# REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)
02-06-2022

2. REPORT TYPE
Final Report

3. DATES COVERED (From - To)
3-Jan-2018 - 2-Jan-2022

4. TITLE AND SUBTITLE
Final Report: High power GaSb-based photonic crystal surface emitting lasers.

5a. CONTRACT NUMBER
W911NF-18-1-0057

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

Research Foundation of SUNY at Stony Brc
W-5510 Melville Library

Stony Brook, NY 11794 -3362

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
71925-EL.9

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 15. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | Leon Shterengas |
| UU | UU | UU | UU | | 19b. TELEPHONE NUMBER<br>631-632-9376 |

# RPPR Final Report
as of 02-Jun-2022

Agency Code: 21XD

Proposal Number: 71925EL **Agreement Number: W911NF-18-1-0057**

**INVESTIGATOR(S):**

**Name:** Leon Shterengas
**Email:** leon.shterengas@stonybrook.edu
**Phone Number:** 6316329376
**Principal:** Y

Organization: **Research Foundation of SUNY at Stony Brook University**
Address: W-5510 Melville Library, Stony Brook, NY 117943362
Country: USA
DUNS Number: 804878247 EIN: 141368361
**Report Date:** 02-Apr-2022 Date Received: 02-Jun-2022
**Final Report** for Period Beginning 03-Jan-2018 and Ending 02-Jan-2022
**Title:** High power GaSb-based photonic crystal surface emitting lasers.
**Begin Performance Period:** 03-Jan-2018 **End Performance Period:** 02-Jan-2022
**Report Term:** 0-Other
Submitted By: Leon Shterengas Email: leon.shterengas@stonybrook.edu
Phone: (631) 632-9376
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

**STEM Degrees:** 2 **STEM Participants:**

**Major Goals:** The goal of the project is development of the GaSb-based surface emitting photonic crystal lasers (PCSEL) emitting in mid-infrared region of spectra and generating low divergent beams.

The key technical goal was development of the air-hole retaining epitaxial regrowth technology within III-V-Sb material system.

**Accomplishments:** Photonic crystal surface emitting lasers (PCSELs) with wavelength up to 2.75 ?m have been designed and fabricated within III-V-Sb material system. A high-index-contrast photonic crystal layer was incorporated into the diode and cascade diode laser heterostructures by air-hole-retaining epitaxial regrowth. Transmission electron microscopy studies demonstrated uniform and continuous regrowth of the nano-patterned GaSb surface with AlGaAsSb alloy until air-pockets start being formed. The electrically pumped PCSELs generated narrow spectrum low divergence beams with mW-level output power. The diode PCSELs emitting near 2 ?m operated in continuous waver regime at low temperatures. The angle-resolved electroluminescence analysis demonstrated well resolved photonic subbands corresponding to ?2 point of square lattice and photonic gaps of several meV.

**Training Opportunities:** Four graduate PhD students (including one female PhD student) have been involved into various aspects of the PCSEL development program.

**Results Dissemination:** Invited conference presentations:
1. L. Shterengas, R. Liu, G. Kipshidze, A. Stein, W. Lee, D.N. Zakharov, K. Kisslinger, G. Belenky, “Electrically pumped epitaxially regrown ? > 2 μm GaSb-based photonic crystal surface emitting lasers,” SPIE Photonics West 2022, San Francisco, CA.

2. L. Shterengas, R. Liu, W. Lee, A. Stein, G. Kipshidze, G. Belenky, “GaSb-based photonic crystal surface emitting lasers,” CLEO (2021), virtual meeting.

3. L. Shterengas, J. Jiang, T. Hosoda, A. Stein, A. Belyanin, R. Liu, W. Lee, G. Kipshidze, G. Belenky, "The GaSb-based Y-branch DBR and photonic crystal lasers," SPIE Photonics West 2020, San Francisco, CA.

Publications:
1. L. Shterengas, R. Liu, G. Kipshidze, A. Stein, W. Lee, T. Hosoda, D.N Zakharov, K. Kisslinger, G. Belenky, “Electrically pumped epitaxially regrown GaSb-Based type-I quantum-well surface-emitting lasers with buried high-index-contrast photonic crystal layer,” Phys. Status Solidi RRL 16, 2100425 (2022).

2. J. Jiang, L. Shterengas, G. Kipshidze, A. Stein, A. Belyanin, G. Belenky, "High-power narrow spectrum GaSb-based DBR lasers emitting near 2.1 um," Opt. Lett. 46, 1967 (2021).

3. W. Lee, L. Shterengas, T. Hosoda, J. Jiang, G. Kipshidze, G. Belenky, “Comparison of the thermal and atomic hydrogen assisted oxide desorption methods for regrowth of the GaSb-based cascade diode lasers,” J. Electron Meter. 50, 5522 (2021).

4. T. Feng, L. Shterengas, T. Hosoda, G. Kipshidze, A. Belyanin, C. C. Teng, J. Westberg, G. Wysocki, G. Belenky, "Passively Mode-Locked 2.7 and 3.2 um GaSb-Based Cascade Diode Lasers," J. Lightwave Technol., 38, 1895 (2020).

5. R. Liu, L. Shterengas, A. Stein, G. Kipshidze, J. Jiang, T. Hosoda, G. Belenky, "GaSb-based heterostructure with buried vacuum pocket photonic crystal layer," IET Electron. Lett. 56, 388 (2020).

**Honors and Awards:** Nothing to Report

**Protocol Activity Status:**

**Technology Transfer:** Nothing to Report

**PARTICIPANTS:**

**Participant Type:** PD/PI
**Participant:** Leon Shterengas
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

**Participant Type:** Other Professional
**Participant:** Gela Kipshidze
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

**Participant Type:** Other Professional
**Participant:** Takashi Hosoda
**Person Months Worked:** 7.00 **Funding Support:**

Project Contribution:
National Academy Member: N

**Participant Type:** Co-Investigator
**Participant:** Gregory Belenky
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)
**Participant:** Tao Feng
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)
**Participant:** Ruiyan Liu
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)
**Participant:** Jiang Jiang
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)
**Participant:** WonJae Lee
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

**ARTICLES:**

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Journal of Lightwave Technology
Publication Identifier Type: DOI Publication Identifier: 10.1109/JLT.2020.2971605
Volume: 38 Issue: 7 First Page #: 1895
Date Submitted: 8/28/20 12:00AM Date Published: 4/1/20 4:00AM
Publication Location:
**Article Title:** Passively Mode-Locked 2.7 and 3.2 &#x3f;m GaSb-Based Cascade Diode Lasers
**Authors:** T. Feng, L. Shterengas, T. Hosoda, G. Kipshidze, A. Belyanin, C.C. Teng, J. Westberg, G. Wysocki, G.
**Keywords:** Cascade lasers, GaSb, optical frequency comb, mode-locked lasers, quantum wells, semiconductor lasers
**Abstract:** The passively mode-locked type-I quantum well cascade diode lasers operating near 2.7 and 3.2 ?m generated trains of the ?10 ps long pulses with average power up to 10 mW. The devices based on laser heterostructures with reinforced carrier confinement requires increased reverse bias voltages applied to absorber sections to operate in mode-locked regime. The autocorrelation measurements showed that lasers generated strongly chirped pulses with temporal width an order of magnitude above transform limit. The application of the external feedback led to narrowing of the laser emission spectra accompanied by an order of magnitude reduction of the intermodal beat note linewidth. The multiheterodyne beat notes have been observed for devices stabilized by external feedback.
**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Electronics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1049/el.2019.3710
Volume: 56 Issue: 8 First Page #: 388
Date Submitted: 8/28/20 12:00AM Date Published: 4/1/20 4:00AM
Publication Location: United Kingdom
**Article Title:** GaSb-based heterostructure with buried vacuum pocket photonic crystal layer
**Authors:** R. Liu, L. Shterengas, A. Stein, G. Kipshidze, J. Jiang, T. Hosoda, G. Belenky
**Keywords:** photonic crystal, PCSEL, mid-infrared, GaSb
**Abstract:** The vacuum pocket retaining molecular beam epitaxial regrowth of the nano-patterned GaSb surface was demonstrated. The high contrast 2D photonic crystal layer was incorporated into the test 2 ?m emitting laser heterostructure. The photonic dispersion determined from angleresolved electroluminescence experiment showed four well-resolved bands corresponding to the model predictions for the square lattice. The single-mode lasing near 2 ?m has been observed at the temperature corresponding to the alignment of the photonic crystal bandedge states and the quantum well gain peak. The reference devices without the photonic crystal layer emitted trivial spectra and did not lase at any temperature.
**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Journal of Electronic Materials
Publication Identifier Type: DOI Publication Identifier: 10.1007/s11664-021-09091-4
Volume: Issue: First Page #:
Date Submitted: 8/29/21 12:00AM Date Published: 7/1/21 8:00AM
Publication Location:
**Article Title:** Comparison of Thermal and Atomic-Hydrogen-Assisted Oxide Desorption Methods for Regrowth of GaSb-Based Cascade Diode Lasers
**Authors:** Wonjae Lee, Leon Shterengas, Takashi Hosoda, Jiang Jiang, Gela Kipshidze, Gregory Belenky
**Keywords:** molecular beam epitaxy, atomic hydrogen, cascade diode lasers, epitaxial regrowth, semiconductor lasers
**Abstract:** Epitaxial regrowth of the antimonide-based heterostructures is required either to improve the device performance parameters or to achieve new functionalities. This work compares two major methods used for surface preparation for subsequent epitaxial regrowth in the context of the antimonide heterostructures. An advantage of the atomic hydrogen assisted oxide removal process for regrowth of the GaSb-based type-I quantum well cascade diode lasers is demonstrated experimentally. The wide ridge 2.7 μm cascade diode lasers have been fabricated from heterostructures grown either in a single epitaxial run – benchmark, or in two separate epitaxial steps – regrowth test. The heterostructure used in regrowth experiment was initially grown only up to the top waveguide layer comprising 500 nm of lightly p-doped GaSb. The surface of this incomplete laser heterostructure was exposed to typical hard mask formation and removal processing treatments. Then the surface was chemically cleaned and subjecte
**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.422536
Volume: 46 Issue: 8 First Page #: 1967
Date Submitted: 8/29/21 12:00AM Date Published: 4/1/21 4:00AM
Publication Location:
**Article Title:** High-power narrow spectrum GaSb-based DBR lasers emitting near 2.1 μm
**Authors:** Jiang Jiang, Leon Shterengas, Gela Kipshidze, Aaron Stein, Alexey Belyanin, Gregory Belenky
**Keywords:** DBR, high power, diode laser, mid-infrared
**Abstract:** Stable high-power narrow-linewidth operation of the 2.05–2.1 ┬m GaSb-based diode lasers was achieved by utilizing the sixth-order surface-etched distributed Bragg reflector (DBR) mirrors. The DBR multimode devices with 100 ┬m wide ridge waveguides generated ↾850mW in the continuous wave (CW) regime at 20♬C. The device CW output power was limited by thermal rollover. The laser emission spectrumwas defined byBragg reflector reflectivity at all operating currents in a wide temperature range. The devices operated at DBR line with detuning from gain peak exceeding 10meV.
**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** physica status solidi (RRL) – Rapid Research Letters
Publication Identifier Type: DOI Publication Identifier: 10.1002/pssr.202100425
Volume: 16 Issue: 1 First Page #: 2100425
Date Submitted: 6/2/22 12:00AM Date Published: 10/1/21 4:00AM
Publication Location:
**Article Title:** Electrically Pumped Epitaxially Regrown GaSb?Based Type?I Quantum?Well Surface?Emitting Lasers with Buried High?Index?Contrast Photonic Crystal Layer
**Authors:** Leon Shterengas, Ruiyan Liu, Gela Kipshidze, Aaron Stein, Won Jae Lee, Takashi Hosoda, Dmitri N. Za
**Keywords:** Photonic crystal, regrowth, mid-infrared, cascade diode lasers, PCSEL, GaSb.
**Abstract:** Epitaxially regrown electrically pumped photonic crystal surface emitting lasers (PCSEL) emitting near 2 and 2.6 µm have been designed, fabricated, and characterized. A high-index-contrast photonic crystal layer was incorporated into the GaSb-based laser heterostructure by air-hole-retaining epitaxial regrowth. A square lattice of triangular holes was etched in the top waveguide core layer of the incomplete laser heterostructure. The nano-patterned surface was subsequently cleaned and regrown with AlGaAsSb p-cladding material. Transmission electron microscopy studies demonstrated uniform regrowth over the nano-patterned GaSb surface. The selected regrowth regimes yielded buried 2D array of the elongated air-holes. The diode PCSELs based on moderately etched nano-patterns demonstrated band edge lasing near 2 µm up to room temperatures. The cascade diode PCSELs operated near 2.6 µm with minimum threshold current densities of about 500 A/cm2 achieved at 180 K. The devices generated mW lev
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

**CONFERENCE PAPERS:**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** Novel In-Plane Semiconductor Lasers XIX, Photonics West 2020
Date Received: 28-Aug-2020 Conference Date: 01-Feb-2020 Date Published: 06-Feb-2020
Conference Location: San Francisco, United States
**Paper Title:** The GaSb-based Y-branch DBR and photonic crystal lasers
**Authors:** L. Shterengas, J. Jiang, T. Hosoda, A. Belyanin, R. Liu, W. Lee, G. Kipshidze, G. Belenky
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 0-Other
**Conference Name:** CLEO 2021
Date Received: Conference Date: 09-May-2021 Date Published: 14-Aug-2021
Conference Location: Virtual, CLEO 2021
**Paper Title:** GaSb-based photonic crystal surface emitting lasers
**Authors:** Leon Shterengas, Ruiyan Liu, WonJae Lee, Aaron Stein, Gela Kipshidze, Gregory Belenky
Acknowledged Federal Support: **Y**

**Partners**

Brookhaven National Laboratory
Upton, NY  USA
4
TEM studies of the regrown structures; E-beam lithography

I certify that the information in the report is complete and accurate:
Signature:  Leon Shterengas
Signature Date: 6/2/22  11:04AM

# Electrically pumped epitaxially regrown $\lambda > 2$ µm GaSb-based photonic crystal surface emitting lasers.

L. Shterengas[1], R. Liu[1], G. Kipshidze[1], A. Stein[2], W. Lee[1],
D.N. Zakharov[2], K. Kisslinger[2], G. Belenky[1]

[1] State University of New York at Stony Brook, Stony Brook, NY 11794, USA
[2] Brookhaven National Laboratory, Upton, NY, 11973, USA

## ABSTRACT

Photonic crystal surface emitting lasers (PCSELs) with wavelength up to 2.75 µm have been designed and fabricated within III-V-Sb material system. A high-index-contrast photonic crystal layer was incorporated into the diode and cascade diode laser heterostructures by air-hole-retaining epitaxial regrowth. Transmission electron microscopy studies demonstrated uniform and continuous regrowth of the nano-patterned GaSb surface with AlGaAsSb alloy until air-pockets start being formed. The electrically pumped PCSELs generated narrow spectrum low divergence beams with mW-level output power. The diode PCSELs emitting near 2 µm operated in continuous waver regime at low temperatures. The angle-resolved electroluminescence analysis demonstrated well resolved photonic subbands corresponding to $\Gamma_2$ point of square lattice and photonic gaps of several meV.

**KEYWORDS:** surface emitting lasers, mid-infrared, antimonides, photonic crystal, regrowth.

## INTRODUCTION.

GaSb-based type-I quantum well (QW) edge emitting diode and cascade diode lasers operate in continuous wave (CW) regime at room temperature (RT) in spectral range from 1.9 to 3.5 µm [1,2]. The lasers with 100-µm-wide aperture generate multimode beams with CW power of ~2 W near 2 µm [3] and ~1 W near 3 µm [4]. The threshold current densities of 2 – 3 µm emitting wide stripe high power edge emitters are about 100 A/cm$^2$. The beam divergence in fast axis direction is ranging from 40 to 60 degrees full-width-at-half-maximum (FWHM) depending on specific heterostructure design. In slow axis direction the beam divergence increases up to 10-15 degrees FWHM at high output power levels and corresponds to highly multimode emission of wide ridge. The reduction of the ridge width by more than order of magnitude is required to achieve single spatial mode operation in lateral direction but this improvement of the beam quality comes at the expense of almost proportional decrease of the maximum laser output power. The beams emitted by the narrow ridge devices, though correspond to diffraction limited case in both directions, suffer from astigmatism. The emission spectrum of the edge emitting laser, even if single spatial mode operation is established, still represents ensemble of multiple laser lines corresponding to closely spaced modes of mm-scale Fabry-Perot laser resonator. Stabilization of the emission spectrum of the monolithic lasers can be achieved by introduction of the distributed feedback elements in the form of etched gratings but often at the expense of further reduction in output power and increase of the fabrication complexity. This set of suboptimal parameters is by no means exclusive to GaSb-based lasers but universal for majority of the edge emitting lasers based on any material system and operating at any wavelength. Edge emitters also require facet cleaving followed by passivation/coating step which add additional, in some cases, rather tedious manufacturing steps.

Photonic crystal surface emitting laser (PCSEL) architecture addresses deficiency of the edge emitting laser design leading to significantly enhanced coherence and reduced divergence of the beams emitted by current injected compact and monolithic semiconductor lasers. The potential of the PCSEL design was successfully demonstrated within nitride, arsenide, and phosphide-based laser technologies, see recent reviews and references in them [5,6]. In this work we present our progress in development of the antimonide-based PCSELs operating in spectral region from 2 to 3 µm.

The distributed feedback (DFB) diode lasers utilizing second order grating can serve as a simplified 1D analogy of the PCSEL device. Majority of the GaSb-based DFB lasers have been fabricated in laterally coupled DFB (LC-DFB) format, see for instance [7], due to previously limited interest to development of the regrowth technology within this materials system [8,9,10]. Figure 1 illustrates one of the 2 μm range 2-nd order LC-DFB lasers fabricated in our research group. The diffraction in the second order provides for in-plane feedback required to establish narrow spectrum laser operation, while diffraction in the first order provides for radiative loss which can be used to convert edge emitting device into surface emitting one. The coupling coefficients responsible for in-plane feedback and surface outcoupling [11] scale with overlap of the laser in-plane guided mode to grating layer ($\Gamma_{gr}$) and refractive index step between layers in grating ($\Delta n_{gr}$). It is also dependent on the grating tooth geometry. The latter factor becomes valuable design tool permitting unprecedented optimization flexibility when 1D DFB case is converted into 2D PCSEL. In PCSEL design, the 2D grating (photonic crystal) should be integrated into the device heterostructure since lateral coupling can not be used effectively for large area devices – epitaxial regrowth becomes one of the most promising technological solution.

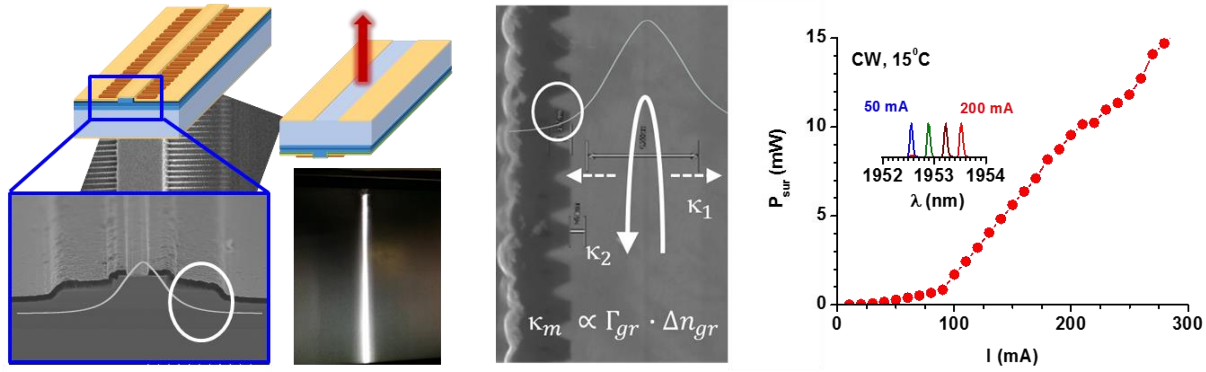


**Figure 1.** From left to right: Schematic illustration of the LC-DFB lasers with scanning electron microscope (SEM) image of the laser emission facet overlapped with the generic lateral near field distribution with overlap with grating indicated by circle; Schematic illustration of the radiative loss through the window in n-side contact and experimental infrared camera image of the 2 μm surface emission; Cross-section SEM image of the cleaved-through-grating section overlapped with generic laser fundamental mode with coupling to grating section indicated by circle. The in-plane feedback and surface outcoupling radiation loss are illustrated; Power-current characteristics measured in continuous wave regime at 15 $^{O}$C showing power emitted from window in n-contact of the epi-side-down mounted LC-DFB laser. Inset shows laser emission spectra at several current above threshold.

Thus, an essential technological step in the fabrication of the antimonide-based PCSELs is integration of the high-index-contrast 2D photonic crystal layer into diode or cascade diode laser heterostructure. It is also critical to achieve adequate coupling of the laser mode to this photonic crystal layer to ensure coherent 2D distributed feedback laser operation over large area. Once these key technological and design challenges are resolved, the fabrication and packaging of the PCSELs roughly follows that of basic etched mesa light emitting diodes. Figure 2 illustrates PCSELs fabricated and characterized in this work.

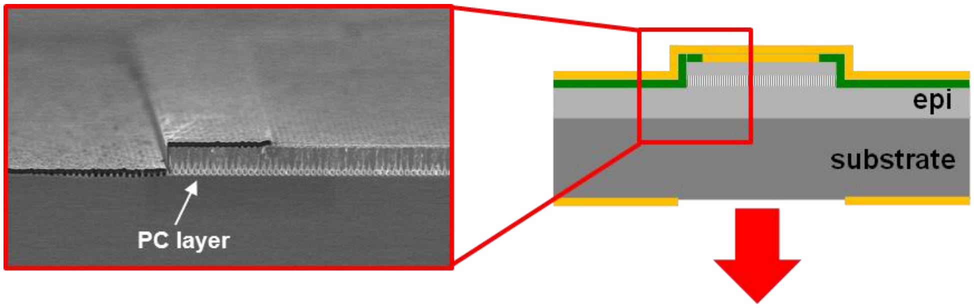


**Figure 2.** Schematic illustration of the antimonide-based epitaxially regrown PCSELs fabricated and characterized in this work. SEM image on the left shows cleaved-through mesa of ~2 μm diode GaSb-based type-I QW PCSEL with buried high index contrast photonic crystal layer.

## GASB-BASED PCSEL FABRICATION.

Laser heterostructures were grown by solid-source molecular beam epitaxy (MBE) using cracked arsenic and antimony sources on tellurium doped GaSb-substrates. The growth was performed in two steps. First, an incomplete laser heterostructure was grown - the first epi. The first epi comprised AlGaAsSb n-cladding, the n-side waveguide core layer, and active region containing quantum wells (QW) with barriers made of AlGaAsSb in case of diode lasers and of InAs/AlSb superlattice and AlGaAsSb graded layers in case of cascade diodes. The first epi was terminated with 400 – 500 nm thick GaSb layer – a provision to host a photonic crystal layer. The incomplete laser heterostructures were removed from MBE reactor and covered with ~300 nm thick silicon nitride film. Electron beam lithography was used to form a hard mask for dry etching of the photonic crystal pattern. The pattern comprised 2D square lattice of right isosceles triangles with ~300 nm legs roughly aligned to (110) planes of III-V crystal. The period of the square lattice for the 2 µm range diode lasers was either 540 or 560 nm, while three stage cascade diode lasers operating near 2.7 µm utilized periods ranging from 734 to 790 nm.

The epitaxial regrowth step (the second epi) required preparation of the surface of the nano patterned GaSb layer, which included chemical cleaning and surface oxide desorption. The remnants of the silicon nitride mask were removed by $CF_4/O_2$ plasma and then the structures were immersed into concentrated ultra-pure HCl right before loading into the load-lock chamber of the Veeco GEN-930 MBE system. We tested two different methods of oxide desorption: thermal and atomic hydrogen assisted ones. The thermal oxide desorption was performed in the main MBE reactor at ~540 ºC. The atomic hydrogen assisted oxide desorption was performed in the buffer chamber of the MBE reactor at the temperature of ~350 ºC. The readiness of the GaSb surface for the regrowth was controlled by reflection high energy electron diffraction measurements – clear 1x3 surface reconstruction was observed. The low temperature atomic hydrogen oxide desorption process helped to minimize blue shift of the luminescence spectra in the cascade diode structures containing GaInAsSb QWs with high (~50%) indium content and was expected to yield smooth regrown interface [12].

Transmission electron microscopy (TEM) was used to investigate the formation of the buried air-holes during regrowth with AlGaAsSb p-cladding material. The TEM sample lamella was made using the in-situ lift-out method on the Helios 600 Nanolab. The ion beam milling voltage was progressively lowered as the sample was thinned, ending with a 2 keV final milling. The prepared TEM lamella was then studied in FEI Talos F200X S/TEM operated at 200kV. Figure 3 shows the cross-section TEM images of the regrown diode PCSEL structures. The native oxide was thermally removed from nanopatterned incomplete laser heterostructure and regrowth with AlGaAsSb cladding material was performed at relatively low temperature ~430 ºC and moderate V/III overpressure of about 1.3 ml/ml. This regime limited lateral growth rates and led to the formation of elongated air-pockets. Uniform coverage of the nano-patterned GaSb surface with ~100 nm of AlGaAsSb was observed even inside the ~300-nm-deep etched holes. For a given growth regime, we observed incomplete and not uniform closure of the air-pockets which contributed to excess scattering losses of the photonic crystal modes.

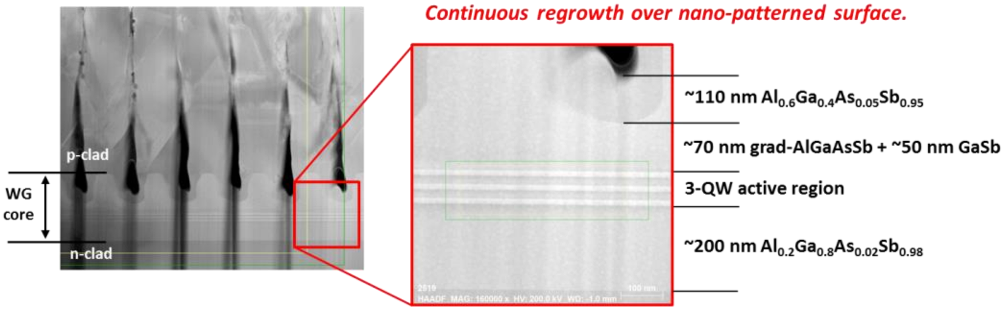


**Figure 3.** Cross-section TEM images of the regrowth interface and the air-holes of 2 µm emitting diode PCSELs.

The deep-etched square mesa (200 µm side) PCSELs were fabricated from the regrown structures. The Ti/Pt/Au p-contact pads were formed by lift-off on the regrown structures. Then a silicon nitride hard mask for mesa etching was fabricated and chlorine-based inductively coupled plasma reactive ion etching was performed. The square mesas with sides roughly aligned to the X-direction of the photonic crystal (and (110) planes in III-V crystal) were etched through regrown p-claddings. The remnants of the hard mask were cleaned and ~500 nm thick silicon nitride passivation layer was deposited. The windows were opened in the passivation layer and final Ti/Au p-metal overlay was e-beam deposited. The structures with finished p-side were lapped and polished to ~200 µm thickness. The alloy n-contact was deposited and covered by Ti/Pt/Au overlay. The n-side metallization had square windows (200 µm side) aligned to the mesas on p-side. The individual 500 µm by 500 µm chips were cleaved from the processed wafer. The devices were attached epi-side down onto copper blocks and characterized. Figure 2 shows fabricated PCSELs with SEM images of the device cleaved through the mesa and revealing the buried high index contrast photonic crystal layer.

## DIODE PCSELS OPERATING NEAR 2 µm.

The diode PCSELs with square lattice period of 540 nm emitted near 1.95 µm at 160 K. The laser threshold took minimum value of about 70 mA near 160 K (Figure 4). Both increase and decrease of the PCSEL temperature resulted into increase of the threshold current, hence, we conclude that QW gain peak and photonic crystal band edge aligned at this temperature. The laser surface emission spectra were narrow band but apparently not single mode (Figure 4, rightmost panel) and number of lasing modes increased with pumping current. The laser far field pattern also corresponded to multimode behavior. The far field width in one of the X-directions (vertical in Figure 4) was narrow with divergence angle corresponding to coherent emission from 200 µm aperture. The polarization of the surface emission corresponded to radiative surface outcoupling of the coupled waves propagating in the same X-direction. In perpendicular direction, the far field pattern comprised wide angle two-lobe beam indicating lack of coherence in another X-direction. The far field pattern for perpendicular polarization was significantly less intensive but qualitatively similar, just rotated by 90 degrees. In ideal square lattice with square isosceles triangular atoms, the perpendicular X-directions are equivalent. Apparent disparity between X-directions indicates asymmetry of the regrowth rates in two perpendicular (110) directions leading to corresponding asymmetry of buried air-holes. The lack of beam coherence in one of the X-directions can be caused by insufficient 2D coupling of the partial waves comprising band edge laser emission state. The insufficient coupling can be associated with suboptimal area fill-factor of the buried air-holes. The PCSEL devices operated in CW regime at 160 K temperature with output power limited by thermal roll-over at ~8 mW. Intercept of the CW power-current characteristics with those measured in 1% duty cycle regime allowed estimating the device thermal resistance as ~50 K/W which is in agreement with values previously observed for GaSb-based lasers scaled according to the thermal footprint (200x200 µm$^2$ here).

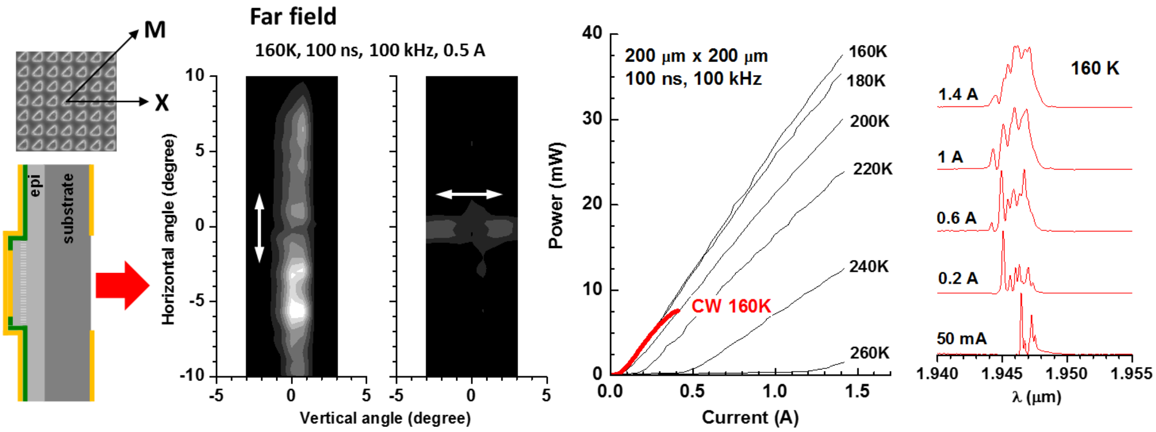


**Figure 4.** From left to right: Schematic illustration of the operating PCSEL with inset showing etched square photonic crystal with two high symmetry directions indicated by arrows; Far field patterns measured for two perpendicular polarizations – the arrows show the polarization direction; Power-current characteristics measured in 1% duty cycle and in CW regime at several temperatures; Laser emission spectrum at 160 K for different injection currents above threshold.

The PCSELs with 540 nm period did not lase at room temperature due to detuning of the gain peak from photonic crystal band edge. The devices with period 560 nm operated at photonic crystal stabilized wavelength up to room temperatures. At room temperatures the PCSEL threshold increased to about 4 A and devices generated mW level power in 1% duty cycle regime. Figure 5 (right panel) shows the results of the angle resolved electroluminescence measurements of the photonic crystal band structure in the X-direction of the square photonic lattice with period 560 nm. The left panel of Figure 5 shows schematically the device electronic band structure and cross-section SEM image of the buried photonic crystal layer. The central panel plots series of the electroluminescence spectra collected below threshold at room temperature and at variable angles from the surface normal. The corresponding PCSEL line is also shown. The $\omega$ vs $k_{||}$ ($k_{||}$ - in-plane photon wavevector) dispersion dependence (Figure 5 – right panel) obtained from peaks in electroluminescence spectra clearly shows four sub-bands as expected near $\Gamma_2$ point for square photonic crystal. The laser emission spectra plotted in the same reduced frequency coordinates and with intensity in log scale indicates the lasing from low energy band edge (the non-lasing peak corresponding to high energy band edge is also apparent). The PCSEL operates at the low energy band edge thanks to the reduced radiation loss of the corresponding photonic subband.

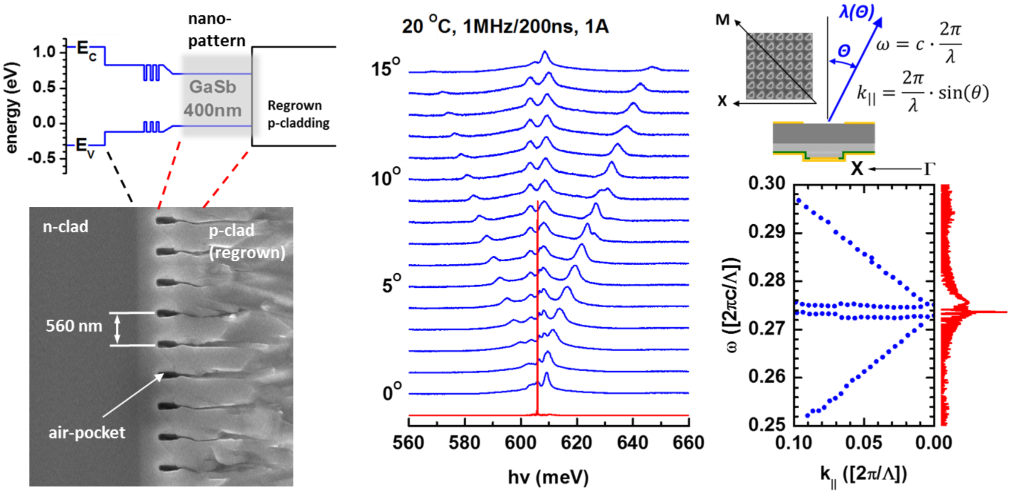


**Figure 5.** From left to right: Schematic band diagram of the diode PCSEL with corresponding cross-section SEM image showing buried square lattice of air-pockets with period of 560 nm; Electroluminescence spectra measured below lasing threshold and collected at different angles with respect to surface normal in X-direction. The lasing line is shown on the same graph; The dispersion relationship of the photons propagating in plane of the photonic crystal layer determined from angle resolved surface electroluminescence. The top inset illustrates the method of reconstruction of the photonic band structure near $\Gamma_2$ point. The laser spectra plotted in log scale next to the dispersion curves confirms the band edge lasing.

## CASCADE DIODE PCSELS OPERATING NEAR 2.7 μm.

The PCSELs operating at longer wavelength have been fabricated based on three-stage cascade diode laser heterostructure illustrated in Figure 6. In cascade diode lasers, the GaSb binary alloys can naturally serve as waveguide cores simplifying the integration of the buried photonic crystal layer into laser heterostructure. The depth and lateral dimension of the etched holes control the amplitudes of Fourier harmonics which determine coupling between partial waves responsible for in-plane feedback and radiative loss providing for surface emission. The lateral dimension of the etched triangular holes was fixed in this work, but the etching depth was varied. Figure 6 illustrates the model of the unit cell of the square photonic crystal after regrowth - about 100 nm of the AlGaAsSb alloy is expected to grow inside of the holes etched in GaSb (Figure 3). The effect of varied etching depth on overlap of the laser fundamental guided mode with buried photonic crystal and with active QWs is plotted in the right panel of Figure 6. Notably, the overlap of the laser mode with photonic crystal layer depends strongly on hole etching depth while coupling to QWs shows only modest dependence.

We have fabricated cascade PCSEL lasers using deep, shallow and moderate etching of the photonic crystal layer. The left panel of Figure 7 shows the cross-section SEM image of the PCSEL structure based on deeply etched photonic crystal layer. In this case the etching went all the way through ~500 nm thick GaSb waveguide core layer and reached layers containing Al. The associated oxidation dramatically degraded optical properties of the top QW. However, the bottom two QWs provided enough gain to start laser operation (see inset in the SEM image) albeit at low temperature and with increased threshold current. The angle resolved electroluminescence studies (not shown) revealed photonic crystal band structure which was qualitatively very similar to the one measured for 2 µm diode PCSELs (Figure 5). In another extreme case, when etching was shallow (~100 nm), the regrowth resulted into complete filling of the etched holes (Figure 7 – central panel) leading to order of magnitude reduction in the index contrast and multifold reduction of the overlap with the guided mode.

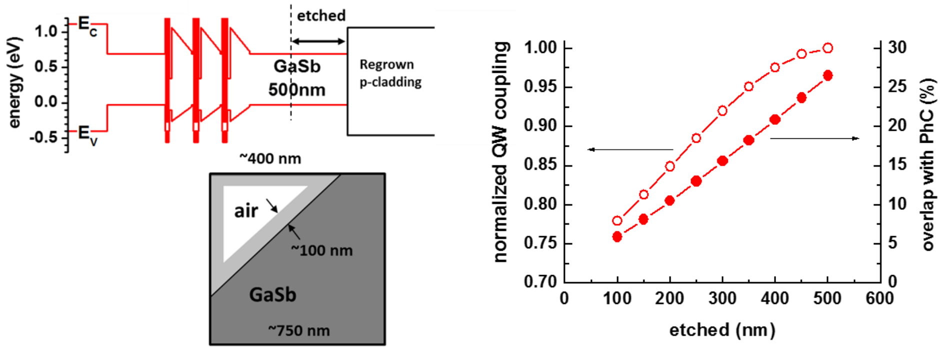
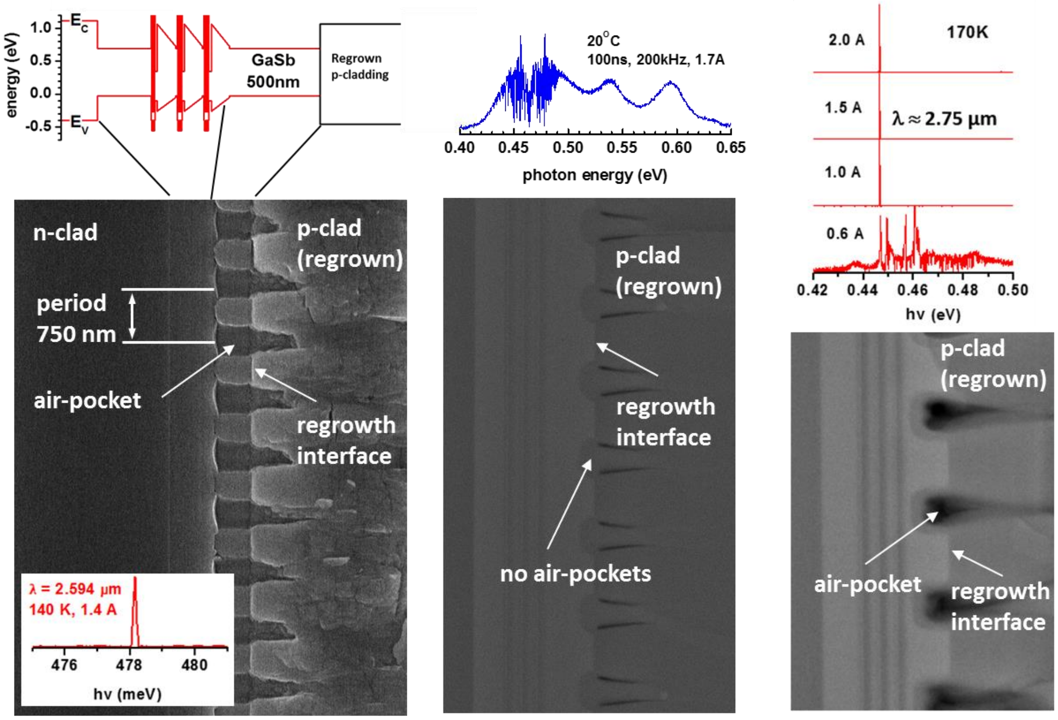


**Figure 6.** Left: Schematic band diagram of the cascade PCSEL. The simplified model of the unit cell of the buried photonic crystal is shown underneath. Right: Calculated dependence of the overlap integral of the fundamental in-plane laser mode with buried photonic crystal layer and QW active region as a function of the etching depth.



Deep etch Shallow etch Moderate etch

**Figure 7.** Cross-section SEM images of the buried photonic crystal layers in three PCSEL structures with variable etching depth of the photonic crystal patterns. The left panel corresponding to the deeply etched case includes schematic band diagram and emission spectrum of the corresponding PCSELs. The middle panel shows etching/regrowth profile of the shallow etched structure which does not demonstrate lasing – inset shows the electroluminescence spectrum with apparent photonic crystal features. The right panel corresponds to the moderately etched case resulting in PCSEL operation with reasonable threshold current. The inset shows the device surface emission spectrum measured at several currents near and above threshold.

The ensuing degradation of the values of the coupling coefficients precluded the devices from reaching laser threshold at any temperature (from 100 to 300 K). However, spectral features associated with presence of the buried photonic crystal layer has been observed in electroluminescence spectra at all temperatures (20 $^{O}$C spectrum is shown above SEM image corresponding to shallow etching). The PCSELs fabricated from the devices with moderately etched photonic crystal layer (Figure 7 – right panel) showed minimal threshold current of about 0.7 A at the temperature of 170 K and emitted near 2.75 µm, i.e. demonstrated significantly better operating parameters compared to both deep and shallow etched cases. The details of the etching and regrowth profile corresponding to the moderately etched case are presented in Figure 8. The right angle isosceles triangular holes which was etched in the GaSb top waveguide core level down to ~ 300 nm have been uniformly regrown with ~100 nm of AlGaAsSb p-cladding material before the air-pocket start to form. This correspond to ~200 nm etching depth for Figure 6 calculation and area fill-factor below 5%. The shape of the etched hole was approximately preserved as can be concluded from cross-section SEM of the device in which photonic crystal X-direction was slightly misaligned with respect to III-V crystal (110) cleavage plane. The power-current characteristics measured in 1% duty cycle regime (100ns, 100kHz) demonstrated low efficiency, presumably, due to insufficient coupling of the partial waves. The far field pattern was qualitatively similar to the one measured for 2 µm PCSELs (Figure 4). However, the overall divergence angles of two lobes in one of X-directions (vertical direction in Figure 8) was lower. In perpendicular X-direction, the far field pattern corresponded to nearly diffraction limited emission from 200 µm aperture (scans along dotted line for different polarizer orientation is shown underneath of the 2D far field image).

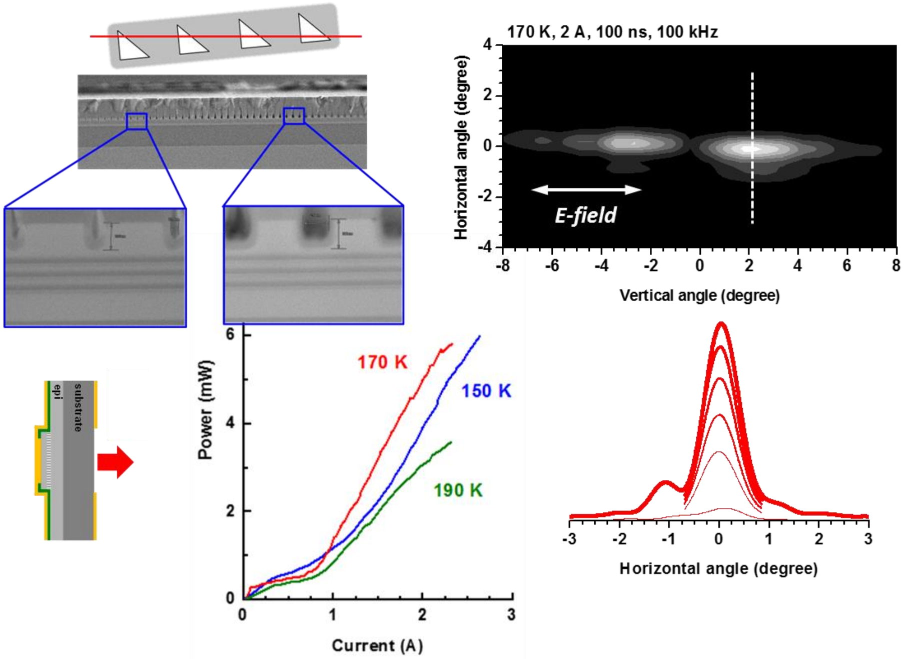


**Figure 8.** Cross-section SEM images of the moderately etched cascade PCSEL. The corresponding power-current characteristics and far field pattern are shown below and to the right of the SEM image. The set of the far field scans along horizontal direction (underneath of the 2D far field image) shows the dependence of the emitted signal on polarizer angle. The maximum intensity corresponds to the polarizer orientation parallel to the vertical direction while minimum one corresponds to 90-degree rotation.

Further improvement of the cascade PCSEL operating parameters was observed in the slightly deeper etched structure which was regrown under conditions limiting lateral growth (like those used for 2 µm PCSEL regrowth). The resulting regrowth profile yielded increased coupling of the fundamental in-plane laser mode to the buried photonic crystal layer. The devices demonstrated minimal threshold currents near 200 mA at 180 K and improved slope efficiency (Figure 9 – left panel). The far field pattern still demonstrated dual lobe emission but with both lobes having more symmetric profiles (Figure 9). The laser emission spectra corresponded to narrow spectrum band edge emission but with apparent multimode features.

The right panel of Figure 9 shows the photonic band structure measured near $\Gamma_2$ point by angle resolved electroluminescence. There are two distinct sets of photonic subbands observed. We ascribe each of them to the two supported modes of the laser vertical waveguide structure (inset). Due to the significant difference (calculated to be more than 0.2) of effective refractive indexes of the fundamental and the first modes of the vertical waveguide, they originate two well-separated sets of photonic crystal bands. The lasing threshold is achieved at the band edge corresponding to the fundamental mode thanks to its strong overlap with active QWs. The photonic gap for the first order mode, however, is wider due to its stronger coupling to the air-pocket containing layer.

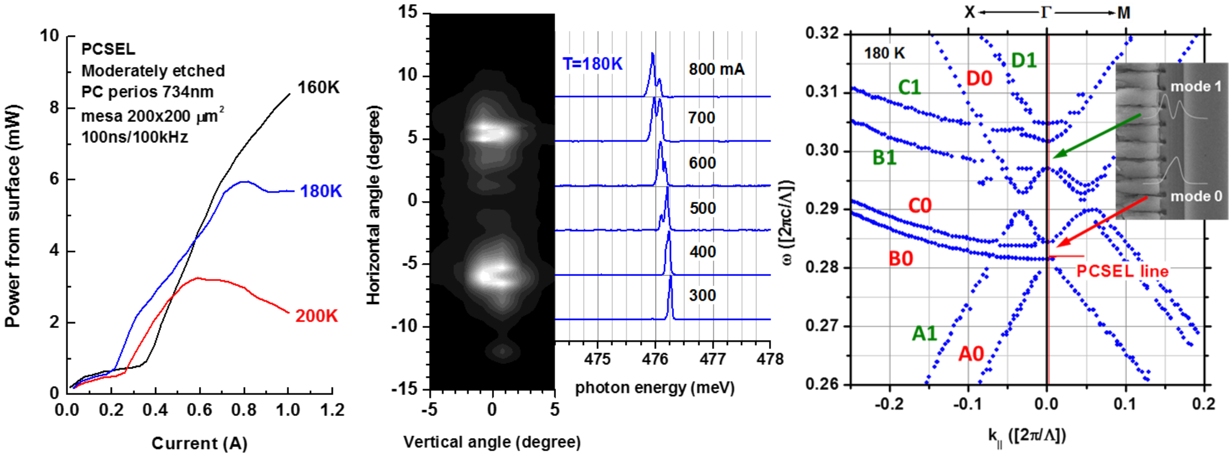


**Figure 9.** From left to right: Power-current characteristics of another moderately etched PCSEL; 2D far field pattern and emission spectra of this device; The band structure of the photonic crystal (period of 734 nm) incorporated into cascade diode laser heterostructure showing interacting two sets of the subbands corresponding to fundamental (mode 0) and the first order (mode 1) modes of the vertical waveguide. The right inset shows the SEM cross-section image for the corresponding PCSEL overlapped with calculated mode 0 and mode 1 intensity distributions.

## CONCLUSION.

The continuous wave operation of the epitaxially regrown GaSb-based diode PCSELs operating near 2 μm has been demonstrated for the first time. The cascade diode PCSELs emitted near 2.7 μm. The device heterostructures contained buried high-index-contrast 2D photonic crystal layers. The high-index-contrast layer was incorporated into p-cladding by means of an air-hole-retaining epitaxial regrowth step. TEM studies confirmed uniform and continuous regrowth of the nano-patterned GaSb surface with AlGaAsSb alloy until air-pockets start being formed. The PCSEL devices operated at the band edge modes with mW-level output power. Both diode and cascade diode PCSELs emitted linearly polarized beams with low divergence but dual-lobe patters. The angle-resolved electroluminescence analysis demonstrated presence of well resolved sets of four photonic bands corresponding to $\Gamma_2$ point of square photonic lattice. In the special case when the laser heterostructure supported two modes in vertical direction, the number of resolved photonic subbands doubled and anti-crossing between subbands belonging to different subsets was observed experimentally. The photonic gaps of the value of several meV have been detected as expected for high-index-contrast photonic crystals.

## ACKNOWLEDGEMENTS.

The authors would like to thank Dr. T. Hosoda and Dr. T. Feng for their contributions at the initial stages of the development of the GaSb-based PCSEL laser technology as well as fabrication and characterization of surface emitting 2nd-order LC-DFB lasers. The work at Stony Brook University was supported by U.S. Army Research Office Grant W911NF1810057. The work at Center for Functional Nanomaterials at Brookhaven National Laboratory was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract DE-SC0012704.

# REFERENCES.

---

1 L. Shterengas, G. Kipshidze, T. Hosoda, R. Liang, T. Feng, M. Wang, A. Stein, G. Belenky, "Cascade pumping of 1.9-3.3 µm type-I quantum well GaSb-based diode lasers," J. Sel. Top. Quant. Electron. 23, 16921011 (2017).

2 G. Belenky, L. Shterengas, G. Kipshidze, T. Hosoda, “Type-I diode lasers for spectral region above 3 µm,” IEEE J. Select. Top. Quantum Electron. 17, 1426 (2011).

3 T. Hosoda, T. Feng, L. Shterengas, G. Kipshidze, G. Belenky, “High power cascade diode lasers emitting near 2 µm,” Appl. Phys. Lett. 108, 131109 (2016).

4 L. Shterengas, R. Liang, G. Kipshidze, T. Hosoda, G. Belenky, S. S. Bowman, R. L. Tober, “Cascade type-I quantum well diode lasers emitting 960 mW near 3 µm,” Appl. Phys. Lett., 105, 161112 (2014)

5 S. Noda, K. Kitamura, T. Okino, D. Yasuda, Y. Tanaka, “Photonic-crystal surface-emitting lasers: review and introduction of modulated-photonic crystals,” IEEE J. Sel. Top. Quantum Electron. 23, 4900107 (2017).

6 M. Yoshida, M. De Zoysa, K. Ishizaki, W. Kunishi, T. Inoue, K. Izumi, R. Hatsuda, S. Noda, “Photonic-crystal lasers with high-quality narrow-divergence symmetric beams and their application to LiDAR,” J. Phys. Photon. 3, 022006 (2021).

7 T. Hosoda, M. Fradet, C. Frez, L. Shterengas, S. Sander, S. Forouhar, G. Belenky, “Laterally coupled distributed feedback cascade diode lasers emitting near 2.9 µm,” IET Electron. Lett. 52, 857 (2016)

8 A. Bachmann, K. Kashani-Shirazi, S. Arafin, M.-C. Amann, “GaSb-Based VCSEL with buried tunnel junction for emission around 2.3 µm,” IEEE J. Sel. Top. Quantum Electron. 15, 933–940 (2009).

9 Q. Gaimard, M. Triki, T. Nguyen-Ba, L. Cerutti, G. Boissier, R. Teissier, A. Baranov, Y. Rouillard, A. Vicet, “Distributed feedback GaSb based laser diodes with buried grating: a new field of single-frequency sources from 2 to 3 µm for gas sensing applications,” Opt. Exp. 23, 19118 (2015).

10 R. Rehm, M. Walther, F. Fuchs, J. Schmitz, J. Fleissner, “Passivation of InAs⁄(GaIn)Sb short-period superlattice photodiodes with 10µm cutoff wavelength by epitaxial overgrowth with $Al_xGa_{1-x}As_ySb_{1-y}$,” Appl. Phys. Lett. 86, 173501 (2005).

11 R.F. Kazarinov, C.H. Henry, “Second-order distributed feedback lasers with mode selection provided by first-order radiation losses,” IEEE J. Quantum. Electron. QE-21, 144 (1985).

12 W. Lee, L. Shterengas, T. Hosoda, J. Jiang, G. Kipshidze, G. Belenky, ”Comparison of the thermal and atomic hydrogen assisted oxide desorption methods for regrowth of the GaSb-based cascade diode lasers,” J. Electron Meter. 50, 5522 (2021).