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Simulation of anticipated operation characteristics of designed constructions of broad-contact double-heterostructure (AlGa)As diode lasers. II. Free-carrier absorption*

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This work is the second part of the model of braod-contact double-heterostructure (AlGa)As diode lasers. Thes formulae given in this part enable us to connect the coefficient of free carrier absorption in the $Al_xGa_{1-x}As$ material with its composition and temperature.

1. Introduction

In the previous part of this work, the procedure of a calculation of the threshold current of broad-contact double-heterostructure (AlGa)As diode lasers has been proposed.This part deals with the most important, unavoidable kind of losses of radiation within the diode laser, namely, the free-carrier absorption. The third part will be devoted to quantum efficiencies and thermal properties of the lasers.

2. Free-carrier absorption near the energy gap for GaAs at room temperature

The measurement data of Spitzer and Whelan [1] show that the free-carrier absorption in GaAs varies linearly with carrier concentration. Various published data [1]–[4] enable Casey and Panish [5] to express this absorption near the energy gap of GaAs at room temperature in the following form:

$$\alpha^*_{FC}[\mathrm{cm}^{-1}] = 3\times 10^{-18} n + 7\times 10^{-18} p \tag{1}$$

where n and p are the electron hole concentrations, respectively (in cm^{-3}).

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3. Free-carrier absorption in $Al_xGa_{1-x}As$

Following the approach proposed by JORDAN [6], the free carrier absorption coefficient in the $Al_xGa_{1-x}As$ material may be expressed in the following form

$$\alpha_{FC} = \alpha_{FC,E} + \alpha_{FC,H} \tag{2}$$

where the electron component reads as follows

$$\alpha_{FC,E} = \alpha^*_{FC,E}\left[\frac{1}{1+f_{0A,E}}\frac{\alpha_{A,E}(x,T)}{\alpha^*_{A,H}} + \frac{1}{1+f^{-1}_{0A,E}}\frac{\alpha_{0,E}(x,T)}{\alpha^*_{0,E}}\right], \tag{3}$$

and the formula for the hole component has an analogous form. In the above equations, $\alpha^*_{A.E(H)}$ and $\alpha^*_{0.E(H)}$ correspond to free-carrier absorption in GaAs at room temperature due to accoustic and optical phonons, respectively, f_{0A} is the absorption coefficient ratio

$$f_{0A,E(H)} = \alpha^*_{0,E(H)}/\alpha^*_{A,E(H)} \tag{4}$$

and, according to Eq. (1), $\alpha^*_{FC,E} = 3\times10^{-18}n$, $\alpha^*_{FC,H} = 7\times10^{-18}p$.

For the symmetrical double-heterostructure, the free-carrier absorption in the confinement layers (c.f., Eq. (13), in the first part of the work) may now be given by

$$\alpha_{OUT} = (\alpha_N + \alpha_P)/2 \tag{5}$$

where α_N and α_P are the free-carrier absorption coefficients in the N-type and the P-type layers.

4. Free-carrier absorption due to optical phonos

The free-carrier absorption due to longitudinal optical phonons in the $A^{III}B^{V}$ compound semiconductors was considered by VISVANATHAN [7], who derived the corresponding absorption coefficient (for electrons) in the following form

$$\alpha_{0,E} = \Omega\frac{4\pi(\varepsilon_{\infty}^{-1} - \varepsilon_0^{-1}}{n_R C_0}\frac{ne^4}{3}\left(\frac{2}{\pi m_E}\right)^{1/2}\frac{\hbar\omega_{PH}}{(\hbar\omega)^{2.5}}A_0(v,z) \tag{6}$$

where

$$A_0(v,z) = [(1-e^{-v})/v^{1/2}]\,[2/(e^z-1)]\,[e^z G(v-z) + G(v+z)], \tag{7}$$

$$z = \hbar\omega_{PH}/k_B T, \tag{8}$$

$$v = h\omega/k_B T, \tag{9}$$

$$\Omega = 9\times10^{14}/4. \tag{10}$$

In the above equations, $\hbar = 1.05450\times10^{-27}$ erg sec, ε_{∞} and ε_0 are the high-frequency and the static dielectric constants, respectively, C_0 is the speed of light in vacuum, e – the unit charge ($e = 4.80298 \times 10^{-10}\,\mathrm{cm}^{3/2}\,\mathrm{g}^{1/2}\,\mathrm{s}^{-1}$), n – the electron concentration m_E – the electron effective mass and $\hbar\omega$ and $\hbar\omega_{PH}$ are the energies of the absorbed photon and of the longitudinal optical phonon (taking part in the absorption), respectively. The function G may be expressed in the form

$$G(u) = \exp(u/2)\,[K_0(u/2) + (u/2)\,K_1(u/2)] + f(u) \tag{11}$$

where K_0 and K_1 are the modified Bessel functions of the zero and the first orders, respectively, and the function $f(u)$ may be written as [6]

$$f(u) = \left.\begin{matrix} -2-(0.74/u^{0.69}) \\ -2-(0.74/u^{0.75}) \\ -2-(4/3u)+(24/15u^2) \end{matrix}\right\} \begin{matrix} \text{for } u \leqslant 1, \\ \text{for } 1 < u < 7, \\ \text{for } u \geqslant 7. \end{matrix} \tag{12}$$

The analogous relations may be written for the hole component.

In our case $v \gg 1$, therefore using the algorithms recommended by ABRAMOWITZ and STEGUN [8] for both K_0 (Eq. (9.8.6)) and K_1 (Eq. (9.8.8)) we can reduce the formula for G and A_0 to the following forms:

$$G(u) = 0.886\,u^{1/2} - 2 + 2.437\,u^{-1/2}, \tag{13}$$

$$A_0 = (v, z) = (2/v^{1/2})\,[e^z G(v-z) + G(v+z)]/(e^z - 1). \tag{13a}$$

5. Free-carrier absorption due to acoustic phonons

The free-carrier absorption due to acoustic phonons was examined by FAN et al. [9], and ROSENBERG and LAX [10]. They expressed the corresponding formula for electrons in the following form:

$$\alpha_{AE} = \Omega \frac{4\pi}{n_R C_0} \frac{ne^2}{3} \frac{(2m_E)^{1/2}}{\pi^{3/2}\hbar^2} \frac{E_D^2}{(\hbar\omega)^{1/2} C_{44}} A_A(v) \tag{14}$$

where

$$A_A(v) = v^{-1/2}\,[\exp(v/2) - \exp(-v/2)]\,K_2(v/2). \tag{15}$$

In the above equations, E_D is the deformation potential, C_{44} – the elastic modulus, and K_2 – the modified Bessel function of the second order which is related to the previously introduced K_0 and K_1 by the recursion formula [11]

$$K_2(v/2) = (4/v)\,K_1(v/2) + K_0(v/2) \tag{16}$$

For the considered case $v \gg 1$, the A_A function is reduced to the following form:

$$A_A(v) = 1.772\mathrm{v}^{-1} + 6.647\,v^{-2}. \tag{17}$$

6. Absorption coefficient ratio

By substitution of the Equations (6) and (14) into (4), the absorption coefficient ratio $f_{0A,E}$ for electrons takes the following form

$$f_{0A,E} = \frac{2\pi(\varepsilon_\infty^{-1} - \varepsilon_0^{-1})e^2\hbar^2 C_{44}}{m_E E_D^2}\frac{\hbar\omega_{PH}}{(\hbar\omega)^2}A_F(v,z), \tag{18}$$

with

$$A_F(v,z) = \frac{A_0(v,z)}{A_A(v,z)} = \frac{e^z G(v-z) + G(v+z)}{(e^z - 1)\exp(v/2)K_2(v/2)}. \tag{19}$$

The analogous expression may be written for holes.

7. Dielectric constants

Based on the data published in the papers [12] and [13], the static dielectric constant of $Al_xGa_{1-x}As$ material reads as follows:

$$\varepsilon_0(x,T) = (13.1 - 3.0x)(1 + 2.01\times 10^{-4}T)\varepsilon^*, \tag{20}$$

and by virtue of papers [14] and [15], the high-frequency dielectric constant is given by

$$\varepsilon_\infty(x,T) = (10.9 - 2.3x)(1 + 0.90\times 10^{-4}T) \tag{21}$$

where ε^* is the dielectric constant of vacuum.

8. Long-wave LO phonon energy

The numerical data published in papers [15] and [16] enable us to present the long-wave LO phonon energies as follows:

$$\hbar\omega_{PH}(x,T) = (36.21 + 13.39x^{1.264})(1 - 4.0\times 10^{-5}T), \quad [\mathrm{meV}] \tag{22}$$

9. Elastic modulus

Taking into account numerical data given in papers [17] and [18], the elastic modulus C_{44} may be expressed as

$$C_{44}(x,T) = 59.5\times 10^{10}(1 - 8.91\times 10^{-2}x)[1 - 3\times 10^{-5}(T - 300)],\ \mathrm{dyne/cm^2}. \tag{23}$$

10. Deformation potential

The $E_D(T)$ dependence has not been found. On the basis of the papers [19]–[21], the following relation for the deformation potential E_D is assumed:

$$E_D(x) = 8.5 + 1.5x, \quad [\mathrm{eV}] \tag{24}$$

11. Steady-state carrier pair concentration in the active layer

The steady-state value of the injected carrier pair concentration in the active layer may be written as

$$N_{\mathrm{INJ}} = \left.\begin{array}{l} j t_{\mathrm{E}}/(e d_{\mathrm{A}}) \\ j_{\mathrm{TH}} t_{\mathrm{E}}/(e d_{\mathrm{A}}) = N_{\mathrm{TH}} \end{array}\right\} \quad \begin{array}{l} \text{for } j < j_{\mathrm{TH}}, \\ \text{for } j \geqslant j_{\mathrm{TH}} \end{array} \tag{25}$$

where j and j_{TH} are the supply and the threshold current densities, respectively, d_{A} is the active-layer thickness, and t_{E} – the minority-carrier lifetime.

12. Free-carrier concentration in the active layer

In order to fulfil the condition of the electrical neutrality in the active layer, the free electron and the free hole concentrations in this region should be equal to

$$n = N_{\mathrm{IJN}} + n_{\mathrm{A}}, \tag{26}$$

$$p = N_{\mathrm{IJN}} + p_{\mathrm{A}} \tag{27}$$

where n_{A} and p_{A} are initial (induced by doping) electron and hole, respectively, concentrations in the active layer.

13. Conclusions

This paper deals with the second part of the model of broad-contact double-heterostructure (AlGa)As diode lasers. The formulae presented in the paper enable us to determine the free-carrier absorption in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ material for a given temperature.

Knowledge of precise values of the coefficients of the above absorption process in all the layers of the double-heterostructure of a diode laser under consideration is necessary in determination of its threshold current density. The absorption processes are strongly temperature-dependent ones, therefore for detailed calculations the temperature profiles within the structure should be first determined. Those, however, are in turn dependent on the distribution of heat sources within the laser volume, i.e., on the rate distribution of the absorption processes, so the temperature profiles should be determined with the aid of the method proposed in the third part of the work and the self-consistent method of the calculations should be used.

The third part of the work will be devoted to quantum efficiencies and thermal properties of the diode lasers.

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Имитация предусматриваемых экспулатационных характеристик ширококонтактных лазерных диодов (AlGa)As с двойной гетероструктурой. II. Поглощение свободными носителями

Настоящая работа является второй частью модели ширококонтактного лазерного диода (AlGa)As с двойной гетероструктурой. Формулы, представленные в этой части, делают возможным связать коэффициент поглощения свободными носителями в материале $Al_xGa_{1-x}As$ с его составом и температурой.