Carrier Capture and Escape Processes in $In_{0.25}Ga_{0.75}As$–GaAs Quantum-Well Lasers

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***Abstract*— We have extracted the ratio between the carrier capture and escape times, η, for $In_{0.25}Ga_{0.75}$As–GaAs lasers containing one, two, or three quantum wells, from high-frequency subthreshold impedance measurements at different temperatures. Our results show that the carrier capture process dominates over the diffusion along the confinement region in the overall transport/capture process. The obtained value for η is comparable to unity, and this fact has to be taken into account to obtain real material parameters, such as the carrier lifetime and the radiative recombination coefficient.**

***Index Terms*— Gallium compounds, impedance measurement, laser measurements, quantum-well lasers, semiconductor lasers.**

THE RATIO between the carrier capture and escape times ($\tau_{\rm cap}$ and $\tau_{\rm esc}$, respectively), $\eta \equiv \tau_{\rm cap}/\tau_{\rm esc}$, is an important parameter in quantum-well (QW) lasers, since it can limit the maximum achievable modulation bandwidth [1], and it influence many other device characteristics. It has been shown that when η is comparable to unity, the effective differential gain decreases and the damping factor K increases [1]. In consequence, both the modulation bandwidth at a given bias level and the maximum modulation bandwidth decrease. However, there is a lack of experimental results relating η with the epilayer structure and the laser operating conditions.

In standard single-particle rate equation models, $\tau_{\rm cap}$ includes the contributions of two different processes: 1) the diffusion of carriers along the separate confinemen layer (SCH) and 2) the intrinsic capture of carriers into the well. It can be expressed as [2]

$$\tau_{\rm cap} = \frac{d_{\rm SCH}^2}{8D} + \tau_{\rm cap0}\frac{d_{\rm core}}{d_{\rm QW}} \qquad (1)$$

where $\tau_{\rm cap0}$ is the intrinsic or local capture time, $d_{\rm core}$ is the core region width, $d_{\rm QW}$ is the total QW width, $d_{\rm SCH}$ is the SCH layer width, and D is the diffusion constant related to the carrier mobility. The firs and second terms of the right-hand side of (1) represent the contributions of the transport and intrinsic capture processes, respectively. The question of which of them is the dominant one has been debated for a long time [1], [2]. It was finall concluded that depending on the lengths of the confinement barrier and QW regions one effect will dominate over the other or vice-versa.

In In_xGa_{1-x}As–GaAs lasers the escape time is expected to decrease with decreasing indium concentration, due to the exponential dependence of the escape time on the effective barrier height [3], [4]. This decrease can have dramatic consequences on the modulation bandwidth of these structures if the condition $\eta \ll 1$ is no longer valid.

We have recently demonstrated [5]–[7] that high-frequency electrical impedance (HFEI) measurements can provide valuable information about the carrier dynamics in QW lasers. We have also concluded that, for properly designed $In_{0.35}Ga_{0.65}$As–GaAs lasers, η is much lower than unity due to the strong confinemen of electrons in the well, and this fact has contributed to the demonstration of very high-modulation bandwidths (40 GHz) in these devices [8].

In this letter, we present subthreshold HFEI impedance measurements for $In_{0.25}Ga_{0.75}$As–GaAs lasers with one, two, or three QW's. The analysis of the results yields that η for these structures is comparable to unity, causing a discrepancy between real and apparent values of the effective carrier lifetime τ_2 and the radiative recombination coefficien B. A similar result was previously obtained by Odagawa *et al.* [9] in InGaAs–InGaAsP lasers. The dependence of the apparent radiative recombination coefficien on the structural differences in the samples indicates that the total transport/capture process is dominated by the capture of carriers from the three-dimensional (3-D) states to the two-dimensional (2-D) states, and not by the diffusion of carriers along the confinemen layer. The conclusions obtained at room temperature (RT) were confirme by measurements at different temperatures ranging from 15 °C to 85 °C.

Using a single-particle rate equation model, the frequency dependence of the subthreshold electrical impedance in QW lasers can be expressed as a transfer function with one zero and two poles [6]. According to [5], when $\tau_{\rm cap}$ and $\tau_{\rm esc}$ are much lower than τ_2, both the zero and the second pole lie at high frequencies and are difficul to observe experimentally due to the series resistance. Therefore, the intrinsic impedance (and also the subthreshold small-signal response of the spontaneous

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emission) shows a single low-frequency pole:

$$Z(\omega) \propto \frac{1}{(1+j\omega p_1)} \tag{2}$$

with

$$p_1 = \tau_2\left(1+\frac{\tau_{\rm cap}}{\tau_{\rm esc}}\right). \tag{3}$$

This expression indicates that when the capture/escape interplay is negligible ($\tau_{\rm cap}/\tau_{\rm esc} \ll 1$)$p_1$ and τ_2 coincide, but if not, the measurements of the pole have to be corrected in order to obtain τ_2.

In the case of negligible Auger recombination, the dependence of τ_2 on the bias current I is given by [10]

$$\frac{1}{\tau_2^2} = A + \frac{4B}{qV_{\rm QW}} I \tag{4}$$

where A and B are the nonradiative and radiative recombination coefficients respectively, $V_{\rm QW}$ is the active region volume, and q is the elementary charge. With the help of (3) and (4), we can relate the injection current to the pole of the measured impedance

$$\frac{1}{p_1^2} = A^* + \frac{4B^*}{qV_{\rm QW}} I \tag{5}$$

where A^* and B^* are the effective (or apparent) nonradiative and radiative recombination coefficients respectively. The relationship between B and B^* is given by

$$\frac{1}{\sqrt{B^*}} = \frac{1}{\sqrt{B}}\left(1+\frac{\tau_{\rm cap}}{\tau_{\rm esc}}\right). \tag{6}$$

Combining (1) and (6), we can consider two different limiting cases, which yield different dependencies of B^* on the geometrical structure.

1) The quantum capture dominates over the transport:

$$\frac{1}{\sqrt{B^*}} = \frac{1}{\sqrt{B}}\left(1+\frac{\tau_{\rm cap0}}{\tau_{\rm esc}}\frac{d_{\rm core}}{d_{\rm QW}}\right). \tag{7}$$

2) The transport process dominates over the capture:

$$\frac{1}{\sqrt{B^*}} = \frac{1}{\sqrt{B}}\left(1+\frac{d_{\rm SCH}^2}{\tau_{\rm esc}8D}\right). \tag{8}$$

The samples used in this study were grown by molecular beam-epitaxy on GaAs substrates. A detailed description of the layer sequence, and of the dc properties of the devices can be found elsewhere [11]. In brief, the epilayer structure consist of one, two or three 7-nm $\rm In_{0.25}Ga_{0.75}As$ QW's separated by 14- and 17-nm GaAs barriers for the double-quantum-well (DQW) and triple-quantum-well (3QW) samples, respectively. The total core width was 200 nm and the cladding layers consist of $\rm Al_{0.6}Ga_{0.4}As$. The lasers were fabricated in a triple mesa structure [12] with an active mesa width of 16 μm, and they were cleaved to a length of 200 μm. On-wafer measurements of both magnitude and phase of the impedance were performed at different temperatures ranging from 15 °C to 85 °C, using a fully calibrated HP 8722A network analyzer up to frequencies of 40 GHz.

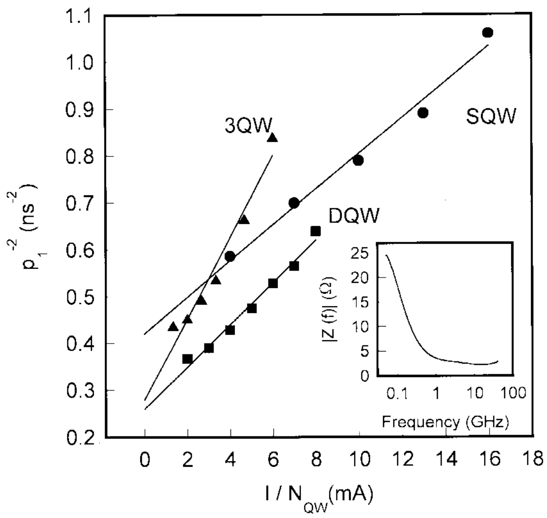

Fig. 1. Inverse of the squared pole versus injected current per well for the three samples analyzed in this work: SQW, DQW, and 3QW. The lines are the linear regressions to the data. The inset shows an example of the measured subthreshold impedance versus frequency at a bias level of 2 mA for the SQW laser.

TABLE I
EFFECTIVE RADIATIVE RECOMBINATION COEFFICIENT, CORE/QW WIDTH RATIO, η AT 298 K OBTAINED (a) FROM FITTINGS AT ROOM TEMPERATURE AND (b) CONSIDERING THE TEMPERATURE DEPENDENCE

Sample	B^* (cm^{3}s^{-1})	$d_{\rm core}/d_{\rm QW}$	η (298) (a)	η (298) (b)
SQW	0.35 x 10^{-10}	27.6	1.1	1.1
DQW	0.52 x 10^{-10}	13.3	0.5	0.7
3QW	0.98 x 10^{-10}	8.5	0.3	0.3

The inset of Fig. 1 presents an example of the measured magnitude of the subthreshold impedance versus frequency for the single-quantum-well (SQW) sample at 2 mA. The curve shows a single low-frequency pole as predicted by (2). The values of p_1 were extracted by fittin (2) (including a parasitic series resistance) to the measured impedance. The values of $(1/p_1)^2$ versus bias current per well are presented in Fig. 1 for the three samples under study. By making a linear regression of the experimental points (as shown in Fig. 1), we obtained the values of B^* which are listed in the second column of Table I. The different values obtained for A^* are not fully understood and are attributed to differences in the material quality of the different samples. As B is a material parameter, it should not depend on the number of QW's; therefore, the differences observed in B^* for the three samples denote different values of η, attributed to differences in physical dimensions (the ratio $d_{\rm core}/d_{\rm QW}$ and $d_{\rm SCH}$).

In order to determine the dominant contribution to the overall transport/capture process (diffusion or capture), we have made linear regressions of $1/B^{*1/2}$ versus $d_{\rm core}d_{\rm QW}$ (case I) and versus $d_{\rm sch}^2$ (case II), respectively. Although three points are not enough for extracting reliable quantitative parameters, it is possible to obtain valuable qualitative information. By extrapolating the linear regressions in both cases, to $d_{\rm core} = 0$ in case I and to $d_{\rm sch} = 0$ in case II, we obtained values for B of 1.4 × 10^{-10} and 60 × 10^{-10} cm^3·s^{-1}, respectively. The firs value is in good agreement

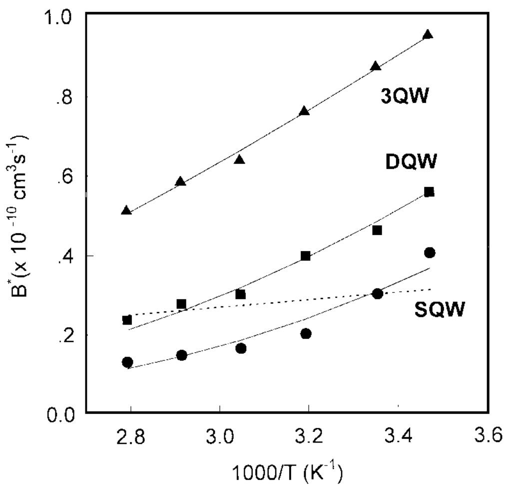

Fig. 2. Effective radiative recombination coefficien B^* versus the inverse of the temperature for the SQW, DQW, and 3QW samples (points), and best fi to (10) (lines). The dashed line shows the ideal linear behavior of the radiative recombination coefficien B for the SQW sample.

with the typical value for GaAs-based QW's [13], while the second one is unrealistic. Therefore, we can conclude that in these samples the carrier capture dominates over diffusion in the overall transport/capture process. The values of η coming from the regression in case I are listed in the fourth column of Table I. These values are comparable to unity, and therefore any measurement of τ_2 based on the position of the low frequency pole has to be corrected with (3).

In order to confir the results obtained at RT, we analyzed the HFEI measurements at different temperatures. From the slopes of the linear regressions of p_1^{-2} versus I, we extracted B^* for each sample at different temperatures. We obtained a superlinear dependence of B^* on T^{-1}, which is clearly shown in Fig. 2, where this behavior is compared with the theoretical linear dependence of B on $1/T$ [14] (dotted line). This superlinear dependence is attributed to the exponential dependence of $\tau_{\rm esc}$ on the inverse of the temperature [3], [4]:

$$\tau_{\rm esc}(T) = \tau_{\rm esc}(298)\left(\exp\frac{V_b}{k}\left(\frac{1}{T}-\frac{1}{298}\right)\right) \quad (9)$$

where V_b is the effective barrier height, k is the Boltzmann constant, and T is the measurement temperature. Combining (6) and (9), and neglecting the dependence of $\tau_{\rm cap}$ on T, we get the temperature dependence of B^*

$$B^*(T) = B(298)\,\frac{298}{T}\left(1+\frac{\eta(298)}{\exp\frac{V_b}{k}\left(\frac{1}{T}-\frac{1}{298}\right)}\right)^{-2}. \quad (10)$$

Expression (10) was fitte to the experimental data, using a single value for $B(298)$ and different $\eta(298)$ for each sample as fittin parameters. The effective barrier height V_b was set to 0.11 eV (calculated by solving the Schrödinger equation for electrons in a squared QW). The fittin procedure yielded a value of 1.4×10^{-10} cm^{3}s^{-1} for $B(298)$ and the values for $\eta(298)$ which are listed in fift column of Table I. The agreement between these values, obtained independently for each sample from the temperature dependencies, and the ones obtained from the regressions at 25 °C using (7), considering the structural dependence, is quite good, confirmin the coherence of the model.

In conclusion, we have performed and analyzed high-frequency electrical impedance measurements in $In_{0.25}Ga_{0.75}As$–GaAs MQW lasers with different QW numbers in the active region. We have shown that this technique provides valuable information about the time constants that govern the capture and escape processes in the QW. Our results demonstrate that the $\tau_{\rm cap}/\tau_{\rm esc}$ ratio in $In_{0.25}Ga_{0.75}As$–GaAs lasers is comparable to unity, and this fact has to be taken into account when performing carrier lifetime measurements to obtain real material parameters. The capture process in these samples dominates over diffusion on the overall transport/capture process.

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