Multiscale & Multiphysics Modelling of VCSELs

Alberto Gullino

Supervisors: Prof. M. Goano, F. Bertazzi, G. Ghione

ScuDo
Scuola di Dottorato – Doctoral School
WHAT YOU ARE, TAKES YOU FAR

XXXV Cycle

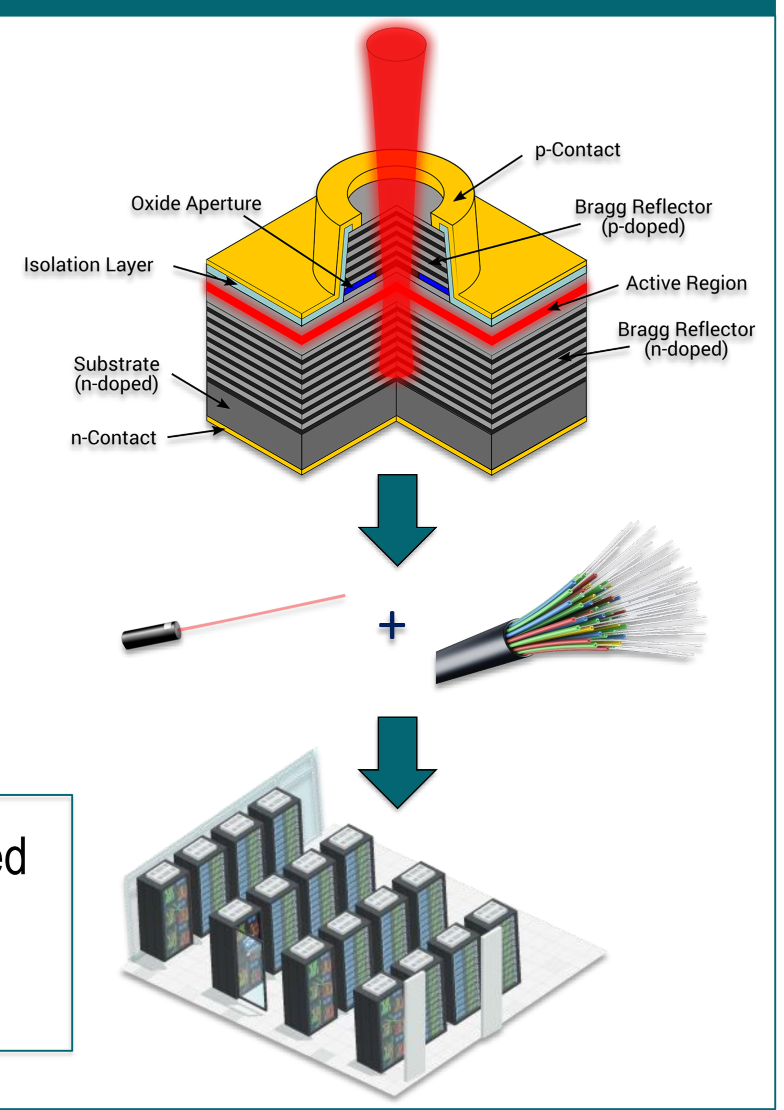
Research context and motivation

850 nm
AlGaAs oxide-confined
Vertical-Cavity Surface-Emitting Lasers
(**VCSELs**)

- ➢Ideal for optical fiber coupling
- ➢Excellent dynamic properties
- ➢Low production, testing and packaging costs

They represent the state-of-the-art for **short-range communication** in datacenters.

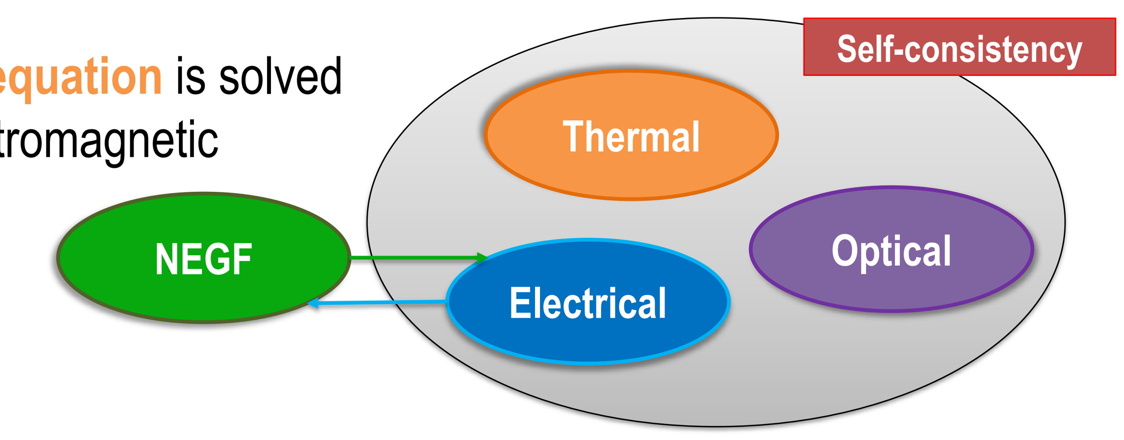
TCAD (technologically computer aided design) approach avoids slow and expensive prototyping campaigns



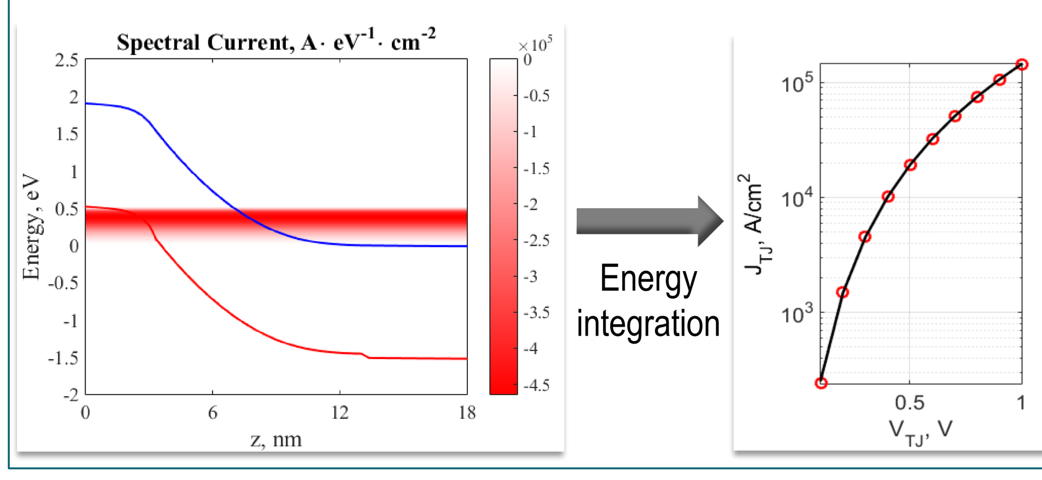
Adopted methodologies

Multiscale and multiphysics **physics-based** approach:

- **Electrical** solver → quantum-corrected (for QWs) **drift-diffusion** (DD) model solved applying Newton's scheme
- **Thermal** solver → **static heat equation** is solved
- **Optical** solver → in-house electromagnetic solver **VELM**



→ TJ modeling with NEGF



$$G_{BTBT}(z,V_{TJ}) = \frac{1}{q}\frac{J_{TJ}(V_{TJ})}{L_{TJ}}, z \in TJ$$

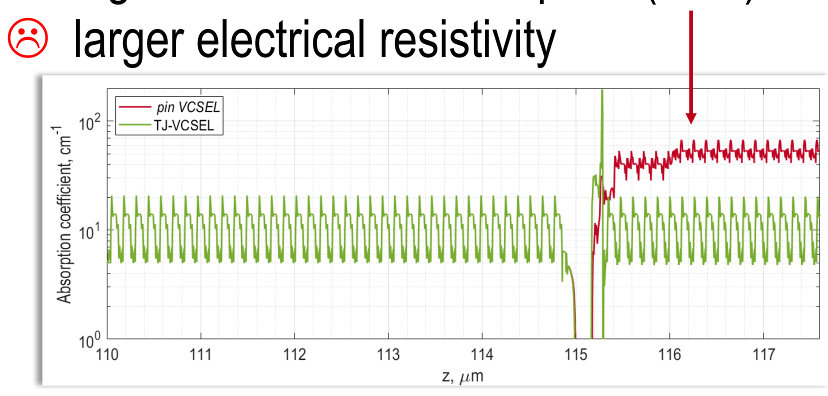
Added to other **GR** mechanisms in the DD (Auger, SRH, radiative)

Addressed research questions/problems

pin VCSEL

***p*-doped** top mirror (DBR) introduces:

- ☹ higher free-carrier absorption (FCA)
- ☹ larger electrical resistivity

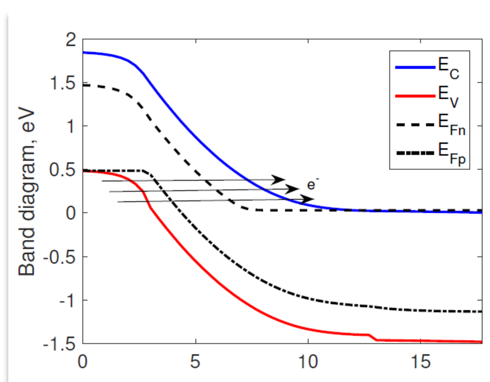


- earlier **thermal roll-over**
- worse RC time constant (limits the VCSEL bandwidth)

TJ-VCSEL

Alternative design relies on **tunnel junctions:**

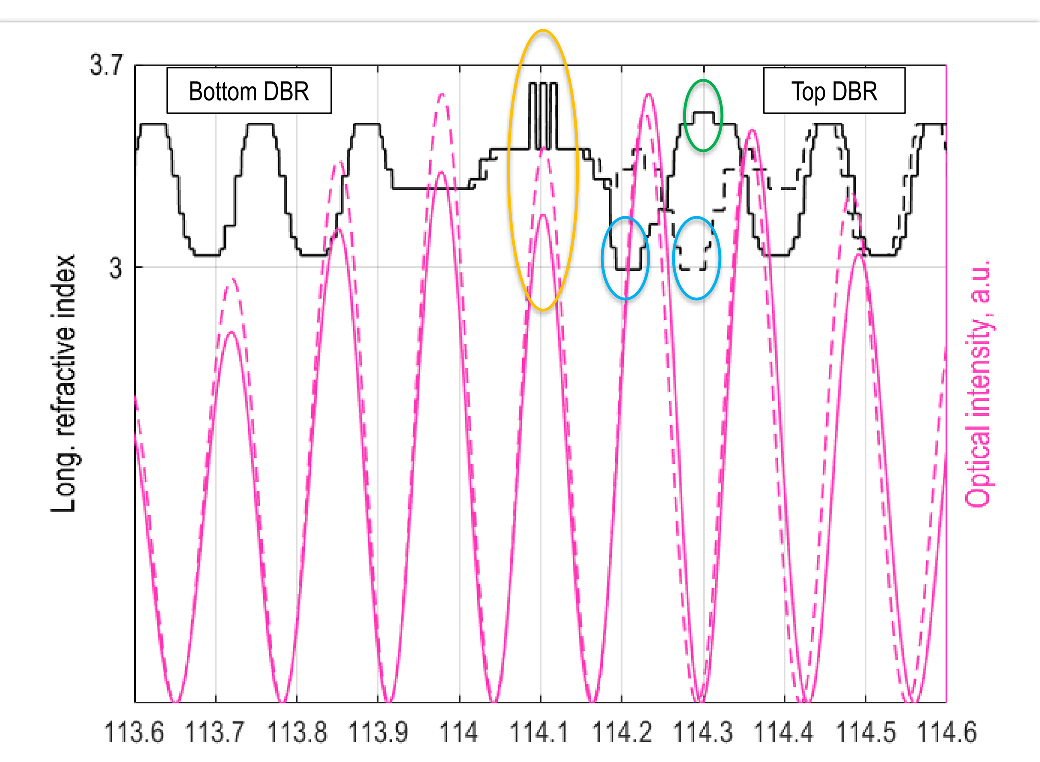
- ☺ holes injection inside the active region
- ☺ lossy *p*-doped region limited to just few nm of the TJ → top-DBR is ***n*-doped**!



TJ

- Heavily doped
- Reverse bias

→ band-to-band tunneling (BTBT) dominates!



Structure details

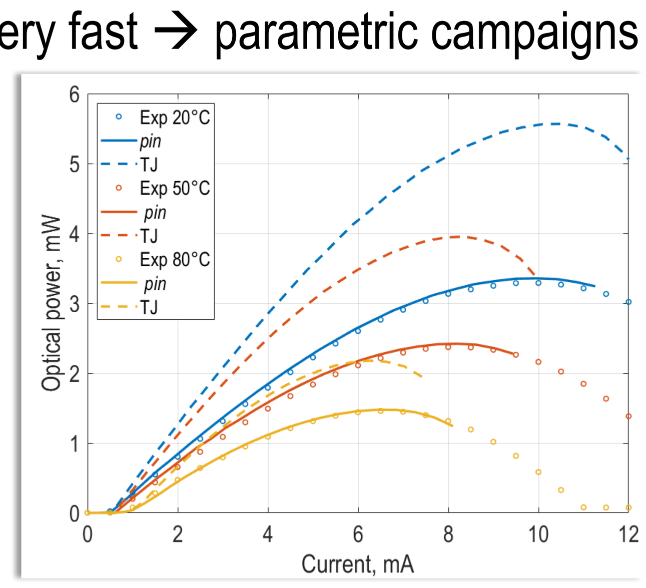
(**Solid**: TJ-VCSEL; **Dashed**: *pin*)

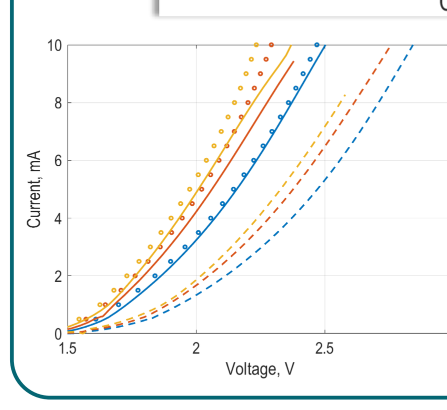
- **MQW**: 3 GaAs QWs → SW antinode
- **TJ**: AlGaAs → SW node; radially extended over all the VCSELs
- **Oxide aperture**: provides current and optical confinement
  - *pin* → SW node
  - TJ → between MQW and TJ
- DBRs

Novel contributions

D1ANA

- **1D** simulation → no radial features
- Needs to be calibrated
- Very fast → parametric campaigns

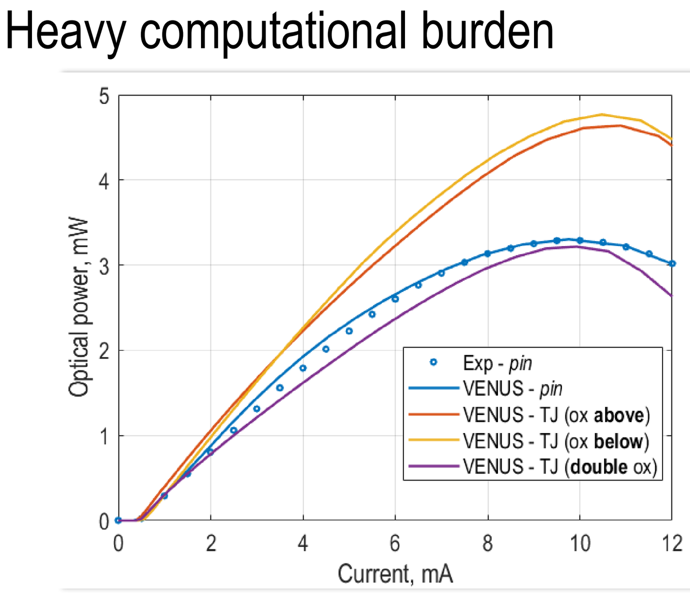


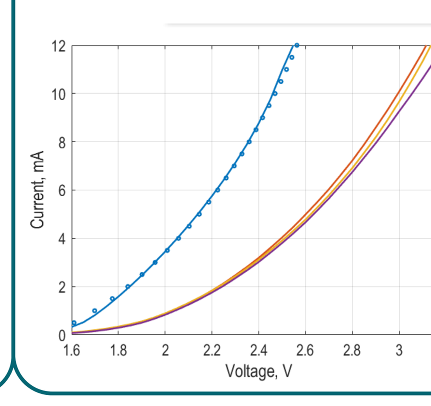


Static figures of merit at different heat sink temperatures

VENUS

- **3D** full simulation (cylindrical symmetry)
- Accurate on commercial *pin* VCSELs
- Heavy computational burden





Impact of oxide position w.r.t the TJ: 3D simulation is needed

- ✓ **VENUS** well reproduces experimental data of a commercial *pin* VCSEL
- ✓ After our calibration, similar results come out from **D1ANA**
- × TJ-VCSEL: prediction from the two solvers (keeping fixed all the parameters) are slightly different → highly doped TJ improves radial carrier diffusion? Better confinement?

Future work

The first step is to get experimental data on TJ structures, to properly calibrate VENUS and D1ANA with NEGF (a collaboration with TRUMPF Photonics just started).

Then, there are some interesting directions that must be pursued:

Lithographically defined TJ, that gets rid of the critical oxide aperture	**Dynamic** (small-signal) response of the two VCSELs	**Multiple TJ (MTJ)** VCSELs: stack of TJs and MQWs enhances the internal quantum efficiency of the VCSELs through the "carrier recycling" principle

Submitted and published works

- Gullino, A., Tibaldi, A., Bertazzi, F., Goano, M., Daubenschuz, M., Michalzik, R., Debernardi, P., "*Modulation response of VCSELs: a physics-based simulation approach*", Proc. Of NUSOD 2020, Turin, 2020
- Tibaldi, A., Gullino, A., Montoya, J. G., Matteo, A., *et al*, "*Modeling Tunnel Junctions for VCSELs: A Self-Consistent NEGF-DD Approach*", Proc. Of NUSOD 2020, Turin, 2020
- Tibaldi, A., Montoya, J. G., Matteo, A., Gullino, A., *et al.*., "*Analysis of Carrier Transport in Tunnel-Junction Vertical-Cavity Surface-Emitting Lasers by a Coupled Nonequilibrium Green s Function Drift-Diffusion Approach*", Phys. Rev. Appl., vol. 14, n. 2, 2020, pp. 024037
- Gullino, A., Tibaldi, A., Bertazzi, F., Goano, M., Debernardi, P., "*Reduced dimensionality multiphysics model for efficient VCSEL optimization*", Appl. Sc., vol. 11, n. 15, 2021, pp. 6908
- Gullino, A., Pecora, S., Tibaldi, A., Bertazzi, F., Goano, M., Debernardi, P., "*A multiscale approach for BTJ-VCSEL electro-optical analysis*", Proc. Of NUSOD 2021, Turin, 2021
- D'Alessandro, M., Gullino, A., Tibaldi, A., Bertazzi, F., Goano, M., Debernardi, P., "*Physics-based time-domain modeling of VCSELs*", Proc. Of NUSOD 2022, Turin, 2022

List of attended classes

- 01UJGRV – Advanced devices for high frequency applications (27/5/2020, CFU: 4)
- 01DOJRV – Computational (opto) electronics: a journey through device-level models (30/8/2022, CFU: 3.6)
- 02IUGKG – Il metodo Monte Carlo (3/4/2020, CFU: 6)
- 01UIYRV – Physics-based modeling of semiconductor devices (1/4/2020, CFU: 3)
- 01SFURV – Programmazione scientifica avanzata in matlab (25/5/2020, CFU: 4)
- 01DNYRV – Semiconductor light sources for engineers (12/9/2022, CFU: 4)