Analysis of 6-nm AlGaAs SQW Low-Confinement Laser Structures for Very High-Power Operation

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Abstract— This paper reports experimental results on single quantum-well separate confinement heterostructures (SQW SCH) with low-confinement factor, designed for very high-power operation. The maximum power output for AR/HR coated 3-mm-long devices, measured in very short pulsed conditions (100 ns/1 kHz), from 10- μ m-wide stripes was as high as 6.4 W before catastrophic optical degradation. If scaled to continuous-wave (CW) conditions, this value would be 800–1100 mW, which would mean a factor of 2–2.7 times more than reported for the best devices with normal design for threshold minimization. The absorption coefficient for the symmetrical structure is as low as 1.1 cm⁻¹, in spite of the low trapping efficiency of carriers in the quantum well (QW). The maximum differential efficiency is 40% (both faces, uncoated devices) for symmetrical structure and 33% for the asymmetrical one (all measurements in pulsed conditions). Threshold current densities were 800 A/cm² for 5-mm-long devices in the symmetrical case and 2200 A/cm² in the asymmetrical one. The effects of inefficient carrier trapping in the QW on the threshold current densities and differential efficiency are discussed.

Index Terms— Gallium materials/devices, injection lasers, optoelectronic devices, quantum-well devices, semiconductor lasers.

I. INTRODUCTION

THE CONCEPT of “low confinement” [1], [2] for optimization of high power operation of laser diodes seems to have a very promising potential for increasing the output power from single devices by a factor of three. This concept can be also integrated with the other designs for high power operation [antiguidded arrays, master oscillator power amplifier (MOPA)] leading to the further increase of the available power from semiconductor devices, with a very high market potential.

Recently, using this concept, values as high as 8-W continuous-wave (CW) power from broad waveguide Al free diode lasers were reported [3]. This paper aims to study AlGaAs structures with a single quantum well (6 nm), having a design that lowers the value of the confinement factor by a factor of three compared to normal commercial structures.

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Using the symmetrical approach, the minimum value of the confinement factor is around 1% and is practically limited by the thickness of the confinement layers needed to keep the absorption coefficient in the substrate and contact layer lower than 0.03 cm⁻¹. The asymmetrical approach is much more flexible with respect to this point of view, and offers the possibility to obtain optical confinement factors lower than 0.005, with good discrimination against the second-order mode or eliminating it completely. Also, it allows the possibility to minimize free carrier absorption by keeping the major part of the optical field in an n-type low-doped separate layer, where free carrier absorption is lower. We assume here the free carrier absorption coefficient $\alpha_{fc} = 3 \times 10^{-18}n + 7 \times 10^{-18}p$, where n and p are the free electron and hole concentrations in cm⁻³.

II. LOW-CONFINEMENT CONCEPT

We present here very briefly the low confinement concept [2].

The optimization for high-power operation does not coincide with the optimization for threshold current density, which is normally taken into consideration for laser diode design. In many situations, the limiting factor of the device is the catastrophic optical degradation of the mirror. In this case, optimizing the device for high power is related to the lowering of the confinement factor for the active region, keeping at the same time the threshold current density at a reasonable value (200–400 A/cm² compared with an operating current density of 2000–4000 A/cm², design for CW operation).

Given the COD power density value p for a certain material, the available output power is

$$P_{\text{out}} = \frac{p w d}{\Gamma} \quad (1)$$

where w is the stripe width, d is the active region thickness, and Γ is the confinement factor. Looking at (1), we easily notice that if the value of the confinement factor is decreased, the value of the output power is increased by the same factor. As a consequence, the modal gain

$$G = \Gamma g = \alpha + \frac{1}{L} \ln \frac{1}{R} \quad (2)$$

where g is the material gain, is also decreased, which means that lower absorption coefficients and longer device lengths are needed if we want to keep the same value of the material gain.

Fig. 1. (a) Refractive index and optical field distribution for the symmetrical structure and (b) refractive index and optical field distribution for the asymmetrical structure.

The differential efficiency is given by

$$\eta = \eta_i \frac{\frac{1}{L} \ln \frac{1}{R}}{\alpha + \frac{1}{L} \ln \frac{1}{R}} \quad (3)$$

where η_i is the internal efficiency, L is the device length, R is the facet reflectivity, and α is the value of the absorption coefficient. As we can see examining (3), in order to keep a high value for the differential efficiency, a very low value of the absorption coefficient is necessary, i.e., $<1 \text{ cm}^{-1}$ for 2–4-mm device lengths.

Also, the low confinement design offers the possibility of increasing the value of the stripe width operating in the fundamental lateral mode (without filamentation) due to the smaller free carriers induced antiguiding in the active region [1], [2].

III. THE STRUCTURES

Using the design presented above, the purpose of our structures is to decrease the confinement factor in the active region by a factor of three. At the same time, the doping level must be correspondingly modified in order to keep the value of the absorption coefficient lower than 1 cm^{-1} . The simulation of the I - V characteristic in the lasing regime, for the symmetric structure, shows that the value of the series

Fig. 2. P - I front facet output power characteristic for a $10 \mu\text{m}$ wide stripe, $L = 3\text{-mm}$ -long AR/HR coated device from the symmetrical structure.

resistance due to the relatively low-doped layers is lower than 0.1Ω for a $10 \mu\text{m} \times 5 \text{ mm}$ device, which is adequate for CW operation.

If we use only the traditional symmetrical scheme, the lowest value we can get for the confinement factor is only $7\text{--}9 \times 10^{-3}$. This value is limited by the thickness of the cladding layers needed to keep the attenuation coefficient due to absorption in the substrate and contact layers lower than 0.03 cm^{-1} , which should be smaller than $2.5 \mu\text{m}$ for practical reasons.

In order to study the influence of the asymmetrical design, we also used a symmetrical one, having the same value for the thickness of the active region and a slightly higher value of the confinement factor.

These two structures based on AlGaAs, one symmetric and one asymmetric, are presented in Fig. 1(a) and (b), respectively. Both structures have a 6-nm QW active region. The value of the confinement factor is 0.0115 for the first one and 0.0092 for the second one. The waveguide thickness has the normal value of $0.3 \mu\text{m}$ in the first case and $1.0 \mu\text{m}$ in the second one. For the symmetric structure, the AlAs mole fraction difference between the barrier and the cladding layers is as low as 0.09, while for the second one the confinement layer configuration consists of two $0.037 \mu\text{m}$, $x = 0.3$ barrier layers sandwiched asymmetrically in the $1\text{-}\mu\text{m}$ -wide $x = 0.35$ waveguide.

IV. EXPERIMENTAL RESULTS

A. Device Growth and Processing

The structures were grown by molecular beam epitaxy (MBE) at TUE Tampere and at TUE Eindhoven. In the case of the symmetric structure, the waveguide region is undoped and the confinement layers have a low doping ($5 \times 10^{16} \text{ cm}^{-3}$) level in regions $0.35\text{-}\mu\text{m}$ wide close to the active region. For

Fig. 3. (a) Plot of the inverse of the differential efficiency as a function of device length for the symmetrical structure, (b) threshold current density as a function of device length for the symmetrical structure, (c) plot of the inverse of the differential efficiency as a function of device length for the asymmetrical structure, and (d) threshold current density as a function of device length for the asymmetrical structure.

the asymmetric one, the large (1- μm -thick) waveguide layer has a low doping level ($5 \times 10^{16} \text{ cm}^{-3}$).

The two MBE structures were processed in standard 60- and 10- μm -wide stripes, using a liftoff SiO_2 technique followed by deposition of Cr-Au p-side and AuGe n-side ohmic contacts. Wide stripe devices (60 μm) were used for obtaining threshold current densities and differential efficiencies while the 10- μm stripe ones were HR/AR coated for testing the catastrophic degradation level.

B. Output Power P - I Characteristic

The results of an AR/HR coated device from the symmetrical structure, having $L = 3 \text{ mm}$ length and 10- μm stripe width are presented in Fig. 2. As we notice, the maximum output power before catastrophic degradation is as high as 6.4 W. This measurement was done in very short pulsed conditions (100-ns pulse length, 1-kHz repetition rate). If we scale this value to CW conditions [17], we would get a value of 800–1100 mW which corresponds to a power/stripe width ratio of 80–100 mW/ μm . These values would be a factor of 2–2.7 times greater than the best values reported for structures optimized for

threshold current densities and in good agreement with CW values obtained by Botez and all [3] using a similar design on 980-nm wavelength devices. We did not test our devices in CW conditions due to the relatively high threshold current density and differential efficiency and to the lack of a suitable power source up to the levels corresponding to catastrophic degradation.

C. Threshold Current Densities and Differential Efficiencies

The differential efficiencies and threshold current densities in both symmetrical and asymmetric case are presented in Fig. 3(a)–(d), respectively. In this case, all measurements were made in pulsed (1% duty factor) conditions.

The threshold current density is 800 A/cm² for 5-mm-long devices with the symmetrical design and 1500 A/cm² for 2-mm length. The values of the threshold current density is approximately a factor of three higher for the asymmetrical case, which could be correlated with an abnormally high carrier population in the three times wider waveguide. A detailed discussion is presented in the next section. It is interesting to notice that 0.6-mm devices (corresponding to

a high material gain) are not lasing at all for the asymmetric structure.

The differential efficiencies are relatively low, (maximum 40% for the symmetrical case and 33% for the asymmetrical one). This can also be related, although not as directly as the threshold current density, with an abnormally high carrier population in the waveguide and cladding layers. In this case, the well-known dependence of the inverse of the differential efficiency as a function of device length must be carefully used, in order to extract laser parameters like absorption coefficient and internal efficiency as in [3]. A detailed discussion is also following in the next section.

D. Lasing Wavelength and Far Fields

The lasing wavelength is around 826 nm for long devices (3–5 mm), in both cases. For the 0.6-mm-long devices in the symmetric case (in the asymmetric one, as mentioned above devices are not lasing at all) the wavelength at threshold shifts to 810 nm. This shift corresponds to a shift of the wavelength corresponding to the peak gain from the 1e–1hh transition for low-material gain to that corresponding to the 1e–1lh hole transition for relatively large material gain (1000 cm^{-1}). This value is in good agreement with the theoretical one obtained using a valence band mixing model for computing the gain as a function of wavelength for different injection levels.

The far-field transverse angle $\theta_{1/2}$ is 32° for the symmetrical structure and 28° for the asymmetrical one. For the $10\text{-}\mu\text{m}$ -wide stripes the lateral $\theta_{1/2}$ value is as low as 5° , but it is stable only until 100–200 mW due to the nonoptimized thickness control in the case of chemically etch ridge fabrication.

V. DISCUSSION

A. Classical Modeling of the Device

The modeling of device parameters was first made using a standard transfer matrix approach for computing the optical confinement factor and absorption coefficient in the substrate and contact layer, and a standard drift-diffusion model for the computation of the injection efficiency. The gain in the QW was also modeled using a valence band mixing model. In this case, the threshold gain is reduced by a factor greater than two when compared to the parabolical approximation. Also, the threshold sheet carrier density is increased up to values as high as $3.5 \times 10^{12} \text{ cm}^{-2}$ ($5.75 \times 10^{18} \text{ cm}^{-3}$) for peak gains larger than 1500 cm^{-1} .

In normal conditions, the material gain for our devices should not be greater than 700 cm^{-1} for 2-mm device length. The lasing wavelength is a proof that the actual gain in 2–5-mm devices is less than 900 cm^{-1} . But even for such high QW threshold carrier densities ($4 \times 10^{12} \text{ cm}^{-2}$), the high values for the threshold current density and the low values of the differential efficiency can not be explained, even taking a value as short as 1 ns for the nonradiative recombination time in the AlGaAs layers. For example, for the asymmetric structure, the threshold current density in such a case should be only 1000 A/cm^2 (compared to 2200–6000 A/cm^2 experimental values) and the injected carrier density within the barriers and cladding

layers would be lower than $2 \times 10^{17} \text{ cm}^{-3}$, which cannot explain the abnormal low value of the differential efficiency. In the symmetrical case, also the relatively high value of the threshold current density for low material gains (confirmed by the lasing wavelength) and most of all, low internal efficiency can not be explained using this model.

In the above modeling, the QW nature of the active region was taken into consideration only by using the specific “step like” density of states. On the other hand, early reports [4], [5] revealed that, in the case of very thin QW’s, barrier recombination in photoluminescence studies is enhanced due to inefficient trapping of carriers in the QW. This means a much higher barrier population than found by computations using normal thermionic emission. Also in [6], experimental results of the threshold current density for single quantum-well separate confinement heterostructures (SQW SCH) structures are given, showing higher threshold current densities for this type of structures compared to GRIN designs, for very thin QW’s. Moreover, recently unambiguous quantum capture effects in quantum well laser parameters, especially dynamic parameters, were proved [7], [8] and discussed [9]–[11]. However, the role played by quantum capture and escape times in determining the steady-state laser parameters were not investigated.

In the following, an explanation of the effects noticed in the 6-nm SQW structures based on carrier capture/escape times is going to be proposed.

B. Introduction of the Carrier Capture/Escape Times to the Classical Drift Diffusion Model

The original drift-diffusion model takes into account the three semiconductor equations: the continuity equations of the hole and electron current densities and Poisson’s equation for the potential.

$$\frac{d^2\varphi}{dx^2} = q(p - n + N_D^+ - N_A^-) \quad (4)$$

$$\frac{dJ_n}{dx} = qR(n, p) \quad (5)$$

$$\frac{dJ_p}{dx} = -qR(n, p) \quad (6)$$

where φ is vacuum potential, J_n , J_p are the electron, respectively, hole current densities, N_D^+ and N_A^- are the concentrations of ionized impurities, and $R(n, p)$ is the recombination rate which includes Shockley–Read–Hall, bimolecular and Auger types of recombination. The populations in the heterostructure are described using the Fermi distributions.

This simple model is not valid for regions very close to the active region, where quantum carrier and escape rate equations should be used [9], [11]. An attempt to fit the quantum rate equation model (valid in the range given by the carrier coherence length) with the classical diffusion one for large SCH waveguides (thickness $> 500 \text{ \AA}$) is made using the concept of “ambipolar local capture time” in [9], [11]. Following that approach, in this paper the local capture/escape times are taken into consideration by imposing a Fermi level discontinuity between the active region and the barrier layers (or between the area near the QW where the transport is governed by quantum

Fig. 4. Schematic diagram of the theoretical model of carrier transport in the device.

rate equations and the neighboring regions in our case, scaling correspondingly the local carrier capture/escape time). Fig. 4 shows schematically the theoretical model described above. In the SCH region, with the exception of an area of the size of the coherence length, which also includes the QW, the classical drift-diffusion equations are used. We describe the behavior in the QW and in the neighboring areas in the limit of the coherence length, using a Fermi level discontinuity related with the escape/capture time by the rate equations [9] using a net capture rate density I_{net} in the QW given by

$$\frac{I_{net}}{q} = \frac{d_{coh}n_b}{\tau_{cap}} - \frac{d_{QW}n_{QW}}{\tau_{esc}} \quad (7)$$

and a net barrier injection rate density I_{nb} at the limit between the region where classical equations describe the carrier transport and the region where rate equations which impose the Fermi level discontinuity are used.

$$\frac{I_{nb}}{qd_{coh}} = \frac{I_{net}}{qd_{coh}} - R_b(n_b) \quad (8)$$

$$\frac{I_{net}}{qd_{QW}} = R_{QW}(n_{QW}) + v_g G s \quad (9)$$

where d_{coh} is the coherence carrier length, $R_b(n_b)$ is the recombination rate in the region very close to the QW, n_b is the carrier density in the d_{coh} range, $R_{QW}(n_{QW})$ is the recombination rate in the QW at threshold, $v_g G s$ describes the stimulated recombination rate with v_g the group velocity of photons, G is the gain, and s is the photon density.

Combining (8) and (9), we obtain the barrier carrier concentration in the region governed by quantum rate equations n_b as

$$n_b = n_{QW} \frac{d_{QW}}{d_{coh}} \frac{\tau_{cap}}{\tau_{esc}} + (R_{QW} + v_g G s) \frac{d_{QW}}{d_{coh}} \tau_{cap} \quad (10)$$

The first term describes the increased population in the barrier (next to the QW) due to the carrier capture/escape time rate and the second the increase in the barrier carrier concentration due related to the recombination in the QW (spontaneous or stimulated). Equation (10) describes the Fermi level discontinuity between the region governed by quantum rate equations and the one where classical drift-diffusion model is valid. The second term is unimportant in our case, if we take a value of 1.25 ps [11] for the local ambipolar carrier capture time. The first term instead can be very high for very thin quantum well

Fig. 5. Computed electron and hole current densities in lasing conditions for the symmetrical structure.

regions in the high injection regime, due to the high τ_{cap}/τ_{esc} ratio in this case. Values as high values 0.4–0.5 for such ratios were computed for AlGaAs SCH [12].

In such a case, because of the increased population in the barrier layers, the threshold current is much increased by decreasing the injection efficiency due to recombination in the barriers. The modeling of the differential efficiency is more subtle [13], [14] because, in principle, carrier densities are pinned after threshold. In this case, the differential efficiency can be decreased due to the increase of the leakage current in the barriers and due to the increase of the absorption coefficient on barrier and waveguide injected carriers. Considering the whole heterostructure in the mixed quantum-classical model as described above, and concentrating on the symmetrical structure, we obtain the modeled differential efficiency as in Fig. 3(a). The agreement with experimental data is quite good. It is to be noticed that the relatively low values of the differential efficiency in this case are related to the lowering of the internal efficiency due to the increase in the leakage current after threshold and not to the increase of the absorption coefficient, which has a very low value (1.1 cm^{-1}).

Fig. 5 gives the electron and hole current densities in the heterostructure in lasing conditions, showing very clearly the electron current leakage in the undoped barrier (assumed to be p-type) and p-type confinement layer. As noticed in [15], [16], the barrier seen by electrons at threshold is higher than in lasing conditions, so that after threshold this is an important mechanism for lowering the differential efficiency, especially in our conditions when the composition difference between the barrier layer and the low-doped confinement layer is very low.

Both the threshold current density can be decreased and the differential efficiency increased by using a better capture efficiency (improving LO phonon scattering efficiency) in the following ways:

- using a larger QW;
- using more QW's; and
- using the graded index design.

VI. CONCLUSION

- Two low confinement structures designed for very high-power operation, one symmetrical and one asymmetrical are studied.

- A very high power output (6.4 W/10- μ m stripe width) is obtained before catastrophic degradation for 3-mm-long AR/HR coated devices; if scaled to CW conditions [17], this would mean 800–1100 mW (80–110 mW/ μ m) which would be a factor of 2–2.7 more than the best values reported for structures optimized for threshold current density.
- A very low value of the absorption coefficient (1.1 cm^{-1}) is obtained for the symmetric structure.
- A model taking into consideration the quantum carrier capture/escape time is proposed to explain the relatively low values of the differential efficiency and high values for the threshold current densities.

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