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Current crowding in oxide-confined intracavity-contacted VCSELs

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An important problem for intracavity-contacted oxide-confined Vertical-Cavity Surface-Emitting Lasers (ICOC-VCSELs) is current crowding at the inner edges of the oxide current constrictions, which introduces extra losses and leads to excitation of unwanted higher-order transverse modes. We have proposed novel 'asymmetric' ICOC-VCSELs, where the contact metallisations are restricted to opposite mesa sides, for more homogeneous current injection and polarisation control. Here, results of simple 2D drift-diffusion calculations are presented for symmetric and asymmetric ICOC-VCSELs. Current crowding in our 'asymmetric' devices is reduced, but depends on the design of the layer structure.

Introduction

Vertical-Cavity Surface-Emitting Lasers (VCSELs) have rapidly developed into the source of choice for many fiber-optic datacom applications and free-space parallel optical interconnects because of their low-threshold, high-efficiency, high-speed operation, their low-divergent output beam, and the possibility to manufacture on-wafer testable, large, 2D VCSEL arrays [1]. In intracavity-contacted oxide-confined VCSELs (ICOC-VCSELs) the active region is bordered by two highly doped contact layers to inject current and the substrate and both Distributed Bragg Reflectors (DBR) remain undoped to minimize optical losses (see Fig. 1(a)). Oxide windows next to the quantum-well active region are formed by lateral selective steam oxidation of AlAs to guide both the current and the optical mode through the central region of the resonator. Nevertheless, such a design still leads to heavy current crowding at the rim of the oxide window [2, 3] resulting in higher losses, lower device bandwidth, and limited single-mode operation [4].

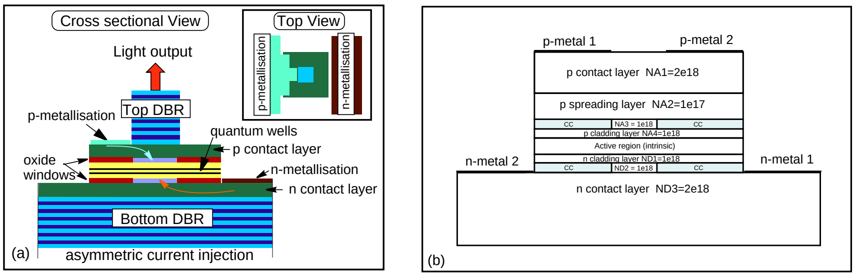


Figure 1: (a) ICOC-VCSEL with asymmetric current injection; (b) model of the ICOC-VCSEL. p-metal 2 and n-metal 2 only occur for the symmetrically injected VCSEL.

To reduce this current crowding we have proposed [5] an asymmetric current injection scheme for ICOC-VCSELs, where p and n contact metallisations are restricted to opposite sides of the top and bottom mesa, respectively. Additional advantages are the reduction of device capacitance to obtain a higher modulation speed [4] and stabilisation of the VCSEL polarisation in the direction perpendicular to the net lateral current [6, 7].

Model description

Fig. 1(b) shows the model for the ICOC-VCSEL. The following set of coupled equations is solved:

$$\nabla^2 V = \frac{q}{\varepsilon}(n - p - C) \qquad \text{Poisson equation,} \tag{1}$$

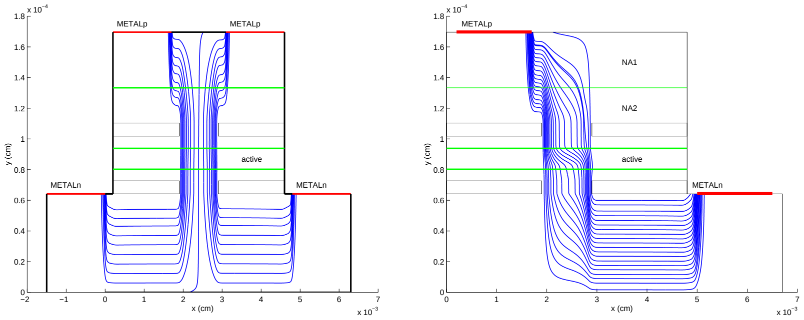
where V is the potential, q the elemental charge , $\varepsilon = \varepsilon_0 \varepsilon_r$ is permittivity of the material, n and p electron and hole densities, and $C = N_D - N_A$ the doping concentration, and:

$$\nabla \cdot \mathbf{J}_n = qR \qquad \text{Electron continuity equation,} \tag{2}$$

$$\nabla \cdot \mathbf{J}_p = -qR \qquad \text{Hole continuity equation,} \tag{3}$$

where R is the recombination rate and $\mathbf{J}_n = qn\mu_n\mathbf{E} + qD_n\boldsymbol{\nabla}$ and $\mathbf{J}_p = qp\mu_p\mathbf{E} - qD_p\boldsymbol{\nabla}p$ the electron and hole current densities. Here μ_n and μ_p are the mobilities, and D_n and D_p the diffusion coefficients for electrons and holes. The mobility models are taken from [8] and include dependence on aluminium fraction x, temperature T, doping concentration $N_I = N_A + N_D$, and carrier energy. Carrier-carrier effects and electron velocity overshoot have been neglected. Only radiative recombination in the active region is included by $R = B(np - n_i^2)$, where n_i is the intrinsic carrier concentration. The above set of partial differential equations is solved within the semiconductor device simulation tool SGFramework [9] using the Box Integration method and Scharfetter-Gummel discretisation of the carrier continuity equations.

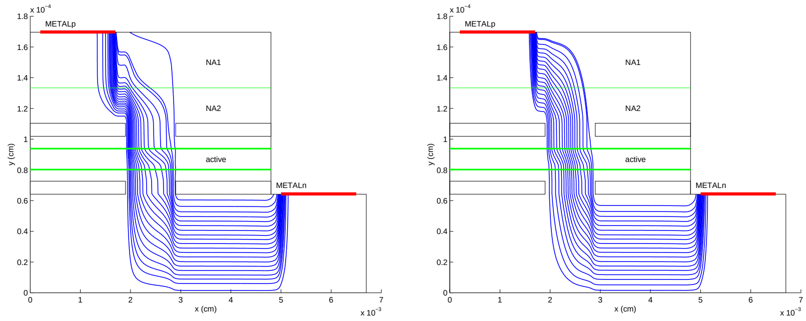
Results



(a) Symmetric VCSEL (b) Asymmetric VCSEL

Figure 2: Current streamlines for ideal case with equal hole and electron mobility.

The basic idea behind the Asymmetric Current Injection (ACI) is illustrated in Fig. 2, where we have plotted current streamlines through the device. All simulations in this paper are done for a forward bias of 0.1 V. The density of lines corresponds to the magnitude of the vertical current density J_y. In the conventional devices with Symmetric Current Injection (SCI) in Fig. 2(a) the shortest current paths between the contacts lie along the inner perimeter of the oxide window and strong current crowding is observed. In case of ACI (Fig. 2(a)) all current paths have equal length and a much more homogeneous injection of current into the active region is found. Also net lateral components E_x and J_x occur that lift the rotational symmetry of the device and are responsible for stabilisation of the polarisation [6, 7].



(a) VCSEL structure of [6, 7] with limited p-conductivity

(b) structure of Fig. 2(b) with optical mode, $w = 1.06$ μm, $B_0 = 1 \times 10^{-10}$ cm^3/s, $B_I = 1 \times 10^{-8}$ cm^3/s.

Figure 3: Current streamlines for VCSELs with ACI.

In Fig. 2 the electron mobility model was used for both electrons and holes to ensure equal conductivity of the p and n contact layers. However, in the structure used in our experiments [6, 7] the conductivity of the p contact layer is significantly lower and current crowding still occurs at the oxide window edge near the p-contact (Fig. 3(a)). Experimentally we have observed this as a shift of the optical mode toward the p-contact side for large-aperture VCSELs. Therefore, in order to take full advantage of ACI the contact layers have to be redesigned to have equal conductivity. However, it should be kept in mind that increasing the p-doping will also lead to higher free carrier absorption which deteriorates the optical performance of the VCSEL. Alternatively, one could use an n-doped contact layer together with a tunnel junction to inject holes. This idea is especially attractive for long-wavelength VCSELs, where the problem of free hole absorption is more severe [10].

To estimate the influence of the optical mode on the carrier distribution and current profile in our VCSELs, the radiative recombination rate in the active region is made dependent on the intensity of the optical mode according to the formula $B = B_0 + B_I \exp(-x^2/w^2)$, where w is the beam radius of the optical intensity, and B the coefficient of radiative recombination with B_0 due to spontaneous and B_I due to stimulated emission. The result is shown in Fig. 3(b) for the idealized case of ACI with equal electron and hole mobility.

Compared to Fig. 2(b) the current density is highest in the center and crowding has disappeared completely. This current self-distribution effect [11, 12] is caused by a decrease of the junction voltage due to the depletion of carriers by the optical mode and hence partially counteracts the spatial hole burning.

Conclusions

A simple drift-diffusion model is used to illustrate the advantages of asymmetric current injection, the limitations imposed on this idea by the limited hole mobility in the p contact layer, and influence of the optical mode by the current self-distribution effect that counteracts spatial hole burning.

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