Buried Heterostructure and Shallow Ridge lasers: a theoretical comparison

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Buried Heterostructure (BH) lasers have considerable advantages compared to shallow ridge (SR) lasers. The active layer heterostructure is buried with an InP overgrowth leading to differences in the electronic and photonic confinement resulting in higher current injection efficiency, enhanced optical overlap, and thermal dissipation from the sides of the waveguide as well as the substrate. In this work, we present a model to quantify the improved current injection efficiency by analyzing the carrier distribution in BH and SR lasers. In particular, we focus on the effect surface recombination and lateral carrier out-diffusion play in BH and SR lasers respectively.

Introduction

In laser diodes, photon confinement, current confinement and carrier confinement can be achieved in many ways [1]. Gain guided, shallow ridge (SR), deep ridge (DR) and buried heterostrucutre (BH) laser diodes are the most widely known examples.

Deep and shallow ridge structures offer a compromise between fabrication complexity and performance, but there has been relatively little comparison with respect to buried heterostructure devices. In SR lasers (see Figure 1-a), weak optical confinement and current confinement are combined together. Because the optical confining layer is only partially etched, charge carriers diffuse laterally and recombine without providing gain, thus decreasing the efficiency of the device [2].

BH lasers offer strong optical, current and charge carrier confinement (see Figure 1-b). This is thanks to the fact that the active region is completely etched and then replaced by InP, which has a higher band-gap and lower refractive index with respect to the active and confinement layer materials (usually quaternary alloys).Therefore carriers and photons are strongly confined in the gain region and the current injection is efficient [3]. This becomes particularly important when photonic devices are operated in high temperature environments such as data communications.

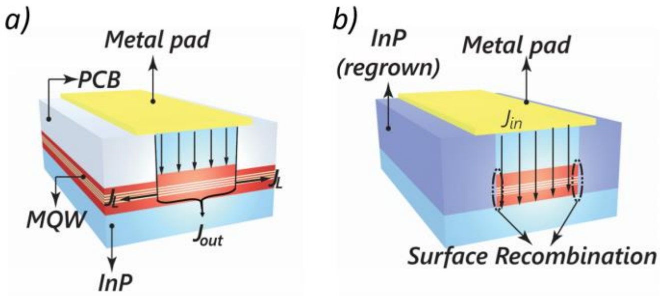

Figure 1 Schematic representation of a SR lasers (a) and a (b) BH lasers. The schematics show also the dominant current leakage paths.

Modelling of Shallow Ridge laser

In this work we evaluate the structural dependence of the electrical injection efficiency. In order to compare current injection efficiency in SR and BH lasers, it is necessary to model the carrier density distribution in the laser stripe by solving the lateral diffusion equation:

$$D\frac{\partial^2 x\, n(x)}{\partial x^2} = -\frac{J(x)}{qd} + \frac{n(x)}{\tau} \quad (1)$$

Equation 1 shows how charge carriers n diffuse away in x from the active stripe in the SR laser. The stimulated emission terms are neglected and we assume the carrier density is pinned to a first order at the threshold condition. The diffusion constant D is $12.26\ cm/s^2$, and the active layer thickness d is $0.03\ \mu m$ The charge carrier lifetime is defined as τ and its value is assumed to be $8.5 \cdot 10^{-10}s.$ To solve (1) we impose boundary conditions to the lateral diffusion equation to ensure continuity of the current $(\partial n(x)/\partial x\ )$ and the continuity of the carrier concentration $n(x)$ at the boundary of the ridge $(x = W/2)$. [2] to give:

$$n(x) = \begin{cases} \frac{J_{in}\tau}{qd}\left(1 - e^{\frac{W}{2L_d}} \cdot \cosh\left(\frac{x}{L_d}\right)\right) & |x| < W/2 \quad (2.a) \\ \frac{J_{in}\tau}{qd} e^{-\frac{|x|}{L_d}} \cdot sinh\left(\frac{W}{L_d}\right) & |x| > W/2 \quad (2.b) \end{cases}$$

Where J_{in} is the injected carrier density, L_d is the diffusion length, W is the width of the active region, τ is the carrier lifetime, q is the electron charge and d is the active layer thickness. In this model, a number of assumptions are made. A first assumption is that the lasers are assumed to work in a single mode regime for every stripe width. A second assumption considers the mode well confined beneath the ridge and the charge carriers diffusing out of the stripe do not contribute to the gain of the device.

The solution to (1) shows a strong carrier density profile dependence on the width of the laser and therefore impacts the current injection level required to achieve threshold in the gain region. Figure 2.a shows the carrier density profile for different stripe widths: the narrower the width, the larger the percentage of carriers outside the boundary of the stripe respect to the carriers inside.

For the graphs in Figure-2, a value 1 µm was used for L_d [2], [5]. As shown in Figure 1.a, we have defined three different current densities: J_{in} (injected current density), J_a (active current density) and J_L (leakage current density), where $J_{in} = J_a + J_L$. Assuming a non-variant carrier lifetime τ, the active current is defined by:

$$J_a = \frac{d \cdot q}{W}\int_{-W/2}^{W/2} \frac{n(x)}{\tau}\partial x = J_{in}\left(1 - \frac{L_d}{W}\left(1 - e^{-W/L_d}\right)\right) \quad (3)$$

The total injected current I_{in} can be expressed as:

$$I_{in} = J_a \cdot L_c \cdot W + \ I_L = J_{in} \cdot L_c \cdot W \quad (4)$$

The current injection efficiency (J_a/J_{in}) is plotted in Figure 2-b for different stripe widths at the threshold condition, when J_r is independent from W[2]. For larger widths, the efficiency of the laser increases since the fraction of charge carriers outside the ridge decreases as well. The plotted relation can be used as a starting point for optimizing the ridge width.

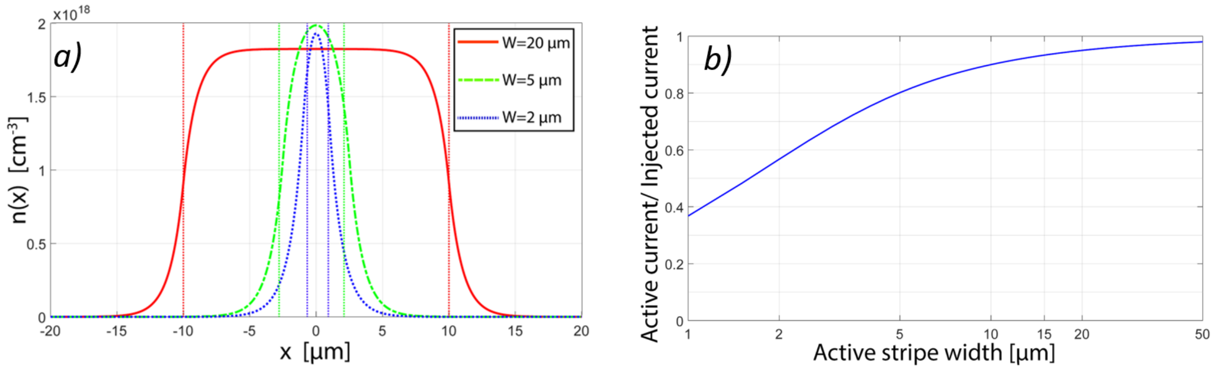

Figure 2 (a) Carrier distribution for different stripe width, (b) Current injection efficiency for different laser widths.

Modelling of Buried Heterostructure laser

In contrast to the SR configuration, in a BH laser, the carriers are confined in the active region but can recombine at the Quaternary/InP interface (see Fig. 1-b) lowering the efficiency of the laser. In this case the two boundary conditions for (1) are: the symmetry of the carrier equation about the center of the active stripe (x=0) and the equivalence between the diffusion current and the surface recombination at the mesa side walls ($x = W/2$) [5], [6]. The solution to the carrier distribution equations is:

$$n(x) = -\frac{J_{in}}{qd}\left(v_s\left[\frac{D}{L_d}sinh\left(\frac{W}{2L_d}\right)+v_s cosh\left(\frac{W}{2L_d}\right)\right]^{-1}\left(\frac{x}{L_d}\right) - 1\right) \quad (7)$$

where v_s is the surface recombination velocity. Standard values of L_d and v_s are 1 μm and 7.5 x 10^3cm/s respectively [6]. To find the J_{th}- W relation, we can start setting the threshold gain equal to the internal losses:

$$G_{th} = \frac{(\alpha_i+\alpha_m)}{\Gamma_x\Gamma_y} \quad (8)$$

where Γ_y is the vertical optical confinement and is equal to 0.06 (the value was calculated using a commercial eigenmode solver FIMMWAVE), and α_i (10 cm^{-1}) and α_m (10.47 cm^{-1}) are the optical and equivalent mirror losses respectively. Γ_x is the vertical horizontal optical confinement and it can be expressed as:

$$\Gamma_x = (4\pi^2W^2\lambda^{-2}(n^2_{eff2}-n^2_{eff1})\left[2\left(\frac{n_{eff2}}{n_{eff1}}\right)^4 + (4\pi^2W^2\lambda^{-2}(n^2_{eff2}-n^2_{eff1})\right]^2 \quad (9)$$

G_{th} may also be expressed in terms of carrier density as follows [1]:

$$G_{th} = g_0 log\left(\frac{n_{th}}{n_{tr}}\right) \quad (10)$$

where n_{tr} $(1x10^{18}cm^{-3})$ is the transparency carrier density and g_0 $(600\ cm^{-1})$ is the gain parameter. The carrier density n_{th} can be estimated as the integral of $n(x)$ normalized to the power [5].

$$n_{th} = \frac{J_{th}\tau}{qd}\left(\frac{v_s\left[\frac{D}{L_d}sinh\left(\frac{W}{2L_d}\right)+v_s cosh\left(\frac{W}{2L_d}\right)\right]^{-1}\pi {L_d}^2 cosh\left(\frac{W}{2L_d}\right)}{\pi^2{L_d}^2+W^2}+1\right) \quad (11)$$

We can now substitute (11) in (10) and substitute for nth and solve for J_{th} in function of the width.

Comparison

We can now plot J_{th}-W both for shallow and buried heterostructure for different values of v_s and L_d. Figure 3 shows that for the same ridge width the threshold current is lower in a BH device. This means that in SR devices, it is necessary to inject more carriers in order to compensate the lateral out-diffusion phenomena. We can also observe that J_{th} increases rapidly with higher values of v_s, motivating good suppression of leakage paths at the buried interface

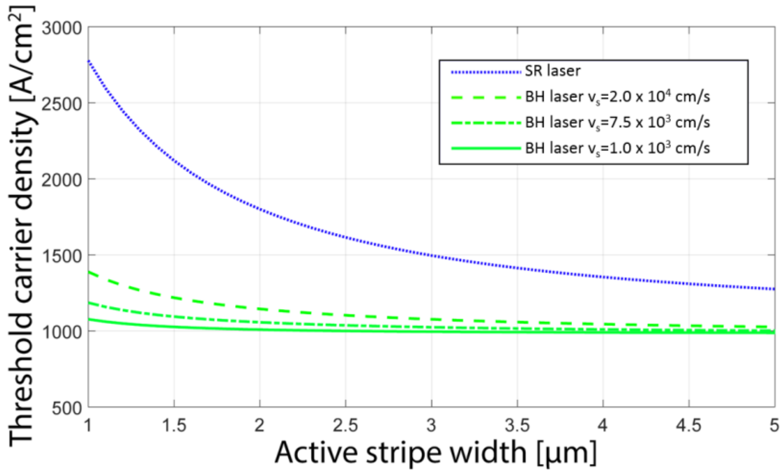

Figure 3 Threshold current density in SR and BH lasers for different widths and surface recombination values

In general, for larger widths, both surface recombination and out-diffusion current start to become less important and the threshold current densities converge.

Conclusions and future work

In this work, we have presented a compact analytical model to compare SR and BH lasers in terms of threshold current density. This is able to predict the performance advances anticipated for buried heterostructure lasers in terms of reduced leakage and threshold currents.

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