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XXXVII Cycle

VCSELs for gas sensing applications: quantum-corrected drift-diffusion

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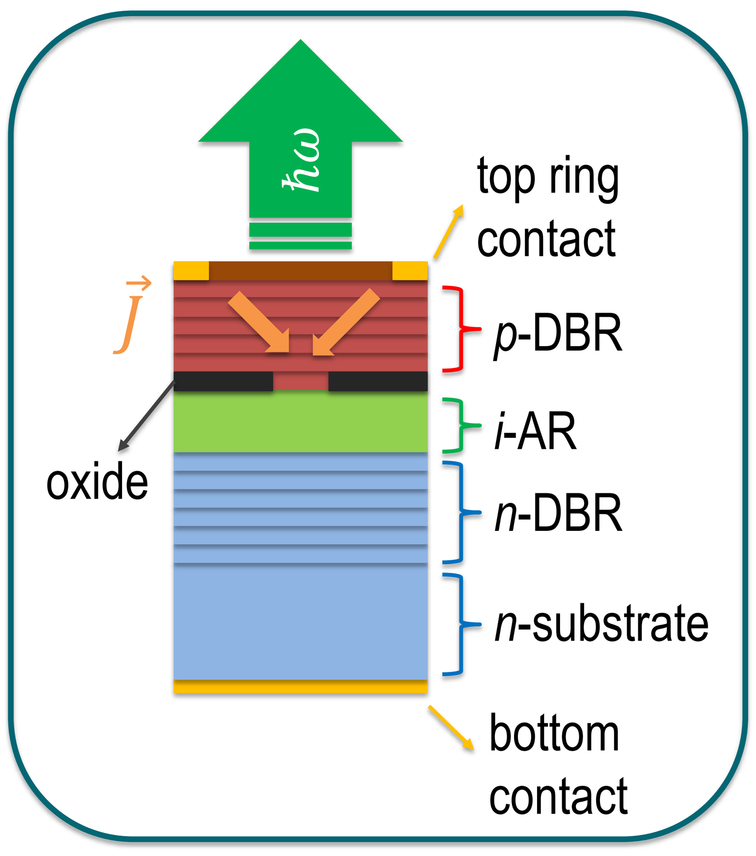
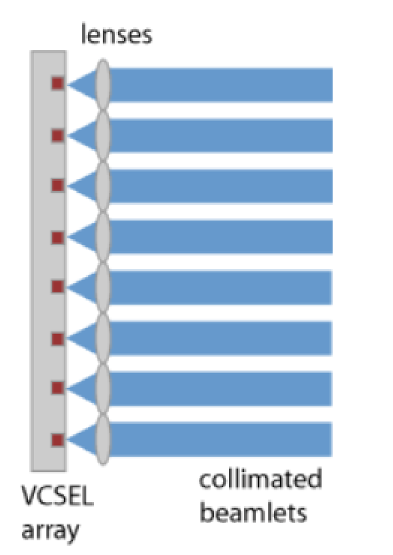
Research context and motivation



Conventional *pin*-VCSEL design

Vertical-cavity surface-emitting lasers (VCSELs)

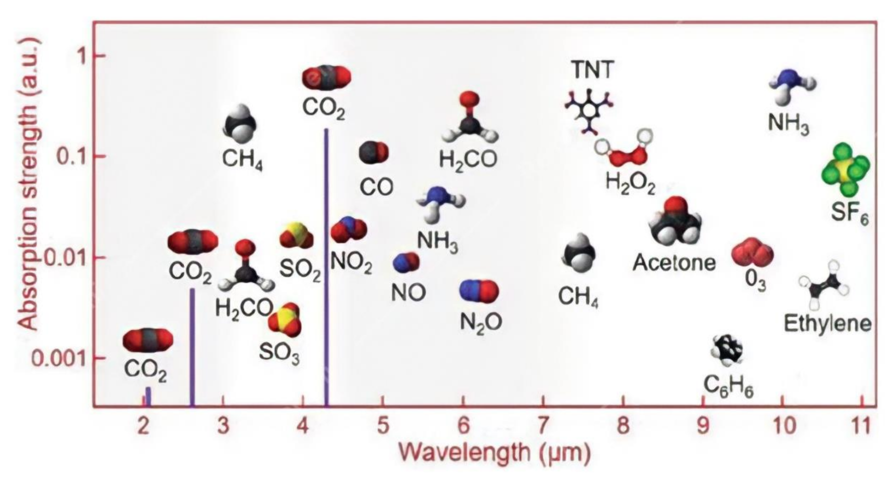


ADVANTAGES

- Low production cost
- High efficiency and low power consumption
- Array-oriented manufacturability

APPLICATIONS

- 3D gesture & face recognition
- LiDAR
- **Intra-datacenter links (AlGaAs)**
- **Gas sensing (antimonides)**

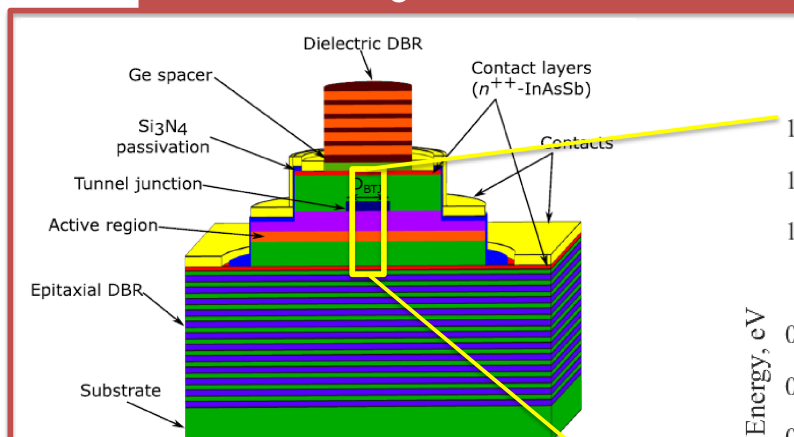


Needed wavelengths for gas sensing

Addressed research questions/problems

Numerical simulations of VCSELs

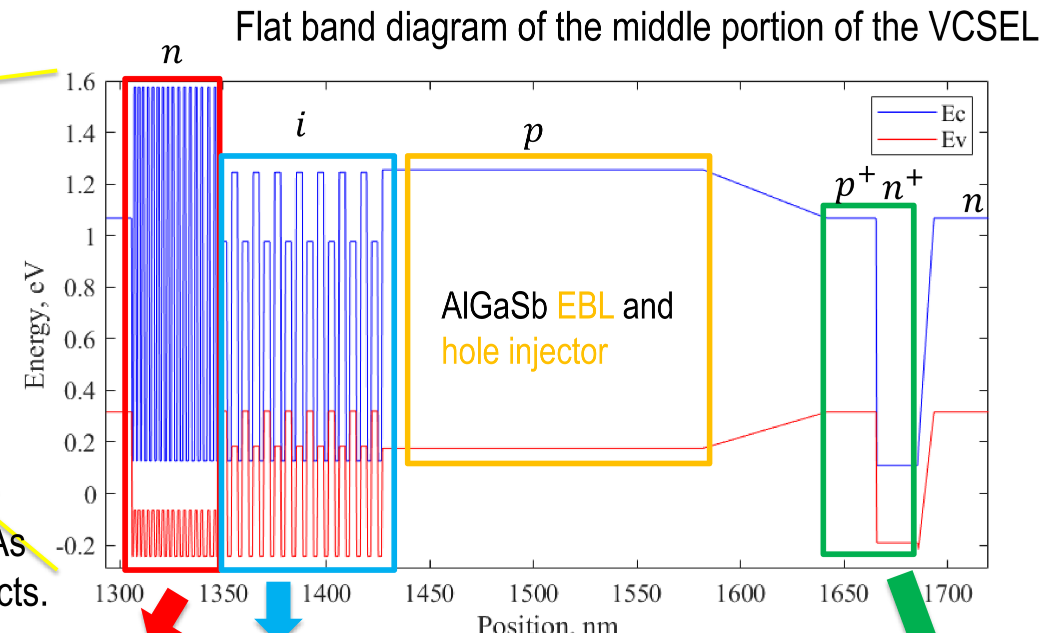
1 - Schrödinger-corrected carrier transport analysis in antimonide TJ-VCSEL



$\lambda = 4\mu m$

Tunnel junction (TJ) VCSEL realized with the 6.1 Å semiconductor family (GaSb, AlSb, InAs and related alloys) and with intracavity contacts.

Flat band diagram of the middle portion of the VCSEL



n-type InAs/AlSb chirped SL injecting electrons in the QWs while simultaneously blocking backward hole propagation

Intrinsic active region consisting in 8 type-II QWs (AlGaSb – InAs – GaInSb – InAs - AlGaSb)

Buried tunnel junction (p^+ GaSb / n^+ InAsSb):

- radial confinement of the current (no oxide due to technological problems)
- minimizing the *p*-doped portion of the device thanks to the **band-to-band tunneling** (**BTBT**) converting electrons into holes ⟹ higher conductivity with respect to the *pin*

Quantum effects ⇒ **not suitable for a Poisson-drift-diffusion (PDD) approach!**

2 - Beyond carrier-transport: electro-opto-thermal analysis of AlGaAs VCSELs

To simulate all of the physical properties of a VCSEL, one should extend the Schrödinger-corrected transport model, including:

DD equations corrected by the Schrödinger equation for the heterostructures treatment where quantum phenomena are relevant

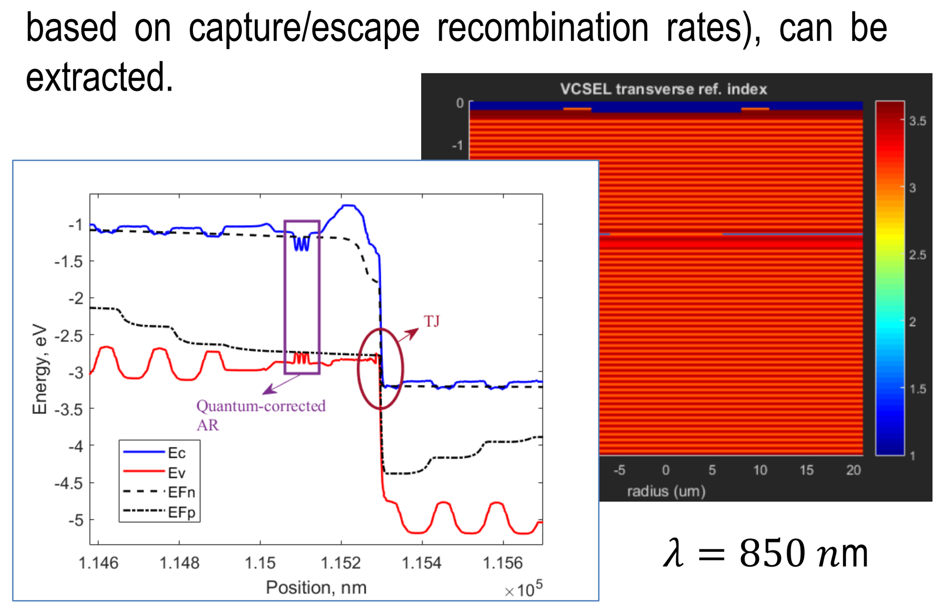
+

Rate equation for the stimulated power

+

Solution of the **heat equation** at each voltage step to tune the T-dependent parameters

This was applied to an AlGaAs TJ-VCSEL since comparisons with our in-house simulator, D1ANA (relying on a different and established quantum-corrected model based on capture/escape recombination rates), can be extracted.



$\lambda = 850\ nm$

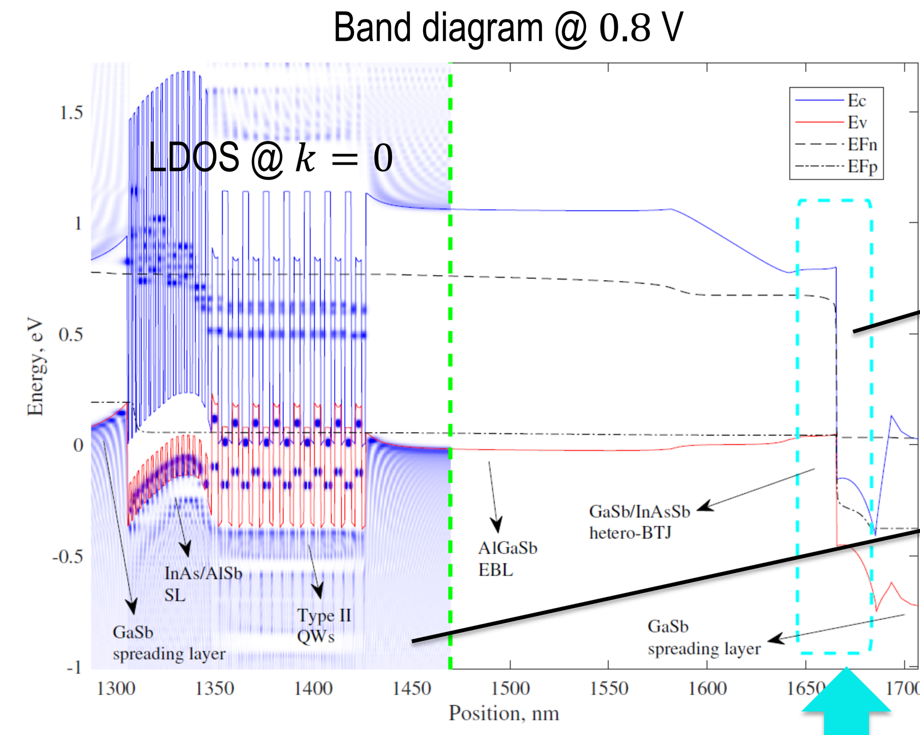
Submitted and published works

- Valerio Torrelli, *et al.*, 22nd International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD 2022) (online, 2022), Modeling carrier transport in mid-infrared VCSELs with type-II superlattices and tunnel junctions

Novel contributions

1 - Schrödinger-corrected carrier transport analysis in antimonide TJ-VCSEL

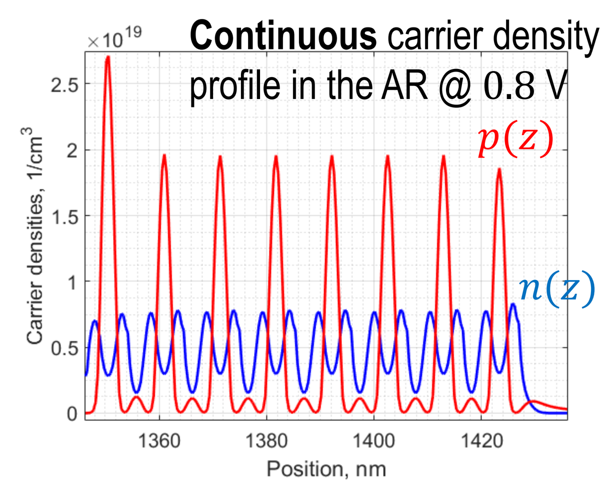
Band diagram @ 0.8 V

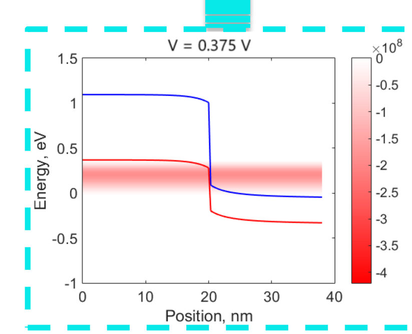


Successful modeling, confirming the device's expected behaviour!

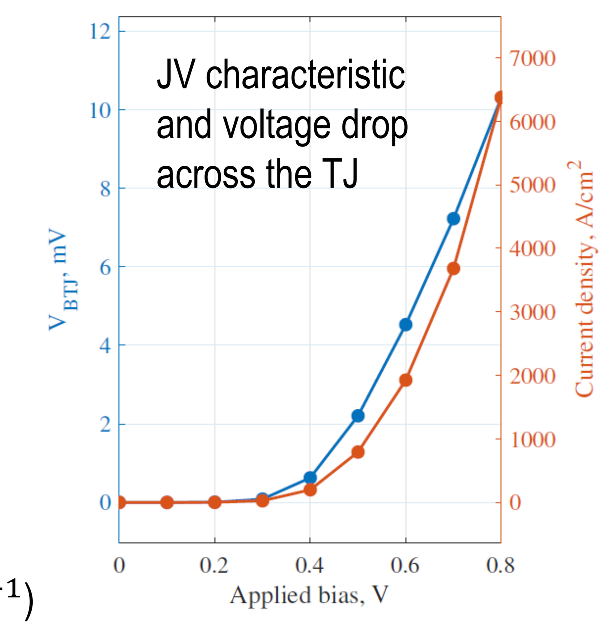
Region where a BTBT generation rate has been introduced in the PDD model extracted from the non-equilibrium Green's function (NEGF) analysis of the TJ

Schrödinger-corrected region yielding a smooth carrier density profile based on the carrier wavefunctions

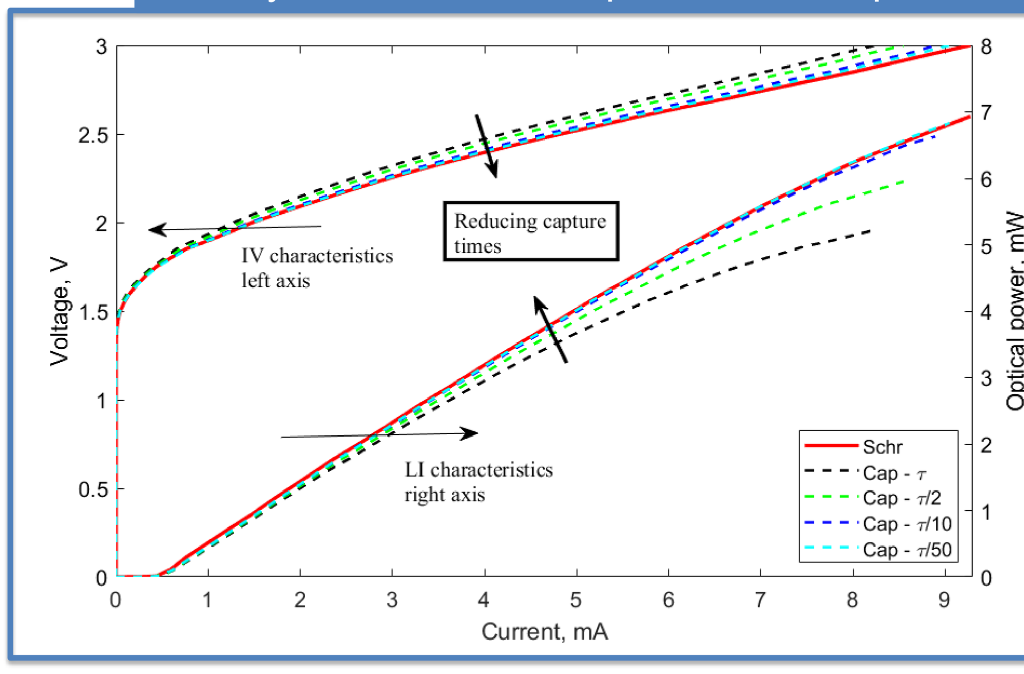




NEGF spectral current across the TJ $(\mathrm{Acm^{-2}eV^{-1}})$



2 - Beyond carrier-transport: electro-opto-thermal analysis of AlGaAs VCSELs



Successful **extension of the Schrödinger-corrected drift diffusion into an electro-opto-thermal simulation**, showing a good agreement with the capture times model with reduced τ

Original capture time values for electrons and holes: $\tau_n = 1 \cdot 10^{-11}$ s, $\tau_p = 5 \cdot 10^{-12}$ s

Adopted methodologies

Poisson-Schrödinger-drift-diffusion (PSDD)

In a standard PDD step, **heterostructures** are accounted for by using as energy reference for the conduction and valence band edges the so called flat band alignments, ΔE_c^{FB}, ΔE_v^{FB}, yielding a non-physical discontinuous carrier density profile.

Initial guess at a given voltage step: (ϕ, n, p) → PSDD

PSDD — YES → Schrödinger solver → Quantum-corrected carrier densities → Q.C. band edges → Q.C. band alignments → PDD

PSDD — NO → Band edges evaluated from ϕ using ΔE_c^{FB} and ΔE_v^{FB} → PDD

Future work

- Moving on to fully 3D simulations by exploiting our in-house solver VENUS
- Implementing the analysis of multi-tunnel-junction VCSELs (MTJ-VCSELs), interesting from the point of view of applications given the possibility to obtain a higher optical power without exploiting VCSEL arrays
- Collaboration with the company *TRUMPF PHOTONICS* to optimize and improve the design of real devices. By exchanging experimental data, it will be possible to properly tune our simulators and to validate their results

List of attended classes

- 01DOJRV – Computational (opto) electronics: a journey through device-level models (29/07/2022, 3.6)
- 01DOBRV – Mathematical-physical theory of electromagnetism (06/06/2022, 3)
- 01MLOKG – Meccanica quantistica dei sistemi a molti corpi (05/05/2022, 6)
- 01SFVRV – Metamaterials: Theory and multiphysics applications (08/04/2022, 4)
- 02SFURV – Programmazione scientifica avanzata in matlab (21/04/2022, 6)
- 01DNYRV – Semiconductor light sources for engineers (12/09/2022, 4)
- 01TSGKG – The Monte Carlo method (06/05/2022, 6)