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Research outputs:

Semiconductor Fano Lasers
In this paper, a new type of semiconductor laser based on Fano interference is described. One of the laser mirrors relies on the interference between the continuum of waveguide modes and a side-coupled nanocavity, leading to a narrow-band mirror that provides the Fano laser with unique characteristics. In addition to being truly single-mode, the laser can be modulated through the mirror at frequencies far exceeding the relaxation oscillation resonance. Furthermore, nonlinearities in the nanocavity can be used to implement a saturable mirror, leading to passive pulse generation with repetition frequencies in the gigahertz range. This paper reviews the theory of Fano lasers and the current experimental status. Experimentally, the Fano laser concept is demonstrated using a photonic crystal platform with quantum dot active material. Both continuous wave operation and self-pulsing is observed for optically pumped lasers operating at room temperature.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications
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Number of pages: 14
Publication date: 1 Nov 2019
Peer-reviewed: Yes

Publication information
Journal: IEEE Journal of Selected Topics in Quantum Electronics
Volume: 25
Issue number: 6
Article number: 8734739
ISSN (Print): 0792-1233
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
Original language: English
Keywords: Nanotechnology, Optical pulse generation, Photonic bandgap materials, Semiconductor lasers
Electronic versions:
Fulltext
DOIs:
10.1109/JSTQE.2019.2922067
Source: Scopus
Source ID: 85069754050
Research output: Contribution to journal › Journal article – Annual report year: 2019 › Research › peer-review

Comparison of processing-induced deformations of InP bonded to Si determined by e-beam metrology: Direct vs. adhesive bonding
In this paper, we employ an electron beam writer as metrology tool to investigate distortion of an exposed pattern of alignment marks in heterogeneously bonded InP on silicon. After experimental study of three different bonding and processing configurations which represent typical on-chip photonic device fabrication conditions, the smallest degree of linearly-corrected distortion errors is obtained for the directly bonded wafer, with the alignment marks both formed and measured on the same InP layer side after bonding (equivalent to single-sided processing of the bonded layer). Under these conditions, multilayer exposure alignment accuracy is limited by the InP layer deformation after the initial pattern exposure mainly due to the mechanical wafer clamping in the e-beam cassette. Bonding-induced InP layer deformations dominate in cases of direct and BCB bonding when the alignment marks are formed on one InP wafer side, and measured after bonding and substrate removal from another (equivalent to double-sided processing of the bonded layer). The findings of this paper provide valuable insight into the origin of the multilayer exposure misalignment errors for the bonded III-V on Si wafers, and identify important measures that need to be taken to optimize the fabrication procedures for demonstration of efficient and high-performance on-chip photonic integrated devices.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, Alight Technologies ApS
Corresponding author: Sakanas, A.
Contributors: Sakanas, A., Semenova, E., Ottaviano, L., Mørk, J., Yvind, K.
Pages: 93-99
Publication date: 1 Jun 2019
Peer-reviewed: Yes

Publication information
Journal: Microelectronic Engineering
Volume: 214
ISSN (Print): 0167-9317
Ratings: BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
Original language: English
Keywords: Alignment, Electron beam lithography, III-V on Si, Metrology, Wafer bonding
DOIs: 10.1016/j.mee.2019.05.001
Source: Scopus
Source ID: 85065746349
Research output: Contribution to journal – Annual report year: 2019 – Research – peer-review

High-confinement gallium nitride-on-sapphire waveguides for integrated nonlinear photonics
We demonstrate a highly effective nonlinearity of 7.3 W⁻¹m⁻¹ in a high-confinement gallium nitride-on-sapphire waveguide by performing four-wave mixing characterization at telecom wavelengths. Benefitting from a high-index-contrast waveguide layout, we can engineer the device dispersion efficiently and achieve broadband four-wave mixing operation over more than 100 nm. The intrinsic material nonlinearity of gallium nitride is extracted. Furthermore, we fabricate microring resonators with quality factors above 100,000, which will be promising for various nonlinear applications.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, RAS - Ioffe Physico Technical Institute
Corresponding author: Yvind, K.
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Pages: 1064-1067
Publication date: 1 Mar 2019
Peer-reviewed: Yes

Publication information
Journal: Optics Letters
Volume: 44
Issue number: 5
ISSN (Print): 0146-9592
Ratings: BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
Characterization and Optimization of Four-Wave-Mixing Wavelength Conversion System

In this work, we present a comprehensive experimental and numerical investigation of the impact of system parameters on wavelength converters based on four-wave-mixing, with focus on practical system implementations in addition to the interaction within the nonlinear medium. The input signal power optimization is emphasized according to the trade-off between the linear and the nonlinear impairments, and the origin of the limitations at the optimum is studied. The impact of the input signal quality on the converted idler is discussed, and depending on the dominant noise contribution a varying conversion penalty is demonstrated. The penalty is also shown to scale with increasing number of WDM channels due to additional nonlinear cross-talk between them. Finally, by means of numerical simulations we extend the experimental characterization to high pump powers, showing the impact of parametric noise amplification, and different pump laser linewidths, which lead to increased phase-noise transfer. The experimental characterization employs an integrated AlGaAs-on-insulator waveguide, and the numerical simulations accompany the results to make the analysis general for $\chi^{(3)}$ materials that satisfy the assumptions of the split-step Fourier method.

General information
Publication status: Accepted/In press
Organisations: Department of Photonics Engineering, High-Speed Optical Communication, Centre of Excellence for Silicon Photonics for Optical Communications, Machine Learning in Photonic Systems, Nanophotonic Devices, Coding and Visual Communication
Contributors: Kaminski, P. M., Da Ros, F., Porto da Silva, E., Pu, M., Yankov, M. P., Semenova, E., Yvind, K., Clausen, A. T., Forchhammer, S., Oxenløwe, L. K., Galili, M.
Number of pages: 9
Publication date: 2019
Peer-reviewed: Yes

Synthesis and systematic optical investigation of selective area droplet epitaxy of InAs/InP quantum dots assisted by block copolymer lithography

We report on the synthesis and systematic investigation of quantum dot based optical gain material potentially suitable for applications in active devices operating around a wavelength of 1.55 µm and above. The quantum dots were selectively grown in a process assisted by block-copolymer lithography. We applied a new type of diblock copolymer, PS-b-PDMS (polystyrene-block-polydimethylsiloxane), which allows for the direct fabrication of a silicon oxycarbide hard mask used for lithography. Arrays of InAs/InP quantum dots were selectively grown via droplet epitaxy. Our detailed optical investigations of the quantum dot carrier dynamics in the 10-300 K temperature range indicate the presence of a significant density of defect states located within the InP bandgap and in the vicinity of the quantum dots. Those defects have a substantial impact on the optical properties of the quantum dots. (C) 2019 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Department of Chemical and Biochemical Engineering, Department of Chemistry, Centre of Excellence for Silicon Photonics for Optical Communications, University
Tunable MEMS VCSEL on Silicon Substrate

We present the design, fabrication, and characterization of a MEMS VCSEL which utilized a silicon on insulator wafer for the microelectromechanical system and encapsulates the MEMS by direct InP wafer bonding in order to improve the protection and control of the tuning element. This can enable more robust fabrication, a larger free spectral range, and bidirectional tuning of the MEMS element. The proposed device uses a high contrast grating mirror on a MEMS stage as the bottom mirror, wafer bonding InP with quantum wells for amplification and a deposited dielectric DBR. A tuning range of 40 nm and a mechanical resonance frequency of >2 MHz is demonstrated. We present design, fabrication, and characterization of an optically pumped MEMS VCSEL which utilizes a silicon-on-insulator wafer for the microelectromechanical system and encapsulates the MEMS by direct InP wafer bonding, which improves the protection and control of the tuning element. This procedure enables a more robust fabrication, a larger free spectral range, and facilitates bidirectional tuning of the MEMS element. The MEMS VCSEL device uses a high contrast grating mirror on a MEMS stage as the bottom mirror, a wafer-bonded InP with quantum wells for amplification and a deposited dielectric DBR as the top mirror. A 40-nm tuning range and a mechanical resonance frequency in excess of 2 MHz are demonstrated.
Wavelength Conversion of 10 Gbit/s Data from 2000 to 1255 nm using an AlGaAsOI Nanowaveguide and a Continuous-Wave Pump in the C Band

We demonstrate wavelength conversion over 744 nm in an AlGaAsOI nanowaveguide using a 17.5-dBm continuous-wave pump. We convert 10 Gbit/s NRZ-OOK and Nyquist PAM 4 signals at a conversion efficiency of −28 dB.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, High-Speed Optical Communication, Centre of Excellence for Silicon Photonics for Optical Communications, Nanophotonic Devices, Diode Lasers and LED Systems
Corresponding author: Kong, D.
Number of pages: 3
Pages: 1-3
Publication date: 2019

High-Quality-Factor AlGaAs-On-Sapphire Microring Resonators

We realize an AlGaAs-on-sapphire platform through a Al<formula>\text{$_2$}\text{O$_3$}</formula>-assisted direct wafer bonding and substrate removal processes. The direct wafer bonding process is optimized concerning the intermediate layer deposition and annealing temperature to obtain a high bonding strength between the AlGaAs and sapphire wafers. High quality-factor (Q) microring resonators are fabricated using electron-beam lithography in which the charging effect is mitigated by applying an thin aluminum layer and a smooth pattern sidewall definition is obtained using a multi-pass (exposure) process. We achieve an intrinsic Q of up to <formula>\sim$</formula>460,000, which is the highest Q for AlGaAs microring resonators. Taking advantage of such high Q resonators, we demonstrate an ultra-efficient nonlinear four-wave mixing process in this platform and obtain a conversion efficiency of -19.8 dB with continuous-wave pumping at a power level of 380 μW. We also investigate the thermal resonance shift of microring resonators with different substrate layouts and observe a superior thermal stability for devices in the AlGaAs-on-sapphire platform. The realization of the AlGaAs-on-sapphire platform also opens new prospects for AlGaAs devices in nonlinear applications in the mid-infrared wavelength range.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Diode Lasers and LED Systems, Centre of Excellence for Silicon Photonics for Optical Communications
Corresponding author: Zheng, Y.
Contributors: Zheng, Y., Pu, M., Sahoo, H. K., Semenova, E., Yvind, K.
Number of pages: 7
Publication date: 1 Jan 2018
Peer-reviewed: Yes

Publication information
Journal: Journal of Lightwave Technology
Volume: 13
Issue number: 9
ISSN (Print): 0733-8724
Ratings:
BFI (2018): BFI-level 2
128 × 2 Gb/s WDM PON System with a Single TDM Time Lens Source using an AlGaAs-On-Insulator Waveguide

We demonstrate a WDM-PON transmitter based on optical Fourier transformation of a single-source TDM-PON. Using a single AlGaAs on-insulator waveguide, 128 WDM-PON signals at 2 Gb/s are generated and transmitted over a 100-km unamplified link.

A Search for Asymmetric Barrier Layers for 1550 nm Al-Free Diode Lasers

A search for materials suitable for implementation of 1.55 µm Al-free diode lasers based on InP with asymmetric barrier (AB) layers is conducted. It is shown that a very high (over 10^6) suppression ratio of the parasitic electron flux can be achieved using common III-V alloys for the ABs. Hence placing such ABs in the immediate vicinity of the active region should completely suppress the parasitic recombination in the waveguide. Several optimal AB designs are proposed that are based on one of the following alloys: Al-free GaInPSb, ternary AlInAs, or quaternary AlGaInAs with a low Al-content. As an important and beneficial byproduct of utilization of such ABs, an improvement of majority carrier capture into the active region occurs.
Broadband Light Sources Based On Highly-Nonlinear AlGaAs-On-Insulator Waveguide Devices

We discuss broadband light generation based on Kerr nonlinearity in the highly-nonlinear AlGaAs-on-insulator waveguide platform. We review the recent demonstrations of utilization of such light sources in telecommunication systems.

Consequence of Non-Uniform Expansion of InP-on-Si Wafers for the Performance of Buried Heterostructure Photonic Crystal Lasers

E-beam metrology is employed to investigate the consequences of non-uniform expansion of 250nm InP layer bonded to Si substrate by BCB and direct wafer bonding for the performance of photonic crystal lasers with buried heterostructures.
Development of design of 808 nm Al-free laser heterostructures with asymmetric barrier layers

We study the possibility of realization of the asymmetric barrier layers (ABL) concept in an 808-nm Al-free GaInAsP/InGaP/GaAs semiconductor laser. Two ABLs on both sides of the active region are aimed to suppress the parasitic recombination in the optical confinement layers. It is shown that such ABL-laser can be made fully Al-free having high suppression ratios for parasitic charge carrier flows (60 and 207 times for electrons and holes, respectively, as compared to a conventional SCH heterostructure).

Feasibility study for Al-free 808 nm lasers with asymmetric barriers suppressing waveguide recombination

The feasibility of implementation of asymmetric barriers (ABs) made of common materials for completely aluminum-free diode lasers is studied. The ABs adjoining a low-dimensional active region on both sides aim to prevent bipolar population in the waveguide layers and thus to suppress parasitic recombination therein, which in turn would enhance the efficiency and temperature-stability of the device. Our search algorithm for appropriate AB materials relies on the minimization of undesired carrier flow (electrons or holes passing through the active region toward the p- or n-type doped cladding layer, respectively), while maintaining the useful flows of hole and electron injection into the active region. Using an example of an 808-nm GaInAsP laser, it is shown that the n- and p-side ABs can be made, for instance, of GaInPSb and GaInP, respectively. In such a laser, the parasitic recombination flux can be suppressed by a factor of 60 for electrons and 200 for holes. It is found that the contribution of the indirect valleys to the electron flow through the p-side AB can be significant and even decisive in some cases. The contribution of light holes to the transmission through the ABs can also be considerable. The optimal thicknesses of the AB layers are determined and the chemical composition tolerances are estimated for a given flux suppression ratio. Published by AIP Publishing.
Highly Nonlinear Gallium Nitride Waveguides
We demonstrate a high effective nonlinearity in high refractive-index-contrast gallium nitride waveguides by performing four-wave mixing characterization. The intrinsic material nonlinearity (n2) of gallium nitride is extracted at telecom wavelengths.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, RAS - Ioffe Physico Technical Institute
Contributors: Stassen, E., Pu, M., Semenova, E., Zavarin, E., Lundin, W., Yvind, K.
Number of pages: 2
Pages: 1-2
Publication date: 2018

Host publication information
Title of host publication: Proceedings of 2018 Conference on Lasers and Electro-Optics (CLEO)
Publisher: Optical Society of America
ISBN (Print): 9781943580422
Electronic versions: Highly_Nonlinear_Gallium_Nitride_Waveguides.pdf
DOIs: 10.1364/CLEO_SI.2018.STh3I.1

Bibliographical note
From the session: Integrated Photonic Platforms (STh3I)
Source: FindIt
Source ID: 2438378248
Research output: Chapter in Book/Report/Conference proceeding – Article in proceedings – Annual report year: 2018 – Research – peer-review

High Q AlGaAs-On-Sapphire Microresonators
We demonstrate an AlGaAs-on-sapphire (AlGaAsOS) microresonator with intrinsic quality factor (Q) as high as 460, 000. We investigate the thermal property of this platform. The realization of the AlGaAsOS platform also opens new prospects for AlGaAs devices in nonlinear applications in the mid-infrared wavelength range.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Diode Lasers and LED Systems, Centre of Excellence for Silicon Photonics for Optical Communications, Quantum and Laser Photonics, High-Speed Optical Communication
Contributors: Zheng, Y., Pu, M., Sahoo, H. K., Semenova, E., Yvind, K.
Number of pages: 2
Pages: 1-2
Publication date: 2018

Host publication information
Title of host publication: Proceedings of 2018 Conference on Lasers and Electro-Optics (CLEO)
Publisher: Optical Society of America
Nano-engineered high-confinement AlGaAs waveguide devices for nonlinear photonics

The combination of nonlinear and integrated photonics enables applications in telecommunication, metrology, spectroscopy, and quantum information science. Pioneer works in silicon-on-insulator (SOI) has shown huge potentials of integrated nonlinear photonics. However, silicon suffers two-photon absorption (TPA) in the telecom wavelengths around 1550 nm, which hampers its practical applications. To get superior nonlinear performance, an ideal integrated waveguide platform should combine a high material nonlinearity, low material absorption (linear and nonlinear), a strong light confinement, and a mature fabrication technology. Aluminum gallium arsenide (AlGaAs) was identified as a promising candidate for nonlinear applications since 1994. It offers a large transparency window, a high refractive index (n approximate to 3.3), a nonlinear index (n2) on the order of 10(-17) m(2)/W(-1), and the ability to engineer the material bandgap to mitigate TPA. In spite of the high intrinsic nonlinearity, conventional deep-etched AlGaAs waveguides exhibit low effective nonlinearity due to the vertical low-index contrast. To take full advantage of the high intrinsic linear and nonlinear index of AlGaAs material, we reconstructed the conventional AlGaAs waveguide into a high index contrast layout that has been realized in the AlGaAs-on-insulator (AlGaAsOI) platform. We have demonstrated low loss waveguides with an ultra-high nonlinear coefficient and high Q microresonators in such a platform. Owing to the high confinement waveguide layout and state-of-the-art nanolithography techniques, the dispersion properties of the AlGaAsOI waveguide can be tailored efficiently and accurately by altering the waveguide shape or dimension, which enables various applications in signal processing and generation, which will be reviewed in this paper.

General information
Publication status: Published
Organisations: Centre of Excellence for Silicon Photonics for Optical Communications, Nanophotonic Devices, Department of Photonics Engineering, Diode Lasers and LED Systems, Fiber Optics, Devices and Non-linear Effects, High-Speed Optical Communication, Technical University of Denmark
Pages: 106721R-106721R-7
Publication date: 2018

Host publication information
Title of host publication: Proceedings of SPIE
Volume: 10672
Publisher: SPIE - International Society for Optical Engineering
Quantifying non-uniform InP-on-Si wafer expansion with a sub-50 nm precision using E-beam metrology
The non-uniform expansion of InP layers bonded directly and with the adhesive-BCB to 2" silicon substrates is quantified and compared on a 2" wafer-scale by using E-beam as metrology tool with a sub-50 nm precision.

Signal-to-Idler Conversion Penalty in AlGaAs-on-Insulator Wavelength Converter
A wavelength converter based on AlGaAsOI waveguide is characterized by varying the input signal quality. Signal-to-idler conversion penalty is measured in terms of effective received SNR, and trade-offs between penalty and converted signal quality are outlined.

Bibliographical note
From the session: Nonlinearity Compensation (STu4C)
Single-source chip-based frequency comb enabling extreme parallel data transmission
The Internet today transmits hundreds of terabits per second, consumes 9% of all electricity worldwide and grows by 20-30% per year(1,2). To support capacity demand, massively parallel communication links are installed, not scaling favourably concerning energy consumption. A single frequency comb source may substitute many parallel lasers and improve system energy-efficiency(3,4). We present a frequency comb realized by a non-resonant aluminium-gallium-arsenide-oninsulator (AlGaAsOI) nanowaveguide with 66% pump-tocomb conversion efficiency, which is significantly higher than state-of-the-art resonant comb sources. This enables unprecedented high data-rate transmission for chip-based sources, demonstrated using a single-mode 30-core fibre. We show that our frequency comb can carry 661 Tbit s(-1) of data, equivalent to more than the total Internet traffic today. The comb is obtained by seeding the AlGaAsOI chip with 10-GHz picosecond pulses at a low pump power (85 mW), and this scheme is robust to temperature changes, is energy efficient and facilitates future integration with on-chip lasers or amplifiers(5,6).

SiNOI and AlGaAs-on-SOI nonlinear circuits for continuum generation in Si photonics
In this communication, we report on the design, fabrication, and testing of Silicon Nitride on Insulator (SiNOI) and Aluminum-Gallium-Arsenide (AlGaAs) on silicon-on-insulator (SOI) nonlinear photonic circuits for continuum generation in Silicon (Si) photonics. As recently demonstrated, the generation of frequency continua and supercontinua can be used to overcome the intrinsic limitations of nowadays silicon photonics notably concerning the heterogeneous integration of III-V on SOI lasers for datacom and telecom applications. By using the Kerr nonlinearity of monolithic silicon nitride and heterointegrated GaAs-based alloys on SOI, the generation of tens or even hundreds of new optical frequencies can be obtained in dispersion tailored waveguides, thus providing an all-optical alternative to the heterointegration of hundreds of standalone III-V on Si lasers. In our work, we present paths to energy-efficient continua generation on silicon photonics circuits. Notably, we demonstrate spectral broadening covering the full C-band via Kerrbased self-phase modulation in SiNOI nanowires featuring full process compatibility with Si photonic devices. Moreover, AlGaAs waveguides are heterointegrated on SOI in order to dramatically reduce (x1/10) thresholds in optical parametric oscillation and in the power required for supercontinuum generation under pulsed pumping. The manufacturing techniques allowing the monolithic co-integration of nonlinear functionalities on existing CMOS-compatible Si photonics for both active and passive components will be shown. Experimental evidence based on self-phase modulation show SiNOI and AlGaAs nanowires capable of generating wide-ranging frequency continua in the C-Band. This will pave the way for low-Threshold power-efficient Kerr-based comb-and continuum-sources featuring compatibility with Si photonic integrated circuits (Si-PtCs).
Ultra-Efficient and Broadband Nonlinear AlGaAs-on-Insulator Chip for Low-Power Optical Signal Processing

Four-wave mixing (FWM) is a versatile optical nonlinear parametric process that enables a plethora of signal processing functionalities in optical communication. Realization of efficient and broadband all-optical signal processing with ultra-low energy consumption has been elusive for decades. Although tremendous efforts have been put into developing various material platforms, it has remained a challenge to obtain both high efficiency and broadband operation. Here, an aluminum...
gallium arsenide nonlinear chip with high FWM conversion efficiency per length per pump power and an ultra-broad bandwidth is presented. Combining an ultra-high material nonlinearity and strong effective nonlinear enhancement from a high-index-contrast waveguide layout, an ultra-high conversion efficiency of 4 dB is obtained in a 3-mm-long nanowaveguide. Taking advantage of high-order dispersion, a scheme is presented to realize an ultra-broad continuous conversion bandwidth covering 1280–2020 nm. A microresonator is also utilized to demonstrate a conversion efficiency enhancement gain of more than 50 dB with respect to a waveguide device, which significantly reduces the power consumption. Moreover, wavelength conversion of an optical serial data signal is performed at a bit rate beyond terabit-per-second, showing the capabilities of this III-V semiconductor material for broadband optical signal processing.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, High-Speed Optical Communication
Corresponding author: Pu, M.
Publication date: 2018
Peer-reviewed: Yes

Publication information
Journal: Laser & Photonics Reviews
Volume: 12
Issue number: 12
Article number: 1800111
ISSN (Print): 1863-8880
Ratings:
BFI (2018): BFI-level 1
Scopus rating (2018): CiteScore 9.79 SJR 3.821 SNIP 2.845
Web of Science (2018): Indexed yes
Original language: English
Keywords: All-optical wavelength conversion, Four-wave mixing, Integrated nonlinear optics, Optical signal processing, Third-order nonlinear materials
Electronic versions:
180905_lpor.201800111_manuscript_post_print.pdf
DOI:
10.1002/lpor.201800111
Source: FindIt
Source ID: 2440629454
Research output: Contribution to journal › Journal article – Annual report year: 2018 › Research › peer-review

Wavelength tunable MEMS VCSELS for OCT imaging
MEMS VCSELS are one of the most promising swept source (SS) lasers for optical coherence tomography (OCT) and one of the best candidates for future integration with endoscopes, surgical probes and achieving an integrated OCT system. However, the current MEMS-based SS are processed on the III-V wafers, which are small, expensive and challenging to work with. Furthermore, the actuating part, i.e., the MEMS, is on the top of the structure which causes a strong dependence on packaging to decrease its sensitivity to the operating environment. This work addresses these design drawbacks and proposes a novel design framework. The proposed device uses a high contrast grating mirror on a Si MEMS stage as the bottom mirror, all of which is defined in an SOI wafer. The SOI wafer is then bonded to an InP III-V wafer with the desired active layers, thereby sealing the MEMS. Finally, the top mirror, a dielectric DBR (7 pairs of TiO2-SiO2), is deposited on top. The new device is based on a silicon substrate with MEMS defined on a silicon membrane in an enclosed cavity. Thus the device is much more robust than the existing MEMS VCSELS. This design also enables either a two-way actuation on the MEMS or a smaller optical cavity (pull-away design), i.e., wider FSR (Free Spectral Range) to increase the wavelength sweep. Fabrication of the proposed device is outlined and the results of device characterization are reported.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Quantum and Laser Photonics, High-Speed Optical Communication, Experimental Surface and Nanomaterials Physics, Department of Micro- and Nanotechnology, Silicon Microtechnology, OCTLIGHT ApS
Contributors: Sahoo, H. K., Ansbæk, T., Ottaviano, L., Semenova, E., Hansen, O., Yvind, K.
Number of pages: 6
Publication date: 2018
An ultra-efficient nonlinear planar integrated platform for optical signal processing and generation

This paper will discuss the recently developed integrated platform: AlGaAs-on-insulator and its broad range of nonlinear applications. Recent demonstrations of broadband optical signal processing and efficient frequency comb generations in this platform will be reviewed.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, High-Speed Optical Communication, Fiber Optics, Devices and Non-linear Effects, Diode Lasers and LED Systems
Publication date: 2017

Host publication information
Title of host publication: Proceedings of Asia Communications and Photonics Conference, ACPC 2017
Volume: 2017
Publisher: Optical Society of America
ISBN (Print): 97815557528209
(Optics Infobase Conference Papers).
Keywords: Electronic, Optical and Magnetic Materials, Mechanics of Materials, Aluminum gallium arsenide, Gallium compounds, Nonlinear optics, Photonics, Signal processing, Frequency combs, Integrated platform, Nonlinear applications, Ultra-efficient, Optical signal processing
DOIs:
10.1364/ACPC.2017.S4J.6
Source: FindIt
Source ID: 2396990319
Research output: Chapter in Book/Report/Conference proceeding » Article in proceedings » Annual report year: 2018 » Research » peer-review

A valence force field-Monte Carlo algorithm for quantum dot growth modeling

We present a novel kinetic Monte Carlo version for the atomistic valence force fields algorithm in order to model a self-assembled quantum dot growth process. We show our atomistic model is both computationally favorable and capture more details compared to traditional kinetic Monte Carlo models based on continuum elastic models. We anticipate the model will be useful to experimentalists in understanding better the growth dynamics of quantum dot systems.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Center for Electron Nanoscopy, Nanophotonic Devices, University of Rome Tor Vergata, Consiglio Nazionale delle Ricerche
Number of pages: 2
Pages: 117-118
Publication date: 2017

Host publication information
Title of host publication: 2017 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD)
Publisher: IEEE
Characterization and optimization of a high-efficiency AlGAs-On-Insulator-based wavelength converter for 64- and 256-QAM signals

In this paper, we demonstrate wavelength conversion of advanced modulation formats such as 10-GBd 64-QAM and 256-QAM with high conversion efficiency over a 29-nm spectral window by using four-wave mixing in an AlGAs-On-Insulator (AlGAsOI) nano-waveguide. A thorough characterization of the wavelength converter is reported, including the optimization of the AlGAsOI nano-waveguide in terms of conversion efficiency and associated bandwidth and the analysis of the impact of the converter pump quality and power as well as the signal input power. The optimized converter enables generating idlers with optical signal-to-noise ratio (OSNR) above 30 dB over a 29-nm bandwidth leading to error-free conversion of 64-QAM and 256-QAM with OSNR penalty below 1.0 dB and 2.0 dB respectively. The generated idlers exhibit an OSNR margin to the chosen forward error correction thresholds of >3 dB and >7 dB for 64-QAM and 256-QAM, respectively, that can be used for transmission after conversion.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, High-Speed Optical Communication, Centre of Excellence for Silicon Photonics for Optical Communications, Coding and Visual Communication, Nanophotonic Devices
Number of pages: 8
Pages: 3750-3757
Publication date: 2017
Peer-reviewed: Yes

Publication information
Journal: Journal of Lightwave Technology
Volume: 35
Issue number: 17
ISSN (Print): 0733-8724
Ratings:
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 4.42 SJR 1.166 SNIP 1.868
Web of Science (2017): Impact factor 3.652
Web of Science (2017): Indexed yes
Original language: English
Keywords: Four-wave mixing, Integrated waveguides, Quadrature amplitude modulation, Coherent communications
Electronic versions:
DaRos_JLT2017_prePrint.pdf
DOIs:
10.1109/JLT.2017.2722013

Bibliographical note
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Source: PublicationPreSubmission
Source ID: 133665129
Research output: Contribution to journal › Journal article – Annual report year: 2017 › Research › peer-review

Demonstration of a self-pulsing photonic crystal Fano laser
The semiconductor lasers in use today rely on various types of cavity, making use of Fresnel reflection at a cleaved facet, total internal reflection between two different median, Bragg reflection from a periodic stack of layers(3-8), mode coupling in a high contrast grating(9,10) or random scattering in a disordered medium. Here, we demonstrate an ultrasmall laser with a mirror, which is based on Fano interference between a continuum of waveguide modes and the discrete resonance of a nanocavity. The rich physics of Fano resonances(12) has recently been explored in a number of different photonic and plasmonic systems(13,14). The Fano resonance leads to unique laser characteristics. In particular, because the Fano mirror is very narrowband compared to conventional laser mirrors, the laser is single mode and can be modulated via the
mirror. We show, experimentally and theoretically, that nonlinearities in the mirror may even promote the generation of a self-sustained train of pulses at gigahertz frequencies, an effect that has previously been observed only in macroscopic lasers(15-18). Such a source is of interest for a number of applications within integrated photonics.

**General information**
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices
Contributors: Yu, Y., Xue, W., Semenova, E., Yvind, K., Mørk, J.
Pages: 81-84
Publication date: 2017
Peer-reviewed: Yes

**Publication information**
Journal: Nature Photonics
Volume: 11
Issue number: 2
ISSN (Print): 1749-4885

**Enhancing Optical Forces in InP-Based Waveguides**
Cantilever sensors are among the most important microelectromechanical systems (MEMS), which are usually actuated by electrostatic forces or piezoelectric elements. Although well-developed microfabrication technology has made silicon the prevailing material for MEMS, unique properties of other materials are overlooked in this context. Here we investigate optically induced forces exerted upon a semi-insulating InP waveguide suspended above a highly doped InP: Si substrate, in three different regimes: the epsilon-near-zero (ENZ), with excitation of surface plasmon polaritons (SPPs) and phonons excitation. An order of magnitude amplification of the force is observed when light is coupled to SPPs, and three orders of magnitude amplification is achieved in the phonon excitation regime. In the ENZ regime, the force is found to be repulsive and higher than that in a waveguide suspended above a dielectric substrate. Low losses in InP: Si result in a big propagation length. The induced deflection can be detected by measuring the phase change of the light when passing through the waveguide, which enables all-optical functioning, and paves the way towards integration and miniaturization of micro-cantilevers. In addition, tunability of the ENZ and the SPP excitation wavelength ranges, via adjusting the carrier concentration, provides an extra degree of freedom for designing MEMS devices.

**General information**
Publication status: Published
Organisations: Department of Photonics Engineering, Metamaterials, Nanophotonic Devices
Contributors: Panah, M. E. A., Semenova, E., Lavrinenko, A.
Number of pages: 8
Publication date: 2017
Peer-reviewed: Yes

**Publication information**
Journal: Scientific Reports
Volume: 7
Issue number: 1
ISSN (Print): 2045-2322

**Research output: Contribution to journal › Journal article – Annual report year: 2017 › Research › peer-review**
Experimental demonstration of a Fano laser based on photonic crystals

Conventional semiconductor laser mirrors are based on Fresnel reflection [1], Bragg reflection [2, 3] or total internal reflection [4]. Here we demonstrate a new laser concept using photonic crystals (PhC), with a mirror based on Fano interference between a waveguide continuum and a discrete resonance of a nanocavity [5]. We show that the very narrowband feature of the Fano resonance [6] can lead to single mode lasing. In addition, when combined with optical nonlinearity, the highly dispersive feature of the Fano resonance can promote self-pulsations at gigahertz frequencies [7], which was previously observed only in macroscopic lasers [8].

Fabrication and experimental demonstration of photonic crystal laser with buried heterostructure

Development of ultra-small and efficient laser sources for photonic integrated circuits is one of the main cornerstones in achieving the requirements imposed for on-chip optical interconnects [1]. The InP photonic crystal (PhC) platform with selectively embedded gain medium [2] is a promising way of separating active light amplification regions from passive regions for light propagation without induced absorption losses and surface recombination. The main focus of this work is the fabrication and experimental demonstration of a buried heterostructure (BH) photonic crystal laser bonded to a silicon wafer, illustrating the effective single-platform active-passive material integration method.
High Q gallium nitride microring resonators
Summary form only given. Gallium nitride (GaN) is a promising material for nonlinear microresonators. It has large intrinsic \( \chi^{(2)} \) and \( \chi^{(3)} \), excellent thermal properties and a relatively large bandgap [1] and can be used for example for parametric conversion and frequency doubling [2]. Furthermore it is quite resilient and can withstand high temperatures and power. In this paper, we demonstrate GaN microring resonators with a quality factor (Q) larger than 10^5, which, to the best of our knowledge, is the highest demonstrated Q for microring resonators in a pure GaN platform [3].

Lasers, switches and non-reciprocal elements based on photonic crystal Fano resonances
We discuss the realization of active photonic devices exploiting Fano resonances in photonic crystal membranes.

Hybrid Si-on-chip Lasers with Nano Structures
Mid-IR optical properties of silicon doped InP
InP is one of the most important materials for optoelectronics as a direct bandgap semiconductor, which can also be regarded as a low loss alternative plasmonic material for mid-infrared (mid-IR). The InP films studied in this work were grown by metal-organic vapor phase epitaxy (MOVPE). The effect of growth conditions on the optical and electrical properties of silicon doped InP (InP:Si) in the wavelength range from 3 to 40 μm was studied. The carrier concentration of up to $3.9 \times 10^{19}$ cm$^{-3}$ is achieved by optimizing the growth conditions. The dielectric function, effective mass of electrons and plasma frequency were determined by Fourier transform infrared spectroscopy (FTIR) for different carrier density levels. The plasma frequency can be tuned effectively via doping from 18.43 to 50.5 THz. Based on the experimental results, a semi-empirical formula for the plasma frequency, as a function of carrier concentration, is derived. Comparison to other semiconductors shows superior plasmonic performance of InP:Si in terms of propagation length and surface confinement.

General information
Publication status: Published
Organisations: Metamaterials, Department of Energy Conversion and Storage, Mixed Conductors, Electrofunctional materials, Department of Photonics Engineering, Nanophotonic Devices, St. Petersburg Academic University
Contributors: Panah, M. E. A., Han, L., Norrman, K., Pryds, N., Nadtochiy, A., Zhukov, A. E., Lavrinenko, A., Semenova, E.
Pages: 2260-2271
Publication date: 2017
Peer-reviewed: Yes

Publication Information
Journal: Optical Materials Express
Volume: 7
Issue number: 7
ISSN (Print): 2159-3930
Ratings:
Scopus rating (2017): CiteScore 2.78 SJR 0.952 SNIP 1.147
Web of Science (2017): Impact factor 2.566
Web of Science (2017): Indexed yes
Original language: English
Keywords: Semiconductor materials, Optical materials, Infrared, Deposition and fabrication, Plasmonics
Electronic versions:
ome_7_7_2260.pdf
DOIs:
10.1364/OME.7.002260
Source: FindIt
Source ID: 2371248133
Research output: Contribution to journal › Journal article – Annual report year: 2017 › Research › peer-review

On the high characteristic temperature of an InAs/GaAs/InGaAsP QD laser with an emission wavelength of ~1.5 μm on an InP substrate
We report on a study of lasers with an emission wavelength of about 1.5 μm and high temperature stability, synthesized on an InP (001) substrate. Self-organized InAs quantum dots capped with a thin GaAs layer are used as the active region of the laser. A quaternary InGaAsP solid solution with a band-gap width of 1.15 eV serves as the waveguide/matrix layer. A high characteristic temperature of the threshold current, $T_0 = 205$ K, is reached in the temperature range 20–50°C in
ridge-waveguide laser diodes. A correlation between the values of $T_0$ and the band-gap width of the waveguide layers is found.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, RAS - St. Petersburg Academic University
Contributors: Zubov, F., Semenova, E., Kulkova, I., Yvind, K., Kryzhanovskaya, N., Maximov, M., Zhukov, A.
Pages: 1332-1336
Publication date: 2017
Peer-reviewed: Yes

Publication information
Journal: Semiconductors
Volume: 51
Issue number: 10
ISSN (Print): 1063-7826
Ratings:
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 0.68 SJR 0.362 SNIP 0.745
Web of Science (2017): Indexed yes
Original language: English
DOIs:
10.1134/S1063782617100207
Source: FindIt
Source ID: 2391259563
Research output: Contribution to journal › Journal article – Annual report year: 2017 › Research › peer-review

Photonic crystal Fano lasers and Fano switches
We show that Fano resonances can be realized in photonic crystal membrane structures by coupling line-defect waveguides and point-defect nanocavities. The Fano resonance can be exploited to realize optical switches with very small switching energy, as well as Fano lasers, that can generate short optical pulses.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices
Pages: 88-89
Publication date: 2017

Host publication information
Title of host publication: Proceedings of the 22nd Microoptics Conference (MOC2017)
Publisher: IEEE
Article number: E-1 (Invited)
ISSN (Print): 9784863486096
DOIs:
10.23919/MOC.2017.8244505
Source: FindIt
Source ID: 2391259563
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2017 › Research › peer-review

Photonic crystal Fano resonances for realizing optical switches, lasers and non-reciprocal elements
We present our work on photonic crystal membrane devices exploiting Fano resonance between a line-defect waveguide and a side coupled nanocavity. Experimental demonstration of fast and compact all-optical switches for wavelength-conversion is reported. It is shown how the use of an asymmetric structure in combination with cavity-enhanced nonlinearity can be used to realize non-reciprocal transmission at ultra-low power and with large bandwidth. A novel type of laser structure, denoted a Fano laser, is discussed in which one of the mirrors is based on a Fano resonance. Finally, the design, fabrication and characterization of grating couplers for efficient light coupling in and out of the indium phosphide photonic crystal platform is discussed.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, High-Speed Optical Communication, Nanophotonic Devices
Photonic Crystal with Buried Heterostructure Platform for Laser Devices Directly Bonded to Si

In pursuit of fabricating compact and efficient light sources for optical interconnects on Si, our directly bonded InP buried heterostructure photonic crystal membrane lasers benefit from the separation between active and passive material regions.

Specific features of waveguide recombination in laser structures with asymmetric barrier layers

The spatial distribution of the intensity of the emission caused by recombination appearing at a high injection level (up to 30 kA/cm2) in the waveguide layer of a GaAs/AlGaAs laser structure with GaInP and AlGaInAs asymmetric barrier layers is studied by means of near-field scanning optical microscopy. It is found that the waveguide luminescence in such a laser, which is on the whole less intense as compared to that observed in a similar laser without asymmetric barriers, is non-uniformly distributed in the waveguide, so that the distribution maximum is shifted closer to the p-type cladding layer. This can be attributed to the ability of the GaInP barrier adjoining the quantum well on the side of the n-type cladding layer to suppress the hole transport.
Towards Polarization-Independent Four-Wave Mixing in Dispersion Engineered AlGaAs-on-Insulator Nano-Waveguide

We demonstrate a polarization-independent continuous wave four-wave mixing conversion bandwidth of 70 nm (1530-1600 nm) in a dispersion engineered high-index contrast AlGaAs-on-insulator nano-waveguide. We obtain constant conversion efficiency over 175 nm for the TE mode.

Towards Ultra-High Q Microresonators in High-Index Contrast AlGaAs-On-Insulator

We demonstrate an AlGaAs-on-insulator microresonator with intrinsic Q as high as 690,000. We optimized the fabrication and investigated the impact of waveguide dimension on the Q in such a high-index contrast platform.
1.5 µm InAs/InGaAsP/InP quantum dot laser with improved temperature stability

Temperature characteristics of InAs/InGaAsP quantum dot (QD) lasers synthesized on InP (001) substrate are presented. The lasers demonstrate high temperature stability: a threshold current characteristic temperature as high as 205 K in the temperature range between 20 to 50°C was measured. Lasing wavelength of 1.5 µm was achieved by covering QDs with 1.7 monolayers of GaAs.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, St. Petersburg State Polytechnical University, St. Petersburg Academic University, KU Leuven
Number of pages: 4
Publication date: 2016
Peer-reviewed: Yes
An Ultra-Efficient Nonlinear Platform: AlGaAs-On-Insulator

The combination of nonlinear and integrated photonics enables applications including optical signal processing, multi-wavelength lasers, metrology, spectroscopy, and quantum information science. Silicon-on-insulator (SOI) has emerged as a promising platform [1, 2] due to its high material nonlinearity and its compatibility with the CMOS industry. However, silicon suffers two-photon absorption (TPA) in the telecommunication wavelength band around 1.55 µm, which hampers its applications. Different platforms have been proposed to avoid TPA in the telecom wavelength range such as Si3N4 and Hydex [3]. Though tremendous technological work in those platforms have greatly improved device performances, the relatively low intrinsic material nonlinearities of those materials limit device performances concerning efficiency. Therefore, an integrated nonlinear platform that combines a high material nonlinearity, a high-index contrast as SOI, and low linear and nonlinear losses is highly desired. Aluminium gallium arsenide (AlGaAs) was early identified as a promising candidate and even nominated as “the silicon of nonlinear optical material” [4] when operated just below half its bandgap energy. It offers a nonlinear index (n2) on the order of 10−17 W/m2 and a high refractive index (n ≈3.3), a large transparency window (from near- to mid-infrared), and the ability to engineer the material bandgap to mitigate TPA [5]. In this presentation, we introduce AlGaAs-on-insulator (AlGaAsOI) platform which combines both strong nonlinear light-matter interaction induced by high-index contrast layout and the potential to fabricate complex designs similar to what is done in silicon-on-insulator photonics. We demonstrate low loss (~ 1.4 dB/cm) nanowaveguides with an ultra-high nonlinear coefficient (~660W−1m−1) and microring resonators with quality factors on the order of 105 [6]. The large effective nonlinearity of such platform enables efficient nonlinear processes such as high-speed optical signal processing [7], supercontinuum generation, and Kerr frequency comb generation [8]. Moreover, the required operation power for signal generation processes such as optical parametric oscillation in the AlGaAsOI platform is well within the range of standard on-chip light sources. In line with the fast-growing hybrid integration trend to combine different materials in multiple levels on a single CMOS compatible chip, the AlGaAsOI platform is very promising for realizing a compact fully-integrated multi-wavelength light source for high bandwidth optical interconnects.
Broadband and efficient dual-pump four-wave-mixing in AlGaAs-on-insulator nano-waveguides

We characterize dual-pump four-wave-mixing in AlGaAs-on-insulator nano-waveguides and demonstrate an output conversion efficiency as high as −8.5 dB at 155-mW pump power. The idler optical signal-to-noise ratio is above 25 dB over a 28-nm bandwidth.

Characterization of a Wavelength Converter for 256-QAM Signals Based on an AlGaAs-On-Insulator Nano-waveguide

High efficiency and broadband wavelength conversion in a 9-mm AlGaAs-On-Insulator waveguide is shown to provide high-quality (OSNR > 30 dB) idler generation over a 28-nm bandwidth enabling error-free conversion of 10-GBd 256-QAM with OSNR penalty below 2.5 dB.
Efficient frequency comb generation in AlGaAs-on-insulator

The combination of nonlinear and integrated photonics enables Kerr frequency comb generation in stable chip-based microresonators. Such a comb system will revolutionize applications, including multi-wavelength lasers, metrology, and spectroscopy. Aluminum gallium arsenide (AlGaAs) exhibits very high material nonlinearity and low nonlinear loss. However, difficulties in device processing and low device effective nonlinearity made Kerr frequency comb generation elusive. Here, we demonstrate AlGaAs-on-insulator as a nonlinear platform at telecom wavelengths with an ultra-high device nonlinearity. We show high-quality-factor (Q > 105) micro-resonators where optical parametric oscillations are achieved with milliwatt-level pump threshold powers, which paves the way for on-chip pumped comb generation.

Discussions

Highly doped InP as a low loss plasmonic material for mid-IR region

We study plasmonic properties of highly doped InP in the mid-infrared (IR) range. InP was grown by metal-organic vapor phase epitaxy (MOVPE) with the growth conditions optimized to achieve high free electron concentrations by doping with silicon. The permittivity of the grown material was found by fitting the calculated infrared reflectance spectra to the measured ones. The retrieved permittivity was then used to simulate surface plasmon polaritons (SPPs) propagation on flat and structured surfaces, and the simulation results were verified in direct experiments. SPPs at the top and bottom interfaces of the grown epilayer were excited by the prism coupling. A high-index Ge hemispherical prism provides efficient coupling conditions of SPPs on flat surfaces and facilitates acquiring their dispersion diagrams. We observed diffraction into symmetry-prohibited diffraction orders stimulated by the excitation of surface plasmon-polaritons in a periodically structured epilayer. Characterization shows good agreement between the theory and experimental results and confirms that highly doped InP is an effective plasmonic material aiming it for applications in the mid-IR wavelength range.
Low-loss high-confinement waveguides and microring resonators in AlGaAs-on-insulator

AlGaAs is a promising material for integrated nonlinear photonics due to its intrinsic high nonlinearity. However, the challenging fabrication of deep etched AlGaAs devices makes it difficult to realize high-performance devices such as low-loss dispersion engineered waveguides and high quality microring resonators. Here, we report a process to make high-quality AlGaAs-on-insulator (AlGaAsOI) wafers where high confinement waveguides can be realized. Using optimized patterning processes, we fabricated AlGaAsOI waveguides with propagation losses as low as 1 dB/cm and microring resonators with quality factors up to 350,000 at telecom wavelengths. Our demonstration opens new prospects for AlGaAs devices in integrated nonlinear photonics.

Nonlinear Optics in AlGaAs on Insulator

AlGaAs on insulator is a powerful nonlinear platform sporting a high effective nonlinearity and the possibility to fabricate complex designs. We will present low loss waveguides enabling efficient optical signal processing and Kerr comb generation.
Optically pumped 1550nm wavelength tunable MEMS VCSEL
The paper presents the design and fabrication of an optically pumped 1550nm tunable MEMS VCSEL with an enclosed MEMS. The MEMS is defined in SOI and the active material, an InP wafer with quantum wells are bonded to the SOI and the last mirror is made from the deposition of dielectric materials. The design brings flexibility to fabricate MEMS VCSELS over a wider range of wavelengths. The paper discusses results from the simulations and bonding results from fabrication. The device will push the boundaries for wavelength sweep speed and bandwidth.

Phase-sensitive Four-wave Mixing in AlGaAs-on-Insulator Nano-waveguides
Phase-sensitive four-wave mixing is experimentally demonstrated in a 5-mm long AlGaAsOI nano-waveguide. More than 7 dB of phase-sensitive extinction ratio are reported without neither using active biasing nor polarization-assisted schemes. Measurements show a good match with numerical predictions.
Silicon doped InP as an alternative plasmonic material for mid-infrared

Silicon-doped InP is grown on top of semiinsulating iron-doped and sulfur-doped InP substrates by metalorganic vapor phase epitaxy (MOVPE), and the growth parameters are adjusted to obtain various free carrier concentrations from $1.05 \times 10^{19}$ cm$^{-3}$ up to $3.28 \times 10^{19}$ cm$^{-3}$. Mid-infrared (IR) reflection spectra of the samples with different carrier concentrations are used to retrieve pertaining dielectric functions as the key factor for understanding plasmonic behavior of InP:Si in the mid-IR wavelength range.

Single-Source AlGaAs Frequency Comb Transmitter for 661 Tbit/s Data Transmission in a 30-core Fiber

We demonstrate an AlGaAs-on-insulator nano-waveguide-based frequency comb with high OSNR enabling a single-source to fully load a 9.6-km heterogeneous 30-core fibre with 661 Tbit/s data achieved by 30xcores, 80xWDM, 40 Gbaud, and PDM-16QAM
Supercontinuum Generation in AlGaAs-On-Insulator Nano-Waveguide at Telecom Wavelengths
We characterize pulse spectral broadening in an AlGaAs-on-insulator nano-waveguide at telecom wavelengths. We obtain a supercontinuum over 500 nm (30-dB bandwidth) with 410-fs pulses and self-phase modulation broadening covering the C-band with 1.1-ps pulses.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, High-Speed Optical Communication
Number of pages: 2
Publication date: 2016

Host publication information
Title of host publication: CLEO: Applications and Technology 2016
Place of publication: San Jose, California United States
Publisher: Optical Society of America OSA
Article number: AM3J.3
DOIs: 10.1364/CLEO_AT.2016.AM3J.3
Source: PublicationPreSubmission
Source ID: 124337228
Research output: Chapter in Book/Report/Conference proceeding » Conference abstract in proceedings – Annual report
year: 2016 » Research » peer-review

Surface Plasmons on Highly Doped InP
Silicon doped InP is grown by metal-organic vapor phase epitaxy (MOVPE) using optimized growth parameters to achieve high free carrier concentration. Reflectance of the grown sample in mid-IR range is measured using FTIR and the result is used to retrieve the parameters of the dielectric function. The derived dielectric function is used to simulate the excitation of surface plasmons by a diffraction grating made of the grown material. The grating structure is fabricated using standard nanofabrication techniques. Spectral features from the grating agree well with the simulations and show spp coupling at predicted angles of incidence and wavelengths.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Metamaterials, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications
Contributors: Panah, M. E. A., Ottaviano, L., Semenova, E., Lavrinenko, A.
Pages: 28-30
Publication date: 2016

Host publication information
Title of host publication: Proceedings of 10th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics
Publisher: IEEE
ISBN (Print): 9781509018031
DOIs: 10.1109/MetaMaterials.2016.7746376
Source: PublicationPreSubmission
Source ID: 126614461
Research output: Chapter in Book/Report/Conference proceeding » Article in proceedings – Annual report
year: 2016 » Research » peer-review

Threshold Characteristics of Slow-Light Photonic Crystal Lasers
The threshold properties of photonic crystal quantum dot lasers operating in the slow-light regime are investigated experimentally and theoretically. Measurements show that, in contrast to conventional lasers, the threshold gain attains a minimum value for a specific cavity length. The experimental results are explained by an analytical theory for the laser threshold that takes into account the effects of slow light and random disorder due to unavoidable fabrication imperfections. Longer lasers are found to operate deeper into the slow-light region, leading to a trade-off between slow-light induced reduction of the mirror loss and slow-light enhancement of disorder-induced losses.

General information
Ultrahigh-speed Si-integrated on-chip laser with tailored dynamic characteristics

For on-chip interconnects, an ideal light source should have an ultralow energy consumption per bandwidth (operating energy) as well as sufficient output power for error-free detection. Nanocavity lasers have been considered the most ideal for smaller operating energy. However, they have a challenge in obtaining a sufficient output power. Here, as an alternative, we propose an ultrahigh-speed microcavity laser structure, based on a vertical cavity with a high-contrast grating (HCG) mirror for transverse magnetic (TM) polarisation. By using the TM HCG, a very small mode volume and an un-pumped compact optical feedback structure can be realised, which together tailor the frequency response function for achieving a very high speed at low injection currents. Furthermore, light can be emitted laterally into a Si waveguide. From an 1.54-μm optically-pumped laser, a 3-dB frequency of 27 GHz was obtained at a pumping level corresponding to sub-mA. Using measured 3-dB frequencies and calculated equivalent currents, the modulation current efficiency factor (MCEF) is estimated to be 42.1 GHz/mA(1/2), which is superior among microcavity lasers. This shows a high potential for a very high speed at low injection currents or very small heat generation at high bitrates, which are highly desirable for both on-chip and off-chip applications.
A Highly Efficient Nonlinear Platform: AlGaAs-On-Insulator

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices
Contributors: Pu, M., Ottaviano, L., Semenova, E., Yvind, K.
Number of pages: 1
Publication date: 2015

Host publication information
Title of host publication: CLEO/Europe 2015 - European Conference on Lasers and Electro-Optics
Publisher: IEEE
ISBN (Print): 978-1-4673-7475-0
Source: PublicationPreSubmission
Source ID: 112087651
Research output: Chapter in Book/Report/Conference proceeding > Conference abstract in proceedings – Annual report year: 2015 > Research > peer-review

AlGaAs-On-Insulator Nanowire with 750 nm FWM Bandwidth, -9 dB CW Conversion Efficiency, and Ultrafast Operation Enabling Record Tbaud Wavelength Conversion

We present an AlGaAs-on-insulator platform for integrated nonlinear photonics. We demonstrate the highest reported conversion efficiency/length/pump-power, ultra-broadband fourwave mixing, and first-ever wavelength conversion of 1.28-Tbaud serial data signals in a 3-mm long dispersion-engineered AlGaAs nano-waveguide

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, High-Speed Optical Communication
Contributors: Pu, M., Ottaviano, L., Semenova, E., Vukovic, D., Oxenløwe, L. K., Yvind, K.
Number of pages: 3
Publication date: 2015

Host publication information
Title of host publication: Proceedings of the Optical Fiber Communication Conference and Exhibition 2015
Publisher: IEEE
Electronic versions:
AlGaAs_On_Insulator_post_print.pdf
DOIs:
10.1364/OFC.2015.Th5A.3
Source: PublicationPreSubmission
Source ID: 107595128
Research output: Chapter in Book/Report/Conference proceeding > Article in proceedings – Annual report year: 2015 > Research > peer-review

AlGaAs-On-Insulator nonlinear photonics

We present an AlGaAs-on-insulator platform for integrated nonlinear photonics. We demonstrate the highest reported conversion efficiency and ultra-broadband four-wave mixing for an integrated platform around 1550nm

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices
Contributors: Pu, M., Ottaviano, L., Semenova, E., Yvind, K.
Number of pages: 1
Publication date: 2015
Diode lasers with asymmetric barriers for 850 nm spectral range: experimental studies of power characteristics
It is demonstrated that the use of asymmetric barrier layers in a waveguide of a diode laser suppress non-linearity of light-current characteristic and thus improve its power characteristics under high current injection. The results are presented for 850-nm AlGaAs/GaAs broad-area lasers with GaInP and AlInGaAs asymmetric barriers.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Russian Academy of Sciences, St. Petersburg Academic University, Virginia Polytechnic Institute and State University
Contributors: Zubov, F. I., Zhukov, A. E., Shernyakov, Y. M., Maximov, M. V., Semenova, E., Asryan, L. V.
Number of pages: 6
Publication date: 2015
Peer-reviewed: Yes

Publication information
Journal: Journal of Physics: Conference Series
Volume: 643
Issue number: 1
Article number: 012042
ISSN (Print): 1742-6596
Ratings:
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 0.35 SJR 0.252 SNIP 0.373
Web of Science (2015): Indexed yes
Original language: English
Electronic versions:
pdf.pdf
DOIs:
10.1088/1742-6596/643/1/012042

Bibliographical note
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Published under licence by IOP Publishing Ltd
Source: Findit
Source ID: 276446677
Research output: Contribution to journal › Journal article – Annual report year: 2015 › Research › peer-review

Highly Efficient Four-Wave Mixing in an AlGaAs-On-Insulator (AlGaAsOI) Nano-Waveguide
We propose an AlGaAs-on-insulator platform for nonlinear integrated photonics. We demonstrate highly efficient four-wave mixing in a 3-mm long AlGaAs-on-insulator nanowaveguide. A conversion efficiency of -21.1 dB is obtained with only a 45-mW pump

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices
Contributors: Pu, M., Ottaviano, L., Semenova, E., Yvind, K.
Number of pages: 2
Publication date: 2015

Host publication information
Title of host publication: Proceedings of 2015 Conference on Lasers and Electro-Optics (CLEO)
Publisher: IEEE
DOIs:
10.1364/cleo_si.2015.stu1i.3
Highly Sensitive Photonic Crystal Cavity Laser Noise Measurements using Bayesian Filtering
We measure for the first time the frequency noise spectrum of a photonic crystal cavity laser with less than 20 nW of fiber-coupled output power using a coherent receiver and Bayesian filtering.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, High-Speed Optical Communication, Quantum and Laser Photonics, Nanophotonic Devices, Metro-Access and Short Range Systems, Helmut-Schmidt-University
Number of pages: 3
Publication date: 2015

Hybrid III-V/SOI single-mode vertical-cavity laser with in-plane emission into a silicon waveguide
We report a III-V-on-SOI vertical-cavity laser emitting into an in-plane Si waveguide fabricated by using CMOS-compatible processes. The fabricated laser operates at 1.54 µm with a SMSR of 33 dB and a low threshold.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices
Contributors: Park, G. C., Xue, W., Semenova, E., Mørk, J., Chung, I.
Number of pages: 2
Publication date: 2015

Hybrid vertical-cavity laser with lateral emission into a silicon waveguide
We experimentally demonstrate an optically-pumped III-V/Si vertical-cavity laser with lateral emission into a silicon waveguide. This on-chip hybrid laser comprises a distributed Bragg reflector, a III-V active layer, and a high-contrast grating reflector, which simultaneously funnels light into the waveguide integrated with the laser. This laser has the advantages of long-wavelength vertical-cavity surface-emitting lasers, such as low threshold and high side-mode suppression ratio, while allowing integration with silicon photonic circuits, and is fabricated using CMOS compatible processes. It has the potential for ultrahigh-speed operation beyond 100 Gbit/s and features a novel mechanism for
transverse mode control.

**General information**
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices
Contributors: Park, G. C., Xue, W., Taghizadeh, A., Semenova, E., Yvind, K., Merk, J., Chung, I.
Pages: L11–L15
Publication date: 2015
Peer-reviewed: Yes

**Publication information**
Journal: Laser & Photonics Reviews
Volume: 9
Issue number: 3
ISSN (Print): 1863-8880
Ratings:
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 8.54 SJR 4.205 SNIP 3.427
Web of Science (2015): Impact factor 7.486
Web of Science (2015): Indexed yes
Original language: English
Electronic versions:
Park_et_al_2015_Laser_Photonics_Reviews.pdf
DOIs:
10.1002/lpor.201400418
Source: PublicationPreSubmission
Source ID: 107810404
Research output: Contribution to journal › Journal article – Annual report year: 2015 › Research › peer-review

III-V/SOI vertical cavity laser structure for 120 Gbit/s speed

Ultrashort-cavity structure for III-V/SOI vertical cavity laser with light output into a Si waveguide is proposed, enabling 17 fJ/bit efficiency or 120 Gbit/s speed. Experimentally, 27-GHz bandwidth is demonstrated at 3.5 times of threshold. © 2015 OSA.

**General information**
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Department of Micro- and Nanotechnology, Nanophotonic Devices
Contributors: Park, G. C., Xue, W., Mørk, J., Semenova, E., Chung, I.
Publication date: 2015

**Host publication information**
Title of host publication: Integrated Photonics Research, Silicon and Nanophotonics 2015
Publisher: Optical Society of America
Article number: JT5a.2
ISBN (Print): 978-1-55752-000-5
Keywords: Electronic, Optical and Magnetic Materials, Magnetic materials, Light output, Si-waveguide, Ultra-short cavity, Vertical cavity lasers, Optical materials, Electrical and Electronic Engineering, Hardware and Architecture, Optical sensors
Electronic versions:
2._IPR_III_V_SOI_vertical_cavity_laser_structure_for_120_Gbit_s_speed.pdf
DOIs:
10.1364/iprsn.2015.jt5a.2

**Bibliographical note**
From the session: Postdeadline (JT5a)
Source: FindIt
Source ID: 2287459226
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2015 › Research › peer-review

III-V/SOI vertical cavity laser with in-plane output into a Si waveguide

We experimentally demonstrate an optically-pumped III-V-on-SOI hybrid vertical-cavity laser that outputs light into an in-plane Si waveguide, using CMOS-compatible processes. The laser operates at 1.49 $\text{nm}$ with a side-mode suppression-ratio of 27 dB and has a similar threshold as long-wavelength VCSELs.
Improvement of power characteristics in 850 nm quantum well laser with asymmetric barriers

Power and spectral characteristics of lasers with asymmetric barrier layers (ABLs) and a wide waveguide are studied. The use of ABLs reduces the saturation of light-current characteristic, associated with the parasitic recombination in the waveguide.

On the optimization of asymmetric barrier layers in InAlGaAs/AlGaAs laser heterostructures on GaAs substrates

Band offsets at the heterointerface are calculated for various combinations of InAlGaAs/AlGaAs heteropairs that can be synthesized on GaAs substrates in the layer-by-layer pseudomorphic growth mode. Patterns which make it possible to obtain an asymmetric barrier layer providing the almost obstruction-free transport of holes and the highest possible barrier height for electrons are found. The optimal compositions of both compounds ([InAlGaAs]-Al-0.232-Ga-0.594-As-0.174/[AlGaAs]-Ga-0.355-As-0.645) at which the flux of electrons across the barrier is at a minimum are determined with consideration for the critical thickness of the indium-containing quaternary solid solution.

On the optimization of asymmetric barrier layers in InAlGaAs/AlGaAs laser heterostructures on GaAs substrates
Overcoming doping limits in MOVPE grown n-doped InP for plasmonic applications

Effect of the growth parameters on carrier concentration in MOVPE grown silicon-doped InP is studied. The dopant flow, V/III ratio and substrate temperature are optimized by considering the origin of the doping limits. In addition, two different group V precursors, namely PH3 and TBP, are compared. The carrier concentration profile is measured using electrochemical capacitance-voltage (ECV) profilometry and the total concentration of silicon atoms is measured by secondary ion mass spectroscopy (SIMS) in order to evaluate the amount of Si atoms contributing as donors. The electron concentration about 4×10^19cm^-3 is achieved. Optical properties of the samples are investigated by Fourier transform infrared reflection (FTIR) spectroscopy and are fitted by a Drude-Lorentz function.

Slow-light effects in photonic crystal membrane lasers

In this paper, we present a systematic investigation of photonic crystal cavity laser operating in the slow-light regime. The dependence of lasing threshold on the effect of slow-light will be particularly highlighted.
Suppression of sublinearity of light–current curve in 850 nm quantum well laser with asymmetric barrier layers

An AlGaAs/GaAs quantum well (QW) laser is fabricated with GaInP and AlGaInAs asymmetric barrier layers (ABLs) and its light–current characteristic (LCC) is compared with that of a reference conventional QW laser without ABLs. It was found that the use of the ABLs suppresses the sublinearity of the LCC at high current densities. As a result, the maximum lasing power of 9.2 W, being limited by catastrophic optical mirror damage, is achieved at a considerably lower operating current in the laser with ABLs as compared to the reference laser (12.5 against 20.2 A). The ABL effect is associated with the suppression of the parasitic recombination in the optical confinement layer, as confirmed by a decrease of the intensity of the spontaneous emission from the layer.

The effect of asymmetric barrier layers in the waveguide region on power characteristics of QW lasers

Current-voltage and light-current characteristics of quantum-well lasers have been studied at high drive currents. The introduction of asymmetric barrier layers adjacent to the active region caused a significant suppression of the nonlinearity in the light-current characteristic and an increase in the external differential efficiency. As a result, the maximum wallplug efficiency increased by 9%, while the output optical power increased by 29%.
Thermal analysis of line-defect photonic crystal lasers
We report a systematic study of thermal effects in photonic crystal membrane lasers based on line-defect cavities. Two material platforms, InGaAsP and InP, are investigated experimentally and numerically. Lasers with quantum dot layers embedded in an InP membrane exhibit lasing at room temperature under CW optical pumping, whereas InGaAsP membranes only lase under pulsed conditions. By varying the duty cycle of the pump beam, we quantify the heating induced by optical pumping in the two material platforms and compare their thermal properties. Full 3D finite element simulations show the spatial temperature profile and are in good agreement with the experimental results concerning the thermal tolerance of the two platforms.

We present a record-low threshold power of 7 mW at ~1.55 µm for on-chip optical parametric oscillation using a high quality factor micro-ring-resonator in a new nonlinear photonics platform: AlGaAs-on-insulator
Butt-joint integration of active optical components based on InP/AlInGaAsP alloys

We demonstrate all-active planar high quality butt-joint (BJ) integration of a QW Semiconductor Optical Amplifier (SOA) and MQW Electro-Absorption Modulator (EAM) based on an InP/AlInGaAsP platform. The degradation of the optical properties in the vicinity of ~1 μm to the BJ interface was determined by means of μPL measurements.

Crystallographic dependent in-situ CBr₄ selective nano-area etching and local regrowth of InP/InGaAs by MOVPE

Selective area etching and growth in the metalorganic vapor phase epitaxy (MOVPE) reactor on nano-scale structures have been examined. Using different mask orientations, crystallographic dependent etching of InP can be observed when carbon tetrabromide (CBr₄) is used as an etchant. Scanning Electron Microscopy (SEM) investigation of etch profiles showed formation of a U-shaped groove along the [01̄1̄] direction, terminated by {111}B planes with an ~15nm {100} plateau and transitional {311}B planes, developed in a self-limiting manner. In the perpendicular direction [01̄1], etching with a dominant lateral component driven by fast etched {111}A and {311}A side planes was observed. A directly grown single InGaAs QW in the etched grooves demonstrated different QW profiles: a crescent-shaped on {311}B and {100} planes (along the [01̄1̄] direction) and two separated quarter-circle curvatures grown preferably on {311}A along [01̄1]. Room temperature micro-photoluminescence measurements indicated a wavelength red-shift in over 125nm along [01̄1] comparing to [01̄1], which is related to both growth enhancement and composition variation of the grown material.
Epitaxial growth of quantum dots on InP for device applications operating at the 1.55 μm wavelength range

The development of epitaxial technology for the fabrication of quantum dot (QD) gain material operating in the 1.55 μm wavelength range is a key requirement for the evolvement of telecommunication. High performance QD material demonstrated on GaAs only covers the wavelength region 1-1.35 μm. In order to extract the QD benefits for the longer telecommunication wavelength range the technology of QD fabrication should be developed for InP based materials. In our work, we take advantage of both QD fabrication methods Stanski-Krastanow (SK) and selective area growth (SAG) employing block copolymer lithography. Due to the lower lattice mismatch of InAs/InP compared to InAs/GaAs, InP based QDs have a larger diameter and are shallower compared to GaAs based dots. This shape causes low carrier localization and small energy level separation which leads to a high threshold current, high temperature dependence, and low laser quantum efficiency. Here, we demonstrate that with tailored growth conditions, which suppress surface migration of adatoms during the SK QD formation, much smaller base diameter (13.6nm versus 23nm) and an improved aspect ratio are achieved. In order to gain advantage of non-strain dependent QD formation, we have developed SAG, for which the growth occurs only in the nano-openings of a mask covering the wafer surface. In this case, a wide range of QD composition can be chosen. This method yields high purity material and provides significant freedom for reducing the aspect ratio of QDs with the possibility to approach an ideal QD shape.
absorption modulator has been successfully performed and their optical and crystalline quality was experimentally investigated. The regrown multi-quantum well material exhibits a slight bandgap blue-shift of less than 20 meV, when moving away from the regrowth interface. In closest vicinity to the mask, the growth profile revealed a bent-up shape which is associated with an increase in the bandgap energy resulting from the combined effect of growth rate suppression and higher Ga concentration. This increase in bandgap energy makes the interface partially transparent (thus beneficial for unaffected light transmission) and forces carriers away from possible interfacial defects. The internal reflectivity below $2.1 \times 10^{-5}$ ensures minimization of detrimental intracavity feedback.

**General information**

Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Center for Electron Nanoscopy, Department of Physics, Quantum Physics and Information Technology
Contributors: Kulkova, I., Kadkhodazadeh, S., Kuznetsova, N., Huck, A., Semenova, E., Yvind, K.
Pages: 243–248
Publication date: 2014
Peer-reviewed: Yes

**Publication information**

Journal: Journal of Crystal Growth
Volume: 243
ISSN (Print): 0022-0248
Ratings:
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 1.69 SJR 0.786 SNIP 1.141
Web of Science (2014): Impact factor 1.698
Web of Science (2014): Indexed yes
Original language: English
Keywords: Butt-joint scheme, Selective area growth, Metalorganic vapor phase epitaxy, AlGaInAs/InP
Electronic versions:
JCrystGrowth_2014.pdf
DOIs:
10.1016/j.jcrysgro.2014.06.026
Source: PublicationPreSubmission
Source ID: 93755090
Research output: Contribution to journal > Journal article – Annual report year: 2014 > Research > peer-review

**Improvement of light-current characteristic linearity in a quantum well laser with asymmetric barriers**

The effect of asymmetric barriers on the light-current characteristic (LCC) of a quantum well laser was studied theoretically and experimentally. It is shown that the utilization of asymmetric barriers in a waveguide prevents the nonlinearity of LCC and, consequently, allows rising of the maximum output power.

**General information**

Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, St. Petersburg Academic University, Virginia Polytechnic Institute and State University
Number of pages: 1
Pages: 1
Publication date: 2014

**Host publication information**

Title of host publication: Proceedings of 2014 International Conference Laser Optics
Publisher: IEEE
ISBN (Print): 9781479938841
Keywords: laser beams, nonlinear optics, quantum well lasers, waveguide lasers, Photonics and Electrooptics, Power, Energy and Industry Applications, asymmetric barrier layers, asymmetric barrier utilization, Laser theory, LCC nonlinearity, light-current characteristic, light-current characteristic linearity, Linearity, maximum output power, Measurement by laser beam, parasitic recombination, quantum well, quantum well laser, Quantum well lasers, Radiative recombination, semiconductor lasers, waveguide, Waveguide lasers
DOIs:
10.1109/LO.2014.6886293
Source: FindIt
Source ID: 270472994
Nonplanar nanoselective area growth of InGaAs/InP

In this study, we have investigated metal-organic vapor phase epitaxial nano-patterned selective area growth of InGaAs/InP on non-planar (001) InP surfaces. Due to high etching resistance and the small molecular size of negative tone electron beam HSQ resist, the protection mask formed in HSQ has small feature sizes in ten nanometers scale and allow realization of in-situ etching. As was observed in the SAG regime, in-situ etching of InP by carbon tetrabromide leads to formation of self-limited structures. By altering etching time, the groove shape can be changed from a triangular trench to a trapeze. Another appealing aspect of in situ etching is that the shape of InGaAs can be tuned from a crescent to a triangular or a line by varying growth parameters. Quantum well wires can be fabricated by growing directly in the bottom of V-shaped groove. In addition, changes of mask orientations lead to anisotropic or isotropic character of etching. The investigated technique of nano-patterned selective area growth allows obtaining different profiles of structures and different quantum structures such as quantum well or wires in the same growth run. To investigate the shape and crystalline quality of the active material, the cross-sectional geometry was observed by field emission scanning electron microscopy and scanning transmission electron microscopy. The optical properties were carried out at room temperature using micro-photoluminescence setup. The results showed different deposition rates for openings oriented along [0-11] and [0-1-1] directions with higher rate along [0-1-1]. The fabricated active material was incorporated into photonic crystal waveguides.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Quantum and Laser Photonics, Center for Electron Nanoscopy, Nanophotonics, St. Petersburg Academic University
Contributors: Kuznetsova, N., Colman, P., Semenova, E., Kadkhodazadeh, S., Kryzhanovskaya, N. V., Ek, S., Xue, W., Schubert, M., Zhukov, A. E., Yvind, K.
Number of pages: 7
Publication date: 2014
Peer-reviewed: Yes

Slow-light-enhanced gain in active photonic crystal waveguides

Passive photonic crystals have been shown to exhibit a multitude of interesting phenomena, including slow-light propagation in line-defect waveguides. It was suggested that by incorporating an active material in the waveguide, slow light could be used to enhance the effective gain of the material, which would have interesting application prospects, for example enabling ultra-compact optical amplifiers for integration in photonic chips. Here we experimentally investigate the gain of a photonic crystal membrane structure with embedded quantum wells. We find that by solely changing the photonic crystal structural parameters, the maximum value of the gain coefficient can be increased compared with a ridge waveguide structure and at the same time the spectral position of the peak gain be controlled. The experimental results are in qualitative agreement with theory and show that gain values similar to those realized in state-of-the-art semiconductor optical amplifiers should be attainable in compact photonic integrated amplifiers.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices
Contributors: Ek, S., Hansen, P. L., Chen, Y., Semenova, E., Yvind, K., Mark, J.
Number of pages: 7
Publication date: 2014
Peer-reviewed: Yes
1060-nm Tunable Monolithic High Index Contrast Subwavelength Grating VCSEL

We present the first tunable vertical-cavity surface-emitting laser (VCSEL) where the top distributed Bragg reflector has been completely substituted by an air-cladded high-index-contrast subwavelength grating (HCG) mirror. In this way, an extended cavity design can be realized by reducing the reflection at the semiconductor–air interface using an anti-reflective coating (ARC). We demonstrate how the ARC can be integrated in a monolithic structure by oxidizing AlGaAs with high Al-content. The HCG VCSEL has the potential to achieve polarization stable single-mode output with high tuning efficiency. The HCG VCSEL shows a total tuning range of 16 nm around an emission wavelength of 1060 nm with 1-mW output power.

Crystallographic dependence of the lateral undercut wet etch rate of Al0.5In0.5P in diluted HCl for III-V sacrificial release

The authors investigated the use of InAIP as a sacrificial layer lattice-matched to GaAs when diluted hydrochloric acid is used for sacrificial etching. They show that InAIP can be used to fabricate submicrometer air gaps in micro-opto-electromechanical systems and that a selectivity toward GaAs larger than 500 is achieved. This selectivity enables fabrication control of the nanometer-size structures required in photonic crystal and high-index contrast subwavelength grating structures. The crystallographic dependence of the lateral etch rate in InAIP is shown to be symmetric around the 〈110〉 directions where an etch rate of 0.5μm/min is obtained at 22°C in HCl:2H2O. Since the etch rate in the 〈100〉 directions exceeds by ten times that of the 〈110〉 directions, InAIP may be used in sacrificial release of high-aspect ratio structures. Free-hanging structures with length to air-gap aspect ratios above 600 are demonstrated by use of critical point
Hybrid III-V-on-Si Vertical Cavity laser for Optical Interconnects

Combining a III-V active material onto the Si platform is an attractive approach for silicon photonics light source. We have developed fabrication methods for novel III-V on Si vertical cavity lasers.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices
Contributors: Park, G. C., Semenova, E., Chung, I.
Pages: B90-B91
Publication date: 2013

Host publication information
Title of host publication: iNOW 2013 : International Nano-Optoelectronics Workshop
Source: dtu
Source ID: u::10718
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2014 › Research › peer-review

Resonant MEMS tunable VCSEL
We demonstrate how resonant excitation of a microelectro-mechanical system can be used to increase the tuning range of a vertical-cavity surface-emitting laser two-fold by enabling both blue- and red-shifting of the wavelength. In this way a short-cavity design enabling wide tuning range can be realized. A high-index-contrast subwavelength grating verticalcavity surface-emitting laser with a monolithically integrated anti-reflection coating is presented. By incorporating an antireflection
coating into the air cavity, higher tuning efficiency can be achieved at low threshold current. The first result shows 24-nm continuous resonant tuning range around an emission wavelength of 1060 nm with 0.9 mW output power.

**General information**
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Quantum and Laser Photonics, Department of Micro- and Nanotechnology, Silicon Microtechnology, Center for Individual Nanoparticle Functionality
Contributors: Ansbæk, T., Chung, I., Semenova, E., Hansen, O., Yvind, K.
Number of pages: 6
Publication date: 2013
Peer-reviewed: Yes

**Publication information**
Journal: IEEE Journal on Selected Topics in Quantum Electronics
Volume: 19
Issue number: 4
Article number: 1702306
ISSN (Print): 1077-260X
Ratings:
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 4.55 SJR 2.249 SNIP 2.335
Web of Science (2013): Impact factor 3.465
ISI indexed (2013): ISI indexed yes
DoIs:
10.1109/JSTQE.2013.2257164
Source: dtu
Source ID: u::7516
Research output: Contribution to journal › Journal article – Annual report year: 2013 › Research › peer-review

**Ultrahigh-speed hybrid laser for silicon photonic integrated chips**
Increasing power consumption for electrical interconnects between and inside chips is posing a real challenge to continue the performance scaling of processors/computers as predicted by D. Moore. In recent processors, energy consumption for electrical interconnects is half of power supplied and will be 80% in near future. This challenge strongly has motivated replacing electrical interconnects with optical ones even in chip level communications [1]. This chip-level optical interconnects need quite different performance of optoelectronic devices than required for conventional optical communications. For a light source, the energy consumption per sending a bit is required to be <10 fJ/bit for on-chip interconnects and <100 fJ/bit for off-chip interconnects; this is two or three orders of magnitude smaller than the conventional devices. To meet the energy/bit requirement, many innovative laser diode and light-emitting diode (LED) structures have been proposed so far. Our hybrid laser is one of these efforts [2].

The hybrid laser consists of a dielectric reflector, a III-V semiconductor active material, and a high-index-contrast grating (HCG) reflector formed in the silicon layer of a silicon-on-insulator (SOI) wafer. 'Hybrid' indicates that a III-V active material is wafer-bonded to a silicon SOI wafer. In the hybrid laser, light is vertically amplified between the dielectric and the HCG reflectors, while the light output is laterally emitted to a normal Si ridge waveguide that is connected to the HCG reflector. The HCG works as a vertical mirror as well as a vertical-to-lateral coupler. Very small field penetration into the HCG allows for 3-4 times smaller modal volume than typical vertical-cavity surface-emitting lasers (VCSELs). This leads to high direct modulation speed. Details on device operating mechanism will be explained in the lecture.

Recently, a nano light-emitting diode (LED) with energy/bit < 1fJ/bit [3] and a nano laser diode with a buried heterostructure (BH) active material [4] have been recently reported in the literature. Additionally, device physics, engineering issue, and error-free light detection issue in quantum limit will be discussed in relation to these two structures.
41 GHz and 10.6 GHz low threshold and low noise InAs/InP quantum dash two-section mode-locked lasers in L band

This paper reports recent results on InAs/InP quantum dash-based, two-section, passively mode-locked lasers pulsing at 41 GHz and 10.6 GHz and emitting at 1.59 μm at 20 degrees C. The 41-GHz device (1 mm long) starts lasing at 25 mA under uniform injection and the 10.6 GHz (4 mm long) at 71 mA. Their output pulses are significantly chirped. The 41-GHz laser exhibits 7 ps pulses after propagation in 60 m of a single-mode fiber. The 10.6-GHz laser generates one picosecond pulses with 545 m of a single-mode fiber. Its single side-band phase noise does not exceed -80 dBc/Hz at 100 kHz offset, leading to an average timing jitter of 800 fs.

Effect of Asymmetric Barrier Layers in the Waveguide Region on the Temperature Characteristics of QuantumWell Lasers

The temperature sensitivity of the threshold-current density in quantum-well lasers is studied and the factors affecting the characteristic temperature and its dependence on optical losses are analyzed. It is shown that the inclusion of asymmetric potential barriers (one barrier on each side of the quantum well), which prevent the formation of bipolar carrier population in the waveguide region and lead to weakening of the temperature dependences of the transparency-current density, the gain-saturation parameter and, consequently, to a higher characteristic temperature for both long- and short-cavity laser diodes.
Enhanced Gain in Photonic Crystal Amplifiers

We experimentally demonstrate enhanced gain in the slow-light regime of quantum well photonic crystal amplifiers. A strong gain enhancement is observed with the increase of the group refractive index, due to light slow-down. The slow light enhancement is shown in a amplified spontaneous emission study of a 1 QW photonic crystal amplifier. Net gain is achieved which enables laser oscillation in photonic crystal micro cavities. The ability to freely tailor the dispersion in a semiconductor optical amplifier makes it possible to raise the optical gain considerably over a certain bandwidth. These results are promising for short and efficient semiconductor optical amplifiers. This effect will also benefit other devices, such as mode locked lasers.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices, Nanophotonics
Contributors: Ek, S., Semenova, E., Hansen, P. L., Yvind, K., Mørk, J.
Number of pages: 4
Publication date: 2012
Host publication information
Title of host publication: Proceedings of International Conference on Transparent Optical Networks (ICTON)
ISBN (Print): 9781467322287
Keywords: Photonic crystal, Semiconductor optical amplifier, Amplified spontaneous emission, Laser, Cavity resonators, Laser excitation, Optical waveguides, Slow light.
Electronic versions:
icton2012_SaraEk_DTU.pdf
DOIs:
10.1109/ICTON.2012.6253790
Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2012
High-speed photodetectors in a photonic crystal platform

We demonstrate a fast photodetector (f3dB > 40GHz) integrated into a high-index contrast photonic crystal platform. Device design, fabrication and characterization are presented.

General information
Publication status: Published
Improvement of temperature-stability in a quantum well laser with asymmetric barrier layers
We fabricated and tested a quantum well laser with asymmetric barrier layers. Such a laser has been proposed earlier to suppress bipolar carrier population in the optical confinement layer and thus to improve temperature-stability of the threshold current. As compared to the conventional reference laser structure, our laser with asymmetric barrier layers demonstrates reduced internal optical loss, lower threshold current density at elevated temperatures, and higher characteristic temperature (143 vs. 99K at 20 degrees C).
Individual optimization of InAlGaAsP-InP sections for 1.55-μm passively mode-locked lasers
We present integrated single QW semiconductor optical amplifier and MQW electroabsorber modulator based on InAlGaAsP-InP materials for application in a monolithic mode-locked laser. Optimized structures with high-quality butt-joint interfaces are demonstrated.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Nanophotonics
Contributors: Kulkova, I., Larsson, D., Semenova, E., Yvind, K.
Pages: 133-134
Publication date: 2012

Host publication information
Title of host publication: 2012 23rd IEEE International Semiconductor Laser Conference (ISLC)
Publisher: IEEE
ISBN (Print): 978-1-4577-0828-2
Keywords: Mode-locked lasers, Semiconductor lasers, Selective area growth
DOI: 10.1109/ISLC.2012.6348364
Source: dtu
Source ID: n::oai:DTIC-ART:iel/373906484::21866
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2012 › Research › peer-review

Nano-selective area growth of InGaAs/InP using CBr4 insitu etching
We are investigating the conditions for nano-patterned selective area epitaxial growth using e-beam lithography on HSQ resist and in-situ etching in the MOVPE reactor.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Center for Electron Nanoscopy, Nanophotonics
Contributors: Kuznetsova, N., Semenova, E., Kadkhodazadeh, S., Schubert, M., Yvind, K.
Number of pages: 3
Pages: JTu5A.12
Publication date: 2012

Host publication information
Title of host publication: Advanced Photonics Congress
Publisher: Optical Society of America
Electronic versions:
SOF-2012-JTu5A.12.pdf
Source: dtu
Source ID: u::7046
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2012 › Research › peer-review

Slow-light enhancement of spontaneous emission in active photonic crystal waveguides
Photonic crystal defect waveguides with embedded active layers containing single or multiple quantum wells or quantum dots have been fabricated. Spontaneous emission spectra are enhanced close to the bandedge, consistently with the enhancement of gain by slow light effects. These are promising results for future compact devices for terabit/s communication, such as miniaturised semiconductor optical amplifiers and mode-locked lasers.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices
Contributors: Ek, S., Chen, Y., Semenova, E., Hansen, P. L., Yvind, K., Mørk, J.
Pages: 82731A
Publication date: 2012
Peer-reviewed: Yes
Active III-V Semiconductor Photonic Crystal Waveguides
We experimentally demonstrate enhanced amplified spontaneous emission in a quantum well III-V semiconductor photonic crystal waveguide slab. The effect is described by enhanced light matter interaction with the decrease of the group velocity. These are promising results for future compact devices for terabit/s communication, such as miniaturised semiconductor optical amplifiers and mode-locked lasers.

Enhanced Gain in Slow-Light Photonic Crystal Waveguides with Embedded Quantum Dots
We experimentally demonstrate enhanced gain in the slow-light regime of quantum dot photonic crystal waveguide slabs. These are promising results for future compact devices for terabit/s communication, such as compact optical amplifiers and mode-locked lasers.
InAs/InGaAsP Quantum Dots Emitting at 1.5 μm for Applications in Lasers

In this work the epitaxial growth of InAs quantum dots (QDs) in an InGaAsP matrix on an InP wafer is described. A new approach to shift the emission wavelength to the 1.5μm region using deposition of a thin GaAs capping layer on top of the QDs is suggested and exploited. Laser structures based on 5 layers of such dots as the gain material demonstrate lasing in continuous wave regime at 1.5 μm wavelength at room temperature.

Investigating the chemical and morphological evolution of GaAs capped InAs/InP quantum dots emitting at 1.5μm using aberration-corrected scanning transmission electron microscopy

The emission wavelength of InAs quantum dots grown on InP has been shown to shift to the technologically desirable 1.5μm with the deposition of 1–2 monolayers of GaAs on top of the quantum dots. Here, we use aberration-corrected scanning transmission electron microscopy to investigate morphological and compositional changes occurring to the quantum dots as a result of the deposition of 1.7 monolayers of GaAs on top of them, prior to complete overgrowth with InP. The results are compared with theoretical models describing the overgrowth process.
Metal organic vapor-phase epitaxy of InAs/InGaAsP quantum dots for laser applications at 1.5 μm
The epitaxial growth of InAs/InGaAsP/InP quantum dots (QDs) for emission around 1.5 μm by depositing a thin layer of GaAs on top of the QDs is presented in this letter. The influence of various growth parameters on the properties of the QDs, in particular, size, shape, chemical composition, and emission wavelength are investigated. Continuous wave lasing in ridge waveguide QD laser structures in the 1.5 μm wavelength range is demonstrated. VC 2011 American Institute of Physics. [doi:10.1063/1.3634029]

Quantitative strain mapping of InAs/InP quantum dots with 1 nm spatial resolution using dark field electron holography
The optical properties of semiconductor quantum dots are greatly influenced by their strain state. Dark field electron holography has been used to measure the strain in InAs quantum dots grown in InP with a spatial resolution of 1 nm. A strain value of 5.4%±0.1% has been determined which is consistent with both measurements made by geometrical phase analysis of high angle annular dark field scanning transmission electron microscopy images and with simulations.
Towards quantitative three-dimensional characterisation of buried InAs quantum dots

InAs quantum dots (QDs) grown on InP or InGaAsP are used for optical communication applications operating in the 1.3 – 1.55 μm wavelength range. It is generally understood that the optical properties of such QDs are highly dependent on their three-dimensional structural and chemical profiles. However, morphological and compositional measurements of quantum dots using transmission electron microscopy can be ambiguous because the recorded signal is usually a projection through the thickness of the specimen. Here, we discuss the application of scanning transmission electron microscopy tomography to the morphological and chemical characterisation of surface and buried quantum dots. We highlight some of the challenges involved and introduce a new specimen preparation method for creating needle-shaped specimens that each contain multiple dots and are suitable for both scanning transmission electron microscopy tomography and atom probe tomography.

General information
Publication status: Published
Organisations: Center for Electron Nanoscopy, Nanophotonic Devices, Department of Photonics Engineering, Chalmers University of Technology
Contributors: Kadkhodazadeh, S., Semenova, E., Schubert, M., Thuvander, M., Stiller, K. M., Yvind, K., Dunin-Borkowski, R. E.
Pages: 012046
Publication date: 2011
Peer-reviewed: Yes

Publication information
Journal: Journal of Physics: Conference Series
Volume: 326
Issue number: 1
ISSN (Print): 1742-6588
Ratings:
BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 0.43 SJR 0.293 SNIP 0.359
ISI indexed (2011): ISI indexed no
Original language: English
Electronic versions:
MSM_Extended.pdf
DOIs:
10.1088/1742-6596/326/1/012046
Source: orbit
Source ID: 312171
Research output: Contribution to journal › Conference article – Annual report year: 2011 › Research › peer-review

Towards quantitative three-dimensional characterisation of buried InAs quantum dots
InAs quantum dots (QDs) grown on InP or InGaAsP are used for optical communication applications operating in the 1.3 – 1.55 μm wavelength range. It is generally understood that the optical properties of such QDs are highly dependent on their three-dimensional structural and chemical profiles. Whilst conventional transmission electron microscopy (TEM) techniques can be used to study capped QDs in plan-view or cross-sectional geometries, the resulting images can provide...
ambiguous information about their three-dimensional properties. Here, we describe an approach for investigating the applicability of both high-angle annular dark-field (HAADF) scanning transmission electron microscopy (STEM) tomography and atom probe tomography (APT) to the study of surface and buried InAs/InGaAsP QDs grown by metal organic vapour phase epitaxy (MOVPE). Electron tomography was carried out in an FEI Titan TEM instrument operated at 300 kV. TEM specimens were prepared in plan-view geometry using mechanical grinding, polishing and Ar ion milling. Both original HAADF STEM images and final tomographic reconstruction of surface QDs suggest an elongated hexagonal shape for the bases of the QDs (Figure 1). The elongation direction was determined to be [110], using selected area electron diffraction and atomic force microscopy. The HAADF STEM images also suggest that surface QDs have a double-terraced geometry, with steeper facets around their bases and shallower facets close to their tops. This geometry is consistent with a theoretical model of InAs QDs formed on an InGaAs substrate that is lattice matched to InP [1] shown in Figure 1(b). Despite the large inner detector semi-angle used (approximately 50 mrad), strong diffraction effects were present in the original tilt series of HAADF STEM images, resulting in departure from the projection requirement for electron tomography, which states that the recorded intensity should be a monotonic function of a property of the object [2]. These diffraction effects are likely to be associated with diffraction and may lead to artefacts in the tomographic reconstruction. The same tomographic analysis was applied to a buried InAs/InGaAsP QD (Figure 1(d) and (e)). The buried QD appears to be elongated along the [110] direction, although not as strongly as the surface QD. Similarly, the faceting that is clearly visible in both the original HAADF STEM images and the final reconstruction of the surface QD, is not as pronounced for the buried QD. This difference may result from chemical intermixing between the buried QD and the capping material during overgrowth. A limiting constraint in STEM tomography of thin film specimens is the limited tilt range available before the specimen becomes too thick for imaging. This limitation can, in principle, be overcome by fabricating needle-shaped specimens using focused ion beam (FIB) milling, in order to allow unlimited tilting without significant increase in projected specimen thickness. However, FIB milling can introduce considerable damage into III-V semiconductors, including amorphisation and Ga ion implantation [3]. We have fabricated needle-shaped specimens that are 100 nm in diameter, using reactive ion etching, selective wet etching and critical point drying in plan-view geometry (Figure 2). The choice of a plan-view geometry for the needles means that each specimen will contain several QDs. The needles can either be detached from the substrate by cleaving (Figure 2(b)) or lifted out and mounted onto suitable grids using a micro-manipulator in the FIB with minimal additional damage (Figure 2(c)). Significantly, in addition to their suitability for electron tomography, these specimens can be used for APT, for which needle-shaped specimens with sharp tips (narrower than 100 nm) are required. Our ongoing experiments involve the application of both HAADF STEM tomography and APT to the same QD, in order to better understand its morphology and composition. A comparison between reconstructions obtained using both techniques will also assist in the evaluation and mitigation of potential artefacts that are present when using each technique.

**General information**
Publication status: Published
Organisations: Center for Electron Nanoscopy, Nanophotonic Devices, Department of Photonics Engineering, Chalmers University of Technology
Contributors: Kadkhodazadeh, S., Semenova, E., Kuznetsova, N., Schubert, M., Thuvander, M., Stiller, K. M., Yvind, K., Dunin-Borkowski, R. E.
Pages: IM3-P151
Publication date: 2011

**Host publication information**
Title of host publication: MC 2011 Kiel : Microscopy Conference 2011
Publisher: DGE – German Society for Electron Microscopy
ISBN (Print): 978-3-00-033910-3
Keywords: Electron Tomography, InAs Quantum Dots, Atom Probe Tomography
Electronic versions:
IM3_P151.pdf
URLs:
http://www.mc2011.de/

**Bibliographical note**
Poster presentation.
Source ID: 312305
Research output: Chapter in Book/Report/Conference proceeding › Conference abstract in proceedings – Annual report year: 2011 › Research › peer-review

**10-GHz 1.59-μm quantum dash passively mode-locked two-section lasers**
This paper reports the fabrication and the characterisation of a 10 GHz two-section passively mode-locked quantum dash laser emitting at 1.59 μm. The potential of the device's mode-locking is investigated through an analytical model taking into account both the material parameters and the laser geometry. Results show that the combination of a small absorbing section coupled to a high absorption coefficient can lead to an efficient mode-locking. Characterisation shows mode-locking operation though output pulses are found to be strongly chirped. Noise measurements demonstrate that the single side band phase noise does not exceed -80 dBc/Hz at 100 kHz offset leading to an average timing jitter as low as 800 fs.
As compared to single QW lasers these results constitute a significant improvement and are of first importance for applications in optical telecommunications.

Lambda shifted photonic crystal cavity laser

We propose and demonstrate an alternative type of photonic crystal laser design that shifts all the holes in the lattice by a fixed fraction of the targeted emission wavelength. The structures are realized in InGaAsP =1.15 with InGaAsP quantum wells =1.52 as gain material. Cavities with shifts of 1/4 and 3/4 of the emission wavelength were fabricated and characterized. Measurements show threshold behavior for several modes at room temperature. Both structures are simulated using a finite difference time domain method to identify the resonances in the spectra and calculate the mode volume of the dominant mode.
Quarter-lambda-shifted photonic crystal lasers
A new design for photonic crystal lasers is proposed and realised. It allows an intuitive design for ultralow mode volume and high Q cavities which can be realized in a connected membrane structure.

General information
Publication status: Published
Organisations: Nanophotonic Devices, Department of Photonics Engineering, Quantum and Laser Photonics
Contributors: Schubert, M., Skovgaard, T. S., Ek, S., Semenova, E., Hvam, J. M., Yvind, K.
Publication date: 2010
Peer-reviewed: Yes
DOIs: 10.1109/ISLC.2010.5642717
URLs: http://ieeexplore.ieee.org.globalproxy.cvt.dk/xpls/abs_all.jsp?arnumber=5642717
Source: orbit
Source ID: 268496
Research output: Contribution to conference › Poster – Annual report year: 2010 › Research › peer-review

Projects:

III-V Nanowire Selective Area MOVPE Growth for High Efficiency Solar Cell
Lebedkina, E., PhD Student, Department of Photonics Engineering
Semenova, E., Main Supervisor
Canulescu, S., Supervisor
Technical University of Denmark
01/01/2018 → 31/12/2020
Award relations: III-V Nanowire Selective Area MOVPE Growth for High Efficiency Solar Cell
Project: PhD

Tailored nanoscale optical materials and devices
Sakanas, A., PhD Student, Department of Photonics Engineering
Yvind, K., Main Supervisor
Mørk, J., Supervisor
Semenova, E., Supervisor
Stobbe, S., Examiner
Moselund, K. E., Examiner
Reithmaier, J. P., Examiner
Samfinansierede - Virksomhed
01/08/2015 → 08/05/2019
Award relations: Tailored nanoscale optical materials and devices
Project: PhD

Developing of III-V epitaxy of highly efficient quantum dot gain material to the silicon platform
Viazmitinov, D., PhD Student, Department of Photonics Engineering
Semenova, E., Main Supervisor
Yvind, K., Supervisor
Hansen, O., Examiner
Hannappel, T., Examiner
Tchernycheva, M., Examiner
Frandsen, L. H., Supervisor
Eksternt finansieret virksomhed
01/10/2014 → 30/06/2018
Award relations: Developing of III-V epitaxy of highly efficient quantum dot gain material to the silicon platform
Project: PhD

Block Copolymer Precursors for Chemical Nanopatterning of Graphene
Wang, Z., PhD Student, Department of Micro- and Nanotechnology
Almdal, K., Supervisor
Semenova, E., Examiner
Design and fabrication of mid-infrared plasmonic materials based on highly doped III-V semiconductors
Panah, M. E. A., PhD Student, Department of Photonics Engineering
Laurynenka, A., Main Supervisor
Semenova, E., Supervisor
Yvind, K., Examiner
Engheta, N., Examiner
Bordo, V. G., Examiner
Technical University of Denmark
15/02/2014 → 23/08/2017
Award relations: Design and fabrication of mid-infrared plasmonic materials based on highly doped III-V semiconductors
Project: PhD

Femtosecond semiconductor lasers
Kulkova, I., PhD Student, Department of Photonics Engineering
Yvind, K., Main Supervisor
Larsson, D., Supervisor
Semenova, E., Supervisor
Yvind, K., Main Supervisor
Decobert, J., Examiner
Centerfinansieret
01/08/2010 → 24/09/2014
Award relations: Femtosecond semiconductor lasers
Project: PhD

Nanoscale semiconductor optical devices
Kuznetsova, N., PhD Student, Department of Photonics Engineering
Yvind, K., Main Supervisor
Semenova, E., Supervisor
Malureanu, R., Examiner
Kardynal, B., Examiner
Cirlin, G., Examiner
Centerfinansieret
01/09/2010 → 18/06/2015
Award relations: Nanoscale semiconductor optical devices
Project: PhD

Vertical-cavity laser with a novel grating mirror
Park, G. C., PhD Student, Department of Photonics Engineering
Chung, I., Main Supervisor
Semenova, E., Supervisor
Frandsen, L. H., Examiner
Heck, M., Examiner
Kapon, E., Examiner
Technical University of Denmark
15/02/2013 → 15/06/2016
Award relations: Vertical-cavity laser with a novel grating mirror
Project: PhD

QUEENS: QUantum dot Energy level Engineering for laser applicatioNs on InP and Si platforms
This project is dedicated to the research of quantum dot (QD) epitaxial growth on both indium phosphide (InP) and silicon (Si) based platforms with the aim of creating superior gain material emitting in the 1.5-1.6 μm wavelength range. The majority of the proposed research is quite fundamental but will have noticeable impact to device applications for our everyday life in the near future. Diverse areas like telecommunication, optical coherence tomography including medical applications, sensing, computer and network clock-distribution, THz generation, and metrology can benefit from the
The projected research covers two directions. The first is the development of QDs which possess desired electronic and optical properties in the InP based material system, i.e. tailoring the energy level structure and wave functions in the dots. Manipulating the shape, chemical composition and surroundings of the nanostructures is the key to achieving the set goals. In the frame of the project I will implement two different approaches to design and grow high optical quality arrays of QDs. Those approaches are self-assembled quantum dot growth and selective area growth using block copolymer lithography. The second direction of the research is the deployment of the highly efficient QD gain material to a silicon platform. The development of epitaxial growth technology of III-V materials on Si combines the benefits of high optical quality III-V QD gain material with low cost silicon photonics, which is a key platform to push towards increased integration, higher speed and lower energy consumption.

Viazmitinov, D., PhD Student, Department of Photonics Engineering, Nanophotonic Devices
Shikin, A., PhD Student, Department of Photonics Engineering, Nanophotonic Devices
Kadkhodazadeh, S., Project Participant, Center for Electron Nanoscopy, DTU Danchip
Ottaviano, L., Project Participant, Department of Photonics Engineering, Nanophotonic Devices
Willatzen, M., Project Participant, Department of Photonics Engineering
Barettin, D., Project Participant, University Niccolò Cusano

The GOSPEL project aims at developing new, highly effective technologies for enabling slow and fast light propagation as a tunable feature in photonic devices. In fact, controlling the speed of light offers a solution to a necessary, and often missing, functionality in broadband ICT systems: a time-delay/phase-shift line. The proposed research will address three slow and fast light device platforms: linear and nonlinear semiconductor photonic crystal waveguides with position controlled embedded quantum dots, active semiconductor waveguides based on quantum dots and advanced, specifically engineered optical fibers. These technologies will be harnessed in microwave and millimeter wave applications, such as: true time delay antenna feed systems for radars and ultra wide band wireless communication; complex microwave filters; high spectral purity opto-electronic oscillators and electro optical sampling systems.

This project gathers world leading experts in microwave photonics and semiconductor and fiber technologies, under a unified vision of the role that slow and fast light can play in advanced microwave applications. The project tackles several key challenges of the 7th Framework Work programme in the ICT domain and represents a significant step towards the removal of a major roadblock, i.e. the lack of practical, tunable, broadband, low distortion time-delay/phase-shift lines for microwave signals. This elemental component, besides enabling several applications, can ease the convergence of photonics and electronics and can attribute new functions to photonic devices. The proposed fundamental research will produce new results in multi-disciplinary topics like semiconductor physics, quantum dots, photonic crystal design and fiber technology and it will also represent a significant advancement across many sectors of ICT.

Mørk, J., Project Manager, Department of Photonics Engineering
Gregersen, N., Project Participant, Department of Photonics Engineering
Kadkhodazadeh, S., Project Participant, Center for Electron Nanoscopy, DTU Danchip
Kadkhodazadeh, S., Project Participant, Center for Nanostructured Graphene, Department of Micro- and Nanotechnology
Almdal, K., Project Participant, Department of Photonics Engineering, Nanophotonic Devices

The QDLaser project is the development of portable, low-cost, reliable and highly-efficient ultrashort pulse (down to 100 fs) laser sources based on quantum dot (QD) material working in the spectral range 1.0-1.6 microns. This new generation of QD based mode-locked lasers has to become an alternative to the conventionally used ultrafast solid-state lasers, which are very expensive, cumbersome and complex to operate. The proposed research has a very high practical significance because it creates the possibility for evolution in different science and medical areas, in particular, advanced
telecommunication, terahertz generation, optical sampling, biophotonics, non-invasive medical diagnosis and therapeutics. By placing a primary emphasis on novel materials, devices and system designs, this project will encompass a range of challenging and cutting-edge research directions that exploit QD-based semiconductor structures. The work in the frame of this project will mainly be focused on epitaxial growth of QD-based laser structures. It will be devoted to the optimisation of the epitaxial growth procedure, testing optical, structural and transport measurements and working on the design of epitaxial structure and design of the final devices. This research is in the area of interest of the host organisation and is interdependent with other projects running at the department. I will closely collaborate with other researchers in the fields of laser device design, laser characterisation and discuss results at every stage of the project. Moving to DTU, I bring all of my knowledge gained during my PhD and postdoctoral research work in Russia and France, which will lead to new scientific achievements at DTU. My connections to international scientists will increase the collaboration of DTU with other European and Russian Universities as well
Departments of Photonics Engineering, Photovoltaic Materials and Systems, Centre of Excellence for Silicon Photonics for Optical Communications

**Related event**

*44th International conference on Micro and Nano Engineering*

24/09/2018 → 27/09/2018
Copenhagen, Denmark
Keywords: MOVPE, GaAs, Nanowires
Activity: Talks and presentations › Conference presentations

**Epitaxy of Quantum Dots operating in the 1.55 µm wavelength range for device applications**

Period: 17 Sep 2018 → 21 Sep 2018
Elizaveta Semenova (Invited speaker)
Centre of Excellence for Silicon Photonics for Optical Communications
Nanophotonic Devices
Department of Photonics Engineering

**Description**

invited talk
Degree of recognition: International

**Related event**

*International Conference on Metamaterials and Nanophotonics*

17/09/2018 → 21/09/2018
Sochi, Russian Federation
Activity: Talks and presentations › Conference presentations

**International Conference on Metamaterials and Nanophotonics**

Period: 17 Sep 2018 → 21 Sep 2018
Elizaveta Semenova (Participant)
Department of Photonics Engineering

**Description**

https://metanano.ifmo.ru/2018/
Degree of recognition: International

**Related event**

*International Conference on Metamaterials and Nanophotonics*

17/09/2018 → 21/09/2018
Sochi, Russian Federation
Activity: Attending an event › Participating in or organising a conference

**Epitaxial growth of GaAs Nanowires on Silicon substrate for photovoltaic applications**

Period: 12 Sep 2018 → 14 Sep 2018
Elizaveta Lebedkina (Speaker)
Dmitrii Viazmitinov (Other)
Stela Canulescu (Other)
Elizaveta Semenova (Other)
Nanophotonic Devices
Department of Photonics Engineering
Photovoltaic Materials and Systems
Description
Direct bandgap III-V semiconductor nanowires (NWs) grown directly on silicon are very promising materials for optoelectronic and photovoltaic applications [1]. It is well known that it is impossible to grow a monocrystalline planar film of Gallium Arsenide (GaAs) or Indium phosphide (InP) on silicon (Si) without structural defects. However, in case of nanowires these materials can be directly grown on Si with high crystalline quality due to their small footprints and the resulting low stress on the NW/Si interface. Recently it was demonstrated that III-V NW on top of a single junction Si solar cell can greatly improve the power conversion efficiency (PCE) [2]. A PCE of 28.15% can be theoretically obtained in such a GaInP NW/Si tandem solar cell, even considering the possible surface and bulk defects in III-V semiconductors [3].

Here we present selective area non-catalytic metalorganic vapour phase epitaxy (MOVPE) of GaAs NWs on Si (111) substrates. We investigate the influence of growth parameters on GaAs NWs grown through the openings in a Si3N4 mask with a diameter of 200nm and altering pitch. Optimization of the mask etching process improved the yield of vertical standing NWs, which can be seen by comparing fig.1a with 1b. In order to improve the optical properties of a GaAs NW array we investigated different approaches of surface passivation of GaAs NWs. Figure 1c illustrates a 7 times increase of photoluminescence signal from GaAs NWs after surface passivation with GaP monolayer in-situ the MOVPE chamber.


Degree of recognition: International

Related event
Northern Optics & Photonics 2018
12/09/2018 → 18/09/2018
Lund, Sweden
Keywords: Nanowires, GaAs, silicon, epitaxy, MOVPE, Material Technology
Activity: Talks and presentations › Conference presentations

Epitaxial methods of quantum dot growth for 1550 nm operating wavelength
Period: 3 Jun 2018 → 8 Jun 2018
Elizaveta Lebedkina (Speaker)
Artem Shikin (Other)
Shima Kadkhodazadeh (Other)
Sokol Ndoni (Other)
Kristoffer Almdal (Other)
Lior Asor (Other)
Uri Banin (Other)
Czcibor Ciostek (Other)
Marcin Syperek (Other)
Kresten Yvind (Lecturer)
Elizaveta Semenova (Other)
Department of Photonics Engineering
Center for Electron Nanoscopy
Department of Chemistry
Center for Nanostructured Graphene
Department of Micro- and Nanotechnology
Degree of recognition: International
Links:
http://www.icmovpe.jp/program/ICMOVPE-XIX-Final_Program.pdf (the program of the conference)

Related event
19th International Conference on Metalorganic Vapor Phase Epitaxy
03/06/2018 → 08/06/2018
Nara, Japan
Activity: Talks and presentations › Conference presentations
Monolithic integration of immersed InP on Si
Period: 3 Jun 2018 → 8 Jun 2018
Dmitrii Viazmitinov (Speaker)
Lars Hagedorn Frandsen (Other)
Kresten Yvind (Other)
Elizaveta Semenova (Other)
Department of Photonics Engineering
Degree of recognition: International
Links:
http://www.icmovpe.jp/program/ICMOVPE-XIX-Final_Program.pdf (conference program)

Related event
19th International Conference on Metalorganic Vapor Phase Epitaxy
03/06/2018 → 08/06/2018
Nara, Japan
Activity: Talks and presentations › Conference presentations

Tunable MEMS VCSEL on silicon substrate
Period: 12 Apr 2018 → 13 Apr 2018
Hitesh Kumar Sahoo (Speaker)
Thor Ansbæk (Speaker)
Luisa Ottaviano (Speaker)
Elizaveta Semenova (Speaker)
Fedor I. Zubov (Guest lecturer)
Ole Hansen (Speaker)
Kresten Yvind (Speaker)
Centre of Excellence for Silicon Photonics for Optical Communications
Quantum and Laser Photonics
High-Speed Optical Communication
Nanophotonic Devices
Department of Photonics Engineering
Degree of recognition: International

Related event
11th European VCSEL Day 2018
12/04/2018 → 13/04/2018
Ulm, Germany
Activity: Talks and presentations › Conference presentations

Presentation title: "A valence force field-Monte Carlo algorithm for quantum dot growth modeling".
Period: 24 Jul 2017 → 28 Jul 2017
Shima Kadkhodazadeh (Other)
Elizaveta Semenova (Other)
Morten Willatzen (Other)
Alessandro Pecchia (Other)
Matthias Auf de Maur (Other)
Daniele Barettin (Speaker)
Center for Electron Nanoscopy
DTU Danchip
Department of Photonics Engineering