

Effect of Free-Carrier Absorption on Performance of 808 nm High-Power Laser Diodes

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Abstract. We examine effects of free-carrier absorption produced by non-equilibrium electrons and holes injected in the waveguide on characteristics of high-power AlGaAs laser diodes emitting light at 808 nm. The carrier transport in the laser heterostructures is studied theoretically, using the drift-diffusion numerical approach. On the basis of simulations, a relation between the current density and non-equilibrium carrier concentrations in the waveguides is found. The internal optical losses of the waveguide modes, and their effect on the differential quantum efficiency of the laser diodes are estimated from the computed carrier concentrations. Some approaches aimed at reducing the free-carrier absorption and, thus, improving the laser performance are discussed. The theoretical predictions are compared with available data to validate the theoretical model and justify the simulation-based conclusions.

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1. Introduction

High-power laser diodes operating at 808 nm are widely employed for optical pumping of YAG:Nd³⁺ solid-state lasers [1]. This application requires primarily a high light output power and a small beam divergence combined with a high wall-plug efficiency of the laser diodes. In terms of laser parameters and characteristics, these requirements imply (i) a high catastrophic optical damage (COD) threshold of the output facet, (ii) a low series resistance of the diode, (iii) a high differential efficiency of coherent light emission, and (iv) a narrow radiation far-field.

To increase the COD threshold, three basic approaches are currently employed. The first one uses passivation of the laser output facet with a dielectric coating [2, 3, 4, 5] to improve its chemical stability and reduce the non-radiative carrier recombination at the facet surface. The second approach utilizes an Al-free active region (see, for instance, [6, 7, 8]) that is found to be much more resistant to COD than a conventional AlGaAs one. The third approach invokes heterostructures with a low optical confinement factor, thus reducing the photon absorption and non-equilibrium carrier generation in the active layer near the output facet of the diode. A reduced optical confinement factor can be naturally obtained in the lasers with a wide waveguides [7, 9, 10], providing at once a narrow emission far field [9, 10].

Reduction in the series resistance of the laser diodes can be achieved by optimization of the impurity doping and using graded-composition interfaces in the laser heterostructures instead of abrupt ones. Increasing of the donor and acceptor concentrations, primarily in the cladding layers, may lead, however, to higher internal optical losses due to free-carrier absorption and, eventually, to a lower differential efficiency of the lasers. Therefore, a careful optimization of doping is required to provide a lower series resistance without deterioration of other device characteristics.

Generally, to increase the differential quantum efficiency of a laser diode, one should reduce the internal optical losses of the waveguide mode that first reaches the oscillation threshold. The internal losses are primarily controlled by free-carrier light absorption in the heterostructure. There are three main origins of the carrier absorption. The first one is the absorption in the doped cladding layers doped with donors or acceptors to provide the carrier access to the active region of the laser. The second origin is the light absorption in the active region where the concentration of the non-equilibrium carriers is extremely high. Despite a small active layer thickness its contribution to the total absorption may be comparable with that in the claddings. The third origin is the light absorption in the nominally undoped waveguide where non-equilibrium electrons and holes are injected to. In wide waveguides, its contribution is especially important and may affect significantly the laser performance at high-current operation [11, 12, 13]. Therefore, optimization of high-power laser diodes should account for their operational conditions along with the heterostructure design itself.

To date, heterostructures with wide waveguides are conventionally employed for fabrication of high-power laser diodes [9, 10, 14]. Nevertheless, pathways for their

optimization are yet insufficiently understood. The reason for this is a limited number of studies dealing with specific mechanisms underlying the operation of the high-power lasers. In particular, comparably little attention was given to specific properties of AlGaAs alloys affecting the free-carrier absorption, the role of graded-index (GRIN) materials in the carrier transport inside the heterostructure, and effects of the non-equilibrium carrier injection in the waveguide on the laser characteristics, occurring at high operation currents through the diodes.

This paper reports on the combined theoretical and experimental study of 808 nm AlGaAs high-power laser diodes with the focus on free-carrier absorption effects that control the device performance. Mechanisms determining the optical losses in the heterostructures are examined in detail to identify the most important factors limiting the laser differential quantum efficiency. A number of approaches aimed at reducing the free-carrier absorption and, thereby, at improving the laser diode characteristics are discussed in terms of simulations. The experimental information is used to validate the theoretical model and justify the simulation-based conclusions.

The paper is organized as follows. Details of the laser diode heterostructure and fabrication procedure are described in Sec.2. The simulation approach and basic assumptions of the theoretical model are discussed in Sec.3. The results of the modeling analysis are presented in Sec.4 where comparison of theoretical predictions with available observations is also done. The summary of the study and conclusions are given in Sec.5.

2. Fabrication of high-power laser diodes

The laser heterostructure was grown on *n*-GaAs(001) substrate by sub-atmospheric metalorganic chemical vapor deposition (MOCVD), using TMGa, TMI_n, TMAI, AsH₃, DMZn, and Si₂H₆ as precursors. The structure consisted of a 0.3 μm *n*-GaAs buffer layer ($n=2\times 10^{18}$ cm⁻³), a 1.5 μm *n*-Al_{0.6}Ga_{0.4}As cladding layer ($n=1\times 10^{17}$ cm⁻³), an undoped 0.15 μm GRIN AlGaAs waveguide layer with the AlAs molar fraction descending from 0.6 to 0.3, a 10 nm strained InGaAlAs active region providing the light emission at 808 nm, an undoped 0.15 μm graded-index (GRIN) AlGaAs waveguide layer with the AlAs molar fraction ascending from 0.3 to 0.6, a 1.5 μm *p*-Al_{0.6}Ga_{0.4}As cladding layer ($p=2\times 10^{17}$ cm⁻³), and a 0.2 μm *p*⁺-GaAs contact layer ($p=1\times 10^{19}$ cm⁻³). The background electron concentration in the undoped layers did not exceed $\sim 10^{15}$ cm⁻³.

Broad-area laser diodes with the stripe width of 200 μm and the cavity length between 0.8 and 1.1 mm were fabricated from the above heterostructure. Ion etching was used to form a shallow mesa beyond the stripe followed by deposition of a 0.15 μm SiO₂ insulator film passivating the etched surface. Thinning of the GaAs substrate to 100 μm was applied before the ohmic contact formation. AuGe and AuZn alloys were chosen as the materials for *n*- and *p*-contact electrodes, respectively. High-reflective and low-reflective coatings were deposited on the output and back facets of the diodes, providing the fundamental mode reflectivities of 20% and 90%. To measure the laser CW characteristics, the samples were mounted on a polished Ni-covered copper heat

sink with the p -side down. The heat-sink temperature of 25°C was controlled during the measurements.

3. Model and simulation approach

In order to analyze the operation of high-power lasers, we used the SiLENSe 1D-simulator initially developed for III-nitride wurtzite semiconductors [15] and adapted to cubic III-V compounds. The SiLENSe package implemented a drift-diffusion model of non-equilibrium carrier transport and accounted for the bimolecular radiative recombination of electrons and holes, their non-radiative Shockley-Read recombination, and the Auger recombination important at a high injection level. The simulator predicted the distributions of the electric potential, electron and hole concentrations, and recombination rates across the laser heterostructure for a certain forward bias applied. Then, such important parameters and characteristics were computed as the internal quantum efficiency η_{int} , i. e. the ratio of the radiative recombination rate integrated over the heterostructure to the total recombination rate in the structure, the optical gain $g(\lambda)$ and its maximum value, and the current density j corresponding to the applied bias.

The SiLENSe simulator was supplemented with a special module computing the electromagnetic field in the waveguide. All the transverse waveguide modes were found from the solution of scalar wave equations derived from the Maxwell equations for particular cases of TE- and TM polarizations. The scalarization of the Maxwell equations was possible due to neglecting the edge effects related to the finite stripe width of the laser. Using the computed field distributions, the optical losses of every mode produced by the free-carrier absorption were calculated in a standard way (see, for instance, [16]). For this purpose, the local free-carrier absorption coefficients α_n and α_p were estimated from the computed electron n and hole p concentrations by the expressions [17]

$$\alpha_n = \frac{q^3 \lambda^2 n}{4\pi^2 \mu_n m_n^2 N_r \epsilon_0 c^3} \quad , \quad (1)$$

$$\alpha_p = \frac{q^3 \lambda^2 p}{4\pi^2 \mu_p m_p^2 N_r \epsilon_0 c^3} \quad ,$$

where q is the electron charge, λ is the emission wavelength, c is the light velocity in vacuum, N_r is the refractive index of the semiconductor, ϵ_0 is the electric constant, μ_n and μ_p are the electron and hole mobilities, respectively, and m_n and m_p are the effective masses of electrons and holes. The optical losses were calculated separately for heavy and light holes, assuming the same mobility for each of them. The total hole absorption coefficient was found as the sum of the absorption coefficients related to holes of both types. The contribution of split-off holes was ignored due to a negligible occupation of the split-off valence subband.

Figure 1 shows the electron and hole free-carrier absorption crosssections, $\sigma_n = \alpha_n/n$ and $\sigma_p = \alpha_p/p$, calculated for $\lambda = 808$ nm, using Eq.(1) and the experimental data on electron and hole mobilities in AlGaAs reported in [18, 19]. Light holes are found to provide the major contribution to the hole crosssection because of a lower effective mass, and its dependence on the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ composition is related to the hole mobility variation primarily caused by alloy scattering [19]. A sharp peak in the electron crosssection at $0.4 < x < 0.5$ is attributed to a strong intervalley scattering of electrons induced by the crossover of the Γ - and X-valleys in the conduction band. It is worse noting that the electron crosssection σ_n plotted in Figure 1 corresponds to undoped AlGaAs with the background electron concentration of $5\text{-}10 \times 10^{15} \text{ cm}^{-3}$. If AlGaAs is doped with donors up to the concentration of $\sim 10^{17}\text{-}10^{18} \text{ cm}^{-3}$, the crosssection $\sigma_n = \alpha_n/n$ may become several times larger because of a lower electron mobility controlled by the carrier scattering at ionized impurities. Even in the latter case, the hole crosssection is still considerably larger than the electron one. This fact is important to optimize doping of a laser heterostructure.

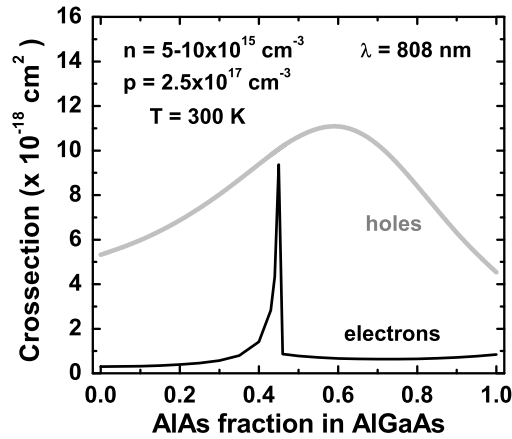


Figure 1. Free-carrier absorption crosssections as a function of AlGaAs composition estimated from the data on electron and hole mobilities reported in [18, 19].

The transverse mode first approaching the oscillation threshold, the threshold current density j_{th} , and the output optical power P_{out} as a function of the current density were found from linearized rate equations relating the mean photon densities in the waveguide with the concentrations of non-equilibrium carriers. As a result, the following expression for the output power was derived:

$$P_{out} = \frac{\hbar\omega}{q} \eta_{st} (I - I_{th}) \cdot \frac{\alpha_R}{\alpha_R + \alpha_i^{th}} F \quad , \quad (2)$$

$$F = \frac{R_B^{1/2}(1 - R_O)}{(R_O^{1/2} + R_B^{1/2})(1 - R_O^{1/2}R_B^{1/2})} \quad , \quad (3)$$

$$\alpha_R = \frac{1}{2L} \ln \frac{1}{R_O R_B} \quad , \quad (4)$$

where \hbar is the Plank constant, $\omega = 2\pi c/\lambda$ is the oscillation frequency, η_{st} is the internal quantum efficiency of the emission directly related to the existence of ring modes in the laser cavity [16], $I = jWL$ is the operation current, $I_{th} = j_{th}WL$ is the threshold current, W is the contact width, L is the cavity length, α_R is the coefficient of radiation losses, α_i^{th} is the internal absorption coefficient of the oscillating mode at the threshold current density, and R_O and R_B are the reflectivities of the output (with low-reflective coating) and back (with high-reflective coating) facets, respectively. The factor F accounts for the radiation losses through the back facet of the diode; it is equal unity at $R_B = 1$. The differential quantum efficiency, $\eta_D = dP_{out}/dI$, can be readily obtained from Eq.(2). In more detail, the model will be described elsewhere.

The materials properties of AlGaAs were largely borrowed from [16, 20]. To account for the crossover of the Γ - and X-valleys in the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ conduction band, we consider separately the composition ranges $0 \leq x \leq 0.45$ and $0.45 \leq x \leq 1.0$, assigning them different materials properties like electron and hole effective masses, carrier mobilities, electron affinities, and bandgaps as a function of the alloy composition.

4. Results

In this section, we will discuss the results of modeling the AlGaAs laser diode operation with the focus on mechanisms controlling the device performance at high current densities. The simulation results are compared with available observations in order to validate the theoretical approach applied.

4.1. Carrier injection and optical losses in high-power laser diodes

To investigate into mechanisms of non-equilibrium carrier injection, we consider at first the laser heterostructure consisting of a $1.5 \mu\text{m}$ $n\text{-Al}_{0.6}\text{Ga}_{0.4}\text{As}$ cladding layer ($n=1 \times 10^{17} \text{ cm}^{-3}$), an undoped $0.5 \mu\text{m}$ $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ waveguide layer with a 10 nm $\text{Al}_{0.07}\text{Ga}_{0.93}\text{As}$ active layer placed in the center of the waveguide, a $1.5 \mu\text{m}$ $p\text{-Al}_{0.6}\text{Ga}_{0.4}\text{As}$ cladding layer ($p=2 \times 10^{17} \text{ cm}^{-3}$), and a $0.2 \mu\text{m}$ $n^+\text{-GaAs}$ contact layer ($n=1 \times 10^{19} \text{ cm}^{-3}$). The undoped waveguide is used to lower the free-carrier absorption in the structure.

Figure 2a,b compares the band diagrams and distributions of non-equilibrium carrier concentrations in the laser heterostructure, computed for the threshold current densities corresponding to the cavity lengths of 1500 and $500 \mu\text{m}$. One can see that the conduction and valence bands in the structure are nearly flat with a slight slope in the waveguide layer indicating the built-in electric field. In both cases, the electron and hole concentrations in the cladding layers are controlled by the respective donor and acceptor concentrations. In contrast, the carriers appear in the waveguide entirely due to injection. Our simulations demonstrate two specific features of the carrier injection. First, electrons and holes exist in the waveguide at nearly equal concentrations, which is the evidence for the ambipolar character of the carrier transport. Second, the carrier concentration in the waveguide depends remarkably on the cavity length that determines

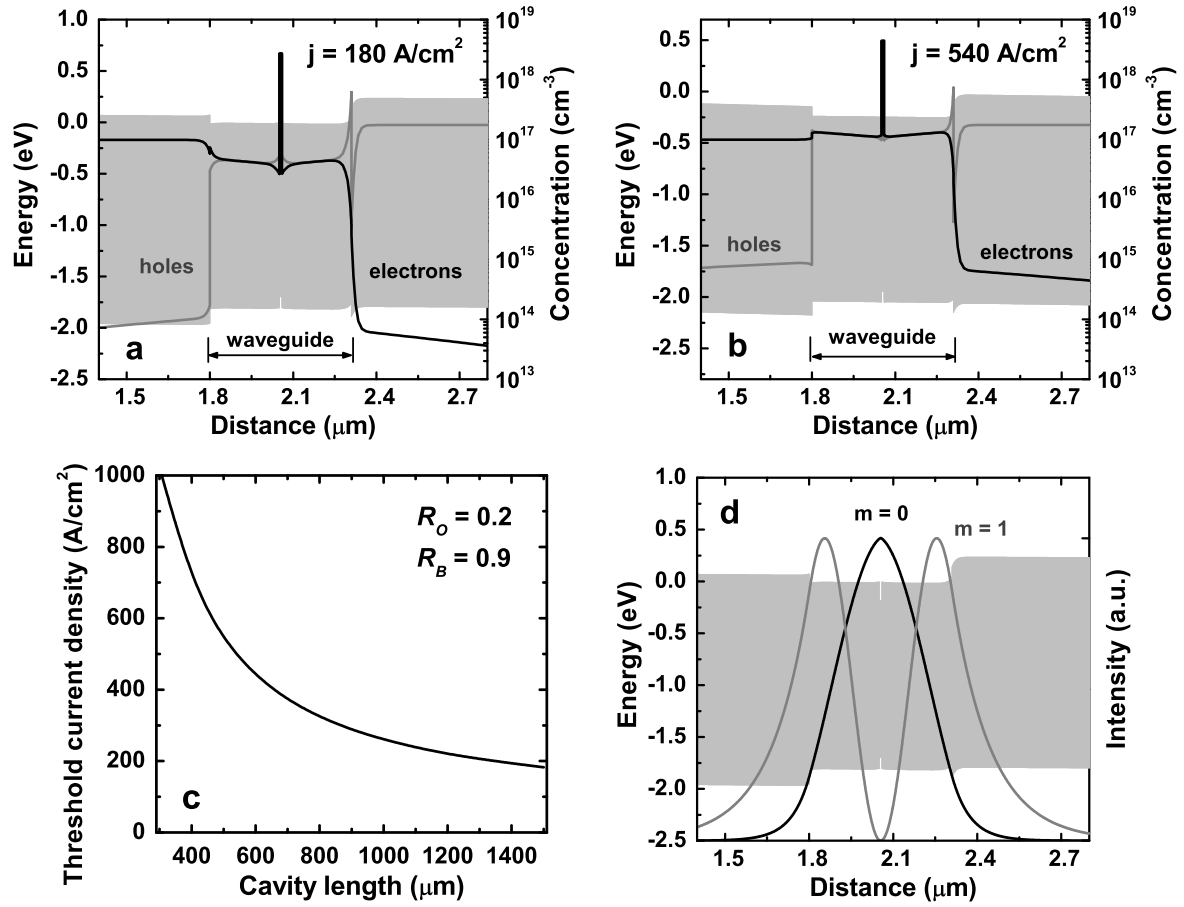


Figure 2. Band diagrams and carrier concentrations in the laser structure with $0.5 \mu\text{m}$ $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ waveguide corresponding to the threshold current density at the cavity lengths of $1500 \mu\text{m}$ (a) and $500 \mu\text{m}$ (b). Threshold current density of the laser diode as a function of its cavity length (c). Intensity distributions of the transverse modes in the laser heterostructure (d). The grey shadow indicate the bandgap.

the threshold current density (Figure 2c). The concentration of electrons and holes is $\sim 4.5 \times 10^{16} \text{ cm}^{-3}$ at $j_{th} = 180 \text{ A/cm}^2$ and $\sim 1.2 \times 10^{17} \text{ cm}^{-3}$ at $j_{th} = 540 \text{ A/cm}^2$ (see Figure 2a,b). In the latter case, the concentration of the injected carriers even exceeds the electron concentration in the n -cladding layer. In order to understand this result, one should regard that the current density $j \propto \mu_{amb} n E$, where μ_{amb} is the ambipolar mobility and E is the built-in electric field in the waveguide. Under slight variation of E and μ_{amb} with the current density, which is confirmed by our simulation, the concentration of the injected carriers n is proportional to the current density. Therefore, a smaller cavity length (a higher threshold current density) leads to a higher non-equilibrium carrier concentration in the waveguide. Since the electromagnetic field of a laser mode is largely concentrated in the waveguide layer (Figure 2d), the increasing concentration of the injected electrons and holes results in a rise of optical losses in the waveguide and, eventually, in a lower differential quantum efficiency of the device.

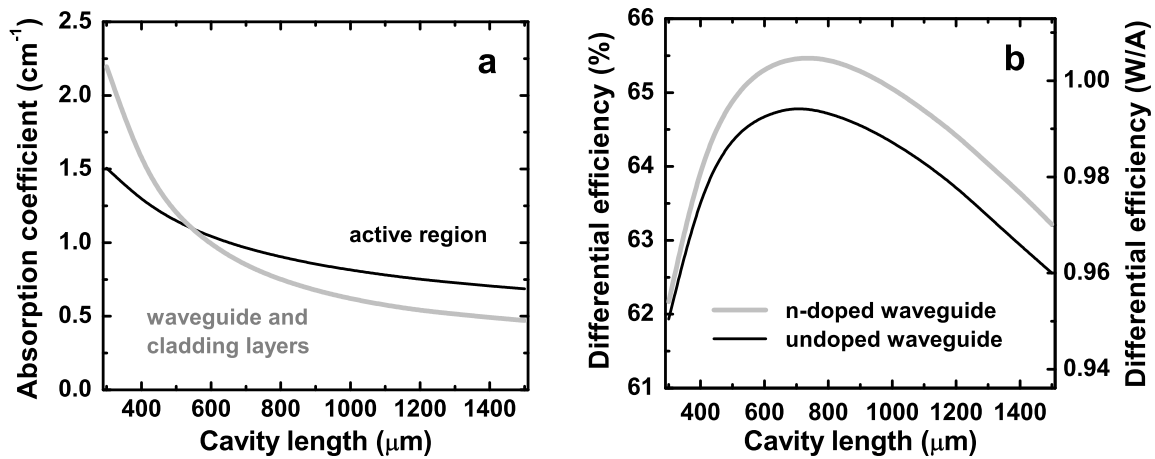


Figure 3. Optical losses of the fundamental mode related to free-carrier absorption in the active region and remainder of heterostructure, corresponding to the oscillation threshold (a). Differential quantum efficiency as a function of the cavity length for doped and undoped waveguide layer (b).

Simulation predict two transverse modes to exist in the laser structure (see Figure 2d), having the optical confinement factors of $\Gamma_0 = 2.7\%$ and $\Gamma_1 = 0.001\%$. The negligible value of Γ_1 results in the fact that only the fundamental ($m=0$) mode is capable of reaching the oscillation threshold. Figure 3a shows the contribution of the active region and remainder of the laser heterostructure to the free-carrier absorption of the fundamental mode, as a function of the cavity length. One can see from the figure that the optical losses in the structure exceed those in the active region at $L < 540 \mu\text{m}$. This is due to the above mentioned effect of the carrier injection in the waveguide, enhancing with the current density.

The dependence of the optical losses on the cavity length results also in a distinct maximum of the differential efficiency η_D at $L \approx 700 \mu\text{m}$ (see Figure 3b). As $\eta_D \propto \alpha_R / (\alpha_R + \alpha_i^{th})$ in accordance with Eq.(2), the decrease in the efficiency at $L > 700 \mu\text{m}$ is related to lowering the coefficient of the radiation losses, α_R . At $L < 700 \mu\text{m}$ the differential efficiency decreases because of a dramatic rise in α_i^{th} (see Figure 3a).

The obtained results clearly demonstrate that the concentration of non-equilibrium carriers injected in the waveguide is an important factor limiting the performance of high-power laser diodes. Some ways to decrease the carrier concentration and, thus, to reduce the optical losses in the waveguide are discussed in the next sections of the paper.

4.2. Waveguide doping to reduce optical losses

The ambipolar character of the carrier transport leads to nearly the same electron and hole concentrations in the waveguide layer, as it can be seen from Figure 2a,b.

As a result, both electrons and holes contribute to the free-carrier absorption in the waveguide, in contrast to the n - and p -cladding layers where only electrons or holes, respectively, control the optical losses. On the other hand, holes provide the major contribution to the light absorption in the waveguide because of a remarkably larger cross-section σ_p (see Figure 1). In this case, it becomes possible to reduce the total absorption by intentional n -doping of the waveguide layers. Indeed, the hole concentration in the waveguide is expected to be reduced under n -doping by the concentration of the ionized donors, which lowers the hole-mediated absorption. Since the electron cross-section σ_n is several times smaller than σ_p , the increase in the electron concentration does not lead in this case to a noticeable rise in the absorption coefficient.

To illustrate this concept, we consider the laser structure different from the structure specified in Sec.4.1 by intentional n -doping of the waveguide. The waveguide region between the n -cladding and active layer is assumed to be doped to the donor concentration of $1 \times 10^{17} \text{ cm}^{-3}$, while the region between the active layer and the p -cladding – to the donor concentration of $2 \times 10^{17} \text{ cm}^{-3}$. The doping is found to affect slightly the threshold current density of the intentionally doped laser diode as compared to the undoped one.

Figure 4 plots the band diagrams and distributions of the carrier concentrations in the laser heterostructure with n -doped waveguide computed for the threshold current densities at the cavity lengths of 1500 and 500 μm . One can see that the intentional doping provides a remarkable reduction in the concentration of holes injected in the waveguide. Despite an increase in the electron concentration, this leads to a reduced free-carrier absorption and, eventually, in a higher differential efficiency of the laser diode, as shown in Figure 3b.

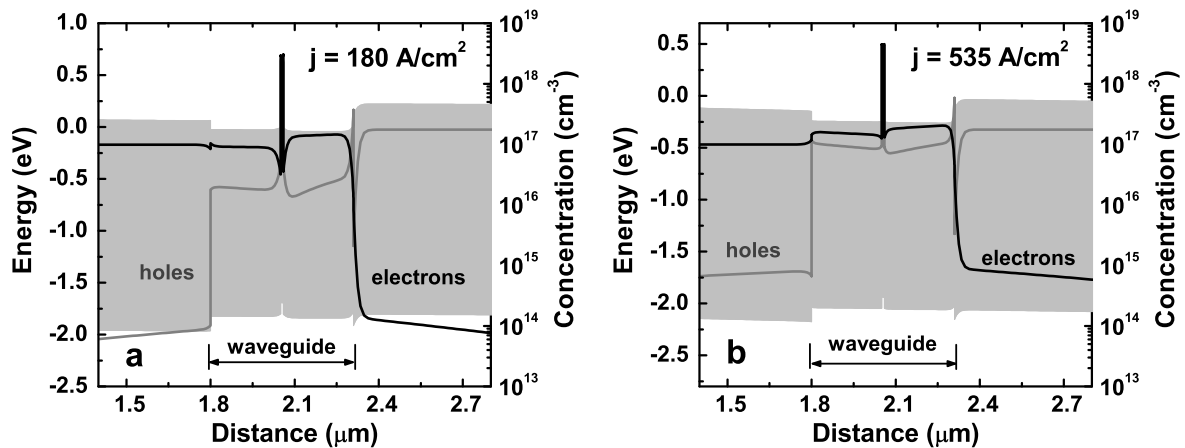


Figure 4. Band diagrams and carrier concentrations in the laser diode with n -doped 0.5 μm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ waveguide, corresponding to the threshold current densities at the cavity lengths of 1500 μm (a) and 500 μm (b). The grey shadow indicates the bandgap.

In the particular case considered above, the effect of the waveguide doping is not

so strong. Nevertheless, it can be helpful for global optimization of high-power laser structures, especially of those having a relatively low optical confinement factor.

4.3. Graded-index waveguides

One can realize from the relationship $j \propto \mu_{amb} n E$ between the current density j and the non-equilibrium electron or hole concentration in the waveguide n that a higher electric field E favors the reduction of n and, hence, of internal optical losses. An effective way to increase E is the use of a GRIN waveguide, producing a built-in electric field due to the bandgap variation in the graded-composition material. In order to examine this effect, we consider here the laser heterostructure specified in Sec.2.

Figure 5a,b presents the band diagrams and distributions of electron and hole concentrations in the heterostructure computed for the threshold current densities related to the cavity lengths of 1500 and 500 μm . A specific feature of the band diagrams is a non-monotonic profile of the conduction band edge. This is due to the crossover of the Γ - and X-valleys resulting in an increasing conduction band offset between GaAs and AlGaAs with composition at $0 \leq x \leq 0.45$ and a decreasing offset at $0.45 \leq x \leq 1$. The crossover leads also in a drop/jump in the electron concentration at the positions corresponding to $x = 0.45$, the composition at which the crossover occurs. At this point, the density of states in the conduction band changes dramatically ‡, and the electron concentration just follows these changes.

Simulation of electromagnetic field in the laser structure predicts the existence of the only fundamental transverse mode in the waveguide (Figure 5d) with the optical confinement factor $\Gamma_0 = 3.3\%$.

In contrast to the laser structure with the 0.5 μm Al_{0.3}Ga_{0.7}As waveguide, the transport of electrons and holes in the structure with the GRIN waveguide is weakly interrelated with each other, so that no ambipolar drift or diffusion occurs. In addition, the concentration of the injected carrier in the GRIN waveguide is remarkably lower than in that having constant composition. The reason for such a behavior is the built-in electric field embedded in the graded-composition alloys, accelerating the carrier motion across the structure. As a result, the free-carrier losses beyond the active layer are considerably suppressed in the GRIN waveguide compared to those in the constant-composition one (see Figure 6a). The reduced optical losses result in a higher differential efficiency of the laser with the GRIN waveguide. The internal quantum efficiency of the laser diode computed for the threshold conditions (Figure 6d) is also found to depend on the cavity length. This is caused by the effect of the Auger recombination increasing at a high current density (a low cavity length) in the active region of the laser diode.

Figures 5 and 6 compare the theoretical predictions on the laser characteristics with observations. Good agreement between the theory and experiment justifies the applied

‡ Actually, one can expect a steep monotonous variation of the electron concentration rather than a drop/jump, which is attributed to the step-like approximation of the AlGaAs materials properties used in this study (see Sec.3).

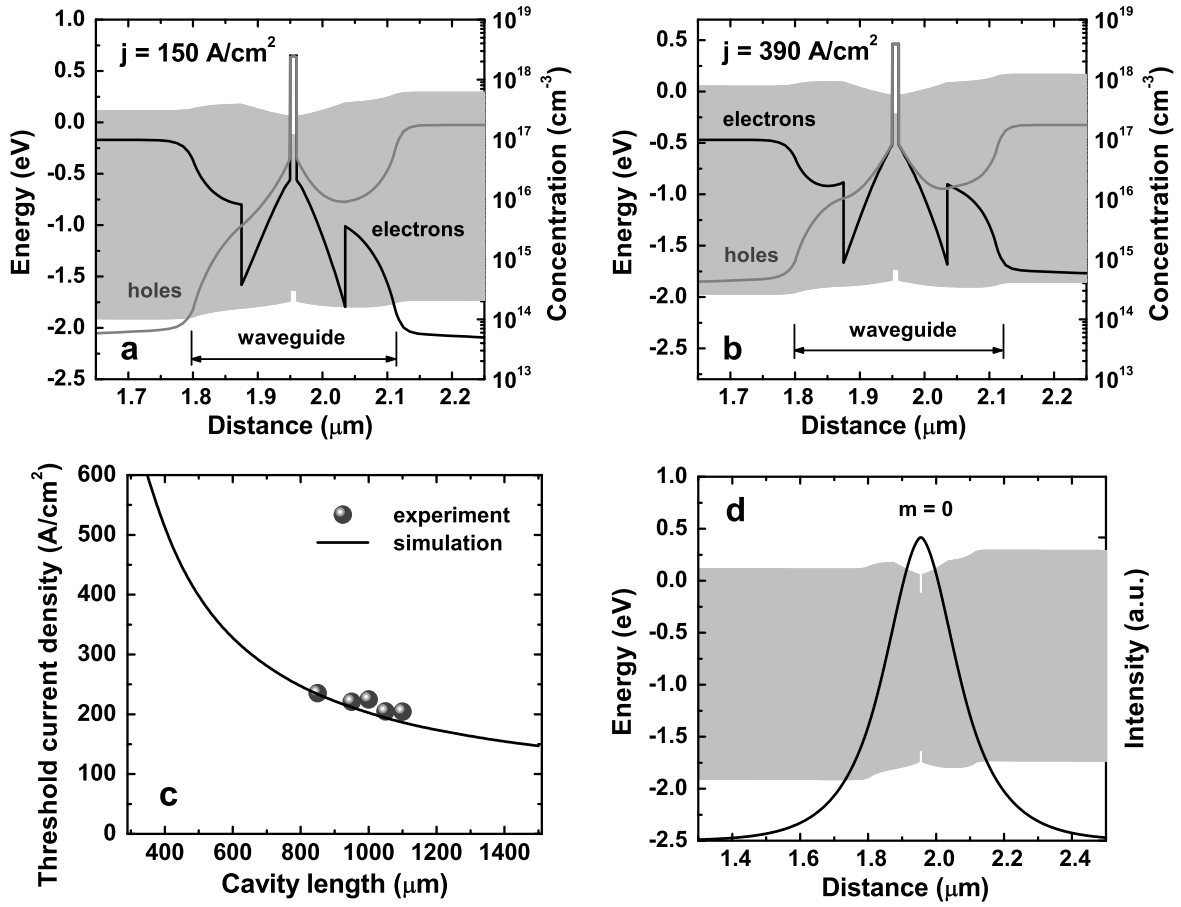


Figure 5. Band diagrams and carrier concentrations in the laser diode with GRIN waveguide corresponding to the threshold current densities at the cavity lengths of 1500 μm (a) and 500 μm (b). Threshold current density as a function of the cavity length (c). Intensity distribution of the fundamental mode in the laser heterostructure (d). The grey shadow indicates the bandgap. Balls are experimental data, lines are simulations.

approach and the main conclusions made on the basis of simulations.

4.4. On experimental estimation of optical losses

There is the well-known procedure for estimation of some important parameters of a laser heterostructure by plotting the total (per two facets) inverse differential efficiency of a diode with uncoated facets *versus* cavity length. For this purpose, a dimensionless efficiency is used defined by the equation [16]

$$\eta_D^{-1} = \eta_{st}^{-1} \cdot \frac{\alpha_R + \alpha_i^{th}}{\alpha_R} \quad (5)$$

At $L \rightarrow 0$ the value of η_D^{-1} tends to η_{st}^{-1} that is generally dependent on the presence of ring modes inside the laser cavity [16]. In turn, the slope of the $\eta_D^{-1}(L)$ dependence

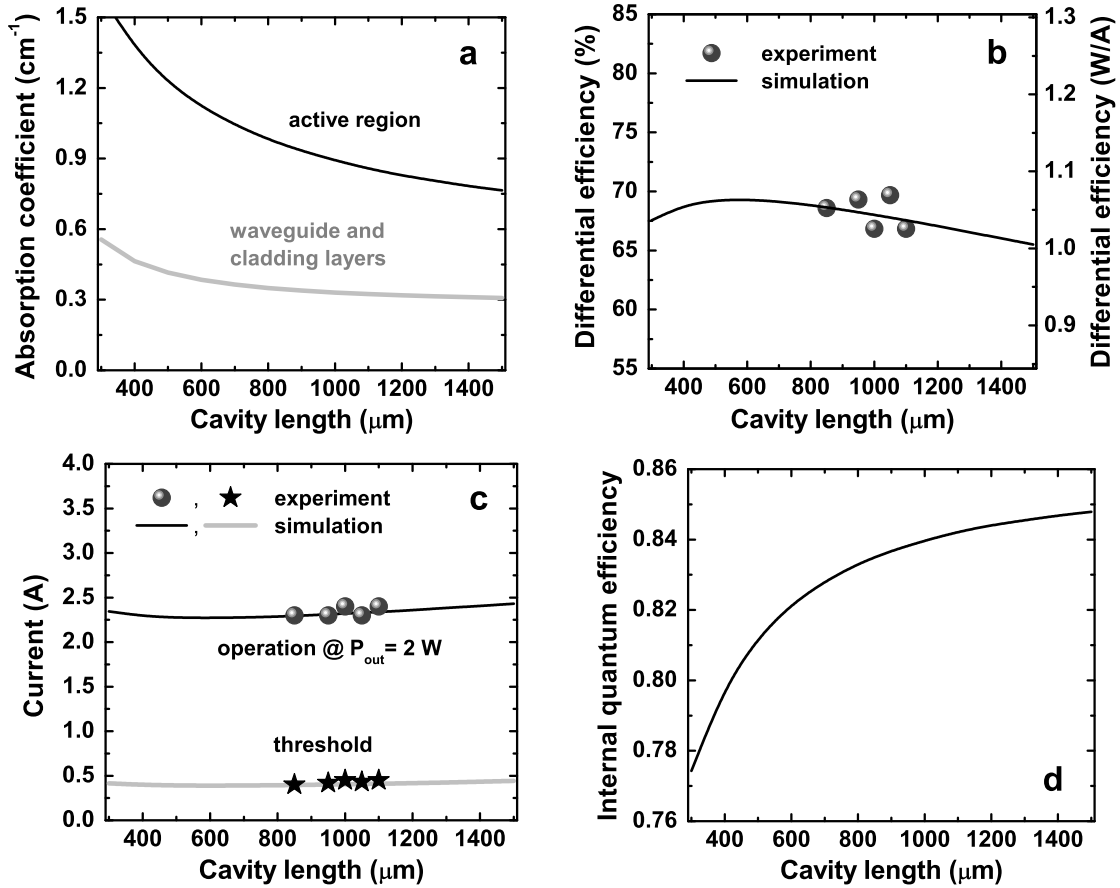


Figure 6. Optical losses of the fundamental mode at the oscillation threshold related to the free-carrier absorption in the active region and remainder of the structure (a). Differential quantum efficiency as a function of the cavity length (b). Predicted and measured threshold current and operation current corresponding to the output power of 2 W (c). Internal quantum efficiency at the threshold as a function of the resonator cavity (d).

provides the value of the absorption coefficient

$$\alpha_i^{th} = \eta_{st} \ln(1/R) \cdot \frac{d\eta_D^{-1}}{dL}, \quad (6)$$

where R is the reflectivity of the uncoated facet nearly equal to 0.3.

The procedure fails, however, in the case of high-power lasers where the internal losses depend on the cavity length. First, there is no unambiguous way to extrapolate the dependence of $\eta_D^{-1}(L)$ to zero value of L (Figure 7a) because of its non-monotonic behavior. Second, even if we accept that $\eta_{st} = 1$, the absorption coefficient α_i^{th} determined from Eq.(6) becomes remarkably underestimated (see Figure 7b), especially at the cavity lengths corresponding to the maximum of differential efficiency. Only at a very large L , at which the role of the carriers injected in the waveguide and active region is of less importance, the optical losses estimated by Eq.(6) become comparable with the actual values coming, for instance, from simulation (Figure 7b).

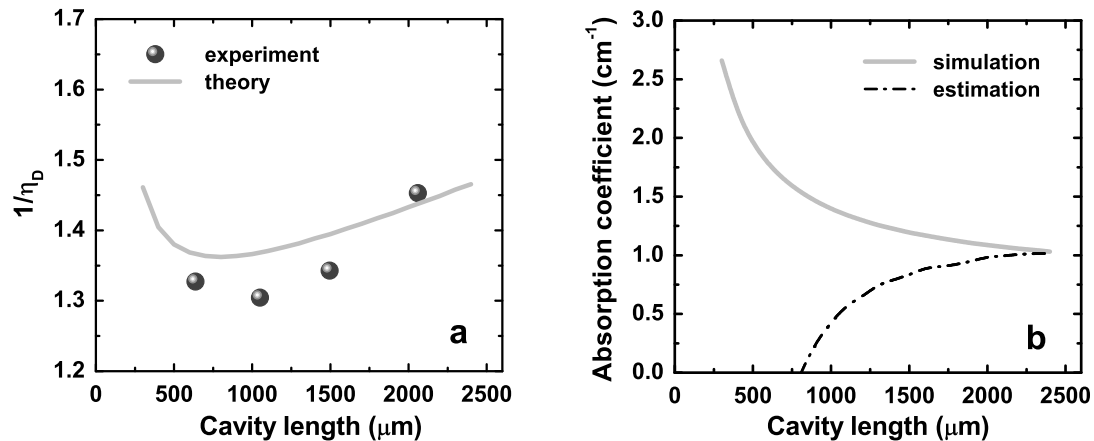


Figure 7. Inverse differential efficiency (a) and total free-carrier absorption coefficient (b) as a function of the cavity length. Grey line are simulation results, dot-dashed line is the estimate based on Eq.(6), balls are measurements.

As the above procedure is commonly used to estimate the optical losses and, thus, to assess the laser diode performance, the results obtained with this procedure may be misleading. Much more reasonable seems the direct estimation of α_i^{th} from Eq.(5), assuming that $\eta_{st} = 1$.

5. Conclusion

In this paper we have examined both theoretically and experimentally the effect of free-carrier absorption produced by electrons and holes injected in the waveguide on performance of high-power AlGaAs laser diodes. Using simulations, we have found that the concentration of the injected carriers depends remarkably on the cavity length (current density in the diode) and, in some cases, may exceed that in the cladding layers. In wide waveguides with a constant composition, the carrier transport is ambipolar, providing nearly equal concentrations of the injected electrons and holes that both contribute to the free-carrier absorption. Two ways of lowering the injected carrier concentration are considered: (i) an intentional n -doping of a waveguide and (ii) the use of a graded-composition waveguide layer, where acceleration of the carrier motion across the waveguide is due to the built-in electric field. The latter way seems to be more promising than the former one. The dependence of the internal optical losses on the current density results in an optimum value of the cavity length that provides a maximum differential efficiency of the laser.

The theoretical predictions are in a good agreement with available observations that justifies the main conclusions based on simulations.

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