Design of Optimum Active Layer Thickness in Double Heterostructure Broad Area $Ga\ As/Al_x\ Ga_{1-x}As$ Laser Diodes

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Abstract

In this work, we calculate optimum thickness of bulk active layer for $Ga\ As/Al_x\ Ga_{1-x}As$ laser diodes. We have done these calculations for fundamental oscillation mode of laser with different aluminium contents (fractional percents) in confinement layers. Our calculations were based on the analytical solution of Maxwell equations. The results indicate that the optimum thickness for fundamental mode is dependent on difference of refractive indices of active and confinement layers. The results reveal that the best active layer thicknesses for fundamental mode of laser are $d_0 = 0.63, 0.44, 0.36$ and $0.32\ \mu m$ for $x = 0.1, 0.2, 0.3$ and 0.4 aluminium percents in separate confinement heterostructure (SCH) layers respectively.

Keywords: Optimum active layer thickness, Maxwell equations, Separate Confinement Heterostructure (SCH).

1. Introduction

Double heterostructure (DH) lasers have been studied by many researchers [1-4]. It is desirable to use low threshold current density operation of broad area laser diodes, therefore it is helpful to optimize the laser cavity. In this work we present an analytical approximation for calculation of the best thickness of active layer for $Ga\ As/Al_x\ Ga_{1-x}As$ broad area lasers. Our calculation is based on solution of Maxwell's equations in a rectangular cavity [5-10-8-9-11].

2. Theory and Calculation

The optical cavity of a laser diode is a three dimensional structure. There are three limitations in this resonant cavity (Fig. 1) [6,9,11,12]:

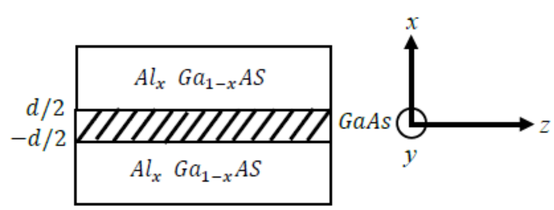

Fig. 1. Three layer of $Ga\ As/Al_x\ Ga_{1-x}As$ laser diode

First, the direction of light propagation is limited by a pair of optical mirrors perpendicular to the plane of as shown in [Figs. 1, 3], second, the direction of perpendicular to the plane of a p-n junction is limited by the stripe structure [6, 12].The electromagnetic wave in optical resonant cavity may be divided into two polarization modes [5, 6, 11, 12]: Transvers electric (TE) wave mode and transverse magnetic (TM) wave mode. Because of TM wave reflectivities are much lower than these of TE wave at the resonant cavity faces, the energy losses are very large [5]. So there are almost TE wave oscillations in DH lasers. TE waves may be described by three cases [5, 12]: TEM $_{qms}$, here q is longitudinal wave order, m is transverse wave order, and s is lateral wave order. In ordinary, 'O' presents fundamental mode. Longitudinal modes are determined by cavity length and material of active layer. Condition for osculation of longitudinal mode along cavity is [5]:

$$L = q\frac{\lambda}{2} = q\ \frac{\lambda_0}{2n_a} \tag{1}$$

Where λ_0, and n_a are wavelength in the vacuum. cavity transverse modes of perpendicular to p-n junction plane are determined by active region thicknesses and the index steps of heterostructure boundaries. The modes of parallel to p-n junction planes are determined by the stripe structures and introduced by lateral modes [1,2].

In this paper we calculate thicknesses of active layer that a laser diode operates in fundamental mode. Our structure is an index guided waveguide, [6,12] that confined with refractive index step.

Determination of optimum active layer thickness by mode analysis

The difference between laser and common light sources is high spatial and temporal coherence of lasers [12]. Electric and Magnetic fields of coherent light along z direction are defined as [6]:

$$E = E_0(x,y)e^{i\omega t-\gamma z} \tag{2}$$

$$H = H_0(x,y)e^{i\omega t-\gamma z} \tag{3}$$

Where $E_0, E_0, \omega, and\, \gamma$ are amplitude of electric field, amplitude of magnetic field, radial frequency, and propagation constant

$$\gamma = \alpha + i\beta \tag{4}$$

Two different cases are introduced.

1) For net propagative wave without loss, α is zero and electric field is defined as

$$E = E_0(x,y)e^{i(\omega t-\beta z)} \tag{5}$$

2) For net loss wave without propagation β is zero

$$E = E_0(x,y)e^{i\omega t}e^{-\alpha z} \tag{6}$$

In this equation electric field increases with exponential function. Analysis of mode is going to determine electric field distribution in the cavity. We obtain the relation of field constants from Maxwell equations [5-7, 11-13]:

$$\vec{\nabla} \times \vec{E} = \frac{-\partial \vec{B}}{\partial t} \tag{7}$$

$$\vec{B} = \mu \vec{H} \tag{8}$$

$$\vec{\nabla} \times \vec{H} = \frac{-\partial \vec{D}}{\partial t} \tag{9}$$

$$\vec{D} = \varepsilon \vec{E} \tag{10}$$

Where $\vec{H}, \vec{D}, \mu$, and ε are magnetic intensity, displacement vector, magnetic permeability and permittivity of the matrial.

With inserting Eq. (8) in Eq. (7) and Eq. (10) in Eq. (9) and expansion of curl of $\vec{E}$ and $\vec{H}$ we obtain:

$$\frac{\partial E_z}{\partial y} + \gamma E_y = i\omega\mu H_x \tag{11}$$

$$\frac{\partial E_z}{\partial x} + \gamma E_x = i\omega\mu H_y \tag{12}$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -i\omega\mu H_z \tag{13}$$

$$\frac{\partial E_z}{\partial y} + \gamma H_y = i\omega\varepsilon E_z \tag{14}$$

$$-\frac{\partial H_z}{\partial x} - \gamma H_x = i\omega\varepsilon E_y \tag{15}$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial H_x}{\partial y} = i\omega\varepsilon E_z \tag{16}$$

From Eq. (11) and Eq.(15) to eliminate E_y we find

$$H_x = \frac{1}{k^2+\gamma^2}\left(i\omega\varepsilon\frac{\partial E_z}{\partial y} - \gamma\frac{\partial H_z}{\partial x}\right) \quad (17)$$

Where

$$k^2 = \omega^2\mu\varepsilon = \frac{\omega^2}{c^2} \quad (18)$$

Also substitution of Eq. (12) into Eq. (14) to eliminate E_x gives

$$H_y = \frac{-1}{k^2+\gamma^2}\left(i\omega\varepsilon\frac{\partial E_z}{\partial x} - \gamma\frac{\partial H_z}{\partial y}\right) \quad (19)$$

In similarly process we obtain

$$E_x = \frac{-1}{k^2+\lambda^2}\left(i\omega\mu\frac{\partial H_z}{\partial y} + \gamma\frac{\partial E_z}{\partial x}\right) \quad (20)$$

$$E_y = \frac{-1}{k^2+\lambda^2}\left(i\omega\mu\frac{\partial H_z}{\partial x} + \gamma\frac{\partial E_z}{\partial y}\right) \quad (21)$$

All of above fields should satisfy the wave equation:

$$\nabla^2\psi + k^2\psi = 0 \quad (22)$$

ψ is an arbitrary wave. In our structure we assume index of active region is n_a and indices of both confined regions are n_1 and n_2 respectively. Propagation direction of wave is z axis and we have not any variation in y direction. With above assumptions equations (15), (17), (18), and (19) yields to:

$$E_x = \frac{-\gamma}{k^2+\gamma^2}\frac{\partial E_z}{\partial x} \quad (21)$$

$$E_y = \frac{-i\omega\mu}{k^2+\gamma^2}\frac{\partial H_z}{\partial x} \quad (22)$$

$$H_x = \frac{-\gamma}{k^2+\gamma^2}\frac{\partial H_z}{\partial x} \quad (23)$$

$$H_y = \frac{-i\omega\mu}{k^2+\gamma^2}\frac{\partial E_z}{\partial x} \quad (24)$$

For a TE polarization wave $E_z = 0$ so that, $E_x = 0$ and $H_y = 0$, therefore there are E_y, H_x and H_z only. For a TM mode wave, $H_z = 0$ so that, $E_y = 0$ and $H_x = 0$, therefore there are H_y, E_x and E_z only. There are almost TE wave oscillations in DH lasers because of high energy losses for TM waves low reflectivity on cavity mirrors. TE wave equation with omission of variation in y direction (because of broad area laser case):

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)E_y + k^2E_y = 0 \quad (25)$$

With inserting

$$E_y = E_{y_0}e^{i\omega t-\gamma z} \quad (26)$$

We obtain

$$\frac{\partial^2 E_y}{\partial x^2} + (k^2+\gamma^2)E_y = 0 \quad (27)$$

With solution of this differential equation for active region and confinement layers (Fig. 1).

We have obtained:

$$E_{y_1} = A_1 exp\left(P_1\left(\frac{d}{2} - x\right)\right) \quad x > \frac{d}{2} \quad (28)$$

$$E_{y_a} = (A_2\cos(hx) + B_2\sin(\mathrm{h}\,x)) \quad (29)$$

$$|x| < \frac{d}{2}$$

$$E_{y_3} = A_3 exp\left(P_3\left(\frac{d}{2} + x\right)\right) \quad x < \frac{-d}{2} \quad (30)$$

Where P_1, h, and P_3 are propagation constants in regions with n_1, n_a, and n_3 respectively.

With inserting E_{y_1} and $\gamma = i\beta$ (net propagation wave) in Eq. (27) we obtain

$$\left.\begin{array}{ll} {P_1}^2 = \beta^2 - {k_1}^2 & (31) \\ {P_1}^2 = \beta^2 - (k_0n_1)^2 & (32) \end{array}\right\}$$

Where k_0 is wave number in vacuum. By inserting of E_{y_a} and E_{y_3} we yields to:

$$h^2 = (k_0n_a)^2 - \beta^2 \quad (33)$$

$${P_3}^2 = \beta^2 - (k_0n_3)^2 \quad (34)$$

With following boundary conditions:

$$E_{y_1} = E_{y_a}\Big|_{x=\frac{d}{2}} \quad , \quad E_{y_a} = E_3\Big|_{x=\frac{-d}{2}} \tag{35}$$

$$\frac{dE_{y_1}}{dx} = \frac{dE_{y_a}}{dx}\Big|_{x=\frac{d}{2}} \quad , \quad \frac{dE_{y_a}}{dx} = \frac{dE_{y_3}}{dx}\Big|_{x=\frac{-d}{2}} \tag{36}$$

For identical confinement layers, $P_1 = P_3$ and we obtained:

$$tg(hd) = \frac{2Ph}{h^2 - P^2} \tag{37}$$

h is dependent on active layer refractive index and P is dependent on refractive index of confinement layers therefore thickness of active layer, d is related to refractive index (Eqs. 32, 37). The solution of (37) in special case $P = 0$ that wave do not penetrate to the confinement layers for all modes is

$$hd = m\pi + \tan^{-1}\frac{2Ph}{h^2-P^2} \tag{38}$$

For fundamental mode of layer (m=0) in the case of P=0 and inserting $P_1 = 0$ in Eq. (32) we obtain:

$$d_0 = \frac{\pi}{h} = \frac{\pi}{\sqrt{k_a{}^2+\beta^2}} = \frac{\pi}{\sqrt{k_0{}^2n_a{}^2-k_0{}^2n_1{}^2}} \tag{39}$$

$$d_0 = \frac{\pi}{k_0\sqrt{n_a{}^2-n_1{}^2}}$$

But $k_0 = \frac{2\pi}{\lambda_0}$ so

$$d_0 = \frac{\lambda_0}{2\sqrt{n_a{}^2 - n_1{}^2}} \tag{40}$$

λ_0 is wavelength of light in vacuum for $GaAs$ energy, and d_0 is maximum thickness of active layer that fundamental mode can propagate. If the condition $d < d_0$ was satisfied the fundamental mode will oscillate along cavity. Refractive index as a function of x for $Al_xGa_{1-x}As$ system is defined as [2]:

$$n(x) = 3.59 - 0.71x + 0.091x^2 \tag{41}$$

We have calculated refractive indices of active and confinement layers and according optimum thickness for different aluminium fractional concentrations in confinement layers. Our results collected in Tab. I.

Tab. I. Optimum thicknesses of active layer

Aluminium mole fraction	**Refractive Index**	**Optimum thickness for fundamental mode oscillation**
x	$n(x)$	d_0
0	3.59	-
0.1	3.52	0.63
0.2	3.45	0.44
0.3	3.38	0.36
0.4	3.32	0.32

3. Discussion

The light intensity distribution in the direction perpendicular to p-n junction plane may be obtained by Eq. (36) to integrate E_y with *x* direction specified region Fig. 2 is the light intensity distribution while the composition of cladding layers is varied with constant active layer thickness. It is readily seen that refractive index steps at heterostructure boundary increases when *x* increase and light intensity is more concentrated (Fig. 2). The distribution of light intensity varies as of with the composition of cladding layers being constant. As the thickness of active layer becomes smaller, the light spreads further, the reason is that effective refractive index decreases when *d* is smaller and index difference between active and cladding layers becomes small.

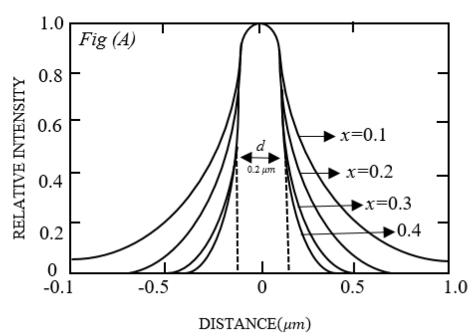

Fig. 2. The light intensity distribution while the composition of cladding layers is varied with constant active layer thickness.

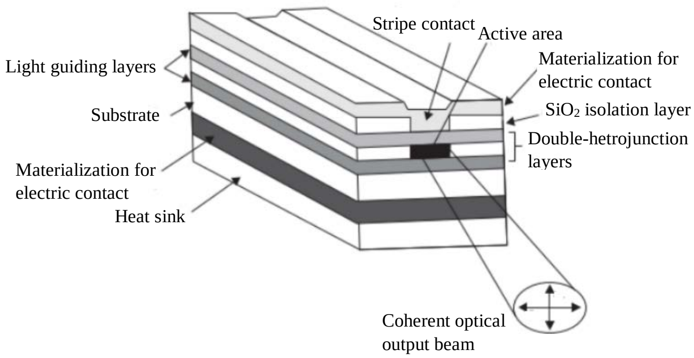

Fig. 3. Structure of a typical laser diode

4. Conclusion

We calculated optimum thickness of active layer in $\mathrm{GaAs/Al_xGa_{1-x}As}$ broad area laser diode for fundamental oscillation mode with different aluminum contents (fractional percents) in confinement layers. Our calculation was based on the analytical solution of Maxwell equations. The results indicate that the optimum thickness for fundamental mode is dependent on difference of refractive indices of active and confinement layers. The best thicknesses are:

$$d_0 = \frac{\lambda_0}{2\sqrt{n_a{}^2 - n_1{}^2}}$$

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