The interpretation of the DC characteristics of LED and laser diodes
to address their Failure Analysis

G.Mura\textsuperscript{(a)} * , M.Vanzi\textsuperscript{(b)}, P.G.Meridda\textsuperscript{(b)}

\textsuperscript{(a)}Telemicroscopy Laboratory - Sardegna Ricerche - 09010 Pula (Ca), Italy
\textsuperscript{(b)}DIEE-INFM, University of Cagliari, Piazza D’Armi, 09123 Cagliari, Italy

Abstract

The interpretation of the forward DC characteristics of LEDs and laser diodes is shown as a valuable tool to infer the internal structure of real devices and to address their analysis after failures. To this purpose, the self-consistent $I(V)$ DC transfer function for the ideal laser diode is introduced.

I. INTRODUCTION

The first step in analyzing the degradation of solid state optical emitters is to measure their failure modes, that is the evidence of something wrong that affected their measurable performances, before any attempt to open their package and start a failure analysis that is necessarily destructive. It is common practice, for such devices, to simply look at the most evident of their performances, the light emission, and to measure the LOP (Loss of Optical Power). For laser diodes, the threshold current $I_{th}$ and the total optical efficiency $\eta$ are the other most investigated quantities. Other measurements are technically possible, as spectral analysis and thermal resistance, but, in practise, are much less commonly performed because of their technical requirements (not suitable to be applied on large numbers of devices or repeated at the many steps of a life test) and also of their not straightforward correlation with the failure mechanisms.

On the contrary, the very simple and standard measurement of the DC forward characteristics of those diodes is able to carry valuable information on their structure, and to refer the optical losses to different regions in the physical structure, addressing the failure analysis.

In this paper, the results of many years of practice are summarized by first recalling the equivalent circuit for some popular types of emitters, and then illustrating the effects of several degradation mechanisms on the DC characteristics.

Some practical examples from real cases will then aim to prove the utility of this approach.

II. THE ELECTRICAL MODEL

In order to build up an electrical model for a laser diode, the first step is to recognize that only a fraction of the injected current $I$ produces light. For devices without lateral current confinement (as for some vertical emitters, where the p and n- side contacts, the junction, and any other vertical element have the same area) the total current $I$ is made of two parts:

a) The current $I_a$ that is due to any recombination inside the active layer. We can split it into the radiative $I_{ph}$ and the non radiative $I_{nr}$ components, indicating in the ratio $\eta_q = \frac{I_{ph}}{I_a}$ the so called quantum efficiency.

b) The current made of charges that do recombine elsewhere, outside the optically active region. It is assumed that this component is a simply Shockley current $I_{sh}$, as suggested by its own definition. The same bias that induces recombination inside the active region is also responsible for this current, that is then represented by a Shockley diode parallel to the element that gives account for the current $I_a$.

For laterally confined devices, another important current fraction $I_W$ flows outside the designated active area at low forward bias, described by a parallel distributed network of resistive paths and junction diodes, as will be shown later.
All elements in this model then are standard electron devices, apart from the pure laser diode, whose transfer function is then the kernel of the problem.

2.1) The light emitting region.

In a previous paper [1] it has been shown that the ideal current-voltage forward characteristics of the “pure” laser diode, that is an ideal element whose current \( I_{\text{ph}} \) is completely transformed into light, can expressed as:

\[
I_{\text{ph}} = I_0 \alpha_T \times \frac{\Omega_{\text{sph}}}{\alpha_T} \left[ \exp \left( \frac{h \nu_0 - qV}{2kT} \right) + 1 \right] \left[ \exp \left( \frac{h \nu_0}{kT} \right) - 1 \right]
\]

(1)

where \( \alpha_T \) are the total (internal \( \alpha_i \) and from the facets, \( \alpha_f \)) optical losses, \( I_0 \) is a parameter proportional to the volume (area \( S \) times the thickness \( d \)) of the actual active layer (that is that fraction of the low-energy-gap epitaxial layer where the injection current is focussed in the different technological ways as, for instance, oxide stripe, or ridge, or buried crescent, etc.) and also to the peak emission energy \( h \nu_0 \), while \( \Omega_{\text{sph}} \) is essentially proportional to the joint density of states of electron and holes that share the same momentum, as required by the selection rule for radiative emission in direct-bandgap semiconductors.

Once all the above parameters are given, this formula draws the dependence of the pure radiative current \( I_{\text{ph}} \) on the forward bias \( V \) (Fig.1). It is a relevant result, because it embeds the dramatic transition that occurs when a certain threshold level, corresponding to that value of \( V \) that leads the denominator in eq.1 to vanish, is reached. It is a threshold voltage \( V_{\text{th}} \), that gives account for recombination events occurring outside the active region is now given, as usual, by

\[
I_{\text{sh}}(V) = I_{s0} \exp \left( \frac{qV}{kT} \right)
\]

(4)

so that the sole radiative current \( I_{\text{ph}} \) may be now be described as a defined part of the total current \( I \):

\[
I_{\text{ph}} = \eta_q I_a = \eta_q (I - I_{\text{sh}})
\]

(5)

The non-negligible role of \( I_{\text{sh}} \) is shown by the consideration that if the most part of the injected current \( I \) would be always converted into light, then the optical power would be proportional to the injected current at the same rate in a LED and in a laser, and the \( P_{\text{OUT}}(I) \) curves should not display any dramatic kink at \( I = I_{\text{th}} \), which is not the case.

On the contrary, the Shockley component dominates over the radiative one up to the firing of the stimulated emission.

\[
I_{s0} \gg I_{\text{sh}}
\]

(6)
The situation is qualitatively indicated in fig.2, where the total current

\[ I(V) = I_{sh}(V) + I_{phon}(V) = I_{sh}(V) + \frac{I_{ph}(V)}{\eta_q} = \]

\[ = I_{sh} \exp \left( \frac{qV}{kT} \right) + \frac{I_{ph}}{\eta_q \Lambda_{\alpha}} \left[ \exp \left( \frac{h\nu_m - qV}{2kT} \right) + 1 \right] - \frac{\Omega_{\alpha}}{\alpha_T} \left[ \exp \left( \frac{h\nu_m}{kT} \right) - 1 \right] \]

(7)

and its components are drawn together.

![Fig. 2: The total current I(V) of an ideal laser diode and its radiative (I_{ph}) and non-radiative (I_{sh}) components. The kink in I(V), that defines the threshold current I_{th}, corresponds to the value of the only I_{sh} at the threshold voltage V_{th}](image)

It also says that the threshold current for a laser diode equals the intensity of the Shockley component at \( V = V_{th} \)

\[ I_{th} = I_{sh}(V_{th}) = I_{sh} \exp \left( \frac{qV_{th}}{kT} \right) = \]

\[ = I_{sh} \exp \left( \frac{h\nu_m}{kT} \right) \left( \frac{\Omega_{\alpha} / \alpha_T + 1}{\Omega_{\alpha} / \alpha_T - 1} \right) \]

(8)

In fig. 2 the dashed line that draws I_{sh} is continued for values \( V > V_{th} \) only for graphical purposes. In real cases, the freezing of the voltage at \( V_{th} \) clamps I_{sh} at its maximum value \( I_{sh} = I_{th} \) for any value of the total current for which \( I > I_{th} \), which says that all the excess current beyond the threshold limit is entirely consumed by recombination inside the active layer.

Theoretically, it follows the possibility to measure first I_{th} from the sub-threshold DC characteristics, and then, based on the knowledge of the peak emission energy, to have also the ratio \( \Omega_{\alpha} / \alpha_T \). The quoted paper [1] reports as this method has been quite successfully applied to external cavity lasers to predict both their threshold current I_{sh} and their total efficiency \( \eta \) as functions of the total losses \( \alpha_T \), that for those devices is a tunable parameter.

2.2) The optical power

As a second important result, through eq.5, the model leads to the emitted optical power \( P_{OUT} \) by recognizing that \( I_{ph} / q \) gives the number of radiative events per unit time that, multiplied by the photon energy \( h\nu_m \), gives the total emitted optical power, whose fraction

\[ \frac{\alpha_m}{\alpha_T} = \frac{\alpha_m}{\alpha_T} \]

leaving the diode facets is just \( P_{OUT} \):

\[ P_{OUT} = \frac{I_{ph}}{q} h\nu_m \frac{\alpha_m}{\alpha_T} = \frac{1 - I_{sh}}{\eta_q} \frac{h\nu_m}{\alpha_T} \frac{\alpha_m}{\alpha_T + \alpha_m} \]

(9)

This is an expression quite similar to the well known formula for laser emission as a function of the injected current [2], but replaces the externally defined threshold current I_{th} by the voltage-dependent current I_{sh}. It is then a formula that links the optical power to both the injected current I and the applied voltage V, which should be, by itself, most troubling than useful. But the joint solution of eq.1, 4 and 8 allows to eliminate the voltage and to write a self-consistent formula for \( P_{OUT} \) that holds for the LED and the laser regime [1].

3.2) The role of the series resistance

The above expressions define the DC electrical behaviour of a LED and of a laser diode when the most part of the active layer is uniformly called to emit light at any injection level. It is the case of the wide area LEDs and of the Vertical Cavity Surface Emitting Lasers (VCSEL).

Anyway, in order to deal with real devices, even in these simplest cases the overall series resistance \( R_s \) cannot be neglected.

![Fig.3: The role of the series resistance \( R_s \).](image)

Fig.3 describes the effect of an increasing series resistance on the characteristics of fig.2. It is clear as
an excess ohmic drop can inhibit the onset of the laser regime.

In practical cases, it is rather straightforward to recover the nearly ideal situation of fig.2 by, for instance, plotting the experimental current $I$ versus the reduced voltage $V-R_sI$, after the evaluation of the value of $R_s$ by simply fitting the highest part of the experimental curve of a laser diode with the equation

$$R_s(I-I_{th}) = V,$$

or looking for the asymptotic value of $\frac{dV}{dI}$ a high injection. Even trial values for $R_s$ quickly converge to the correct result that is achieved when fig.3 reproduces the shape of fig.2.

In summary, the equivalent circuit for a surface emitting diode laser diode may be proposed as in fig. 4. Here, the diode $D_{th}$ represents the Shockley component (eq.4), while the “diode” $D_L$ refers to the current-voltage characteristics of eq. 1, recalling that the total current crossing that element is $I_{th}/\eta q$ and that only a fraction $\eta q$ (that is, just $I_{th}$) is transformed into light. The series resistance $R_s$ completes the network.

As before, for a surface emitting LED the circuit is the same, but the diode $D_L$ never achieves the optical threshold for laser emission, and behaves as a pure Shockley element, according to eq.3.

$$R_s$$

$$D_{sh}$$

$$D_L$$

Fig.4. The equivalent circuit for a surface emitting diode.

2.4) The side areas.

For edge emitters, and also for laterally confined surface emitting devices, the situation is complicated by the existence of side areas, made of the same heterostructure as the active region, but flood with less current at high injection, because of different technological choices for lateral current confinement.

A ridge structure may be here considered (fig.5), keeping in mind that everything can be repeated for oxide stripe or buried crescent, or other laterally confined devices.

![Fig.5. A ridge emitter and its additional elements](image)

Here, the current is allowed to spread under the ridge region everywhere on the junction surface. Anyway, the narrow injecting structure forces the current lines that reach the sides of the device to travel a longer path, and then to face higher ohmic drop than the nearly vertical current lines.

The additional elements are made of a chain elements that build a sort of transmission line at distributed parameters.

Each diode in the lateral wings is made of the same structure and material as the active region, and behaves in the same way. The total area of these lateral diodes is much larger than the area of the active region and, at very low injection, when the ohmic drop along the horizontal paths is still negligible, the drive the most of the injected forward current. At higher current levels, the lateral resistors limit more and more the current, and in practice focus the charge injection into the active region, just under the ridge. The lateral diodes never achieve the population inversion, so that their characteristics are always given by eq.1 in the LED limit (eq.3) that, in turn, because of eq.6, coincide with the pure Shockley component $I_{th}$ in eq.4.

Let us consider $L$ the extension of one of the lateral wings, $R_L$ he total resistance of the group of lateral resistive elements, and $I_{th}$ the saturation current of the complete set of diodes in the wing (if we assume $W$ as the lateral extension of the active area, we have $\frac{I_{th}}{I_{th}} = \frac{L}{W}$ and the ratio easily achieves many decades or hundreds). It is not difficult to set the equations for the $I_{th}(V)$ characteristics of the wing in a distributed-element approach:

$$\begin{align*}
\frac{dI_w(x)}{dx} &= - \frac{I_{th}}{L} \exp \left( \frac{V(x)}{V_T} \right) \\
\frac{dV(x)}{dx} &= - \frac{R_s}{L} I_w(x)
\end{align*}$$

with the boundary conditions:
\[
\begin{align*}
I_W(L) &= 0 \\
V(0) &= V_L
\end{align*}
\]

where \(V_L\) is the voltage across the active layer (that is the applied voltage \(V\) reduced by the effect of the series resistance \(R_s\): \(V_L = V - R_s I\)) and \(V_T = \frac{kT}{q}\).

By solving the coupled equations it is possible to define the total current \(I_{th}(V)\) entering the wing, that is the value of \(I(V(x))\) at \(x=0\):

\[
I_W(V_L) = \frac{V_L}{R_L} \left[ 1 + \frac{R_s I_{th,0}}{V_T} \exp\left(\frac{V_L}{V_T}\right) - 1 \right]
\]

(10)

Taking into account the very small value of the typical saturation currents, even in large diodes, that makes the exponential small compared to unity for a wide range of low forward voltages, we have:

\[
I_W(V_L) = \begin{cases} 
I_{th,0} \exp\left(\frac{V_L}{V_T}\right), & \text{low } V_L \\
\sqrt{\frac{2 V_L I_{th,0}}{R_L}} \exp\left(\frac{V_L}{2V_T}\right), & \text{high } V_L
\end{cases}
\]

(10a)

The contribution of this lateral current (doubled for including both wings) is shown in fig.6.

Finally, some possible parasitic ohmic conduction parallel to the junction (as for leaky surface paths) may be taken into account by including a general shunt resistance, whose regular values are usually extremely high (in the range of giga-ohms and more). The final model, suitable for parameter fitting, is reported in fig. 7.

![Fig.7: The complete electrical model for the light emitting diodes and lasers.](image)

3) Experimental cases

Three different cases will be presented:

A) The evolution of the optical characteristics of a laser diode upon the controlled variation of the total optical losses in an external cavity device.

B) The degradation of a family of laterally confined, surface emitting diodes

C) The quite peculiar degradation mode of a GaN-based blue laser, with ridge structure for the lateral confinement.

3.1 The external cavity tunable laser

The first example is almost only a test of the new equations, and has been reported in the quoted ref.[1].

In an external cavity tunable laser the “mirror” losses \(\alpha_m\) are fixed, while the adjustable length of the cavity directly affects, in a controllable way, the total losses \(\alpha_f\). The knowledge of the imposed total losses in at least two cases allowed to fit the relevant coefficients in eq. 8 and eq.1.

The \(P_{OUT}(I)\) are then drawn (fig.8) as continuous curves for any value of \(\alpha_f\), where the threshold current, the total efficiency and even the smoothed transition between the low and the high emission ranges are completely overlapped on the experimental curves.
3.2 A surface emitting, laterally confined, GaAs-based LED.

For such a device, the equivalent model is identical to that reported in fig.7, with the difference that the laser diode never “fires” the stimulated emission diode never “fires” the stimulated emission.

Fig.9 reports the nice curve fitting that the proposed model allowed, and the obtained values of the relevant parameters for a reference good device. It also draws some curves measured on degraded devices, whose optical emission was almost cancelled after operation in field. The degradation can be read as a strong increase of the sole $I_a$ component, that means a problem of increased recombination rate inside the laterally confined active region. A simple investigation by means of Electroluminescence showed the systematic occurrence of extended DLDs, just inside the active area.

3.3 A GaN-based, ridge-type, blue laser

The newest and more intriguing result comes from the study of a GaN-based MQW edge emitting blue laser, where lateral confinement is achieved by means of a ridge structure, like that schematically drawn in fig.5.
The peculiar findings, at various steps of a 100 h long thermally accelerated, operating life test are:

a) the strong variation of the only current $I_W$, since the very early steps (fig.11), that is not progressive in any direction: the current rises and lowers by nearly decades during the test, while the current in the active area remains nearly unchanged.

b) The optical power (fig.12) remains unchanged for the first steps, and then undergoes some slight variation, with a fair (less than 10%) progressive increase of the threshold current.

Both effects may be explained by the celebrated diffusion of hydrogen atoms from the upper semiconductor-passivation interface [3]. The source of the diffusing particles is by far closer to the junction areas of the side wings than to the active region. They are then expected to reach and affect those parts of the device since the beginning of the test. Their surface density should not be assumed uniform, nor their capture (if any) inside the active layer efficient. Their perturbing effect (sometimes indicated as a local dopant compensation) is then related to their instant density, and may change along the evolution of the test.

The active region should display some effect only after the arrival of those particles after a longer trip, and maybe their dilution. It is not absurd to imagine that the first effect will be on the radiative properties, and only at longer times electrical effects will start to appear.

CONCLUSIONS

The introduction of the DC characteristics of a “pure laser diode”, together with the study of the branching of the injected current in real devices, allows to describe and fit the experimental behaviour of LEDs and solid state lasers.

The correlation of the main current branches with the technological elements in the emitters allows to read the DC characteristics of a degraded device in term of more physical failure mechanisms.

Moreover, the availability of an analytic transfer function for the DC current-voltage relationship allows to include even the laser diodes as circuit elements in many circuit design simulation tools.

REFERENCES

