Clamp voltage and ideality factor in laser diodes

M. Vanzi *, G. Mura, G. Marcello, G. Martines

University of Cagliari — DIEE, Piazza d’Armi, 09123 Cagliari, Italy

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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 \( I_{inr} \) competing with it, and the total current \( I \), that is the sum of the two.

\[
I = I_{ph} + I_{inr}
\]  

(1)

The abscissa reports the reduced voltage \( V_{in} = V - R_SD \) that transforms the applied voltage \( V \) into the actual bias of the active region, by removing the ohmic contribution of the series resistance \( R_S \).
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 $I_{th}$ 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 $I \approx I_{th}$ reasonable for practical cases. Anyway, both theory and direct inspection of the numerical data from experiments show that $I_{th}$ does clamp at the value

$$I_{th} = I_{th}(V_{th})$$

Equation (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

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

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

$$R = \frac{\alpha_f \ln(1 + R)}{g_m} \tag{4}$$

where $\alpha_f$ 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

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

that is the value of the internal voltage at which the denominator in Eq. (3) vanishes. It is evident from Eq. (6) that $V_{th} > V_t$, 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 $I_{th}$ increases rapidly, up to dominate over all other currents, and the non-radiative $I_{ph}$ 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.
of the nominal voltage, even after having removed the ohmic contribution.

Here the problem arises that a reduced voltage would also re-scale the value of both $V_T$ (Eq. (5)) and $V_{th}$ (Eq. (6)), which does not appear in experimental data.

In order to clarify the last point, Fig. 3 shows an attempt to use Eq. (3) for fitting data of Fig. 1. The bold lines represent the cases of $n = 1$ and $n = 1.4$. The corresponding values for both $V_T$ and $V_{th}$ are brought into evidence. It should be noticed that the last case shifts the transparency voltage $V_{tr}$ at more than 1.3 V, which is well beyond the observed value of $V_{th}$.

To support the statement that the measured $V_T$ really depends on $V$ and not on $V/n$, we can recall the results obtained in an experiment [7] where a focused ion beam (FIB) was used to modify the optical losses in a 1310 nm ridge laser diode, and then to change both $V_T$ and $I_{ph}$. The modified thresholds not only followed the theoretical expectations, but also allowed to extrapolate their values to the ideal case of no-losses, when threshold and transparency coincide. It resulted $V_{th} = V_{tr} = 0.947 V$, that is exactly the value of $h\nu/q$.

In other words, the sub-threshold range looks depending on a reduced voltage ($n > 1$), while the threshold voltage seem to follow the full voltage ($n = 1$). The two requirements by no means can be simultaneously fulfilled in Eq. (3).

4. Curve fitting

The first step toward the solution of the puzzle is to observe that a suitable superposition of several functions $I_{ph}$, as given by Eq. (3), can lead to properly fit the experimental curves.

Let us start with Fig. 4, referring to a 850 nm GaAs-based VCSEL that is known to have a single active layer, thick enough to be considered closer to a bulk layer than a quantum well. The transparency voltage is accordingly calculated as $V_{tr} = 1.459 V$, while the threshold was measured at $V_{th} = 1.555 V$. This is compatible with the theoretical $n = 1$ curve, with a loss/gain ratio $R = 0.7$.

The sub-threshold branch, on the other hand, shows an ideality factor $n = 1.55$, and the transition appears sharper than the expectation from Eq. (3). Anyway, a very good fit results from a suitable linear combination of two $I_{ph}$ curves, one depending on $V/n$ and one on $V$. The first nearly completely recovers the sub-threshold range, while the second, that defines the threshold voltage, is suitably scaled down, in order to adjust the transition. It is not necessary here to grant this patchwork with too much significance: it is just a phenomenological observation that will call for deeper analysis in the following.

A second example (Fig. 5) is a 1310 nm DFB laser, as for the case in Fig. 1, but in Buried Heterostructure (BH) technology. The obvious question is about the physical meaning of the superposition of just two theoretical and conflicting curves to get proper fitting of experimental data. To this purpose, Fig. 6 may help. It has been calculated superimposing not two curves, but a continuous set of curves $I_{ph}$ spanning a given interval $n_1, n_2$ of values of the ideality factor $n$, weighted by an adjustable peak function $P(n)$:

$$I_{phTOT}(V) = \int_{n_1}^{n_2} P(n) I_{ph} \left( \frac{V}{n} \right) \, dn.$$  (7)

The specific case reported in figure refers to $n$ ranging from 1 to 2, and a gaussian peak function $P$ with $\sigma = 0.1$, whose maximum is shifted from $n = 1$ to $n = 1.5$ and $n = 2$. This resulting $I_{phTOT}$ curves display, for $V < V_{th}$, a slope corresponding, respectively, to $n = 1.72$, $n = 1.555$ and $n = 1.4$. The relevant result is that all curves display the same threshold $V_{th}$ of the component $I_{ph}(V)$, corresponding to the minimum value $n = 1$.

The scope of Eq. (7) is to represent, at least qualitatively, a situation similar to Fig. 2, where several different separations of the quasi-Fermi level concur to the total recombination rate. The result is a curve that strictly resembles the ideal $I_{ph}$, keeping the correct threshold voltage while the ideality factor deviates from unity.

It is then possible to imagine that a suitable choice of the extremals of the integral and of the shape and position of the peak function $P$ in Eq. (7) can fit real data.

5. Discussion and application

5.1. Ideality factor

At a first glance, in order to explain $n > 1$, in LEDs or laser diodes, three other causes could be considered, besides the distributed recombination inside the active layer represented in Fig. 2: ohmic effects, diffusion currents, and Shockley–Read–Hall (SHR) recombination. Anyway, the first have been removed by introducing the reduced

Fig. 3. $I_{ph}$ curves calculated, by means of Eq. (3) for $n = 1$ and $n = 1.4$, trying to fit experimental data of Fig. 1.

Fig. 4. Experimental $I_{ph}$ (bold line) for a 850 nm VCSEL and the two fitting curves (thin lines), calculated from Eq. (3).

Fig. 5. The same as in Fig. 4 for a 1310 nm BH DFB laser diode.

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abscissa $V - R_s I$, and in any case no ohmic effect can reduce $V$ to the same $V/n$ at any injection level. On the other hand, diffusion currents have been considered since the original papers [1–3] as the residual Shockley current due to incomplete recombination inside the active region, and have been shown to be negligible in real devices. Finally, the Shockley–Read–Hall mechanisms could justify non-unitary values for $n$, but limited to the sole non-radiative components (because none of such recombination mechanisms contributes to light emission), while we are investigating the ideality factor of the sole radiative current $I_{ph}$, no matter the behavior of any other current in the laser diode.

5.2. Non-local interactions

All rate equations for photon emission rely on the joint densities of electrons and holes, that is, they imply “bimolecular” recombination [5]. This, in turn, calls into play the full separation of the quasi-Fermi levels, and never a fraction of it. The theoretically expected clamp of such separation and the observation of a clamping voltage in the $V - R_s I$ representation identifies the measured internal voltage with $\phi_{pr} - \phi_{ph}$, and brings back to the problem of the origin of an ideality factor $n > 1$.

The superposition in Eq. (7) and Fig. 6 partially solves the problem, showing as a distributed recombination across the active layer can both justify the non-unitary ideality factor and the occurrence of a fixed threshold voltage. But it gives, indeed, the correct threshold voltage only if the lowest limit in the integral is exactly $n_1 = 1$. This means that transitions involving the full separation of the quasi-Fermi levels must be included in the range of the possibilities. Looking again at Fig. 2, this seems impossible.

The point is that, in Fig. 2, we consider each recombination rate ruled by the difference between the quasi-Fermi levels calculated at the same position. In other words, we invoke strictly local interactions.

The situation is, if possible, even more evident if we consider a Multi Quantum Well. Fig. 7 describes an ideal double quantum well, that is supposed to be immersed in the middle of the depletion region of a Heterojunction Diode, and draws the qualitative behavior of the quasi-Fermi levels, i.e., for electrons, leading back to the reduced separation. The superposition in Eq. (7) and Fig. 6 partially solves the problem, showing as a distributed recombination across the active layer can both justify the non-unitary ideality factor and the occurrence of a fixed threshold voltage. But it gives, indeed, the correct threshold voltage only if the lowest limit in the integral is exactly $n_1 = 1$. This means that transitions involving the full separation of the quasi-Fermi levels must be included in the range of the possibilities. Looking again at Fig. 2, this seems impossible.

The point is that, in order to have a transition at full separation $qV$ and $n > 1$, we should consider that the population of electrons on the left well can interact with the population of holes in the one on the right. Only in this case we can achieve transparency applying a voltage that is $V_{th} = \hbar v/q \approx E_p/q$, and a measurable threshold $V_{th}$ that is only few percent higher than $V_{tr}$.

Furthermore, the evidence of a non-unitary ideality factor, given by the sub-threshold branches of all experimental cases, states that such a non-local transition should be much less probable than local processes. This is the meaning of the relative position of the two $I_{ph}$ curves in both Figs. 4 and 5: the component depending on $V$ must be much lower than $I_{ph}(V/n)$ in the sub-threshold range. This makes sense: local transitions are likely to be much more probable than non-local ones. It seems reasonable that such situation may be common to all diodes, and not peculiar of laser diodes. What is peculiar is that, in optical emitters, the radiative component $I_{ph}$ behaves as described by Eq. (3), with its vertical increase at threshold. This feature allows a current, that should be negligible in all other cases, to become dominant as far as the bias reaches the threshold $V_{th}$.

It seems necessary to accept in full the ultimate consequence of the Uncertainty Principle that leads to non-locality of the interaction. If one considers the different linewidth of the spontaneous and stimulated emission, it follows that the sharp definition of the electron–hole transition energy for a stimulated process requires an uncertainty in the carrier position larger by far than the thickness of the active regions, no matter if bulk, QW or MQW. On the contrary, the much wider lineshape of the spontaneous transitions allows locality to keep some meaning, and classical (including MQW transitions) recombination rates between carriers may be distinguished by their position.

The non-local interaction is of course not new, and is based on the overlap of the electron and hole wavefunctions in quantum-sized solid-state structure system. It is mentioned in several experiments as Quantum Coupling, for explaining observations in closely spaced Quantum Dots and micro-cavities (see ref. [9,10] for examples).

Anyway, in the current paper, non-locality is called into play for explaining features as simple as DC characteristics displayed even by commercial optoelectronic devices. Its novelty should be then surprising, because of the decades of science and technology in this field. It...
may be useful to consider that two things allowed to point out the problem: a) the availability of Eq. (3), that predicts the behaviour of $I_{ph}$ continuously across the whole injection range and embeds the threshold condition as a computable consequence of theory, and b) the reference of the quasi-Fermi levels to the measurable applied voltage $V$, that brings down a laser diode to the practical playground of device engineering.

5.3. Application: proton irradiation on a 1310 nm DFB

The proposed update of an existing model for laser diode DC characteristics has been applied to the case of an InP-based DFB laser diode emitting at 1310 nm, that was irradiated by 3 MeV protons for studying the effect of radiations on optical emitters for space applications. The complete report of that experiment, that shows the evidence of diffusion kinetics after irradiation, is going to be published[11]. The result relevant for this paper is summarized in Fig. 8, where the sole $I_{ph}$ is plotted, before and after irradiation, versus the reduced voltage $V - R_I$ as for the previous cases. For the sake of clarity, no calculated curve has been added, although excellent results can be easily obtained by the extended model, as reported for all previous cases. This allows focusing on the experimental evolution of the laser characteristics.

Contrary to the large majority of degradation cases, the threshold voltage $V_{th1}$ of the damaged device decreases with respect to its initial value $V_{th0}$ which should indicate a small reduction of the optical losses inside the cavity. In Fig. 8 $V_{th}$ indicates the ideal threshold voltage in case of no losses. In the sub-threshold range, on the other hand, the intensity of the radiative current reduces, which is typical of a smaller quantum efficiency of the active region.

But the most intriguing figure is the reduction also of the ideality factor.

It is beyond the scopes of this paper even to attempt the physical interpretation of the observed characteristics, that display some puzzling features. The role of the proposed example is to point out that, at least in some particular cases, the accurate analysis of some degradation kinetics must include the possibility of changes also of the ideality factor. The proposed extended model operates in that direction.

6. Conclusions

The study of the electrical characteristic and Trans-characteristics of commercial laser diodes pointed out a contradictory determination of the separation of the quasi-Fermi levels in the sub-threshold and above the threshold ranges. Several practical explanations have been considered, all based on classical arguments in Physics of Solid State Devices. Nevertheless, only the reference to deep Quantum Mechanical concepts as non-locality of photon-induced electron–hole transitions seems to be able to fully solve the contradiction.

A fascinating experiment could be imagined to verify the proposed interpretation: would it be possible to build a laser diode with two Quantum Wells of different bandgaps, and provided that the selection rules allow the “non-local” transitions, then lasing would take place at a photon energy different from the characteristic emission of each of the two wells.

References