7th Workshop on Physics and Technology of Semiconductor Lasers

Kraków 15-18 Oct 2017

Book of Abstracts

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Workshop programme

Sunday, October 15

19.30-20.00	Registration
20.00	Glass of wine, Qubus hotel

Monday, October 16

Hour	Speaker	Title	No
8.30-9.00		Registration	
9.00-9.10		Opening	
9.10-9.40	**Johann Peter Reithmaier**	1.5 µm InP-based quantum dot lasers for high bit rate telecom applications	1
9.40-10.10	**Il-Sug Chung**	Micro-cavity lasers based on high-contrast gratings	2
10.10-10.30		Break	
10.30-11.00	**Thomas Wunderer**	E-beam pumped edge-type emitting UV lasers	3
11.00-11.20	Jens W. Tomm	Catastrophic Optical Damage of GaN-based diode lasers: Sequence of Events, Damage Pattern, and Comparison with GaAs-based Devices	4
11.20-11.40		Break	
11.40-12.00	Szymon Stańczyk	(Al,In)GaN optical amplifiers	5
12.00-12.20	Witold Trzeciakowski	Laser sources for dermatological applications	6
12.20-14.00		Lunch	
14.00-14.20	Ryszard Piramidowicz	Generic technologies of integrated photonics	7
14.20-14.40	Anna Jusza	InP-based integrated transceivers for fiber-optic access systems	8
14.40-15.00		Break	

15.00-15.20	Andrzej Kaźmierczak	Integrated read-out unit for fiber-optic sensor network	9
15.20-15.40	Stanisław Stopiński	Optical gyroscopes in generic technology on InP platform	10
15.40-16.00	Break		
16.00-16.20	Marcin Motyka	Carrier dynamics in type I InGaSb/GaSb and type II InAs/GaIn(As)Sb/ AlSb quantum wells	11
16.20-16.40	Grzegorz Sęk	Novel solutions in the active region of interband cascade lasers	12
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Tuesday, October 17

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10.00-10.20	Jan Muszalski	Double diamond enclosure of Vertical External Cavity Surface Emitting Laser - a new way to new spectral ranges	14
10.20-10.40	Artur Broda	Semiconductor Disk Lasers with Two-Resonance Microcavity – improvement of wavelength tuning range	15
10.40-11.00	Break		
11.00-11.30	**James A. Lott**	Simplicity VCSELs	16
11.30-11.50	Nasibeh Haghighi	Bandwidth versus oxide aperture diameter for 980 nm Simplicity VCSELs	17
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12.10-12.30	Szymon Grzanka	Quantum confined Stark effect and reliability of the nitride near ultraviolet lasers	18
12.30-12.50	Anna Kafar	Quantum Confined Stark Effect screening under high carrier injection in nitride laser diodes and superluminescent diodes	19
12.50-14.30	Lunch		
14.30-14.50	Magdalena Marciniak	VCSELs incorporating High Contract Gratings as one-device sensor	20
14.50-15.10	Marta Więckowska	Antiresonant reflecting optical waveguide VCSEL with oxide island	21
15.10-15.30	Break		
15.30-16.00	**Daniel Cohen**	Tunnel Junctions for III-Nitride VCSELs and High Efficiency Edge Emitting Lasers	22
16.00-16.20	Czesław Skierbiszewski	Nitride laser diodes with tunnel junctions by plasma assisted MBE	23
16.20-16.40	Tomasz Czyszanowski	Monolithic nitride-based VCSEL with semiconductor-metal subwavelength grating	24
19.00-2.00	Diner		

Wednesday, October 18			
Hour	Speaker	Title	No
10.00-10.30	**Ji-Hye Kang**	DFB laser diodes based on GaN using 10th order laterally coupled surface gratings	25
10.30-10.50	Grzegorz Muzioł	Nitride-based laser diodes with extremely long lifetime grown by plasma assisted molecular beam epitaxy	26
10.50-11.10	Agata Bojarska	Optimization of Electron Blocking Layer design for nitride laser diodes	27
11.10-11.30	Break		
11.30-11.50	Kamil Pierściński	Limitations of high duty-cycle operation of InP-based QCLs	28
11.50-12.10	Piotr Gutowski	Growth of InAlAs/InGaAs/InP Quantum Cascade Lasers by MBE and MBE+MOVPE Hybrid Approach	29
12.10-12.30	Grzegorz Sobczak	Influence of the thermal annealing of the strain-compensated AlInAs/GaInAs/InP heterostructure on the properties of quantum cascade lasers	30
12.30-12.50	Break		
12.50-13.20	**Erik Haglund**	Wavelength Control of VCSELs using High-Contrast Gratings	31
13.20-13.40	Marcin Gębski	Monolithic Subwavelength Grating	32
13.40-14.00	Maciej Dems	What about Monolithic High-Contrast Gratings	33
14.00	Lunch		

1. InP-Based Quantum Dot Lasers for Telecom Applications

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An overview is given about recent results on static and dynamic properties of InP based quantum dot lasers. High temperature stability in directly modulated lasers (T_0> 100 K, T_1> 500 K, up to 35 GBit/s) and narrow linewidth (< 150 kHz) with wide wavelength tuning range (C+ band) in an integrated QD DFB laser chip are obtained.

Very recently, improved InP-based quantum dot (QD) laser materials were developed with low inhomogeneous broadening [1], high modal and differential gain [2]. As theoretically predicted [3], this new generation of QD lasers exhibit improved temperature stability in static as well as in dynamic properties. Due to a low linewidth enhancement factor (α-factor) and reduced spontaneous emission, QD laser material is also very suitable for the realization of narrow linewidth lasers, e.g., as widely tunable reference laser in coherent communication systems. In this paper, an overview is given about recent results on the static and dynamic performance of short-cavity high-speed lasers as well as of the emission linewidth properties of QD distributed feedback (DFB) lasers.

Improved temperature stability with characteristic temperatures of T_0> 140 K, T_1> 800 K and max. operation temperatures of 195°C (pulsed mode) and 120°C (cw mode) were obtained for ridge waveguide lasers with 8 QD layers. With short cavity lasers (< 350 μm) record values in small signal modulation of more than 17 GHz bandwidth was achieved, which allow digital modulation speeds of 35 GBit/s at room temperature and 26 GBit/s digital modulation at 80°C, respectively.

Due to the potential lowα-factor, a narrowing of the laser linewidth can be expected. With QD laser material a monolithically integrated light source was developed based on an array of DFB lasers, which allow a wide thermal tuning range of more than 10 nm per laser and is covering more than the C+ telecom band. The linewidth obtained in below 150 kHz with a best value of 110 kHz.

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2. Micro-cavity Lasers Based on High-Contrast Gratings

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High contrast gratings (HCGs) are a one- or two-dimensional photonic crystal slab surrounded by low refractive index materials. Their subwavelength period and large refractive-index difference result in strong interactions of the multiple resonances (typically two leaky modes) inside an HCG layer with a single free-space mode outside the HCG layer. The interplay between these multiple modes leads to very rich phenomena such as a broadband reflector or a high quality (Q) factor resonator. Many interesting micro-cavity laser structures employing HCGs or variants of HCGs have been reported by different groups. In this talk, four micro-cavity laser structures recently investigated by our group will be presented with discussions on their interesting properties.

The first laser structure shown in Fig. 1a is a vertical-cavity laser with light emission into an in-plane silicon waveguide [1, 2]. The employed HCG works as a broadband reflector as well as routing light into the silicon waveguide. The second version of this laser demonstrates a record-high speed among silicon-on-chip lasers [3]. Device physics related to laser designs will be discussed, including polarization dependence [4], in-plane hetero-structures [5], and broadband MEMS tuning [6, 7].

In the second laser structure shown in Fig. 1b, the HCG works as a resonator. The resonance occurs at a frequency above the light line and has an infinite Q factor if the HCG has infinite extension in the in-plane direction. This is known as bound-states in the continuum (BIC), since the resonance occurs in the continuum of free-space mode frequencies. Our recent work on quasi-BIC, which allows for high-Q micro-cavities with two or three unit cells will be discussed [8]. A recent demonstration of a silicon-on-chip BIC laser will also be presented.

The third laser structure shown in Fig. 1c employs a variant of HCG named *hybrid grating* (HG), which works as a broadband reflector. The hybrid grating consists of a grating layer and an un-patterned cap layer, which can provide an even broader stop band than HCGs [9]. Its broadband reflection mechanism will be discussed with experimental results [10]. It will be discussed how lasing threshold condition can be reached when a gain material is included in the cap layer, as well as an example application to resonant-cavity photodetectors [11].

The fourth laser structure shown in Fig. 1d employs the hybrid grating as a high-Q resonator [12]. Its resonance mechanism and numerical investigation results will be presented.

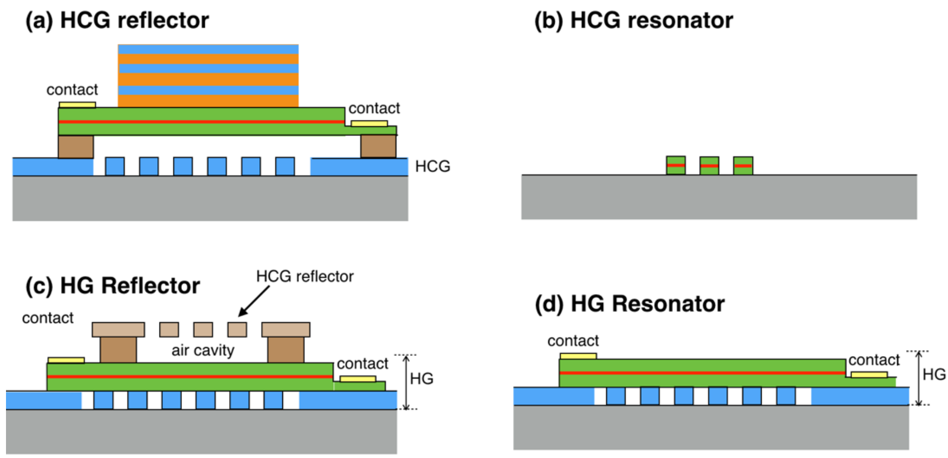

Fig. 1 Laser structures based on (a) HCG reflector, (b) HCG resonator, (c) HG reflector, and (d) HG resonator.

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3. E-beam pumped edge-type emitting UV lasers

Thomas Wunderer

PARC, A Xerox Company

Electron-beam pumping offers compelling benefits as an excitation source for wide-band-gap AlGaN-based optical emitters. Eliminating p-type doping in the heterostructure design of the devices is one particularly enabling feature. Both high-power spontaneous-emission light sources in the UV-C and low-threshold lasers in the UV-A spectral regimes have been demonstrated. A record measured peak optical output power of 230 mW of spontaneous emission at 246 nm under pulsed e-beam excitation was realized. E-beam-pumped edge-type emitters lasing at λ=380 nm, with threshold currents for the focused beam of only I = 170 μA, will be described.

4. Catastrophic Optical Damage of GaN-based diode lasers: Sequence of Events, Damage Pattern, and Comparison with GaAs-based Devices

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Damage patterns caused by the Catastrophic Optical Damage (COD) are analyzed in GaN-based high-power diode lasers. In contrast to standard failure analysis, the devices were intentionally degraded under well-defined conditions. We find that defect growth during COD is fed by the optical mode, i.e., laser energy. This process involves melting and even vaporization of MQW and waveguide materials, indicating the presence of very high local temperatures. Defect propagation velocities along the laser axis of 110 m/s are observed. COD results in material loss including the formation of an empty channel, which is well consistent with material loss due to ejections of hot material out of the front facet of the device. The laser structure in the immediate vicinity of the empty channel seems to be absolutely undisturbed and no transition regions or remaining material are observed. These results are compared with earlier findings from comparable experiments obtained with GaAs-based devices.

5. (Al,In)GaN optical amplifiers

Szymon Stanczyk[1]* , Anna Kafar[1,2], Anna Nowakowska-Siwinska[2], Irena Makarowa[2],
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In last few years, there has been strong development of plastic optical fibers (PMMA POF) and high speed visible light communication. With the growing demand for such specialized telecommunication systems, the need of developing basic components of visible light optoelectronic systems - such as optical amplifiers – appeared. Moreover, optical amplifiers - if placed after laser diode source – can work as an optical booster or – if placed in front of detector – as an optical signal enhancer.

This work shows the optoelectrical properties of (Al,In)GaN optical amplifiers emitting at 430 nm and 450 nm. All samples have graded index separate confinement heterostructure (GRIN SCH) grown by MOVPE technique on bulk GaN substrates. We investigated properties of semiconductor optical amplifiers made by different type of devices like AR/AR coated broad area lasers, AR/AR coated tapered waveguide lasers and uncoated superluminescent diodes.

The measured optical gain in CW operation in room temperature was over 20 dB for 1 mW of input optical power and over 10 dB for 10 mW of input power. We also investigated the temperature dependence of the amplifiers.

The results shows that every type of the investigated devices can work as an optical amplifier, however the superluminescent diodes shows the best performance among others.

6. Laser sources for dermatological applications

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We developed high power laser sources based on visible laser diodes and we have tested them for the treatment of hemangiomas and for Photodynamic (PDT) treatment of skin cancer. Visible wavelengths are strongly absorbed by hemoglobine and therefore can be used for closing blood vessels but high powers of a few Watt are required. In the case of PDT lower powers are required (up to 500 mW) and typical wavelengths are 635 nm for treatment and 410 nm for diagnosis. Using our method for coupling 8-19 laser diodes into a multimode optical fiber we achieved 3.5 W for 410 nm (violet), 5 W for 520 nm (green), 8 W for 635 nm (red) and 50 W for 450 nm (blue). Our lasers operate both CW and in pulsed regime (pulses from 1 ms upwards). The beam size is variable from 0.5 mm to 5 mm. We can also mix different colors in the same fiber which turned out to be useful in PDT method. The outcome of clinical tests is promising; it turned out that the best results have been obtained for short (10-20 ms) pulses and high peak powers (40-50 W).

7. Generic technologies of integrated photonics

Ryszard Piramidowicz, Stanisław Stopiński, Anna Jusza, Krzysztof Anders, Andrzej Kaźmierczak, Aleksandra Paśnikowska, Mateusz Słowikowski and Paweł Szczepański

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Photonic integrated circuits (PICs), which common introduction to the commercial market is anticipated within the next few years, are considered as one of the most attractive and promising solutions for modern optoelectronics, with the potential impact similar to integrated electronic revolution. Generally, when compared to their discrete equivalents, PICs offer improved performance in terms of multiplied functionality, reduced energy consumption, size and weight, as well as increased efficiency and reliability. Depending on the technological platform, photonic chips provide efficient integration of a number of individual photonic components – various passive elements and modulators in the case of silicon platform and full set of passive and active elements (including optical amplifiers and lasers) for hybrid and indium phosphide-based platforms.

In this work we compare these two major technologies present on the market – silicon and InP photonics, discuss the potential of both platforms with respect of versatility and availability of key active elements, like lasers, modulators and detectors, and present a novel way of realizing photonic integrated circuits, completely different from hitherto applied methods of manufacturing integrated optoelectronic devices. This concept, called the generic technology, is a revolutionary way of thinking about photonic devices. The basic assumption of the generic approach is that photonic circuits of any complexity can be designed by using a limited set of standardized building blocks such as an optical amplifier, a phase modulator, a photodetector and a passive waveguide. This idea has been already proven to work well in the silicon microelectronics industry, which uses the CMOS technology standard, and now is successfully implemented in modern photonics.

To prove the concept of photonic integration and show its potential we present the selected examples of successfully designed and realized highly complex photonic integrated circuits dedicated to applications in optical communication systems, sensors, sensing networks and others (see Fig. 1). In particular, examples of multichannel lasers and amplifiers, interrogators and sensor elements will be introduced and briefly characterized with respect of their potential deployment in commercial systems.

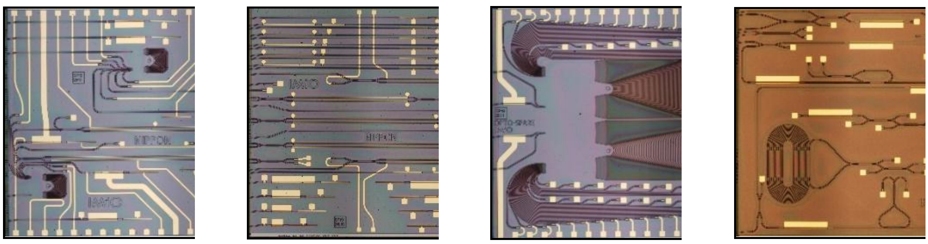

Fig. 1. Microscope pictures of InPphotonic integrated circuits – twomultichannel transceivers for fiber-optic access systems, a read-out unit for fiber Bragg grating sensor network and a ring laser gyroscope.

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8. InP-based integrated transceiversfor fiber-optic access systems

Anna Jusza[1], Aleksandra Paśnikowska[1], Andrzej Kaźmierczak[1], Stanisław Stopiński[1],
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A constantly growing market of broadband telecommunication services, covering not only phone calls and data transmission, but also video on demand (VoD), voice over IP (VoIP), teleconferencing, teleworking, monitoring and many others, requires continuous development of fiber-optic communication systems, capable of supporting symmetric high speed (10 Gb/s and more) transmission to the client premises. One of the possible ways of achieving this is introducing the wavelength division multiplexing (WDM) technique into the access network systems. However, due to economic limitations, common implementation of WDM access networks requires development of non-standard solutions for providing high-speed and cost-effective optical transmitters and receivers.

One of the most attractive and promising ways of meeting such demands is making use of photonic integrated circuits (PICs),which integrate many optical components on a single semiconductor chip. In particular, the indium phosphide technology allows to integrate various types of active and passive components such as semiconductor optical amplifiers, photodetectors, phase and amplitude modulators, passive waveguides, splitters, couplers, reflectors, wavelength multiplexers and others. This, in turn, enables designing an integrated chip of any desired functionality.

In this work we present and discuss the properties of InP-based multi-channel integrated transceivers dedicated to application in WDM-PON systems. All of the discussed solutions make use of an array of single-mode lasers, each operating at different wavelength within the ITU grid, followed by Mach-Zehnder amplitude modulators. The signals from all of the channels are multiplexed to a single output through an arrayed waveguide grating (AWG), which is the integrated variant of a wavelength mutliplexer. Single-frequency operation is provided by using distributed feedback (DFB) lasers, distributed Bragg reflector (DBR) lasers or Fabry-Perot lasers with filtered feedback to force a single mode operation. The receiver part comprises an equivalent AWG wavelength demultiplexer and an array of photodiodes for detection of all WDM signals. All chips were carefully tested with respect of main parameters of integrated lasers and modulators. The obtained characterization results confirmed the general concept and proved the applicability of developed PICs in fiber-optic access systems.

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9. Integrated read-out unit for fiber-optic sensor network

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Recent progress in fiber optic sensors has led to development of network systems enabling simultaneous strain monitoring at multiple points. A typical sensor network has a bus or star topology with a number of fiber strain-sensing components, most often fiber Bragg gratings - FBGs. The key component of such a system is the readout unit that interrogates all sensors within the network. In general, it has a form of an optoelectronic circuit that couples the optical signal to the optical fibers and detects the shift of the Bragg wavelength caused by strain applied to individual FBG sensors.

In the OPTO-SPARE system a network of FBG sensors is implemented for monitoring the condition of the patient exposed to magnetic resonance imaging (MRI) scan. For this particular application the implementation of a photonic integrated circuit (PIC) in the readout unit seems to be an interesting option as it offers substantial reduction of size and power consumption, together with increased mechanical durability and reliability exceeding the traditional discrete solutions.

In a typical configuration of integrated readout unit for a fiber-optic sensor network two solutions are considered: (i) a broadband, non-coherent optical source (e.g. LED/SLED) and a wavelength selective detector (e.g. AWG-based spectrometer) and (ii) a tunable, coherent optical signal source (integrated laser) and a broadband detector (e.g. photodiode). In the first configuration a broadband signal is coupled into the optical fiber and the wavelength spectrum of the signal reflected by FBGs is analyzed by an AWG spectrometer. On the contrary, the measurements using the second configuration of the readout unit are considerably slower, as full wavelength range has to be swept for reconstruction of the FBG reflection spectrum. This configuration has, however, a number of advantages, including reduction of required number of active components as there is only one photodetector needed, higher spectral power density leading to the higher S/N ratio, and insensitiveness to polarization state of the light reflected by FBG sensors, which is a major drawback of the AWG based interrogators.

Currently at the Institute of Microelectronics and Optoelectronics, Warsaw University of Technology a number of integrated read-out unit topologies have been studied for the implementation using a commercially available PIC indium phosphide (InP) technology. The test structures of such devices have been fabricated in openly available multi-project wafer runs and investigated experimentally.

In this work the prototype integrated readout units are presented and discussed in details with a specific attention given to the design based on a tunable laser. Designed, manufactured and tested device with four independent tunable DBR lasers ($\Delta\lambda_{max}$ = 3 nm), providing a total bandwidth coverage of approximately 12 nm, was carefully tested with respect of its applicability in interrogation units. The results of characterization have confirmed the correctness of the proposed approach, giving a good starting point for further development and optimization of the ready-to-the-market device.

Acknowledgements: This work was supported by the National Centre for Research and Development (project OPTO-SPARE of the 3rd Applied Research Programme, grant agreement PBS3/B9/41/2015).

10. Optical gyroscopes in generic technology on InP platform

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Modern airplanes, drones, guided missiles and spacecrafts require highly accurate and reliable inertial navigation systems. One of the essential components of such systems is the gyroscope, a device that measures the angular velocity of the flying object. Gyroscopes can be realized utilizing various techniques of rotation rate detection – mechanical, microelectromechanical or optical. Nowadays, the optical gyrosare widely deployed due to their compact dimensions combined with an excellent performance. However, so far they are constructed mostly from discrete optoelectronic and fiber-optic elements. It seems that exploring the potential of photonic integration technologies may enable further reduction of size, weight and reliability of optical gyroscopes. In particular, the generic platform of indium phosphide enables fabrication of miniaturized and simultaneously highly complex optoelectronic systems, comprising both active and passive elements – light amplifiers, modulators, detectors, connected through a network of passive optical waveguides. In this work we propose and discuss two novel gyroscope systems that use monolithic photonic integrated circuits fabricated on a generic InP platform.

The first configuration uses an optical fiber loop, in which the rotation induces a relative phase change between the signals propagating in the clockwise (CW) and counter-clockwise (CCW) directions. The photonic integrated circuit is a readout unit connected to the loop. Integrated semiconductor optical amplifier (SOA) is used as the light source. A cascade of two multi-mode interference (MMI) couplers is used to split the power between the two signals (CW and CCW). When the signals return to the chip, the interference takes place in the MMI couplers and the resulting power is detected by integrated PIN photodiodes.

The second configuration is a fully integrated variant of the optical gyroscope, based on a ring laser. Two amplifiers are connected with passive waveguides that form a racetrack. An arrayed waveguide grating (AWG) wavelength multiplexer is used as an intra-cavity filter to force single-frequency operation. The beating signal, which is a result of frequency split of CW and CCW ring laser modes under rotation, is monitored by an integrated readout circuit, formed by a cascade of two MMI couplers and two PIN photodiodes.

Both photonic circuits described above were designed, fabricated and initially characterized. The Sagnac effect was detected in the interferometric fiber-optic gyroscope system with an integrated readout unit. Single frequency operation of the ring laser was recorded. These results are promising with respect to application of indium phosphide chips in optical gyroscope systems.

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11. Carrier dynamics in type I InGaSb/GaSb and type II InAs/GaIn(As)Sb/ AlSb quantum wells

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There are several experimental approaches which allow to look for improvement of the active part of emitters based on semiconductor low-dimensional systems. It is worth noticing that such activities as optimization of confining potential of the applied quantum wells, detection of the possible carrier escaping channels or improvement of the overlap between electrons and holes wavefunctions are important from the point of view of quantum efficiency, gain broadening, and emission power and consumption of the final device. On the other hand, any modifications in the active part also cause changes in carrier dynamics within the modified low-dimensional system. Knowledge of carrier life times and their dynamic processes are crucial to determine characteristics of the pulsed lasers such as 'mode lock' devices. In this presentation we will focus on possible ways of experimental determination of information about carrier dynamics in the low-dimensional systems e.g. InAs/GaIn(As) Sb/AlSb type II quantum wells grown on GaSb substrate, predicted for emission light in the mid infrared range (2-8 μm).

The results obtained by using single photon counting technique for quantum wells emitting at 2.5 μm allowed to determine typical characteristic (2 ns) life time for confined carriers in type II InAs/GaInSb/AlSb quantum wells.

In addition the results of the non-degenerate pump-probe experiment in the reflectance configuration show a fast 2.3 ps carrier relaxation time from the upper to the ground state of the InAs/GaInAsSb/AlSb well, driven, most probably, by the carrier–phonon (optical or acoustic) scattering processes. Furthermore the second relaxation channel, characterized by a 230 ps decay time constant was detected. This time was attributed to the tunneling of a hole out of its 2D confining potential towards the distant GaAsSb barrier [1].

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12. Novel solutions in the active region of interband cascade lasers

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Interband cascade lasers (ICLs) are efficient mid-infrared (MIR) semiconductor light sources based on InAs and GaInSb materials forming a broken gap system and hence type II quantum wells (QWs) being the active part in this kind of emitters. There has already been achieved a significant progress in the performance of ICLs, which had been stimulated by increasing importance of such lasers in many applications, including medical diagnostics, trace-gas analysis, pollution monitoring and molecular spectroscopy. The application potential originates mostly from unique operational characteristics of ICLs as they can cover the spectral ragion of below 3 to above 7 μm with room temperature continuous wave operation, and in most of this range also with single mode emission [1,2]. They also offer much smaller electrical power consumption [3] when compared to the main competitor, which are quantum cascade lasers. However, there are still growing demands when regarding the characteristics of the lasers as well as new areas of applications, which drive the improvements of the currently exploited ICLs' structures or searching for completely new solutions which could offer properties hardly reachable by the state-of-the-art devices. Hereby, we will discuss such possible modifications in the active region o ICLs concerning three different challenges:

− Polarization independent gain in the MIR range which could be obtained when replacing the compressively strained GaInSb material, commonly used for confinement of holes, with tensely strained GaAsSb. This allows for efficient band structure engineering and making the ground state of the valence band of light-hole character. In consequence, this allows tailoring the TE and TM polarized contributions to the gain function and makes them finally equal under certain conditions.

− The same materials, i.e. InAs/GaAsSb, due to the possible usage of thicker layers, or a multiplication of the so called "W-shaped" QWs made of InAs/GaInSb, exhibit enhanced sensitivity to external electric field. This can be beneficial for constructing passively mode-locked ICLs, in which the saturable absorber and the gain sections are made of the same active region but just inversely electrically polarized and hence offering the required tuning of the optical transitions rates.

− All the existing ICLs' designs deal with strained structures which causes some problems and limitations when regarding the growth technology and when larger total layer thicknesses are required. Utilizing a combination of In(As,Sb) and (Ga,In)(As,Sb) allows to find compositions which can be lattice matched to GaSb or InAs substrates, which paves the way towards fully strain-free interband cascade lasers.

These issues will be examined based on band structure calculations performed within multiband $k\cdot p$ theory including strain, and the optimal designs will be presented. In some cases, the results of theoretical considerations will be referred to recent experimental data used to verify these predictions.

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13. Membrane External-Cavity Surface-Emitting Lasers (MECSELs) - From Infrared to Red, Orange, Yellow and Beyond

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To overcome the limits of common methods in thermal management on VECSELs, the semiconductor membrane external-cavity surface-emitting laser (MECSEL) consisting of a intra cavity heat spreader sandwiched active region without a monolithically integrated distributed Bragg reflector (DBR) was realized. This heat spreader-sandwich approach improves the heat dissipation out of the active region and makes generally low-heat conductive DBRs obsolete. An overview over the rapid developments during the 2 last years will be given as well as a summary of the very latest results in this new emerging field. General benefits and challenges of this heat spreader sandwiching concept will be discussed and the potential for new semiconductor based laser wavelengths especially towards the visible wavelengths will be outlined.

14. Double diamond enclosure of Vertical External Cavity Surface Emitting Laser − a new way to new spectral ranges

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Nowadays, there are two factors which limit further spectral expansion of the Optically Pumped Vertical External Cavity Surface Emitting Laser (VECSEL) known also as Semiconductor Disc Laser: the feasibility of high reflectivity of the distributed Bragg Reflectors (DBR) and the efficient heat extraction.

To overcame those limits we have developed the technology of enclosures of an active region from both sides by two transparent diamond heat-spreaders. The total chemical removal of the substrate enhance the heat extraction. The transparent heat-spreaders permit to use an external dielectric DBR to enclose the resonator. In consequence, we were able to align a new laser. The emission parameters as maximum available power and the tuning range were superior than for a VECSEL based on standard test heterostructure with an identical active region and monolithically grown DBR. Our technology was tested for InGaAs/GaAs epitaxial wafers designed for emission at 976 nm. We believe it is transferable in the 1550-2000 nm spectral region for which the epitaxial growth is carried on InP substrates and both of those factors: heat extraction and poor DBR reflectivity imposes especially strong constrains.

15. Semiconductor Disk Lasers with Two-Resonance Microcavity – improvement of wavelength tuning range

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Nowadays, the optically pumped semiconductors disc lasers (OP-SDL), widely known as Vertical External-Cavity Surface-Emitting Lasers (VECSEL) [1,2] 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.

Special advantages of semiconductor disk lasers are due to band-gap engineering which allow to design and fabricate sources of coherent light in broad range of wavelengths (fundamental emission 630-5000 nm and frequency conversion 315-589 nm) also optimized for simultaneous multi-wavelength emission [3], and most of all permitting for tuning in very wide spectral range [4].

At present, at the Institute of Electron Technology the research is carried intensively to increase the available spectral tuning range of VECSEL emission. The innovative laser design will be presented in this paper, which allow for significant improvement of the above parameter. The VECSEL laser with unique heterostructure containing the active region inside two-mode microcavity [5]. Using of a resonator with high-reflectivity mirrors allowed for spectral tuning in record-wide-range of 95 nm, which in turn is four times broader than for standard VECSEL construction. Relatively high output power exceeding hundreds of milliwatt is suitable for most practical spectroscopic applications. In addition, the laser emission was extended to visible spectrum using the harmonic generation resulting in tunable blue-green emission.

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16. Simplicity VCSELs

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While *simplicity-in-design* principles generally encompass both aesthetic attributes (beauty in form, or perhaps more appropriately beauty in morphology) and functional attributes (optical output power, modulation bandwidth, power conversion and energy efficiency, reliability), we focus here on functional epitaxial designs of vertical-cavity surface-emitting lasers (VCSELs) that remove all but the essential VCSEL parts and yet still lead to superior and in some cases record static and dynamic device figures-of-merit. Although contemporary VCSELs consist of a few basic optical, electrical, mechanical, and thermal building blocks in the form of many repetitive layers, a plethora of doping, grading, grating, intracavity, selective oxidation, tunnel-junction, regrowth, and other novel designs have been introduced over the past roughly 30 years that perhaps improve the VCSEL performance but at the same time increase the device complexity and thus potentially increase the VCSEL manufacturing and life-cycle costs as well. We present static and dynamic results for our 980 nm *Simplicity* VCSELs [1,2] and ponder the application of these VCSELs in a variety of applications, from very short reach and very low optical output power on-chip optical sources to high power, energy efficient, and high bandwidth VCSEL arrays for free space optics data communications. We achieve record small signal modulation bandwidth performance for our *conventional* single-cavity oxide aperture 980 nm VCSELs using direct current modulation. We conclude by discussing further possible design simplifications including physical device geometries and processing schemes.

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17. Bandwidth versus Oxide Aperture Diameter for 980 nm Simplicity VCSELs

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We present the fabrication and characterization of cylindrically symmetric, 980 nm top-emitting vertical-cavity surface-emitting lasers (VCSELs) composed of a λ/2-thick optical cavity with five compressively-strained pseudomorphic InGaAs quantum wells (QWs) surrounded by GaAsP barrier layers (in tension) [1,2]. We use $Al_xGa_{1-x}As$ (x=0.0/0.9) p-doped-top and n-doped-bottom distributed Bragg reflectors (DBRs) on doped (n+)GaAs substrates. We further use a simplified epitaxial DBR design with linear AlGaAs compositional grading and constant doping except at the very top (p+)GaAs surface. The optical cavity is surrounded by two, 20 nm-thick (before selective oxidation) $Al_xGa_{1-x}As$ (x=0.98) oxide aperture layers centered on nodes of the LP01 optical field intensity on resonance at the edges of the physical optical cavity. On one processed wafer we obtain sets of neighbor 980 nm VCSELs in columns with 16 different oxide aperture diameters(ϕ) ranging from ϕ~3 µm (in an 18 µm diameter Mesa-1) up to about ϕ~16 µm (in a 31 µm diameter Mesa-1), in ~0.5 µm (Rows 0 to 3) and ~1.0 µm (Rows 4 to F) Mesa-1 and ϕ steps. For these ϕ~3 and 16 µm VCSELs at room temperature we achieve ~6 and 21 mW of maximum CW optical output power, peak L-I slope efficiencies of almost 1.0 (mW/mA), peak external differential quantum efficiencies (η_{ed}) of about 0.77, peak power conversion efficiencies above 32 and 22%, and typical small signal modulation bandwidths (f_{3dB}) of ~28 and 20 GHz, respectively.

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

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18. Quantum confined Stark effect and reliability of the nitride near ultraviolet lasers

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Nitrides semiconductors (AlInGaN) have a direct energy band-gap across a very broad spectral range: from deep ultraviolet to near infrared. The most efficient, light emitters are made using InGaN quantum wells. Unfortunately, when we approach UV wavelengths, we have to reduce the In content to few percent only making the quantum wells very shallow. Additionally, the shorter emission wavelength needs more aluminum in the electron blocking layer and cladding, leading to the formation of additional strain, and making p-type doping more difficult.

UV-laser diodes are exposed to high density electromagnetic field of the photon energy exceeding 3 eV. Such a light has a pronounced chemical and physical effect and may lead to faster device degradation. From the other point of view, low In content reduces the quantum confined Stark effect, allowing for the use of broader quantum wells.

In the present work we analyze the properties of light emitting diodes and laser diodes manufactured by Metal-Organic Chemical Vapor Depositions (MOCVD)with InGaN multi-quantum wells active region and emitting in the near ultraviolet spectral region (around 390nm).

We have compared several structures with quantum wells of different widths from 2 to 8 nm. We tested their performance at low and high currents (below and above the laser action) for light output, efficiency, and threshold current. We compared the results obtained with the theoretical predictions obtained from the SiLENSe package.

We have attempted to investigate the effect of external ultraviolet light exposure on the properties of single laser chips and structures with analogues layer structure but with contacts like in light-emitting diodes.

The first results suggest a gradual degradation of properties of devices, which may have a direct impact on the reliability of near-ultraviolet lasers.

19. Quantum Confined Stark Effect screening under high carrier injection in nitride laser diodes and superluminescent diodes

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Nitride based laser diodes utilize as an active medium extremely strained InGaN quantum wells. As the nitride materials are piezoelectric in their nature, this strain is reflected in a strong piezoelectric field. This tilts the energy bands and shifts the emission spectrum position through the Quantum Confined Stark Effect (QCSE). As the laser diode is operated at elevated currents, the built-in electric field is reduced due to the screening by injected carriers. This leads to the increase of emission energy (blue-shift). It has been a subject of many discussions whether the field is preserved at lasing, or is it completely screened.

In this work we compare the emission wavelength shift of nitride laser diodes and superluminescent diodes having different QW compositions. The superluminescent diodes allow us to study the emission spectrum at higher carrier densities than for laser diodes. In laser structures, we clearly see the saturation of the blue-shift at threshold current. While, on the other hand, we see the continuous shift of the emission wavelength in case of superluminescent diodes. This suggests, that the piezoelectric fields are not fully screened at threshold current. We also see that for UV laser diodes the emission line shift is much smaller than for blue wavelength devices. This implies practically complete screening of the electric field for UV laser while the lasing of blue laser diodes occurs at high electric field conditions.

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20. VCSELs incorporating High Contract Gratings as one-device sensor

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Optoelectronic sensing systems consist of two devices: a light emitter and a light detector. We propose a novel approach wherein the optical sensing system is merged into one device. In this design the emitted light of the laser is not detected but changes to the laser's electrical characteristics may be detected, and hence the laser itself functions as a detector. In our example the sensing device is based on vertical-cavity surface-emitting laser (VCSEL) incorporating monolithic subwavelength high contrast grating (HCG) as a top mirror.

The sensing mechanism depends on mechanism in which modification of the quality factor (*Q*) of a VCSEL affects the laser's stimulated emission characteristics which in-turn induces a modification of the electrical properties of the VCSEL. This *Q*-sensing mechanism can be utilised in VCSELs that use MHCG mirrors to form a single-device that serves as a sensor. VCSELs that use a top MHCG mirror are sensitive to changes in the refractive index and absorption coefficient of the laser's surroundings. Since an MHCG confines light between stripes [1] it gives access to the VCSEL's resonating light without opening the VCSEL's cavity. Base on that we are able to design the construction of a new optical sensor without an external optoelectronic detector.

The mechanism is experimentally shown for 980 nm arsenide-based VCSELs and numerically investigated for long wavelength MHCG VCSEL. We show that this sensing mechanism enables the construction of a new compact optical sensing system without the need for a photodetector.

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21. Antiresonant reflecting optical waveguide VCSEL with oxide island

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We study optical properties of an antiresonant-reflecting-optical-waveguide vertical-cavity surface-emitting laser (ARROW VCSEL). The anti-resonant effect if provided by an oxide island located inside the optical cavity manufactured with planar oxidation [1]. The simulated VCSEL is designed for 850 nm wavelength emission from 3 GaAs quantum wells. In the resonant cavity there are two oxidation layers: one forming the 10 μm electrical aperture and the other providing the oxidation island with diameter changed in range from 0 to 6 μm.

We show that the new design of oxide-island ARROWs can successfully induce single-mode emission. By investigating the dependence of the oxidation island diameter on the wavelength and modal loss (photon lifetime) of emitted radiation, we show that it can increase modal discrimination. However, the strength of this discrimination depends in the length of the resonant cavity.

By presenting the dependence of the VCSEL optical properties and electromagnetic field distribution of each mode, we suggest the design parameters of the oxide-island ARROW VCSEL that improve the laser modal discrimination.

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22. Tunnel Junctions for III-Nitride VCSELs and High Efficiency Edge Emitting Lasers

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Efficient tunnel junctions (TJs), which provide a means of carrier conversion between p-type and n-type material in semiconductor devices, could be particularly advantageous for III-Nitride laser diodes where the poor conductivity of p-GaN and resistive p-type contacts are responsible for significant losses in device efficiency. In this talk, we will describe a hybrid growth approach that involves growing the active region and top p-GaN layers of the device by MOCVD, and subsequent regrowth of the n-side of the TJ by ammonia assisted molecular beam epitaxy. This hybrid TJ has been incorporated into high performance blue c-plane LEDs, and very recently into optically polarized m-plane VCSELs that operate CW. We will discuss the growth, fabrication and performance of this TJ VCSEL, the remaining problems to be solved, and some prospective solutions. We will also describe experimental implementation in an edge emitting laser and discuss where in the broad design space the TJ might be beneficial.

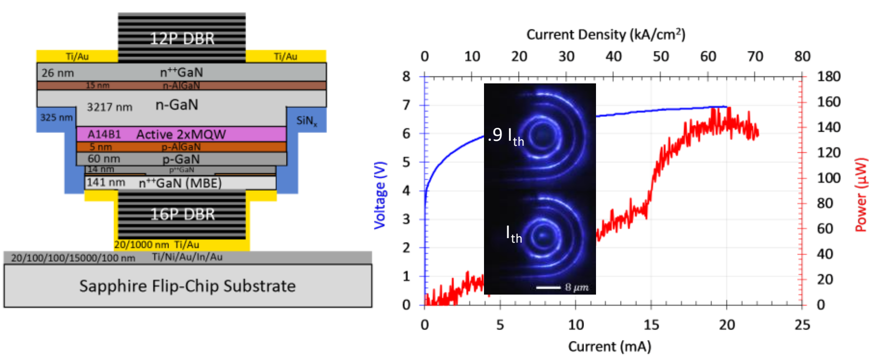

Fig. 1. Schematic and CW LIV characteristics of a TJ VCSEL with a 6 μm aperture.

23. Nitride laser diodes with tunnel junctions by plasma assisted MBE

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The one of the most challenging issues for nitride based devices like light emitting diodes (LEDs) and laser diodes (LDs) is poor conductivity of p-type region. Also a high resistance of the p-type contact which is very difficult to reduce determines performance and influences design of InGaN LEDs and LDs. Recently, there has been increasing attention given to the interband tunnel junctions (TJ) for effective carrier conversion between n-type and p-type material region in nitride LEDs and LDs. It was clearly demonstrated that TJ resistance for wide bandgap semiconductors can be effectively suppressed by making use of the piezoelectric fields in the region of the junction. The low resistance TJ were investigated and realized using GaN/InGaN/GaN heterostructures. The MBE technology seems to be more efficient than MOVPE for practical realization of the devices with TJ. For MOVPE it is difficult to activate the p-type conductivity in the (In)GaN:Mg layers which are deeply buried below n-type layers due to the fact that diffusion of hydrogen is completely blocked through n-type layers. Therefore several attempts for hybrid MOVPE/MBE growth was performed and TJ LEDs, TJ LDs and TJ VCSELs was shown where active p-i-n region was grown by MOVPE and p-n TJ by MBE. However, the presence of the impurities in the regrowth surface can deteriorate/limit performance of devices grown by hybrid method.

In this work we demonstrate TJ LDs grown entirely by Plasma Assisted Molecular Beam Epitaxy (PAMBE). The LDs were grown on low dislocation density (0001) GaN crystals from Ammono Ltd. The TJ LDs consist of aluminum free LDs structure capped with heavily doped p-n $In_{0.02}GaN/In_{0.17}GaN/In_{0.02}GaN$ TJ. The TJ operate in reverse bias conditions (Zener diode). The devices were processed as ridge-waveguide, oxide-isolated lasers. The 3- um-wide and 1000- µm-long stripes were used as laser resonators. For both sides of LDs we used n-type Ti/Al/Ni/Au contacts. The continuous wave operation was achieved at 450 nm. The voltage across device at the lasing threshold (3 kA/cm2) was 5.5 V which is only about 0.8 V higher than for reference PAMBE LDs without TJ.

We will discuss the influence of the TJ growth parameters like InGaN well width (from monolayer InN/GaN superlattice), doping profiles, polarity of substrate (0001)GaN or (000-1) GaN for performance of TJ LDs and TJ LEDs. The comparison of I-V characteristics of TJ LDs with standard PAMBE LDs and commercial LDs will be given. Our demonstration open possibility for design new architecture of edge emitting LDs and can be very important for realization of monolithic VCSELs, where high absorption of the p-type distributed Bragg reflectors is one of the main challenging issues.

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24. Monolithic nitride-based VCSEL with semiconductor-metal subwavelength grating

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Semiconductor-metal subwavelength grating (SMSG) can serve a dual purpose in vertical-cavity surface-emitting lasers (VCSELs), as both optical coupler and current injector. SMSGs provide optical as well as lateral current confinement, eliminating the need for ring contacts and lateral build-in optical and current confinement, allowing their implementation on arbitrarily large surfaces. Using an SMSG as the top mirror enables fabrication of monolithic VCSELs from any type of semiconductor crystal [1].

In this talk we propose new design of the nitride-based VCSEL with top SMSG mirror which is monolithically integrated with the VCSEL cavity (see Fig. 1). Using three dimensional optical model together with three dimensional thermal and electrical self-consistent model we demonstrate that SMSG enables axial current injection, uniform current distribution across the laser junction and broad area laser emission. Proposed design enables elimination of the tunnel junction and modulation of metal stripes resistivity enables shaping of the carrier concentration distribution within active region.

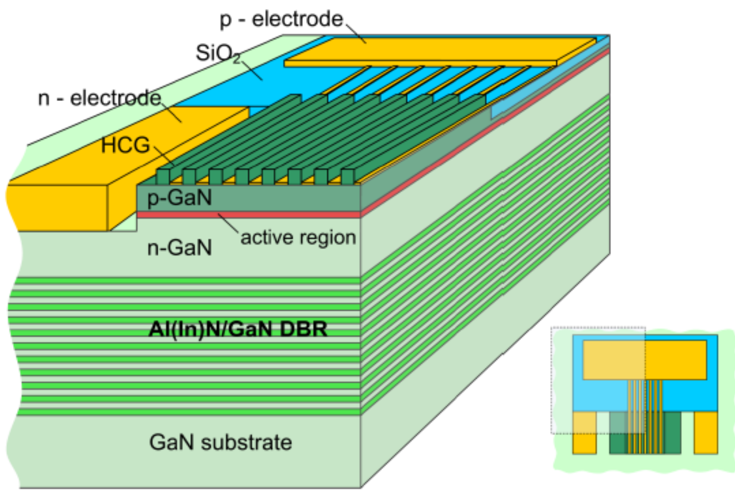

Fig. 1 Schematics of nitride-based SMSG VCSEL structure with top electrode integrated with GaN subwavelength grating. Left figure illustrates quarter of the VCSEL. Right bottom inset shows top view of the structure.

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25. DFB laser diodes based on GaN using 10th order laterally coupled surface gratings

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We present the simulation, fabrication, and operation of laterally coupled-distributed feedback (LC-DFB) laser diodes (LDs) based on InGaN/GaN multi-quantum-well structures containing 10th-order surface Bragg gratings with V-shaped grooves. The V-shaped grooves were fabricated on a GaN-based laser structure by i-line stepper lithography and inductively coupled plasma etching which makes use of redeposition effects from sputtering using heavy ions such as BCl3. The V-shaped grooves had a pitch of 802 nm, an etch depth of 600 nm (i.e. around 40 nm above the topmost quantum well), a slant angle of 20° and a width of the groove tip of 10 nm which should correspond to a reflectivity above 0.9 of the optical mode based on simulations. The gratings were placed alongside a 2 μm wide ridge waveguide (RW) where no grooves were etched. Threshold currents of 80 mA were measured both for RW-Fabry-Perot (FP) LDs without grating and LC-DFB LDs for pulsed operation at room temperature. A single peak emission of LC-DFB LDs at 404.5 nm with a full width at half maximum of 0.04 nm was achieved at an output power of about 46 mW whereas the spectrum of the RW-FP LDs consisted of multiple peaks independent of the injection current. In the temperature range from 22°C to 45°C, the shift of the lasing wavelength was 0.077 and 0.025 nm/K for the RW-FP LDs and the LC-DFB LDs, respectively. The narrow single peak emission of the LC-DFB LDs as well as their small sensitivity to the injection current and to the temperature indicate the effective coupling of the optical mode to the high-order laterally coupled surface grating.

26. Nitride-based laser diodes with extremely long lifetime grown by plasma assisted molecular beam epitaxy

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Nitride-based laser diodes (LDs) cover a broad spectral range and are used in many applications such as optical data storage, projection, printing etc. The vast majority of commercially available LDs are grown using Metal Organic Vapour Phase Epitaxy (MOVPE). However, the significant differences in growth conditions between MOVPE and Plasma Assisted Molecular Beam Epitaxy (PAMBE) may lead to some unique features of electronic and optical devices grown by the latter.

The LDs grown by PAMBE contain thick high indium content InGaN waveguides which significantly improve the optical confinement [1] and lead to full elimination of leakage of optical modes to the GaN substrates [2]. This leads to a substantial improvement in the optical beam quality of the LDs.

In this paper we will present the recent advancements in the development of laser diodes grown by PAMBE. The influence of epitaxial design on both internal and external parameters will be discussed. Blue laser diodes operating at λ=460 nm with low threshold current density of 2 kA/cm^2 will be demonstrated. The improvement of the material quality of LDs grown by PAMBE resulted in an extremely long lifetime of the devices exceeding 100 000 hours.

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27. Optimization of Electron Blocking Layer design for nitride laser diodes

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Electron blocking layer is considered an important part of nitride light emitters such as LEDs and LDs. It's main role is to limit the electron overflow of the active region and their non-radiative recombination in the p-side of the device structure. Although it serves its purpose in LEDs, EBLs role in LDs still remains controversial, as this layer also limits unintentionally the hole injection due to insufficient doping and polarization effects.

To shed more light on this issue we fabricated structures with different types of EBL: conventional step-like EBL, very low EBL and GaN/AlGaN superlattice EBL. Devices were grown by Metal Organic Chemical Vapor Deposition (MOCVD) on GaN bulk substrates. We compared their electrical and optical properties as well as structural quality. The efficiency of magnesium doping was checked by Secondary Ion Mass Spectometry (SIMS) technique.

The results of characterization of LDs reveal surprisingly modest role of electron blocking layer composition in determination of the threshold current and differential efficiency at the ambient temperature. Its structure influences only the operating voltage (decreased for lower EBL and superlattice) and thermal stability (T_0 parameter smaller for lower EBL). This results suggest that superlattice EBL can be a good replacement of graded EBL with high (12%) Al content as it has similar thermal stability and lower operating voltage.

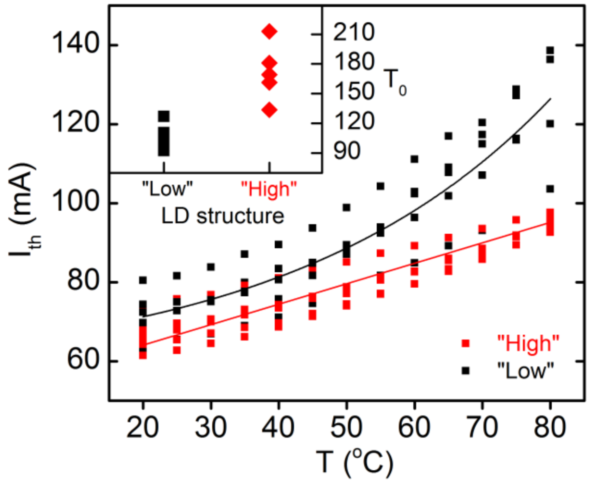

Fig. 1 Threshold current as a function of temperature for LDs with high and low EBLs. Characteristic temperature T_0 of these devices is shown in the inset graph.

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28. Limitations of high duty-cycyle operation of InP-based QCLs

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In this work analysis of key parameters influencing CW operation of quantum Cascade lasers (QCLs) is analysed. Recently, QCLs based on the AlInAs/GaInAs/InP became promising light sources for applications requiring radiation from mid- to longwave infrared e.g. gas sensing systems, free-space-optical communication systems (FSO) or optical countermeasures.

QCLs are complex, multilayer structures in which lasing transition takes place between subbands of conduction band. Since they rely on properties of coupled quantum wells system, engineering of electronic states is their inherent property. However, achieving continuous wave operation is also limited by the complex nature of the device.

High current and voltage required to polarize the structure to obtain level alignment results in high heat generation. Thermal limitations in case of QCL are the most important factor decreasing the performance of device. High electrical power combined with relatively low wall-plug efficiency results in high temperature increase in the active core. Efficient heat dissipation is difficult due to hundreds of layers impeding thermal conductivity of the structure. Moreover, the materials composing the gain region are ternaries with composition of roughly 50%, what results in thermal conductivity lower by a factor of 10 than in case of bulk InP.

Increased temperature of active core on the other hand, results in lowering of inversion coefficient thus limiting available gain and consequently lack of laser emission at elevated temperatures.

Characterization of devices provides necessary information to optimize thermal and electronic design of the structure. Standard characterization includes temperature dependent light-current and voltage-current measurements and spectral characterization. Knowledge of the temperature is gained through unique temperature measurement technique – CCD thermoreflectance.

In this work, results of characterization of different designs of QCLs are discussed in respect to increased duty cycle operation of devices.

29. Growth of InAlAs/InGaAs/InP Quantum Cascade Lasers by MBE and MBE+MOVPE Hybrid Approach

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Quantum Cascade Lasers (QCLs) are mid-infrared emitters based on intersubband transitions in multilayer semiconductor structures. Despite, that they were first demonstrated over 20 years ago [1], their epitaxial growth, still represents one of the most challenging tasks for semiconductor material growers. This is mainly because the growth of the QCL's active region demands extreme precision of thickness and composition of individual layers as well as the growth stability over a long time.

In this paper we present the development of MBE growth process for lattice matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As/InP$ and strain compensated $In_{0.67}Ga_{0.33}As/In_{0.36}Al_{0.64}As/InP$ quantum cascade lasers (QCLs) by solid-source molecular beam epitaxy (MBE) and hybrid MBE + MOVPE technology. The extensive discussion of growth process optimization is presented. The grown structures were examined by HRXRD, AFM, and TEM techniques. The on-line implementation of obtained results in subsequent growth runs was crucial for achieving high performance, room temperature operating lasers [2].

Acknowledgements: This work was partially supported by Polish National Science Centre grant UMO-2015/17/B/ST7/04015 (OPUS 9).

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30. Influence of the thermal annealing of the strain-compensated AlInAs/GaInAs/InP heterostructures on the properties of quantum cascade lasers

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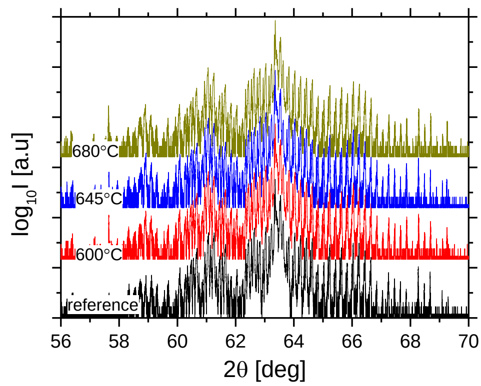
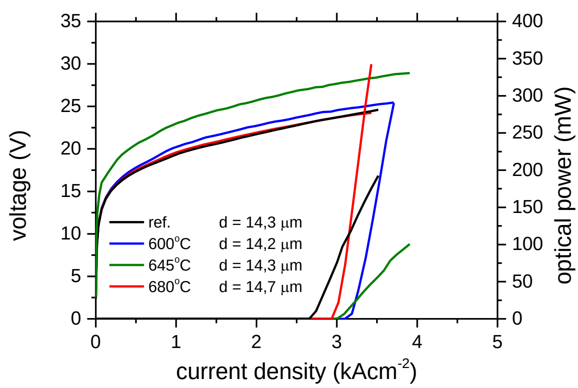
Quantum cascade lasers (QCLs) based on the AlInAs/GaInAs/InP are promising light sources for the applications which require radiation from mid- to longwave infrared e.g. gas sensing systems. To obtain emission at ~4,5 µm band in such material system it is necessary to design strain-compensate heterostructures [1]. Commonly such heterostructures are grown in the molecular beam epitaxy (MBE) because it ensures sharp interfaces and good control of layers thickness [2]. On the other hand, for this wavelength, it is favorable to use InP thick layer as a cladding because of lower losses, but in the MBE growing of the thick InP layers is dangerous because of the risk of white phosphorus deposition. This problem does not exist in the metalorganic vapour phase epitaxy (MOVPE). It was proposed to use hybrid MBE+MOVPE process, where active region is grown by MBE, and then cladding layers by MOVPE. However, typical temperature in the MOVPE are ~600°C [3] which could cause strain-relaxation in such strain-compensate heterostructures [4].

In this work, the study of the influence of annealing temperature on the strain-compensated AlInAs/GaInAs/InP heterostructure is presented. Active cores were grown by MBE in the Department of Photonics of Institute of Electron Technology (ITE), then annealing was performed in the MOVPE reactor in the Faculty of Microsystem Electronics and Photonics of Wroclaw University of Science and Technology. During annealing, high flow of As-precursor was kept to avoid deterioration of the crystalline quality. The temperature range used for annealing was between 600°C and 680°C. Full processing and the characterization of the QCLs was done in the ITE. Here the differences between the properties of the lasers heterostructures are presented and discussed, based on the results of the electrooptical and spectral characteristics. The laser action was achieved for all annealed heterostrctures and the degradation of the active core was not observed.





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31. Wavelength Control of VCSELs using High-Contrast Gratings

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The vertical-cavity surface-emitting laser (VCSEL) is a well-established light source for sensing and short-reach optical links. The surface emission allows wafer-scale testing enabling low-cost manufacturing, while the VCSELs' small modal volume leads to low power consumption, high-speed modulation at low currents, and small footprint [1]. Conventional VCSELs consist of an active region sandwiched between two distributed Bragg reflectors (DBRs). Replacing the top DBR with a high-contrast grating reflector offers unique possibilities to engineer and control VCSEL emission wavelength and modal properties [2,3].

A high-contrast grating (HCG) is typically formed by bars of high refractive index material suspended in air. For certain grating parameters (duty cycle, period, and thickness), HCGs can function as ultra-thin reflectors with close to 100% reflectivity [4]. Besides reflectivity, the grating parameters also influence the reflection phase. This enables fabrication of multi-wavelength VCSEL arrays by fabricating HCG-VCSELs with different grating parameters [2]. However, in order to utilize the extraordinary properties of the HCG, the VCSEL mode must be sensitive to the HCG, which leads to complicated cavity configurations with coupled cavity effects and low optical confinement.

This talk will summarize work performed at Chalmers University of Technology in collaboration with Hewlett Packard Enterprise. The design of HCGs and HCG-VCSELs will be presented as well as fabrication and experimental results from 980 nm HCG-VCSELs. Finally, multi-wavelength HCG-VCSEL arrays will be presented [5].

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32. Monolithic Subwavelength Grating

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Since they were presented for the first time subwavelength high refractive index contrast gratings (HCG) have brought attention due to their extraordinary features – large polarization discrimination, wide high reflectivity band, low size, and scalability with wavelength. It has been shown that they can be successfully used as mirrors in vertical-cavity surface-emitting lasers (VCSELs). This fact is of great importance especially for the devices emitting at wavelengths for which no good quality distributed Bragg reflectors (DBR) can be manufactured. On the other hand, since an HCG has to be surrounded by a low refractive index material, additional conditions are put on the HCG VCSEL designs making their manufacturing very demanding. In order to overcome this issue we proposed a monolithic HCG (MHCG). We show novel designs of VCSELs with MHCG top mirrors and hybrid MHCG DBR mirrors. We show an impact of number of pairs of residual DBR on cavity properties as well as mechanism of shaping of cavity modes by the manipulation of size and geometrical parameter of an MHCG.

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33. What about Monolithic High-Contrast Gratings?

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The thick multi-layered Bragg mirrors in surface-emitting lasers can be replaced with subwavelength High-Contrast Gratings (HCGs) only a few-hundred nanometers thick, which—if properly designed—can reflect 100% of the incident light [1]. Such gratings are composed of parallel high-refractive-index bars separated by air gaps and arranged periodically with a pitch smaller than the incident light wavelength. Conventionally, it has been assumed that HCGs must be surrounded on both the top and bottom sides by a low-refractive-index material, such as air or an oxide. However, we have recently demonstrated subwavelength Monolithic HCGs (MHCGs), in which the low-refractive-index layer on one side is replaced by a layer with high refractive index. Such MHCGs are still equally as good as classical HCG mirrors [2,3].

Although MHCGs support multiple diffraction orders of the reflected wave, they show no scattering: all the energy is reflected into the zero diffraction order. This effect is the key factor enabling application of MHCGs in VCSELs. Without it, the scattering losses would dominate significantly over the laser gain and would make lasing impossible.

In the talk, I explain this phenomenon. I present visually the results of a numerical analysis of the transition between classical HCGs and MHCGs and I identify the source of the differences between the scatter-less reflection peaks and those that either show strong scattering or do not occur in MHCGs. I show that the key property of MHCGs is a very special form of the grating's impedance/admittance matrix, which causes the zero-order reflectivity peak to be independent of the substrate refractive index. This form of matrix can be obtained for any wavelength and in almost any material system by tuning the geometrical parameters of the grating—its pitch, fill-factor, and height [4].

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Poster abstracts

Thermal properties and degradation mechanisms of InGaN - based diode lasers investigated by thermoreflectance spectroscopy and focused ion beam etching

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Investigation of temperature distribution on the facet of the device, with high spatial and temperature resolution, is crucial to gain insight into thermally activated degradation modes in GaN-based lasers. This work undertakes the problem of temperature distribution measurement on the facet of the nitride lasers. Thermal investigation of the nitride devices is mainly based on thermal imaging. However, this approach is characterized by inherently low spatial resolution, as well as the fact, that the registered image, is averaged over the volume of the device, limiting the ability to observe the enhanced thermal processes occurring at the vicinity of the surface (front facet). Thermoreflectance spectroscopy, provides the possibility of registering of high spatial and temperature resolution images of the surface of the device operating in quasi-CW or pulsed mode.

In this paper, thermal properties of InGaN-based diode lasers are investigated. The thermoreflectance technique was employed to study temperature distributions on the front facet of device. Measurements were performed, allowing investigation of the contribution of two main heat sources to the total temperature rise observed on the facet of device. It has been found that the contribution from reabsorption of laser emission at the facet, is much smaller than the one caused by Joule heating (electrical power). Additionally, devices have been investigated by means of SEM and FIB to determine the degradation sources. Inspection of the devices confirmed the lack of mirror damage or deposits. The main source of degradation was found to be located in the

region of ridge and caused by extended defects. Our findings confirm the hypothesis that injected current is the major driving force of degradation.

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Modelling the electronic structure and optical properties of M-shaped type II InAs/GaInSb quantum wells

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There has recently been reported a significant progress in various concepts of coherent radiation sources in the MIR. As one one of very efficient solutions there evolved the interband cascade lasers (ICLs), proven to have several advantageous features, like broad tuning range of the emission [1-3], minimized influence of the Auger related carrier losses [4], and a very low power consumption [5]. However, in order to fully utilize the potential of ICLs, many parameters of these multilayer structures need to be still further optimized. This concerns especially active region which is composed of a cascade of type II quantum wells (QWs) made of broken gap materials, InAs and GaInSb, forming the so called "W-like" quantum well due to the shape band edge profile of InAs/GaInSb/InAs layers, with usually AlSb barriers. The use of a double InAs layer for confinement of electrons increases the oscillator strength of the optical transitions, when compared to a single sequence of just InAs and GaInSb.

In this work, we discuss a possibility of implementing a novel type-II QWs design, which we called M-shaped, being a combination of GaInSb/InAs/GaInSb layers, i.e. with a double QW for confinement of holes, which affects many important factors, as e.g. the overlaps of the conduction and valence band confined states or sensitivity to system parameter changes (as compositions, layer thicknesses, or electric field). We have modelled the electronic structure and optical properties of such QWs considered as to be grown on a GaSb substrate. The calculations have been carried out within the eight-band $k \cdot p$ theory including strain. There has been considered the use of a double well M-design and a triple type II quantum well structure of that kind, with respect to their utilization in lasers. There will be reported such issues as variation of compositions and thicknesses and external factors crucial in operational devices as electric field. We have obtained that such a design allows preserving the large optical matrix elements in spite of indirect in the real space character of the optical transition, allows for simultaneous red shift of the transitions and exhibits low sensitivity to different nonuniformities. In order to verify the application prospect the results will be confronted with the common W-design QWs. Advantages of M-shape QWs will indicated and prospects of these solutions with respect to the existing ones in interband cascade lasers will be elaborated.

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Time-resolved photoluminescence of GaSb-based type I and type II quantum wells in mid-infrared

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Antimony based compounds have shown great promise as a material system of choice for the next generation 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 3.5 μm. 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) [1], which e.g. enables their exploitation in light emitters and detectors covering spectral range beyond 6 μm [2,3]. 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 electron, 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.

In this work, we present a comprehensive comparison of the carrier dynamics in the type I GaIn(As)Sb and type II InAs/GaInSb quantum wells, including:

- the influence of In and As compositions 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 0.6 and 2.1 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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MBE Growth Process and Structural Characterization of Strained InGaAs/AlGaAs/GaAs Quantum Cascade Lasers

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The main issue that limits high temperature performance of GaAs/$Al_{0.45}Ga_{0.55}As$ devices is the low conduction band-offset, causing the electrons to escape to 3D continuum of states at elevated temperatures of the active region [1]. There were attempts taken to increase the band-offset by e.g. increasing the Al content in the barrier layers. Unfortunately, increased Al content leads to increased inter-valley scattering to X and L minima and consequently to decreased laser performance [2].

In this work we report on the design, realization and structural characterization of a mid-IR QCLs based on $In_xGa_{1-x}As$/AlGaAs/GaAs structures grown by molecular beam epitaxy (MBE). Structures were grown with indium content up to 3% in QWs and 45% of Al in AlGaAs barrier layers. The design results in strained heterostructure, however, no strain relaxation was observed as documented by X-ray diffraction measurements. Alloying of GaAs quantum wells with In increases the energy spacing between upper laser level and three dimensional continuum of states. Also, which is even more significant, it decreases interface roughness and consequently the interface roughness scattering losses. As a result $In_xGa_{1-x}As$/AlGaAs/GaAs devices exhibit performance largely improved over standard AlGaAs/GaAs QCLs. More than 2 times reduction of threshold current density was observed. Lasing at ~9.4 µm was achieved in pulsed mode up to T = 50°C with characteristic temperature T_0 = 120 K [3]. However this modification makes the growth process of laser structures more challenging, particularly in the case of higher indium content.

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Hybrid integration of a multi-channel photonic integrated circuit with an integrated microelectronic driver

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In recent years photonic integration technologies have been extensively developed with specific attention given to telecom and sensing applications, where multiple channel operation is highly advantageous in comparison to traditional solutions based on discrete photonic devices. However, despite excellent performance in the laboratory environment, very few integrated devices are nowadays offered on a commercial basis. One of the major problems is lack of an efficient technique for integration of high-speed active photonic components, i.e. lasers, modulators and detectors, with microelectronic drivers. A typical scheme of bonding, when the photonic chip is positioned next to the electronic driver circuit, may result in long bondwires, and thus also high inductance of such a connection. This, in turn, hampers the RF performance of the optoelectronic system. On the other hand, designing dedicated RF micro-strip lines or coplanar waveguides on the surface of the photonic chip sacrifices too much of its area. A hybrid integration scheme proposed in this work could be an efficient technique of connecting integrated microelectronic drivers with high-speed multi-channel photonic integrated circuits.

The discussed concept is based on the flip-chip technique and will be presented using an example of a four-channel transmitter for fiber-optic access networks, realized as an application specific photonic integrated circuit (ASPIC) complemented with an integrated electronic circuit. It comprises four filtered-feedback lasers, each operating on a single frequency. The lasers generate optical carriers that are digitally modulated by Mach-Zehnder amplitude modulators. The output arrayed waveguide grating multiplexes all four WDM signals into a single output. The circuit has been designed and fabricated in the generic process of SMART Photonics.

The ASPIC is driven by an electronic application specific integrated circuit (ASIC). It provides laser pumping currents and digital signals that drive the Mach-Zehnder modulators. The chip comprises three different drivers and biasing circuits, a CMOS driver, a pseudo-differential driver, and a common mode logic CML driver. The first two provide high output amplitude, while the third driver allows to achieve higher bandwidth – according to simulation results 3 GHz instead of 1.5 GHz, while driving 5 pF load, but at a cost of a smaller output swing. To further increase the bandwidth of the CML driver the inductive peaking technique was used. The ASIC has been designed and fabricated in the AMS 0.35 μm CMOS technology process.

The two devices will be flip-chip bonded using a standard technique. The electrical connections will be made using dedicated bonding pads on both chips. Such a connection minimizes parasitic capacitance and inductance between the driver and the transmitter, which is advantageous with respect to the high frequency performance.

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Pressure-tuned laser diodes for applications in optical spectroscopy of up-converting luminescent materials

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Optical materials offering short-wavelength luminescence and/or lasing in near-UV, violet and blue-green spectral range are continuously considered as extremely attractive from the point of view of broad range of applications in imaging techniques, medical diagnosis and therapy, data processing and storage, entertainment and many others. Today, short-wavelength emission (specifically in UV-violet range of electromagnetic spectrum) is provided by many mature laser technologies. The most prominent examples are different types of gas lasers, like solid state lasers with nonlinear crystals for frequency multiplication, continuous-wave Ar+ ion lasers, He-Cd vapour lasers as well as nitrogen lasers and excimer lasers. Rare-earth doped up-converting optical materials, emitting short wavelength radiation under long wavelength pumping (typically within IR spectral range, easily available to typical laser diodes), may provide an interesting alternative for all above mentioned solutions.

In-depth characterization of up-conversion phenomena in active optical materials requires tuneable pumping sources operating at non typical wavelengths in the near-infrared part of spectrum, hardly available on the market. The commercial offer is limited to Ti:sapphire or certain types of dye lasers, with relatively narrow spectral range of operation. Pressure-tuned high-power laser diodes might offer an attractive solution of this problem, offering broadband tuneable operation (up to few hundreds nm of tuning range in the IR, depending on the original wavelength of operation and type of the chip), easiness of integration with the measurement set-ups and relatively high output powers. Pressure tuning of laser diodes’ lasing wavelength is based on a well-known influence of hydrostatic pressure on the lattice constant, and hence the energy-gap of the material. Development of pressure tuned laser diodes modules required overcoming of multiple technological and technical obstacles related with laser chip mounting schemes (axial strain control), heat dissipation, optical power maintaining etc.

In this work we present a practical application of pressure-tuned laser diodes in optical spectroscopy of RE^{3+} doped up-converting materials. The several up-conversion experiments were performed for different glassy materials doped with various RE^{3+} ions, emitting the short wavelength light under IR pumping, which has enabled simultaneously investigation of the up-conversion phenomena and practical validation of the unique spectroscopic tool.

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Thermal analysis of nitride tunnel-junction VCSELs

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In this work computer simulations of thermal properties of nitride Vertical-Cavity Surface-Emitting Laser (VCSELs) are presented. Thermal analysis concerned lasers emitting two different wavelengths from the violet-green spectral range. The considered structures had different types of bottom mirrors (based on [1, 2, 3]) namely: dielectric, dielectric with built-in Au contact, nitride made of AlN/GaN with superlattices and nitride made of AlInN/GaN. The calculations were performed using a self-consistent computer model [4, 5] created by Photonics Group from Lodz University of Technology.

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Temperature dependence of contact resistivity and in-plane electrical conductivity of p-type DBR in VCSEL

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We present the transmission line measurement (TLM) performed on a vertical cavity surface emitting laser (VCSEL) structure. The measurements were performed in various temperatures between 10 and 60 degrees Celsius for variable sample treatments. We compare the samples that have been subject to plasma oxidation, wet oxidation, and were not oxidized. We observe that the average in-plane electrical conductivity of p-type DBRs in all three investigated cases is decreasing when the ambient temperature increases, in contrast to complete VCSELs, for which the opposite trend has been observed. Thus, it may be deduced that the cross-plane electrical conductivity in VCSELs is increasing with temperature and dominates the electrical conductivity of the whole laser. We also compare the contact resistivity determined based on the standard TLM calculation procedure with the resistivities obtained based on the two-dimensional modeling.

Impact of Chip Size and Top Gold Thickness on Thermal Resistance of p-up Mounted (Al, In)GaN Laser Diode

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Laser diodes can be found in many applications like BluRay, laser photolithography, automotive headlamps, as a pumping source in solid state lasers, medical diagnostics or image projectors. The key component in those applications is a high power and thermally stable laser diode with high wall-plug efficiency. In the state-of-the-art laser diodes the wall-plug efficiency is only about 40% and, under CW operation, the maximum output power is limited by the thermal roll-over effect. To meet the requirements of nowadays applications, the thermal properties of laser diode are extremely important. Moreover, thermal properties of laser diode influences its lifetime which is crucial in many applications, so the lowering of the thermal resistance of laser diode is necessary.

There are numerous factors that influence the thermal resistance of laser diodes, inter alia: the parameters of substrate and epitaxial structure, the size of the chip, subcontact and metallization, solder, mounting configuration or the cooling system.

In the present work, we want to demonstrate the experimental results of the influence of the size of the chip and thickness of the p-side (top) gold metallization on thermal resistance. The aim of this study was to examine whether the p-side gold metallization in (Al, In)GaN laser diode can be used as an effective heat spreader, which extracts the heat from the active region and distributes it over the whole width of the chip and by that reduces the thermal resistance of the device. The main advantage of such an approach is that it is very simple, universal and does not complicate the processing procedures. Additionally it is independent of the laser diode structure, type of used substrate, its thickness or substrate orientation.

We demonstrate that by choosing proper design of the laser diode contacts it is possible to decrease the thermal resistance from 30 to 22 K/W without changing the laser diode structure, the ridge width and resonator length and even to 13 K/W with the increasing length of the chip. The reduction of the thermal resistance is accompanied by lowering the threshold current density from 3.5 kA/cm^2 to 1.3 kA/cm^2 and increasing the maximum output power above 1 W.

III-N semipolar blue- and green-EELs with ITO, AlInN, GaN:Ge and NPGaN

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Tuesday dinner in *Restauracja Alrina* at 19:00

Address: Bulwar Kurlandzki, first river barge from bridge *Kładka Ojca Bernatka*