Microelectronics Reliability xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr

Introductory invited paper

Clamp voltage and ideality factor in laser diodes

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ARTICLE INFO

Article history:
Received 23 May 2015
Received in revised form 20 June 2015
Accepted 21 June 2015
Available online xxxx

Keywords:
Laser diode
Ideality factor
Threshold voltage

ABSTRACT

A recent model for laser diodes was applied to the decomposition of the experimental characteristics of several laser diodes into their fundamental components. This pointed out a problem involving the ideality factor and the clamp voltage. The two quantities indicate largely different values of the internal voltage, not explained or predicted by any theory. The solution of the puzzle requires going back to points as fundamental as the meaning of locality of band-to-band transitions in quantum or bulk active regions

1. Introduction

This paper deals with a puzzle that troubled the authors along a couple of years, after having published [1–3], a new theoretical model for the DC characteristics of a laser diode (LD). The initial prompt, and the main application field of such a new model, was the search for an interpretation tool for the evolving characteristics of a LD under degradation [4]. In particular, the model attempted the numerical fit of the experimental DC curves by adjusting the relevant coefficients of a set of equations strictly derived by physical considerations. The protocol described in ref. [4] illustrates how to decode the experimental data and reconstruct, for instance, the separate contribution of the radiative and non-radiative phenomena to the overall conduction.

Compared to that model, two experimental points remained puzzling: the apparent continuous reduction of the series resistance beyond the threshold condition, and the measured internal threshold voltage as the upper limit of the sub-threshold domain. The former will be discussed and solved specifically in a next paper, while the latter is the subject of this work.

The kernel of the problem can be summarized as follows: experimental data for several different laser diodes show that the pure radiative component I_{ph} of the total laser current I exactly behaves as in a Shockley diode with an ideality factor $n > 1$. This is not surprising for a MQW structure, as it will be discussed in the following chapters, and simply states that the effective internal voltage V_{in} driving the optically active material is n times lower than the voltage V applied to the electrical junction. But the threshold condition, that is the experimentally observable clamp of the junction voltage $V = V_{th}$, always occur at $qV_{th} \approx h\nu$, where q is the electron charge and $h\nu$ is the peak photon energy, and not at $V = nV_{th}$, as the sub-threshold domain predicts.

The simplest explanations based on ohmic effects or parasitic currents fail after simple considerations, and the problem stands in its full evidence.

The paper will start from experimental measurements on a real device, according with the protocol described in [4], and will then summarize the results of the model of the cited references [1–3] that are relevant for this paper.

The attempt to fit theory with experiments will point out the puzzling question of the effective voltage.

With the aid of further experimental data, belonging to both bulk and Quantum Well active area devices, the authors will propose an interpretation, that calls into play concepts as fundamental as the locality of photon-charge interaction.

2. Experimental data and modeling

Fig. 1 displays the experimental characteristics of an edge-emitting DFB laser diode in ridge technology tuned at 1310 nm. This representation follows the protocol that has been proposed in detail in [4]. It allows drawing all current contributions in a laser diode on a proper scale: the strictly radiative component I_{ph}, responsible for all and sole the light emission, the non-radiative current I_{nr} competing with it, and the total current I, that is the sum of the two.

$$I = I_{ph} + I_{nr} \tag{1}$$

The abscissa reports the reduced voltage $V_{in} = V - R_S I$ that transforms the applied voltage V into the actual bias of the active region, by removing the ohmic contribution of the series resistance R_S.

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http://dx.doi.org/10.1016/j.microrel.2015.06.027

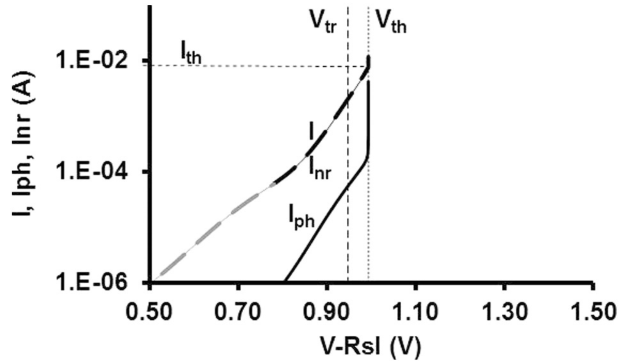

Fig. 1. Experimental plots of the radiative and non-radiative components I_{ph} and I_{nr} of the total current I in a 1310 nm laser diode, as functions of the internal voltage $V - R_S I$.

Moreover, the displayed voltage range focuses, in this paper, on the injection levels close to threshold, and neglects the lower current range (highlighted area on the left), due to lateral conduction paths. Those lateral currents are relevant only in the sub-mA range for a device as in Fig. 1, and are not significant for this study. Anyway, they have been duly considered and completely modeled in ref. [2].

Several other features of Fig. 1 should be commented. The threshold voltage V_{th} now appears as a vertical asymptote for all currents, while the threshold current I_{th} is the corresponding value of the current I. The quoted references refine the last statement, showing that the real definition of the threshold current is the value that the sole I_{nr} assumes at $V = V_{th}$. The small contribution of the radiative current I_{ph} to the total current I in the sub-threshold range, experimentally confirmed in Fig. 1, makes the identification $I \approx I_{nr}$ reasonable for practical cases. Anyway, both theory and direct inspection of the numerical data from experiments show that I_{nr} does clamp at the value

$$I_{th} = I_{nr}(V_{th}) \tag{2}$$

while I continues increasing, because of Eq. (1), following the increase of I_{ph} even when voltage clamps.

This particular feature of I_{ph} is possibly the most peculiar result of the cited model, that describes that current by means of the formula

$$I_{ph}(V) = I_{ph0} 4R \frac{\exp\left(\frac{qV}{kT}\right) - 1}{R\left[1 + \exp\left(\frac{qV - h\nu}{2kT}\right)\right]^2 + \left[1 - \exp\left(\frac{qV - h\nu}{kT}\right)\right]}. \tag{3}$$

Here the voltage V is the internal voltage (that is, the applied voltage reduced by the ohmic contribution), q is the electron charge, $h\nu$ is the photon energy (we are dealing with single-mode lasers, so that it has a well-defined and sharp peak value), kT is the thermal energy, I_{ph0} a suitable constant, corresponding to the value of I_{ph} at transparency and duly evaluated in the referenced papers, and, finally, R is the loss/gain ratio

$$R = \frac{\alpha_T}{g_m} \tag{4}$$

where α_T is the total loss coefficient, and g_m can be shown to coincide with the absorption coefficient of the un-pumped material. This last term also results to be $g_m = 4\,g_0$, being g_0 a coefficient that appears in ref. [5], Table 4.5, as a phenomenological “fitting parameter” that now gains physical significance.

The reference voltages in Fig. 1 are, respectively, the transparency voltage

$$V_{tr} = \frac{h\nu}{q} \tag{5}$$

at which stimulated emission balances absorption, and gain is null, and the threshold voltage

$$V_{th} = V_{tr} + \frac{2kT}{q} \ln\left(\frac{1+R}{1-R}\right) \tag{6}$$

that is the value of the internal voltage at which the denominator in Eq. (3) vanishes. It is evident from Eq. (6) that $V_{th} > V_{tr}$ and that the condition for voltage clamping at a finite value, that is for achieving the laser regime, is $R < 1$.

For the case given in Fig. 1, one has $V_{th} = 0.993$, $V_{tr} = 0.947$ V, and, at room temperature, $R = 0.42$.

Authors feel intriguing the parallelism (that means the proportionality) of all currents in the sub-threshold range in Fig. 1, and have discussed it in their previous papers.

Anyway, for the scope of the present paper, the sole I_{ph} is relevant, so that we will focus on it in the following.

The plot of I_{ph} calculated from Eq. (3) and the experimental measurements as in Fig. 1 will show, in the next chapters, a nice qualitative agreement: the subthreshold range (when exponentials in the denominator of Eq. (3) are negligible with respect to the unity) displays a Shockley-like behavior, that is an exponential dependence of current on voltage. As far as the voltage approaches the threshold limit (Eq. (6)), the current I_{ph} increases rapidly, up to dominate over all other currents, and the non-radiative I_{nr} blocks (Eq. (2)).

3. Ideality factor and threshold voltage

When one moves to a more quantitative analysis, two differences appear between theory and experiments: the transition at threshold is sharper in the experimental curves than in the theoretical ones, and the slope of the sub-threshold branch in real data is significantly lower than predictions.

Measuring the slope of I_{ph} in the sub-threshold range in Fig. 1, one gets an ideality factor $n = 1.4$, instead of the expected $n = 1$.

At a first glance this seems not a problem: many diodes show non-unitary ideality factors, and even the seminal work of Shockley [6] predicts that, in case of recombination inside the depletion layer (that is the case for optical emitters, although radiative recombination hopefully overcomes trap-driven transitions), the ideal voltage V appears reduced.

The interpretation, indeed, of a value $n > 1$ could be that recombination leads several carriers to be lost before they reach the region where the dominant recombination rate takes place, as represented in Fig. 2.

This means that the leading current appears to depend not on $\exp(qV/kT)$, but on $\exp(qV/nkT)$, with $n > 1$. This would simply require to re-define the “internal voltage” that appears in Eq. (3) as a fraction

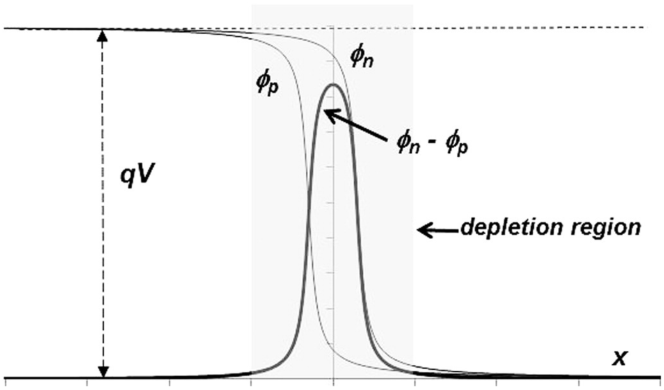

Fig. 2. Quasi-Fermi levels ϕ_n and ϕ_p in a junction where all recombination takes place inside the depletion region. Their difference is everywhere lower than the junction bias qV.

Please cite this article as: M. Vanzi, et al., Clamp voltage and ideality factor in laser diodes, Microelectronics Reliability (2015), http://dx.doi.org/10.1016/j.microrel.2015.06.027