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Simple formula for the thermal resistance of a stripe-geometry double-heterostructure GsAs/(AlGa)As diode laser without oxide barriers*

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In the present paper, a simple formula for the thermal resistance of a stripe-geometry double-heterostructure GaAs/(AlGa)As diode laser without oxide barriers is derived. The temperature distribution within an active area of a diode laser is shown to be a simple analytical function of both laser construction parameters and supply power.

1. Introduction

The operation of a diode laser is disturbed by an increase in temperature within its volume, which leads to a deterioration of diode laser performance, resulting in an increase in the threshold current, a decrease in the radiation intensity, reduction of the laser lifetime and the spectral shift of both the stimulated radiation modes and the whole spontaneous radiation band.

The detailed analysis of thermal phenomena in stripe-geometry GaAs/(AlGa)As diode lasers without oxide barriers, e.g., proton-bombarded or diffused-stripe lasers, has been performed by JOYCE and DIXON [1]. Subsequent papers on this subject have added some improvements to this approach: NEWMAN et al. [2] have taken into account the radiative transfer of energy of spontaneous radiation; DUDA et al. [3] have investigated the relative influence of various heat sources including Joule heating; BUUS [4] has taken into consideration a more correct distribution of heat sources as a result of the current spreading effect; ITO and KIMURA [5] have considered influence of heat radiation from the top surface of a diode laser on the ambient atmosphere and conduction through a bonding wire; MATTOS et al. [6] have taken into account the temperature dependence of the heat generation rate using a self-consistent method. For the (InGa)/(AsP) stripe diode lasers, the model of JOYCE and DIXON has been adapted by STEVENTON et al. [7] and YANO et al. [8] KOBAYASHI and IWANE [9] have carried out the numerical analysis of the three-dimensional thermal problem of the stripe diode lasers.

All the above approaches are very computer-time consuming. Therefore, a simple approximate method would be useful for a rapid evaluation of a thermal behaviour

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of a specified diode laser. Hitherto known approximate approaches [10], [11] seem not to be accurate enough.

The aim of this paper is to formulate such an approximate method of accuracy sufficient to determine the thermal resistance of diode lasers without oxide barriers, i.e., all stripe-geometry diode lasers in which a current confinement mechanism is not realized with the aid of oxide barriers, e.g., proton-bombarded stripe lasers, diffused-stripe lasers, etc.

2. Assumptions

Let us consider a standard structure of the stripe-geometry double-heterostructure (DH) GaAs/AlGa)As diode laser without oxide barriers shown in Fig. 1. Its typical construction parameters (let us say: the nominal set of data) are presented in Tab. 1, whereas values of thermal conductivities of materials used are listed in Tab. 2.

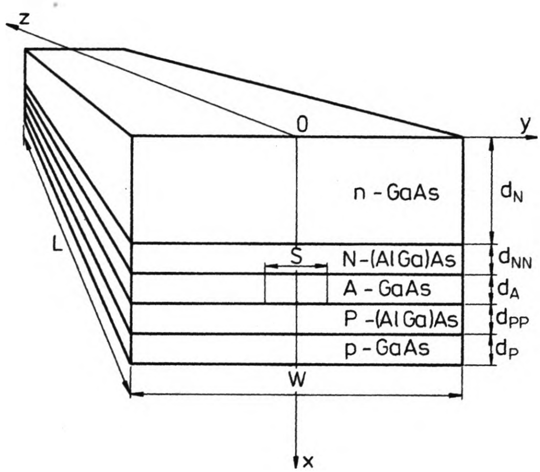

Fig. 1. Schematic representation of the stripe-geometry double-heterostructure GaAs/(AlGa)As diode laser without oxide barriers. Not to scale. Notation system is explained in Tab. 1

The main heat source in a diode laser is located in an active area. This heat generation and a phenomenon of nonradiative recombination are related. The density q_A of a heat flux generated there reads as follows [16]:

$$q_A = U\{j_{TH}(1-f_T a_{SP}) + (j-j_{TH})[1-a_E-(1-a_i)a_{SP}f_T]\} \quad (1)$$

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, a_{SP}, a_E and a_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_T describes a fraction of the spontaneous radiation which is transferred radiatively from the active region through the wide-gap confinement (AlGa)As layers and for the DH structure may be expressed as follows [17]:

$$f_T = 2\sin^2[(1/2)\arcsin(1-0.62(X/n_R))] \quad (2)$$

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
Laser chip dimensions:		
– length	L	500 μm
– width	W	300 μm
Stripe width	S	10 μm
Thicknesses of the layers		
– semiconductor layers:		
n – GaAs substrate	d_N	93.8 μm
N – (AlGa)As confinement	d_{NN}	2 μm
A – $p(n)$ active	d_A	0.2 μm
P – (AlGa)As confinement	d_{PP}	2 μm
p – GaAs capping	d_P	2 μm
– contact layers		
Ti	d_{TI}	0.1 μm
Pt	d_{PT}	0.3 μm
Au	d_{AU}	0.3 μm
– indium solder layer	d_{IN}	10 μm
AlAs mole fraction in $Al_xGa_{1-x}As$ confinement layers	X	0.25

Table 2. Thermal conductivities of the materials

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

where $n_R = 3.59$ is the refractive index of the active region material and X is the AlAs mole fraction in $Al_xGa_{1-x}As$ confinement layers. The spontaneous radiation transferred through the confinement layers is absorbed in the capping GaAs layer and in the lower part of the substrate.

The total power Q of heat generation in diode lasers, i.e., in the active layer, the capping layer and the lower part of the substrate may be expressed then in the following form:

$$Q = SLU\{j_{TH} + (j - j_{TH})[1 - a_E - (1 - a_i)a_{SP} f_T]\} \tag{3}$$

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

Usually thermal response of a diode laser is described in terms of the position-dependent thermal resistance

$$R_T(y) = \Delta T_A(y)/Q \tag{4}$$

where ΔT_A is an increase in the active-layer temperature. Our task in this work is to determine the above thermal resistance as a function of the construction parameters of the laser, i.e.

$$R_T(y) = f(S, d_P, d_{PP}, d_N, X, y) \tag{5}$$

where, on the basis of preliminary results, the insignificant dependence of R_T on the width W of the laser crystal has been neglected. All calculations are carried out for a room temperature ($T_0 = 300$ K) of the ambient.

3. Solution

Acceptable ranges of the construction parameters considered in the model are listed in Tab. 2. For those ranges, the R_T versus y dependence is assumed to be of the following form:

$$R_T = \begin{cases} \mathrm{A}\cos^2[\mathrm{B}|y|^{\mathrm{C}}] & \text{for } |y| \leqslant S/2, \\ \mathrm{D}\arctan[|y|/\mathrm{L}] & \text{for } |y| > S/2, \end{cases} \tag{6}$$

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

Exact values of the adjustable parameters have been determined for various sets of the construction parameters (changing within the ranges in Tab. 3) and are listed in Tab. 4. As an example, an exact profile of the thermal resistance $R_T(y)$ and the other approximated with the aid of Eq. (6) are plotted in Fig. 2 for the diode laser of the stripe width $S = 8$ μm. The exact curve has been calculated with the aid of the semi-analytical model presented in papers [1]–[3]. As one can see, both the profiles are practically identical (the relative difference between them is less than 4%), which confirms validity of the model used. In the next Section, the approximate functional dependence of the adjustable parameters (see Eq. (6)) on the construction parameters will be determined with the aid of the interpolation method, using their exact values mentioned above.

Table 3. Ranges of variations of the construction 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

Table 4. Values of the adjustable parameters determined for various sets of the construction parameters. For all the sets, only the parameter given in the first column of the table is changed, the remaining parameters being constant and equal to those of the nominal set (Tab. 1)

Parameter	A [K/W]	B [μm^{-C}]	C
S [μm] = 25	13.10	0.80	1.51
20	15.22	0.96	1.58
15	18.71	1.25	1.67
8	27.67	5.75	1.30
6	33.46	12.28	0.96
5	36.33	14.59	0.94
4	39.03	16.67	0.96
3	40.81	18.24	0.96
X = 0.40	26.23	1.47	1.98
0.35	25.57	1.49	1.97
0.30	24.69	1.51	1.96
0.25	23.64	1.53	1.95
0.20	22.06	1.55	1.94
0.15	20.57	1.57	1.93
d_P [μm] = 4	25.61	1.72	1.85
3	24.74	1.97	1.78
1.5	23.20	2.08	1.76
1	22.59	2.22	1.72
d_{PP} [μm] = 4	29.56	2.36	1.64
3	26.89	2.31	1.67
1.5	21.62	1.39	2.01
1	19.17	1.08	2.18
d_{NN} [μm] = 4	24.91	2.37	1.68
3	24.34	1.93	1.82
1.5	22.89	0.94	2.24
1	22.11	1.15	2.10

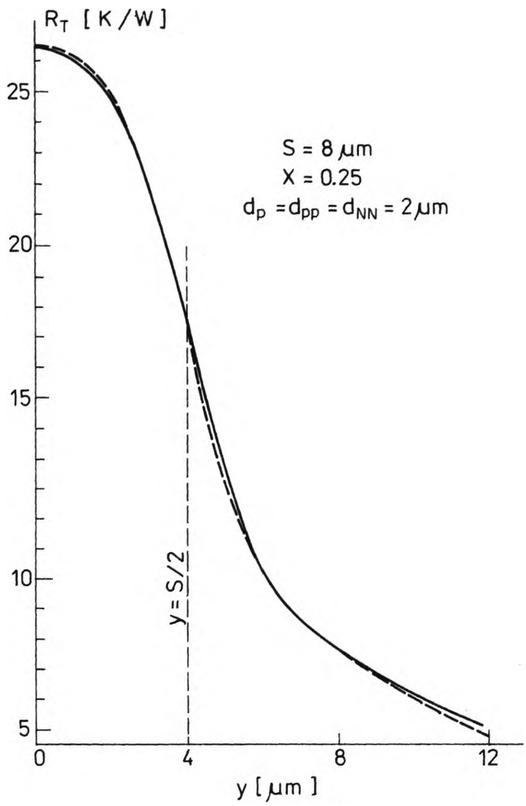

Fig. 2. Example of a thermal resistance profile $R_T(y)$ for the specified diode laser: $S = 8$ μm, $X = 0.25$, $d_P = d_{PP} = d_{NN} = 2$ μm. Solid line corresponds to the exact profile, whereas dashed line represents out approximate solution

4. Interpolation

Let us consider profiles of a thermal resistance within the active area, i.e., for $|y| \leqslant S/2$. Then functions describing the adjustable parameters may be expressed as:

$$\mathrm{A} = f_{\mathrm{A}}(S, d_{\mathrm{P}}, d_{\mathrm{PP}}, d_{\mathrm{NN}}, X), \tag{7a}$$

$$\mathrm{B} = f_{\mathrm{B}}(S, d_{\mathrm{P}}, d_{\mathrm{PP}}, d_{\mathrm{NN}}, X), \tag{7b}$$

$$\mathrm{C} = f_{\mathrm{C}}(S, d_{\mathrm{P}}, d_{\mathrm{PP}}, d_{\mathrm{NN}}, X). \tag{7c}$$

In the calculations, we use the Newton's interpolation polynomials $P(\varrho)$ of the following form:

$$P(\varrho) = W_0 + W_1(\varrho-\varrho_0) + W_2(\varrho-\varrho_0)(\varrho-\varrho_1) + \ldots + W_n(\varrho-\varrho_0)\ldots(\varrho-\varrho_{n-1}) \tag{8}$$

where $\varrho_0, \varrho_1, \varrho_{n-1}$ are nodal points.

The f_{A} function appears to be in the following form:

$$f_{\mathrm{A}} = A_0 \frac{P^{\mathrm{A}}(S) P^{\mathrm{A}}(d_{\mathrm{P}}) P^{\mathrm{A}}(d_{\mathrm{PP}}) P^{\mathrm{A}}(d_{\mathrm{NN}}) P^{\mathrm{A}}(X)}{P^{\mathrm{A}}(S_{\mathrm{N}}) P^{\mathrm{A}}(d_{\mathrm{P,N}}) P^{\mathrm{A}}(d_{\mathrm{PP,N}}) P^{\mathrm{A}}(d_{\mathrm{NN,N}}) P^{\mathrm{A}}(X_{\mathrm{N}})} \tag{9}$$

where $A_0 = 23.64$ K/W, S_N, $d_{PP,N}$, $d_{NN,N}$, and X_N compose the nominal set of the parameters (Tab. 1), and P^A are the appropriate polynomials of parameters listed in Tab. 5. The averaged error of estimation of the thermal resistance R_T $(y = 0)$ in the centre of the active area is equal to 4%, whereas the maximal error is less than 10%.

The f_B function is assumed to be in the following form:

$$f_B = B_0 M_B P^B(S) P^B(d_P) P^B(d_{PP}) P^B(d_{NN}) P^B(X) \tag{10}$$

Table 5. Parameters of the polynomials used for determination of the A, B, and C parameters

Parameter		P^{A}		P^{S}		P^{C}	
	i	W_i	ϱ_i	W_i	ϱ_i	W_i	ϱ_i
				10 µm < S < 25 µm		10 µm < S < 25 µm	
S	0	13.1	25	0.8	25	1.77	10
	1	−0.42	20	−0.032	20	−0.02	15
	2	−0.027	15	2.6×10^{-3}	15	2×10^{-4}	20
	3	-2×10^{-4}	10	-5×10^{-4}		1.3×10^{-4}	
	4	5×10^{-4}	8				
	5	5×10^{-5}		3 µm < S < 10 µm		3 µm < S < 10 µm	
	0			18.24	3	0.96	3
	1			−1.57	4	−0.013	5
	2			−0.21	6	0.013	6
	3			−0.01	8	0.008	8
	4			0.016		−0.002	
X	0	20.3	0.15	1.51	0.3	1.84	1.96
	1	35.2	0.20	−0.4		0.2	
	2	−36	0.25				
	3	−466	0.30				
	4	4733	0.35				
	5	3×10^4					
d_P	0	22.59	1	2.22	1	1.72	1
	1	1.23	1.5	−0.28	1.5	0.08	1.5
	2	−0.1	3	0.1	3	0.03	3
	3	0.014		−0.06		0.02	
d_{NN}	0	22.11	1	1.15	1	2.1	1
	1	1.71	1.5	−0.42	1.5	0.28	1.5
	2	−0.31	3	0.54	3	−0.28	3
	3	0.049		−0.21		0.112	
d_{PP}	0	19.17	1	1.08	1	2.18	1
	1	4.91	1.5	0.62	1.5	−0,34	1.5
	2	−0.7	3	−0.003	3	0.056	3
	3	0.12		0.074		0.007	

where

$$M_B = \{P^B(X)[P^S(S_N)+B_1\Omega(S)][P^B(d_{P,N})+B_2\Omega(d_P)][P^B(d_{PP,N}) + B_3\Omega(d_{PP})][P^B(X_N)+B_4\Omega(d_{NN,N})]\}^{-1}, \quad (11)$$

$$\Omega(\varrho) = \operatorname{sgn}|\varrho-\varrho_N| = \begin{cases} 0 & \text{for } \varrho = \varrho_N, \\ 1 & \text{for } \varrho \neq \varrho_N. \end{cases} \quad (12)$$

P^B are the polynomials whose parameters are listed in Tab. 5, and B_i are the normalization constants listed in Tab. 6.

Table 6. Normalization constants in Eqs. (11) and (14)

i	0	1	2	3	4
B_i	1.53 μm	−0.49	−0.49	−0.13	0.43
C_i	1.95	0.18	0.18	0.09	−0.23

In the analogous way, the f_C function is assumed to have a following shape:

$$f_C = C_0 M_C P^C(S) P^C(d_P) P^C(d_{PP}) P^C(d_{NN}) P^C(X). \quad (13)$$

where

$$M_C = P^C(X)[P^C(S_N)+C_1\Omega(S)][P^C(d_{P,N})+C_2\Omega(d_P)][P^C(d_{PP,N}) + C_3\Omega(d_{PP})][P^C(X_N)+C_4\Omega(d_{NN,N})]\}^{-1}, \quad (14)$$

P^C are the polynomials of parameters listed in Tab. 5, while the C_i normalization constants are listed in Tab. 6.

5. Conclusions

A simple formula for the thermal resistance of a stripe-geometry double-heterostructure GaAs/(AlGa)As diode laser without oxide barriers was proposed in the present paper. The used model enables us to determine a temperature distribution within the active area of a stripe-geometry diode laser as a simple analytical function of its construction parameters and supply power. The same model will be used in our next paper [18] to perform a thermal optimization of a construction of diode lasers under consideration.

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Простая формула для тепельного сопротивления полосатого лазера бигетероразделительного GaAs/(AlGa)As, в котором ограничение распределеиия тока реализуется без учета оксидных слоев

В представленной работе выведена простая формула для тепельного сопротивления полосатого лазера бигетероразделительного GaAs/(AlGa)As, в котором ограничение распределения тока реализуется без учета оксидных слоев. Эта формула дает возможность представления распределения температуры в активной области лазера в виде простой аналитической функции конструкционных параметров и мощности источника питания.