Electrical Properties of Oxide-Confined Vertical-Cavity Surface-Emitting Lasers

V. P. Kalosha, V. A. Shchukin, N. Ledentsov Jr., and N. N. Ledentsov
VI Systems GmbH
Hardenbergstr. 7, 10623 Berlin, Germany
{vladimir.kalosha, vitaly.shchukin, nikolay.ledentsov-jr, nikolay.ledentsov}@v-i-systems.com

***Abstract*—We present a comprehensive description of electrical properties of vertical-cavity surface-emitting lasers (VCSELs) based on a drift-diffusion model applied to carrie r transport in 3D multilayer semiconductor laser heterostructure with a p-n junction. We address the impact of interface grading in distributed Bragg reflectors (DBRs), modulation doping of the DBRs and surrounding layers of the quantum well (QW) as well as material-dependent carrier mobilities and recombination constants and are focused on oxide-confined GaAs/AlGaAs VCSELs. We evaluate both depletion and diffusion capacitance and show that both contributions to the capacitance as well as the differential series resistance critically depend on the injection current and chip design such that, in general, VCSEL cannot be properly modeled by an equivalent circuit approximation. Current profiles demonstrate significant inrease of the current density at the edges of the oxide-confined aperture (current crowding) which could be supressed by a proper design.**

***Index Terms*—vertical cavity surface-emitting laser, oxide aperture, carrier transport, modulation frequency bandwidth, differential resistance, capacitance, current crowding**

I. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) have been developed into the key component of datacom, sensor and free-space applications because of their low-threshold, high-efficiency, high-speed operation, low-divergent output, and possibility of low-cost production of large on-wafer arrays [1-2]. Electrical properties of laser diodes have been extensively studied experimentally and a number of models to match the performance were introduced. Most of them relied on fitting the experiment by selecting the related values of the equivalent circuit elements. Current- and voltage-independent resistance and capacitance elements were used as fiting parameters. Specific complicated shapes and locations of the n- and p-mesas, metal contacts, active region and aperture(s) were not considered. In other papers the differential Ohm law equation was solved. The laser structure was represented by the spatial profile of the conducting regions, and the p-n junction region was approximated by an ideal-diode current-voltage relation adjusted to experiment.

In contrast, in this work we developed a comprehensive model based on the drift-diffusion equations [3] to describe carrier transport in 3D axially-symmetric semiconductor heterostructure, which is capable to take into account the actual VCSEL epitaxial design, double heterostructure recombination region, practical shapes and sizes of the VCSEL mesas and contact areas and predict the key parameters related to current distribution and high-frequency modualtion. All material parameters, such as electron and hole band diagrams, mobilities, dielectric constants, doping, all as a function of the related compositions, are used.

II. Results and discussion

Figure 1 depicts distribution of the current density calculated for a typical VCSEL structure [4] having a 4-μm-diameter, 70-nm thick oxide-confined aperture at a bias 2 V and a current 5.3 mA. The current density in the DBRs is larger in low-Al-content layers, where the lateral component is the dominant one and the current flows predominantly in plane of the related epitaxial layers. The mobility of holes is higher in these regions and the small in-plane potential caused by the aperture results in in-plane current strongly contributing to the overall effective conductivity of the device. In the layers with high-Al content, where the mobility is lower by more than an order of magnitude, the current flow predominantly occurs in the vertical direction. As we observed in our simulations, grading of the Al content and introduction of high doping of the interfaces between the layers with different mobilities and bandgaps substantially facilitates the carrier transport between the DBR layers, as opposite to the the case of abrupt DBR interfaces. The proper design allows to decrease the resistance of the heterostructure to the acceptable level below 100 Ω without a need in extreme doping which would lead to high free carrier absorption, overheating and reduced dufferential efficiency of the device. Current crowding at the rim of the aperture visible in Fig. 1 (upper panel) depends on aperture and epitaxial layers arround and can be minimized by a proper design.

The parameter critical for the modulation response of the laser is the effective RC-product, which should be minimized to reach high-speed electrical modulation efficiency. Two types of the capacitance, namely depletion capacitance and diffusion capacitance, are important for semiconductor laser diodes and are defined by the type of the charge distribution [5]. These two capacitances are connected in parallel and their sum is involved in the frequency response. The depletion capacitance is related to the spatially separated total charge occurring in the p-n junction. Such charge is high at zero bias, increases with forward bias, and reaches its maximum value at an intermediate voltage before the p-n junction becomes fully open. The diffusion capacitance is related to the minority

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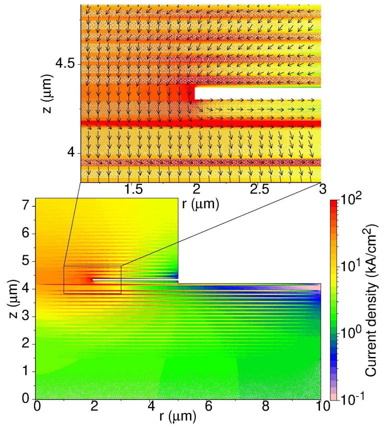

Fig. 1. Spatial distribution of the current density magnitude in the color map view for the aperture radius 2 μm, thickness 70 nm and circular n- and p-contacts at the bottom of the substrate and at the top of the VCSEL mesa, respectively, at the bias 2 V and the current 5.3 mA. The upper panel shows also the current flow directions in the vicinity of the aperture and active region.

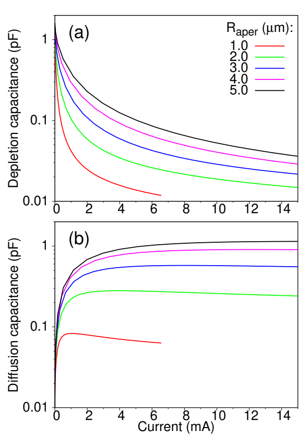

Fig. 2. Depletion (a) and diffusion (b) capacitance of the VCSEL versus current for the aperture thickness 20 nm and different aperture radii.

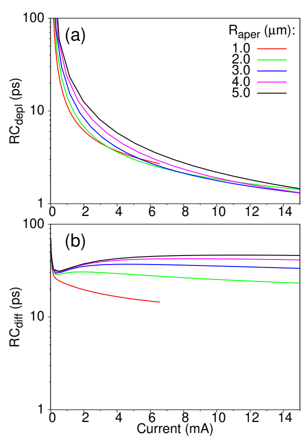

Fig. 3. RC-product for the depletion (a) and diffusion (b) capacitance of the VCSEL versus current for the aperture thickness 20 nm and different aperture radii.

charge generated by carrier injection. The positive and negative charges including both nonequilibrium and equilibrium carriers are not spatially separated, but are rather separated by the energy gap. Opposite to the case of depletion capacitance where the charging or discharging occurs by applying external bias and thus the external series resistances are involved, the diffusion charge in the double heterostructure can be reduced by the recombination of nonequilibrium carriers, a fast process allowing observation of ultrafast relaxation oscillations.

At the operational regime of external bias above the bandgap in the active region the diffusion capacitance is significantly larger than the depletion capacitance since in this regime the depletion of the carriers vanishes in the aperture region whereas their diffusion increases (Fig. 2). Thus, in this most interesting regime the diffusion capacitance represents the major factor defining the high-speed performance of the laser diode. It should be noted that the depletion capacitance at a given bias is nearly independent of the aperture diameter but is governed by the voltage applied and the lateral size of the top p-mesa.

Similarly, both contributions to the RC-product from the depletion and diffusion capacitances versus the current are displayed in Fig. 3. For the diffusion capacitance the parameter RC_{diff} depends only weakly on the current in the whole operation range of the laser diode and is larger than the parameter RC_{depl} for the depletion capacitance except of the range of very small aperture diameters. RC-product for the sum of the depletion and diffusion capacitance decreases with the decrease of the aperture radius. At a given current RC-product for the sum of the depletion and diffusion capacitance decreases with the decrease of the aperture radius.

Current crowding at the inner edges of the oxide current confining aperture (Fig. 1) is an important issue for oxide-confined and buried heterostructure VCSELs. At high currents it may cause degradation and non-uniform injection of nonequilibrium carriers causing preferable excitation of higher-order transverse optical modes having a high optical field intensity at the boundary of the oxide-confined aperture, as opposite to the fundamental mode. The current crowding is manifested by a tremendous increase of the vertical component of the current density at the aperture edge as compared to that in the center of the aperture. We have shown that the effect may be substantially suppressed for a given current by modification of the oxidation layer forming the aperture and/or the layer sequence between the oxidation layer and the active region. Larger thickness of the oxidation layer results in a substantial weakening of the effect. Almost complete elimination of the crowding effect is possible in the case of the optimized aperture design.

III. Conclusion

3D modeling of electric properties of VCSEL including depletion and diffusion capacitance and current crowding at the aperture has been carried out based on the drift-diffusion equations for semiconductor heterostructure p-n junction laser diode. A realistic cylindrical-symmetric mesa shape is considered with different radii of the p- and n-doped sides. The impact of both oxide-confined aperture diameter and thickness and of the design of epitaxial layers in the vicinity of the aperture on RC-product defining the frequency response of the VCSELs and current crowding is evaluated.

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