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3th WORKSHOP ON PHYSICS AND TECHNOLOGY OF SEMICONDUCTOR LASERS

Book of abstracts

October 4-7th, 2009

Program

Sunday, October 4th, 2009

19:00 Barbecue

Monday, October 5th, 2009

08:00 Breakfast

08:50 Opening Address

9:00 – 9:30 **Ulrich Schwarz** (Fraunhoffer Institute, Freiburg, Germany)
Optical eigenmodes and gain in semipolar and nonpolar InGaN/GaN laser diodes

9:30 – 10:00 **Katarzyna Holc** (Institute of High Pressure Physics "UNIPRESS", Warsaw)
New method of the suppression of a mode leakage in violet laser diodes

10:00 – 10:30 **Jakub Goss** (Institute of High Pressure Physics "UNIPRESS", Warsaw)
Optical gain in InGaN laser diodes

10:30 – 11:00 Coffee Break

11:00 – 11:30 **Kamil Kosiel** (Institute of Electron Technology, Warsaw)
GaAs-based (λ~9.4 mm) quantum cascade lasers – Development of technology and basic properties

11:30 – 12:00 **Dorota Pierścińska** (Institute of Electron Technology, Warsaw)
Influence of different operating conditions on QCL temperature

12:00 – 12:30 **Kamil Pierściński** (Institute of Electron Technology, Warsaw)
Heat management in QCLs

12:30 – 13:00 **Michał Wasiak** (Technical University of Łódź)
Thermal analysis of a quantum cascade laser in the short-pulse regime

13:00 Lunch

14:30 – 15:00 **Piotr Perlin** (Institute of High Pressure Physics "UNIPRESS", Warsaw)
Reliability of nitride laser diodes

15:00 – 15:30 **Marcin Siekacz** (Institute of High Pressure Physics "UNIPRESS", Warsaw)
High indium content laser structures grown by MBE

15:30 – 16:00 **Robert Czernecki** (Institute of High Pressure Physics "UNIPRESS", Warsaw)
Growth of InGaN quantum wells for the efficient laser diodes

16:00 Coffee Break

16:30 – 17:00 **Bernard Piechal** (Institute of High Pressure Physics "UNIPRESS", Warsaw)
Package induced strain in laser diodes – the influence of submount material

17:00 – 17:30 **Monika Maziarz** (Institute of High Pressure Physics "UNIPRESS", Warsaw)
The influence of the package induced strain on the high pressure tuning of laser diodes

18:00 Dinner

Tuesday, October 6th, 2009

08:00 Breakfast

9:00 – 13:00 **Free time**

13:00 Lunch

14:30 – 15:00 **Gatien Cosendey** (Ecole Polytechnique Federale de Lausanne, Switzerland)
GaN-based blue SLEDs

15:00 – 15:30 **Szymon Grzanka** (Institute of High Pressure Physics "UNIPRESS", Warsaw)
Efficiency droop in violet and blue laser diodes

15:30 – 16:00 **Robert Kudrawiec** (Wrocław University of Technology)
Dispersion of the recombination time for InGaN quantum wells

16:00 Coffee Break

16:30 – 17:00 **Marta Gładysiewicz-Kudrawiec** (Wrocław University of Technology)
Broadening of interband and intersubband transitions in Ga(In)N/Al(In)N quantum wells

17:00 – 17:30 **Marcin Motyka** (Wrocław University of Technology)

Fourier Transformed Infrared (FTIR) modulation spectroscopy of low dimensional semiconductor structures designed for laser applications in mid and far infrared region

17:30 – 18:00 **Ewa Papis** (Institute of Electron Technology, Warsaw)

The aspects of wet and dry surface etching in AlGaAs/GaAs quantum cascade lasers processing

18:00 – 18:30 **Damian Pucicki** (Wrocław University of Technology)

Influence of arsenic-flux on the annealing of the 1.6 μm laser structures containing GaInNAs quantum wells

19:00 Workshop Banquet

Wednesday, October 7th, 2009

08:30 Breakfast

9:30 – 10:00 **Elżbieta Machowska – Podsiadło** (Rzeszów University of Technology)

Modelling of type II InAs/GaSb superlattices

10:00 – 10:30 **Filip Janiak** (Wrocław University of Technology)

Band gap discontinuities and thermal photoluminescence quenching of GaInAsSb/Al(In)GaAsSb quantum wells emitting in the 3 – 4 μm range

10:30 – 11:00 Coffee Break

11:00 – 11:30 **Adam Szyszka** (Wrocław University of Technology)

Microscale characterisation of optical and electrical parameters of UV GaN planar detectors

11:30 – 12:00 **Michał Szymański** (Institute of Electron Technology, Warsaw)

Solution of nonlinear carrier diffusion equation in axial direction of broad-area lasers

12:00 Lunch

Contents

Abstracts

Optical eigenmodes and gain in semipolar and nonpolar InGaN/GaN laser diodes

Ulrich Schwarz

Fraunhoffer Institute, Freiburg

Semipolar group-III nitrides may be the choice of substrate for green laser diodes (LDs). It has been shown that the optical gain in semipolar LDs depends on the orientation of the waveguide ridge. However, the strong birefringence of the material and its impact on the waveguide modes has not been considered up to now. We show that even in the presence of strong birefringence there exist lilnearly polarized modes. For c′-oriented waveguides (where c′ is the projection of the c-axis on the epitaxial plane) the modes are polarized nearly parallel or perpendicular to the c-axis, i.e. they are extraordinary or ordinary polarized modes and replace the usual TE and TM modes. Only for a waveguide orientation with nonpolar facet, the TE and TM modes still exist. We investigate the anisotropic optical gain in non-c-plane InGaN quantum wells with 20% indium content including band-gap renormalization and the screening of the quantum confined Stark effect. Waveguide modes and their polarizations are determined as TE and TM modes or extraordinary and ordinary modes, depending on the birefringence and the orientation of the laser diode's ridge waveguide relative to the c axis. The band structures and optical matrix elements along the polarization directions are calculated using a 6x6 k·p Hamiltonian and a self-consistent Schrödinger-Poisson solver. From these calculations the reduced density of states and the optical gain for the different polarizations are determined in the free-carrier picture with an ad hoc inclusion of the band-gap renormalization and compared to a c-plane quantum well. It is found that for high indium concentrations the gain can be significantly increased by going from the c plane to a semipolar or a nonpolar crystal orientation. However, due to birefringence and composition of the topmost valence-band wave function, the ridge has to be oriented along the [1-1123] direction for semipolar and along the [0001] direction for nonpolar laser diodes. We were also able to experimentally verify the tilted polarization of the waveguide modes. We measured the amplified stimulated emission using the strip length method as function of polarization angle for different semipolar and nonpolar epitaxial planes and different orientations of the excitation stripe and facet. We found that the polarization aligns with the c-axis within an angle of 3°, confirming the existence of extraordinary polarized modes.

New method of the suppression of a mode leakage in violet laser diodes

Katarzyna Holc[1,2], Marcin Sarzyński[1], Robert Czernecki[1,2], Michał Boćkowski[1,2], Tadek Suski[1], Wolfgang Scheibenzuber[3], Ulrich Schwarz[3] and Piotr Perlin[1,2]

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We present a new idea of the suppression of a mode leakage into the substrate in violet InGaN/GaN laser diodes. The improvement of the transversal waveguiding of the optical mode in the device was achieved by introducing a highly doped (plasmonic) layer on the top of the GaN substrate. Applying this layer we were able to suppress the electromagnetic mode leakage without increasing the amount of strain, introduced by AlGaN claddings. The plasmonic substrate is built as a stack of gallium nitride layers of various electron concentrations deposited by both hydride and high-pressure solution method. Performing theoretical simulations we confirmed the improvement in the waveguide quality and showed that with application of this new layer we were able to suppress the mode leakage completely. The mentioned improvements led to the reduction of the threshold current density of our devices down to 2 kA/cm^2, and to the optimization of the near and far field patterns.

Optical gain in InGaN laser diodes

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The knowledge of the optical gain in semiconductor quantum structures is of a primary importance for the proper design of efficient laser diodes. In the present work we will present the application of two experimental methods: Hakki- Paoli method and Variable Stripe Length method for determining the gain spectra in InGaN laser diodes. We will show the evolution of the gain spectra for quantum structures with the increasing content of indium fabricated by the both MOVPE and MBE growth methods.

GaAs-based ($\lambda \sim 9.4$ µm) Quantum Cascade Lasers - Development of Technology and Device Properties

Kamil Kosiel, Anna Szerling, Piotr Karbownik,
Justyna Kubacka-Traczyk, Emilia Pruszyńska–Karbownik,
Kamil Pierściński, Artur Trajnerowicz, Maciej Bugajski

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Quantum cascade lasers (QCLs) are unipolar devices, in which the mechanism of emission of coherent radiation is based on the intraband optical transitions of carriers. The idea of QCL exploits the features of low dimensional systems, generated on the basis of the conduction band edge discontinuities in complicated multilayered semiconductor structures.

The needed emitter properties are strictly dependent and controllable by thicknesses and compositions of active region individual layers. This places stringent requirements on the growth precision, as well as run-to-run reproducibility of appropriate realization of these constructional assumptions. Hence the perfect temporal stability and spatial uniformity of growth conditions (i.e., accuracy of spatial-temporal growth rate pattern of binaries constituing the structure) is necessary. The very high standards are set in the field of the post-epitaxial, device processing technology, as well. e.g., the highly smooth mesa walls are necessary to avoid the strong losses of radiation.

In this paper the technology issues pertinent to AlGaAs/GaAs QCL devices are reported. The adopted structure design followed an "anticrossed-diagonal" scheme of Sirtori et al.1 with further improvements towards its temperature performance, made by Page et al2. The planar optical confinement was ensured by double plasmon waveguide. The double trench lasers were fabricated using processing technology, which combined the wet etching of mesa with dielectric isolation applied to limit the lateral current spreading.

The AlGaAs/GaAs quantum cascade lasers emitting $\sim$ 9.4 µm, with over 1 W peak powers (77 K) per uncoated mirror, have been fabricated. The maximum temperature of pulse operation was 264 K, which is the region accessible for TE Peltier coolers.

Influence of operating conditions on the temperature of Quantum Cascade Lasers

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The quantum cascade lasers (QCLs) are the most advanced class of semiconductor sources operating in the midinfrared wavelengths (3.5 - 24 μm) [1] and also in the terahertz range (1.2 – 4.9 Thz) [2, 3]. The first demonstration of emissions in GaAs/ AlGaAs QCL was reported in 1994 by C. Sirtori group [4]. From this time QCL based on this materials have undergone a rapid development over the last few years. However still, the highest operating temperature in continuous wave are 150 K. The main limiting factors are the large electrical power density required for operation, and the low thermal conductivity characteristic of ternary alloys and complex multilayer heterostructure. Those factors contribute to high temperature gradients in the device. Additionally, temperature causes the leakage of the electrons into delocalized continuum states, lowering the population inversion. These effects are the main limiting factors of the high temperature operation of the devices.

In order to gain insight into the thermal management in QCLs we have examined the influence of different operating conditions on the temperature of QCL. The heat load in the device was changed either by changing the pulse time at constant frequency or by changing of the frequency of constant pulse time. Both ways provide the same duty cycle and we have investigated the temperature of the device in these two modes. In this paper we use spatially resolved thermoreflectance (SRTR) to measure temperature distribution over the facet of pulsed operated quantum cascade lasers [5]. The method is based on the measurement of the change in the refractive index caused by current-induced heating of working device. The technique has a spatial resolution of about ~1 μm and temperature resolution better than 1 K. It has been previously applied to study facet heating in edge emitting lasers [6, 7].

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Thermal management in Quantum Cascade Lasers

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The Quantum Cascade Laser (QCL) is a unipolar device in which the emission takes place between the electronic levels in the conduction band, unlike the bipolar edge emitting lasers based on the optical transitions between bands. The QCLs have undergone a rapid development since the demonstration of the first operating device in 1994 [1]. However in lasers based on gallium arsenide, the room temperature continuous wave operation is still a challenge. The performance of the QCL is strongly limited by thermal processes. At elevated temperatures, the carriers are subjected to thermal excitation and escape to continuum rather than being injected into the next cascade. Also, the energies of phonons, taking part in removing the carriers from lower state are changed. Thermal management in QCLs will be presented. The devices are characterized by means of optical modulation technique – thermoreflectance [2, 3]. The method relies on measurement of the relative reflectivity changes due to periodic perturbation of the sample's temperature. In this case the device temperature is modulated by operating it in pulse mode. The thermoreflectance provides information about the temperature distribution on the device facet.

The thermal properties are also investigated by numerical simulations. The finite element analysis was performed to gain the insight into the thermal management in QCLs. The model provides useful information and hints on the impact of different factors on device temperature.

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Thermal analysis of a quantum cascade laser in the short-pulse regime

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Quantum-cascade lasers (QCLs) suffer from great amount of Joule's heat dissipated inside them. With voltages of order of 10 V and multi-amps currents the temperature rises are significant even in short pulses. In this paper we focus on the distribution of the heat sources and possibility of finding an analytic expression describing the temperature of a QCL's active-region superlattice. Measurements presented in [1] show that the electrical conductivity of the superlattice depends strongly on the temperature. The method used in [1] requires a calibration, in which the temperature rise after time of order of ten nanoseconds is assumed to be negligible. Here we want to verify this assumption and find the actual temperature.

First we determined the distribution of the heat source. In order to do that we use our numerical model to find the resistance of both the superlattice and the rest of the structure. Replacing the superlattice with a perfectly conducting layer, we calculated the resistance of the rest of the laser. In temperatures slightly above the room temperature this resistance is about 0.1 Ω, which is only about 3% of the total resistance. It means that almost whole heat source is distributed in the superlattice.

Since the numerical calculations of the evolution of the temperature are time-consuming, we tried to find an approximated analytical formula describing the temperature in the middle of the superlattice. It is possible to find a reasonably compact formula using Green's function and assuming homogeneity of the medium. In fact the medium is not a homogeneous one, since at least the thermal conductivity of the superlattice is very different from the conductivity of the adjacent layers. It is the reason why this formula may be valid only for a limited time. We compared this formula with the numerical calculations, which simulate the whole structures. This comparison suggests that the analytical formula remains valid within first a few hundreds nanoseconds.

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Reliability of nitride laser diodes

Piotr Perlin[1,2], Lucja Marona[1], Mike Leszczyński[1,2], Tadek Suski[1],
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We discuss various mechanisms of laser diode degradation based on our own experiments and on the available literature data. In most of the cases degradation of InGaN laser diodes occurs through the increase of the threshold current with almost constant slope efficiency. The threshold current change follows frequently the square root on time dependence. Though this type of behavior has been usually attributed to magnesium acceptor diffusion, no firm proof of such a hypothesis was so far presented. In contrast, there is an increasing number of reported experiments showing that the most important factor contributing to fast (hours), and medium time (hundreds of hours) degradation is the process of carbon deposition. This process involves photochemical reactions leading to the decomposition of hydrocarbons existing in the laser diode environment. This process resembles very closely the mechanism responsible for 980 nm laser diode degradation and known as Package Induced Failure.

High indium content laser structures grown by MBE

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The one of the demanding tasks for nitride laser diodes is to move the emission wavelength from blue-violet to green region. The substantial limitations like InGaN decomposition, large piezoelectric fields, large lattice mismatch in structures for green emitters are still challenging for epitaxy. In this work we discuss the growth by plasma assisted molecular beam epitaxy (PAMBE) and characterization of LD structures with high In content in active region (MQWs), which span the photoluminescence emission wavelength from 480 nm to 550 nm. Photoluminescence at low excitation powers for these MQWs was investigated as a function of the quantum well width with the purpose of determination carrier recombination mechanisms. Further on, we present the lasing at 470 - 480 nm on optically pumped InGaN/GaN/AlGaN separate-confinement heterostructure laser structures grown by PAMBE on GaN substrates grown by HVPE with threading dislocation density $10^6 cm^{-2}$.

Growth of InGaN quantum wells for the efficient laser diodes

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InGaN quantum wells form the active layer of almost all nitride based emitters operating in the wavelength range between 370 and 530 nm. This material however, forms a complicated system both from the point of view of its properties (large strain, high built in fields and strong tendency to phase separation) and the growth conditions. In this work we would like to pay special attention to the determination of the optimum growth conditions of InGaN quantum wells with the variable indium content. We will discuss the influence of the growth temperature and also substrate misorientation on the indium content of the layer. Finally we will demonstrate the applicability of the described technology for the fabrication of InGaN laser diodes operating between 390 and 440 nm.

Deformations of laser diodes induced by mounting on various submounts

Bernard Piechal[1], Grzegorz Maciejewski[2], Monika Maziarz[3], Witold Trzeciakowski[1]

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We present the finite-element calculations of the mounting-induced strains in the active layers of laser diodes mounted on various submounts, under pressure up to 2GPa. The accuracy of the calculations is confirmed by the profiles measurements of the top surfaces of the submounts mounted on Cu (and deformed by thermal strains). Our measurements indicate that Indium solder relaxes most of the mounting-induced strain while the Au/Sn solder can be treated as an ideal bond.

Finally, we discuss the calculated strain in the active layers of the mounted laser at pressures of 2GPa. The calculations show that the use of the different submount affects not only the amount, but also to the large extent the geometry of the mounting induced strain. For the lasers mounted epi-side down on diamond and Si the mounting induced strains are almost purely biaxial. Contrary, for the laser mounted epi-side down on AlN there exists significant [110] uniaxial component.

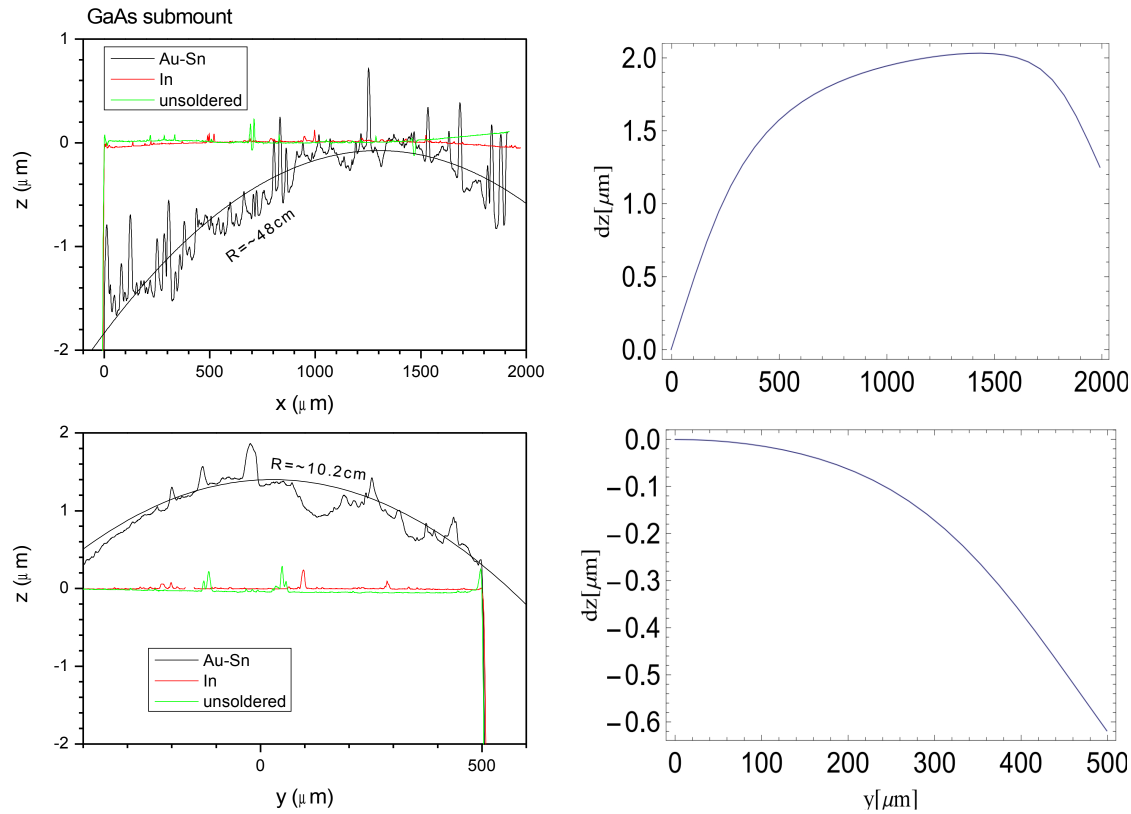

Figure 1: Experimental (left) and calculated (right) surface profiles of the GaAs submount (2 mm long, 1 mm wide and 0.25 mm thick) soldered onto the Cu heatsink. In experiment the submount has been soldered with Au-Sn (black), In (red) and unsoldered (green). x and y are the directions along the longer and shorter edge of the submount respectively. Note, that y=0 is set at the middle of the submount whereas x=0 – at the front edge.

Impact of the mounting-induced strains on pressure tuned laser diodes

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Wide-range wavelength tuning of semiconductor lasers can be achieved by applying high pressure or low temperature [1]. The efficiency of wavelength tuning is mostly determined by the physical properties of the laser structures. However, the fabrication process of laser diodes introduces other factors that can influence the emission and its dependence on pressure. In particular, for the reliable modeling of the pressure tuned LDs, one has to take into account the mounting-induced strain. Only then, modeling can help to design optimal laser structures and the quantitative assessment of the mounting-induced strain effects is crucial for proper choice of submounts in the fabricated LDs. The choice of submounts affects the reliability of the laser diode submitted to pressure and temperature cycling.

We have performed the modeling of the pressure tuned LDs mounted on AlN, diamond and Si. The modeling was performed employing simulation package nextnano3 [2]. In addition to the strain resulting from the lattice mismatch of the QW, we implemented the external strain into the nextnano3 code to account for the mounting-induced strain. The strain tensor was obtained by finite-element calculations. The energy spectra and corresponding 8-component spinor eigenstates have been found by solving standard 8x8 k·p Hamiltonian, coupled with the Poisson equation. These eigenfunctions have been used to calculate absorption of the QW laser structure, using standard procedure [3] with lorentzian broadening. By differentiating the absorption profiles in TE and TM polarizations we were able to identify the electron-heavy hole and electron-light hole transitions and to compare them with the experimental data (differential photocurrent spectra).

Mounting-induced strains were found to affect significantly the pressure dependence of the transition energies. For the devices packaged p-down on diamond we observed the lowest pressure tuning range, whereas laser diodes mounted on Si were the least affected by mounting-induced strains.

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GaN-based blue lasers

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Thanks to the tremendous development of III-nitrides (GaN and its alloys) over the past decade, white light emitting diodes (LEDs) are entering the market of general illumination and UV-blue laser diodes (LDs) are now used in mass consumer products such as DVD players.

Here we report on InGaN/GaN multiple quantum well (MQW) based LDs with and without an $Al_{0.83}In_{0.17}N$ cladding layer. The samples have been grown on sapphire or freestanding GaN substrates by metal organic vapor phase epitaxy. The emission properties of our state of the art LDs exhibit a current threshold of 3 kA/cm^2 and a differential quantum efficiency of 0.5 W/A (per facet – uncoated) under cw operation. The lifetime is exceeding 100 h without facet coating. Then we will discuss the impact of the AlInN cladding on I-V characteristics and the field distribution pattern. Finally, the potential of GaN materials for novel optoelectronic devices like blue superluminescent LEDs will be presented.

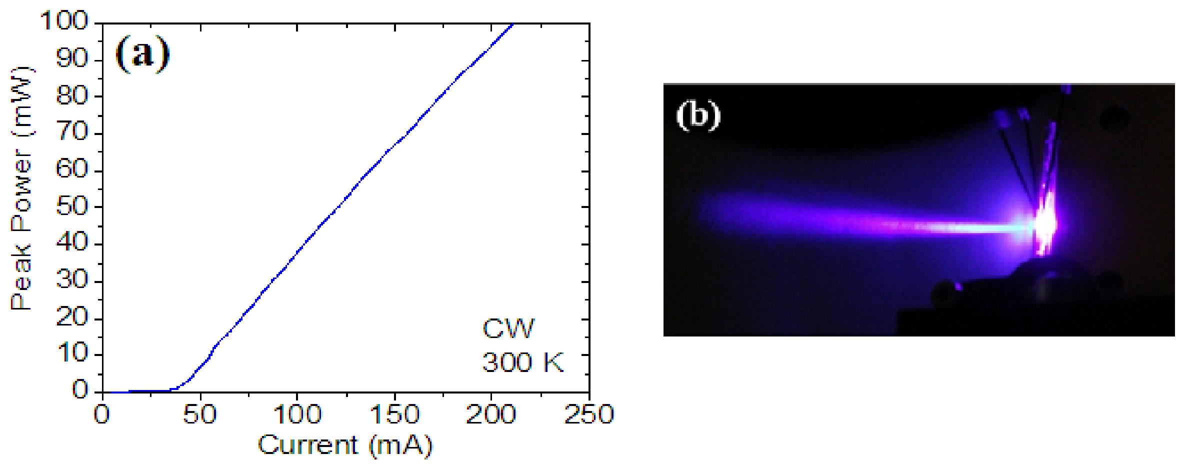

Figure 1: (a) L-I curve of an LD under cw operation at RT, (b) micrograph of a working LD

This work was supported by the NCCR Quantum Photonics research instrument of the Swiss National Science Foundation (SNSF).

Effect of efficiency droop in violet and blue InGaN laser diodes

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The decrease of the light emission efficiency at high currents in the nitride based light emitting diodes (LEDs) – nicknamed as ″droop″ attracts a lot of attention because of its importance for the production of very bright white LEDs which could in perspective completely replace the incandescent bulbs. The proposed reasons for the observed phenomenon were: internal polarization related current escape, poor holes injection and finally Auger effect. In the present paper we do not give an answer concerning the nature of this effect, but we study the influence of droop on the operation of InGaN laser diodes which in principle should be the most affected by this high-injection effect.

We have studied two types of InGaN laser diodes emitting at 410 and 440 nm. Each device was characterized by measuring light-current dependences in the broad range of current densities, up to the lasing threshold. The measurements were performed in two geometries for which the light was collected: a) along the resonator axis (mirror side), b) perpendicularly to the cavity (substrate side). In the "mirror side" configuration, the 410 nm device displays no reduction of differential efficiency (droop) while 440 nm laser shows evidence of droop. In the "substrate side" configuration both devices show the pronounced droop. We associate the suppression of the droop in the "mirror side" configuration with the early appearance of the stimulated recombination which shortens the radiative life-time of the carriers, making the nonradiative recombination (e.g., Auger mechanism) less competitive. For the blue laser this mechanism may be less efficient because it shows a higher onset of the stimulated emission in this material.

Dispersion of the recombination time for InGaN quantum wells

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It is usually reported that the decay time of photoluminescence from InGaN quantum wells (QWs) exhibits a dispersion behavior, i.e., the decay time increases for longer wavelengths. This phenomenon is attributed to the carrier localization in InGaN QW due to indium and/or quantum width fluctuations. In this work the dispersion of recombination time has been calculated for InGaN QWs. In these calculations we have considered separately QW width fluctuations and indium content fluctuations. In addition, the two fluctuations have been considered at the same time. It has been found the simultaneous presence of QW width and indium content fluctuations significantly enhances the dispersion of recombination time for InGaN QWs.

Broadening of interband and intersubband transitions in Ga(In)N/Al(In)N quantum wells

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The homogeneous broadening of intersubband absorption in GaN/AlN QW with no QW width fluctuation (a system with perfect QW interfaces) has been found to be 67 meV [1]. From the viewpoint of band structure as well as growth conditions, an incorporation of indium atoms into GaN/AlN QWs is needed or/and profitable in many applications. On the other hand, it is expected that alloying of GaN (or AlN) with InN should lead to higher inhomogenities in this system including higher fluctuations of QW width and hence an inhomogeneous broadening of intersubband absorption. Therefore, the issue of broadening of intersubband absorption in GaN-based QWs containing indium is important to explore, understand and optimize. This issue is also very interesting for interband transitions. So far homogeneous broadening for interband transitions in GaN/AlN QWs (i.e., narrow peaks with Lorentzian-like broadenings) were not reported. However, it should be noted that intersubband transitions in GaN/AlN were explored less intensively than in InGaN/GaN QWs, i.e. QW systems dedicated for laser applications. In the case of the last QWs, the energy gap fluctuation, which is associated with the alloy content fluctuations, are very important and lead to inhomogeneous broadening of optical transitions. In addition, the energy difference between the fundamental electron (hole) level and excited electron (hole) levels in this system is much smaller because of very small band gap discontinuity at QW interfaces in comparison to GaN/AlN system (for electrons it is 100 - 300 meV vs. 2eV). In this paper, the influence of (i) alloy content fluctuations and (ii) QW width fluctuation on the broadening of intersubband and interband transitions has been studied theoretically within the electron effective mass approximation and compared with the available experimental data for various GaN-based QWs.

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Fourier Transformed Infrared (FTIR) modulation spectroscopy of low dimensional semiconductor structures designed for laser applications in mid and far infrared region

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Modulation spectroscopy, due to its absorption and differential character, is an excellent tool to study the energies of optical transitions (including the excited state ones) in quantum well (QW) and quantum dots as well as energies of bulk-like QW barriers or intermediate layers. Such experiments have already been successfully employed to study GaSb-based QWs for infrared applications up to 2 μm [1, 2] and including type II structures for even longer wavelengths [3]. Nevertheless, the standard modulation spectroscopy based on diffraction grating monochromators has some limitations due to several reasons like e.g. less sensitive detectors or less efficiency of the probing light sources in case of mid and far infrared (comparing e.g. to the tools used in the visible range) [4]. Because there is a growing interest and necessity to investigate structures designed for operation in mid and far infrared range (e.g. infrared detectors, quantum cascade lasers, etc.) it has been proposed to exploit modulation spectroscopy realized by using Fourier transformed spectrometer [4]. This approach has already been used to investigate mainly the bulk-like materials and layers. In this work we are demonstrating the application of FTIR modulation spectroscopy for investigation of low-dimensional structures like type I or II quantum wells designed for mid infrared spectral region (up to 5 μm). High signal to noise ratio of the measured spectra shows that this approach might by very perspective for the characterization of electronic and optical properties of structures designed for longer wavelength QCLs at 10 - 15 μm and further into the infrared.

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The aspects of wet and dry surface etching in AlGaAs/GaAs quantum cascade lasers processing

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GaAs-based layered structures are very suitable for obtaining high-performance semiconductor lasers, in particular AlGaAs/GaAs quantum cascade lasers (QCLs), which are very attractive sources for many laser-based applications areas such as medicine, chemical sensing and fee-space communication. Specific layered construction of QCLs requires high quality of surface with good morphology and controlled composition, properties that depend on Ar^+ sputter etching before metal deposition process. Sputter etching would be effective and promising method of *in-situ* surface preparation prior to metal deposition if ion-induced damage of semiconductor surface could be minimized. On the other hand, the formation of mesa structures for electrical isolation is a critical part of QCLs processing. We present the results of recent investigations of (100) GaAs surface pretreatment by Ar^+ plasma sputter etching for AlGaAs/GaAs QCLs processing and chemical wet etching in HCl-based solution for formation of mesa structures. Finally, a practical application of the two steps treatment: HCl-based chemical and Ar^+ ion etching for surface preparation prior Ni/AuGe/Ni/Au layered contact deposition is demonstrated. A Variable Angle Spectroscopic Ellipsometry was used to provide complementary information on the thickness, refractive and coefficient index and dielectric function of defected surface layer. X-ray Photoelectron Spectroscopy provided information on surface chemistry and AFM on surface morphology. Additionally, the surface was analyzed by Photoluminescence method. In summary, application of Ar^+ sputter etching and mesa chemical etching in HCl-H_2O-H_2O_2 (40+4+1) solution allows to obtain ohmic Ni/AuGe/Ni/Au contact with rc= $1.7 \times 10^-7\Omega cm^2$ with excellent adhesion and long term-stability.

Influence of arsenic-flux on the annealing of the 1.6 μm laser structures containing GaInNAs quantum wells

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Dilute nitride lasers have attracted much attention in the past years because of their ability to realize GaAs-based laser diodes emitting in the telecom wavelength windows around 1.31 μm and 1.55 μm. Annealing is considered as an essential step to obtain good optical quality of GaInNAs quantum well (QW) material. The use of low As-fluxes during the growth of GaInNAs QWs has been shown to improve the homogeneity of the alloy [1]. In this work we show that the As-flux also strongly influences the annealing properties and that over-annealing of the QW can lead to strong degradation of the optical quality (Fig.1) Over-annealing can already occur during the growth of the top cladding layers in a laser structure and can be avoided by choosing an optimized As-flux.

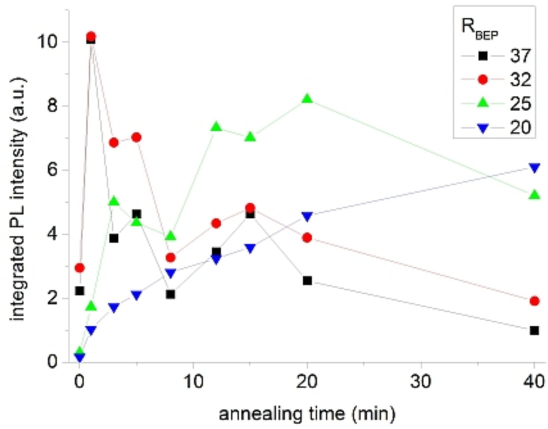

Figure 1: Integrated PL intensity of samples S1-S4 as a function of annealing time (lines between measurement points only to guide the eye)

Using lower As fluxes results in an increase of the time the QW can withstand under annealing without degradation preventing over-annealing. Optimized As-fluxes allowed realization of antimony-free lasers with wavelengths up to 1.61 μm and a threshold current density of 3.2 kA/cm^2.

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Electronic states in type-II superlattices

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The type-II superlattices are expected to be the important part of modern semiconductor devices. They may be used e.g. for the infrared radiation (IR) detection , but they also may be a part of a quantum cascade laser structure.

Optical properties of the superlattices (SLs) are described with the help of the three-band Kane model in which the Hamiltonian of the system describes the electron states in the conduction band taking into account the valence band with the heavy holes (HHs) and the light holes (LHs) states. In the work [1] the method for solving of the system is presented. The method relies on the composing of the solutions which describe: 1) the dispersionless HHs miniband and 2) the coupled minibands of the electrons and the light holes. Such solutions do not respect the interaction between the HHs and the LHs states, which occurs mainly at the interfaces of the SL.

In our work the electronic states in the type-II superlattices are demonstrated. Band dispersions of InAs/GaSb periodic structure were calculated with the respect of the LHs and the HHs states mixing at the interfaces of the SL [3]. Basic properties of the SLs with different InAs layers thickness were determined. The effect of narrow InAs energy gap was taken into account with the help of the three-band Kane model [1, 2] and the wavelengths, corresponding to the interband optical transitions in the SL, were presented.

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Band gap discontinuities and thermal photoluminescence quenching of GaInAsSb/Al(In)GaAsSb quantum wells emitting in the 3 – 4 μm range

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Many industrial branches use or emit (as a side product in production processes) different, dangerous or harmful gases like CO_2, SO_x, NH_3, and many others, including hydrocarbons. It causes a necessity to construct tools which give the possibility to detect and control their presence or concentration. Semiconductor lasers with GaInAsSb/Al(In)GaAsSb quantum wells (QWs) operating in the wavelength range above 3 μm are attractive light source for applications including remote gas sensing, pollutant detection, medical procedures or laser spectroscopy. Most of the existing reports are focused on the lasing properties i.e. threshold current, light output power, T_0 values, etc. Much less attention has been paid to the electronic structure parameters of this QWs. We present more fundamental optical and electronic properties of such a QW system predicted for laser-based gas sensing application in hydrocarbons detection in 3 – 4 μm spectral range. Combining two spectroscopic experiments, like photoluminescence and photoreflectance, allowed the detection of the optical transitions and after a comparison to the effective mass energy level calculations their unambiguous identification. Based on that, conclusions regarding the band gap discontinuities in such structures have been drawn for different well and barrier compositions giving, for instance, a clear experimental evidence of the hole confinement enhancement when changing from quaternary to quinary barrier material. In addition, the thermal quenching of photoluminescnence has been investigated (including the effect of post-growth thermal annealed) and hence the activation energies determined. Based on that and the temperature dependence of the PL peak position revealing the localization effects two main carrier loss mechanism have been recognized as: delocalization of carriers at low temperatures and the escape of heavy holes to the barrier via the excited states levels in the well.

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Microscale characterisation of optical and electrical parameters of UV GaN planar detectors

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Ultraviolet detectors based on gallium nitride could be applied in: control units for drinking water disinfection systems, monitoring of sun UV radiation influence on biological actions, flame detection, combustion engine control, rocket missile detection and outer space communication. The main advantage of using GaN and its alloy with Al is natural solar blind characteristic and possibility of forming the spectral characteristic shape of detector by changing the alloy composition. The main difficulty in the designing process of devices based on heteroepitaxial layers of GaN is their structure which is not monocrystalline but consists of columns/grains of different sizes. Potential barriers which are created in the region of grain boundaries due to electron trapping are the reason of spatial micro nonuniformities of optical and electrical properties of the material. Planar optical detectors have a low cost of production caused by their relatively simple construction that include one type of semiconductor substrate (n or p type) on which one type of metallization is placed (ohmic in a photoresistor structure and Schottky in a MSM (metal-semiconductor-metal) structure). Simplified model of the performance principles of planar detectors allow to analyze them in two dimensions, so, techniques which enable to evaluate surface distribution of optical and electrical properties are fully applicable to characterize such structures. Investigation of devices was performed applying Scanning Surface Potential Microscopy and Optical Beam Induced Current technique.

Microscale characterization of UV detectors based on gallium nitride allowed to study the effects which influenced on the performance of devices. In case of photoresistors that effects were: potential drop along electrodes and nonlinearity of ohmic contact. In case of MSM structure the potential barriers at grain boundaries influenced mostly on the distribution of photogenerated current.

Solution of nonlinear carrier diffusion equation in axial direction of broad-area lasers

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The presence of carriers in the active layer of a broad-area laser plays a crucial role in the device operation. First, it enables the light propagation by ensuring the material transparency and, second, it gives rise to radiative recombination, which is the basic process for lasing. However, carriers often manifest their presence in other ways as well. For example, they are involved in heat generating processes like non-radiative recombination, Auger recombination or surface recombination. Their movement is governed by diffusion.

It is widely known, that the thermal runaway of broad-area lasers is often a big problem. Sometimes it leads to deterioration of the main laser parameters, in other cases it may result in irreversible destruction of the device via catastrophic optical damage (COD) of the mirrors [1]. Thus deep understanding of thermal phenomena is necessary for designing the improved devices. Thermal models of edge-emitting devices are based on heat conduction equation with carrier-dependent heat sources. To obtain realistic values of temperature, 3D heat flow must be considered, while the dimensionality of the diffusion equation can be reduced to 2 or 1 dimension [2, 3].

In my lecture I will present two methods of solving the nonlinear carrier diffusion equation in axial direction of broad-area lasers. The first method is based on analytical solutions, while the second – uses the finite-element analysis implemented in a commercial software. Both approaches are dedicated for thermal models. The carrier concentration profiles for standard devices will be shown, however initial results for devices with non-injected facets (so called NIFs) will also be discussed.

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