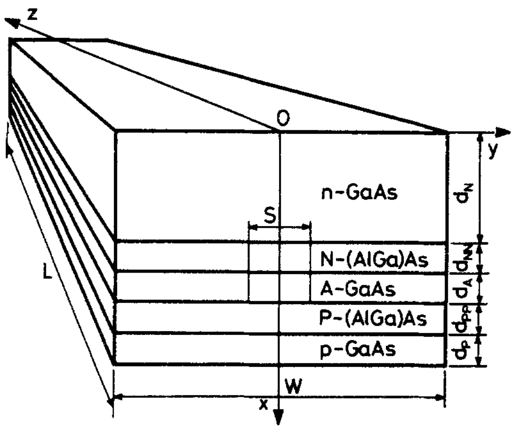

Fig. 1 Schematic representation of a stripe-geometry double heterostructure GaAs/(AlGa)As diode laser without oxide barriers. Not to scale. Notation system is explained in Table 1.

Table 1 Typical construction of the stripe-geometry double heterostructure GaAs/(AlGa)As diode lasers without oxide barriers: nominal set of data for numerical calculations

Parameter	Notation	Value	Unit
Laser chip dimensions:			
length	L	500	μm
width	W	300	μm
Stripe width	S	10	μm
Thickness of the layers:			
semiconductor layers			
n – GaAs substrate	dN	93.8	μm
N – (AlGa)As confinement	dNN	2	μm
A – p(n) active	dA	0.2	μm
P – (AlGa)As confinement	dPP	2	μm
p – GaAs) capping	dP	2	μm
contact layers			
Ti	dTI	0.1	μm
Pt	dPT	0.3	μm
Au	dAU	0.3	μm
in solder layer	dIN	10	μm
AlAs mole fraction in $Al_xGa_{1-x}As$ confinement layers	X	0.25	-

ranges of their variation. Lower bounds of thicknesses of the P and N confinement layers are established to confine losses connected with leaking of radiation field beyond these layers [3]. An analogous bound of a thickness of the p capping layer is related to technological problems in preparing a p-side contact of a device [4]. A minimal considered value of the AlAs mole fraction of the confinement layers is determined in order to keep to a minimum the penetration of a radiation field into these layers [5].

Table 2 Thermal conductivities of materials

Material	Thermal conductivity, W/mK	Reference
GaAs	45	[12]
$Al_{0.25}Ga_{0.75}As$	13.15	[12]
$Al_xGa_{1-x}As$	$100/[2.27+28.83X-30.0\,X^2]$	[12–14]
Ti	22	[15]
Pt	73	[15]
Au	318	[15]
In	87	[15]
Cu	400	[15]

Table 3 Acceptable range of the contruction parameters considered in the model

Parameter	Range	Unit
S	3–25	μm
X	0.15–0.40	-
d_P	1–4	μm
d_{PP}	1–4	μm
d_{NN}	1–4	μm

Calculation

Let us introduce the position-dependent thermal resistance $R_T(y)$:

$$R_T(y) = \Delta T_A(y)\,/\,Q \tag{1}$$

In Eq. (1), $\Delta T_A(y)$ is an increase in the active-area temperature and Q is the power of heat generation in diode lasers under consideration which may be expressed in the following form [6]:

$$Q = SLU \left\{ j_{TH} + (j - j_{TH}) \left[1 - a_E - (1 - a_i) a_{SP} f_T \right] \right\} \tag{2}$$

where S and L are the stripe width and the resonator length, respectively, j and j_{TH} are the supply current density and the threshold current density, respectively, U is the voltage drop at the p-n junction, a_{SP}, a_E and a_i are the internal quantum efficiencies of the spontaneous emission, the external differential quantum efficiency of the lasing and the internal quantum efficiency of the lasing, respectively.

The coefficient f_T describes a fraction of the spontaneous radiation which is transferred by radiation from the active area through the wide-gap confinement layers and may be for the DH structure expressed as follows [7]

$$f_T = 2\sin^2 \left\{ (1/2) \arcsin \left[1 - 0.62 . (X / n_R) \right] \right\} \tag{3}$$

where $n_R = 3.59$ is the refractive index of the active area material.

The spontaneous radiation transferred radiatively from the active area is absorbed in the capping p-GaAs layer and in the lower part of the substrate. Therefore the distribution of the heat generation in diode lasers is a function of the AlAs mole fraction X in the confinement layers to a considerable extent. Strictly speaking, an increase in the X parameter causes a corresponding decrease in the importance of the radiative transfer in the whole energy transport phenomenon in the laser. On the other hand, the above increase in X causes a decrease in the thermal conductivity of the confinement layers (c. f. Table 2). Both these effects have been taken into account in the present model.

In Reference 8, the position-dependent thermal resistance of a diode laser under consideration is shown to be of the following form:

$$R_T(y) = \begin{cases} A \cos^2 [B . |y|^c] & \text{for} \quad |y| \le S/2 \\ D \arctan[|y| / L] & \text{for} \quad |y| > S/2 \end{cases} \tag{4}$$

where A, B, C, D and L are the coefficients dependent on the construction parameters.

In order to determine the condition for the minimal increase in the active area temperature it is necessary to consider only the parameter A:

$$A = f_A(S, d_P, d_{PP}, d_{NN}, X) \tag{5}$$

because

$$R_T\,(y = 0) = f_A \tag{6}$$

The f_A function appears to be in the following form:

$$f_A = A_0 \frac{P^A(S)P^A(d_P)P^A(d_{PP})P^A(d_{NN})P^A(X)}{P^A(S_N)P^A(d_{P,N})P^A(d_{PP,N})P^A(d_{NN,N})P^A(X_N)} \tag{7}$$

where $A_0 = 23.64$ K/W, S_N, $d_{P,N}$, $d_{PP,N}$, $d_{NN,N}$ and X_N compose the nominal set of the parameters (Table 1), and P^A are the appropriate Newton's interpolation polynomials:

$$\begin{aligned} P^A(\rho) = W_0 + W_1(\rho-\rho_0) + W_2(\rho-\rho_0)(\rho-\rho_1) + \\ + \ldots + W_N(\rho-\rho_0)\ldots(\rho-\rho_{N-1}) \end{aligned} \tag{8}$$

whose parameters W_i and nodal points ρ_i are listed in Table 4.

Results

Searching for the conditions for a minimal increase in the active area temperature corresponds to searching for the condition for a minimal value of the f_A function (c. f. eq. (6)). The f_A function is expressed in a form of a product of five polynomials (see eq. (7)). Its minimal value occurs for the set of the considered parameters for which all the polynomials have their minimal values. This set is listed in the first row of Table 5.

The thermal resistance of the optimal construction of a diode laser is equal to:

$$R_{T,OPT}(y = 0) = 8.25\ \mathrm{K/W} \tag{9}$$

For comparison, thermal resistances of other laser constructions are listed in Table 6. Their values may be as high as 20 K/W, or even higher.

The relative influence of the values of the construction parameters considered in the model on a value of the thermal resistance $R_T(y = 0)$ is illustrated in Figs 2 and 3 with respect to the nominal set of the parameters and to the optimal set of the parameters, respectively. As one can see, the influences of the stripe width and of the P confinement layer thickness are more pronounced than that of the other parameters.

Table 4 Parameters of the polynomial used in the calculations

Parameter	i	W_i	p_i
S	0	13.1	25
	1	- 0.42	20
	2	–0.027	15
	3	2.10^{-4}	10
	4	5.10^{-4}	8
	5	5.10^{-5}	
X	0	20.3	0.15
	1	35.2	0.20
	2	–36	0.25
	3	–466	0.30
	4	–4733	0.35
	5	3.10^{4}	
d_P	0	22.59	1
	1	1.23	1.5
	2	–0.1	3
	3	0.014	
d_{NN}	0	22.11	1
	1	1.71.	1.5
	2	–0.31	3
	3	0.049	
d_{PP}	0	19.17	1
	1	4.91	1.5
	2	–0.7	3
	3	0.12	

To verify the above analytical calculations, a computer aided optimization [9] has been carried out with an IBM PC/AT computer. The results, listed in the second row of Table 5, are in a very good agreement with the set obtained analytically.

Additionally, computer aided optimization has been used to determine the optimum set of the construction parameters from the point of view of a minimal averaged increase in the active area temperature. The results, presented in the third row of Table 5, differ from those in the previous two rows only in one position: the optimal value of the stripe width is equal to 23.6 μm whereas the previous values are a little greater.

Table 5 Optimal sets of the constuction parameters

Method	Aim	S,μm	X	d_P,μm	d_{PP},μm	d_{NN},μm
Analytical optimization	Minimal increase in the active area temperature	25	0.15	1	1	1
Computer aided optimization	Minimal increase in the active area temperature	24.7	0.15	1	1	1
Computer aided optimization	Minimal increase in the active area temperature	23.6	0.15	1	1	1

Table 6 Thermal resistances of lasers of various constructions

S,μm	X	d_P, μm	d_{PP}, μm	d_{NN}, μm	R_T (y = 0), K/W
10	0.15	1	1	1	14.75
10	0.25	2	2	2	23.64
25	0.25	2	2	2	13.10
10	0.15	2	2	2	20.30
10	0.25	1	2	2	22.60
10	0.25	2	1	2	19.10
10	0.25	2	2	1	22.11

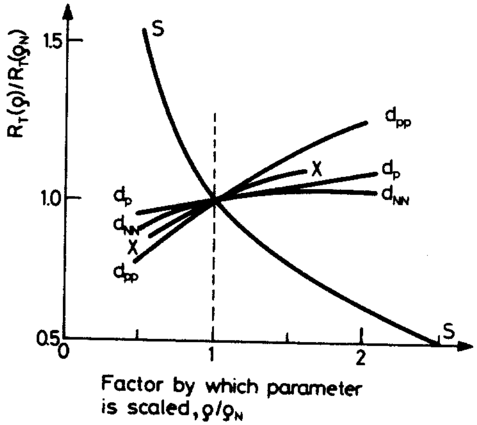

Fig. 2 Relative influence of the values of the construction parameters considered in the model on a value of the thermal resistance R_T (y = 0) with respect to the nominal set of the parameters (Table 1). For each curve only the indicated parameter is changed, the rest being constant and equal to their nominal values

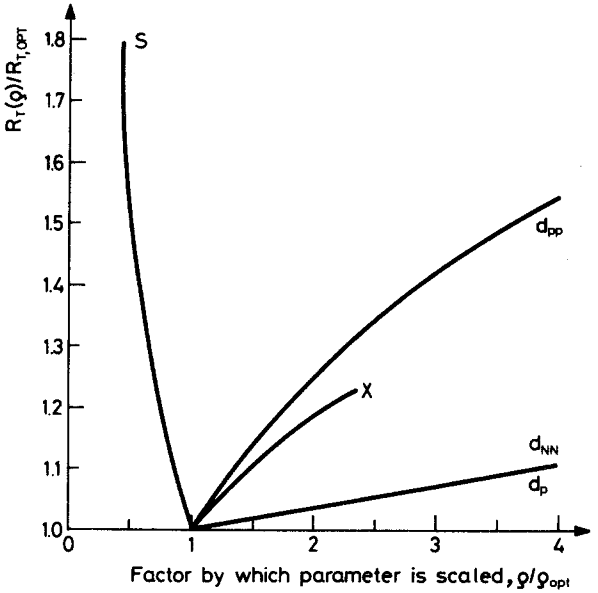

Fig. 3 Relative influence of the values of the construction parameters considered in the model on a value of the thermal resistance R_T (y = 0) with respect to the optimal set of the parameters (Table 5). For each curve only the indicated parameter is changed, the rest being constant and equal to their optimal values

Conclusion

The results of a thermal optimization of a construction of a stripe-geometry double-heterostructure GaAs/(AlGa)As diode laser without oxide barriers are in agreement with our anticipation. The presented model enables us to evaluate the relative influence of various construction parameters on the value of a laser thermal resistance. Now we can predict to what extent a value of a considered construction parameter may be changed without a noticeable deterioration of the laser thermal properties.

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Zusammenfassung — Die Konstruktion eines doppelt-heterostrukturellen GaAs/(AlGa)As Diodenlasers mit Streifengeometrie wurde sowohl analytisch als auch computergestützt thermisch optimiert. Es wurde der relative Einfluß verschiedener Konstruktionsparameter auf die Hitzebeständigkeit des Lasers gezeigt.