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SensHy

SEVENTH FRAMEWORK PROGRAMME

Book of Abstracts

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8.50	9.00	Opening Address	
9.00	9.30	**M Korn**	Ingredients for successful Photonics proposals
SESSION: **Quantum Wells for Mid-Infrared Laser Emission**			
9.30	10.15	**J Gupta**	GaSb-based Interband Laser Diodes for Hydrocarbon Gas Sensing Beyond 3 m
10.15	11.00	**Y Rouillard**	Incursion into the 3-4 m range with quantum well lasers
11.00	11.20	Coffee break	
11.20	11.40	**T Krier**	Mid-infrared GaInSb/AlGaInSb Strained Quantum Well Laser Diodes grown on GaAs
11.40	12.00	**L Nähle**	DFB Laser Diodes for Sensing Applications beyond 3 m
12.00	12.20	**K Vizbaras**	Recent Progress on Electrically-Pumped Single-Mode GaSb-based VCSELs Emitting around 2.3 µm and 2.6 µm
12.20	12.40	**M de La Mare**	Mid-Infrared Photoluminescence of InAsNSb/InAs Multi Quantum Wells Grown by Molecular Beam Epitaxy
12.40	13.00	**R Kudrawiec**	The concept of new dilute nitrides for quantum wells emitting in mid-infrared spectral range
13.00	13.20	**S Suomalainen**	GaSb-based Distributed Feedback Laser Fabricated by Nanoimprint Lithography
13.20	14.05	Lunch	
SESSION: **Interband Cascade Lasers**			
14.05	14.50	**I Vurgaftman**	Interband cascade lasers for gas sensing in the 3-4 m band
14.50	15.10	**A Bauer**	Interband Cascade Lasers for Hydrocarbon-Sensing Applications
15.10	15.30	**M Motyka**	Fourier mode modulation spectroscopy characterization of mid-infrared semiconductor structures
15.30	15.50	Coffee break	

Thursday, 06.05.2010

SESSION: **Applications - Part I**			
15.50	16.35	**P Kaspersen**	Challenges of Mid-Infrared Spectroscopy in Emission Control
16.35	17.20	**S Lundqvist**	Process control applications in the Mid Infrared
17.20	17.40	**B Basnar**	Intracavity gas sensing using quantum cascade lasers with chromic transducers
17.40	18.00	**Y Bonetti**	IrSens: Integrated Sensing Platform for Gases and Liquids in the Near and Mid-Infrared Range
18.00	20.00	Conference Dinner	

Friday, 07.05.2010

SESSION: **Quantum Cascade Lasers**			
9.00	9.45	**C Sirtori**	Quantum cascade lasers: a unifying concept for laser action in the 3 to 300 m wavelength range
9.45	10.30	**T Masselink**	Short-wavelength InP-based QCLs
10.30	12.00	Coffee and Poster Session	
12.00	12.20	**K Kosiel**	GaAs/AlGaAs (~9.4 m) Quantum Cascade Lasers Operating at the Room-Temperature
12.20	12.40	**M Wasiak**	Numerical modelling of thermal properties of mounting and processing modification of quantum cascade lasers structures
12.40	13.00	**T Slight**	Single Wavelength InGaAs/AlAsSb Quantum Cascade Lasers with Emission in the 3-4 μm Range
13.00	14.00	Lunch	
14.00	14.45	**A Baranov**	Antimonides - alternative materials for quantum cascade lasers
14.45	15.05	**K Pierściński**	Thermoreflectance Analysis of AlGaAs/GaAs Quantum Cascade Lasers
15.05	15.25	**A Wójcik-Jedlińska**	Microphotoluminescence characterisation of quantum cascade lasers
15.25	15.40	Coffee break	
SESSION: Applications - Part II			
15.40	16.25	**F Tittel**	Recent advances in mid- infrared semiconductor laser based trace gas sensor technologies
16.25	17.10	**G Wysocki**	Molecular dispersion spectroscopy in the mid-IR - new approach to sensitive chemical detection
17.10	17.30	**P Kluczynski**	A Faraday modulation spectrometer for detection of nitric oxide using a room temperature cw DFB QCL
17.30	17.50	**B Lendl**	Liquid Phase Spectroscopy With A Widely Tunable External-Cavity Quantum Cascade Laser
17.50	18.00	Closing Address	

Saturday, 08.05.2010

10.00	14.30	Touristic programme - guided tour over the most interesting places of Wroclaw downtown

Ingredients for successful Photonics proposals

Markus Korn

European Commission
Information Society and Media Directorate-General, Components and Systems Photonics, B-1049 Brussels, Belgium

It will be briefly presented, how the proposal evaluation process in the 7th EU-Framework Programme is structured. The evaluation criteria will be discussed in more detail also pointing at the critical requirements to write a good proposal. Time will be available for questions and answers.

Session:

Quantum Wells for Mid-Infrared Laser Emission

Invited

GaSb-based Interband Laser Diodes for Hydrocarbon Gas Sensing beyond 3 m

James A. Gupta, Philip Waldron, Pedro J. Barrios, Geof C. Aers and Craig Storey

Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Canada K1A 0R6

There are currently many applications for sensitive gas detection systems in industrial settings for safety, process monitoring and for environmental studies. High performance semiconductor lasers provide an enabling technology for such applications in the mid-infrared, where many hydrocarbons have strong absorption features. Absorption-based sensing may be accomplished using the technique of tunable diode laser absorption spectroscopy (TDLAS), in which a singlemode laser is modulated through an absorption feature of the target gas in a region which is free of interferences from other species.

Several approaches are being actively pursued to provide laser sources in the important 3-4 m range, including intersubband quantum cascade lasers (QCLs) and interband cascade lasers (ICLs). In the present work, we discuss a more conventional approach which is based on extending the wavelength of type-I interband lasers beyond 3 m. The lasers are grown on GaSb substrates by molecular beam epitaxy and employ lattice-matched AlGaAsSb cladding layers, with compressively-strained InGaAsSb quantum well active regions. A key challenge in obtaining longer emission wavelength lies in designing an appropriate active region. To this end we have investigated bandgap engineering approaches such as the use of quinary AlInGaAsSb separate confinement and quantum well barrier layers[1-3]. The improved hole confinement provided by these quinary layers have enabled us to demonstrate laser diodes with continuous wave operation as long as 3.24 m near room temperature. Ridge waveguide Fabry-Perot lasers near this wavelength have been used to make direct absorption measurements of methane, providing a compelling example of the potential for these devices in hydrocarbon detection.

[1] M. Grau, C. Lin, O. Dier, C. Lauer, and M.-C. Amann, *Appl. Phys. Lett.* **87**, 241104 (2005).

[2] T. Hosoda, G. Belenky, L. Shterengas, G. Kipshidze, and M.V. Kisin, *Appl. Phys. Lett.* **92**, 091106 (2008).

[3] J.A. Gupta, P.J. Barrios, G.C. Aers, P. Waldron, and C. Storey, *Electron. Lett*. **45**, 835 (2009).

Invited

Incursion into the 3-4 µm range with quantum well lasers

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Institut d'Electronique du Sud, UMR 5214 CNRS, Université Montpellier 2, 34095 Montpellier, France

Quantum well laser diodes made from GaInAsSb/AlGaAsSb have proven to be the solution of choice in the 2-3 µm range. Despite having excellent characteristics around 2.0 µm, these devices suffer an increase of their threshold current density with growing wavelength. The maximal wavelength reached with such a laser diode was 3.04 µm under cw operation at 20°C for a threshold current density of 343 A/cm^2 in the pulsed regime [1]. With growing Indium content in the well, the offset for holes decreases and the one for electrons increases (left hand side of Figure 1). This situation has two major drawbacks: The weak confinement of holes enhances hole leakage and the strong confinement of electrons results in an inhomogeneous electron distribution in the wells. An elegant solution to this problem was proposed by D. Z. Garbuzov [2]: The use of the quinary alloy AlGaInAsSb for the barriers may allow for the tailoring of both offsets independently from one another (right hand side of Figure 1).

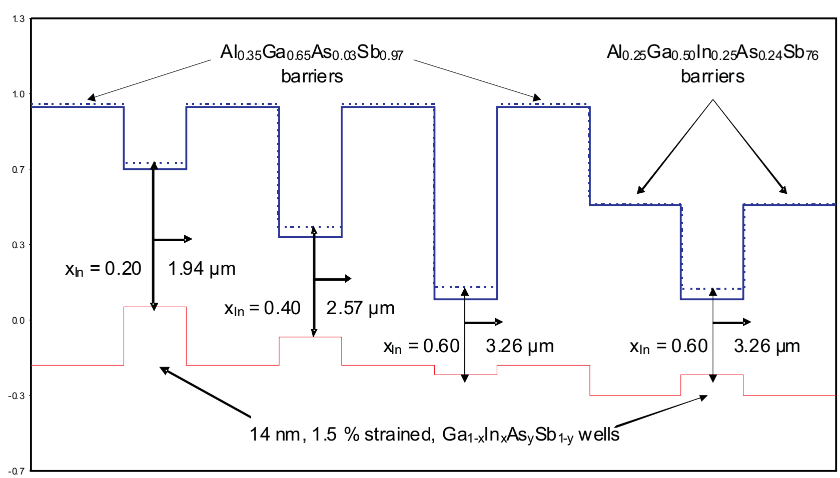

Fig. 1 Imaginary structure constituted of GaInAsSb quantum wells embedded between AlGaAsSb and AlGaInAsSb barriers.

This new concept actually opened the way to the 3-4 µm range, a range which is of primary importance for gas sensing of hydrocarbons by Tunable Diode Laser Absorption Spectroscopy (from 2.98 to 3.11 µm for Acetylene and from 3.15 to 3.50 µm for Methane). We present here our works toward the realization of laser diodes for TDLAS constituted of GaInAsSb quantum wells embedded between AlGaInAsSb barriers. Broad area lasers have been operated in the pulsed regime at room temperature and have demonstrated threshold current densities of 138 A/cm^2 at 2.6 µm, 255 A/cm^2 at 3.0 µm and 824 A/cm^2 at 3.3 µm. DFB lasers made in collaboration with Nanoplus GmbH have been operated in the continuous wave regime at 20°C (and up to 38°C) with a wavelength of 3.06 µm and a threshold current of 54 mA.

[1] C. Lin, M. Grau, O. Dier and M.-C. Amann, *Appl. Phys. Lett.* **84**, 5088 (2004).
[2] D. Z. Garbuzov, M. Maiorov, H. Lee, J. Connolly,V. Khalfin, R. Martinelli, D. Baer, R. Hanson, J. Wang, G. Belenky, D. Donetski, 4th MIOMD Conference, Montpellier, France (2001).

Mid-infrared GaInSb/AlGaInSb Strained Quantum Well Laser Diodes grown on GaAs

A. Krier[1] , M. Yin[1], P. Carrington[1], G.R. Nash[2], S.J. Smith[2], S.D. Coomber[2], S. Przeslak[2], L. Buckle[2], M.T. Emeny[2] and T. Ashley[2]

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The aluminium-indium-gallium-antimonide $Ga_xIn_{1-x}Sb/Al_xGa_yIn_{1-x-y}Sb$ material system has great potential for efficient diode laser operation across the technologically important 3-5 μm spectral range. This material system has the advantage of being able to achieve effective optical and carrier confinement within an active region comprising compressively strained type I $Ga_xIn_{1-x}Sb$ quantum wells providing increased gain, reduced non-radiative Auger recombination and lower threshold current densities [1]. In this work we report on lasers fabricated with 0.55%, 0.62%. 0.78%, and 1.1% strain in the quantum well, grown by molecular beam epitaxy onto semi insulating (001) GaAs substrates.

The diode laser structure consists of a high Al content $Al_zIn_{1-z}Sb$ interfacial layer grown directly onto the GaAs, $Al_{0.25}In_{0.75}Sb$ cladding regions, $Al_{0.12}Ga_{0.12}In_{0.76}Sb$ barriers, and two $Ga_{0.16}In_{0.84}Sb$ QW active regions. The $Al_zIn_{1-z}Sb$ layer and bottom $Al_{0.25}In_{0.75}Sb$ cladding region together accommodate the lattice mismatch between the GaAs substrate and the GaInSb quantum wells. Analysis of the temperature dependence of the photo- and electroluminescence suggests that population of excited quantum well hole subbands occurs at high temperature, leading to a reduction in the emission intensity. An eight band $k\cdot p$ model was used to calculate the energy levels within the quantum well, with strain taken into account [2] giving values of the e_1- hh_1 transition as 364, 361, 392, and 386 meV at 100 K for structures with increasing strain, in close agreement with the measured values [3].

Ridge lasers with sloping sidewalls and a width of ~30 μm at the active region were defined using contact photolithography and wet chemical etching. The devices were cleaved to cavity lengths of 2 mm and indium soldered (substrate-side-down) onto coated copper blocks. The light-current characteristics from each device were measured as a function of temperature, using a 1 kHz square wave and a 1% duty cycle (pulse length of 100 ns).

Lasing was observed up to a temperature of 219 K, with the lowest threshold current density obtained from a laser fabricated from the structure with the highest strain (1.1%) in the QWs. Further improvements to the diode mounting, facet polishing and coating, coupled with the realization of quantum wells with higher strain offer the prospect of relatively low current operation at room temperature.

[1] G.R. Nash, S.J. Smith, S.D. Coomber, S.J.B. Przeslak, A.D. Andreev, P.J. Carrington, M. Yin, A. Krier, L. Buckle, M.T. Emeny and T. Ashley, *Appl. Phys. Lett.* **91**, 131118 (2007)

[2] A. D. Andreev, E. P. O'Reilly, A. R. Adams, and T. Ashley, *Appl. Phys. Lett.* **78**, 2640 (2001).

[3] M. Yin, G.R. Nash, S. D. Coomber, L. Buckle, P. J. Carrington, A. Krier, A. Andreev, S.J.B. Przeslak, G. de Valicourt, S.J. Smith, M.T. Emeny and T. Ashley, *Appl. Phys. Lett*. **93**, 121106 (2008)

This work was supported by the UK Technology Strategy Board Technology Programme (CHBT/006/00058).

DFB Laser Diodes for Sensing Applications beyond 3 m

L. Nähle[1], M. von Edlinger[1], M. Fischer[1], J. Koeth[1], S. Belahsene[2] and Y. Rouillard[2]

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Mid infrared (MIR) laser sources experience a growing demand due to their excellent potential of use in diverse fields of applications, including for example military (e.g. detection of explosives [1]), medical (e.g. glucose level monitoring [2]) and industrial process control [3]. The fact that many technologically relevant gas species have their strongest absorption lines in the MIR region makes Tunable Diode Laser Spectroscopy (TDLS) a powerful means of monitoring such gases. Especially interesting for the detection of hydrocarbons (such as methane, ethane, propane, butane and acetylene) is the wavelength regime around 3 - 4µm [4]. There are different approaches to attain laser emission in this wavelength range of interest. A very promising approach is using the quinary GaInAsSb/AlGaInAsSb/GaSb material system, where cw operation of a multimode device at 3.36µm has been demonstrated lately [5].

For sensing applications monomode emitting devices are of particular importance. We will present here DFB laser sources emitting in the 3.0 - 3.4µm wavelength range based on type-I quantum well epitaxial material with an active region constituted of a GaInAsSb/AlGaInAsSb. The DFB concept underlying these MIR sources is based on the application of lateral metal gratings next to the sidewalls of an etched ridge waveguide structure [6]. The evanescent light wave coupling to the grating structure leads to DFB operation with excellent performance figures, as will be discussed in this talk, qualifying the novel devices for TDLS applications of hydrocarbons.

[1] C. Bauer, P. Geiser, J. Burgmeier, G. Holl, W. Schade, *Appl. Phys.* **B85**, 251 (2006).
[2] A. Lambrecht, T. Beyer, K. Hebestreit, R. Mischler, W. Petrich, *Appl. Spectroscopy* **60**, 729 (2006).
[3] M. Lackner, *Reviews In Chemical Engineering* 23, 65 (2007).
[4] P. Kluczynski, S. Lundqvist, S. Belahsene, Y. Rouillard, *Optics Lett.* **34**, 3767 (2009)
[5] L. Shterengas, G. Belenky, T. Hosoda, G. Kipshidze, S. Suchalkin, *Appl. Phys. Lett.* **93**, 011103 (2008).
[6] M. Kamp, J. Hofmann, F. Schäfer, J.P. Reithmaier, A. Forchel, *Appl. Phys. Lett.* 74, 483 (1999).

Recent Progress on Electrically-Pumped Single-Mode GaSb-based VCSELs Emitting around 2.3 µm and 2.6 µm

K. Vizbaras, A. Bachmann, S. Arafin and M.-C. Amann

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Long wavelength lasers with emission in the mid-infrared wavelength range above 2 µm are attractive light sources for trace-gas sensing systems with tunable diode laser absorption spectroscopy (TDLAS) [1]. Here, a single-mode emitting tunable laser is used in order to rapidly scan the absorption of a certain gas species. The use of electrically pumped VCSELs offers several advantages, such as the inherent longitudinal single-mode operation, low-cost production, small power consumption and the wavelength tunability by changing the applied pumping current. Most gases show strong absorption lines in the spectral range between 2 and 3 µm, which can be covered by GaSb-based devices, making them the most promising candidates for gas sensing applications.

In this work we present recent progress on electrically-pumped single-mode GaSb-based VCSELs, emitting at wavelengths around 2.3 µm and 2.6 µm [2]. Devices were grown using solid-source Varian Gen II MBE with valved cracker cells for Antimony and Arsenic. The device structure typically consists of an epitaxial distributed Bragg mirror, on top of which a multi-quantum-well active region is grown, followed by a buried tunnel junction, current spreading layers and a contact layer. Further processing includes structuring and passivating the mesas, contact evaporation and a 3-pair Si/SiO_2 dielectric top mirror deposition.

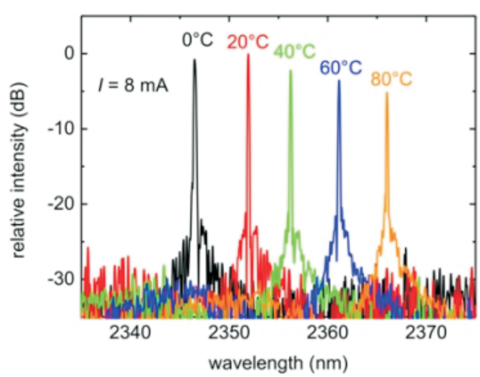

Fig. 1 Measured spectra of a VCSEL, emitting around 2.35 µm, at different temperatures, under continuous wave operation.

Devices emitting around 2.35 µm had low threshold currents of 1.5 mA at room temperature. The side-mode suppression ratio (SMSR) was found to be above 20dB (see figure 1). They were also found to operate under continuous wave up to 90°C.

2.6 µm devices had threshold currents of 4 mA at room temperature and a SMSR above 20 dB. Their continuous wave operation range extended up to 50°C. These are Today's state-of-the-art results and they clearly demonstrate the huge potential of GaSb based devices for gas sensing applications.

This work has been supported by the European Union via NEMIS (contract no. FP6-2005-IST-5-031845).

[1] A. Vicet, D.A. Yarekha, A. Pérona, Y. Rouillard, S. Gaillard and A.N. Baranov, *Spectrochimica Acta Part A*, **vol. 58**, pp. 2405-2412, (2002).
[2] A. Bachmann, S. Arafin and K. Kashani-Shirazi, *New J. Phys*, **11**, 125014, (2009).

Mid-Infrared Photoluminescence of InAsNSb/InAs Multi Quantum Wells Grown by Molecular Beam Epitaxy

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Department of Physics, Lancaster University, Lancaster, LA1 4YB, UK

InAsN dilute nitride alloys could be particularly useful in tailoring optoelectronic devices for the technologically important mid-infrared spectral range (2–5 µm) [1-3]. The growth of InAsNSb alloys is of particular interest due to the potential for producing strain balanced alloys on InAs to further improve material quality. Our previous studies of bulk InAsNSb have shown that the addition of Sb to InAsN increased the incorporated nitrogen concentration and also improved the optical quality [3]. In this work we report the first mid-infrared photoluminescence (PL) from InAsNSb grown by molecular beam epitaxy (MBE).

InAsNSb multi-quantum wells (MQWs) were grown by solid source MBE using a radio frequency nitrogen plasma source. A 200 nm thick un-doped buffer layer was grown at 480°C, before the growth of the ten period InAsNSb/InAs MQW region followed by a 100 nm thick un-doped InAs capping layer. For the active region a $6\ \ 10^{-6}$ mbar N flux was used at a plasma power of 160 W. The structural properties of the resulting material were studied using electron microscopy and HR-XRD. Detailed PL measurements were made over the range from 4–300 K to investigate the InAsNSb optical properties and luminescence efficiency.

Optimisation of the growth conditions for this material led to good crystalline quality material, with weak localisation effects and a low residual carrier concentration of $2\ \ 10^{17}$ cm^{-3} [4]. Bright PL was observed without thermal annealing. The 4 K spectra obtained from the MQW originate from e-hh_1 and e-lh_1 transitions. We observed emission up to 250 K which is a significant improvement in temperature quenching compared with that for InAsN MQWs [5,6]. Our experimental observations are in good agreement with calculations and are consistent with a type I band alignment due to the large conduction band reduction produced by the incorporation of nitrogen.

In summary, InAsSbN/InAs MQWs were grown by MBE which exhibit PL emission in the mid infrared spectral range around 3.6 µm at 4 K. This material system shows promise since it provides a unique opportunity to achieve a type I QW system which can be tailored for use in mid-infrared diode lasers and other optoelectronic devices.

[1] M. de la Mare, Q. Zhuang, A. Krier, A. Patanč and S. Dhar, *Appl. Phys. Lett.* **95** 031110 (2009)
[2] Q. Zhuang, A.M.R. Godenir, A. Krier, K.T. Lai, and S.K. Haywood, *J. Appl. Phys.* **103** 063520 (2008)
[3] Q. Zhuang, A.M.R. Godenir, A. Krier, G. Tsai, and H.H. Lin, *Appl. Phys. Lett.* **93** 121903 (2008)
[4] A. Patanč, W.H.M. Feu, O. Makarovsky, O. Drachenko, L. Eaves, A. Krier, Q.D. Zhuang, M. Helm, M. Goiran and G. Hill, *Phys. Rev. B.* **80** 115207 (2009)
[5] S. Kuboya, Q.T. Thieu, W. Ono, F. Nakajima, R. Katayama and K. Onabe, *J. Cryst. Growth* **298** 544 (2007)
[6] J.S. Wang, H.H. Lin, L.W. Sung, G.R. Chen, Indium Phosphide and Related Materials, Conference Proceedings 549 (2000) ISBN: 0-7803-6350-5

The concept of new dilute nitrides for quantum wells emitting in mid-infrared spectral range

R. Kudrawiec

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The incorporation of a few percent of nitrogen atoms into III-V host leads to both the reduction of the lattice constant and the energy gap. This unusual behavior of dilute nitrides is very promising from the viewpoint of bandgap engineering for laser applications. For recent years a lot of attention was focus on GaInNAs(Sb)/GaAs QWs because of N-related shift of the emission peak to longer wavelength (1.3-1.6μm). Unfortunately, it was also recognized that the incorporation of nitrogen atoms into III-V host deteriorates its optical properties (i.e. the quantum efficiency of luminescence). Recently, it has been found that dilute nitrides have a tendency to pin the Fermi level near the Fermi stabilization energy (E_{FS}) because of a significant concentration of N-related defects in as-grown material [1, 2]. On the other hand it is known that the formation energy of native point defect depends on the Fermi level position versus the conduction (valence) band. For GaInNAs alloys with high indium and nitrogen content the E_{FS} is located in the conduction band that is unfavorable from the viewpoint of the formation energy of native point defects and, therefore, it is difficult to growth longwavelength GaInNAs materials with low concentration of native defects and good luminescence properties [3]. In this work we analyzed the conduction (valence) band position versus the E_{FS} for various dilute nitrides (GaInNAs, GaNAsSb, GaNAsP, GaNPAs, InNAsSb, InNAsP, and InNAsSb,) in the whole range of alloy content within the method which has been proposed in Refs. [4, 5]. In this presentation we want to focus on dilute nitrides which could be a good candidate for quantum wells emitting in the mid-infrared spectral range (>3.0μm).

[1] R. Kudrawiec and J. Misiewicz, *Solid. Stat. Commun.* **150**, 227 (2010).

[2] R. Kudrawiec, H.B. Yuen, S.R. Bank, H.P. Bae, M.A. Wistey, J.S. Harris, M. Motyka, and J. Misiewicz, *J. Appl. Phys*. **104**, 033526 (2008).

[3] R. Kudrawiec, *J. Phys. D: Appl. Phys*. **41**, 245107 (2008).

[4] R. Kudrawiec, *J. Appl. Phys*. **101**, 023522 (2007).

[5] R. Kudrawiec, *J. Appl. Phys.* **101**, 116101 (2007).

GaSb-based Distributed Feedback Laser Fabricated by Nanoimprint Lithography

S. Suomalainen[1], K. Haring[1], J. Viheriälä[1], M-R. Viljanen[1], J. Paajaste[1], R. Koskinen[1], A. Laakso[1], K. Leinonen[2], T. Niemi[1], M. Guina[1]

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We report the fabrication and performance of an InGaSb/GaSb laterally-coupled [1] DFB laser based on nanoimprint lithography (NIL). Previously reported laterally-coupled GaSb DFB lasers have employed metal gratings fabricated by electron-beam lithography [2]. NIL simplifies the processing and potentially enables higher throughput and lower cost for commercial devices.

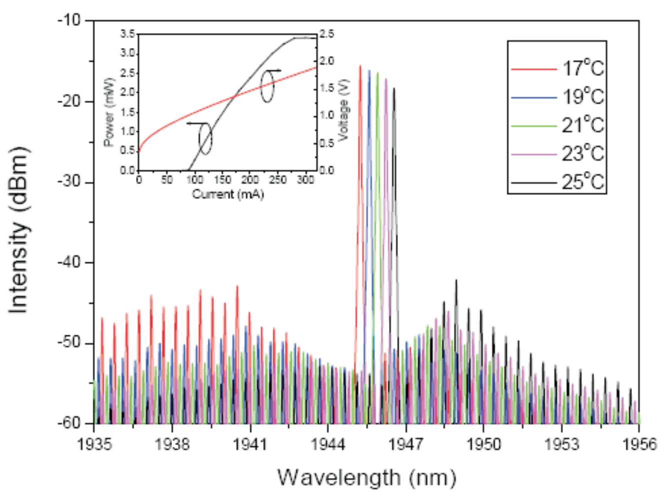

Fig. 1 Optical spectra measured at 180 mA current for different temperatures. Inset: ILV characteristic.

The gain structure was grown by molecular beam epitaxy (MBE) on an n-GaSb (100) substrate. The active region comprised two 8 nm thick $In_{0.2}GaSb$ quantum wells (QWs) with GaSb barrier layers embedded within $Al_{0.2}GaAsSb_{0.97}$ waveguide. The NIL-mask pattern had a centre ridge width of 1.5 m and lateral extension of 0.5 m. The lateral third order grating had a filling factor of 0.5 and a period of 810 nm. Third order grating was used instead of a first order grating in order to reduce the aspect ratio required in the dry-etching step when transferring the pattern to the semiconductor layers. After transferring the DFB grating onto structure by multistep NIL-process the silicon dioxide layer, deposit on surface, was opened from the top of the ridge using conventional UV lithography. After deposition of contact metals, the processed sample was cleaved into 1000 m long devices that were placed p-side up on submounts for characterization. Scanning electron microscope images of a finished component is shown in Fig 1.

The emission spectra, which were measured at a current of 180 mA for several temperatures, reveal single mode operation at around 1945 nm. The corresponding output power was approximately 2 mW. The laser output spectrum remained locked to the DFB grating over a temperature range from 17 °C to 25 °C with output wavelength shift rate of 0.16 nm/°C. The maximum achieved side-mode suppression ratio (SMSR) was over 30 dB at operating temperature of 19 °C. The DFB laser had a threshold current of 90 mA and maximum continuous wave (CW) output power of over 3 mW, as seen in inset of Fig 1. Improvements of the output power and threshold should be possible by optimizing the processing steps. The SMSR can be further improved by optimizing the coupling of the lateral extension with the optical mode.

[1] R.D. Martin et al., *IEEE Photon. Technol. Lett.* **7**, 244 (1995).
[2] T. Bleuel et al., *IEEE Photon. Technol. Lett.* **13**, 533 (2001).

Session:

Interband Cascade Lasers

Invited

Interband Cascade Lasers for Gas Sensing in the 3-4 m Band

I. Vurgaftman, W. W. Bewley, C. S. Kim, M. Kim, J. R. Lindle, C. L. Canedy, J. Abell and J. R. Meyer

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The interband cascade laser (ICL), a hybrid of the conventional interband semiconductor laser and the quantum cascade laser geometry, allows access to any wavelength in the 3-5 m mid-infrared (mid-IR) atmospheric transmission window using the InAs/Ga(In)Sb/AlSb type-II material system. The effective series connection of the active wells in different stages reduces the parasitic voltage drop due to the series resistance, which is particularly important at these long wavelengths. Considerable progress in the design and growth of ICLs recently resulted in continuous-wave operation at and above ambient. Our attainment of $T_{max}^{cw} = 62^{o}C$ was the highest reported for any semiconductor laser operating in the 3.0-4.6 m spectral range. This presentation will review the basic design principles and latest results for broad-area and narrow-ridge devices, including single-mode distributed-feedback lasers (DFBs).

Interband cascade lasers with 5 active stages were grown on GaSb substrates and included an active region with the “W” configuration, GaSb/AlSb hole and InAs/AlSb electron injectors, two GaSb separate-confinement layers (SCLs), and InAs:Si/AlSb superlattice claddings. Iterative optimization of the device design was based on the pulsed characterization results for broad-area lasers. Room-temperature thresholds as low as 400 A/cm^2 were obtained for emission wavelengths of = 3.3-3.7 m, with characteristic temperatures T_0 in the 42-50 K range (over the span 77-300 K). Internal losses inferred from the pulsed differential slope efficiencies at room temperature yielded values as low as 6 cm^{-1} in the 3.5-3.8 m spectral range. The typical pulsed threshold power densities of 1.0-1.7 kW/cm^2 at 300 K are as much as an order of magnitude lower than for the best mid-IR QCLs, although this advantage is partially negated by the lower T_0 of the ICLs.

The ridges of width 4-10 m were fabricated by photolithography and reactive-ion etching using a Cl-based inductively-coupled plasma process that stopped at the GaSb SCL below the active QWs. The ridges were subsequently cleaned with a phosphoric-acid-based wet etch to minimize damage from the ICP RIE process. The ridges were covered with Au electroplating to improve heat dissipation in the epi-side-up geometry. When one facet of a 10 m 3 mm ridge was HR-coated whereas the other was AR-coated or left uncoated, the maximum cw output power at 600 mA was 59 or 51 mW, respectively, while the maximum wallplug efficiency was 3.4% or 3.1%. Although these early WPEs do not yet match the 11% values obtained recently for 4-mm-long HR-coated QCLs emitting at = 4.6 m, they nonetheless demonstrate the promise of ICLs to perform well in the intermediate = 3.0-4.2 m spectral band.

For DFB lasers, ridges were defined in the manner described above except that 4^{th}-order gratings with 2000 nm period and 1000 nm amplitude were etched into both sidewalls of the ridges. Each grating serves the dual purpose of providing longitudinal feedback and suppressing higher-order lateral modes. For operation at T = -20^{o}C, more than 45 mW of cw output is generated in a single spectral mode. At a current of 165 mA, where the input power is only 460 mW, 35 mW of single-mode cw power is produced with 7.6% wallplug efficiency. The tuning range is 11 nm for any temperature between 0 and 25^{o}C, and tuning by up to 25 nm is possible if both current and temperature are varied. The device maintains single-mode operation at current densities up to 10 times the lasing threshold, which is challenging for most DFB lasers in view of hole-burning and other nonlinear phenomena far above threshold. One recent ridge with straight sidewalls operated in cw mode up to a new record T_{max}^{cw} of 72^{o}C.

Interband Cascade Lasers for Hydrocarbon-Sensing Applications

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Out of the various different semiconductor laser approaches trying to grant access to the 3-4 μm spectral region [1-4], antimony based interband cascade lasers (ICLs) have proven to be very promising candidates. Especially due to their versatility in adjusting the desired emission wavelength with only minor design changes [5] the perspective of entirely covering this "gap" in continuous-wave (CW) operation at room temperature (RT) is within close reach [6]. With the recently achieved single-mode emission at 3.6μm under RT CW conditions [7], ICLs have particular promise for tunable laser spectroscopy applications.

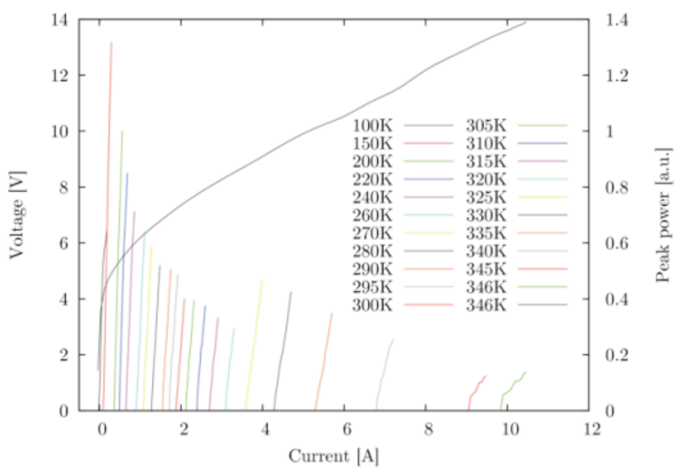

Fig.1 Pulsed I-P and I-V characteristics of a 14-cascaded ICL RWG reaching 73 °C.

In this contribution, ICL devices specifically aimed at emission around 3.3-3.5 µm are presented. Use of a newly developed short injector design incorporating In-free AlSb barriers only, in principle allows for higher carrier confinement and therewith increased modal gain. Shallowly etched broad area structures with 6-14 cascades yield maximum operation temperatures (T_{max}) up to 50°C in pulsed mode, emitting around 3.35-3.55µm at 300K. Deeply etched ridge waveguide (RWG) structures show an increased T_{max} value of 73°C for the 14-cascade material (fig. 1), indicating their potential for single-mode device processing.

Financial support by the EC within the FP7 project SENSHY is gratefully acknowledged.

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Fourier mode modulation spectroscopy characterization of mid-infrared semiconductor structures

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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 3 μm [1] and including type II structures for even longer wavelengths [2]. 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) [3]. 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 [4,5]. 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)[5]. In addition, we would like to introduce the Fast Differential Reflectance (FDR) spectroscopy[6]. This technique allowed to posses the photoreflectance-like spectra similar to this achieved by modulation concept utilize lock-in amplification technique. Nevertheless in FDR approach, the time of collecting spectra might by reduce from hour to seconds in comparison to standard grating- based technique.

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Session:

Applications - Part I

Invited

Challenges of Mid-Infrared Spectroscopy in Emission Control

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Laser-based gas spectroscopy in the Near-Infrared (760 nm to 2300 nm) has been accepted by industrial users as the best available technology for a number of different applications both in process and emission control. Robust and well proven products that will survive a harsh industrial environment are available from several vendors at affordable prices. Careful design of optics and electronics as well as advanced signal processing has made it possible to measure relative absorptions down to better than 10^{-6}, thus resulting in sensitivities that are quite adequate for most industrial applications.

However, for some gases specifically of interest for emission control it is necessary to move into the mid-infrared range, either because the gas of interest (e.g. SO_2) has no absorption features in the Near-Infrared or, in case of NO and NO_2, the absorption strength and thus the detection limit is too low.

To meet customer requirements, measurements of these gases should be done in-situ. This is a very challenging situation where, in addition to a very harsh environment, cross-interference with other gases in the process as well as the actual process gas temperature and pressure have to be taken into account. A detailed spectroscopic analysis of all gases in the process at the actual/expected concentrations and temperature is required to find the most suitable wavelength (i.e. absorption line). Available spectroscopic databases like HITRAN are generally not sufficiently reliable (especially at elevated gas temperatures). Experiences from the Near-IR implicate that an experimental verification is always necessary.

Even if single-line spectroscopy in the mid-infrared spectral region (5 µm – 12 µm) is a powerful and often unique way to provide highly sensitive detection and identification of many relevant species, lack of reliable and affordable single-frequency radiation sources in this spectral region has limited the introduction of industrial instruments.

Many different laser sources have been developed and utilized in mid-infrared spectrometers. Especially the development of quantum cascade lasers has experienced a vast progress during the last decade. QCLs are considered to be the most realistic choice for a robust Mid-IR spectrometer suitable for industrial applications but the challenges in turning a laboratory prototype into a product are manifold: wavelength availability, heat management, optical noise suppression, quality of mid-infrared detectors.

However, a QCL based Mid-IR Gas Analyzer suitable for industrial applications is under development and measurements from initial lab experiments will be presented.

The limited tuning range of QCLs generally allows only the detection of one to two species with the same laser chip. The growing field of industrial applications often demands highly sensitive detection of several molecular species simultaneously. Due to strong interference with other process gases (especially water vapor) it is usually necessary to choose absorption lines that are widely separated even if the corresponding bands are overlapping. Therefore the development of a broadly tunable laser source is very desirable.

Efforts have been made to set up a broadly tunable laser source based on optical parametric oscillation or difference frequency generation. Utilizing an orientation patterned (OP) GaAs crystal for nonlinear conversion allows the generation of radiation covering a wide spectral range interesting for Mid-IR gas spectroscopy.

Even if the current DFG set up is not sufficiently robust to be used in an industrial application it will be a very useful tool to identify suitable absorption lines for specific applications.

Invited

Process control applications in the Mid-Infrared

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Since the mid nineties, analytical instrumentation based on tunable diode laser spectroscopy (TDLS) has gone from laboratory equipment to commercial products were the market is served by a growing number of companies around the world, with a combined sales approaching several thousand units per year. Using telecom grade lasers TDLS analyzers achieves years of unattended operation and are utilized for process control in areas such as combustion control, industrial heating, optimization of deNOx processes, natural gas pipeline monitoring, and environmental monitoring. Progress in antimonide DFB laser fabrication has extended the wavelength range of commercial TDLS instrumentation to 2.8 m where several important gases such as CO, CO_2, CH_4 and NH_3 are accessible in regions reasonable free of water interference. Recently the wavelength range for room temperature single-mode antimonide laser operation has been extended beyond 3 m enabling high sensitivity detection of several important hydrocarbons [1]. The development of the interband cascade laser technology is a strong contender to fill the rest of the frustrating gap in the 3 - 4 m range so important for application in the hydrocarbon industry [2].

The short response time offered by the TDLS technique has the potential to improve the efficiency of many hydrocarbon cracking processes, leading to reduced energy consumption during manufacturing and lower production costs. We have identified a number of applications in hydrocarbon manufacturing especially in ethylene and propylene manufacturing. On-line gas chromatographs are the present standard method for on-line monitoring in the process stream. However, even the fastest chromatographs have a response time exceeding several minutes which is too slow to catch any impurities or to be used in process control.

Ethylene is the largest volume industrially produced organic material and has very stringent purity specifications. Acetylene is a common impurity in ethylene and it is removed in a converter stage. There exist several measurement applications in the process around the acetylene converter and in the final ethylene product at the output of the ethylene plant. It is critical that the acetylene level is controlled to reduce the amount of finished product out of specification that is sent downstream contaminating storage or columns. Acetylene has favorable absorption features at wavelengths around 3.06 m and its spectra have several narrow features further relaxing the tuning requirements of the laser.

Propene is the world's second largest petrochemical commodity and is used in the production of polypropylene, and a number of common chemicals like isopropyl alcohol and acetone. When propene is produced in the presence of hydrogen it is often accompanied by the formation of propane. It is necessary to separate propane from propene before it can be used to produce more valuable products. The most suitable absorption line candidate for detection of propane in a propene background is the line centered about 3.37 m. At telecom wavelengths there are no corresponding sharp spectral features in propane or propene that could be covered by a DFB diode laser

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Intracavity gas sensing using quantum cascade lasers with chromic transducers

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The detection of gaseous compounds using lasers is dominated by the direct interaction of the laser light with the analyte. The narrow absorption lines of gases allow for a highly specific detection of the respective compounds within the gas matrix. However, this specificity is disadvantageous if a group property (e.g. the "acidity" of the atmosphere) is to be investigated, as no specific absorption band can be attributed to this property.

We present a novel method [1] combining chromic transducers and intracavity sensing. In this way we are able to probe the acidiy/basicity of the atmosphere with a sensing volume of 30 pL.

The method is based on the interaction of the evanescent field of the laser mode with a chromic cladding. This cladding changes its absorbance as a function of interaction with the analyte, leading to wavelength-specific changes in the absorbance which, in turn, influences the emitted wavelength and power of the laser (see Fig 1).

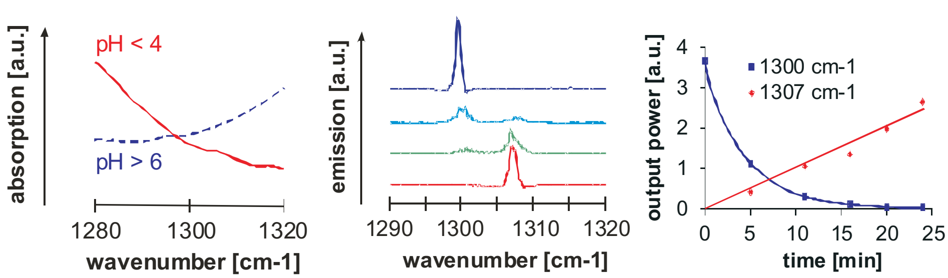

Fig. 1 a) Spectral changes for polyacrylic acid exposed to acidic (red solid line) or basic (blue broken line) vapours. b) Changes in the laser emission during the transition of the coating from salt to acid state, top to bottom. c) Detection of the effusion of ammonia by following the emission of the laser.

Polyacrylic acid (PAA) is acidichromic, i.e. it changes its absorbance as a function of pH. By exposure of a laser with such a PAA coating to the vapours of hydrochloric acid or ammonia, the emission wavelength is changed from 1307 to 1300 cm^{-1}, respectively. Comparing the emission of these two wavelengths allowed for a detection of the acidity of the atmosphere.

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IrSens: Integrated Sensing Platform for Gases and Liquids in the Near and Mid-Infrared Range

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Infrared semiconductor sources and detectors are increasingly becoming commercial products, and a multitude of systems aimed at specific measurement needs are already available, but there exist few attempts yet to integrate them into general-purpose gas or liquid phase measurement platforms for monitoring or in-the-field applications.

In the project presented here [1], we combine various source and detector types in the near- and mid-infrared range with optical waveguide and bench systems together with gas and microfluidic cells, to build a versatile and portable platform with small power and space requirements and capable of measuring various selected trace gases and molecules with fingerprints in a large wavelength range from 2 to 10 micrometers and beyond.

Design considerations, simulations and preliminary results are presented and compared to other projected, published or commercialized systems.

The project was launched in the scope of the Swiss Nano-Tera [2] research framework and is based on the collaboration of several research institutes, aggregating expert knowledge in VCSELs, quantum cascade lasers and detectors, Si avalanche photodetectors, signal processing, microfluidics, microoptics, nonlinear optics, gas and liquid spectroscopy.

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Session:

Quantum Cascade Lasers

Invited

The quantum cascade laser: a unifying concept for laser action in the 3 to 300 m wavelength range

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The quantum cascade (QC) laser is based on artificial potentials made of a sequence of nanometric semiconductor layers. The electronic and optical properties of this device are dependent on the potential design and can be tailored by choosing the appropriate layer sequence [1].

In this device there is no electron-hole recombination across the bandgap as the laser transition occurs between conduction band states arising from size quantisation in quantum wells. A direct consequence is that the emission wavelength does not depend on the band gap of the constituent materials and can be tuned by tailoring the thickness of the quantum wells.

In recent years the performance of these devices has improved markedly and this semiconductor technology is now an attractive choice for the fabrication of infrared lasers for spectroscopic and security applications. Presently, the best performances are obtained in the 4 – 12 m wavelength range, where continuous-wave room temperature operation is routinely achieved with Watt level optical power [2]. Conversely, in the far infrared (> 70 m) quantum cascade lasers operate only up to cryogenic temperatures.

After an introductory part on the principles of operation, I will present the state-of-the-art and performances of these devices. I will then comment on the fundamental physical challenges that still hold in this domain, pointing out some of our recent results on high frequency modulation [3,4]. I will conclude with a perspective on how these devices could be exploited in well established technologies for short range datacom transmission or spectroscopy.

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Invited

Short-wavelength InP-based QCLs

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Quantum-cascade lasers (QCLs) operating in the 3-5 m spectral region are increasingly finding application in a number of areas including gas sensing for both environmental and medical uses, communication, and military countermeasures. QCLs emitting at wavelengths near 4 m and below have been especially challenging, requiring a very large conduction band discontinuity, a small electron effective mass, but also a relatively mature materials system. Short wavelength QCLs with emission near 3 m have been realized based on three designs: 1) InAs-AlSb on InAs [1], lattice-matched InGaAs-AlAsSb on InP [2], and straincompensated InGaAs-AlAs on InP [3].

In this presentation, we focus on our own QCL designs based on the use of strain compensation with very high levels of strain in the individual layers; barriers based on AlAs, wells on $In_{0.73}Ga_{0.27}As$, and the entire structure on average lattice-matched to InP [1]. For more flexibility to control both strain and conduction band potential, "composite barriers" are used, composed of AlAs and $Al_{0.5}In_{0.5}As$. For wavelengths near 3 m, InAs added to the otherwise $In_{0.73}Ga_{0.27}As$ well. A remaining obstacle to very short wavelength emission is the presence of the and X valleys within the well material that can limit the photon energy to the energy difference between these valleys and the lower laser state. By locating the upper laser state in a well based on a material with a larger band gap than the material where the lower laser state is located, however, leakage into the and X valleys can also be avoided. Combining these design components, we have produced QCLs emitting at wavelengths covering the entire range down to 3.05 m [4].

The location of the upper laser states, whether they are predominately in the well layers or in the barrier layers, has a large effect on the oscillator strength, with vertical transitions being stronger. The coupling of the upper states to the lower-lying indirect valleys is, however, also stronger for structures based on vertical transitions. Our results indicate that for short wavelength emission, diagonal transitions are advantageous [4].

QCLs fabricated with narrow 5- m stripes can result in an approximately circular beam profile. Such QCLs are demonstrated with average power of 60 mW using thermoelectric cooling and a beam quality of M^2 1.6 in the lateral direction and approximately diffraction limited in the vertical direction [5].

We have used the same design concept to realize single mode QCLs emitting at 2316 cm^{-1} for spectroscopy of CO_2.

We have also made similarly designed InP-based lasers emitting at 11.3 m with lowtemperature pulse powers of 20 W, maintaining a single transversal mode. At Peltier temperatures, these lasers emit 40 mW average power in high-duty-cycle pulsed operation.

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GaAs/AlGaAs (~9.4 m) Quantum Cascade Lasers Operating at the Room-Temperature

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The fabrication of Quantum Cascade Lasers (QCLs) emitting at ~9.4 mm is reported. The devices operated in pulsed mode, emitting 12 mW peak power at 291 K. The peak powers recorded at 77K were over 1 W, and the slope efficiency 0.5 - 0.85 W/A per uncoated facet.

The laser structure discussed in this paper was the 36 period sequence of modules made of $Al_{0.45}Ga_{0.55}As/GaAs$ coupled quantum wells with 3QW anticrossed-diagonal active region design originally proposed by Page *et al.* [1]. The planar optical confinement has been ensured by double plasmon waveguide. The results of our work referring to the operation at cryogenic temperatures have been reported in ref. [2-5]. Here we concentrate on the improvements in technology and device processing leading to the operation at the room-temperature.

The QCL structures have been grown by Molecular Beam Epitaxy (MBE). The perfect temporal stability and spatial uniformity of growth conditions turned out to be crucial for achieving lasing devices. The thickness accuracy of the QCL module, as documented by X-ray diffraction, was ~ 1 %.

The double trench lasers were fabricated using technology, which combined the wet etching of mesa with dielectric isolation applied to limit the lateral current spreading. The low resistivity Ni/AuGe/Ni/Au ohmic contacts were used at the top of the devices. For current injection, windows were opened through the insulator with width 15, 25 and 35 m. After the wafer was thinned down to about 100 m, an alloyed AuGe/Ni/Au contact was deposited on the backside. The lasers were cleaved into bars of 1, 2 and 3 mm length.

We have examined the influence of different supply conditions; i.e., pulse length and filling factor on the output power, threshold current, value of T_0 parameter, and on the maximum operation temperature. The experimental results indicate a strong dependence on pulse length itself in the submicrosecond range, even for high pulse frequencies.

The work was financially supported by Grant PBZ-MIN-02/I/2007.

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Numerical modelling of thermal properties of mounting and processing modification of quantum cascade lasers structures

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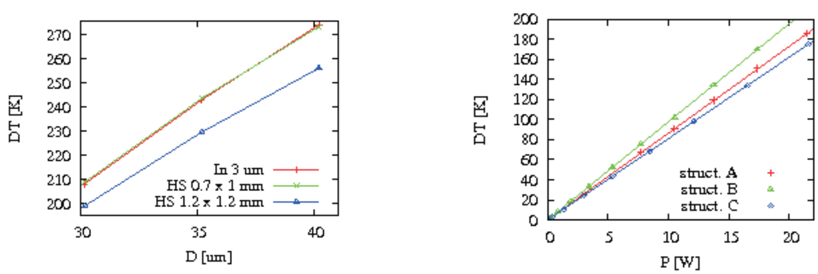
In the Quantum Cascade Lasers (QCLs), the high values of the Joule's heat and reduced thermal resistance of the active core are one of the most serious problems. Extensive optimisation of the device is necessary in order to achieve continuous wave (CW) or room temperature (RT) operation of this kind of laser. In this paper we present results of our 3D numerical modelling of several variants of double-trench QCL fabricated in Institute of Electron Technology in Warsaw. The device is described with details in paper [1]. We analyse influence of mounting and processing features, for instance the diamond heat spreader (HS), parameters of the solder and the trenches, on the thermal properties under DC conditions.



(a) Temperature rise for three different mesa widths and three kinds of mountings. The DC voltage is 10 V.

(b) Comparison of thermal resistance of three different mountings:
A = 30.2 m, HS 1.2 1 mm, trenches filled, R_{th} = 8.64 K/W;
B = 30.2 m, HS 0.7 1 mm, R_{th} = 9.77 K/W;
C = 40.2 m, HS 0.7 1 mm, R_{th} = 8.10 K/W.

Fig. 1 Influence of the mounting methods on the thermal properties of the QCL. In the right graph linear fit of the calculated points together with resulting thermal resistances are presented.

In figure 1(a) one can see that using the small diamond heat spreader of small dimensions does not give any advantage over using thin indium solder. Even the larger heat spreader gives only a limited improvement. Figure 1(b) shows the theoretical values of the thermal resistance of differently processed and mounted structure. The real values are expected to be worse, as we used the highest possible (as the actual value is unknown) value of the superlattice's thermal conductivity, in order to get the limit of R_{th} of the structures.

This work was supported by NCBiR, grant PBZ-MNiSW-02/I/2007.

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Single Wavelength InGaAs/AlAsSb Quantum Cascade Lasers with Emission in the 3–4 μm Range

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This need for efficient and compact sources for the detection of molecular trace gases in the mid infrared region has motivated strong research and development efforts on quantum cascade laser (QCL) technology in the last ten years. Recently, significant progress has been made in the development of short wavelength QCLs emitting in the 3 m < < 4 m wavelength range [1], where many molecular species of interest have their strongest rotational-vibrational absorption bands.

For gas sensing applications the laser must have a narrow spectral width in order to differentiate between the fine features of the unique absorption fingerprint of the gas. We present results from two different designs of single wavelength QCLs.

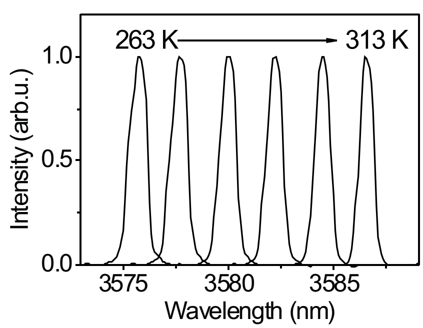

Fig. 1 Emission spectrum of the DM device with Fabry-Perot (FP) spectrum for comparison (T = 300 K)

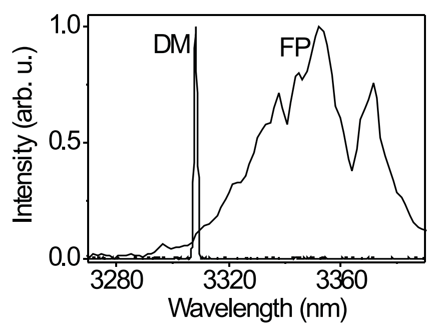

Fig. 2 Emission spectra of the lateral grating distributed feedback QCL

In the discrete-mode (DM) design, single wavelength operation is achieved by introducing index perturbations in the laser cavity [2]. The features modify the Fabry–Pérot (FP) cavity loss spectrum such that lasing is in a single FP mode. At a temperature of 300 K, emission was at wavelength of 3.31 µm (Fig.1) with a side mode suppression ratio (SMSR) of 25 dB.

The second design was of the distributed feedback (DFB) type. First order lateral gratings [3] were etched in the same step as the laser cavity. At a temperature of 283 K, emission was at a wavelength of 3.58 µm (Fig. 2) with a SMSR of 25 dB.

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Invited

Antimonides – alternative materials for quantum cascade lasers

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Quantum cascade lasers (QCLs) employing intersubband transitions in semiconductor heterostructure are now widely used to produce coherent radiation from the mid-IR to THz spectral regions. The most important milestones in the development of this class of semiconductor lasers are associated with two III-V material systems representing compounds and alloys which can be grown on InP or GaAs substrates. III-V compounds with lattice parameters close to 6.1 A is another material family suitable to fabricate QCLs. This group of semiconductors is called usually "antimonides" though it comprises also InAs and its alloys.

Due to the large conduction band discontinuity between InAs and AlSb, appropriate to host high energy intersubband transitions, the antimonides are especially attractive for the development of short wavelength QCLs emitting below 3.5 µm. The remarkable intrinsic properties of this material system allowed us to demonstrate first quantum cascade lasers operating below 3 µm. InAs/AlSb QCLs emitting at wavelengths as short as 2.6 µm have been realized. These results and general issues related to the development of short wavelength antimonide QCLs will be discussed. The small electron effective mass in InAs can be exploited to achieve high intersubband gain in QCLs operating at longer wavelengths. Prospects of use of antimonides in QCLs emitting beyond 8 µm and some results concerning such devices will be presented.

Thermoreflectance Analysis of AlGaAs/GaAs Quantum Cascade Lasers

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The quantum cascade lasers (QCLs) are the most advanced class of semiconductor sources operating in the mid-infrared wavelengths region (3.5 µm –24 µm)[1] and also in the terahertz range (1.2 THz–4.9 Thz)[2,3]. The QCLs based on AlGaAs/GaAs materials have undergone a rapid development over the last few years. However still, the highest operating temperature in continuous wave mode 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. These factors contribute to high temperature gradients in the device. Additionally, temperature causes the leakage of electrons from the upper laser level into delocalized continuum states and backfilling of the lower laser level, both effects lowering the population inversion. These are the main limiting factors of the high temperature operation of the devices.

In this paper we use spatially resolved thermoreflectance (SRTR) to measure temperature distribution over the facet of pulse operated quantum cascade lasers[4]. 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 the edge emitting lasers[5,6]. The experimental data was confronted with the FEM numerical simulations.

In order to gain insight into the thermal management in QCLs we have examined the influence of different operating conditions and mounting as well as device geometry on the temperature of QCLs. The experimental results clearly indicate that to achieve long pulse and ultimately CW operation one has to improve the heat dissipation away from the active region, and to reduce the heat accumulation effects.

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Microphotoluminescence characterisation of quantum cascade lasers

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The Quantum Cascade Lasers (QCLs) suffer from a very strong heating caused by both high values of Joule's heat dissipated mainly in the active core, and by low thermal conductivity of the active-core superlattice. Therefore achieving the room-temperature or continuous-wave operation of a QCL requires some thermal optimisations. Thus, the possibility to determine the temperature of the crucial parts of the laser is vital. Fortunately, in the unipolar devices, such as QCLs, the surface recombination is not present, which means, that the temperature of the surface is similar to the temperature of the deeper parts of the device. Using the spatially-resolved techniques, such as micro-photoluminescence, one can obtain optical spectra of individual regions of the device. The red-shift of the spectra collected at particular operating conditions allow to find the temperature rise of the investigated area [1].

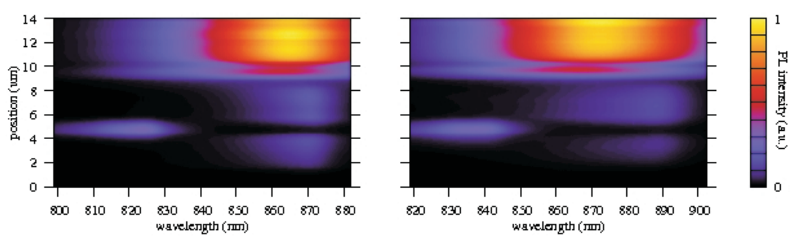

Fig. 1 Spatially-resolved photoluminescence spectra collected along the vertical axis for two different conditions: left - the un-powered device; right - driven by P=1.8 W DC.

We performed microphotoluminescence mappings, with spatial resolution of order of 1 m, along the vertical axis of AlGaAs/GaAs QCLs structure, described in [2], for different driving currents (DC) at the room temperature. Obtained results allow to estimate the influence of different types of the device processing on the thermal properties such as thermal resistance of the laser.

In Fig.1 one can see the spectral red-shift caused by the Joule's heating of: bottom waveguide, active core, top waveguide, top cladding, and substrate, counting from the bottom.

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Session:

Applications - Part II

Invited

Recent Advances in Mid-infrared Semiconductor Laser based Trace Gas Sensor Technologies

Frank K. Tittel, Lei Dong, Longwen Gong, Robert Griffin, Anatoliy A. Kosterev, Rafal Lewicki, and David M. Thomazy

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This talk will focus on recent advances in the development of sensors based on infrared semiconductor lasers for the detection, quantification and monitoring of gas species and their applications to environmental monitoring, medical diagnostics, industrial process control and security. Ultrasensitive chemical analysis of gases based on laser absorption spectroscopy (LAS) is a well-established technology [1,2]. The development of compact trace gas sensors, in particular based on quantum cascade (QC) and interband cascade (IC) lasers permit the targeting of strong fundamental rotational-vibrational transitions in the mid-infrared, that are one to two orders of magnitude more intense than overtone transitions in the near infrared [2,3].

The architecture and performance of several sensitive, selective and real-time gas sensors based on near and mid-infrared semiconductor lasers will be described. High detection sensitivity at ppbv and sub-ppbv concentration levels requires sensitivity enhancement schemes such as multipass optical cells, cavity absorption enhancement techniques, or photo-acoustic absorption spectroscopy (PAS) [4,5]. These three spectroscopic methods can achieve minimum detectable absorption losses in the range from 10^{-8} to 10^{-11} cm^{-1}/ Hz.

Several recent examples of real world applications of field deployable gas sensors will be reported, such as the monitoring of ammonia concentrations in urban environments and exhaled human breath. Monitoring of ammonia in exhaled human breath using laser spectroscopic techniques provides fast, non-invasive diagnostics for patients with liver and kidney disorders [6], and *helicobacter pylori* infections. The exhaled ammonia measurements are performed with quartz enhanced-PAS (QEPAS) in combination with a mid-infrared, continuous wave (cw), high performance QCL. The QEPAS technique is very suitable for real time breath measurements due to the fast gas exchange inside an ultra-compact QEPAS gas cell. The minimum detectable NH_3 concentration with a thermoelectrically cooled, cw, ~20 mW DFB QCL operating at 10.34 μm (965.35 cm^{-1}) is ~ 4 ppbv with a 1sec time resolution.

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Invited

Molecular dispersion spectroscopy in the mid-IR – new approach to sensitive chemical detection

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Laser absorption spectroscopy (LAS) in the mid-infrared can offer unique capabilities of sensitive trace-gas detection with fast response times and in a relatively compact instrumental form factor. Conventional LAS measurements rely exclusively on absorption information, which does not fully exploit the capabilities provided by the coherent nature of the laser radiation. Additionally the signal due to molecular absorption is small and superimposed on a several order of magnitude greater background which is subject to fluctuations. Hence, laser amplitude noise, interference effects, and other intensity fluctuations are the main source of measurement error. Thus, due to such fundamental limitations, the direct LAS-based chemical sensing at parts-per-billion and parts-per-trillion levels in a form of portable and/or field deployable instrument is still difficult to realize in practice.

In this paper a new approach to spectroscopic molecular detection in the mid-IR that has potential to significantly advance the current state-of-the-art in laser based chemical detection is discussed. The new technology takes a full advantage of the coherent nature of laser radiation and combines the advantages of direct LAS (e.g. simplicity, robustness and calibration-free operation), with a precision and noise suppression capability that are characteristic to indirect, zero-baseline spectroscopic sensing methods (such as photoacoustics or laser induced fluorescence). The method is based on measurements of anomalous molecular dispersion that occurs in the vicinity of absorption line using chirped lasers source. Chirped-laser dispersion spectroscopy (CLaDS) presented in this work focuses on mid-infrared spectroscopic region which allows targeting the fundamental ro-vibrational bands and gives an access to the most intense absorption fingerprints of wide range of chemicals.

The method provides several advantages over traditional direct LAS techniques. For example, the measurement of anomalous dispersion is background-free in nature. The method relies on frequency measurements and shows high immunity to variations in the optical power reaching the photo-detector. Therefore, the dispersion signal is baseline-free and immune to fluctuations of the incident laser power. Also, unlike the measurement of direct absorption that saturates at high concentrations, the measurement of dispersion is a completely linear process. Thus, large dynamic range of concentration measurements is achievable, and the accuracy is maintained over this range.

Preliminary experimental results obtained using a mid-IR quantum cascade laser emitting around 1912 cm^{-1} and verification of theoretical models developed for CLaDS will be discussed in details.

Acknowledgements:

Financial support by the MIRTHE NSF Engineering Research Center, the NSF CAREER award CMMI-0954897, and the Earth Observation and Atmospheric Science Division of the Space Science and Technology Department of the STFC Rutherford Appleton Laboratory. Authors would like to thank Antoine Muller at Alpes Lasers for providing a laser for this study.

A Faraday modulation spectrometer for detection of nitric oxide using a room temperature cw DFB QCL

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Faraday modulation spectroscopy (FAMOS) has been particularly useful for detection of nitric oxide on its fundamental vibrational band, since it offers both immunity to optical noise as well as against background absorption [1-2]. A high performance, transportable FAMOS spectrometer using an external cavity QCL has recently been realized by Lewicki, *et al.* [3]. We present a Faraday modulation spectrometer utilizing a cw DFB QCL at 5.33 µm operating at 30°C and a Peltier cooled MCT detector. The magnetic field was modulated at 7.4 kHz whereas the laser wavelength was scanned at 20 Hz across the most optimal transition, ^{2} $_{3/2}$ Q(3/2). The gas concentration was extracted from the FAMOS signal in every

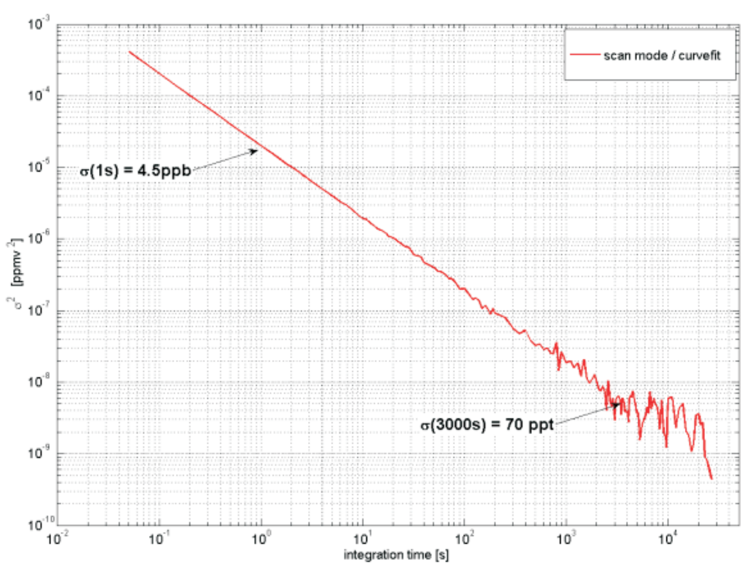

Fig. Allan variance for the spectrometer operating in a scan/curvefit mode.

scan by means of a curve fitting routine using a model stored in a look-up table (LUT). The minimum detection limit of the spectrometer using a 15 cm optical path, was 4.5 ppb at a response time of 1 s. The Allan variance analysis shows good system stability up to several hours of operation. We have also compared the spectrometer performance to the case when the concentration is calculated from the peak value of the line.

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Liquid Phase Spectroscopy with a Widely Tunable External-Cavity Quantum Cascade Laser

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In conventional mid-infrared transmission spectroscopy of liquids the achievable limits of detection are often determined by the limited emission power of the employed thermal emitters. As a consequence the reasonable sample thicknesses which can still be penetrated have to be kept low enough. However, this often leads to unsatisfactory limits of detection according to Beer's law. This is especially true in the case of trace amounts of substances dissolved in highly absorbing matrices, e.g. water. Therefore the use of tunable Quantum Cascade Lasers (QCL) with their high spectral power density could considerably improve the situation in liquid phase spectroscopy.

We employed a commercially available pulsed External-Cavity QCL which provided a spectral tuning range of 200 cm^{-1} and a peak pulse power of 350 mW. A spectral resolution of approximately 1 cm^{-1} was achieved by the EC-QCLs broadband grating. The investigated samples mainly comprised aqueous solutions which were introduced into the beam path by standard flow cells of various pathlengths.

Preliminary measurements showed a major improvement regarding the maximum achievable sample thickness by the use of the EC-QCL. Water layers with up to 200 µm have been successfully penetrated. Furthermore, spectra of several physiological solutions, e.g. glucose or lactate dissolved in Ringer solution (Fig. 1) were acquired at a satisfactory signal to noise ratio.

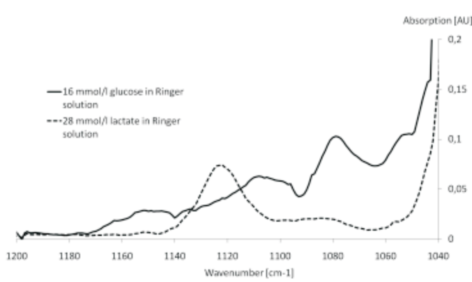

Fig. 1 Lactate and glucose in Ringer solution.

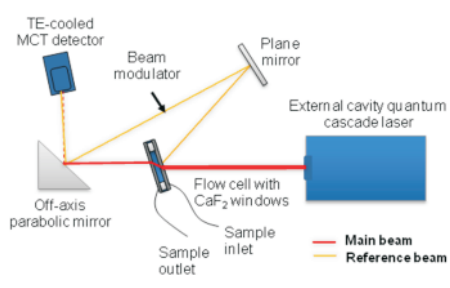

Fig. 2 Balanced detection setup

However, in some cases the reproducibility of the spectral emission power turned out to be insufficient. This could be ascribed to a slight hysteresis of the EC-QCLs grating control. Since the spectral power distribution of the QCL-chip is not constant a deviation in the gratings position also causes a change in the emission power. Therefore, a balanced-detection setup was realised (Fig. 2) where a reference beam covers for instabilities in the emitted intensity. With the development of more precise broadband gratings the wavelength accuracy and thus the emission power stability can be expected to be sufficient to skip the balanced detection.

Poster Presentations

Poster 1

GaInAsSb/AlGaInAsSb quantum well lasers for emission around 3.0 µm

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Acetylene is used in the chemical synthesis of polyethylene plastics and appears as a side product in the ethylene stream from cracking of hydrocarbons. This gas has two strong absorption lines at 3.03 and 3.06 µm which can be used for precise measurement by Tunable Diode Laser Spectroscopy. So far, the lack of single frequency laser diodes operating in the continuous wave regime at room temperature beyond 3.02 µm [1] has limited the use of this technique. We present hereunder our works toward monofrequency quantum well laser diodes emitting between 3.03 and 3.06 µm.

The laser structure was grown by molecular beam epitaxy (MBE) and is constituted of two 12 nm-thick 1.65 % compressively strained QWs of $Ga_{0.41}In_{0.59}As_{0.29}Sb_{0.71}$ embedded between $Al_{0.20}Ga_{0.60}In_{0.20}As_{0.19}Sb_{0.81}$ barriers (Figure 1). Broad area lasers operate at room temperature in the pulsed regime with a threshold current density of 255 A/cm^2 (Figure 2). DFB lasers made in collaboration with Nanoplus GmbH have been operated in the continuous wave regime at 20°C (and up to 38°C) with wavelengths between 3.03 µm and 3.06 µm and a threshold current of 54 mA.

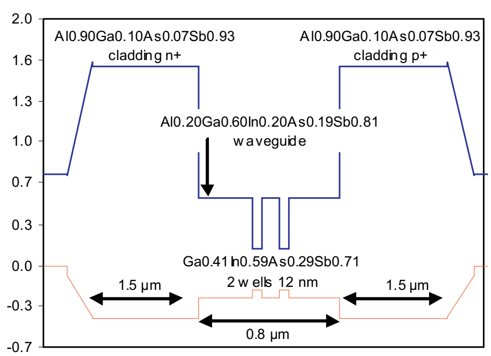

Fig. 1 Band diagram of a laser structure for emission at 3.0 µm

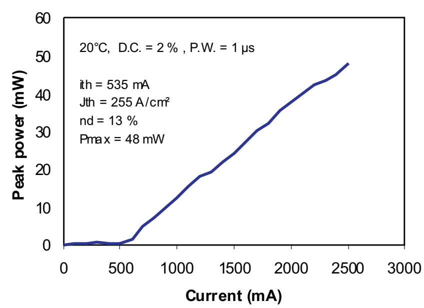

Fig. 2 P(I) characteristic of 100 µm-wide 2100 µm-long broad area laser diode

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Poster 2

Nanosecond Time Resolved Characterization of a Commercially Available Broadband Pulsed External-Cavity Quantum Cascade Laser

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The application of broadband External-Cavity Quantum Cascade Lasers (EC-QCL) in mid-infrared spectroscopy offers the future potential for a replacement of bulky standard IR-spectrometers. However, this requires a comprehensive knowledge of the spectral and dynamic emission characteristics of the laser. In this contribution we, therefore, want to present a fast and powerful method to investigate the spectral emission of an EC-QCL over time.

The experimental setup consisted of a high precision vacuum FT-IR spectrometer providing exact spectral information and a 8-bit transient recorder board with a resolution of 2 ns covering the time domain. The setup was operated in StepScan-mode, where the FT-IR spectrometer acquires time resolved interferograms by a step-wise motion of the moving mirror.

A state-of-the-art commercially available pulsed EC-QCL with a tuning range of over 200 cm^{-1} and a peak pulse power of 350 mW served as laser source. Emission characteristics of single infrared laser pulses at a time resolution of 2 ns and a spectral resolution of 0.1 cm^{-1} were measured and are presented in Fig. 1. Mode-hopping dynamics within a pulse which would not be visible at 1 cm^{-1} resolution or in a static FT-IR measurement have now been observed.

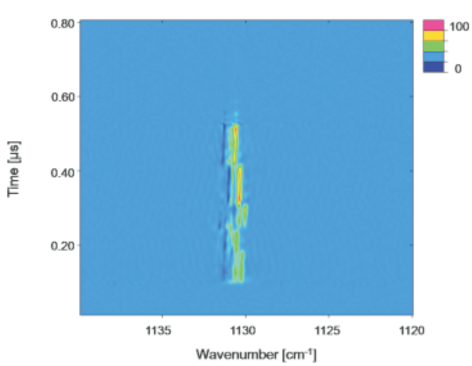

Fig. 1 Time resolved laser pulse of the EC-QCL

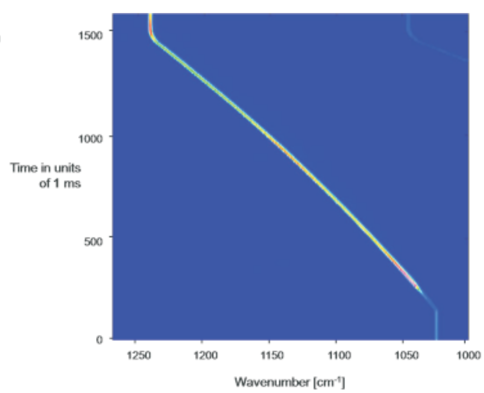

Fig. 2 Time resolved spectral tuning over 200 cm^{-1}

Furthermore, time resolved measurements of the laser emission were performed while the EC-grating was tuning over 200 cm^{-1} (Fig. 2). Slight deviations from a linear relation between emission wavenumber and tuning time were observed. The knowledge of this tuning behavior is however crucial for the application on an EC-QCL for recording IR spectra while tuning the emission wavelength of the laser. This reduces a complex spectral measurement to a simpler measurement in the time domain.

Poster 3

High Quality Epitaxial Growth of Interband-Cascade-Lasers

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A promising approach to cover the important 3-4 m spectral range, which is of interest for various applications, including hydrocarbon detection, is provided by antimony based type-II interband cascade lasers (ICL) [1]. While common diode lasers or quantum cascade lasers haven’t been able to fully close this gap yet, when it comes to continous-wave operation at room temperature, ICLs have recently shown great promise to cover this wavelength range under these conditions [2]. One of the main aspects to consider in the epitaxial growth of ICLs is the compensation of lattice strain, introduced by the missmatch of lattice

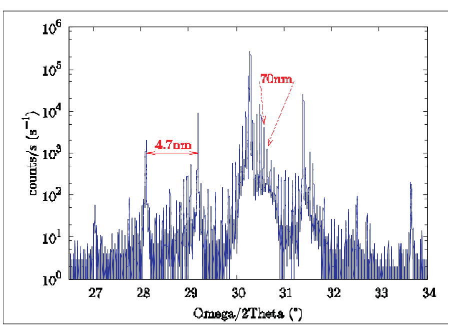

Fig. 1 HRXRD-Measurement of an ICL structure. Sharp sattelite peaks indicate excellent crystal quality and periods of 70nm and 4.7nm can be derived for the periods of the active region and the superlattice claddings

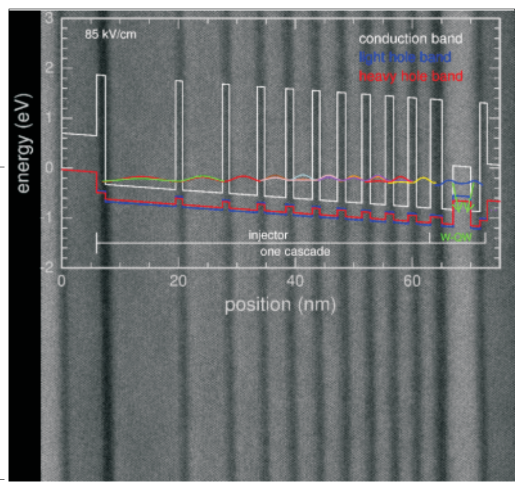

Fig. 2 STEM Measurement of the active region with the calculated band structure

constants between the AlSb and InAs layers, used in the cladding and injector regions, and the GaSb substrate.

In this contribution, various approaches of interface engineering to meet this challenge in each region of an ICL (cladding, injector and W-quantum well) are presented. Different shutter cycles for the Sb and As cells at the heterointerfaces, including no soaks at all and Sb-only soaks, were investigated and excellent crystal quality was achieved, as proven by high resolution X-ray diffraction (HRXRD, figure 1), secondary ion mass spectroscopy (SIMS) and scanning transmission electron microscopy (STEM) measurements. Particular efforts were put in strain compensation of the injector region, with its InAs/AlSb layers of varying thicknesses (figure 2).

Financial support of this work by the European Commission within the project SENSHY is gratefully acknowledged.

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Poster 4

Trace Detection: A new Source of Cold Species, Application to theMid-Infrared Spectral Range

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The spectroscopy of weakly abundant species or the trace detetion of gaseous molecules both require to push some technologies to their limits. To obtain good chances of success several experimental or basic considerations need to be put in perspective. Let us mention here, the spectral range, the detection technique and the source of molecules.

TheMid-Infrared spectral domain (2-10 m) is an appealing range because here, the vastmajority of the organic molecules exhibit a spectral signature. In addition, the fundamental stretch modes usually have a relatively strong absorption strength. However, the molecular richness in this spectral range requires to be able to spectrally discriminate to avoid any misassignment. In other words, gas trace detection requires spectral tunability and resolution.

The relative performances of different optics-based detection techniques have been the subject of numerous controversies. However, the absence of fluorescence emission in the mentioned range, forces the use of direct absorption techniques. This means that the absorption path length is of crucial importance. A way to increase the equivalent absorption path length is to use optical cavities allowing it to reach several tens of kilometers, depending on the quality of the mirrors.

The molecular absorption strength spreads over numerous transitions due to its integral nature. Furthermore each transition exhibits a linewidth which is ultimately limited by the molecule lifetime (or, eventually, the observation time). Thus, it is crucial to minimize the experimental broadening effects as well as the number of absorbing transitions. The experimental spectral linewidth can usually approach a Doppler broadening when using single longitudinal mode CW laser sources. The number of absorption transitions can be reduced by peaking the partition function controlled by the molecule temperature (a spectral simplification arises). A supersonic linear (slit) jet expansion is assumed to address these two issues. In addition it also addresses the length path absorption issue (by its geometry). To obtain a slit expansion of several centimeters long, the slit width has to be limited to only 10-50 m to be compatible with the moderate evacuating pumping group capability. The quality of the slit machining also controls the residual Doppler broadening. We are building such a slit in the aim of featuring its behavior and performances in terms of temperature (expecting T_r 10K), number density and residual Doppler broadening.

Trace detection in ambient air (at 1 atmosphere or higher) can be considered. In a next step, the slit can be equipped with electrodes to create cold plasmas with the aim of studying radicals and ions. Intermediate hydrocarbon radicals play a crucial role in the chemistry of the atmosphere or in combustion processes.

A successful design should combine different techniques, but the challenge is appealing and should open new perspectives in trace detection as well as in spectroscopy studies of species only available in small quantities. The portability of the equipment can be considered only by using single mode diode lasers.

Poster 5

Interband Cascade and Quantum Cascade based Monomode Emitters for Hydrocarbon Sensing

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Detection and monitoring of hydrocarbons play an important role in a wide range of industrial and environmental applications, including for example industrial process control of aliphatic hydrocarbons (e.g. acetylene, propane, propene). Since the strongest absorption bands of several hydrocarbon gases are located in the wavelength region beyond 3 µm, mid infrared (MIR) laser sources are especially well suited for photonic sensor systems based on the characteristic fundamental transitions of those gases [1]. By using the fundamental transitions instead of presently used overtones different hydrocarbons can be more easily distinguished and the sensitivity can be increased by several orders of magnitude.

Two approaches currently appear particularly suited to obtain laser emission in this wavelength range of interest: type II interband cascade lasers (ICLs) and quantum cascade lasers (QCLs) using intraband transitions. In both structures cascaded active regions are used allowing to recycle injected electrons to generate multiple photons per electron, thus leading to high quantum efficiencies [2-5]. Based on the characteristic waveguide design of the underlying material two distributed feedback (DFB) concepts using top-grating and sidewall-grating structures, respectively were investigated to achieve high performance single mode emission.

For the purpose of hydrocarbon sensing we have fabricated DFB devices based on GaSb IC material emitting at 3.45 µm around RT.

Based on InP QC material we demonstrate DFB QCLs at 13.7 µm with side mode suppression ratio around 30 dB. The single mode peak power of these QCL DFBs exceeds 500 mW at room temperature. The maximum operation temperature is higher than 400 K.

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Poster 6

Voltage Tunability of Quantum Cascade Lasers

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Band structure engineering of the active region in quantum cascade lasers (QCLs) has enabled impressive broad band laser operation which has not been attained with other semiconductor lasers. In this contribution we investigate the voltage tunability of QCLs based on two different approaches. The first is based on quantum confined Stark effect. By introducing an additional coupling state to the upper laser level the drop in differential resistance after reaching threshold is reduced [1]. Therefore, tuning continues during lasing, as pinning effects are reduced. We confirm this by comparing electroluminescence spectra from micro-disks with slanted side-walls, broad-ridge lasers and double-channel structures. By increasing the applied voltage we can controllably blue-shift the center of the gainspectrum from 1080 cm^{-1} to 1175 cm^{-1} as shown in fig.1. This tuning behavior is directed opposite to the red-shift associated with QCL-temperature tuning. We compare the results with data obtained from a QCL with vertical transition to prove that the quantum confined Stark effect is the reason for the blue-shift.

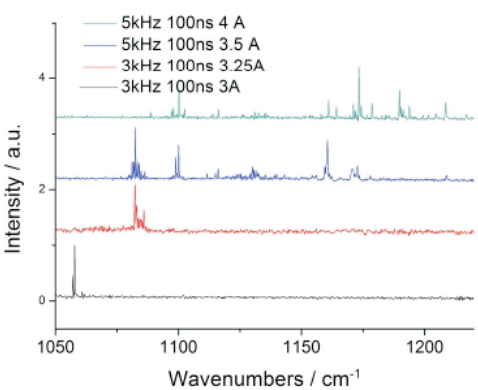

Fig. 1 Spectra of the laser based on the diagonal transition. All data were taken at 100 K .

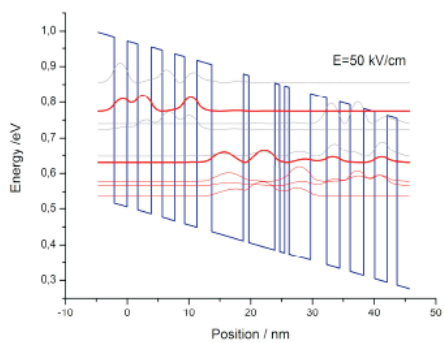

Fig. 2 Simulation of the laser exhibiting intrinsic tuning. Bandstructure and wavefunctions at an electric field of 50kV/cm. Calculated wavelength = 7.1 m, dipole moment z = 111nm.

The second concept is intrinsic to the wave functions which arise from the superlattice. The composition of one active region sandwiched between two injectors is shown in fig.2. By careful design, we manage to keep the transition matrix element on a high level throughout a wide range of electric fields. In addition, the upper and lower laser levels are designed to avoid anti-crossing with their respective adjacent injector-states. Anti-crossing could hamper tunability and deteriorate transport of the electrons. The calculated wavelength changes from 7.1 m to 8.3 m by increasing the applied electric field from 50kV/cm to 78kV/cm. During this range of electric fields the upper laser levels interchange as we show by simulating the QCL by solving the self-consistent Schroedinger-Poisson equation.

Financial support of this work by the German Ministry of Education and Research within the project "QUIP" is gratefully acknowledged.

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Poster 7

Industrial Trace-Gas Analyzer for Phosgene Monitoring Based on QCL Absorption Spectroscopy

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Within the last few years mid infrared absorption spectroscopy between based on quantum cascade lasers (QCLAS) has progressed considerably as a powerful diagnostic technique for studies of the fundamental physics and chemistry of molecular plasmas and gases. The commercial availability of QCLs offers an attractive new option for the monitoring and control of plasma processes and for trace gas analysis in industry [1]. For industrial applications, like workplace monitoring or process control, not only the robustness and stability of the instrument is of great importance, also the reliability and reproducibility of the measurement results are crucial aspects, which have to be considered in the development of a new product.

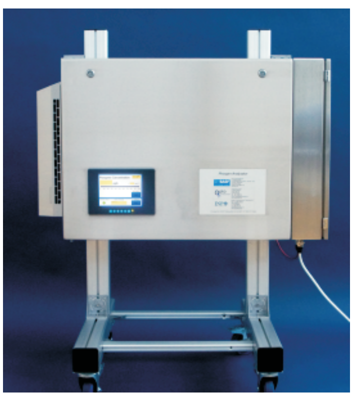

Fig. 1 Phosgene analyzer

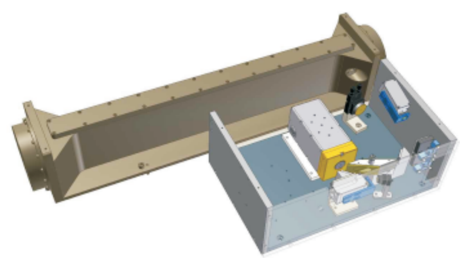

Fig. 2 Optical board with long path cell

In the chemical industry the detection of traces of phosgene is required to fulfil safety regulations. For this purpose a new modular QCL-based analyzer was designed and constructed. In Figure 1 a photo of the Phosgene analyzer is shown. It contains a pulsed QCL in TO-3 package, based on the Q-MACS technology, combined with an optical long path cell of typically 58 m length. The system is controlled by an embedded computer. The external control can be performed via a touch pad monitor or a LAN interface. Details of the optical board are given in Figure 2. Further elements are a reference gas cell and a detector, a water cooler, a pump and several valves for gas handling. The gas sample pressure can be chosen between 200 and 1000 mbar. A typical measurement cycle of the unit lasts about 30s. The instrument has been designed to fulfil industrial field specification as IP56 and is optionally usable in Ex-zone 1 and above. For Phosgene a limit of detection of 30ppbV (3) has been achieved. Actual test results show the applicability of the analyzer in an industrial environment.

This work has been supported by the BMBF of Germany, FKZ: 13N9001.

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Poster 8

Study and development of a multi-species buried probe for gas spectroscopy with bidirectional antimonide-based laser diodes

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We present the study and development of an instrument based on tunable diode laser absorption spectroscopy (TDLS) of gaseous species, using antimonide based laser diodes emitting either at 2.3 µm (CH_4 detection) or 2.6 µm (Water vapor detection) [1-2].

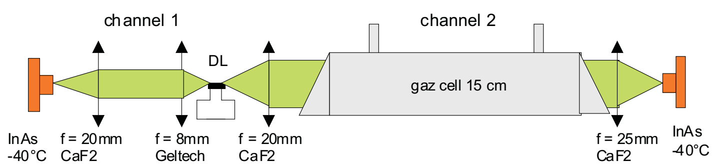

Fig. 1 Simplified optical setup.

The main targeted application of this probe is the study of water vapor flux in the arid soils of Africa, to understand, control and regulate irrigation mechanisms. Another application is the measurement of CH_4 (and CO_2) exchanges between the plant roots and the soil in rhizosphere [3]. The lasers dedicated to these applications were fabricated by molecular beam epitaxy in the IES laboratory. The active regions of the devices are based on InGaAsSb/AlGaAsSb quantum wells grown on GaSb(N) substrate.

The devices are working at room temperature in continuous wave regime. The TDLS detection technique is wavelength modulation spectroscopy (WMS).

We have developed a bi-directional laser mount dedicated to these applications, which

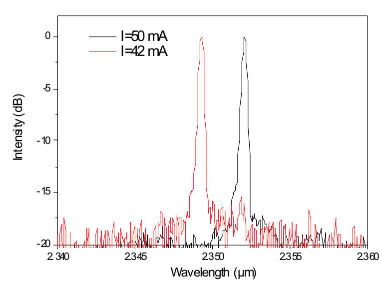

Fig. 2 Emission spectrum, 2.35 µm laser diode.

allows the use of the emitted beams from both facets of the crystal (without any facet treatment). The first beam is directed through a reference cell containing a calibrated mixture while the second beam is directed through the 15 cm long analyze cell (figure 1). A 2.6 µm laser diode has already been used on this setup to detect water vapor [4].

With a fabry-perot 2.35 µm emitting laser diode (figure 2) we managed to measure CH_4 absorption lines of linestrength above 10^{-21} cm^{-1}/molecules.cm^{-2}. Very first results of 2f wavelength modulation spectroscopy gas detection gave a detection limit of 100 ppmv leading to 15 ppm.m CH_4 detection which should be improved.

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Poster 9

Photoluminescence and photoreflectance of AlGaAs/GaAs superlattices for mid and far infrared

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The quantum cascade lasers (QCLs) based on e.g. GaAs/AlGaAs multiple quantum wells or superlattices are considered as an important light source in the mid- and far-infrared region especially, which can be used for spectroscopy, medicine, security and many other applications.

Fabrication of QCLs requires a very high precision with respect to multilayer structure of the entire device consisting of hundreds of thin layers. In particular, one has to provide procedures which allow to control width, content and carrier concentration of all the barriers and quantum wells. Due to multilayer structure of SLs the similarities to QCLs can be find (from the point of view growth process). In result the fabrication of SLs might help in case of calibration and proper growth accuracy achievement before final QCLs growth starts.

Modulation spectroscopy especially in its contactless form as photoreflectance (PR), due to its absorption character and high sensitivity, is an efficient tool to study the energies of interband optical transitions (including transitions between the excited states and those having very small oscillator strengths) in low-dimensional structures and hence can be used as a post-growth technique of the multilayer system electronic structure probe and the growth accuracy verification.

In this work, optical properties of GaAs/AlGaAs superlattice structures with different barrier and quantum well widths were investigated by photoluminescence [1] and photoreflectance [2] (in the spectral range of interband transitions) and Fourier transform infrared (FTIR) photoluminescence (in the range of intersubband transitions). The detailed photoluminescence line shape analysis and interpretation of the PR features have been performed.

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The work has been supported by the PBZ- MNISW-02/I/2007 Project.

Poster 10

Optical properties of GaSb - based type II quantum wells emitting in the mid infrared spectral range

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Mid-infrared lasers find increasingly applications during last years including for instance gas sensing for detection and control of the presence or concentration of harmful gases like CO_2, SOx, NH_3, and many others. The benefits of laser based methods have been limited mainly by the lack of suitable laser light sources, which have to provide the sensing wavelength in single mode and continuous wave (cw) operation in order to provide the required wavelength control and intensity. Hereby, we present fundamental optical and electronic properties of a type II GaSb/AlSb/InAs/InGaSb/InAs/AlSb/GaSb quantum well system potentially able to cover spectrally the range of 2 to 6 μm, and beyond (when the thickness of InAs layer is tuned for instance), and possible to be integrated in a photonic sensor unit for gas detection. Two groups of structures were grown by solid source molecular beam epitaxy on (100) GaSb substrates: conventional type II InAs/$Ga_{0.71}In_{0.29}Sb$ QW and the so called "W" structures with $Ga_{0.71}In_{0.29}Sb$ layer surrounded by InAs on both sides, and then followed by the AlSb barriers. The latter design is introduced in order to enhance the oscillator strength (electron – heavy hole wave functions overlap integral) of the fundamental type II optical transition. Spectroscopic experiments at low temperatures, like photoluminescence and photoreflectance, allowed us the detection of the optical transitions, including the spatially indirect ones, and their unambiguous identification after the comparison to the energy level calculations within 8-band kp model including strain. Based on this model the band gap discontinuities in such a complex system could be estimated. Further, the dependence of the transition oscillator strength and its energy (wavelength) could be determined as a function of both the InAs or $Ga_{0.71}In_{0.29}Sb$ layer thickness. In this work we have also shown the photoreflectance spectra reach with the optical features connected

with above barrier states. Obtained features were identified as a optical transitions associated with confined levels in the surface quantum well.
Additionally, photoluminescence thermal quenching was analyzed for samples with different width of the InAs and GaInSb layers. Possible carrier escaping mechanism was connected with tunneling of the holes form active region into the GaSb layers.

The work has been supported by the PBZ- MNISW-02/I/2007 Project and EU/EC Project Senshy within 7FP No 223998.

Poster 11

Band gap discontinuities and photoluminescence thermal quenching of GaInAsSb/Al(In)GaAsSb quantum wells

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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/AlGaAsSb quantum wells (QWs) operating in the wavelength region up to 3 µm and beyond are attractive light source for applications including remote sensing, pollutant detection, medical procedures or laser spectroscopy. So far various lasers operating in cw mode at room temperature (RT) containing a type I GaInAsSb/Al(In)GaAsSb QW have been demonstrated. It is worth to note that most of this papers are focused on the lasing properties i.e. threshold current, light output power, emission intensity of such a structures. Much less attention was paid on the electronic parameters of this QWs. In this work we have been focused on electronic structure i.e. energy of confined levels, band offsets determination and thermal quenching of photoluminescence.

We present fundamental optical and electronic properties of a type I GaInAsSb/Al(In)GaAsSb quantum well system predicted for gas sensing application in hydrocarbons detection (3-4 µm spectral range). Spectroscopic experiments at low temperatures, like photoluminescence and photoreflectance, allowed the detection of the optical transitions and after the comparison to the effective mass calculations their unambiguous identification. Based on that conclusions regarding the band gap discontinuities in such a systems has been determined. We have found strained band gap discontinuities for electrons 75% and 65% for GaInAsSb/AlGaAsSb and GaInAsSb/AlInGaAsSb systems respectively. The fundamental transitions of the investigated structures has been approved by photoluminescence measurement, very efficient QW emission without any localization features has been observed in 10 K.

In addition the thermal quenching of the photoluminescence was investigated for all samples (annealed and not annealed) and the possible carrier's way of escape from the well has been recognized. We have found that photoluminescence quenching is mostly connected to holes escaping to the barrier thru the excited (holes) states confined in the well.

The work has been supported by the PBZ- MNISW-02/I/2007 Project and EU/EC Project Senshy within 7FP No 223998.

Poster 12

Influence of operating conditions on maximum operating temperature in pulse mode $Al_{0.45}Ga_{0.55}As/GaAs$ quantum cascade lasers

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The influence of operating conditions on maximum operating temperature (T_{max}) of (~9.4 m) GaAs-based quantum cascade lasers (QCLs) is reported. The laser design followed an "anticrossed-diagonal" scheme proposed originally by Page *et al* [1]. The QCL structures were grown by MBE, in Riber Compact 21T reactor [2,3]. The double trench lasers were fabricated using technology, which combined the wet etching of mesa with dielectric isolation applied to limit the lateral current spreading [3,4]. The basic electrical and optical characterization was carried out in the temperature range 77-300 K.

The dependencies of threshold current and laser emission output power on laser operating temperature as well as on supply conditions were extensively studied. For a long-pulse regime a simple dependence on filling factor is characteristic, i.e. the dependence on pulse length as well as on frequency is observed. This fact is interpreted as a result of laser active region temperature increase with the increasing pulse length as well as with the increasing frequency. On contrary, for a short-pulse regime a lack of threshold current and output power dependence on frequency is observed (at least in the wide frequency range, up to the high frequency values). It seems that the temperature of the laser's active region returns to its starting value after every pulse of current. On the other hand, a significant dependence on pulse width has to be emphasized in this regime. Hence, the pulse width itself clearly governs the peak temperature of the active region. These experimental observations were considered on the basis of simple simulations performed by a finite element method (FEM).

The work was financially supported by Grant PBZ-MIN-02/I/2007.

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Poster 13

High Power 2-2.5 m Semiconductor Disk Lasers

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Optically pumped semiconductor disk lasers (OP-SDL) combine many advantages of traditional solid-state lasers with the versatility offered by the wide range of available semiconductor gain materials. SDLs provide a good quality, nearly diffraction limited, Gaussian shaped beam and the external cavity enables the use of intra-cavity filters for achieving narrow linewidth and wavelength tunability. GaSb-based compound semiconductors can be tailored to cover a broad spectral range, extending from 2 m to beyond 3 m. They are the prime choice for the development of lasers to be used in spectroscopy of atmospheric gasses, laser surgery, remote sensing, or military countermeasures [1]. In particular, for spectroscopy application one could make use of the very broad (~150 nm) tuning range of the emission wavelength for GaSb SDLs and the possibility to employ intracavity spectroscopy techniques.

In this paper we demonstrate SDLs emitting in the 2-2.5 m range. The gain structures were grown by molecular beam epitaxy (MBE) on an n- GaSb (100) substrate and employed a highly reflective (R < 99.9%) GaSb/AlAsSb distributed Bragg reflector (DBR). The active region comprised multiple $In_xGa_{1-x}As_ySb_{1-y}$ quantum wells (QWs) embedded in $Al_xGa_{1-x}As_ySb_{1-y}$ waveguide. The group of three QWs were located at the antinodes of the standing wave optical field in the micro-cavity formed by the DBR and the semiconductor-air interface. The structures were closed with a lattice matched $Al_xGa_{1-x}As_ySb_{1-y}$ (x 0.85) window layer to ensure good carrier confinement and capped with a thin GaSb cap layer to prevent oxidation. 2.5 2.5 mm^2-size gain chips were capillary bonded with water to type IIa natural diamond heat spreaders to enable efficient heat removal from the active region. The bonded chips were finally pressed between two copper plates, with a small hole in the top plate allowing the passage of pump and signal. The mounted sample was attached to a water cooled copper heat sink. The gain chips were measured using a V-type cavity configuration comprising also a high reflective folding mirror and a partially reflective planar output coupler (OC). The pump source used was a 980 nm fiber coupled diode laser. The laser schematic is presented in Fig 1. The gain chip designed to operate at 2 m exhibited the highest output powers, over 4 W for near room-temperature operation; output characteristics is shown in Fig 1. About 12 % of the pump was reflected from the sample. The reflected power is not taken into account in this graph. The 2- m laser could be tuned about 75 nm using a birefringent filter inside the cavity. Wider tuning range was demonstrated - more than 150 nm - by utilizing QWs with different thickness in the active region. The gain chips designed for 2.3 and 2.5 m delivered output powers of 1 W and 0.5 W, respectively.

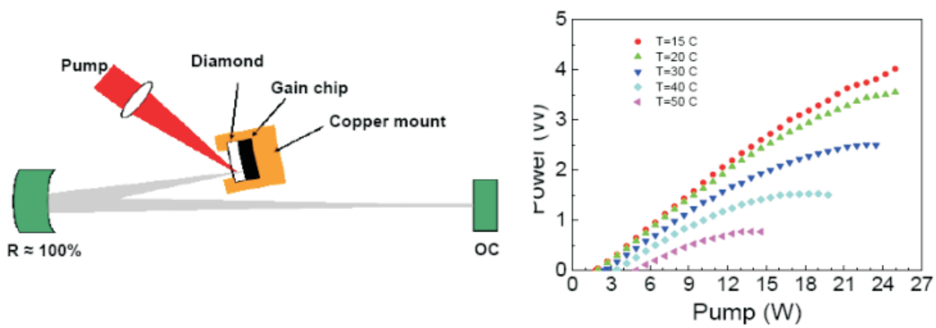

Fig. 1 Left: Cavity configuration (OC=output coupler). Right: Light output characteristics of 2-µm SDL at different mount temperatures.

To conclude, we have demonstrated that GaSb-based SDLs show potential for intra-cavity laser spectroscopy application with their moderate output powers and wide tuning ranges. In future we will focus on realization of the GaSb-based SDLs emission wavelengths beyond 3 m with electrical pumping scheme.

[1] F.K. Tittel, D. Richter, and A. Fried, *Solid-State Mid-Infrared Laser Sources*, I.T. Sorokina and K.L. Vodopyanov (Eds.), Ch. 11, (2003) 445.

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