VCSEL Day 2024

Toulouse, France

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Workshop Program

Thursday, September 12th — 9:30 - 17:10

9:30 – 9:50	Welcome and Introduction
9:50 – 10:30	Session : Integrated systems, coupling and datacom applications [1]
9:50 – 10:10	Multiple Wavelengths High Speed VCSEL for Datacom Applications Bedouin Sassiya, Ulm University, Germany
10:10 – 10:30	Impact of four-wave mixing in multimode VCSELs on noise performance: an experimental and numerical study, Cristina Rimoldi, Politecnico di Torino, Italy
10:30 – 11:00	*Coffee/tea break (Room A003)*
11:00 – 12:00	Session : Integrated systems, coupling and datacom applications [2]
11:00 – 11:20	Enhancing VCSEL Beam Efficiency with a Standalone Tapered Structure for Improved Optical Coupling, Ronghua Zhou, ESYCOM, ICON Photonics, France
11:20 – 11:40	NIR photopolymerization for VCSEL-to-fiber single mode connection, Nessim Jebali, LAAS-CNRS , France
11:40 – 12:00	Meta Optical Element enabling VCSEL module integration and new optical features, Ludovic Marigo, NIL Technology, Switzerland
12:00 – 12:20	Posters short presentation (2 min each)

- Combining in-situ measurements in molecular beam epitaxy : Study of $Al_xGa_{1-x}As$ properties at growth temperature, Pierre Gadras, LAAS-CNRS, France
- Critical aspects of VCSELs fabrication, Karolina Olucha, Lukasiewicz Research Network, Poland
- Thermal management of VECSEL-GaAs for high-power single-mode emission, Abdelmounaim Harouri, C2N, CNRS, Univ. Paris Saclay, France
- 795nm Single-Mode VCSEL with Grating Relief Structure, Julian Lindner, Trumpf Photonics Components, Germany
- Development of coupon fabrication for effective Micro Transfer Printing of VCSEL structure, Wioleta Słaba, Lukasiewicz Research Network, Poland
- Fabrication and Characterization of 940 nm VCSELs on Ge and GaAs Substrates, Karim Ben-Saddik, LAAS-CNRS, France
- « TBD », Alexis Tobias, LAAS-CNRS, France
- Analyzing Sidebands in Multimode VCSELs Through Near-Field Lensed Fiber Scanning, Marco Novarese, Politecnico di Torino, Italy
- Computational inspection of VCSEL oxidation exploiting a spectrally-shaped illuminator, Antoine Rouxel, LAAS-CNRS, France

12:20 – 13:20	*Lunch break (Room A003)*
13:20 – 14:20	Poster session (Room A003)

14:20 – 15:20	Session : Devices modelling
14:20 – 14:40	Modelling of transverse coupled cavity VCSELs, Martino d'Alessandro, Politecnico di Torino, Italy
14:40 – 15:00	Electro-Opto-Thermal modeling of AlGaAs Buried TJ-VCSELs, Alberto Gullino, Politecnico di Torino, Italy
15:00 – 15:20	On-wafer measurements to calibrate active VCSEL simulations, James Meiklejohn, Cardiff University, United Kingdom
15:20 – 15:50	*Coffee/tea break (Room A003)*
15:50 – 17:10	Session : Characterizations, modal and polarization control
15:50 – 16:10	Robustness assessment of grating-based circularly-polarized VCSELs, Valerio Torrelli, Politecnico di Torino, Italy
16:10 – 16:30	Emission spectra of VCSELs with noncircular optical apertures, Magdalena Marciniak, Lodz University of Technology, Poland
16:30 – 16:50	Locking the VCSEL polarization in the horizontal and diagonal polarization basis, Michael Zimmer, University of Stuttgart, Germany
16:50 – 17:10	Micro-photoluminescence and micro-electroluminescence from VCSELs and VCSEL structures, Michal Wasiak, Lodz University of Technology, Poland
20:00	*Social Dinner* *Restaurant Les Beaux-Arts, 1 Quai de la Daurade, 31000 Toulouse*

Friday, September 13th — 9:30 - 12:20

9:30 – 10:30	Session : Fabrication & Technology [1]
9:30 – 9:50	In-situ and ex-situ optical metrology – an enabler for high-quality GaAs-based VCSEL structures, Johannes K. Zettler, LayTec AG, Germany
9:50 – 10:10	940 nm VCSEL epi-structure grown on germanium (Ge) substrates, Włodzimierz Strupinski, VIGO Photonics SA, Poland
10:10 – 10:30	Epicentre : A RIBER/LAAS-CNRS joint lab for optimization and automation of MBE process, Alexandre Arnoult, LAAS-CNRS, France
10:30 – 11:00	*Coffee/tea break (Room A003)*
11:00 – 12:00	Session : Fabrication & Technology [2]
11:00 – 11:20	GaSb Long-Wavelength VCSEL with Low Loss Buried Tunnel Junction, Andrea Simaz, Walter Schottky Institute, Germany
11:40 – 12:00	High-temperature performance of high-speed 940 nm VCSELs for optical communication, Marcin Gebski, Lodz University of Technology, Poland
12:00 – 13:00	*Lunch break (Room A003)*
13:00 – 16:00	Labs tour (2 options): 1. Optical Sensors and smart Integrated Systems @ ENSEEIHT 2. Micro and Nanotechnologies Platform @ LAAS *(Travel by public transport to LAAS: 25-30 min)*

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Session: Integrated systems, coupling and datacom applications

- *Multiple Wavelengths High Speed VCSEL for Datacom Applications*, Bedouin Sassiya, Ulm University, Germany
- *Impact of four-wave mixing in multimode VCSELs on noise performance: an experimental and numerical study*, Cristina Rimoldi, Politecnico di Torino, Italy
- *Enhancing VCSEL Beam Efficiency with a Standalone Tapered Structure for Improved Optical coupling*, Ronghua Zhou, ESYCOM, ICON Photonics, France
- *NIR photopolymerization for VCSEL-to-fiber single mode connection*, Nessim Jebali, LAAS-CNRS , France
- *Meta Optical Element enabling VCSEL module integration and new optical features*, Ludovic Marigo, NIL Technology, Switzerland

Multi-Wavelength High-Speed VCSELs for Datacom Applications

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The rapid growth of internet traffic has led to a significant increase in demand for high-throughput, low-energy optical interconnects, especially in data centers. Oxide-confined vertical-cavity surface-emitting lasers (VCSELs) have become essential in this field due to their high bandwidth, electro-optic efficiency, scalability, and reliability [1]. Today, 100 Gbit/s PAM4 850 nm VCSELs are commercially available.

To further boost optical interconnect performance, short wavelength division multiplexing (SWDM) is employed with VCSELs [2]. By multiplexing four distinct wavelengths of 850, 880, 910, and 940 nm, data transmission rates can be quadrupled. The goal is to achieve 100 Gbit/s per wavelength, increasing the total transmission speed to 400 Gbit/s. Designing VCSELs for each wavelength requires careful consideration and adjustments. The active region, quantum wells, and barrier materials differ between designs, presenting opportunities for optimization. Additionally, the aluminum contrast and concentration in the distributed Bragg reflectors (DBRs) must be tailored to account for absorption at various wavelengths. These design variations and their implications will be discussed in detail.

A key challenge is maintaining consistent performance across all wavelengths. This includes dynamic characteristics such as relative intensity noise (RIN), resonance frequency, and damping, as well as static properties like quantum efficiency, threshold current, and temperature stability. To tackle these challenges, a fast feedback loop is crucial. To address this, a rapid lot processing technique has been developed, allowing VCSELs to be processed within a week, compared to the typical 3 to 4 months timeframe for RF-processed VCSELs. Although the modified chip design precludes RF characterization, the approach is highly effective for evaluating static performance metrics, such as detuning, temperature stability, resistance, voltage, optical spectrum, threshold current, quantum efficiency, and power vs. current slope. Figure 1 shows a comparison between quick lot and RF-processed devices, demonstrating their similarity and validating the reliability of the new process.

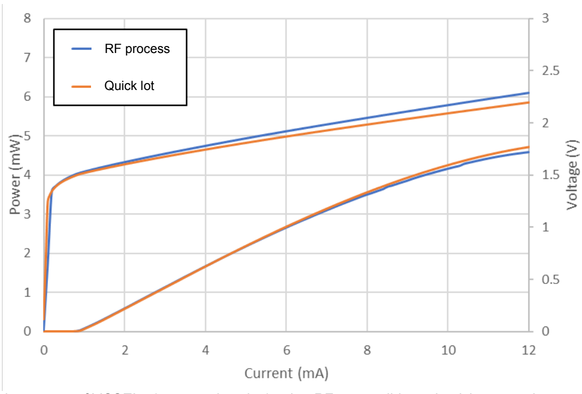

Fig. 1 Operation curves of VCSELs (same active size) using RF-compatible and quick processing.

Additionally it will be demonstrated how spectrally resolved RIN analysis is employed to evaluate the intrinsic dynamic behavior of VCSELs without requiring an RF-compatible chip design.

References

[1] R. Michalzik (Ed.), VCSELs, Springer, Berlin, 2013.
[2] P. Torres-Ferrera et al., "Statistical analysis of 100 Gbps per wavelength SWDM VCSEL-MMF data center links on a large set of OM3 and OM4 fibers," J. Lightw. Technol. **40**, 1018 (2022).

Impact of four-wave mixing in multimode VCSELs on noise performance: an experimental and numerical study

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The use of multimode VCSEL in the context of short-reach data transmission fiber links in datacenters has recently attracted a lot of interest due to the good tradeoff of such devices between power and achievable bandwidth. A known problem in quasi circular multimode VCSELs is the fact that several of the emitting transverse modes are very close in frequency. This leads to spurious peaks in the Relative Intensity Noise (RIN) due to frequency beatings between modes and to a degradation of the laser performance. Elliptical oxide aperture VCSELs have been proposed as a possible solution to this problem [1] because they permit for a larger separation in frequency of the emitting modes: this allows to push the mode beating frequencies beyond the receiver bandwidth. However, this short-term solution will become ineffective when the need for higher modulation speeds, beyond present-day standards, arises. Therefore, it is necessary to understand in depth the origin of such spurious peaks to the aim of finding effective design solution in order to improve laser performance.
In this contribution, we experimentally characterize an 850 nm multimode VCSEL with an elliptical oxide aperture, designed in order to effectively suppress one polarization. In order to assess the number and shape of emitting transverse modes, we perform a near-field measurement [2] by collecting the output light of the VCSEL through an objective lens and passing the resulting far-field collimated beam through 4 diffraction gratings to the aim of separating transverse modes at different wavelengths. The resulting near-field image collected by a camera after a tube lens is reported in Fig. 1(a), for the case at I_{bias}=4.5 mA. A measurement of the RIN is illustrated in black in Fig. 1(b). Here, we observe 3 spurious peaks at the frequencies of 8.3, 18, and 27.3 GHz.

(a) (b)

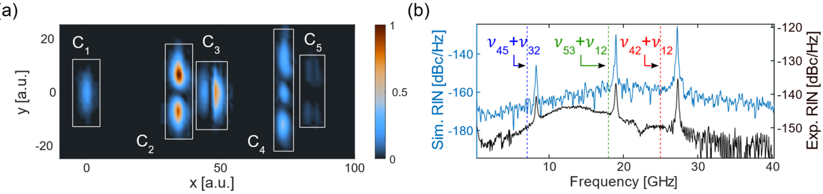

Fig. 1 (a) Spatial profile of (approximate) Hermite-Gaussian modes $C_{1\text{-}5}$ obtained through a near-field measurement of an 850 nm multimode VCSEL with elliptical oxide aperture. (b) Corresponding RIN measurement (black), displaying spurious peaks, and simulated RIN (blue). $\nu_{mn} = \nu_m - \nu_n$, with ν_m being the frequency of the *m*-th mode C_m.

We then develop a model based on a time-domain mode expansion approach, based on [3]. Differently from most approaches present in literature, our model accounts for coherent frequency mixing and spatial hole burning. We demonstrate [2] that these features are fundamental in order to correctly describe the RIN peaks observed experimentally, as exemplified by the simulated blue curve in Fig. 1(b). Our analytical calculations allow to attribute the observed peaks to specific nontrivial four-wave mixing combinations between modes, the frequency of which is plotted with vertical dashed lines in Fig. 1(b). This study allows to identify a few simple design rules for the VCSEL oxide aperture to minimize spurious peak occurrence in the RIN and potentially increase the laser modulation bandwidth.

References

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Enhancing VCSEL Beam Efficiency with a Standalone Tapered Structure for Improved Optical Coupling

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Vertical-cavity surface-emitting lasers (VCSELs) are increasingly used in both fiber optic and free-space communication applications [1]. While coupling VCSEL to fibers is relatively straightforward, the inherent divergence angle of VCSELs still presents some remaining challenges and opportunities particularly in optical free-space and optical fiber coupling optimizing the bandwidth over the varying distances [2]. This study introduces an innovative micro-optic standalone structure designed to mitigate the divergence angle of VCSELs. The proposed taper structure, fabricated from a highly transparent polymer material, enhances optical transmission efficiency by reducing the VCSEL divergence of lower to higher order modes thus minimizing energy loss. The structure is designed for straightforward integration onto the VCSEL, offering an effective solution for beam shaping. Compared to conventional micro-lens approaches [3], this tapered vertical waveguide structure can be spin-coated on VCSEL at the wafer level, providing a cost-effective alternative for VCSEL applications. It can also be exploited as a standalone structure as demonstrated in this work, offering greater flexibility in testing.

An optical power mapping measurement was conducted to evaluate the divergence and beam properties of an 14Gbps 850 nm VCSEL [4]. The measured optical power of the bare VCSEL is 1.53mW under a 4.38mA bias current. The investigation involved placing a standalone tapered structure atop the VCSEL, with a multimode fiber (MMF) serving as an optical probe to measure the optical power distribution in the x-y plane parallel to the VCSEL surface at a fixed distance. The VCSEL was mounted on a custom-designed printed circuit board (PCB), facilitating power delivery via an external source.

The optical power distribution at 200μm from the VCSEL surface is presented in Fig.1: (a) without the standalone taper and (b) with the standalone taper under a biasing of 4.38mA. The taper used in the experiment had a width of 30μm on the fiber side and 20μm on the VCSEL side. The results reveal two significant findings: (1) an increase in the maximum optical power coupled into the fiber from 0.204mW without the taper to 0.261mW with the taper, and (2) a reduction in the VCSEL beam width, based on the $1/e^2$ value of the VCSEL to MMF far field correlation measurements, from 93μm to 70μm at the distance of 200μm.

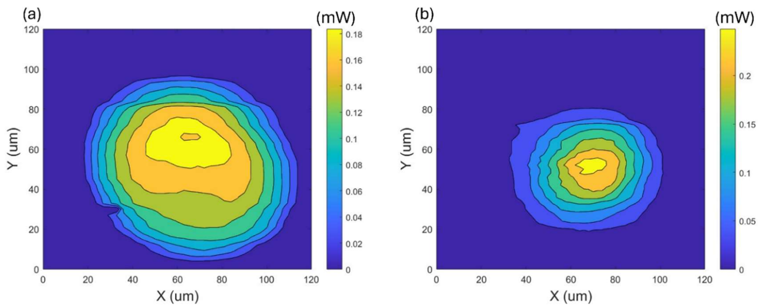

Fig. 1 Optical power mapping measurement result with MMF probe at 200μm from the surface of VCSEL: (a) without the standalone taper and (b) with the standalone taper under a biasing of 4.38mA.

References

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[2] J. Nanni et al., "Exploitability of Butt-Coupling between Single Mode/Multi Mode VCSEL and G.652 SSMF for future Green Radio-over-Fiber Infrastructures," 2022 Italian Conference on Optics and Photonics (ICOP), Trento, Italy, 2022.
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NIR photopolymerization for VCSEL-to-fiber single mode connection

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Coupling VCSELs to optical fibers is a key issue for increasing their use in optical communications and instrumentation systems. However, tolerances on angular tilts and lateral misalignments are tight, especially in the case of single mode (SM) devices. Active alignment methods [1] as well as *in situ* fabrication by using 2-photon polymerization direct laser writing [2] were recently proposed to fabricate optical links between VCSELs and multimode fibers. An alternative solution consists in the creation between both parts a SM self-written waveguide (SWW) by exploiting near-infrared (NIR) photopolymerization (figure 1.a). The specificity of our method (NIR-SM-SWW) is to use a writing wavelength identical to that designed for single mode propagation in the fibers (850nm), leading to a single step NIR photopolymerization process directly transferable to 850nm SM-VCSEL to SM-fiber coupling. For best photochemical conditions, a coupling efficiency as high as 82% (i.e., -0.86 dB loss) was measured for a 300-µm-long SM optical link between two 780HP optical fibers (Figure 1.b) [3]. It is 35 times higher than the coupling measured in the air (2.3 %) and 16 times higher than the coupling measured in the polymer layer (5.06%) at the same distance, demonstrating the creation of a single mode link. A similar connection between a SM-VCSEL and a 780HP fiber has been recently experimentally demonstrated using this process (Figure 1.c).

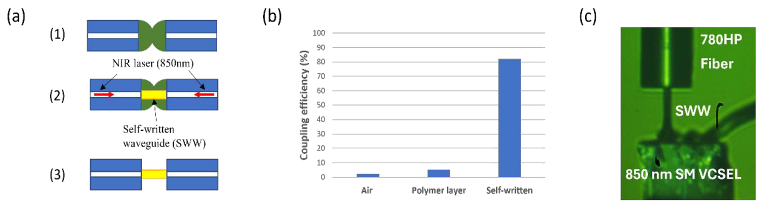

Fig. 1 **(a)** Description of the steps of the NIR-SM-SWW process. **(b)** Coupling efficiency measurements for fiber-to-fiber distance of 300 µm for different connection configurations (air, polymer layer and SWW). **(c)** Self-coupling of SM-VCSEL to SM-fiber at 850nm.

References

[1] **M. Grabherr, et al., "Advanced single-mode VCSEL fiber pigtail", Proc. SPIE 12904, Vertical-Cavity Surface-Emitting Lasers XXVIII, 129040C (13 March 2024)**

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[3] **N. Jebali, et al., (2024), "Self-written single-mode optical link using a single near-infrared photopolymerization step", [submitted]**

Meta Optical Element enabling VCSEL module integration and new optical features

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VCSEL are now broadly used for 3D sensing in Time of Flight (ToF) for consumer, industrial and automotive applications. Dot projectors, combined with the use of multi-junction VCSEL, enable more precise face recognition, surrounding mapping up to tens of meters or activity tracking in cars.
These dot projector patterns are conventionally achieved with refractive elements for the collimation and then Diffractive Optical Elements (DOE) technology for the dot spreading (fanout) as shown in Fig1 left. However, the stacking of several individual elements increases module assembly complexity and costs. We demonstrated in [1] the first assembly simplification step by using only two separated DOE elements, one collimator and one fanout. More recently [2], we demonstrated the use of a single flat surface Meta-Optical element combining both functions enabling high performance, large Filed of illumination and significantly higher assembly tolerances.

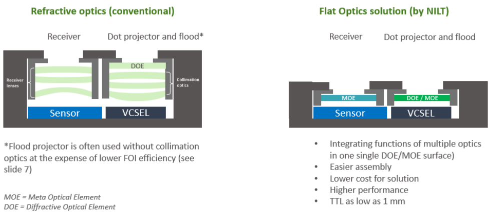

Fig. 1 Comparison of conventional module (left) and flat optics module (right)

The single flat surface element, located at 2 mm away from the VCSEL source, demonstrates diffraction efficiency of 65% and uniformity between the diffraction pattern below 15% making it the highest performing flat optic surface on the market.

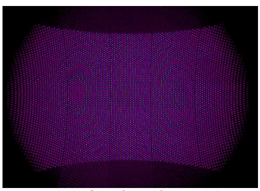

Fig. 2 Dot projector pattern of 144° x 70° containing 8,125 uniform dots

The MOE are created from a Master written by Electron Beam Lithography (EBL) which is used as a hard stamp to replicate the nano pattern by Nanoimprint Lithography (NIL) on the final substrate covered with amorphous silicon (aSi). This aSi layer is then dry etched in a plasma chamber to create nano-pillars. The final elements are then encapsulated and receive Anti-Reflection Coating (ARC) to enable higher optical transmission.
NILT can design from customer's specifications to entire module and system and also act as a nano-foundry where integration directly on VCSEL might be required to enable specific features as polarization control, beam shaping or deflectors.

References

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[2] NILT Record performance of Tx metalens - PressRelease Oct2023

Poster Session

- *Combining in-situ measurements in molecular beam epitaxy: Study of $Al_xGa_{1-x}As$ properties at growth temperature*, Pierre Gadras, LAAS-CNRS, France
- *Critical aspects of VCSELs fabrication*, Karolina Olucha, Lukasiewicz Research Network, Poland
- *Thermal management of VECSEL-GaAs for high-power single-mode emission*, Abdelmounaim Harouri, C2N, CNRS, Univ. Paris Saclay, France
- *795 nm Single-Mode VCSEL with Grating Relief Structure*, Julian Lindner, Trumpf Photonics Components, Germany
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- « Unknown Title », Alexis Loupias, LAAS-CNRS, France
- *Analyzing Sidebands in Multimode VCSELs Through Near-Field Lensed Fiber Scanning*, Marco Novarese, Politecnico di Torino, Italy
- *Computational inspection of VCSEL oxidation exploiting a spectrally-shaped illuminator*, Antoine Rouxel, LAAS-CNRS, France

Combining *in-situ* measurements in molecular beam epitaxy : Study of $Al_xGa_{1-x}As$ properties at growth temperature

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In-situ measurement is a key feature to better understand and precisely control the growth by molecular beam epitaxy (MBE) of VCSEL structures. However, no universal tool has been developed today to control heterostructure growths in real time [1–3].

In this work, we are developing a methodology to deduce the growth rate and the optical constants at growth temperature (500-600°C) of thin film grown by MBE from in-situ measurement of spectral reflectance. The reflectance is measured over a wide spectral range (390 – 1700 nm), allowing the study of epitaxial alloys nearly lattice-matched on GaAs such as $AlGaAs$ or $InGaAs$. Moreover, the knowledge of the optical constants of these alloys at the growth temperature is a key milestone in order to monitor and control the MBE growth of VCSEL in the near infrared range (850-940nm).

By combining the in-situ spectral reflectance, and the accurate optical constants database, it is possible to directly deduce the growth rate. In order to ensure precise andreproducibilible estimation, we have to measure independently the temperature and the alloy composition of the growing film, respectively by optical absorption edge and [4] and wafer curvature measurements [5].

Our methodology to retrieve the complex refractive indices of $Al_xGa_{1-x}As$ at growth temperature relies on *in-situ* reflectance measurement, as illustrated in figure 1a, in combination with ex-*situ* X-ray diffraction measurements (HRXRD). The thicknesses of the sample will be confirmed through FTIR measurement. The accuracy of the thickness measurement by HRXRD is analyzed as well as its impact on the deduced optical indices. As a result the wavelength dispersion of the refractive indices can be obtained as shown on figure 1b.

In the future work, based on this optical constant database of $Al_xGa_{1-x}As$ materials, our goal is to control the growth rate of complex VCSEL heterostructure from real time reflectance and wafer curvature measurements.

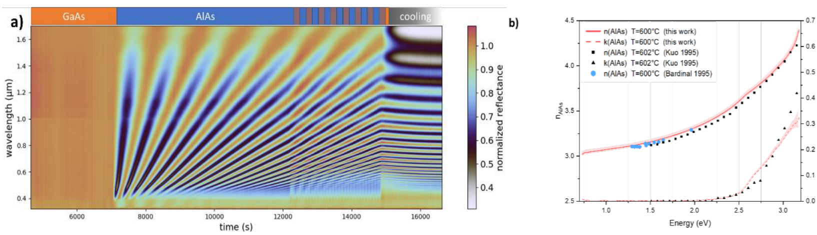

Fig. 1 a) *In-situ* spectral reflectance measurement during the growth, **b)** Deduced refractive indices *n* and *k* of AlAs at 600°C and comparison to literature.

This work was partially supported by LAAS-CNRS and the the French Renatech network. And founded by EPICENTRE, a joint laboratory between RIBER and LAAS-CNRS

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Critical aspects of VCSELs fabrication

Karolina OLUCHA[1], Marek EKIELSKI[1], Marcin GĘBSKI[1,2], Magdalena ZADURA[1], Karolina BOGDANOWICZ[1,2], Wioleta SŁABA[1], Oskar SADOWSKI[1,3], Tomasz CZYSZANOWSKI[2], Anna SZERLING[1]

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High requirements for VCSEL fabrication are essential for enhancing functionality, like increasing optical output power, maximum operating temperature, and reducing threshold current. Processing includes several critical steps, like: contact formation, mesa fabrication, passivation and oxidation. One of the goals of our work was to develop an ICP-RIE plasma etching procedure that would allow obtaining walls of the etched mesa with a straight or trapezoidal profile and straight, undamaged edges. A procedure was developed covering the process gas flow and composition, pressure, power, and temperature, which allowed achieving the desired wall profile. The study results showed that increasing the power allowed obtaining a vertical profile of the walls, while increasing the power with an additionally reduced temperature resulted in a trapezoidal shape of the walls. It should be noted, however, that in all examined cases, the diameters of the obtained mesas were smaller than planned, with the smallest deviation at the base and increasing towards the top of the mesa, which should be taken into account when calculating the oxidation time. Additionally, an etching mask consisting of SiN and a positive resist was used, which had a dual function—the resist was a mask for etching, and the SiN underneath it protected the previously applied contacts during the next stage, oxidation. The development of these conditions, together with the use of a SiO_2 passivation layer, allowed for a simplified VCSEL fabrication method, with a lower contact placed on the bottom side of the sample and a shallower mesa.

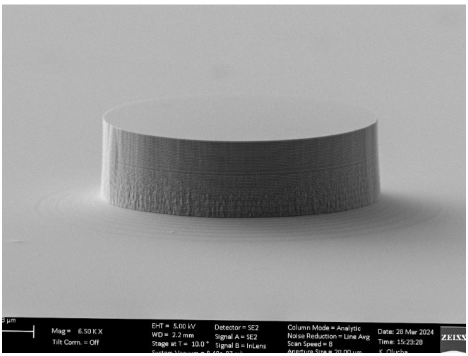

Fig. 1 Side view of the etched VCSEL mesa from a scanning electron microscope. Increased power and reduced temperature allowed to obtain a mesa with slightly trapezoidal walls.

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Thermal management of VECSEL-GaAs for high-power single-mode emission

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Information and communication technologies have revolutionized our world and reshaped our industries. Vertical emission in external cavity lasers (VECSEL) combine simultaneously high-power and highly coherent tunable single-frequency laser emission. VECSELs are promising candidates for various applications such as transmitter, sensors, ….

In our study,we are interested in reducing the thermal impedance of our ½ VECSELs on GaAs substrate, emitting between 800 and 1100nm. Part of the power of the optical pump is converted into a significant heating of the component [see Fig. 1(A)]. This heating reduces the gain of the QWs and induces a shift of the emission wavelength towards longer wavelengths [1]. In the literature, many strategies to improve the heat dissipation for ½ VECSEL are proposed [2][3]. In our case, our approach is to integrate a heat sink as close as possible to the Bragg mirror [see Fig. 1(B)] by dry etching and electrolytic metal growth. As a first step, we studied both the diameter of the aperture and the metal material to be used in order to have a good mechanical stability of the semiconductor structure while ensuring a very good heat dissipation.

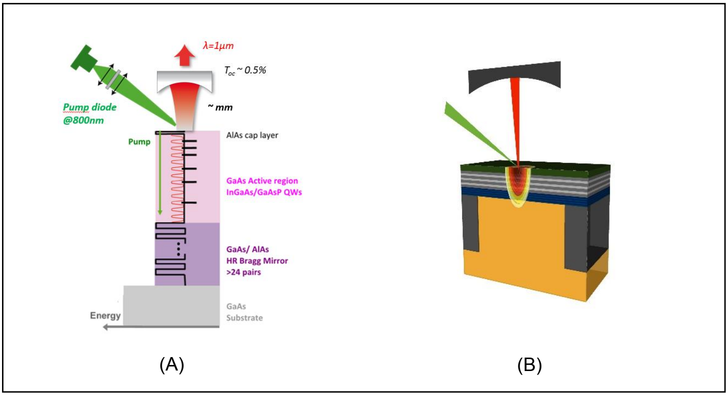

Fig. 1 : (A) VECSEL laser structure / (B) Integrate heat sink on VECSEL

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795nm Single-Mode VCSEL with Grating Relief Structure

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Due to their high degree of coherence, spectral purity and excellent beam quality, single-mode VCSELs are attractive light sources for a wide variety of applications such as sensing technologies, gas analysis via spectroscopy or miniaturized atomic clocks [1]. Their compactness, efficiency and low costs further position single-mode VCSELs as the leading candidates for chip-scale atomic technologies [2]. In the framework of the BMBF funded project Qyro [3] focused on nuclear magnetic resonance (NMR) gyroscopes, 795 nm single-mode VCSELs are being devloped to serve as both pump and probe sources for rubidium gas cells. To meet the stringent requirements of single-mode operation and linear polarization, grating relief structures have been introduced on the out-coupling facet (see Fig. 1). These structures, in combination with specific oxide aperture (OA) diameters, are critical for providing the mode-selective optical feedback necessary to suppress higher-order transverse modes (see Fig. 2). However, this single-mode operation comes at the cost of increased optical losses, which in turn reduce both the efficiency and output power of the device. This study discusses the optimization of these design elements, with a focus on balancing the trade-offs to achieve maximum single-mode output power.

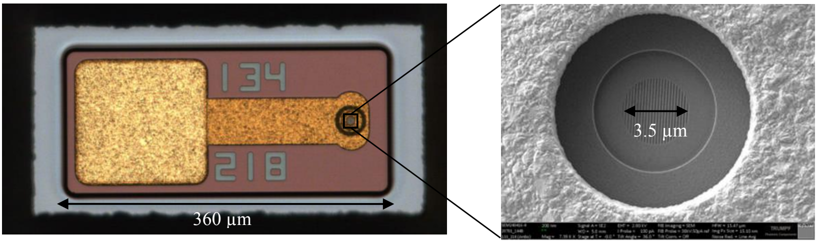

Fig. 1 Top view of a VCSEL with grating relief – microscope image of whole chip (left) and scanning electron microscope image of outcoupling facet with grating relief (right).

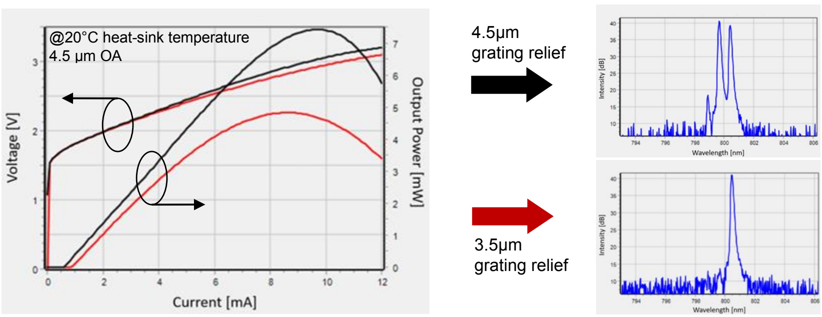

Fig. 2 Illustrating mode selection by surface relief structure: Light-current-voltage (LIV) curves and spectra for VCSELs with 4.5 µm oxide aperture diameter and different grating relief diameters. At 6 mA, the VCSEL with 4.5 µm grating relief shows two lateral modes while the one with 3.5 µm grating relief only has one active mode.

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Development of coupon fabrication for effective Micro Transfer Printing of VCSEL structure

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Modern technologies for fabricating photonic and electronic devices are constantly evolving, searching for newer methods to increase efficiency, miniaturize, and reduce production costs. One of the most promising approaches in this field is micro-transfer printing (MTP). In the context of vertical-cavity surface-emitting lasers (VCSELs), the MTP technique involves growing the laser structure on a native substrate to achieve a high-quality device, and then transferring it using an elastomeric stamp, typically made of polydimethylsiloxane (PDMS), to the target substrate. This operation is possible due to the selective etching of the sacrificial layer grown on the substrate and the release of structures that are temporarily suspended on so-called tethers. After the stamp contacts the surface, the tethers are broken, and the material coupons are picked up. In the final stage, the devices are transferred to the target substrate and then bonded to it by adhesive forces.

The MTP method allows heterogeneous integration of different classes of materials into organized layouts on many types of substrates, including silicon, ceramics and metal. This makes it possible to combine electronics with photonic devices in an efficient and scalable way what opens up the possibilities for creating new device configurations that are difficult to reproduce using conventional manufacturing techniques.

The aim of the study was to develop technology allowing for MTP of VCSEL structure. The work has been performed on “VCSEL like” structure grown on one-sided polished, undoped GaAs containing $In_{0.49}Ga_{0.51}P$ acting as a sacrificial layer followed by a layer of GaAs, with doping $n=2\times10^{18}$ cm^{-1}, a layer of GaAs $p=2\times10^{18}$ cm^{-1} and GaAs p++. In order to develop coupon fabrication technology, fast VCSEL processing has been performed utilizing three different approaches for tethers fabrication. The first approach involved the fabrication of tethers made of resist. The second solution involved creating tethers embedded in the VCSEL structure. The third method, unlike the first two, consists in maintaining the planarity of the structure through a mesa defined by trench around, and, as in the first case, creating tethers made of resist. Fabricated coupons have been characterized by SEM and evaluated in terms of its usability and robustness using double glued carbon tape as well as MTP using PDMS stamp.

The performed studies have provided valuable information on the effectiveness of methods of preparing coupons for transfer into the target substrate, with a particular emphasis on the different ways of manufacturing tethers and surface planarity. Each of the solutions offers significant advantages which can be effectively used in the further development of microstructure transfer technology, as will be discussed in the paper.

Funded by the European Union

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Fabrication and Characterization of 940 nm VCSELs on Ge and GaAs Substrates

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Vertical cavity surface-emitting lasers (VCSELs) at 940 nm are attracting a lot of interest due to their integration in photonics industry applications such as communication systems, LiDAR, 3D sensing and advanced technologies for smartphones and autonomous vehicles [1]. Traditionally, these types of VCSELs have been fabricated on GaAs substrates, but there is a strong interest in exploring other substrates to fabricate these devices, such as Ge [2,3], which is proposed as a viable alternative due to its superior scalability, lower environmental impact and possible integration on Si platform [4]. In fact, Ge material offers several advantages over GaAs, such as better lattice matching to $Al_xGa_{1-x}As$, relative higher thermal conductivity and the possibility to use larger wafer sizes, which makes it attractive for high-volume production. These properties help to reduce defect density, improve thermal management and lower fabrication costs. In this work, 940 nm VCSELs on both Ge and GaAs substrates were processed and characterized in order to perform a comprehensive comparison between the two. The VCSEL fabrication process includes mesa etching, thermal oxidation, SiO_x passivation, contact metallization and rapid thermal annealing. The results showed that the oxidation rate in Ge was approximately 20-30% faster than in GaAs (Figure 1). VCSELs on either type of substrates showed comparable threshold currents and series resistance values, nevertheless, a decrease in performances of VCSELs grown on Ge was observed when operating for long time or for several cycles. This deficiency is expected to be due to the epitaxial quality of these devices where their structures show line-shaped defects along the wafer. In addition, spectral measurements were performed, which confirmed the single-mode emission of VCSELs on both substrates, with emission peaks around 935 nm for the VCSELs on Ge and around 959 nm for the VCSELs on Ge (Figure 2). These results shows that Ge-based VCSELs exhibit promising initial performance, but challenges remain in achieving long-term operational stability.

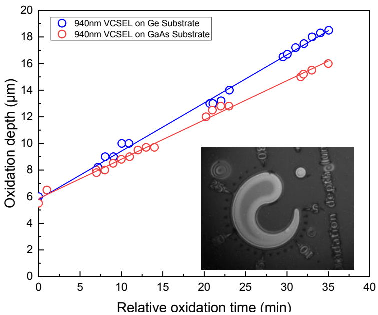

Figure 1*:* Oxidation depth versus relative oxidation time; inset: in-situ infrared microscopic image (888 nm) of the oxidation process of a reference pattern on GaAs.

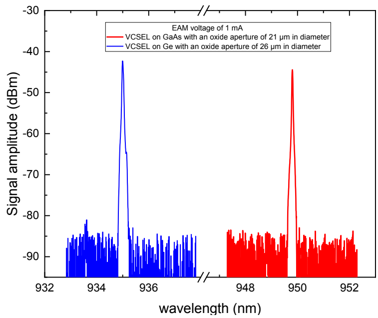

Figure 2*:* Emission spectra at 1 mA applied current for 5 µm oxide aperture GaAs-VCSEL (blue), and 3 µm aperture Ge-VCSEL (red).

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- « Unknown Title », Alexis Loupias, LAAS-CNRS, France

- *Analyzing Sidebands in Multimode VCSELs Through Near-Field Lensed Fiber Scanning*, Marco Novarese, Politecnico di Torino, Italy

> *Computational inspection of VCSEL oxidation exploiting a spectrally-shaped illuminator*, Antoine Rouxel, LAAS-CNRS, France

Session: Devices modelling

> *Modelling of transverse coupled cavity VCSELs*, Martino D'Alessandro Politecnico di Torino, Italy

> *Electro-Opto-Thermal modeling of AlGaAs Buried TJ-VCSELs*, Alberto Gullino, Politecnico di Torino, Italy

> *On-wafer measurements to calibrate active VCSEL simulations*, James Meiklejohn, Cardiff University, United Kingdom

Modelling of transverse coupled cavity VCSELs

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Transverse-coupled-cavity (TCC)-VCSELs [1-2] can be designed to achieve an ultrabroad modulation bandwidth. Indeed, these devices, including two or more cavities transversally connected, exhibit quasi-degenerate modes, whose properties (gain and wavelength detuning) can be engineered to obtain photon-photon-resonance, hence intensity modulation response (IMR) enhancements. Although demonstrated by diverse research groups, this technology is still considered immature for industrial production. To this aim, we propose a physics-based model solving the coupled carrier diffusion problem and the scalar wave equation. The latter is attacked by expanding the electric field as a sum of the cold cavity modes [3], computed with a full-wave electromagnetic solver [4].

The method is applied to the geometry manufactured and characterized in [1-2]. In Fig. 1, we show a sketch of the geometry together with the computed even and odd optical modes. The optical modes feature a nearly-equal threshold gain and a frequency separation of tens of GHz. We show how the coupled dynamics of these two modes can lead to an enhanced IMR. The effect of technological error and thermal lensing on the computed modes can be naturally handled, providing an understanding of the experimental observations.

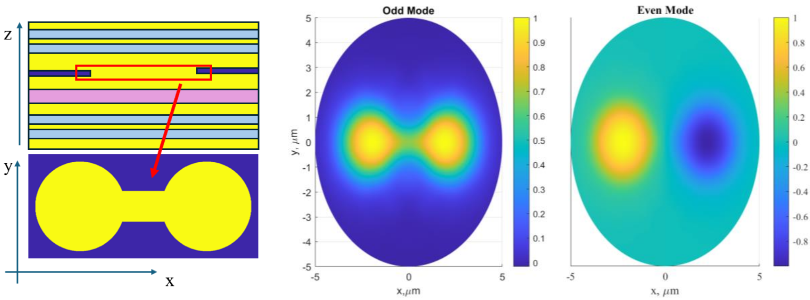

Fig. 1. Left: sketch of the geometry. The red region is the active layer, the dark blue region is the oxide and the periodic blue and yellow regions represent the DBRs. Right: section of computed modes at the active layer.

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Electro-Opto-Thermal modeling of AlGaAs Buried TJ-VCSELs

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Optical and electrical confinement in AlGaAs-based VCSELs relies on the presence of oxide apertures. Despite the success of oxide-confinement scheme, it also poses serious limitations regarding reliability for small active diameters ($d_{ox} < 2\mu m$), modulation bandwidth, and array density (mesa).

A promising alternative could come from the implementation of lithographic buried tunnel junctions (BTJs) inside the conventional VCSEL design. BTJs were initially proposed for long-wavelength VCSELs, where the formation of oxide apertures is limited by the absence of aluminum layers (InGaAsP- and GaSb-VCSELs). More recently, Dr. Tirelli and its group at Coherent Corporation have been successfully demonstrated such an oxide-free design for 940 nm emission [1-3].

With the aim of optimizing BTJ-VCSELs, here we propose to exploit our in-house VCSEL solver VENUS, recently updated to deal with planar TJs [4], to get further insights about their operation. In Fig. 1, we compare the 2D refractive index profile of a BTJ-VCSEL (purple box) with an oxide-confined TJ-VCSEL (green box) emitting at 850 nm, with identical TJs ($x_{Al}^{TJ} = 12\%$). Both are placed in the node of the optical standing wave, to reduce their impact on the free-carrier absorption. The TJs allow to realize *n*-doped bottom and top DBRs. Optical confinement is demanded to the BTJ (with 40 nm of etching depth) refractive index step, that the MBE propagates through the top DBR up to the output facet. In the radial region outside the BTJ, a "blocking" *pn* junction in reverse bias imposes the current confinement. The active diameter is kept equal across the proposed designs, *i.e.*, $d_{ox} = d_{BTJ} = 4\ \mu m$.

In the black box of Fig. 1, we report the static electrical and optical characteristics of three structures. A conventional VCSEL, with a typical *pin* configuration, serves as reference device. Compared to the oxide-confined TJ-VCSEL, the BTJ-VCSEL shows worse performances. The electrical penalty coming from the TJ is worsened by the non-planar top DBR. However, the blocking junction has a strong blocking ratio of $\sim 10^{-4}$. Similar threshold current of oxide-confined VCSELs is ensured. These represent some of the preliminary results obtained with VENUS: a small-signal analysis will be necessary to assess the improvements offered by an oxide-free design.

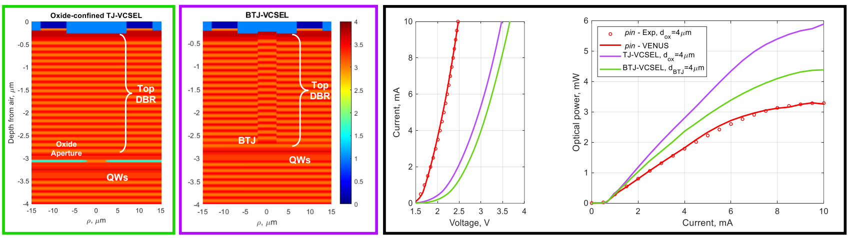

Fig. 1 Green and purple box: refractive index profiles of oxide-confined (left) and BTJ-VCSELs (right). Right box: static electrical and optical characteristics of oxide-confined *pin* (as a reference, in red), TJ- and BTJ-VCSELs.

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On-wafer measurements to calibrate active VCSEL simulations

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The operation of a semiconductor diode laser can be simulated by accounting for all the physical mechanisms in such a device. The relationships describing the internal processes of a laser depend on the material and operating conditions, and for each type of device it is necessary to calibrate the simulation by obtaining a number of relevant values from the literature and from specific experimental measurements. When performing numerical simulations, consideration is required to ensure that the simulation accuracy is not unduly affected by numerical effects, but also that the computation is tractable with the available resources. The aim of this work is to outline a process for calibrating a 850 nm multi-mode VCSEL simulation with the Harold-VCSEL multi-physics software.

Harold-VCSEL performs a multi-physics electrical-thermal-optical simulation by finding a self-consistent solution to the electromagnetic, transport, and rate equations in a (*r, z*) coordinate system. Harold is a commercially available tool developed by Photon Design, and the VCSEL module is related to a (*x, y*) solver for other types of laser device. A split-view of the Harold model simulation domain, (layer structure and optical mode) is shown in Figure 1. On-wafer measurements of the electrical and optical properties of a VCSEL can be performed rapidly and in a highly repeatable manner with a semi-automated probe-station (shown in Figure 2) [1]. Using pulsed and continuous-wave (CW) current injection, these measurements can then be used to derive other device properties, such as the electrical series resistance and the thermal resistance. Secondary ion mass spectroscopy (SIMS) is used to find the alloy composition and doping concentration of the samples under investigation, which are input into the model to ensure that representative structures is simulated.

These measurements provide a way to isolate the electrical transport model, optical model, and thermal model. By comparison of the measured and simulated results at a range of operating conditions, we can show that the simulation is effectively capturing the internal workings of the device, and demonstrate how the improved understanding of its operation leads to the use of the software as a design optimisation tool.

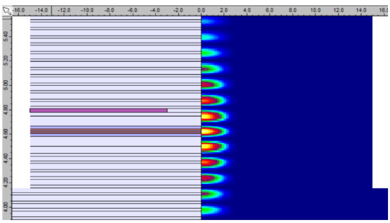

Fig. 1 An optical mode found using the Harold mode solver, shown against the structure of the VCSEL, centred on the quantum-well active region and oxide aperture.

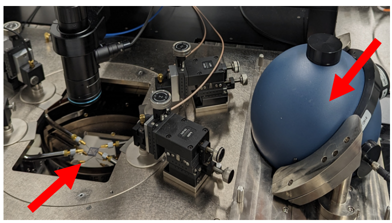

Fig. 2 The measurement apparatus used to carry out on-wafer measurements, showing the piece of wafer containing the VCSELs (left arrow) and the fibre-coupled integrating sphere (right arrow) that gathers the light output.

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Session: Characterizations, modal and polarization control

> *Robustness assessment of grating-based circularly-polarized VCSELs*, Valerio Torrelli, Politecnico di Torino, Italy

> *Emission spectra of VCSELs with noncircular optical apertures*, Magdalena Marciniak, Lodz University of Technology, Poland

> *Locking the VCSEL polarization in the horizontal and diagonal polarization basis*, Michael Zimmer, University of Stuttgart, Germany

> *Micro-photoluminescence and micro-electroluminescence from VCSELs and VCSEL structures*, Michal Wasiak, Lodz University of Technology, Poland

Robustness assessment of grating-based circularly-polarized VCSELs

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Recent experimental observations [1] have proven that misaligned optical anisotropies in vertical-cavity surface-emitting lasers (VCSELs) enable elliptical polarization, confirming the theoretical expectations presented in [2]. In this work, a possible AlGaAs *pin* VCSEL structure is examined (Fig. 1a), where the two competing optical anisotropies are the electro-optic effect (EOE) and a tilted subwavelength grating. Circular polarization with Stokes parameter $S_3 > 0.99$ has been obtained by tuning the grating tilting angle and thickness. Moreover, we investigate the impact of external strain σ and modulation doping on the emitted polarization, aiming at understanding the robustness of grating circularly polarized VCSELs (GCP-VCSELs). This is evaluated through a simulation study, performed using in-house 1D drift-diffusion and optical solvers.

The tilted grating is not varied throughout this work, while we address the optical anisotropies aligned with crystalline axes, x and y, using the semi-difference between the anisotropic relative dielectric constants, *i.e.*, $\Delta\epsilon = (\epsilon_{xx} - \epsilon_{yy})/2$.

EOE is caused by the electrostatic field [3]. Normally, for a non-modulated doping profile, positive and negative $\Delta\epsilon$ peaks occur at the DBR interfaces, as shown in Fig. 1b, although positive peaks are not effective. In fact, they are aligned with the nodes of the standing wave, overall resulting in an averaged negative anisotropy, which competes with the grating to create circular polarization. If modulation doping is employed to reduce free carrier absorption, only slight differences arise, maintaining $S_3 > 0.99$, thus allowing GCP-VCSELs to coexist with a modulated doping profile.

Uncontrolled strain σ, introduced by manufacturing, packaging and experimental setup, can be included in $\Delta\epsilon$ according to [3], shifting upwards or downwards the $\Delta\epsilon$ curve depending on its sign as reported in Fig. 1b, reducing or enhancing the negative EOE peaks and adding an offset. The sign of σ determines whether strain and EOE compete and eventually compensate each other ($\sigma > 0$) or synergize overall enhancing the relevant negative peaks ($\sigma < 0$). Careful strain design is required to maintain perfectly circular polarization.

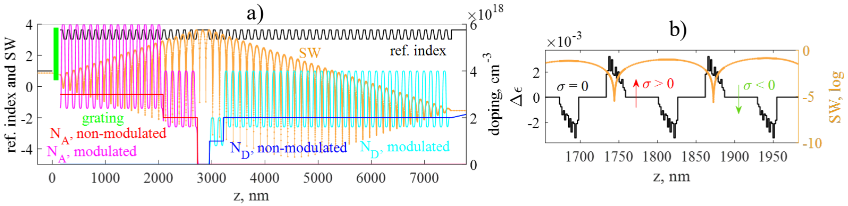

Fig. 1 a) Most relevant quantities of the investigated structure including the refractive index profile, the grating position, the standing wave, and the doping profiles with and without modulation. b) Optical anisotropy induced by EOE superimposed with the SW in the left DBR, together with the qualitative effect of strain.

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Emission spectra of VCSELs with noncircular optical apertures

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Breaking the circular symmetry in VCSELs by altering the shape of the emission area (defined by the oxide aperture) can lead to an increase in the VCSEL's optical output power and its quantum efficiency, as demonstrated in our previous studies [1]. We demonstrate that introducing a local side deformation to a 980 nm GaAs VCSEL with a nearly circular oxide aperture (Fig. 1a top) results in a significant increase in the VCSEL's maximum optical output power. Compared to circular VCSELs with approximately equal emission areas but without the side deformation, we achieve more than twice the optical output power, higher quantum efficiency, and higher allowable drive currents (Fig. 1b).

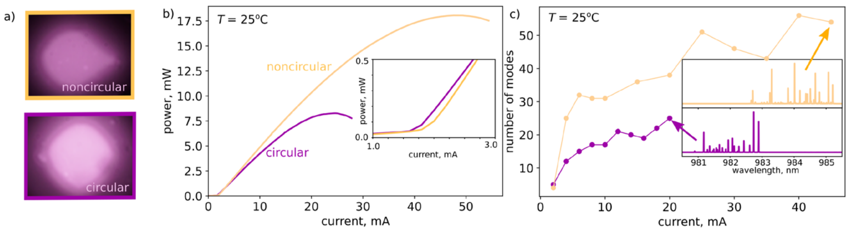

Fig. 1 a) spontaneous emission for forward bias currents below the lasing threshold for a VCSEL with a noncircular (top) and a circular (bottom) oxide aperture of the same area ~300 μm^2; b) static LI curves at room temperature for VCSELs with circular and noncircular optical oxide apertures of the same area (inset: zoomed in LI curves around lasing threshold); and c) the number of modes in the emitted spectrum for different forward bias currents for the VCSELs in a) (inset: the emission spectra plotted in linear-linear scales at the LI rollover current)

We extend the analysis we presented at last year's VCSEL Day by demonstrating an extensive analysis of the emission spectra of the VCSELs to elucidate the impact of the aperture shape on the distribution of their emitted modes (see examples of emission spectra in the inset in Fig. 1c). In our analysis, we examine the number of modes in the spectrum (see Fig 1c) and the mode density, as well as the width of the spectrum for our VCSELs with various aperture shapes. A different spectral modal distribution may lead to more efficient stimulated emission, which manifests itself in higher optical output power and higher allowable drive currents, since a more efficient device generates less heat.

We consider VCSELs with various side deformation shapes and investigate VCSELs with two apertures in close proximity that are fabricated within one mesa and with shared electrodes.

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Locking the VCSEL polarization in the horizontal and diagonal polarization basis

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VCSELs have taken their place in a large amount of todays-world applications ranging from the field of sensing, metrology, spectroscopy over to communication systems. While many of these applications require VCSELs to emit in a stable polarization, polarization switching is a common phenomenon observed in VCSELs. To address this issue, various methods to control the VCSEL polarization such as metal wire grids, non-circular resonators and surface gratings have been developed [1-3]. Most of these methods have been applied to stabilize the polarization in one of the naturally preferred polarization directions. However, in order to apply VCSELs for quantum key distribution (QKD) protocols for instance, several VCSELs on a single array or chip are required to emit in different polarization directions (e. g. 0°,45°,90°,135°) [4] [5]. Due to the electro optical effect [6], GaAs based VCSELs around 850 nm tend to emit in a polarization aligned along the [0 1 1] and [0 -1 1] crystallographic axes, along which polarization stabilization can be achieved ordinary. Though, a good polarization control along other polarization directions turns out to be more complicated. Here we investigate VCSELs grown by metal-organic vapor-phase epitaxy (MOVPE) with integrated surface gratings. The active region contains a set of three GaAs quantum wells (QWs) in AlGaAs barriers for emission at 850 nm and is embedded by a top and bottom distributed Bragg reflector (DBR) consisting of 22.5 and 30 DBR pairs, respectively. To control the laser polarization, subwavelength surface gratings are integrated into the cap layer of the upper DBR. The cap layer thickness of ¾ λ allows also for the investigation of the deep etching regime. In order to examine the ability of the surface gratings to lock the angle of polarization, surface gratings with angle orientations in the range from 0° to 180° were fabricated in step sizes of 5°. The obtained angle of polarization as well as the orthogonal polarization suppression ratio (OPSR) are analyzed with regard of their orientation with respect to the crystallographic axes.

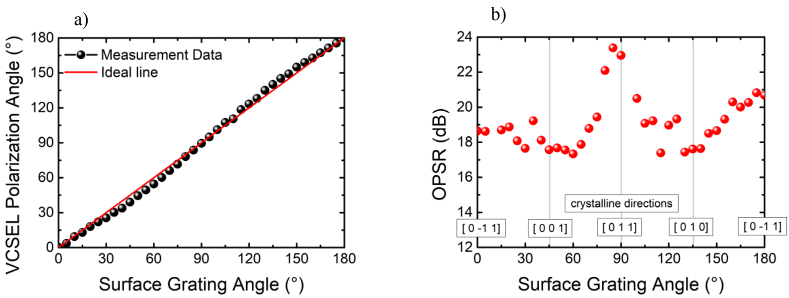

Fig. 1 a) VCSEL polarization angle versus the surface grating orientation. A s-curve behavior is observed with good aligned polarization angle for 0° and 90° gratings.
b) OPSR in dependence of the surface grating orientation. The highest OPSR is achieved for gratings oriented along the [0 1 1] & [0 -1 1] direction.

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Micro-photoluminescence and micro-electroluminescence from VCSELs and VCSEL structures

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We present the results of our investigation on lateral (measured from the cleaved edge) emission from lasers and laser structures. Electroluminescence can be measured from processed laser (if the sample edge is close to the laser's aperture), from below TLM pads on a procesesed wafer, and even from unprocessed epi structures. Measurements

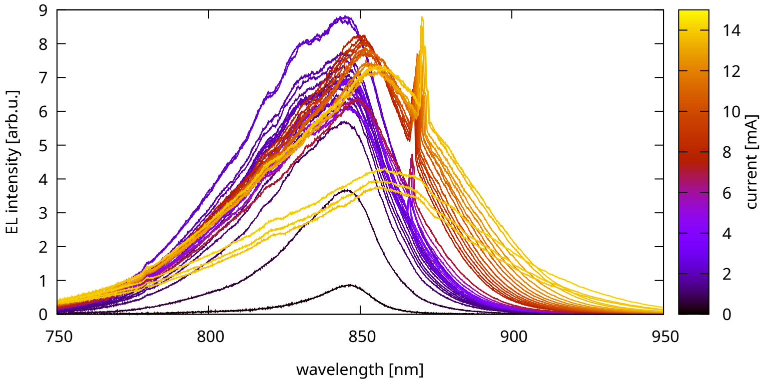

Figure 1: Emission spectra measured from the edge of a VCSEL, for different values of the driving current. The sharp peak is the laser emission.

performed on lasing devices provide us a unique opportunity to observe simultaneously the active region emission spectrum and the cavity resonance, as it can be seen in Fig. 1. This allows for, among other things, investiation of the evolution of the laser detuning, which one of the crucial design parameters which impacts strongly on the VCSEL performance.

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Session: Fabrication & Technology

> *In-situ and ex-situ optical metrology – an enabler for high-quality GaAs-based VCSEL structures*, Johannes K. Zettler, LayTec AG, Germany

> *940 nm VCSEL epi-structure grown on germanium (Ge) substrates*, Włodzimierz Strupinski, VIGO Photonics SA, Poland

> *Epicentre: A RIBER/LAAS-CNRS joint lab for optimization and automation of MBE process*, Alexandre Arnoult, LAAS-CNRS, France

> *GaSb Long-Wavelength VCSEL with Low Loss Buried Tunnel Junction*, Andrea Simaz, Walter Schottky Institute, Germany

> *High-temperature performance of high-speed 940 nm VCSELs for optical communication*, Marcin Gebski, Lodz University of Technology, Poland

In-situ and ex-situ optical metrology – an enabler for high-quality GaAs-based VCSEL structures

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The very thin cavity of VCSEL structures, allowing for only one longitudinal mode which defines the wavelength of the light emitted, requires very precise control of layer thicknesses in the cavity and the surrounding DBRs in the sub-percentage range. On the other hand, growth rate accuracy using state-of-the-art MOVPE machinery is typically considered to be in the ±1% range. Hence, in an MOVPE production campaign (without any in-situ metrology available) iterative run-to-run adjustments based on post-epi metrology are needed to optimize the total yield.

In this work, however, we show how in-situ and ex-situ optical metrology can be used to allow for optimal growth rate control. This is accompanied by growth rate uniformity improvements using the EpiX white light reflectance and photoluminescence mapping station.

We will demonstrate a VCSEL calibration scheme to achieve a better "first-attempt" accuracy when targeting new emission wavelengths. First the targeted VCSEL layer sequence is grown with the number of DBR periods strongly reduced in the p- and n-DBR layer stacks. Using a non-linear optimization scheme for modelling and fitting to the measured room temperature WLR spectrum, we can determine adjustments required to tune the full recipe, now with complete DBR period counts, to meet the targeted emission properties.

This full growth process is again guided by EpiTT VCSEL in-situ metrology system, providing measurement of multiple wavelength reflectance, emissivity corrected temperature and wafer curvature and automatically performing a VCSEL analysis after each DBR period. With the knowledge of the stop band center wavelength target at growth temperature, we can spot deviations already during the 1st half of the n-DBR growth. Those deviations can be counteracted for each individual wafer by adjusting process parameters during the n-DBR growth for the subsequent layers of the VCSEL structure. This way cavity resonance and p-DBR stopband wavelengths will shift accordingly, so that the VCSEL as a whole will still have a good alignment between n-DBR, cavity and p-DBR and will also have the cavity resonance wavelength inside the targeted window.

This scheme has been successfully applied many times using datasets that have been collected during several VCSEL growth processes.

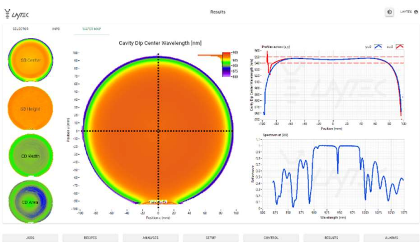

Fig. 1 Exemplary VCSEL wafer map result from LayTec EpiX white light reflectance and photoluminescence wafer mapping station

940nm VCSEL epi-structure grown on germanium (Ge) substrates

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The global VCSEL market is developing dynamically, with laser production projected to triple in the next five years. The driving forces behind this growth is VCSEL's wide application in the photonics industry, including short-distance communication systems, smartphones, IoT, LIDARs, time-of-flight sensors, autonomous vehicles, robots, and drones. A huge demand for cheap, long lifetime, high-output-beam-quality, and energy-efficient laser light sources stimulates the works on epitaxial growth by MOVPE of VCSEL epi-structures grown on germanium (Ge) substrates instead of traditional gallium arsenide. The critical challenge in this development is to achieve high crystal quality of grown GaAs/AlGaAs layers on Ge substrates while taking advantage of a better crystallographic lattice sameness between Ge and AlGaAs, which reduces misfit defects density and increases the quantum efficiency of the device. Germanium, offering higher yield and fewer production losses due to higher uniformity at larger-size wafers, is promised to lower the environmental impact compared to more expensive GaAs substrate. With the demand for VCSELs growing and technical requirements becoming more rigorous, there is a need to scale to larger wafer diameters and demonstrate a path for integration with CMOS technology. The Ge-VCSEL device technology is developing by the PhotoGeNIC consortium which is industrial-oriented for mass production on up to 6-or 8-inch Ge wafers, offering different architecture configurations in relation to the specifications of the targeted applications. The goal is to meet the demand of the constantly growing photonics market by providing a novel solution that will increase production yield, reduce defectivity, and introduce reduced environmental impact. These epitaxial technological efforts, with particular attention paid to the growth mechanism of nucleation layer bridging Ge substrate with GaAs/AlGaAs epi-stack, were supported by several characterization methods to be used as X-ray diffraction and topography, depth high-resolution SIMS, electron microscopy (SEM/TEM), atomic force microscopy, Nomarsky optical microscopy, PL mapping, ECV, Hall, optical spectroscopy, reflectance, epi-wafer bowing measurements. The aim was to discover differences and critical parameters of VCSEL structure grown on Ge substrates versus GaAs at the material characterization level and to develop and produce VCSELs ready for use in the demonstrators. We also present static and dynamic characteristics of 940nm VCSELs grown on Ge substrates in comparison to the devices with benchmark 940nm VCSELs grown on GaAs.

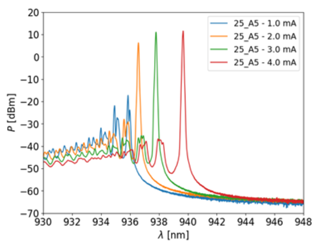

Fig. 1 An exemplary emission spectrum of the 940nm VCSEL grown on Ge.

The PhotoGeNIC project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101069490

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GaSb Long-Wavelength VCSEL with Low Loss Buried Tunnel Junction

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Mid-infrared (Mid-IR) vertical cavity surface emitting lasers (VCSELs) are highly sought after for spectroscopy and gas sensing application in the 3-5 µm spectral range, owing to their inherent properties such as single-mode operation, compact design, and suitability for low energy consumption applications. State-of-the-art monolithic single mode mid-infrared VCSELs are processed using a buried tunnel-junction (BTJ) to confine the current to a small aperture and to provide waveguiding in the vertical direction [1]. However, this approach requires a careful placement of the tunnel junction in the node of the electric field due to its high absorption. Because of the intrinsic uncertainty in the thickness of the layers grown by the Molecular Beam Epitaxy (MBE), high optical losses in the tunnel junction layers limit the yield in BTJ VCSEL processing. In this work we demonstrate an electrically pumped GaSb VCSEL emitting at 3.35 µm that implements a semi-metallic interface between GaSb and InAs/AlSb superlattice, shown in Fig.1 (center), similar to the tunnel junction (without structuring) used to connect the stages in ICLs [2]. In contrast to the tunnel junction based on interfaces between highly doped semiconductors, the new design has orders of magnitude lower losses at mid-IR wavelengths and does not need to be positioned exactly at the mode node for VCSEL operation. The new buried tunnel junctions are structured by dry etching of mesas of different radii in the GaSb-InAs/AlSb tunnel junction layer. To precisely etch the tunnel junction layer, a methane-oxygen recipe at 60 °C was developed. After the etching, the sample undergoes a chemical cleaning and a high temperature (550 °C thermocouple, 10 minutes) deoxidation in MBE. On top of it, a GaSb spreading layer and InAsSb contact layer are overgrown to complete the VCSEL cavity. The schematic of the fabricated BTJ VCSELs is shown in Fig. 1 (left) and it is similar to the structure described in [3] with the exception of the BTJ structure.

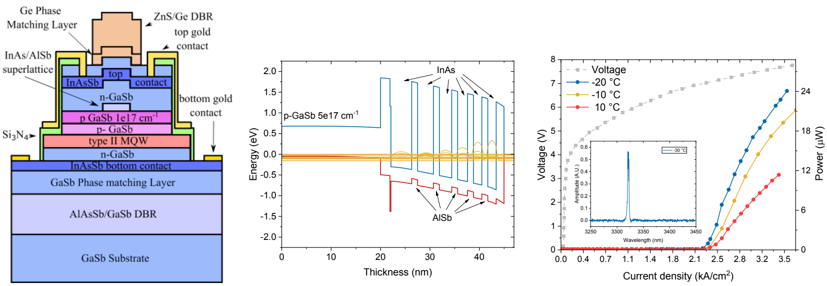

Fig. 1 (left) Schematics of the implemented low-loss tunnel junction VCSEL structure. (center) and structure diagram of a tunnel junction based on a semi-metalic interface between GaSb and InAs/AlSb superlattice used in our VCSELs. (right) Pulsed light-current-voltage (LIV) characteristic of a 3.4 µm VCSEL with the BTJ radius of 7.5 µm and a mesa of 26 µm measured at two different temperatures. Inset shows the emission spectrum of the device at -30 °C.

Light-current-voltage (LIV) measurements of the processed device were acquired with 50 ns current pulses at 200 kHz repetition rate using a calibrated liquid-nitrogen-cooled InSb photodetector in a nitrogen-purged chamber. Emission spectra were acquired using a Fourier-transform infrared spectrometer. In Fig. 1 (right) the performance of a typical device is shown. The high parasitic voltage suggests that the oxide removal during the BTJ fabrication step should be further optimized to enable room temperature continuous wave device operation.

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High-temperature performance of high-speed 940nm VCSELs for optical communication

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The first commercial application of vertical-cavity surface-emitting lasers (VCSELs) was in in the mid-90's in optical communication. Ever since the lasers have been massively used as light sources in short-reach (datacom) communication modules. The main reasons behind this are their low price, relatively small size, circular cross-section of the emitted beam, inherent single longitudinal mode lasing, very low power consumption, and competitive high-speed performance. The aforementioned features of the devices and the maturity of the GaAs-based short-wavelength infra-red (SWIR) VCSEL technology resulted in their application in many technologies that have grown big in XXI century such as light detection and ranging (LiDAR) systems, smartphones and Internet-of-Things (IoT), airplane and spacecraft onboard communication modules, and many others.

In this work we present the static and dynamic characteristics of 940nm VCSELs designed for high-speed performance in elevated temperatures. We show the impact of the oxide-aperture diameter and other geometrical and epitaxial parameters on the performance of the devices.

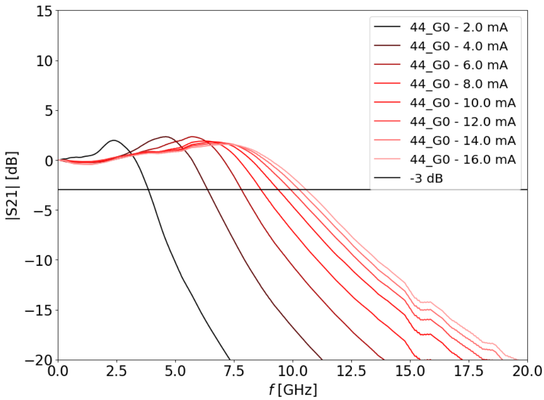

Fig. 1 An exemplary S21 (small-signal modulation response) of the 940nm VCSEL.

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