8TH WORKSHOP ON PHYSICS AND TECHNOLOGY OF SEMICONDUCTOR LASERS

KRAKÓW, OCTOBER 13-16 2019

Book of abstracts

8TH WORKSHOP ON PHYSICS AND TECHNOLOGY OF SEMICONDUCTOR LASERS

13 – 16 October 2019
Kraków, Poland

Venue

LWOWSKA 1 APARTHOTEL, Lwowska 1 Str., Kraków, Poland

8th Workshop on Physics and Technology of Semiconductor Lasers

The Workshop on Physics and Technology of Semiconductor Lasers for the eighth time gathers the "semiconductor lasers" community, continuing the tradition of previous workshops organized biannually. The event venue was travelling across different places in Poland until finally settled down in Kraków, one of the oldest and most beautiful towns in Poland, where it has been held for last six years.

The event addresses main challenges in the field, providing a forum for presentation of up-to-date results and developments in design, physics, fabrication technologies and applications of semiconductor lasers. One of the workshop's goals is to promote the interaction between academic and industrial institutions active in this multidisciplinary field. It is also a great opportunity to share knowledge and expertise with young generation of researchers and students, who are always a large part of the participants.

The meeting is thought as a creative space, providing a comfortable and stimulating scientific environment. The workshop program is composed of invited lectures, delivered by leading experts in the field, and short contributed communications, providing insight into cutting-edge trends in semiconductor lasers development. There is also organised an afternoon poster session allowing for direct exchange of information and informal discussions between the workshop attendees.

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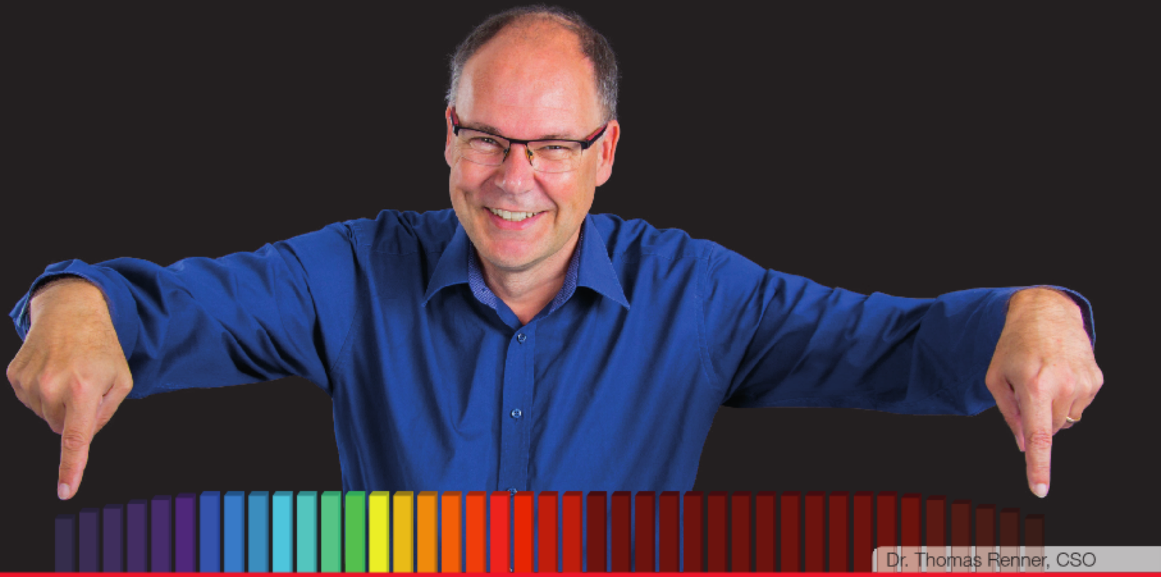

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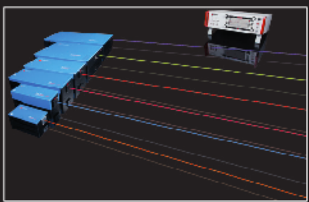

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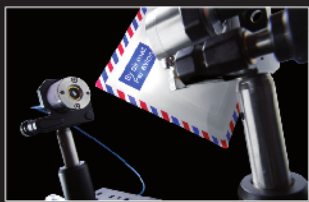

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Sunday – 13.10.2019		
19:00	21:00	***Welcoming glass of wine and registration***

Monday – 14.10.2019			
9:00	9:10	***Opening Address***	
SESSION I: Vertically Emitting Lasers I			
9:10	9:50	**J. Guenter**	A short long VCSEL history
9:50	10:05	**M. Gębski**	Progress in Monolithic High-Contrast Grating Vertical-Cavity Surface-Emitting Lasers
10:05	10:20	**J. Muszalski**	Peculiar emission properties of MECSEL
10:20	10:35	**M. Marciniak**	Impact of top mirror on VCSEL performance
10:35	10:50	**M. Wasiak**	Numerical model for impedance in semiconductor lasers
10:50	11:05	**E. Pruszyńska-Karbownik**	Impact of oxidation parameters on electrical modulation properties of GaAs-based VCSELs
11:05	11:30	***Coffee break***	
SESSION II: Novel materials and designs I			
11:30	12:10	**J. Pan**	Two-dimensional Large-angle Scanning Optical Phased Array with Single Wavelength Beam
12:10	12:25	**J. Suffczyński**	Triple threshold lasing from a photonic trap in a Te/Se-based optical microcavity embedding a single quantum well
12:25	12:40	**H. Teisseyre**	Towards a new laser application of (MgZn)O/MgO based quantum structures
12:40	12:55	**L. Frasunkiewicz**	Mixing of transverse modes in VCSELs with vertically coupled-cavities and Parity-Time symmetry breaking of mixed modes
12:55	13:10	**H. Mączko**	Strain Engineering of Material Gain Coefficient in a GeSn/SiGeSn Quantum Wells
13:10	14:10	***Lunch break***	
SESSION III: Nitride Lasers			
14:10	14:25	**G. Muzioł**	Optical properties of III-nitride laser diodes with wide InGaN quantum wells
14:25	14:40	**S. Stańczyk**	(Al,In)GaN Distributed Feedback Laser Diode
14:40	14:55	**S. Grzanka**	Beyond the comfort zone: challenges for nitride laser diodes below 400 nm and above 470 nm
14:55	15:10	**K. Gibasiewicz**	Towards integrated on wafer InGaN laser diodes
15:10	15:30	***Coffee break***	
15:30	15:45	**M. Chlipała**	Low temperature study of inverted nitride light emitting devices
15:45	16:00	**M. Hajdel**	Influence of InGaN waveguide on injection efficiency in III-nitride laser diodes
16:00	16:15	**A. Bojarska**	Dislocation related nonradiative recombination in InGaN laser diodes
16:15	16:30	**K. Nowakowski-Szkudlarek**	Optimization of p-type contacts to InGaN-based LDs and LEDs grown by plasma assisted MBE
POSTER SESSION			
16:30	18:30	***Posters, beer and snacks***	

Tuesday – 15.10.2019			
SESSION IV: Novel materials and designs II			
9:00	9:40	**J. Koeth**	NIR and MIR Lasers and their use in sensing applications
9:40	9:55	**M. Motyka**	The interface importance in different types of mid infrared emitters
9:55	10:10	**Z. Wang**	Large Area Surface-Emitting Photonic Crystal Quantum Cascade Laser
10:10	10:25	**E. Rogowicz**	Optical properties and carrier dynamics in GaSbBi(In)/GaSb quantum wells for laser applications in the 1.9-2.5 μm spectral range
10:25	10:40	**E. Semenova**	MOVPE of InAs/InP quantum dots operating at 1550 nm for photonics applications
10:40	10:55	**P. Holewa**	Optical properties of InAs/InP quantum dots grown via selective area droplet epitaxy assisted by block-copolymer lithography
10:55	11:20	***Coffee break***	
SESSION V: Vertically Emitting Lasers II			
11:20	12:00	**J. Lott**	VCSELs and small VCSEL arrays for communication and sensing
12:00	12:15	**N. Haghighi**	Triple 980 nm VCSEL arrays
12:15	12:30	**M. Gębski**	Temperature Stable 980 nm Vertical-Cavity Surface-Emitting Lasers for Optical Communication
12:30	12:45	**A. K. Sokół**	Transparent grating contacts for vertical-cavity surface-emitting lasers
12:45	13:00	**W. Głowadzka**	Observation of high quality factor Fano resonance in subwavelength gratings
13:00	13:15	**M. Marciniak**	Monolithic High Contrast Gratings as highly reflective mirrors for VCSEL applications
13:15	14:15	***Lunch break***	
SESSION VI: Applications of Semiconductor Lasers			
14:15	14:55	**G. Wysocki**	Dual-comb spectroscopy and hyperspectral imaging with quantum- and interband-cascade frequency combs
14:55	15:10	**P. Kluczyński**	Multi-laser in-situ analyzer for real time control of deSOx and deNOx processes in a waste incinerator plant
15:10	15:25	**M. Nikodem**	Quantum Cascade Lasers and Hollow Core Fibers – Towards Integration and Size Reduction in the Mid-Infrared Systems
15:25	15:40	**M. Singleton**	Compressed Pulses from a Mid-IR QCL Comb
15:40	15:55	**J. Wojtas**	Low noise photoreceivers for trace gas detection techniques
15:55	16:10	**F. Kapsalidis**	RF-Enhanced Waveguide Quantum Cascade Laser Frequency Combs
CONFERENCE DINNER			
20:00	***Dinner on a boat***		

Wednesday – 16.10.2019			
SESSION VII: Vertically Emitting Lasers III			
10:00	10:40	**D. Cohen**	Polarized blue InGaN VCSELs and Monolithic VECSELs
10:40	10:55	**P. Śpiewak**	Computer Modeling of Nitride VCSELs
10:55	11:10	**N. Fiuczek**	Nanoporous DBRs – towards monolithic nitride VCSELs
11:10	11:25	**A. Brejnak**	Spectrally resolved modes in real-world VCSELs with irregular shapes of broad oxide-confined apertures
11:25	11:40	**S. Grzempa**	Parameter optimization of quantum-cascade VCSELs
11:40	12:00	***Coffee break***	
SESSION VIII: Quantum Cascade Lasers			
12:00	12:40	**A. Albo**	Towards Room Temperature Operation of Terahertz Quantum Cascade Lasers: Carrier Leakage Engineering as a Novel Design Concept
12:40	12:55	**K. Pierściński**	Monolithic, optically-coupled, multi-section mid-IR quantum cascade lasers
12:55	13:10	**M. Badura**	Challenges of MOVPE growth of quantum cascade lasers
13:10	13:25	**P. Gutowski**	Optimization of MBE Growth Conditions of InP-based quantum cascade lasers
13:25	13:40	**M. Shahmohammadi**	Exceptional Point in Distributed Feedback Quantum Cascade Lasers
13:40	13:55	**D. Pierścińska**	Influence of design variations on QCL performance
13:55	14:00	***Closing Remarks***	
14:00	***Farewell lunch***		

14 October (Monday)

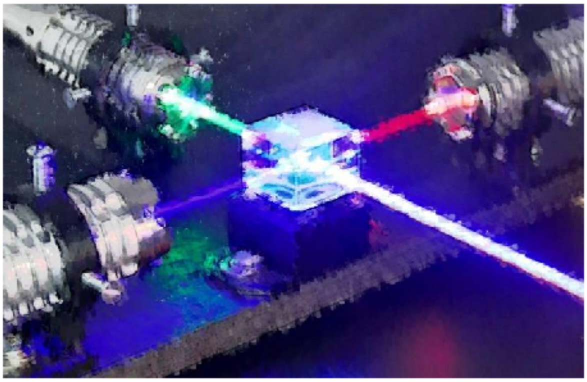
Sessions

Vertically Emitting Lasers I

Novel materials and designs I

Nitride Lasers

Poster session



MoS1Inv

Invited Lecture

A Short Long VCSEL History

J. Guenter

Finisar Corporation, 600 Millennium Dr., Allen, TX 75013

The VCSEL as an economic force known by the general public has a history of perhaps three years. As a commercially available technology that history extends to just less than a quarter of a century. They were envisioned constructed of materials commonly used for VCSELs today more than forty years ago. And as a concept their history extends to about sixty years. That's nearly half the history of the incandescent light bulb, and almost exactly the same as the history of the LED that replaced it.

The long timeline for the development of the VCSEL is paradigmatic: the success of complex technologies is contingent on the prior success of multiple enabling developments, and the original motivations for those enablers are often unrelated to the final combined result. A practical VCSEL was not possible without developments in materials, growth techniques, and concepts in physics and chemistry that were not envisioned at the end of the 1950s when both the first laser of any type and the first pn-junction LED were demonstrated. Arguably the invention of the VCSEL was immediately inevitable once those two demonstrations were made, and in fact the first electrically-pumped VCSEL was demonstrated less than five years later [1]. But it was almost another thirty years before a commercially viable VCSEL became available.

It is paradigmatic other respects as well. As with many concepts that were "in the air" at times of intellectual ferment when many researchers are simultaneously exploring the same developments, it is arguable that there is no VCSEL inventor. Or rather, that there were multiple inventors and that it would be nearly impossible to properly apportion their fractions of the credit even if all had published, in journals widely read, using terms that today's practitioners would recognize. Search for VCSEL or for vertical-cavity surface-emitting laser prior to 1990 and almost no results appear. Search using those terms prior to about 1987 and there are none at all. But nearly all the major VCSEL concepts and certainly the enabling technologies were developed in that earlier period.

More than one billion VCSELs will be sold in 2019. The winding development path to today's VCSEL has some important nexuses where either enabling concepts coalesce or where outside factors—killer apps—lead to rapid commercialization. Among many others, some important milestones include the work of Iga in the 1970s and Jewell in the 1980s, and perhaps the development of steam oxidation of AlGaAs by Holonyak (and their colleagues—no single inventors, remember). Killer apps include gigabit fiber optics in the 1990s and cell phone applications in the 2010s.

The invention of the VCSEL continues today. Among the many concepts for further miniaturization, integration with other technologies, and performance improvements and extensions it is impossible to say what the next major nexus will be. What we can say with confidence, however, is that whatever it is it will have been incrementally invented by multiple practitioners working both in concert and in competition.

[1] I. Melngailis, "Longitudinal injection plasma laser of InSb,", *App. Phys. Lett.* **6**, p. 59 (1965).

MoS1C1

Progress in Monolithic High-Contrast Grating Vertical-Cavity Surface-Emitting Lasers

M. Gębski[1, 2], J.A. Lott[2], and T. Czyszanowski[1]

[1] *Photonics Group, Institute of Physics, Łódź University of Technology, Wólczańska 219, 90-924 Łódź, Poland*
[2] *Institute of Solid State Physics and Center of Nanophotonics, Technische Universität Berlin, Hardenbergstraße 36, D-10623 Berlin, Federal Republic of Germany*

Recently, interest in vertical-cavity surface-emitting lasers (VCSELs) has exploded again due to the huge demand for smartphones, low cost and compact laser detection and ranging (LIDAR) systems, illumination and tracking systems, and the sensing requirements envisioned for the Internet-of-Things. It is expected that in the next five years the Mobile and Consumer market will grow more than six times and make the most of more than 3B$ VCSEL market [1]. To ensure human eye safety it is highly desirable to manufacture VCSELs emitting at wavelengths longer than the wavelengths available in the common galliumarsenide system (~600 to 1100 nm). Unfortunately, for material systems enabling emission at wavelengths longer than ~1100 nm, the refractive index contrast of distributed Bragg reflectors (DBRs) is small. As a result the DBRs must have many periods and the result is a very thick and fragile, highly absorbing when doped, and difficult to epitaxially grow structure.

In our approach, the DBRs of a VCSEL cavity are replaced with a subwavelength Monolithic High refractive index Contrast Grating (MHCG) mirror [2]. The MHCG is a special case of an High-Contrast Grating (HCG) that can be designed to provide ~100% power reflectance for linearly polarized light at a desired VCSEL design wavelength. At the same time the MHCG is monolithically grown with the rest of the VCSEL and its optical thickness is comparable to the emission wavelength. Furthermore, an MHCG can be made of most of the semiconductor materials commonly used in optoelectronics [3]. This MHCG mirror design concept opens a way for simple design, ultrathin, and low-materialconsumption VCSELs emitting at any wavelength.

In the presentation we show our latest results on electrically-injected VCSELs incorporating an MHCG mirror. The processing of those devices has been improved significantly. The result is a factor of 3 improvement in the optical output power at rollover and threshold current with respect to the previous results [4]. Additionally, we performed spatially resolved near-field (SRNF) measurements in order to verify the modal properties of the VCSELs. We also performed small-signal modulation frequency response measurements (S21) in order to assess the high-speed modulation capabilities of the lasers.

This work is jointly supported by: 1) the German Research Foundation via the Collaborative Research Center (Sonderforschungsbereich) 787; 2) the Polish National Science Centre OPUS project 2014/15/B/ST7/05258; and 3) the Polish National Science Centre ETIUDA scholarship 2015/16/T/ST7/00514.

[1] P. Boulay, Yole Développement, VCSEL Day 2019 Book of abstracts, 32 (2019)
[2] M. Gębski, M. Dems, J. A. Lott, T. Czyszanowski, *IEEE PTL* **27** (17), 1953-1956 (2015)
[3] M. Gębski, et al., *Opt. Express* **23**, 11674–11686 (2015).
[4] M. Gębski, J. A. Lott, and T. Czyszanowski, *Opt. Express* **27**, 7139-7146 (2019).

MoS1C2

Peculiar Emission Properties of MECSEL

A. Broda, B. Jeżewski, I. Sankowska, A. Kuźmicz, J. Muszalski

Łukasiewicz Research Network - Institute of Electron Technology, Al. Lotników 32/46, 02-668 Warsaw, Poland

In case of semiconductor laser only those capable for surface emission provides good optical quality Gaussian beams. Electrically driven Vertical-Cavity Surface-Emitting Laser (VCSEL) are however limited in power to single milliwatts. The current crowding along circular contact prevents the uniform injection of the carriers in spatially large active region. The high power emission is achieved in Vertical Extended Cavity Surface-Emitting Laser (VECSEL) when optical pumping is used instead of electrical. The uniform excitation of spots of hundreds of micrometers in diameter together with external dielectric mirror which discriminates the high order modes boost the TEM_{00} mode emission to tens of Watts. Also the optically pumped Membrane External Cavity Surface Emitting Laser (MECSEL) is capable of emission with the power exceeding 10 Watts. MECSEL advantage is that, the simplified heterostructures similar to VECSEL but without Distributed Bragg Reflectors opens the technology of optically pumped semiconductor disc laser for emission in the spectral regions which are not well penetrated by high power semiconductor lasers. The epitaxial DBR are not always easily feasible because of either the small refractive index contrast, large thickness of the layers, high thermal resistance or poor epitaxy.

In MECSEL the resonator is enclosed by two external dielectric mirrors like in a solid state laser (SSL) but in contrast to those laser the gain is generated in quantum wells not in a large volume. This makes the spectra of free running MECSEL unique. Certain longitudinal modes can be suppressed by simply changing the position of heterostructures along the resonator. Moreover in opposition to VECSEL we observe that the emission wavelength is much longer that this which could be deduced from photoluminescence and reflectivity characterization of as grown wafer. This phenomena was observed for our MECSEL fabricated for emission in 980nm and 1600nm bands as well. Those emission properties of MECSEL will be discussed in the presentation.

The work has been supported by the Grant No. 2017/25/B/ST7/00437 of the National Science Centre in Poland

MoS1C3

Impact of Top Mirror on VCSEL Performance

M. Marciniak[1,2], M. Gębski[1,2], T. Czyszanowski[2], and J.A. Lott[1]

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[2] *Institute of Physics, Lodz University of Technology, Łódź, Poland*

Vertical-cavity surface-emitting lasers (VCSELs) are experiencing a renaissance due to their massive applications in short-distance optical telecommunication fiber systems, automotive LIDAR systems, and as the optical sources for various time-of-flight sensing systems. VCSELs are characterized by a single longitudinal mode emission, low threshold currents, and a high beam quality making them ideal coherent light emitters in communication and sensing applications. Presently the monolithic growth of the entire epitaxial VCSEL structure is possible in arsenide-based materials that emit near-infrared radiation in the wavelength range from 850 to 1100 nm. The dominant VCSEL applications of today require single transverse mode operation, high emitted power, and high modulation frequency. Hence optimization of VCSELs with respect to these parameters is of significant importance for modern VCSEL development. In our work we consider GaAs-based telecommunication VCSELs designed for emission at the wavelength of 980 nm. The schematic structure of the laser is shown in figure 1. VCSEL top distributed Bragg reflector (DBR) is composed of only 5.5 pairs of GaAs/AlGaAs quarterwavelength layers providing too low power reflectance to support stimulated emission. In our experiment we modify the power reflectance of the top mirror by depositing various numbers of dielectric SiN/SiO DBR layers. We also influence the VCSEL's electrical and optical properties by varying the VCSEL's oxide aperture diameter.

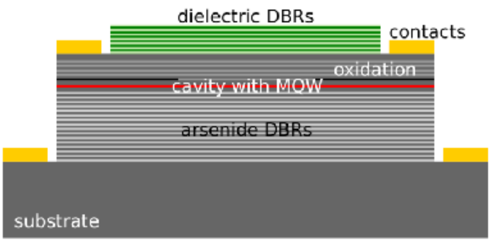

Fig. 1: Schematic structure of the investigated VCSEL with combined arsenide and dielectric top DBRs.

By deposition of extra DBR layers on top of the VCSEL we engineer the power reflectance of the top mirror and hence the quality factor of the VCSEL cavity. In this work we analyze the VCSEL structures with different numbers of top dielectric DBR periods and with various oxide aperture diameters to investigate their influence on the static and dynamic properties of the VCSELs. In particular we investigate the influence of top DBR's power reflectance and oxide aperture diameter on the light-current-voltage (LIV) characteristics, emitted spectra, and small signal modulation response.

Acknowledgments: This work is supported by the German Research Foundation via the Collaborative Research Center 787. Magdalena Marciniak would like to acknowledge the support from the Lodz University of Technology. This work is also supported by the Polish National Center of Science within the project Preludium (2018/29/N/ST7/02460).

MoS1C4

Numerical Model for Impedance in Semiconductor Lasers

M. Wasiak and R.P. Sarzała

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We present a numerical model for calculating the impedance of a semiconductor laser biased with a voltage with an AC component modulated with an arbitrary frequency. Our previous model [1] was based on an equivalent circuit whose elements were calculated using the potential distribution in a DC-biased structure. In the presented model, instead of using an approximation in the form of an equivalent circuit, we use complex values of electrical conductivities in the electric model. This way, we obtain a full description of the electric phenomena related to the presence of capacitance in the laser. Using this model we can simulate, among others, small-signal modulation reflection (the complex impedance of the laser) and the amplitude of the active current in the laser's active region.

[1] M. Wasiak, P. Śpiewak, P. Moser, J. Walczak, R.P. Sarzała, T. Czyszanowski, J.A. Lott "Numerical model of capacitance in vertical-cavity surface-emitting lasers", *Journal of Physics D: Applied Physics,* **49**, 2016

MoS1C5

Impact of Oxidation Parameters on Electrical Modulation Properties of GaAs-based VCSELs

E. Pruszyńska-Karbownik, P. Komar, M. Wasiak and R.P. Sarzała

Institute of Physics, Lodz University of Technology, Wólczańska 219, 90–924 Łódź, Poland

In this paper, we present computer simulations results of electrical modulation properties of all-semiconductor GaAs-based Vertical-Cavity Surface-Emitting Lasers (VCSELs). We calculated the complex impedance of the VCSELs for various numbers of the oxide layers on the p- and n-type side with various oxide-aperture radii. The calculations are aimed to reduce the negative impact of the oxidation capacitance on the laser modulation properties.

The simulations were preformed using a self-consistent VCSEL model [1,2] created by Photonics Group of Lodz University of Technology.

Acknowledgements: This work has been supported by Polish National Science Centre grant no. 2016/21/B/ST7/03532

[1] R. P. Sarzała, et al., *Optical and Quantum Electronics*, **36**(4), pp. 331–347 (2004).
[2] M. Wasiak et al.,, *J. Phys. D Appl. Phys.*, **49**(17), 175104 (2016)

MoS2Inv

Invited Lecture

Two-dimensional Large-angle Scanning Optical Phased Array with Single Wavelength Beam

Jiaoqing Pan, Pengfei Wang, Guangzhen Luo, Yajie Li, Fangyuan Meng, Wenyu Yang, Hongyan Yu, Xuliang Zhou and Yejin Zhang

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Beijing Key Laboratory of Low Dimensional Semiconductor Materials and Devices, Beijing 100083, China

With the development of automatic driving and remote sensing technology, light detection and ranging (LIDAR) has attracted great attention. The optical phased array (OPA) based on silicon photonics have become one of the major solutions for LIDAR. But most of the OPA reported still adopt multi-wavelength beam to achieve two-dimensional scanning [1]. In this work, we adopt a novel type of 2D scanning OPA with HCG antenna, which improves the OPA's performance with single-wavelength beam.

As shown in Fig. 1(a), the OPA we proposed mainly consists of four parts: the input port, the optical switches and MMI tree, phase tuners, and 2D HCG antenna. It divides the input beam into 256 channels through the MMI tree, and each 16 channels is one group. It realizes time division multiplexing between each group through optical switch arrays. The beam is tuned, and then emits to the free space through the optical antenna, as shown in Fig. 1(b). Because each group is with a specific angle, the proposed OPA will achieve a circular 2D scanning when each group completes a 1D scan, as shown in Fig. 1(c). The photo of the proposed OPA chip is shown in Fig. 2(a). The chip was mainly finished by CMOS process and combined with poly-Si process to realize the HCG antenna. As shown in Fig. 2(b), the far-field spot can achieve a steering range of ±25.92°.

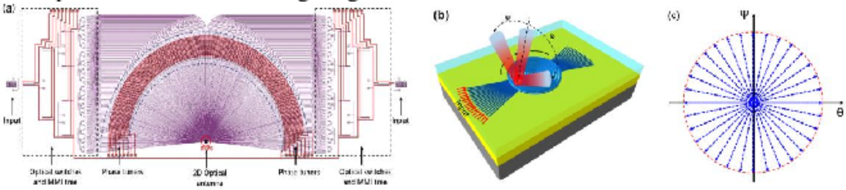

Fig. 1. (a) Schematic diagram of the proposed 2D scanning OPA; (b) Schematic of the proposed 2D HCG optical antenna; (c) Scanning range of the proposed 2D scanning OPA.

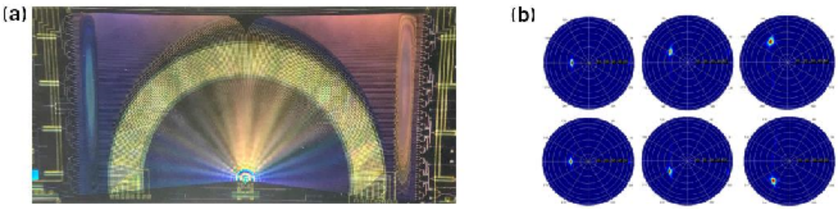

Fig. 2. (a) Photo of the proposed 2D scanning OPA; (b) The simulated far field profile when the phase difference between adjacent waveguides changes.

[1] C. V. Poulton, M. J. Byrd, P. Russo, E. Timurdogan, M. Khandaker, D. Vermeulen, and M.R. Watts, *IEEE Journal of Selected Topics in Quantum Electronics PP*, 1-1 (2019).

MoS2C1

Triple Threshold Lasing from a Photonic Trap in a Te/Se-based Optical Microcavity Embedding a Single Quantum Well

K. Sawicki, J.-G. Rousset, R. Rudniewski, W. Pacuski, M. Ściesiek, T. Kazimierczuk, K. Sobczak, J. Borysiuk, M. Nawrocki and J. Suffczyński

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Pasteura 5 St., PL-02-093 Warsaw, Poland

There are three types of lasing in the emission from a quantum well strongly coupled to a semiconductor microcavity. In the strong coupling regime it is exciton-polariton lasing; in the weak coupling regime - photon lasing involving excitons or, under sufficiently strong excitation, electron-hole plasma. So far, only one or two out of this three regimes have been reported for a given structure and an actual relation between all three thresholds has still not been established.

Here, we explore a full phase space of three lasing types in the emission from an optimized, half-wavelength Se/Te based microcavity embedding a single CdSe/(Cd,Mg)Se quantum well. We observe all three lasing regimes in the order of consecutively increasing excitation power at 8 K (see Figure 1):

(i) polariton-type lasing exhibiting the ultra-low threshold (0.7 kW/cm^2);
(ii) photon-type lasing involving excitons - after increasing the excitation power density by two orders of magnitude, when the strong coupling conditions are lost;
(iii) photon-type lasing arising from recombination of unbound electrons and holes when the power is increased further by an order of magnitude, above the Mott transition for excitons. The electron-hole plasma lasing is maintained up to the room temperature.

The onset of the each type of lasing is accompanied by a narrowing of the emission and a blueshift, which appears to be not limited only to the strong coupling regime, as commonly assumed. Emission dynamics measurement at the room temperature shows a blueshift following the excitation pulse, which is in a striking contrast to a redshift of the emission observed typically in the case of polaritonic lasing.

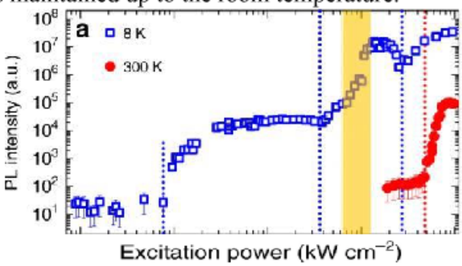

Fig. 1. The integrated emission intensity vs the excitation power density at 300 K and at 8 K for a single CdSe/(Cd,Mg)Se quantum well embedded to a microcavity.

A photoluminescence spatial mapping indicates that nonlinear dependences in the emission are observed only at discrete, randomly distributed, points on the sample. The full tomography of photon momentum space indicates that the emission for these points exhibits discrete energies of the mode and a radiation pattern such as reported previously for micropillar microcavities. The emission remains linearly polarized at the room temperature, when polaritonic effects are negligible. This enables tracing back the locally increased light-matter interaction to an increased light confinement in the planar direction of the microcavity resulting from inhomogeneities formed during the sample epitaxial growth.

[1] K. Sawicki, J-G. Rousset, R. Rudniewski, W. Pacuski, M. Ściesiek, T. Kazimierczuk, K. Sobczak, J. Borysiuk, M. Nawrocki, and J. Suffczyński, *Communications Physics* **2**, 38 (2019).

MoS2C2

Towards a New Laser Application of (MgZn)O/MgO Based Quantum Structures

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Rocksalt $Zn_xMg_{1-x}O$ alloys have been proposed as wide band gap semiconductors for short wavelength optoelectronic applications operating in the deep UV region. A very small value of *c/a* in MgO (1.55) and the high ionicity of this material results in a tendency to crystalize in rocksalt structure. The key idea of our work , instead of growing ZnMgO/ZnO system in wurtzite (the most common approach), is to deposit such layers in rocksalt crystallographic structure and perform growth on rocksalt MgO substrates.

By combing MBE growth and HRTEM we were able to determine conditions in which the rocksalt phase of ZnO and $Zn_xMg_{1-x}O$ alloys can be grown on MgO substrates. In the case of $Zn_xMg_{1-x}O$ compounds, it was found that the maximum of the layer thickness in rocksalt phase strongly depends on Zn concentration, decreasing with *x*, which reflects the alloy phase instability. The band structures of $Zn_xMg_{1-x}O$ alloys in the rocksalt structure are obtained by ab-initio calculations based on the Local Density Approximation (LDA) to density functional theory. The calculated band gaps for $Zn_xMg_{1-x}O$ alloys as functions of composition *x* are compared with the experimental data of single quantum wells and super lattice grown by PA-MBE technique. X-ray diffraction and high-resolution transmission electron microscopy were used for microstructure analysis of (MgZn)O/MgO based rocksalt structure. Optical data was obtained by using deep UV cathodoluminescence. We observed emission from samples which, according to our calculations, should possess indirect bad gap. Theoretical calculations concerning possible deep UV laser designs are also presented. The field of possible applications is broad, and should further increase due to low cost of MgO substrates.

MoS2C3

Mixing of Transverse Modes in VCSELs with Vertically Coupled-Cavities and Parity-Time Symmetry Breaking of Mixed Modes

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In VCSELs with vertically coupled cavities, that is two cavities within the same stacked structure separated with additional middle Distributed Bragg Reflector (DBR), two longitudinal modes exist. The number of middle DBR pairs, together with cavities total thickness and thickness difference (cavity detuning), are responsible for the coupling strength between the cavities and determine the resonant wavelengths and their spectral distance. It was shown in previous research that in such structures the two longitudinal modes are subject to anti-crosing (dotted-green circle in Fig. 1). However, interactions between different order transverse modes of the two longitudinal modes were not considered.

In this talk I would like to show that by carefully adjusting the number of the middle DBR pairs and cavity detuning in a vertically coupled-cavity VCSELs, it is possible to achieve various interactions between different order transverse modes of the two resonant longitudinal modes (solid-purple circle in Fig. 1). Certain mode pairs are subject to anti-crossing assisted with exchange of their energy distributions (mixing, shown in Fig. 2), while other cross, but only in the real part of the complex wavelength. Finally, I will show that the mixing modes can form a Parity-Time symmetry system if gain and loss are introduced to the cavities.

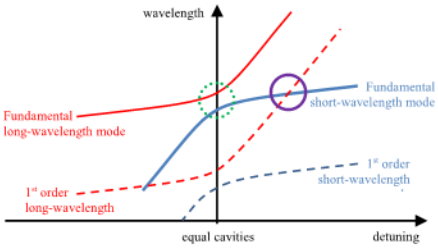

Fig. 1. Schematic drawing of interactions between two lowest order transverse modes of the two longitudinal modes in a vertically coupled-cavity VCSEL.

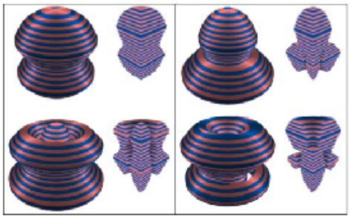

Fig. 2. Electric field isosurfaces (in the whole structure and a quarter-slice) of the LP_{01} and LP_{02} modes: typical shape (left frame) and when subject to mixing (right frame).

Novel materials and designs I

MoS2C4

Strain Engineering of Material Gain Coefficient in a GeSn/SiGeSn Quantum Wells

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For many years, group IV semiconductors such as silicon or germanium have been well known for their applications in the electronics, but since the indirect gap nature limits their usefulness in the photons generating devices, they weren't considered as good gain media. However, over the last years the growth techniques have been developed to the degree, that GeSn alloys, which are characterized by direct gap, can be grown on Si substrate with satisfying quality. The improvement in the growth technology have allowed for the recent observations of photoluminescence, electroluminescence, and even lasing actions in the various structures made of the alloys. These are effects of the current growth of the interest in the group IV alloys applications to the active regions of near- and mid-infrared radiation emitting devices. Within our study, we have performed the theoretical analysis of the material optical gain coefficient spectra in various GeSn/SiGeSn quantum wells (Fig. 1.) for both transverse electric and transverse magnetic optical field polarizations [1]. In the work, we have focused on the epitaxial device designing in which a tensile strain is introduced in to the thin GeSn layer under the condition that quantum confinement for both electrons and holes is preserved. The study of the system begins with the investigation of the band valleys energies for various fractions in the binary alloys SiGe, GeSn and SiSn without strain and with strain yielded by the chosen exemplary substrates. The gain spectra analysis begins with the case of unstrained thin GeSn layer, which is further extended to the cases with the strain up to 1.5%. The study is finalized by the evaluation of the system polarization potential for various fractions and thicknesses of the thin film. The main result of the work is the prediction, that by the strain effects in the system it is possible to obtain from 100% transverse electric to about 80% transverse magnetic polarization of the spontaneously emitted radiation.

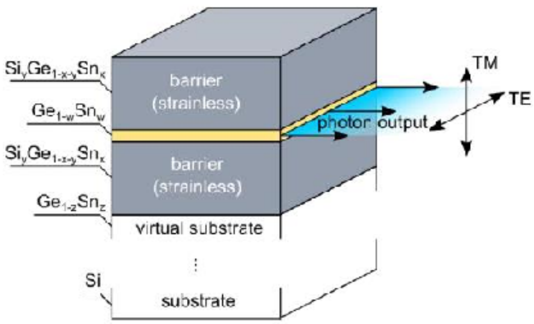

Fig. 1. Schematic picture of the studied GeSn/SiGeSn quantum well deposited on a virtual GeSn substrate.

[1] H.S. Mączko, R. Kudrawiec, and M. Gladysiewicz, "Strain engineering of transverse electric and transverse magnetic mode of material gain in GeSn/SiGeSn quantum wells," *Sci. Rep. Rep.*, vol. **9**, no. 1, pp . 1 14, 2019.

MoS3C1

Optical Properties of III-nitride Laser Diodes with Wide InGaN Quantum Wells

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The III-nitride semiconductor family exhibits extremely strong spontaneous and piezoelectric polarization due to the wurtzite crystal structure. The active region of III-nitride LDs consists of InGaN quantum wells (QWs), in which a significant built-in electric field forms. It leads to red-shift of the emission wavelength (quantum-confined Stark effect) and spatial separation of electron and hole wavefunctions. The latter causes a detrimental decrease of the wavefunction overlap. It is commonly understood that this effect increases with composition and/or thickness of the QW.

In this paper we demonstrate that wide InGaN QWs can be used as the active region in devices despite the build-in electric field. We show by means of both simulations and experiments that wide QWs have an efficient optical transition path through excited states [1,2]. Figure 1 presents the calculated band diagrams of thin and wide QWs showing a higher wavefunction overlap between excited states in wide InGaN QWs than in the thin QWs.

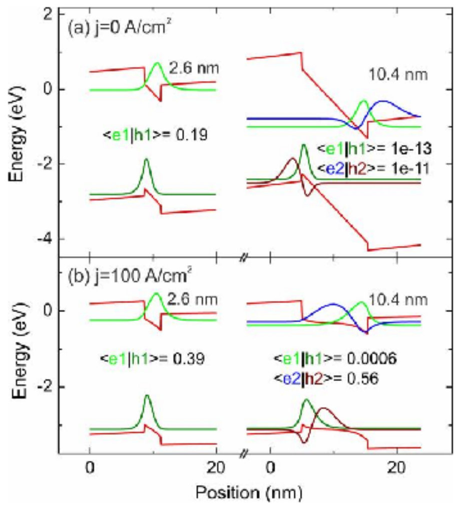

Figure 1. Band profiles of two $In_{0.17}Ga_{0.83}N$ QWs with thicknesses of 2.6 nm and 10.4 nm calculated for: (a) j=0 A/cm2 and (b) j=100 A/cm2. The values of wavefunction overlaps are given in the figure. There is a significant difference in the behavior of the two QWs with current. The built-in electric field in case of the wide QW is fully screened leading to an efficient transition path through excited states.

[1] G. Muziol et al., *arXiv*:1810.07612 (2018).
[2] G. Muziol et al., *Appl. Phys. Express* **12**, 072003 (2019)

Nitride Lasers

(Al,In)GaN Distributed Feedback Laser Diode

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(Al,In)GaN based laser diodes have a wide range of applications, including atomic spectroscopy, metal processing and optical communication – both underwater and free-space. However, some types of the applications require very specific parameters of the emitted light. One of such applications is the optical atomic clock, which shows a need for very stable emission of a very specific wavelength with very narrow FWHM and – at the same time – relatively high optical power in continuous wave (CW) operation. One type of the optoelectronic devices which can meet this challenge is distributed feedback laser diode (DFB LD). Despite a quite long time since the first report on the CW working (Al,In)GaN DFB laser diode [1], due to the difficulty in the fabrication of this type of the device, it is still a novelty in the III-N field.

In this work, we will show the recent progress in the CW (Al,In)GaN based DFB laser diodes working at room temperature. The single peak emission in blue-violet spectral range was achieved with an optical power over 20 mW and with side mode suppression ratio higher than 30 dB. Our DFB laser diode was fabricated by the use of the grating formed along the sidewalls of the ridge waveguide of the laser diode. This type of distributed feedback realization is one of the simplest ways in terms of the complexity of fabrication. We used 3rd and 39th order of the grating and in both of the cases we succeed in obtaining the single mode lasing (see Fig. 1).

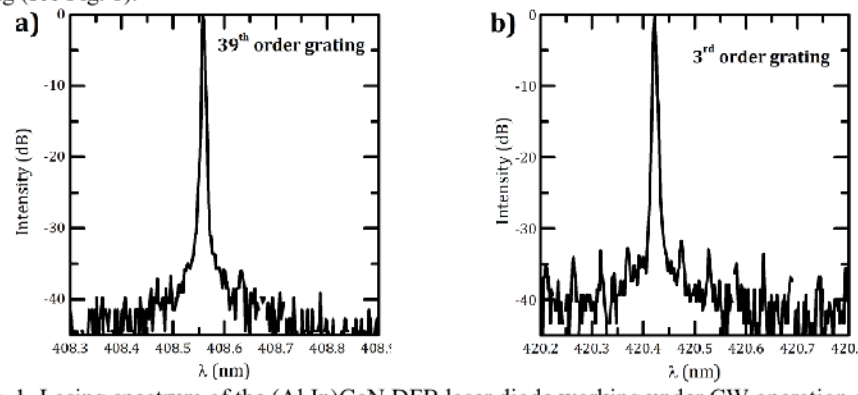

Fig. 1. Lasing spectrum of the (Al,In)GaN DFB laser diode working under CW operation at room temperature with a) 39th and b) 3rd order grating.

[1] S. Masui, K. Tsukayama, T. Yanamoto, T. Kozaki, S. Nagahama, and T. Mukai, *Japanese Journal of Applied Physics Part 2 – Letters & Express Letters*, vol. 45, no. 46-50, 2006, pp. L1223-L1225.

MoS3C3

Beyond the Comfort Zone: Challenges for Nitride Laser Diodes Below 400 nm and Above 470 nm

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By using semiconductors from the (InAlGa)N family, we can change the emission wavelength of laser diodes from ultraviolet to green. The mainstream lasers, located between 400 and 470 nm (UV-A and blue region), have all operating parameters and reliability at a very similar level. However, lowering the wavelength below 400 nm results not only in the production yield decrease, but also in the deterioration of parameters. Similarly, for the wavelengths above 470nm.

The presented paper will discuss the challenges associated with the reduction of indium amount in active layers with the simultaneous increase in the amount of aluminum in laser claddings in the case of ultraviolet lasers. The lower indium content in quantum wells causes reduction of band-offsets and consequently an increased escape of carriers outside the active area. This phenomenon can be suppressed by adding aluminum to quantum barriers and to the electron blocking layer. However, the presence of aluminum leads to the reliability problems and possible increase of the operation voltage.

Difficulties related to increasing the indium content in quantum wells and waveguides for lasers emitting light with wavelength above 470 nm will also be discussed. We obtain a high content of indium in quantum wells by lowering the temperature of growth. However, the overgrowth of the active region with p-type layer should be performed at much higher temperatures to maintain the good crystallographic quality of the layers and secure high enough free holes concentration. At the same time, we must make sure that the growth temperature of the upper layers would not lead to InGaN QWs decomposition. We will discuss some of the trade offs needed to achieve high structural quality and excellent device parameters at the same time.

An attempt will be made to discuss how to grow a structure with good structural, electrical and reliability properties.

MoS3C4

Towards Integrated on Wafer InGaN Laser Diodes

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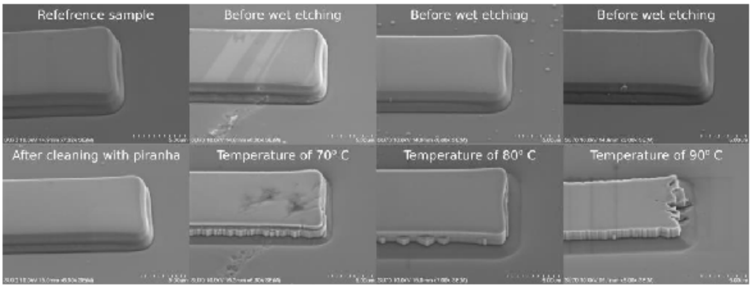
Etched laser mirrors are a needed technology for the development of laser diode integrated on wafers. Integrated on wafer laser diode would enable the creation of visible light photonic integrated circuits (visible PICs), beam combiners etc. The etched mirror should be smooth enough to provide good reflection, and to be vertical in order to minimize cavity losses and finally defectless to avoid unwanted absorption in the region of the facet.

Within this work we first optimize dry etching procedures (Cl+Ar plasma) and we succeded in obtaining flat and smooth surfaces. However, the etched surface is not completely vertical having the inclination of around 80°. We are able to solve the last issue by applying crystallographic direction sensitive wet etching with TMAH, which in turn leads sometimes to less smooth surfaces. This process in our experiments exhibits that the surface roughness for the same wet etching conditions depends on free carier concentrations, and therefore on epitaxial structure of the sample. By using InGaN quantum wells as test samples, we can monitor quality of the near etch regions by measuring the cathodoluminescence intensity in the lateral directions and thus the extension of etching damage caused by ICP RIE. Once the low voltage RIE process is chosen, we are able to minimize the etching damage range below 0.5 µm for the etch plane.

Wet etching time of 10 mins for different temperatures



This work was supported by the Foundation of Polish Science (Grant No. TEAM TECH/2017-4/24).

Nitride Lasers

MoS3C5

Low Temperature Study of Inverted Nitride Light Emitting Devices

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Group-III nitride semiconductors gained extensive attention due to its band gap that spans the widest spectral range [1] among semiconductors. This feature, together with direct bandgap, allows for design of high-efficiency and high-power optoelectronic devices such as laser diodes [2]. The built-in polarization causes some challenges in nitride optoelectronic devices. Standard light emitters grown on top of the most stable polar (0001) GaN surface suffer from non-optimal built-in field alignment with respect to current flow. This field cause barrier lowering carrier injection into quantum well (QW) in pn junction on standard n type substrates [3]. Using bottom tunnel junction (TJ), the sequence of p and n type doped layers in junction can be inverted and grown with n type layer on the top of devices. This leads to inversion of current flow direction with respect to built-in fields. As a result, energy barrier present due to built-in field is moved to the other side of the QW. This prevents carriers from escaping the QW and lowers unwanted recombination outside the QW. This increases injection efficiency and could be beneficial at high injection currents for example in laser diodes. Additionally, bottom tunnel junction allows to use low resistance n-type contacts, which has lower and less temperature dependent resistance. These parameters make LEDs utilizing TJ attractive for low temperature operation.

We studied characteristics of LEDs with bottom TJ at low temperatures (12–300 K). Samples consisted of bottom InGaN TJ, AlGaN electron blocking layer and an active region containing InGaN quantum well, one with 2.6 nm and the other one with wide 25 nm. Devices were grown using Molecular Beam Epitaxy (MBE) on GaN substrate along [0001] direction. The S-shape behavior in electroluminescence was reduced in sample with wide 25 nm QW proving that, comparing to 2.6 nm QW, this designee is less affected by QW width fluctuation (fig. 1a). Both devices operated down to 12K (fig. 1b).

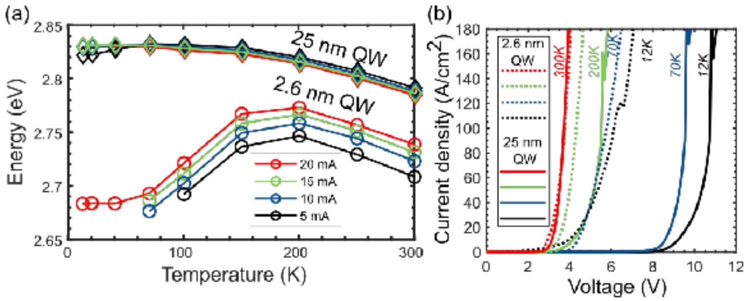

Fig 1. (a) The temperature-dependent peak energy of electro-luminescence at different current densities.
(b) I-V curves for LED with 2.6 and 25 nm QW.

[1] H. Wang et al., *Opt Express* 2016;24:11594. doi:10.1364/oe.24.011594.
[2] C. Skierbiszewski et al., *Appl. Phys. Express* **11**, 034103, (2018)
[3] H. Turski et al., *Journal of Applied Physics* **125**, 203104 (2019)

This work is carried out within the TEAM-TECH POIR.04.04.00-00-210C/16-00 and Homing POIR.04.04.00-00-5D5B/18-00 projects of the FPS co-financed by the European Union under the European Regional Development Fund and by the PNCRD grant LIDER/29/0185/L-7/15/NCBR/2016.

Nitride Lasers

MoS3C6

Influence of InGaN Waveguide on Injection Efficiency in III-nitride Laser Diodes

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III-nitride laser diodes (LDs) are finding applications as efficient light sources for data storage, laser projectors and general lighting [1]. The majority of commercially available LDs utilize GaN waveguides. Theoretical studies show that replacing conventional GaN waveguides with InGaN can increase the confinement of light especially for long wavelength emission (>450nm) [2]. Additionally, InGaN waveguides can be used to prevent light leakage to GaN substrate which deteriorates the beam quality [3]. On the other hand, it is known that Mg doped layers cause high internal optical loss (α_i) in III-nitride LDs [4,5]. Unfortunately, heavily Mg-doped electron blocking layer (EBL) is necessary to ensure high injection efficiency (η_i).

In this work we show that InGaN waveguides increase η_i allowing to use lower Mg doping in EBL and thus obtain lower α_i. We performed carrier transport simulations using a 1D drift diffusion model and a 2D optical waveguide calculations.

The band diagram simulations show that the InGaN waveguide composition changes the effective barrier for electrons provided by EBL. In the high Mg doping regime η_i does not depend on InGaN composition. However, for low Mg doping a high influence of InGaN waveguide is found. Therefore, by the use of high In content waveguides we can decrease the Mg doping in EBL and thus decrease α_i without significant change of η_i. The theoretical findings will be compared with LDs grown by plasma assisted molecular beam epitaxy.

[1] J. J. Wierer, J. Y. Tsao, and D. S. Sizov, *Laser Photon Rev*. **7**, 963 (2013).
[2] C. Huang, Y. Lin, A. Tyagi, A. Chakraborty, H. Ohta, J. S. Speck, S. P. DenBaars, and S. Nakamura, *J. Appl. Phys*. **107**, 023101 (2010).
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[4] S. Uchida, M. Takeya, S. Ikeda, T. Mizuno, T. Fujimoto, O. Matsumoto, S. Goto, T. Tojyo, and M. Ikeda, *IEEE J. Sel. Topics Quantum Electron*. **9** (5), 1252-1259 (2003).
[5] M. Kuramoto, M. Sasaoka, C. Futagawa, N. Nido, and M. Yamaguchi, *Phys. Stat. Sol*. (a) **192** (2), 329–334 (2002).

MoS3C7

Dislocation Related Nonradiative Recombination in InGaN Laser Diodes

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Gallium nitride material system enables fabrication of optoelectronic devices emitting in the broad range of visible spectrum, from UV to green. Emission wavelength is determined by indium composition of the quantum wells, varying from a single percent up to approximately 35%. Such a difference requires significant modifications in growth procedure and results in variation of properties of lasers emitting at different wavelengths.

In this work we investigate the role of threading dislocations in nitride light emitters with different indium content. We compare the properties of commercial laser diodes grown on the low defect density GaN substrate with their counterparts grown on sapphire substrate in the same epitaxial process. All investigated structures were grown by Metalorganic Vapour Phase Epitaxy (MOVPE) and emit light in the range 385 nm – 456 nm.

We observe that intensity of light is strong in the whole spectral region for all structures grown on low dislocation density GaN substrates, while steady decrease in electroluminescence signal is visible for shorter wavelengths in case of LDs on sapphire substrates.

We interpret this behavior in terms of increasing importance of dislocation related nonradiative recombination for structures with low In content. Cathodoluminescence images show a dens network of small dark spots in the case of UV emitting samples and much reduced density of dark spots of larger diameter in the case of blue light emitting structures. After chemical etching of the samples, by the means of scanning electron microscopy, we were able to assign small spots to edge dislocations and bigger spots to screw dislocations.

We propose and discuss possible explanations of observed effects. The first one is different dislocation decoration due to difference in temperature of the epitaxial growth. Another possibility is that the diffusion length of carriers varies in structures emitting at different wavelengths.

MoS3C8

Optimization of p-type Contacts to InGaN-based LDs and LEDs Grown by Plasma Assisted Molecular Beam Epitaxy

K. Nowakowski-Szkudlarek[1], **G. Muziol**[1], **M. Żak**[1], **M. Hajdel**[1], **M. Siekacz**[1], **A. Feduniewicz-Żmuda**[1], **C. Skierbiszewski**[1,2]

[1] *Institute of High Pressure Physics PAS, Sokolowska 29/37, Warsaw, POLAND*
[2] *Top-Gan Sp. z o. .o, Sokolowska 29/37, Warsaw, POLAND*

The vast majority of commercially available optoelectronic devices based on III-nitrides are grown using metal organic vapor phase epitaxy (MOVPE). There are literature reports on the influence of contact layer [1] and metallization [2] on the contact resistance. However, in case of other growth methods such as plasma assisted molecular beam epitaxy (PAMBE) there is a lack of literature data. The recent advancement in the PAMBE in the fabrication of III-nitride laser diodes (LDs) [3], especially the demonstration of devices with a lifetime of 100 000 hours [4], generates a need for optimization of contacts to p-type layers.

There are big differences in the growth conditions of the p-type layers between these two methods. In PAMBE the growth temperature is 200-300C lower than in MOVPE. High quality layers are obtained in metal-rich conditions in PAMBE whereas in MOVPE only ammonia-rich conditions are used. Additionally, the p-type layers grown by PAMBE do not require post-growth thermal activation due to the lack of hydrogen. Such differences in growth conditions allow to expect a need for separate optimization of contacts to p-type grown by PAMBE.

In this work we will study the influence of p-type contact layer and metallization on properties of LDs and LEDs grown by PAMBE. Firstly, the implications of the metal-rich growth conditions will be presented. Droplets due to excess metal flux during epitaxy can form and cause inhomogeneity in the contact layer. Secondly, the influence of thickness, composition and doping of the contact layer will be studied. Thirdly, the influence of metallization annealing on contact resistivity will be presented.

[1] Kumakura, K.; Makimoto, T.; Kobayashi, N., Low-resistance nonalloyed ohmic contact to p-type GaN using strained InGaN contact layer. *Appl. Phys. Lett.* **2001,** *79* (16), 2588-2590.

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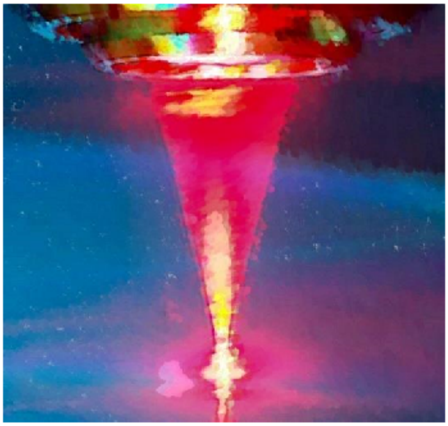
Poster Session



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19. **T. Czyszanowski**, M. Dems, M. Wasiak: *Quasi bound states in the continuum of monolithic high-contrast grating microcavities*
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Poster-1

Carrier Lifetimes Determination in Type I and II QWs Emitting at 2 μm

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Antimony-based compounds are promising as a material system of choice for the next generation of laser sources due to their superior intrinsic properties and versatility. Notably, they offer a number of possibilities to design an active region of laser operating in the mid-infrared spectral range. Among materials lattice-matched to the GaSb substrate, the GaIn(As)Sb quantum well is worth attention. It offers a type I alignment with respect to the barrier material, thus providing a high overlap integral between the upper and lower lasing states. However, the emitted wavelength is limited by the material properties to 3.7 μm [1]. Compared with conventional type I laser diodes, the InAs-GaSb-AlSb material system offers a broad spectrum of bandgap energies and band alignments from staggered to broken (type-II) [2], which e.g. enables their exploitation in light emitters and detectors covering spectral range beyond 6 μm [3,4]. In this quantum system, the AlSb layer functions as a common type-I barrier for electrons and holes, whereas the InAs part functions as a trap for electrons, while enhancing the hole barrier within the valence band. We demonstrate light emission from this system in the spectral range between 3 and 8 μm[5].

In this work, we present a comprehensive comparison of the carrier dynamics in the type I GaInSb and type II AlSb/InAs/GaInSb quantum wells emitting close to 2μm, including:

- ✓ the influence of In compositions and well thickness on the carrier lifetime,
- ✓ temperature-dependent lifetime measurements – the various carrier recombination processes are differentiated and the dominant mechanisms identified for each material system
- ✓ lifetime dispersion – the emission band has a linewidth of several meV

Measurements at 4.4 K provided minority carrier lifetime of ~0.5 and ~2 ns for type I and type II structures, respectively. Obtained values are in agreement with theoretical predictions since the overlap integral in type II structures is expected to be at least two times lower than in similar type I QWs. Furthermore, for type I QWs the PL traces captured at higher temperatures (up to 180 K) exhibit a moderate trend towards higher values of decay time.

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Poster Session

Poster-2

The Influence of Bismuth Incorporation into GaSb on the Photoluminescence Quenching and Carrier Lifetimes

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Incorporation of a few percent of Bi into the GaSb host leads to a substantial bandgap reduction (30-35 meV/at % Bi) [1,2] and could even make it possible to reach a semimetallic state. In addition to large bandgap tuneability, suppressed Auger recombination due to sizeable spin-orbit coupling, and the type-I band alignment are what make Ga(Sb,Bi)/GaSb quantum wells such an attractive candidate for a laser gain medium. This concept is useful mostly in near-infrared range (NIR) applications between 1.7 - 2.5 µm wavelengths, although continuous studies and development of high Bi content Ga(Sb,Bi) alloys [3] could result in the necessary improvement for reaching further emission wavelengths in the mid-infrared range (MIR) [4](between 2.5-5 µm). This opens a broad market of optoelectronic applications – in particular, optical gas sensing devices, requiring efficient emitters and sensitive detection in MIR, since numerous substances have their typical absorption lines in this particular range. In this work, we present carrier dynamics studies in the Ga(Sb,Bi) alloys emitting close to 2 µm, including:

- ✓ Influence of Bi composition on carrier lifetime,
- ✓ Temperature-dependent lifetime measurements – various carrier recombination processes are distinguished, and the dominant mechanisms are identified
- ✓ Lifetime dispersion – the emission band has been found to be strongly modified by increasing bismuth incorporation in GaSb host material.
- ✓ Photoluminescence quenching in a function of Bismuth incorporation.

Time resolved measurements realized at 4.4 K provided minority carrier lifetime of ~200 ps and 250 ps for alloys with 6% and 8%, respectively. Obtained values relate to fundamental radiative emission of the excitons. For the sample with 8% of bismuth, at low energies, modification of photoluminescence signal's line shape was detected. Its decay times were revealed as increasing up to even 500 ps, which might be connected to defect-related capturing processes – influencing the exciton lifetimes. These studies were additionally expanded by temperature dependent photoluminescence measurements.

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Poster-3

Studies of the Atom's Interface Diffusion Processes in InGaAs/AlInAs Quantum Cascade Lasers

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Here we present optical spectroscopy studies to examine structural and optical properties of active region of quantum cascade lasers (QCLs) samples grown fully by MOCVD technique. The active parts are InGaAs/AlInAs based multilayers grown in different temperatures at different stages of growth, nominally lattice-matched to InP substrate. The X-ray spectroscopy (XRD) allowed to compare width of the layers with nominal, respectively. Fourier-transformed photoluminescence (FTPL) and photoreflectance (PR) measurements provided high signal to noise spectra, proving good optical and structural properties of investigated samples. A model of atoms interdiffusion processes was presented to explain observed small energy shifts of the transitions energies within the investigated multilayer structures. We have discussed changes to energy shifts versus diffusion path. As a result there has been established changes of confining potential due to atomic diffusion on the interfaces. Moreover, it allowed to concur, that group-III atoms are mainly involved in that process [1].

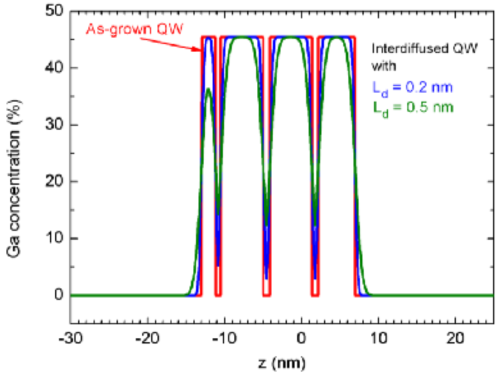

Fig.1. The QWs profile changes after including atom's interdiffusion processes.

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Poster Session

Poster-4

Towards Broad Gain Interband Cascade Lasers in the Mid-Infrared: Theoretical Considerations

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Recently, coherent radiation sources in the MIR have been gaining increasing interest due to their applications related to the detection of hazardous and environmentally-relevant gasses driving the growing demands with respect to all the sensor system components requiring cheap and compact laser sources. The latter can be well fulfilled by approaches based on semiconductor lasers. One of the efficient solutions is the interband cascade laser (ICL), which is beneficial due to the following reasons: good control in a broad range of the target emission wavelength [1, 2], minimized influence of the Auger related carrier losses [3], and a very low power consumption [4]. To fully utilize the potential of ICLs, many parameters of these multilayer structures need to be still further optimized. This concerns especially their active region which is composed of a cascade of type II quantum wells (QWs) made of broken gap materials, e.g. InAs and GaInSb, with usually AlSb barriers.

In this work we present results of theoretical modelling in the framework of eight-band k·p theory of the ICLs' band structure under external electric field imitating the conditions occurring in an operational device. We aim at achieving broad gain functions required in some of the applications, as broadly tunable lasers or superluminescent diodes in the MIR. We considered a possibility of implementing a type-II QWs based on a common combination of InAs/GaInSb layers in the active region, as well as especially modified type-II designs [5], [6]. We have modelled the electronic structure and optical properties of such QWs to be grown on InAs or GaSb substrates. Then, the optical material gain is derived from Fermi's golden rule [7]. To include the spectral broadening of transitions, we convolved the expression for the optical gain with spectral broadening function to simulate the effect of all sources of the carrier scattering. There are taken into account such issues as variation of compositions and thicknesses, including asymmetry of the active part and external factors crucial in operational devices as electric field. We have obtained that some of the designs offer gain significantly broader than reported previously and still preserving its high values in spite of indirect in the real space character of the optical transition.

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Poster Session

Poster-5

Optical Gain in Unstrained Interband Cascade Lasers

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Developments of laser-based gas sensors cause increasing demands with respect to radiation sources, especially in the 3 to 12 µm range, where many of environmentally relevant gasses have their unique absorption lines. Semiconductor lasers are able to satisfy all the requirements, as they are compact, low power consumption and relatively cheap to fabricate. Due to maturity of the semiconductor technologies their characteristics can be tailored to a great extent. The so called interband cascade lasers (ICLs) have especially important advantageous features, when compared over their competitors, as minimized influence of the Auger related carrier losses and very low threshold powers [1, 2]. However, still the existing ICLs' designs which are type II heterostructures deal with strained structures, which causes certain limitations when regarding the growth technology and when larger total layer thicknesses are required.

In this communication we discuss a proposition of a modified type II quantum well (QW) design of the ICLs' active region, which would allow avoiding the abovementioned strain-related problems, make the system more robust and fabricate a fully unstrained ICL device. We propose a combination of multinary compounds as InAsSb and GaInAsSb (instead of commonly used GaInSb/InAs system), which allows to find compositions which can be lattice matched to GaSb or InAs substrates, while still keeping the type II band edge diagram [3]. We have modelled the electronic and optical properties employing the eight-band k·p theory including strain and external electric field. Based on that the optical gain has been calculated [4] for various carrier concentrations and temperatures to finally derive the threshold current densities. The obtained results show that these solutions can be beneficial with respect to the existing ones, and hence pave the way towards fully strain-free interband cascade lasers in the MIR.

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The project has been supported by the Polish National Agency for Academic Exchange and by the iCspec project of the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 636930.

Poster Session

Membrane Technology for MECSEL Fabricated on InP Substrate

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Membrane External Cavity Surface Emitting Lasers (MECSELs) gain considerable attention because they open the possibility for application of semiconductor materials for high power emission in TEM00 beams in the spectral regions not penetrated by semiconductors up to now. The technology of MECSELs imposes however the challenge of etching off the epitaxial substrate and bonding the membrane on or in between transparent heatsinks.

We have developed the technology of fabrication of the membranes of InP based heterostructures for applications in lasers emitting in 1550 – 1750 nm band. The MECSEL's ~2.5 µm thick heterostructure was deposited on the InP substrate by Molecular Beam Epitaxy. It consists of 8 strained InGaAs quantum wells (QWs) in between the InGaAlAs barriers and is enclosed symmetrically by InAlAs window layers and 15 nm thick InGaAs surface protection layers. The QWs strain was compensated by the proper composition of InGaAlAs barriers. The InGaAs layer on the substrate side was used as an etch-stop layer. Since the heterostructure consists of exclusively arsenide, the InP substrate was etched by HCl/H_3PO_4 based solutions. After the etching, mirror like surface was obtained in a central part of the sample (Fig. 1). In order to avoid damaging 2.5 µm thick membranes, priory to etching we attached the semiconductor sample to transparent heatsink - a single crystal diamond. The sample was 2x2 mm and the diamonds 3x3x0.3 mm. The heterostructure was bonded to heatsink using capillary forces with use of water or methanol. This approach of first bonding then etching turns out to be beneficial in case of the heavily strained structures since it prevents the rolling or breaking of membranes due to not fully compensated strains in epilayers.

After etching, the heterostructure was covered by another diamond and enclosed in a copper mount and set into a resonator. The lasing with power of over 160 mW at the wavelength of 1600 nm was registered under optical pumping with a power of 5 W at 980 nm. Further increase in the power emission is expected after improving uniformity of smoothness of the etched surface.

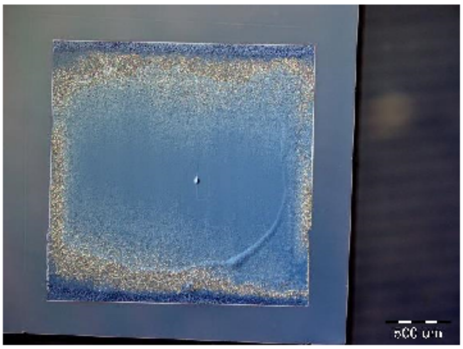

Fig. 1 Etched surface of MECSEL heterostructure bonded to diamond heatsink, Nomarski interference contrast reveal the mirror like smoothness in central part of the sample.

The work has been supported by the Grant No. 2017/25/B/ST7/00437 of the NSCentre in Poland.

Poster-7

Optical Wafer Characterization For MECSEL Laser Emitting Above Telecommunication Band

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Nowadays, the optically pumped semiconductors disc lasers (OP-SDL), widely known as Vertical External-Cavity Surface-Emitting Lasers (VECSEL) are rapidly being developed into a new kind of optoelectronic device. The VECSEL have many advantages over other laser sources gaining both from the solid state type design of the resonators and the band-gap engineering of modern semiconductor technologies. The external resonator with optical pumping permits for scalability of the output power up to values of many tens of watts preserving the Gaussian beam, single mode operation and kHz linewidth. However, there are two main factors which limit further spectral expansion of the VECSEL: the feasibility of high reflectivity of the distributed Bragg Reflectors (DBR) and the efficient heat extraction.

For this reason, at the Institute of Electron Technology the research is carried intensively to develope the technology of Membrane External Cavity Surface Emitting Laser, known as MECSEL lasers. In this kind of design the active region without integrated distributed bragg reflector is enclosed between two transparent diamond heat-spreaders and put inside external dielectric mirror resonator. This technology was earlier tested for InGaAs/GaAs heterostructeres for emission at 980 nm. We managed to transfer this technology for spectral region above telecommunication band 1550-1750 nm for which the epitaxial growth is carried on InP substrates. We studied series of strain-compensated heterostructures with 8QW. Each sample is designed for slightly different emission wavelength with corresponding resonant periodic gain arrangement.

In this report we present detailed optical wafer characterization analysis, emission parameters of the device, we discuss also potential for tuning in very wide spectral range due dbr-free design. The extensive discussion of further optimization of heterostructure design will be described.

Funding: The work has been supported by the Grant No. 2017/25/B/ST7/00437 of the National Science Centre in Poland

Poster-8

Long Focal-Length Planar Focusing Reflectors Based on Monolithic High Contrast Gratings

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A High Contrast Grating (HCG) is a physical structure composed of stripes of a material with high refractive index that are separated with low refractive index medium, e.g. air. A monolithic HCG (MHCG) is a special kind of an HCG, where the stripes are etched in a substrate material. Thanks to that, MHCGs are more rigid as compared to air-suspended HCGs and their fabrication causes less issues as compared to HCGs grown on oxide layer. Varying MHCG period, fill factor and height one can obtain either very high reflectivity or very high transmission. Thanks to the fact that in MHCGs it is possible to adjust the reflectivity and the phase change separately, one can select the periods and fill factors that maintain high reflectivity and at the same time mimic the phase change of the parabolic reflector. As a result, a planar focusing reflector is constructed. In principle, planar reflectors based on MHCGs may substitute at least one distributed Bragg reflector (DBR) conventionally used in a vertical-cavity surface-emitting-lasers leading to simplification of the laser structure due to the fact that an MHCG is around ten times thinner compared to a DBR.

We will present the simulations of long focal-length (1 mm) GaAs-based focusing HCGs. In particular the dependence of their reflectivity and the maximum intensity of reflected light in the focal point as a function of wavelength and angle of incidence.

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Tapered Quantum Cascade Lasers With Different Shape of the Taper Section

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Quantum cascade lasers (QCL) based on AlGaAs/InGaAs/InP heterostructures designed to emit at 4.5 μm band are promising sources for many applications. Some of them, like infrared countermeasures, require relatively high-power and fundamental lateral mode emission. The power scaling in QCLs technology can be realized by increasing the ridge width, but since wider ridges result in higher order mode excitation, this approach is very limited. It was found that in case of ~4.5 μm emission the waveguide width should be lower than 5 μm [1,2]. Solution maintaining fundamental mode operation and at the same time providing high optical power is to use taper geometry of the waveguide [3].

The tapered lasers consist of two parts. The first one (rear part of the resonator) is a narrow waveguide, supporting only the fundamental mode propagation. The second one is the tapered part where the waveguide is typically linearly widening in the direction of the light propagation e.g. from ~ 5 μm to 100 μm at the front mirror of the laser. The narrow part discriminates higher order modes and the optical mode is adiabatically expanded in the taper section. Large volume of the AR being electrically pumped allows to reach high optical power within fundamental mode.

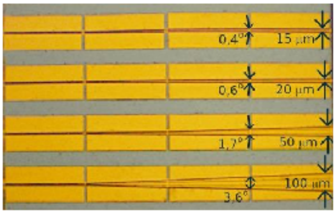

Fig. 1. Optical microscope image of part of processed taper QCL heterostructure with linear taper geometries with different taper angles 0.4º, 0.6º, 1.7º and 3.6º; 0.5 μm straight part and 1.5 μm taper part (ratio 1:3).

In this work, three types of tapered lasers geometries are presented: linear, convex and concave. Each of them is characterized by a different shape of the tapered region [4]. The light-current, current-voltage and far field distributions are presented. The full processing of the presented QCL and the MBE growth of the AlGaAs/InGaAs/InP heterostructure was performed in the Department of Photonics of Łukasiewicz – ITE.

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Poster-10

Preparation of 9 µm Wavelength QCLs with Double Optical Gap Using Plasma Etching

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Laser waveguides with precisely controlled depth, smooth mesa walls and vertical side profiles play essential role in amplifying the light and defining the wavelength band of the resulting device. High quality of the processed semiconductor surface is essential for minimizing unwanted effects such as light scattering, absorption, high contact resistance and also to maintain photons is the correct heterostructure layer. Additional complexity is added when optical waveguide has to be "cut" into distinct isolated sections of the precise length with strictly defined narrow gaps in-between. Such system of coupled sections can be utilized to supress unwanted side modes to produce monochromatic effect similar to DFB [1].

From the technological point of view, though wet chemical etching can be successfully utilized to define mesa structure lateral geometry, it is poorly suitable for obtaining highly anisotropic etch profile [2] which is essential to minimize internal reflection between coupled optical sections. Dry etching of InP-based materials for QCL processing formally meets the technology requirements, however, for the case of epitaxially-grown heterostructure of InGaAs/InAlAs/InP type is rather challenging. Difficulties arise because of specific chemical properties of etched layers with respect to reactive gases used. For instance, the formation of non-volatile $InCl_3$ in Cl-based plasma prevents deep etching of the above-mentioned heterostructures, often producing unacceptable surface quality [3].

Previously, we have shown that methane/hydrogen-base plasma can be used to produce complex waveguide geometries for InGaAs/InAlAs/InP type material while maintaining steep mesa side angle [4]. In this work we use it to produce a precisely defined double optical gap (9 um) QCLs with normal as well as InP-overgrown waveguides (Fig. 1). The difference in material processing will be discussed together with some parameters of the produced monochromatic devices.

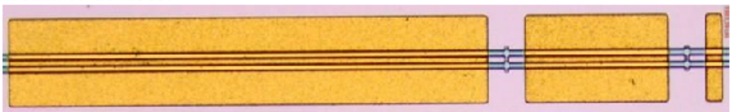

Fig. 1 Optical image of a double optical gap QCL.

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Acknowledgements: *This work was partially financially supported by the National Centre for Research and Development (NCBR) grant no. TECHMATSTRATEG1/347510/15/NCBR/2018 (SENSE)*

Poster Session

Poster-11

Towards Realization of Two-Dimensional Vertical Emission Arrays of Visible Laser Diodes

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With the technological advancement in optoelectronics and fast-growing range of lasers applications, there is a need for new concepts of high-optical power, easy to use sources of radiation for laser projector, laser lights and even welding. To achieve high-optical power, the integration of many emitters is critical. However, unfortunately, the use of Vertical Cavity Surface Emitting Laser Diode (VCSEL) which are easy to integrate in 2D arrays, is still very difficult in case of III-N nitrides. Owing to this fact, an alternative approach to VCSEL fabrication has been proposed in this project. The aim is to fabricate a laser diode which combines the properties of both VCSEL and EEL (Edge emitting laser).

Proposed light emitter will have a horizontal cavity with 45^0 deflectors. The role of these deflectors would be to deflect light perpendicular to the cavity, achieving vertical out-coupling. The most challenging part of this project is the fabrication of the micro-mirrors which act as both as beam deviating mirrors and cavity forming mirrors.

Our experiments show that fabrication of high-quality laser diode along with micro-mirrors is very demanding but achievable. In this paper I will describe our new device design and processing, giving insight to its possible applications and advantages over simple light emitting laser diode.

Poster Session

Poster-12

Photoluminescence and Raman Spectroscopies as an Optical Approach of Stresses Determining in MOVPE Grown Quantum Cascade Laser Structures

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Quantum Cascade Laser (QLC) is unipolar device based on intersubband transitions [1]. Due to the possibility of emitting wavelengths in the THz range, InGaAs/AlInAs heterostructures lattice-matched to InP substrate are most commonly used [2]. Core of QCL contains hundreds or even thousands repetitions of quantum wells and barriers with a thickness of the order half to ten nanometers. Such a sophisticated structure requires technology with a resolution of the nanometers or even few angstroms order.

One of the epitaxial growth techniques provides nanometer resolution is Low Pressure Metal Organic Vapour Phase Epitaxy (LP-MOVPE). For investigations, four QCL core structures grown at LP-MOVPE AIXTRON 3×2" FT system at low pressure of 100 milibars were used. The 100% concentrated AsH_3 and PH_3 were used as the sources of anions, whereas TMGa, TMAl and TMIn were sources of gallium, aluminium and indium cations, respectively. At first only core of the QCL at 645°C was grown. After this process samples were reloaded and 1.5 µm InP top claddings were deposited on each of them at different temperatures: 600, 645 and 680°C.

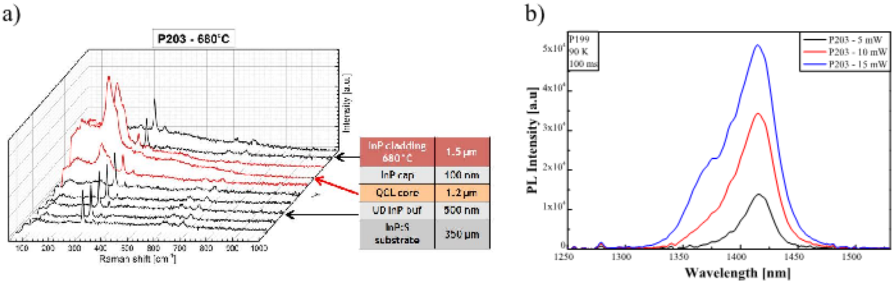

Fig. 1. a) Raman spectra and b) photoluminescence spectra of sample P203 with cladding deposited at 680°C.

In the case of such sophisticated structures containing hundreds of thin layers, it is important to minimize the stresses generated in the QCL core. Techniques enabling determination of stresses in such thin layers as those described in the article are photoluminescence and Raman spectroscopies [3]. Based on Raman shift or changes in maximum photoluminescence signal position it is possible to calculated stresses occurring in the structure.

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Poster Session

Poster-13

Compact and High Speed Drivers for Quantum Cascade Lasers

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The paper presents investigations of drivers for quantum cascade lasers dedicated to laser absorption spectroscopy. The main goal of the research was to determine influence of lasers driver parameters on gas sensors performance using some commercial devices and low-noise custom electronics. The QC lasers are very common and convenient mid-IR radiation sources applied in gas sensing systems. They can operate in both pulse and continuous modes providing single mode radiation and wavelength tuning, depending on the requirements of the specific application [1]. Experimental setups usually use laboratory equipment for laser supplying and stabilizing its operation conditions. Such devices as stabilized power supplies, temperature controllers, waveform generators provide parameters in a wide range of changes, which is a big advantage at the initial stage of laboratory research. However, for more advanced studies it is necessary to develop dedicated components of the laser control system. Examples of custom laser drivers for compact laser heads consisting of a power supply, a temperature controller and a generator are presented (Fig. 1).

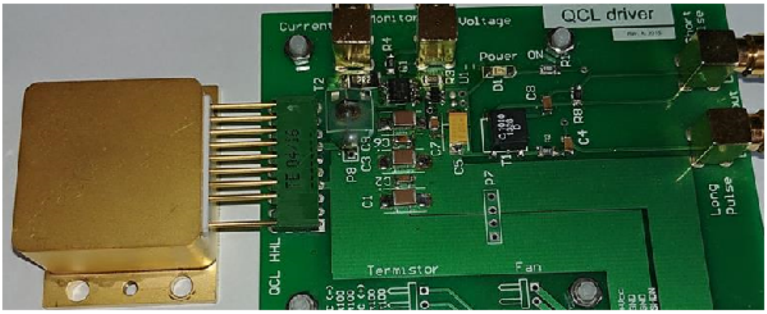

Fig. 1. Example of the custom controller for a quantum cascade laser in an HHL housing.

They provide current pulses exceeding the value of 1 A and 10 V voltage, low noise, short and stable pulses (8 to 800 ns) with a frequency up to 10 MHz or continuous operation, temperature stabilization (up to 0.01 K), laser polarization and external current modulation.

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Acknowledgements
Works carried out in the laboratory of Institute of Optoelectronics MUT, financially supported by the National Centre for Research and Development in the scope of project ID: 347510.

Poster Session

Poster-14

Impact of the Imperfections in Fabrication of Selected Elements of a Nitride TJ VCSEL on Its Emission Characteristics

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This paper presents results of numerical simulations of a semiconductor vertical-cavity surface-emitting (VCSEL) laser made of nitride materials. The modeled laser is based on a structure created at the University of California in Santa Barbara [1]. The analyzed VCSEL has 22.5λ resonator and emits 405 nm wavelength. The active area of the laser consists of two 14-nm/1-nm InGaN/GaN quantum wells. The simulations were performed using the self-consistent thermal-electrical-optical model [2] created by the Photonics Group at the Lodz University of Technology. The analysis concerns the impact of the imperfections in fabrication of various laser elements on its emitted power. Different locations of the active area (Fig.1a) and the tunnel junction in the laser resonator with respect to the originally designed structures were considered. The influence of changes in the thickness of the DBR mirrors layers on the laser performance was also investigated (Fig.1b).

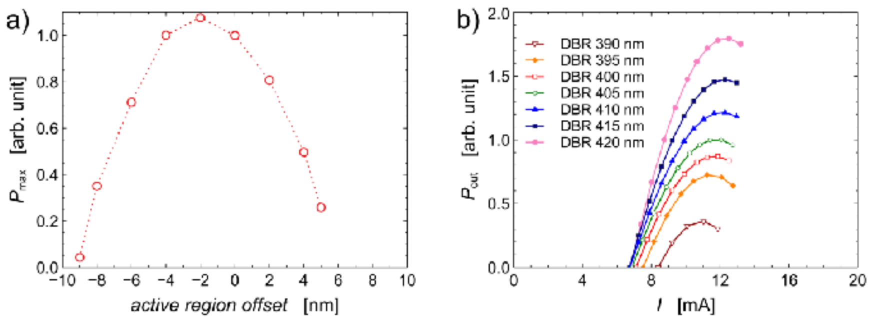

Fig.1. a) Maximal output powers as a function of the active area offset, the initial position is "0 nm". b) the output power characteristics for lasers with DBRs which maximal reflection corresponds to different wavelengths for both DBRs modified.

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Poster Session

Lateral Carrier Injection for the Uniform Pumping of Several Quantum Wells in InGaN/GaN Optoelectronic Devices

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The nitride materials (AlInGaN) have acquired an enormous importance in the production of optoelectronic devices such as light-emitting diodes (LEDs), edge-emitting laser diodes (LDs) and vertical-cavity surface-emitting laser diodes (VCSELs). All these devices share the same basic epitaxial structure, which consists of a stack of quantum wells (QWs) sandwiched between an *n*-side (doped with donors) and a *p*-side (doped with acceptors).

An inconvenience of this structure is that the carriers of each type can only reach the farthest QW after having traversed all the QWs closer to the correspondingly doped side. In the case of the nitride materials, in which the mobility of the holes is not particularly effective, this design only allows for a significant population of holes in the topmost two or three quantum wells [1]. The inability to spread the holes in a large-enough active region has been recognized as the main cause of the efficiency droop in LEDs (and consequently of the green gap) [2] and the limited overlap of the optical mode with the gain region of VCSEL devices (whence their need for extremely low optical losses).

Lateral carrier injection is an alternative design, in which the *n*-side and *p*-side are located at the sides of the active region (see Fig. 1), so that carriers may flow laterally (i.e., parallel to the epitaxial layers) into the active region. Given that the carriers are now injected fairly and homogeneously into all available QWs, it now makes sense to grow structures with a large number of QWs. This provides a solution to the aforementioned problems and, as an additional bonus, both the *n*-side and the *p*-side can now be contacted from the top surface of the structure. The only downside of lateral carrier injection is the need to etch and regrow the regions corresponding to the *n*-side and *p*-side, though this is a topic that has have already been investigated in the production of GaN high-electron-mobility transistors (HEMTs). The concept of lateral carrier injection has been explored to quite an extent in the arsenide and phosphide material systems in the past 30 years [3], but surprisingly not much in the nitrides despite all the unique advantages that it can bring specifically to that material system.

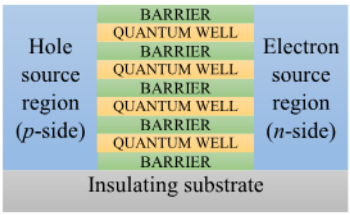

Fig. 1: Structure with lateral carrier injection.

Our group has carried out preliminary research on InGaN/GaN lateral-carrier-injection structures. Numerical simulations have shown the feasibility of the concept and confirmed the theoretical advantages. The first attempts at producing the structures have exposed issues with the regrowth of the *n*-side and *p*-side and with a parasitic current flowing on the top surface of the active region—all problems that we believe are solvable. We intend to present our latest results at the conference.

This presentation is funded by the FNP Team-Tech grant POIR.04.04.00-00-4113/17.

[1] A. David et al., *Appl. Phys. Lett.* 92, 053502 (2008).
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Poster-16

Towards Room Temperature Polaritonic Lasing in a GaAs-Based Microcavity System

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To reach high temperature lasing from an optically pumped GaAs-based microcavity system it is of primary importance to stabilize Coulomb bound electron-hole pairs (excitons), the critical ingredient for the formation of a polariton condensate. For typical GaAs-based systems, the exciton binding energy can be as high as a few meV, which prevents exciton formation at elevated temperature, as the thermal energy reaches nearly 26 meV at T=300 K. In the current work, we propose to use quantum well engineering in order to enhance the Coulomb interaction within an exciton, towards obtaining high-temperature polaritonic emission. The polaritonic structure under study is composed of an AlAs/AlGaAs vertically emitting microcavity with embedded ternary $Al_{0.2}Ga_{0.8}As$/AlAs quantum wells (QWs). The estimated QW exciton binding energy exceeds 25 meV, as a result of states mixing effect, involving confined QW and its barrier states. The QW exciton emission at T=5 K occurs near the 673 nm photon wavelength. Emission from the polaritonic structure is examined by angle -resolved photoluminescence measurements, where the photon emission angle (connected to the polariton in-plane wavevector $k_{\parallel}$) is detected simultaneously with its wavelength, allowing for obtaining the full information on the polariton energy dispersion in given experimental conditions. Experiments are performed in the temperatures ranging from 5 up to 300 K, with different exciton-cavity-photon detuning, and with various excitation power. A semiconductor continuous-wave laser is used a pumping source. The pump beam is focused on a polaritonic structure to a spot diameter of a few microns, and the pump photon wavelength is spectrally tuned to the reflectance minimum of the first high-energy Bragg mode near 638 nm.

The low-temperature data show apparent polaritonic emission indicated by a well visible deviation from the parabolic dispersion, as well as a spectral blueshift with the increasing excitation power. Despite that, observation of the polariton lasing remains challenging, due to the limited pump power and the intrinsic disorder present in the sample, leading to loss of the strong coupling. Different pumping schemes, such as implementation of the higher power pulsed laser, together with the separation of the excitonic reservoir from the polariton emission area, may be necessary in order to observe the linewidth narrowing and nonlinear increase of the emission intensity, characteristic to lasing. Nevertheless, preliminary results of measurements at elevated temperatures give hope for achieving polariton emission and lasing even at room temperature, after implementing suitable excitation scheme.

The project has been supported by the National Science Centre in Poland within the SONATA BIS grant No. 2018/30/E/ST7/00648.

Poster-17

Near-Threshold Behaviour of Single-Mode and Multiple-Mode 980 nm VCSELs

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In this paper, we present results of measurements performed near the threshold current of vertical-cavity surface-emitting lasers (VCSELs). The studied lasers are GaAs-based 980 nm VCSELs [1] with various oxide aperture diameters. We measured their near-field optical output profiles and their optical output power versus current characteristics. Based on the experimental results, we show and analyse the differences in the near-threshold behaviour between single-transverse-mode and multiple-transverse-mode VCSELs.

Acknowledgements: This work has been supported by the Polish National Science Centre grant no. 2015/18/E/ST7/00572

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Poster-18

1300 nm VCSELs on GaAs: Return of the Dilute Nitrides?

M. Gębski[1, 2], D. Dontsova[1], K. Nunna[3], R. Yanka[3], A. Johnson[4], R. Pelzel[5] and J.A. Lott[1]

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We present the key results of our recent work on vertical-cavity surface-emitting lasers (VCSELs) based on *dilute nitride* (DN) GaInNAs(Sb)/GaNAs active regions. Incorporation of only a few percent of nitrogen in the InGaAs quantum wells opens a way to extend the emission wavelength to 1300 nm and even up to 1550 nm. Since the golden age of DN lasers at the break of the millennia virtually no improvements have been achieved in this area.

There has always been an interest for 1300 nm wavelength VCSELs for long-reach optical communication systems. Recently, other potentially lucrative markets for 1300 nm VCSELs and VCSEL arrays have emerged such as light sources for free-space optical (FSO) communication links, the Internet-of-Things, smartphones, and light detection and ranging (LiDAR) systems. This rebirth of interest in 1300 nm VCSELs has sparked a return to DN laser diode research.

We present DN VCSELs emitting in a quasi-single mode (with a SMSR ~20 dB) at ~1300 nm with an oxide aperture diameter ϕ ~3 up to 12 μm. The maximum room temperature (RT) optical output power reaches ~1 mW at rollover and threshold currents slightly higher than 1 mA were measured. From our RT standard small-signal modulation response measurements using on-wafer probing we achieve a record bandwidth (f_{3dB}) of ~10 GHz at a bias current of 4.5 mA.

This work is jointly supported by the German Research Foundation (Deutsche Forschungsgemeinschaft) via the Collaborative Research Center (Sonderforschungsbereich) 787 and by the Polish National Science Centre ETIUDA scholarship 2015/16/T/ST7/00514.

Poster-19

Quasi Bound States in the Continuum of Monolithic High-Contrast Grating Microcavities

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Semiconductor microcavities are crucial for fundamental science as powerful tool for quantum information processing, quantum dynamics, exciton-polaritons observations as well as for large scale production of sensing and emitting devices. Microcavities significantly enhance interaction between matter and light that can be confined to very small volume to build-up optical power. Fabricating such devices with arbitrary material used in photonics yields great freedom in exploration of new material functionalities. Here we propose microcavity design composed of two monolithic high-contrast gratings (MHCGs) as the microcavity mirrors. We demonstrate by numerical analysis very large magnitude quality factors on the level of 10^5 and more that is attributed to bound states in continuum (BICs) that are spatially localized states in infinite periodic structures. BICs although are located in leaky-mode region of wavevector space are lossless, hence their *Q*-factors are infinite. Lossless BICs are possible due to theoretical idealization of the structure that assumes infinite size, lack of absorption and perfect periodicity. In real structures BICs transform into quasi-BICs of *Q*-factor reduced by limited size of periodic structure, absorption and structural imperfections however still of noticeably large *Q*-factor value that cannot be achieved by Fabry-Perot resonance.

Acknowledgements: This work has been supported by the Polish National Science Centre grant no. OPUS 2018/29/B/ST7/01927.

Poster-20

Carrier Dynamic in GeSn Alloys: the Issue of Below Bandgap States

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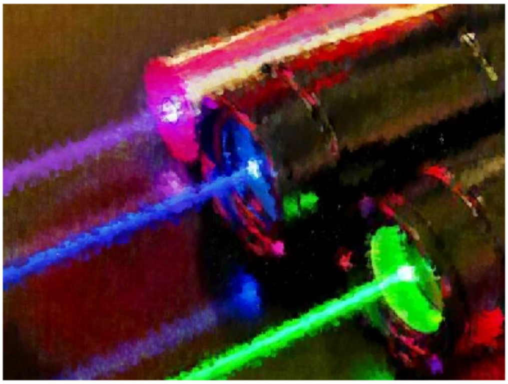
Silicon (Si) is a primary material for today's microelectronics mainly due to unique integration possibilities in very large and complex electronic systems. As a result, Si plays a dominant role in information processing. Unfortunately, the data streaming in Si-based microelectronic modules has now reached the speed limit. The ultimate solution is to use light as a medium for data transfer, but it is genuinely challenging for Si-based optoelectronics since Silicon, or Si-compatible Germanium (Ge), are weak light emitters. A high-quality GeSn semiconductor alloy can change the situation. A small fraction (~10%) of Tin (Sn) can transform GeSn to optically active material still compatible with a Si-based platform. Despite the latest successive presentation of the GeSn-based laser [S. Wirths et al., Nat. Photonics 9, 88 (2015)] the knowledge on GeSn gain material is very limited.

In the presentation, attention is focused on the optical properties of GeSn alloys having a different Tin content in the range of 6-12%. The alloys are examined by photoluminescence (PL), photoreflectance (PR), time-resolved photoluminescence and transient reflectivity (TR) techniques as a function of optical excitation and temperature. The low-temperature PL spectra show an efficient emission band near the GeSn bandgap energetically shifting from 637 meV to 527 meV with a change in the Tin content from 6% to 12%. As expected, there is no observable PL emission from the reference Ge sample. However, the optical absorption examined by the PR experiment show absorption features that are blueshifted with respect to PL band positions. The observation suggests that PL emission from investigated GeSn alloys can be governed by the existence of a density of states located below the fundamental gap of GeSn. This conclusion seems to be confirmed by the results of TRPL and TR experiments were an evident dispersive character of carrier relaxation times is observed across PL band emission. The results show that PL emission in the GeSn system is not necessarily related to the band-to-band optical transition, but can involve states energetically located below the GeSn fundamental gap. Chemical and structural imperfections of the GeSn crystal lattice can be a source of these states. However, their exact origin is currently unknown.

15 October (Tuesday)

Sessions

Novel materials and designs II
Vertically Emitting Lasers II
Applications of Semiconductor Lasers
Sensing systems III



NIR and MIR Lasers and Their Use in Sensing Applications

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Tunable Diode Laser Absorption Spectroscopy (TDLAS) has proven to be a versatile and mature tool for gas sensing applications with significant advantages compared to other techniques such as Fourier Transform Infrared (FTIR) or gas chromatography. These advantages include real-time in-situ measurements, low maintenance and ruggedness of the sensor. TDLAS enables the detection of trace gas concentrations down into the ppb range [1, 2]. For these measurements a longitudinally single mode laser line is scanned through a characteristic absorption feature of the gas to be detected. The typical wavelengths for these absorption lines originating from vibrational rotational transitions of molecules can be found from the near infrared to mid infrared (MIR) region for many industrially relevant gases.

The present talk illustrates several novel sensing applications in the field of biomedicine and pollution control and gives an overview of recent progress in the development of novel laser concepts such as Interband Cascade Lasers (ICL) [3, 4].

The ICL technology enables the fabrication of application grade single mode lasers in the mid infrared region (3-6 µm). The MIR spectral region is of special interest as the fundamental absorption features of many relevant gases are located within that spectral window offering the highest absorption and thus highest sensitivity possible. Figure 1a) shows the emission lines of several distributed feedback (DFB) ICLs for which single mode operation is achieved by applying a lateral metal grating, defined by electron beam lithography. A scanning electron microscope (SEM) image of the metal grating of such a laser is shown in Figure 1b).

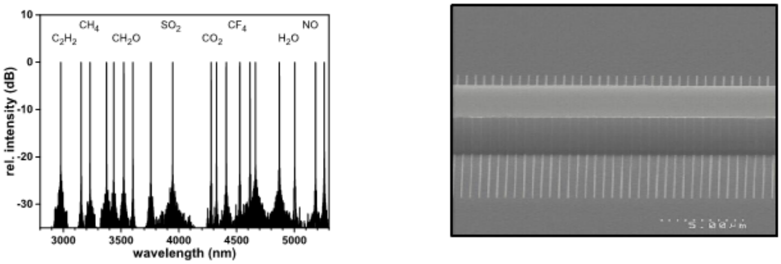

Figure 1: a) Single mode emission lines of different single mode DFB interband cascade lasers in the 3 µm to 5.2 µm range suitable for the detection several industrially relevant gases. b) SEM image of an ICL.

[1] J. Hodgkinson and R. P. Tatam, *Measurement Science and Technology,* **24**, 012004 (2012).
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[4] M. v. Edlinger, J. Scheuermann, R. Weih, C. Zimmermann, L. Nähle, M. Fischer and J. Koeth, *IEEE Phot. Tech. Lett*. **26**, 480-482 (2014).

TuS4C1

The Interface Importance in Different Types of Mid Infrared Emitters

M. Kurka, M. Dyksik and M. Motyka

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The interface quality is a crucial issue in the process of fabrication of low dimensional semiconductor structures. In this work, several material systems predicted for light emitters in mid infrared range will be discussed, from the point of view of difficulties which can appear and have to be overtaken in terms of proper growth conditions. Such parameters as growth temperature of different parts of the multilayer device structure, shutter sequences for respective atoms compositions in various layers, layer width stabilization and process repeatability might be found employing a feedback loop between growth and advanced optical spectroscopy. Several exemplary results, including completed and those still requiring attention and effort for both growth and spectroscopy, will be presented. There will be discussed type I and type II single and multiple quantum well structures being active regions in semiconductor interband and quantum cascade lasers as well as super-luminescent diodes and heterojunction lasers. The following issues will be elaborated:

- ✓ Interface roughness in AlSb/InAs/InGa(As)Sb type II quantum wells grown by MBE [1,2]
- ✓ Indium atoms segregation in GaInAsSb/AlGa(In)AsSb type I and II quantum wells grown by MBE [3]
- ✓ Atoms interdiffusion processes in InGaAs/AlInAs multi quantum wells for QC lasers, grown by MOCVD/MOVPE technique
- ✓ Strong quantization at the interface in InAsSb/InAsSbP quantum wells grown by MOVPE techniques [4]

All the spectroscopic studies were performed by using photoluminescence and photoreflectance measurements utilizing Fourier transform spectrometer allowing for high sensitivity to detect the optical transitions [5]. Finally, the mentioned feedback loop between spectroscopy and growth allowed to solve most of the problems with interface stabilization and physics understanding therein, which is important for correcting the parameters in the given growth technique as well as advances in the device fabrication and the related device performance.

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Large Area Surface-Emitting Photonic Crystal Quantum Cascade Laser

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Quantum cascade lasers (QCLs) are the sources of choice for many laser-based applications in the mid-infrared region. Because of the unique 2D in-plane coupling mechanism, a photonic crystal (PhC)- QCL has superior advantages on mode selection, surface emission, and beam control. In this work, we present a large-area (1.5 mm × 1.5 mm) PhC-QCL operating under pulsed mode at room temperature (289 K) with the surface-emitting peak power of 1 W.

The active region (2.6 µm thick) of the PhC-QCL is based on strain-balanced $In_{0.58}Ga_{0.42}As/Al_{0.64}In_{0.36}As$ materials with an emission wavelength of 8.7 µm, grown by molecular beam epitaxy. The active region is etched into PhC patterns by using deep-ultraviolet (220 nm) lithography and inductively coupled plasma (ICP) dry-etching (Cl_2 and H_2). A scanning electron microscopy (SEM) image after ICP etching is shown in Fig. 1(a). After ICP, the negative space of the PhC pillars in the active region is filled with semi-insulating InP via hydride vapor phase epitaxy (HVPE) regrowth, building the high index contrast (3.34/3.06) PhC layer (2.6 µm thick). An InP:Si cladding layer (5 µm thick) is grown by metal-organic vapor phase epitaxy (MOVPE). This cladding is then wet-etched into square mesas with the dimension of 1.5 mm × 1.5 mm (> 500 periods in each in-plane dimension).

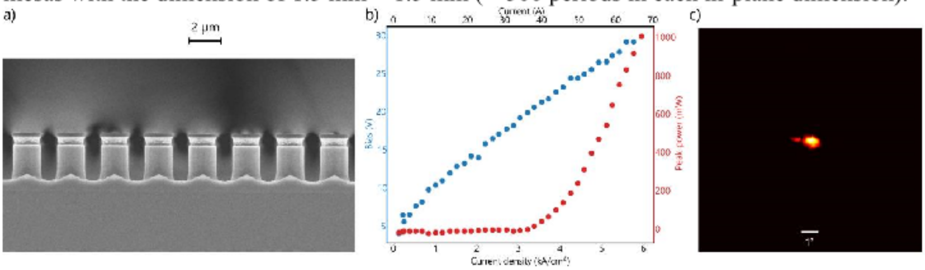

Figure 1 (a): SEM image of the PhC-QCL after ICP dry etching. The part between the SiNx hard mask (dark feature on the top) and the active region pillar is Si-doped InP. (b): L-I-V curve of the PhC-QCL measured in pulsed mode (52 ns at 9.615 kHz) at 289 K. Structural parameters of the PhC-QCL: period = 2.73 µm, filling factor = 0.50, square shaped pillars. (c): Profile of the surface-emitting beam under pulsed mode (52 ns at 9.615 kHz), with a current of 55.6 A at 289 K.

Figure 1(b) shows the LIV curve of the PhC-QCL measured at 289 K under pulsed operation (52 ns at 9.615 kHz). The power is collected through the surface, with a maximum peak power 1003 mW. The lasing threshold is around 3.5 kA/cm^2. The slope efficiency is 39 mW/A. Figure 1(c) shows the surface-emitting beam profile, measured with an infrared camera. The PhC-QCL is driven at 4.9 kA/cm^2 (55.6 A). The far-field is remarkably narrow, due to large-area 2-dimensional mode oscillation.

In summary, we present large-area (1.5 mm × 1.5 mm) high-index contrast PhC-QCL with a lasing wavelength 8.5 µm. The laser works at room temperature (289 K) with 1 W peak surface-emitting power and a narrow far-field beam pattern. These results indicate a promising outlook of surface-emitting PhC-QCL in the mid infrared region.

TuS4C3

Optical Properties and Carrier Dynamics in GaSbBi(In)/GaSb Quantum Wells for Laser Applications in the 1.9-2.5 µm Spectral Range

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We present optical properties and carrier dynamics in type-I GaSbBi(In)/GaSb quantum wells (QWs) devoted to laser applications in the 1.9-2.5 µm spectral range. Two groups of structures are considered here: (i) GaSbBi/GaSb triple QWs were the spectral tunability of emission is obtained via control of the well width (~6.6 nm, ~10.4, and ~14.4 nm) and Bi content (~10-11%), and (ii) GaSbBiIn/GaSb triple QWs with a nominal well width of ~15 nm, In content of 3.8±0.1%, but various Bi content ranging from ~6% to ~8%. High-resolution transmission electron microscope micrographs show good quality of QW interfaces for all investigated structures revealing only small well width fluctuations. Unexpected properties of the QWs are unveiled by performing various spectroscopic experiments, including photoluminescence (PL), modulated-reflectivity (MR), time-resolved photoluminescence (TRPL), and transient reflectivity (TR).

For the GaSbBi/GaSb QWs, low-temperature (T=20 K) power-dependent PL shows a nearly linear increase in QWs emission with excitation power and a barely visible Stokes shift between absorption and emission. Moreover, temperature-dependent PL spectra do not indicate of the so-called S-shape typically observed for highly mismatched alloys. All these suggest that in the case of GaSbBi/GaSb QWs the role of localized states below the fundamental gap play a minor role and band-to-band optical transitions largely determine emission properties of QWs. This hallmark makes the QW system similar to that made of binary compounds. The lack of strong PL lifetime dispersion also supports the aforementioned scenario. The low-temperature carrier dynamics is characterized by 147-265 ps decay time depending on the well width that suggests exciton localization due to well width fluctuations.

For the GaSbBiIn/GaSb QWs, general optical properties are similar to that for GaSbBi/GaSb QWs. The PL intensity becomes only twice higher at the same experimental conditions suggesting a similar quality of all investigated structures. Temperature-dependent PL does not exhibit a strong S-shape, and the Stokes shift between absorption and emission seems to be negligible. The only difference between indium containing structures and the ones without it is related to a strong PL lifetime dispersion in the emission energy. We believe that this observation can be related to chemical fluctuations across the QW interface induced by the presence of indium. Although it does not introduce new structural defects acting as non-radiative recombination centers, however, it can lead to large scale electronic potential fluctuations among which excitons can be actively transferred leading to the observed PL lifetime dispersion.

TuS4C4

MOVPE of InAs/InP Quantum Dots Operating at 1550 nm for Photonics Applications

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The delta function like density of electronic states and the unique carrier dynamics [1] make quantum dots (QDs) a very attractive active material for various directions of fundamental and applied research, as well as technological applications. While the wavelength range 950-1300 nm is covered by InAs/GaAs self-assembled QDs, which demonstrate impressive performance as gain medium for edge emitting lasers [2] and sources of indistinguishable single photon with high efficiency [3], the QDs for the 1550 nm range are still a challenge. The main problems of existing 1550 nm emitting QDs are a large size distribution and their shallow shape, which both result from an insufficient lattice mismatch between the QD material and the surrounding matrix. Recent progress in self-assembled InAs/InP QD development enabled to demonstrate various designs of laser devices based on a self-assembled InAs/InP QD gain medium. Those works include photonic crystal lasers [4, 5], edge emitting lasers [6,7] and single photon emitters [8,9]. However, the properties of QDs still require a significant improvement of size, shape, surface density and uniformity to provide necessary device characteristics for telecommunication and long wavelength sensing. Understanding the epitaxial nucleation process and the following development of an array of self-assembled QDs is the tool to tailor the parameters of resulting QDs on demand.

The present work presents a systematic investigation of self-assembled InAs/InP QD growth dynamics. The mechanism of wetting layer formation and the following transition to QD nucleation with increasing the wetting layer thickness are investigated. The influence of growth parameters including growth temperature, V/III ratio, and a growth rate on the QD surface density, size and shape of QDs are explored. Furthermore, we will demonstrate a photonic crystal laser with a QD based gain medium operating at 1550 nm in the continues wave regime.

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TuS4C5

Optical Properties of InAs/InP Quantum Dots Grown via Selective Area Droplet Epitaxy Assisted by Block-Copolymer Lithography

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In this work, we present an investigation of the optical properties of selectively grown InAs/InP quantum dots (QDs) operating near 1.55 µm. The QDs were selectively grown in an epitaxial process assisted by block-copolymer lithography. An oxycarbide hard mask with an array of 28-30 nm openings was formed on InP (100) substrate by employing self-assembly properties of polystyrene-block-polydimethylsiloxane (PS-b-PDMS) copolymer with following exposure to an O_2 plasma. After the lithography step, the InAs QDs formation in the mask openings is realized via droplet epitaxy.

We used time-integrated (PL) and time-resolved photoluminescence (TRPL) to examine the optical properties of the QDs. The PL shows the Gaussian-like emission band profile with the broadening of ~100 meV at T = 10 K and centered at 1.55 µm. Thus, indicates a good spectral response of the QDs comparable to those typically obtained for Stranski-Krastanow (SK) grown InAs/InP QD systems. Temperature-driven PL spectra reveal that a PL quench mechanism in these dots can be highly imprinted either by the trap states in the barrier or states located at InAs/InP interfaces. The role of trap states imprinting carrier relaxation processes to the dots is reflected in the temperature-controlled TRPL experiment. With increasing the temperature from 10 K up to 300 K, the TRPL rise time increases from ~200 ps to ~550 ps. However, once the carrier is trapped in the QD ground state, a high confinement energy seems to stabilize the emission process, which is indicated by a relatively high PL emission intensity at T = 300 K and barely changed PL lifetime across the temperature range between 10-300 K.

The obtained results demonstrate that the selective area growth approach is prospective for the realization of an active material for applications in photonic devices operating near 1.55 µm. Further process optimization is required to improve the uniformity of the QD array and to minimize the number of lithography related point defects acting as nonradiative recombination centers.

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TuS5Inv

Invited Lecture

VCSELs and Small VCSEL Arrays for Communication and Sensing

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Vertical cavity surface emitting lasers (VCSELs) enable a plethora of commercial applications in communication and sensing. Sensing systems based on VCSELs or small VCSEL arrays with eye safe beams may well be suited for the Internet-of-Things concept where VCSEL light sources could possibly be used for object tracking, dynamic distance measurements, illumination, or perhaps for sending modulated data over free-space at optical output powers of 10s of milliwatts or much less. The same VCSEL technology may be scaled to much higher optical output powers for applications in free-space backhaul and data center optical communication, pulsed laser detection and ranging, and more. We investigate various configurations of single 980 nm VCSELs and VCSEL arrays with varying VCSEL-to-VCSEL spacing, mesa shapes, emitting diameters, and number of emitters. We discuss some wafer processing issues and the key results of our work to date on single VCSELs compared to small area, electrically parallel VCSELs arrays with 3 (triple), 7 (septuple), and 19 (novemdecuple) active laser elements. We focus on a discussion of trade-offs in device optical output power, bandwidth, and efficiency [1].

Acknowledgement: This work is supported by the German Research Foundation (Deutsche Forschungsgemeinschaft (DFG)) via the Collaborative Research Center (Sonderforschungsbereich (SFB)) 787.

[1] N. Haghighi, P. Moser, and J. A. Lott, "Power, bandwidth, and efficiency of single VCSELs and VCSEL arrays," *IEEE Journal of Selected Topics in Quantum Electronics*, Early Access (June 2019). doi: 10.1109/JSTQE.2019.2922843.

TuS5C1

Triple 980 nm VCSEL Arrays

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We design, process and characterize small arrays of electrically parallel oxide confined vertical single-cavity surface emitting lasers (VCSELs) with a peak emission wavelength of about 980 nm. Each triple array consists of three identical top-surface-emitting VCSELs configured geometrically as an equilateral triangle with a conventional ground-source-ground high frequency contact pad layout. We process new VCSELs in the form of triple arrays using the same epitaxial material from our previous work [1,2]. We compare the performance of our triple arrays with and without top mesa VCSEL-to-VCSEL semiconductor ridge structures that, if present physically connect the VCSELs in a given triple array. With an oxide aperture diameter of ϕ ~7.5 µm we achieve a room temperature small-signal modulation bandwidth of f_{3dB} ~25 GHz at a corresponding optical output power of ~30 mW (as determined from static light output power-current-voltage *LIV* measurements) [3]. We furthermore achieve 25 Gbps error-free data transmission (with a bit error ratio (BER) < 1E-12) via a standard non-return-to-zero, back-to-back data transmission test across OM3 multiple mode optical fiber using a pseudorandom binary sequence of bit length 2^7-1.

Acknowledgement: This work is supported by the German Research Foundation (Deutsche Forschungsgemeinschaft (DFG)) via the Collaborative Research Center (Sonderforschungsbereich (SFB)) 787.

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TuS5C2

Temperature Stable 980 nm Vertical-Cavity Surface-Emitting Lasers for Optical Communication

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One of the largest markets for vertical-cavity surface-emitting lasers (VCSELs), the optical communication markets, demands low-cost, reliable, and fast devices for optical fiber communication modules used in for example data centers and supercomputer interconnections. We seek temperature stable and energy-efficient VCSELs capable of operating reliably at temperatures up to 85 °C. We seek simultaneously high bit rate data links with reasonably high quasi-single-mode optical output powers so the fiber links may extend to a kilometer.

We present the static and dynamic characteristics of oxide aperture 980 nm VCSELs emitting with varying oxide aperture diameters that are designed for both temperature insensitive operation and low power dissipation. Our lasers achieve maximal small-signal modulation bandwidth frequencies (f3dB) of up to 32 GHz at 15°C. This important dynamic figure-of-merit for our VCSELs decreases by ~15% for operation at 85°C. We show that our differential resistance and our wall plug efficiency are almost constant while the D-factor and the thermal resistance increase only slightly within 15 to 85 °C.

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TuS5C3

Transparent Grating Contacts for VCSELs

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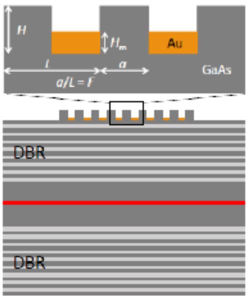
Efficient performance of broad area vertical-cavity surface-emitting lasers (VCSELs) is strongly limited by the current crowding effect. In the case of lasers emitting in the visible range, indium tin oxide (ITO) layers are used to enable more uniform current injection to active region. However, using ITO in VCSELs emitting infrared radiation becomes problematic due to large absorption of ITO in that spectral range. In this talk we propose an alternative approach based on deep-subwavelength GaAs grating integrated with gold stripes (Fig. 1a).

One can observe that for the grating period smaller than λ/n (λ – wavelength, n – refractive index of grating) dielectric grating properties can be interpreted on the basis of the average refractive index and broad spectra of large transmission can be expected for those grating periods. Therefore, presence of metal in the grating should reduce transmission significantly. However, results of numerical simulations show that grating enables "bypassing" the metal stripes by optical field and hence large transmission can be achieved. Figure 1b presents the map of power transmittance as the function of metal stripes thickness and fill factor of the grating. The figure shows that transmittance of the contact can be larger than 90% for metal stripes as thick as 100 nm.

In this talk, we discuss properties of the contacts composed of various materials and confront VCSELs with conventional top contact with VCSEL with grating contact implemented at the facet of top DBR.

a)



b)

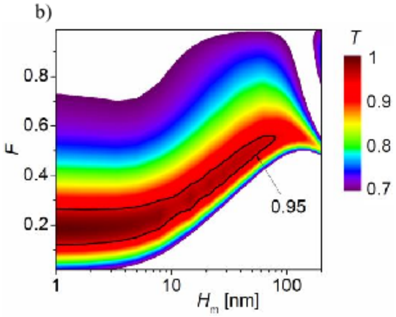


Fig. 1 a) Grating with metal implemented between the stripes. b) Power transmittance (T) of TE light polarization as incident from the dielectric side shown as a map in the domain of metal stripe height (H_m) and grating fill factor (F).

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TuS5C4

Observation of High Quality Factor Fano Resonance in Subwavelength Gratings

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Subwavelength Grating (SG) is a novel structure being an attractive alternative for Distributed Bragg Reflectors (DBRs) in VCSELs. It consists of a periodic array of grating bars called "membrane" made of high refractive index material, that are immersed in a material of a low refractive index e.g. air. To assure stability and resistance to mechanical damage it is preferable to place the membrane on a low refractive index cladding (see Figure 1a). That kind of grating can be not only a perfect reflector, but also a perfect transmitter or a high quality factor resonator. Here we focus on properties of SGs as high quality resonators that can be coherent light emitters if quantum wells are embedded in the grating stripes.

Using a numerical optical model developed at Lodz University of Technology, we observe the evolution of quality factor of the Fano resonance under the influence of the membrane's construction parameters and the refractive index of cladding material. The membrane is assumed to be gallium arsenide (GaAs) and the refractive index of cladding ($n_{cladding}$) is chosen to be greater than 1.5. We show that the Fano resonance of high quality factor is present in SG for strictly chosen parameters of $n_{cladding}$, F, L and h. We observe that the quality factor exponentially decreases with the increase of the refractive index of the substrate (see Figure 1b). We demonstrate that Q-factor greater than 1000 enabling domination of stimulated emission can be achieved for substrate that refractive index is not larger than 2.8 and we also show that Q-factor is sensitive to the fabrication precision of grating.

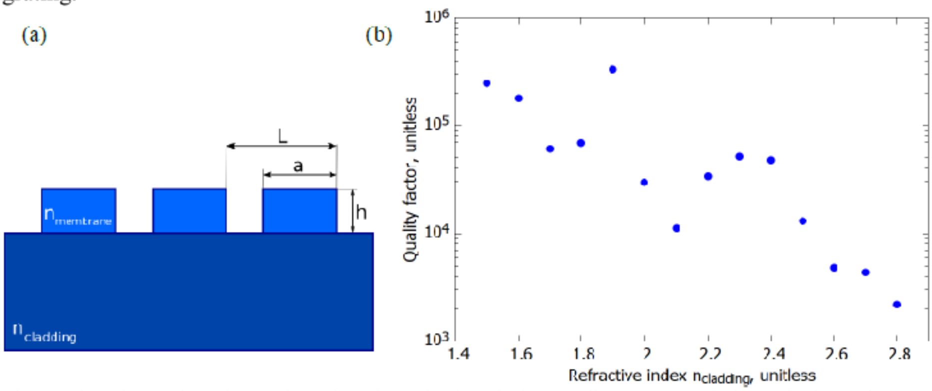

Fig. 1. a) Subwavelength Grating placed on the low index medium surrounded by air from the top. Membrane and cladding are made of the materials of refractive index respectively: $nmembrane$ and $ncladding$. L is membrane's period, a its width and h height. The Fill Factor F is defined as the ratio of the grating's period and width. b) Quality factor versus the refractive index $ncladding$ dependence (Q-factor is given in a logarithmic scale).

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Vertically Emitting Lasers II

TuS5C5

Monolithic High Contrast Gratings as Highly Reflective Mirrors for VCSEL Applications

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High Contrast Gratings (HCGs) are diffraction gratings of subwavelenth period that require stripes of high refractive index and a layer implemented below the grating of significantly lower refractive index. Monolithic HCGs (MHCGs) are HCGs composed of monolithic material of relatively high refractive index. MHCGs can be designed to provide very high power reflectance approaching to 100%. MHCGs are thinner than distributed Bargg reflectors (DBRs), can be made of any common semiconductor material, and are characterized by high polarization discrimination [1,2]. This makes MHCGs perfect mirrors for vertical-cavity surface-emitting laser (VCSEL) applications [3,4]. However, the MHCGs can be also used as passive optical elements, for example as flat focusing mirrors or lenses.

In our experiment we consider GaAs MHCGs for reflecting the wavelength of 980 nm. We designed and processed more than 100 different MHCG mirrors. The theoretical optical power reflectance of MHCGs with rectangular cross-section of stripes is close to 100% at 980 nm. The process of etching may cause the stripe cross-section to become different from that of a perfect series of repeating rectangles. Therefore, the optimum stripe width that is produced in practice may be different from the stripe width determined with perfect rectangular stripes. We have fabricated mirrors that differ in the width of the stripes to find the real-world design that yields the highest power reflectance.

We fabricated MHCG mirrors at the Technical University of Berlin and measured power reflectance at the Institute of Electron Technology in Warsaw. We present power reflectance spectra in comparison with numerical simulations performed at the Institute of Physics of Lodz University of Technology. Based on our experimental and simulation results we discuss the impact of the shape of the MHCG stripes on the power reflectance of the MHCGs.

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TuS6Inv

Invited Lecture

Dual-comb Spectroscopy and Hyperspectral Imaging with Quantum- and Interband-Cascade Frequency Combs

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Semiconductor laser frequency comb sources such as interband cascade- (ICLs) [1] and quantum cascade lasers (QCLs) [2, 3] have recently shown tremendous potential as spectroscopic sources [4-6]. By simultaneously providing relatively broadband spectral coverage and high-spectral resolution in the mid-IR and THz spectral region, they enable detection of large molecules with broadband absorption spectra and small molecules with well-resolved spectral lines. Such semiconductor laser comb sources show unique potential for monolithic or hybrid integration with photonic platforms that can result in compact integrated photonics systems for sensitive spectroscopic detection of chemicals as well as enable lab-on-chip applications.

A dual-comb spectroscopy (DCS) technique has been implemented to perform spectroscopic sensing with ICL/QCL combs. DCS provides nearly-instantaneous access to optical information across the entire spectral bandwidth provided by the comb sources, which drastically reduces the required acquisition time per spectra. In order to enable reliable DCS with ICL/QCL comb sources we utilize high-speed phase and timing correction algorithms to allow for computational coherent averaging (CoCoA algorithm) of data generated by free-running lasers over extended time-scales [7].

In this talk I will demonstrate DCS systems based on semiconductor sources operating in the mid-IR (at ~3.2 µm, ~8.5 µm, and ~10µm) and THz (~3THz) that are used to perform spectroscopy of gases and hyperspectral imaging of solids. Examples of fast DCS with temporal resolution down to 10 µs/spectrum as well as current limitations and future directions towards fully integrated photonics DCS systems will be discussed.

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Applications of Semiconductor Lasers

TuS6C1

Multi-laser *in-situ* Analyzer for Real Time Control of deSOx and deNOx Processes in a Waste Incinerator Plant

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Keywords
gas analyzers, tunable lasers, interband cascade laser, deNOx, de SOX, process control, emission monitoring

Abstract
In this paper we report, for the first time, application of an *in-situ* cross duct type tunable laser analyzer for simultaneous control of both selective catalytic reduction as well as desulphurization processes in a waste incinerator plant. Incorporation of two interband cascade laser (ICL) sources in Mid-IR wavelength range in one device enabled simultaneous monitoring of NO, SO2, HCl and H2O in a gas stream with high dust loading conditions at 170°C. Real time control of injection of lime slurry and urea for deSOx and deNOx processes respectively was possible thanks to *in-situ* capability and the analyzer's response time below 3 seconds. The measurements were compared also with FTIR and NDIR analyzers on site.
The analyzer can also be configured to measure in addition ammonia and carbon monoxide. The analyzer is compatible with the same process interface as single gas tunable devices and thus an existing infrastructure for single gas deNOx laser analyzers can be utilized. The analyzer requires no calibration on-site thanks to built-in reference cell. The system was operational 24/7 in continuous mode with no single maintenance break throughout the entire measurement campaign of several months.

Quantum Cascade Lasers and Hollow Core Fibers – Towards Integration and Size Reduction in the Mid-Infrared Systems

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Since first demonstration in the mid-90s quantum cascade lasers (QCLs) have revolutionized mid-infrared spectroscopy and gas sensing by providing convenient access to strong and relatively narrow ro-vibrational molecular transitions located between 4 and 12 µm. Simultaneously with the development of semiconductor lasers we observe progress in the area of optical fibers for the mid-infrared spectral region. Recently, even fiber-coupled QCLs become commercially available (e.g. from Alpes Lasers or mirSense).

Various optical fibers can be used in the mid-infrared spectral region, including standard fibers made with special glass (e.g. Zirconium Fluoride or Indium Fluoride) or capillary-type fibers with inner reflective coatings. Recently, we have observed a growing interest in anti-resonant hollow core fibers (AR HCFs) which enable good light transmission even in the spectral regions where material itself has high losses. For example, AR HCF made of silica can be used in the mid-infrared. Moreover, since hollow core can be filled with a gas sample, AR HCFs may be used not only to guide light also as a gas cells.

During presentation we will discuss our recent experiments on using AR HCFs for gas sensing. In the first one light from a laser diode operating near 2 µm was coupled into 1.35-m-long AR HCF and spectroscopy of carbon dioxide (CO_2) was presented with minimum detection limit down to single parts per million (ppm) level [1]. In the second experiment different design of AR HCF was used which allows light transmission beyond 4 µm. This fiber was combined with a distributed feedback QCL operating near 4.54 µm and detection of nitrous oxide (N_2O) was performed (see figure below). These experiments prove, that AR HCFs can be efficiently combined with different types of semiconductor lasers, including those operating in the mid-infrared spectral region. Details about the setup, AR HCF and obtained results will be presented during the conference.

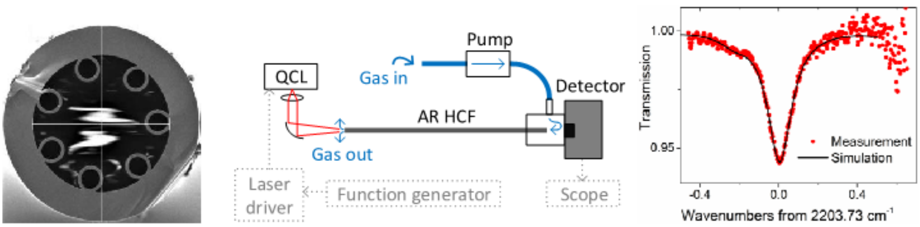

Figure. Left: SEM image of the AR-HCF used for CO_2 detection at 2 µm (hollow core diameter is ~70 µm); Middle: optical layout for mid-infrared spectroscopy of N_2O near 4.54 µm; Right: optical spectrum measured when AR-HCF was filled with N_2O/air mixture (simulation is based on HITRAN database).

[1] M. Nikodem, G. Gomółka, M. Klimczak, D. Pysz, and R. Buczyński, *Opt. Express* **27**, 14998–15006 (2019).

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TuS6C3

Compressed Pulses from a Mid-IR QCL Comb

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Since their first demonstration in 2012[1], mid-IR QCL combs have been produced which are spectrally broad (> 100 cm^{-1}) and powerful (> 1W). Such compact, monolithic sources would be ideal for high-intensity, short pulse-generation in the mid-infrared. However, the sub-ps upper state lifetime, responsible for the efficient, broadband four-wave mixing which drives the self-starting passive mode locking, also precludes direct pulse generation internally. Instead, such lasers output a continuous wave periodic FM waveform[1,2]. Measurements of the spectral phase using a frequency-domain technique called SWIFTS (Shifted Wave Interference Fourier Transform Spectroscopy)[3] confirm this, showing a quadratic character corresponding to a periodic linear sweep over the comb bandwidth[4]. The phases were also found to be stable and reproducible after cycling the power of the device, making them amenable to fixed, external compensation techniques.

In this experiment, we use a device with comb emission at 8.2 um (~100 cm^{-1} bandwidth, and 1 W optical power)[5]. A Martinez-style compressor[6] compensates the field group delay dispersion by 0.53 ps^2 per cm displacement of the grating G2. The complex spectrum of the compensated comb is then characterised using the SWIFTS setup, from which the temporal intensity can be calculated.

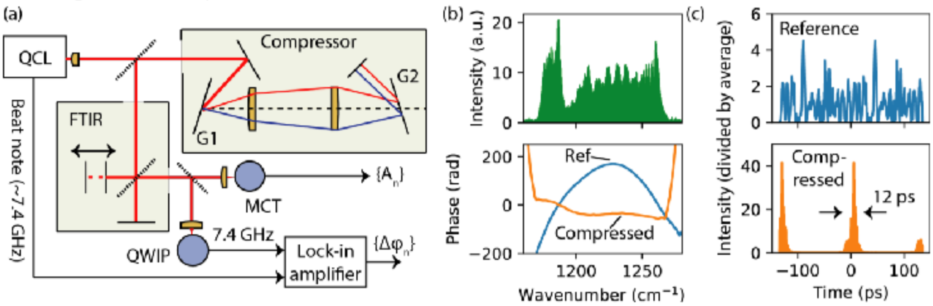

Fig. 1 (a) Experimental setup. QWIP (fast Quantum Well Infrared Photodetector); MCT (Mercury Cadmium Telluride detector). (b) Spectrum (top) and phase (bottom) for uncompressed and compressed field. (c) temporal intensities over two waveform periods

As can be seen from Fig. 1 (c), 134 ps continuous wave waveform has been compressed into discrete 12 ps Gaussian FWHM pulses, increasing the peak to average power tenfold to 40. This pulsed behaviour is confirmed by the beatnote traces (not shown) of the fundamental, through fourth order, which are all simultaneously maximised.

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TuS6C4

Low Noise Photoreceivers for Trace Gas Detection Techniques

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Typical photoreceiver for optical radiation detection consists of a photodetector and front-end electronics. Its performances depend on specific application requirements which are defined by spectral responsivity, signal gain and bandwidth, linearity and dynamic range, photosensitive area, dark current and signal-to-noise ratio (SNR). Two kinds of photodetectors are usually used: thermal and photon one. The first one is characterized by an almost constant value of spectral responsivity, long response time and low detectivity. For example, they are commonly used in optical power meters and in low-cost nondispersive infrared technique. The photon detectors offer higher responsivity values and a wider frequency bands. They can be applied in telecommunication and for construction of high-sensitive optoelectronic sensors, e.g.: in laser absorption spectroscopy. In practice, the signal from the photoreceiver is often digitized and processed according procedures defined by specified application. SNR improvement techniques are frequently implemented in these procedures. They are usually based on signal synchronous averaging or phase-sensitive algorithms. The article presents examples of optical radiation detection systems for various gas detection applications.

Gas sensors are important tools in many areas of technology, industry or everyday life. Detection of low concentration gases is a challenge in many activities such as medical diagnostics, security systems or environmental protection. Therefore, the development of gas sensor characterized by high sensitivity, selectivity and fast response is a key issue. In the case of laser absorption spectroscopy, a better detection limit can be achieved by lengthening the light path in the sample, what is described by Lambert-Beer law:

$$I(\lambda, x) = I_0(\lambda)\exp(-x\sigma(\lambda)C)$$

where $I_0(\lambda)$ is the intensity of input radiation emitted by the source, x is the light path in the absorber, C – concentration of the investigated gas, while $\sigma(\lambda)$ is the absorption cross section. A longer optical path can be obtain by using multi-pass cells, which provide measurements of the absorption coefficient of approx. 10^{-7} cm^{-1}. Additional increase in detection limit (up to 10^{-9} cm^{-1}) can be obtained using a wavelength modulation (WMS) and the phase-sensitive detection procedures. Another solution consists in using the optical cavities, which enables measurements of the absorption coefficient up to 10^{-14} cm^{-1} [1]. Such techniques require photoreceivers, the operating spectrum of which is matched to the selected absorption line of the gas, but also characterized by high speed, wide dynamic range, high detectivity and low noise. Therefore, in the visible (VIS) and near infrared (NIR) range photomultiplier tubes (PMT) are the most popular, and InSb photodiodes, PbSe photoresistors, MCT photoresistors and photodiodes are the most popular for detecting MIR radiation [2].

[1] G. Berden, R. Engeln, *Cavity Ring-Down Spectroscopy: Techniques and Applications*, Wiley-Blackwell, 1nd edition (2009).

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Acknowledgements

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TuS6C5

RF-Enhanced Waveguide QCL Frequency Combs

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Quantum cascade lasers (QLCs) are semiconductor devices, which are the dominant light source in the mid IR part of the electromagnetic spectrum [1], and have recently been demonstrated to operate as frequency combs [2]. Characteristics of the comb operation are a broad, phase locked optical spectrum of equidistant modes, and a strong narrow radio frequency (RF) beatnote, that is generated from the beating of those modes. One unique property of the QCL is the short upper-state lifetime, which allows the coupling between the injected current and the beatnote at the roundtrip frequency.

Since a RF injection at the round trip frequency allows to control the comb formation, this mechanism can be exploited by designing QCL comb devices that have a low loss radio frequency cavity. A broad gain, double stack QCL structure is grown on a highly doped (10^{19} cm^{-3}) InP:Si substrate. Between the QCL structure and the substrate an additional low doped (10^{16} cm^{-3}), 2.8 µm thick InP:Si layer is grown, in order to minimize the optical loses introduced by the highly doped substrate. The fabricated device is processed in a buried heterostructure configuration. The unique feature of these devices is the narrowing of the laser ridge by etching the sides, and restricting the area of the top contact. That way, the parasitic capacitance of the device can be reduced, aiming to improve the RF-frequency response, the cut-off frequency and to enhance the coupling between the comb formation and the transport. In addition, the highly doped substrate, in conjunction with the highly doped top n-contact, can be used as a double plasmon waveguide to improve and have a larger range of dispersion compensation [3,4].

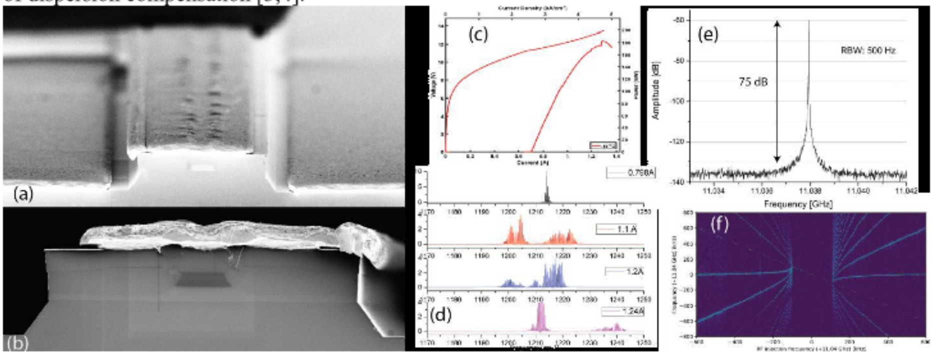

Fig. 1 (a) & (b) SEM micrographs of the whole device and front facet respectively. (c) LIV operation characteristics of the device at -10 °C. (d) Device spectrum at various currents. (e) Extracted RF beatnote, at -10 °C, and 1157mA, (f) RF injection locking of the device.

Results of a 4 mm long fabricated device show good performance with high power CW output of a few hundred mWs, and emission spectra spanning 30 cm^{-1}. The measured RF-beatnote, centred at 11.038 GHz is narrow and strong, at 75 dB above the noise floor. The device was also driven using an RF-injector and it was locked for a range spanning more than 300 k Hz when injected with power of 30 dBm Extensive studies of the comb behaviour and properties of the device under different injection regimes are currently carried out.

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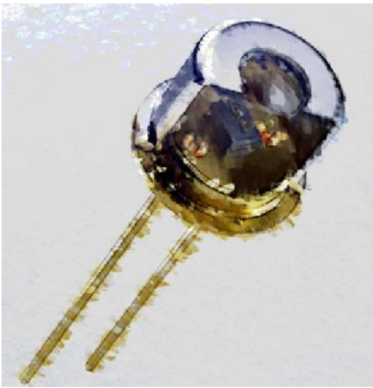
[4] Y. Bidaux, F. Kapsaldis, P. Jouy, M. Beck and J. Faist, *Laser & Photonics Reviews* **12**, 1700323 (2018).

16 October (Wednesday)

Sessions

Vertically Emitting Lasers III

Quantum Cascade Lasers



Invited Lecture

Polarized Blue InGaN VCSELs and Monolithic VECSELs

J. Kearns, S.G. Lee, J. Bak, N. Palmquist, D. Cohen, J. Speck, S. DenBaars, S. Nakamura

Materials Department and the Solid State Lighting and Energy Electronics Center University of California, Santa Barbara, CA 93106, USA

We will present recent progress on Group III-N VCSELs utilizing current apertures formed by ion implantation or buried tunnel junctions, grown entirely by MOCVD on nonbasal substrates. These lasers are inherently polarized and operate CW near the 1 mW level, but still suffer from poor control of the optical mode and excessive optical loss. Thermal mapping of the aperture during operation suggests that the electrical injection is not uniform, and possible reasons for this will be discussed. Planar laser resonators of various cavity lengths and nonplanar extended cavity resonators will be compared, including a survey of the state of the art.

As GaN based VCSEL technology approaches commercial viability, it becomes important to critically examine the performance needs for specific applications. We will discuss power, efficiency, spectral and cost needs for applications in microdisplays, sensing, and communication, and emphasize that no single design of the many resonators currently under study will likely serve for all applications.

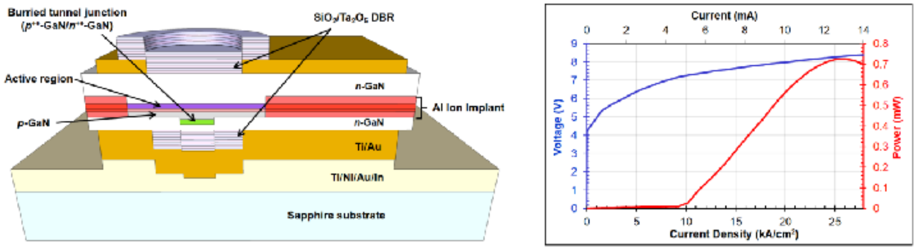
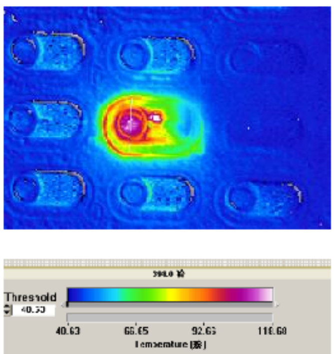


Fig. 1. Schematic and CW LIV characteristics of an 8 μm aperture buried tunnel junction VCSEL

Fig. 2. Thermal map of a tunnel junction VCSEL below threshold, showing nonuniform heating likely due to nonuniform TJ resistance across the aperture.



WeS7C1

Computer Modeling of Nitride VCSELs

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This work presents computer simulations of nitride vertical-cavity surface-emitting lasers (VCSELs) emitting wavelengths from the violet-green spectral range. The analysis concern the capacitance phenomena occurring in this lasers, which are important from the point of view of the potential applications of nitride VCSELs. These applications include, among others, Visible Light Communication (VLC) systems in the range 390–750 nm. In all optical data transmission systems the rate of the modulation of the emitted beam is an important parameter. This parameter can be limited by the presence of capacities and resistances in the structure.

In this work we analyze the influence of the construction parameters of the structure on the capacitance phenomena occurring in the laser. The analysis include e.g. the dimensions of the structure, the thickness of some layers, the size of the electrical aperture and the length of the resonator. The calculations were performed using a self-consistent computer model [1] and a capacitance model [2] created by Photonics Group from Lodz University of Technology.

Acknowledgement: This work is partially supported by the Polish National Science Centre, grants no. 2018/29/N/ST7/02151 and no. 2016/21/B/ST7/03532.

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[2] M. Wasiak et al.,, *J. Phys. D Appl. Phys.*, **49**(17), 2016.

Nanoporous DBRs – Towards Monolithic Nitride VCSELs

N. Fiuczek [1,2], A. Feduniewicz-Żmuda [1], P.Wolny [1], K. Nowakowski-Szkudlarek [1], M. Siekacz [1], G. Muzioł [1], C. Skierbiszewski [1] and M. Sawicka [1]

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[2] *Faculty of Applied Physics and Mathematics, GUT, Narutowicza 11/12, Gdańsk, Poland*

Fabrication of nitride vertical cavity surface-emitting lasers (VCSELs) in a fully monolithic way by molecular beam epitaxy (MBE) poses a great challenge because of the difficulties in growth of highly reflective distributed Bragg reflectors (DBRs) that are lattice-matched to GaN. Several approaches have been reported in the microcavity design e.g. InAlN/GaN, AlGaN/GaN or dielectric DBRs like SiO_2/Ta_2O_5 but these structures suffer from lattice strains or lack of electrical conductivity. [1]

We present a novel way of fabrication of highly reflective DBRs that involves electrochemical etching (ECE). At first, a stack of alternating layers of undoped and Si-doped GaN is grown by plasma-assisted MBE (PAMBE). The doped layers are then selectively etched in acidic environment under positive bias. Thanks to that process the doped layers become nanoporous and therefore have a much lower refractive index than the bulk GaN what results in very high reflectivity of the whole stack. Such DBRs are integrated below and above the active region. [2]

In this work a stack of 10 periods GaN/GaN:Si (n_d=5.6·10^{19}cm^{-3}) was grown and etched under different bias voltages in 0.3M oxalic acid. We explain the mechanism of ECE of the n-type GaN and the step-by-step DBR fabrication procedure. The reflectivity spectra and SEM cross-section images of the fabricated samples are presented. The obtained reflectivity was very high ~95% what makes porous DBRs a promising candidate for a building block of fully monolithic nitride VCSELs.

Combination of MBE and ECE allows to obtain a porous material with controllable refractive index. Tailorability and conceptual simplicity of the presented DBRs opens new possibilities for using them in other optoelectronic devices or for fundamental physics research.

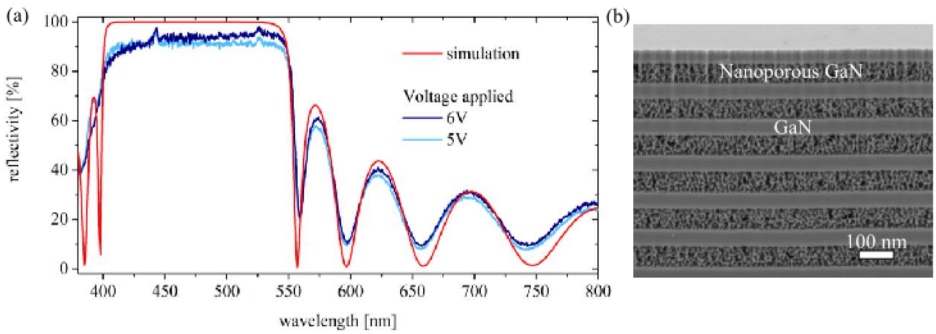

Fig. 1 (a) Reflectivity spectra of the nanoporous DBRs grown by PAMBE and etched under different bias with the corresponding simulation curve (b) SEM image of a porous DBR

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WeS7C3

Spectrally Resolved Modes in Real-World VCSELs with Irregular Shapes of Broad Oxide-Confined Apertures

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[2]*Institute of Solid State Physics and Center of Nanophotonics, Technische Universität Berlin, Hardenbergstraße 36, D-10623 Berlin, Federal Republic of Germany*
[3]*Łukasiewicz Research Network - Institute of Electron Technology, Al. Lotników 32/46, 02-668 Warsaw, Poland*

Broad area vertical cavity surface emitting lasers (VCSELs) have attracted attention as mesoscopic systems that are an analog of quantum systems. Similarities between the Helmholtz and Schrödinger equations enable us to use lateral modes of oxide-confined (OC) VCSELs to observe analogous behaviours to quantum chaos as well as other phenomena that are intriguing for fundamental physics research including optical pattern formation and diffraction-in-time phenomena. We report on the experimental realization of 980 nm gallium-arsenide-based irregular broad aperture OC VCSELs. The epitaxial structure is based on a state-of-art communication VCSEL design with a 37 period bottom distributed Bragg reflector (DBR), a half-lambda (λ/2) optical cavity with two 20 nm-thick Al-rich layers placed in node positions of the standing wave on each side of the λ/2 optical cavity, and a 15.5 period top DBR. Using ultraviolet contact lithography patterning together with inductively coupled plasma reactive ion etching we formed lateral shapes of VCSEL mesas such as: disturbed single circles, and double and triple touching circles of different diameters. Selective thermal wet oxidation is used to form optical and electrical apertures in the Al-rich layers of shapes that correspond to the irregular VCSEL mesas. The lateral size of the optical windows formed by selective oxidation ranges from 20 to 80 μm. We show spectral characteristics of stimulated emission and spectrally resolved lateral mode distributions of the selected VCSEL geometric designs (Fig. 1). We supplement the experimental analysis with fully-vectorial three-dimensional optical simulations confirming the formation of exotic high order modes of irregular polarization.

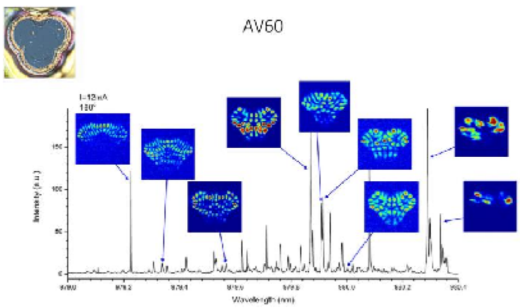

Fig. 1. Emission spectrum of a triple-circle aperture VCSEL with spectrally resolved near fields distributions of selected lateral modes. Inset in the left top corner illustrates the top facet of the VCSEL with gold electrodes.

Parameter Optimization of Quantum-Cascade VCSELs

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Quantum-Cascade Vertical-Cavity Surface-Emitting Lasers (QC VCSEL) [1] are anticipated to exhibit advantages of both: the unipolar Quantum-Cascade Lasers (QCLs) with emission in broad range of infrared radiation up to 100 μm and Vertical-Cavity Surface-Emitting Lasers (VCSELs). The most common applications for QCLs are spectroscopy and free space optical communication. For each of these applications important operation properties include their low threshold current, high modulation speed, narrow emission spectrum, high coherence and low beam divergence. These properties are inherent properties of VCSELs. However if a quantum cascade active region is embedded in a conventional VCSEL structure, stimulated emission is impossible because of the absence of electrical field component which is perpendicular to the cascades.

In the design of QC VCSEL that we propose, stimulated emission and vertical resonance is possible due to embedding QCs into the stripes of a monolithic high (refractive index) contrast grating (MHCG) [2]. The performance and properties of QC VCSELs are sensitive to geometrical parameters of MHCGs. Efficient interaction between radiation modes and electron in active regions is strictly related to design of the laser cavity, MHCG and position of an active region. QC VCSELs are unipolar devices, hence separation of active region on several dispersed active layers is possible. Here we present numerical optimization of active region distributions enabling their optimal interaction with QC VCSEL modes contributing to low threshold currents or high emitted powers.

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Acknowledgements

This work was supported by the Polish national Science Center (NCN) through the project 2017/25/B/ST/02380.

WeS8Inv

Invited Lecture

Towards Room Temperature Operation of Terahertz Quantum Cascade Lasers: Carrier Leakage Engineering as a Novel Design Concept

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Contact email: asafalbo@gmail.com

The terahertz spectral region is subject to intensive research in view of its potential in a number of application domains such as medical diagnostics, trace molecule sensing, astronomical detection, non-invasive quality control and more. However, maximum operating temperature achieved with terahertz quantum cascade lasers (~200 K) imposes cryogenic techniques.

In general, the ideal operation mode of a terahertz quantum cascade laser assumes that an electron injected externally into the device will generate multiple photons – one in each "energy cascade"– while transporting through the heterostructure. However, alternative scattering leakage paths deviate electron transport from the ideal picture and present a considerable effect on devices' performance. In that context, temperature-driven leakage of charge carriers out of the laser's active region states is considered as an unwanted effect that limit its temperature performance. However, as we showed in our latest works, contrary to common sense expectations, carrier leakage under some conditions can be beneficial for the device and enhance lasing.

Our results highlight the importance of the carrier leakage out of the lower laser level to the laser's performance. This understanding clearly points out to a potential improvement direction in the design of highly temperature-insensitive terahertz quantum cascade lasers, namely to minimize thermally activated leakage from the upper laser level and maximize thermally activated leakage from the lower laser level. In other word, to address a carrier leakage engineering procedure as a new design concept for high performance terahertz quantum cascade lasers.

Monolithic, Optically-Coupled, Multi-Section Mid-IR QCL

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Quantum Cascade Lasers (QCLs) are compact laser sources of infrared radiation in mid-IR range (3 – 20 µm) and in THz range (1-3 THz). They have many applications in absorption spectroscopy: air quality monitoring, breath analysis for medical diagnostics, detection of explosives and dangerous substances or industrial process monitoring. One of the basic requirements of spectroscopic applications is single mode emission. Typical QCLs based on the Fabry-Perot (FP) resonator emit multi-mode spectrum, especially at higher operating currents. In this work we concentrate on alternative approach of obtaining single mode emission: monolithic, optically-coupled, multi-section mid-IR QCLs. The coupled-cavity device concept relies on optical coupling of two or more sections what results in strong modification of emission spectrum, giving the possibility of single longitudinal mode operation.

The work focuses on the design, fabrication and characterization of monolithic, multi-section, coupled cavity QCLs. The devices were fabricated by reactive ion etching from InP-based heterostructure designed for emission in 8-9 micrometer range. Figure 1 presents optical images of the two-section CC-QCL, as well as close-up of the optical gap introduced in the resonator.

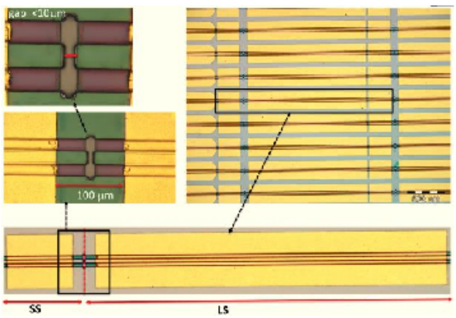

Fig.1 Optical images of the two-section CC-QCL, as well as close-up of the optical gap introduced in the resonator.

We will present a comparison of the performance of different designs, including 3-section devices, and discuss their characteristics, fabrication challenges and stability against operating conditions. Devices routinely exhibited side mode suppression ratio of more than 20 dB. Approach to fabricate two-section devices by dry etching resulted in improved yield as well as high repeatability of the performance of individual devices. We will also discuss possibility of application of such devices in the spectroscopy.

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WeS8C2

Challenges of MOVPE Growth of the Quantum Cascade Lasers

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Quantum cascade lasers are one of the most sophisticated semiconductor light sources. Their principle of working is based on inter-subband transitions, in contrast to classical semiconductor lasers based on inter-band transitions [1]. Core of the QCL consists of hundreds or even more than thousand, subnanometer thin layers. Wherefore, the highest precision of layers deposition has to be preserved. Moreover, core of the laser is sandwiched between two thick cladding layers which have to ensure proper fundamental mode confinement inside the structure.

From the point of view of the interfaces quality, first deposition technique to choose is MBE. But some limitations, like low growth rate or safety issues connected with phosphorus usage, discredit MBE for some applications. Those problems are eliminated concerning MOVPE technique but on the other hand, sharp and narrow interfaces are much more challenging.

Present work analyses challenges of MOVPE growth of the quantum cascade laser structures. Beside more obvious issues, like different approaches of source materials switching to obtain sharp and narrow interfaces, also less expected problems will be discussed, e.g. defects of cladding's binary compound. Moreover, MOVPE growth temperatures are much higher than MBE ones. Thus, influence of the thermal annealing of the laser's core during top cladding deposition on its optical and structural properties will be also discussed. Various types of defects will be analysed on the basis of high resolution TEM images, as shown on Fig. 1.

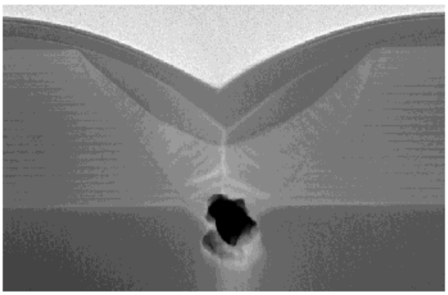

Fig. 1. TEM image of huge defect deteriorating growth of the further layers.

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WeS8C3

Optimization of MBE Growth Conditions of InP-based Quantum Cascade Lasers

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Quantum cascade lasers (QCLs) emitting in the mid-infrared are in high demand for many applications, such as absorption spectroscopy in the molecular fingerprint region, free space communication and infrared countermeasures. Mostly, they are designed using a InGaAs/ InAlAs material system epitaxially grown on InP single crystal substrates, as this group offers wide possibilities of band-gap and wavefunction engineering with high values of band offsets. They consist of the superlattice active region (AR), which is typically built of hundreds of thin layers with thicknesses in the range of few nanometers, and the waveguide layers consisting of a few micrometers of bulk material, both grown in one epitaxial run. A technological feature often observed is that the overall precision of layer thicknesses and their crystalline quality is very hard to achieve at common growth conditions of these two main blocks of different character. In such cases, the main attention is put on strictly required AR superlattice periodicity and thickness control. Epitaxial growth task in MBE is even more complex in the case of strain-compensated QCLs because such QCLs demand a precise control of the composition of four ternary alloys, i.e., InGaAs and InAlAs in AR and waveguide. The optimum MBE growth conditions differ for thin (up to tens or low hundreds of nanometers) and micrometers-thick layers of ternary alloy.

In this paper we report on optimization process of the growth conditions of QCLs, grown by MBE technology on Riber Compact 21T at Łukasiewicz – ITE [1,2]. We present optimization of growth conditions of $In_{0.52}Al_{0.48}As$ waveguide layer leading to the growth of defect free material, with good optical quality. A relatively narrow range of epitaxial conditions for the optimized growth of 2.5 μm thick layers of $In_{0.52}Al_{0.48}As$ alloy used as the main part of the QCL upper waveguide has been determined [3].

Despite very complex manufacturing process: epitaxial growth, processing technology and device characterization a good quality device were obtained. This allows for using this infrared emitter for trace gas sensing application, free space communication and many others.

Acknowledgements: This work was partially financially supported by the National Centre for Research and Development (NCBR) grant no. TECHMATSTRATEG1/347510/15/NCBR/2018 (SENSE).

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WeS8C4

Exceptional Point in Distributed Feedback Quantum Cascade Lasers

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Exceptional points are defined as the points at which the eigenstates of a system described by a non-Hermitian Hamiltonian coalesce [1]. Lasers are prototype non-Hermitian photonic systems, with the additional complexity of being described by a nonlinear wave equation above their first oscillation threshold. Exceptional points are anticipated to appear in lasers when the laser is pumped non-uniformly in space [2–5]. Microlasers built from active QCLs have been suggested as a suitable system to observe exceptional points [6], since they feature sufficient coupling strength in lossy waveguides, while the absorption length in the passive cavity can be designed/tuned to be smaller than the round-trip length.

Here we present the results on a dual-section distributed feedback (DFB) QCL [6], where the lasing properties such as frequency and amplitude of the laser are strongly affected by the state of the system in the parameter space with respect to the exceptional point at current densities above the first threshold. The coupling between the active DFB mode and the passive Fabry-Perot (FP) modes of the dual section DFB QCL leads to a non-Hermitian system with n-dimensional Hilbert space, where the existence of the exceptional points control or even switch off the coherent emission of the laser (see figure 1). The experimental realization of this effect would open up many more possibilities to study the rich physics associated with exceptional points in the pump dependence of a laser.

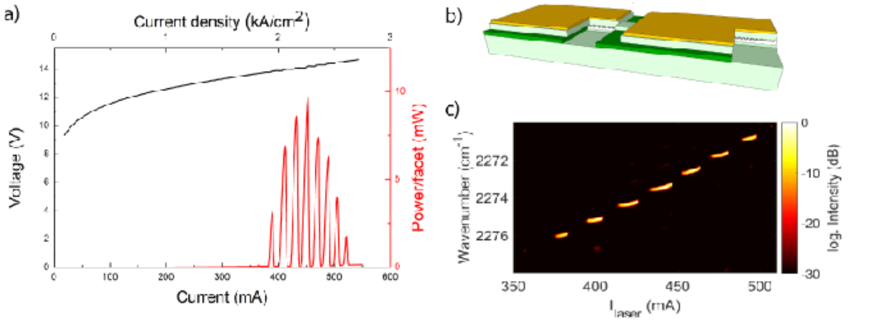

Fig. 1. (a) Light-current-voltage characteristics of a dual-section DFB QCL, where the laser output switches off and on at current densities above threshold. (b) Schematic of dual-section DFB QCL. (c) The spectral map the device as function of the driving current.

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Influence of Design Variations on QCL Performance

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Quantum Cascade Lasers (QCLs) are very desirable sources for many applications, having an advantage over other solutions regarding the range of available wavelengths, wide tunability, single mode emission, high optical power at room temperature. Recently, cascade lasers have achieved operating parameters meeting the requirements imposed by military, optical spectroscopy and telecommunications applications. At the same time, QCLs like other semiconductor lasers are characterized by a strong dependence of working parameters from temperature. This process is very pronounced in QCLs, because even for the highest performance devices, 70-80% of electrical power injected into the device turns into heat. Figure 1 presents an example of the QCL heat balance of InP based QCL emitting at 9.2 μm.

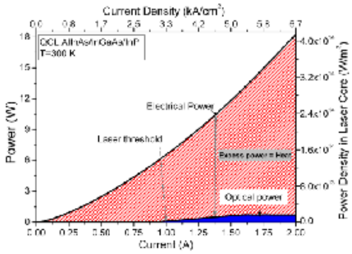

Fig. 1 Heat balance of AlInAs/InGaAs/InP based QCL.

Some methods are used to reduce the laser overheating are optimization of the laser active region and waveguide design, processing technology, mounting and laser packaging. In this paper we present experimental results of improving QCL laser performance by optimization of the laser waveguide design (InGaAs layers thickness) and processing technology (electroplated Au-metallization thickness). The influence of optimized parameters on temperature increases in active region is analyzed based on heat distribution at the laser facet determined from temperature mapping. For this purpose, we employ experimental techniques CCD thermoreflectance which allows to obtain high resolution temperature distribution maps on the laser facet. Figure 2 presents exemplary temperature distribution maps on the front facet of investigated QCL with various Au metallization thickness.

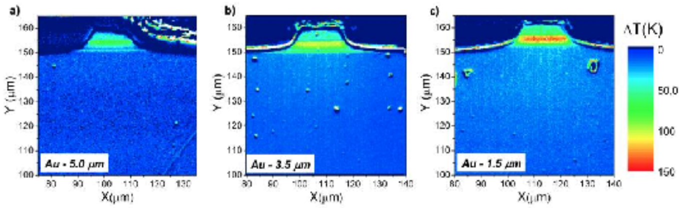

Fig. 2 Temperature distribution maps for RW QCL with different thickness of gold metallization layer measured for pulse width 10 μs, frequency 20 kHz and driving current 1.25A.

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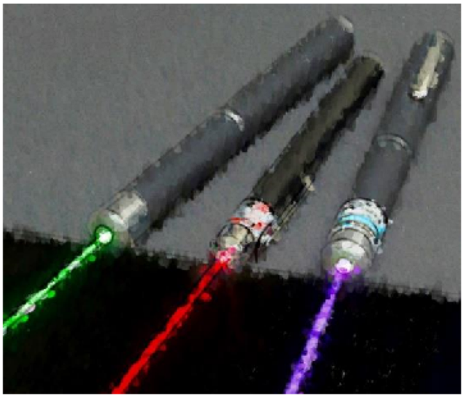

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