Abstract

The challenges posed by the exponentially growing market of hyperscale datacenters require high-speed components, able to withstand harsh conditions during their operations. In this framework, with optical interconnects by now dominant in short-communication links, AlGaAs Vertical-Cavity Surface-Emitting Lasers (VCSELs) take crucial importance. State-of-the-art 850–980 nm VCSELs emit circular beams that are easily coupled to optical fibers and capable of delivering single-mode powers up to some mW. These are based on *pin*-like junctions, where stimulated emission occurs in multi-quantum wells (MQWs), inserted in the intrinsic cavity. Carriers reach the MQWs through oppositely doped distributed Bragg's reflectors (DBRs). Electrical and optical confinement comes from an oxide aperture placed in the proximity of the cavity.

The thesis aims at providing a preliminary assessment of an alternative design, to pave the way for the next generation of VCSELs. A sizable limitation to *pin* VCSELs comes from the massive presence of *p*-doping in the top DBR. This inherently induces worse electrical conductivity and stronger free-carrier absorption losses. Moreover, the wet oxidation process is not capable of growing small oxide apertures for single-mode emission with high reliability. For different reasons, these issues have been addressed in III-nitride, InP and GaSb-based VCSELs by adopting tunnel junctions (TJs). In fact, in AlGaN devices relevant *p*-doping levels cannot be realized due to high acceptor ionization energies. Additionally, oxide aperture concept is hardly reproducible in nitride, InP and GaSb systems due to the absence of Al-rich layers. TJs effectively inject holes in the active regions, allowing *n*-doping in the top DBR. Radially defined TJs are used to realize lateral confinement. Our goal is to verify whether TJ benefits can be transferred to AlGaAs VCSELs.

Pin VCSELs market pervasion prompts a technologically computed-aided design approach. In this perspective, we adopt our in-house tool VENUS, a quantum corrected drift-diffusion (DD) solver dealing self-consistently with the connected optical and thermal problems. Our physics-based framework allows to go beyond the phenomenological rate equations model, a fundamental tool to interpret results of any laser, that fails to predict in depth the effectiveness of new concepts. The merits of various designs can be assessed by inspecting a wide set of inner quantities, that determine the output figures of merits. Eventually, a crucial difference with respect to commercial software is the full control over the simulation parameters and models.

TJ modeling cannot be realized within a semiclassical model, as carrier transport mainly depend on quantum interband tunneling across a reversely biased heavily doped *pn* junction. Non-equilibrium Green's function (NEGF) approach is exploited here as a genuine quantum treatment of TJ interband current. This is ultimately converted into a net generation rate introduced in the DD model. The novel NEGF-DD scheme is initially applied to a 1D version of VENUS: D1ANA. First, this is properly calibrated to extract reliable results on a reference *pin* VCSELs. Then, a TJ-VCSEL obtained from minor modifications of the reference device is generated as a test-bed for the proposed approach. As a final step, the NEGF-DD scheme enters VENUS. The lateral features neglected in D1ANA are explored for two TJ-VCSELs with varying reciprocal position of TJ and oxide aperture. An optimal design is defined, with TJ above the oxide aperture, ensuring a current confinement comparable to the *pin* device. Static electrical and optical characteristics confirm quantitatively the predictions of D1ANA. The voltage drop across the TJ increase the differential resistance. The optical characteristics are enhanced: the maximum output powers are almost doubled at heat sink temperatures ranging from 20 to 110°C, keeping the threshold current and the modal spectrum unchanged, thanks to lower self-heating and top DBR doping conversion.