Studies of Physical Phenomena Limiting the Temperature Performance of GaSb and InAs Based Lasers Operating in the Range of 2 μm – 4 μm

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FINAL TECHNICAL REPORT

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Contents

I. Major objectives of the project

Our project was aimed at finding solutions to one of the urgent problems facing mid-infrared laser development, namely, creating high-efficiency 2.3 μm and 3.3 μm electrical laser sources operating at room temperature. These lasers are essential for chemical sensing for pollution monitoring, leak detection, chemical process control, countermeasures against heat seeking missiles, IR illumination and can be used to engage terrestrial targets from space.

Employment of mid-IR lasers for chemical sensing, detection, pollution control requires single mode devices which can generate light in a narrow band with high spectral power density.

The project objectives are summarized as follows:

1. Design of high-power continuous-wave (CW) room-temperature operated InGaAsSb lasers covering wavelength range longer than 2 μm.
2. Determination of the factors limiting room-temperature operation of GaSb-based lasers.
3. Design and fabrication of broad-area and single mode CW room-temperature InGaAsSb long-wavelength lasers.

II. Achievements of the project and new findings

1. **It is demonstrated that GaSb/InGaAsSb/AlGaAsSb Type I diode lasers can provide room-temperature CW operation covering wavelength range of 2.3 - 2.7 μm.** CW output powers of 500, 250 and 160 mW were obtained at room temperature for 100 μm stripe-width lasers emitting at wavelengths of 2.3, 2.5 and 2.6 μm, respectively. For lasers with wavelength in the range of 2.3 - 2.6 μm, the laser basic parameters (J_{th} and η_d) depend weakly on wavelength ($J_{th} \cong 300$ A/cm^2 and $\eta_d \cong 30\%$) at room temperature.
2. New advanced characterization methods were developed and applied to mid-IR lasers: direct measurement of heterobarrier hole leakage current and direct measurement of modal gain in broad area lasers. These methods allowed obtaining key parameters of a diode laser: the values of internal loss and internal efficiency. These results together with the results of modeling permitted to make a conclusion about the physical causes limiting the external efficiency of GaSb-based lasers.
3. 2.3 - 2.55 μm single lateral mode lasers generating up to 20 mW of CW diffraction limited power at room temperature are demonstrated.
4. Single-longitudinal mode lasers were utilized for high-resolution spectroscopy – combustion measurements. It is shown that moving from existing 1.5 μm laser-based systems to demonstrated 2.3 μm system allows improving the sensitivity to CO-concentration by more than two orders of magnitude.
5. Single lateral mode lasers with twofold extended gain bandwidth are demonstrated for utilization in widely-tunable external cavity lasers for spectroscopy in mid IR range.

III. Approach and methodology

1. Laser design

A new approach to the design of GaSb/(Al)InGaAsSb quantum well separate confinement heterostructure (QW-SCH) diode lasers led to CW room-temperature lasing up to 2.73 μm. This was achieved by using **quasi-ternary heavily-strained** InGaSb(As) QWs inside a **broad-waveguide** SCH laser structure. The QW compositions were chosen in the region outside the miscibility gap (Figure 1a) and, as a consequence, did not suffer from clustering and composition non-homogeneity normally found with quaternary InGaAsSb compounds in 2.3-2.7 μm spectral range. **The In content was varied from 25 to 38% while the As concentration was maintained at the level of 2%**. The corresponding compressive strain in QW increased from 1.4 to 2.3% with increasing In content.

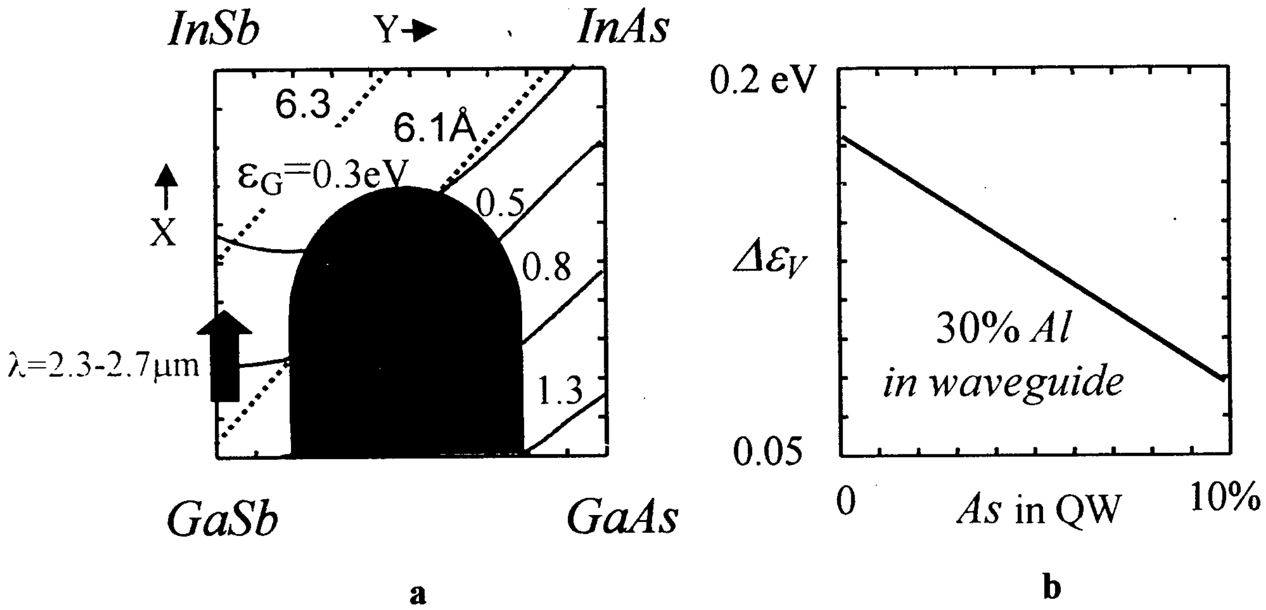

Figure 1. (a) Quantum well compositions (green arrow) are chosen outside the miscibility gap (shaded red area) to avoid material deterioration
(b) Increase of the hole barrier with decrease of As content in QW

The decrease of As content also led to the **improvement of the hole confinement in QW** (Figure 1b) which was considered as a factor affecting the performance of GaSb-based lasers. The diode structure, grown by MBE on n-GaSb substrates, consisted of two QWs to avoid fast gain saturation with current previously observed for single quantum well 2 μm diode lasers. A broad waveguide (0.8 μm thick undoped $Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$) was chosen to decrease the optical loss value due to free-carrier absorption in cladding. The details of the structure design are described in [1].

2. Experimental methods

To clarify the nature of the device temperature performance, we carried out direct measurements of carrier leakage for lasers with the new design using the technique developed in [2]. To measure the heterobarrier leakage current of holes, broad area devices were designed and fabricated on **p-substrates**. A small area n-p-n+ hole collector was grown on the top of the laser structure. The collector area did not exceed 1% of the current-injection area. The collector efficiency was better than 50%. **To fabricate the collector a self-aligned technique for GaSb was developed for the first time.** Holes emitted from the active region into the n-cladding layer were collected by a small reverse biased p-n junction at the top of n-cladding. The saturation current of the collector directly reflects the carrier leakage. Knowledge of the leakage current allows to make a conclusion about the device injection efficiency.

Optical gain determines many essential properties of the device, and it is one of the most important characteristics of a diode laser. Different techniques were developed to extract the value of gain analyzing the contrast of Fabry-Perot fringes in the spectrum of amplified spontaneous emission emerging from the laser cavity [3-5]. To obtain an accurate value of modal gain in broad area lasers it is necessary to select a single lateral mode. **In this work a novel technique was developed for mode selection utilizing the properties of a Michelson interferometer**. The details of the method are described in [6].

The current dependences of the optical gain and loss were extracted from the measurements. **The value of the device total loss was obtained from the intersection point of modal gain spectra for TE and TM modes or from the long-wavelength gain saturation value.** These methods were previously applied to the characterization of single mode telecommunication lasers [7]. The value of internal efficiency was determined based on the value of optical loss and external efficiency using the standard approach [8].

IV. Structures, experimental setup and procedures

Gain-guided Fabry-Perot lasers with 100-μm-wide stripe contact and index-guided ridge waveguide lasers with 5-μm-wide ridges with a cavity length in the range of 0.5 –2 mm were fabricated. The ridge-waveguide structure parameters were defined by modeling using the effective index method. The model included losses caused by mode absorption in unpumped portions of QW active regions adjacent to the ridge and by the contact metal. The chemical ridge etching to the waveguide was chosen since this configuration reduces lateral losses for zero-mode while maintaining high lateral losses for the non-zero modes. The rear facets had high-low dielectric stack reflectors, and neutral (30%) or low-reflecting (3-5%) single layer Al_2O_3 coatings deposited on the front facets. The lasers were mounted p-side down on copper heatsinks and measured in both CW and pulsed regimes with pulse width of 100 ns.

The single lateral mode selection was provided by a Michelson interferometer together with spatial filtering of the far field. The amplified spontaneous emission (ASE) spectra were measured using a Fourier-transform spectrometer Nicolet Magna-860 with resolution as high as 0.125 cm^{-1}. The modal gain calculations were made using Hakki-Paoli and Cassidy techniques [3-4].

V. Major results

The measured hole leakage current did not exceed 0.5% of the injection current in the whole range of measured currents and temperatures. Hence, the **hole heterobarrier leakage current is not a factor limiting high temperature operation of 2.3 μm InGaAsSb/AlGaAsSb lasers.**

Figure 2 shows the CW output power for lasers with 100 μm strip. For lasers with wavelengths shorter than 2.7 μm at temperature < 20°C the laser parameters are weakly dependent on QW composition. Values of differential efficiency are independent of wavelength in the range of 2.3 to 2.6 μm and close to 30% for all 2-mm-long cavity devices.

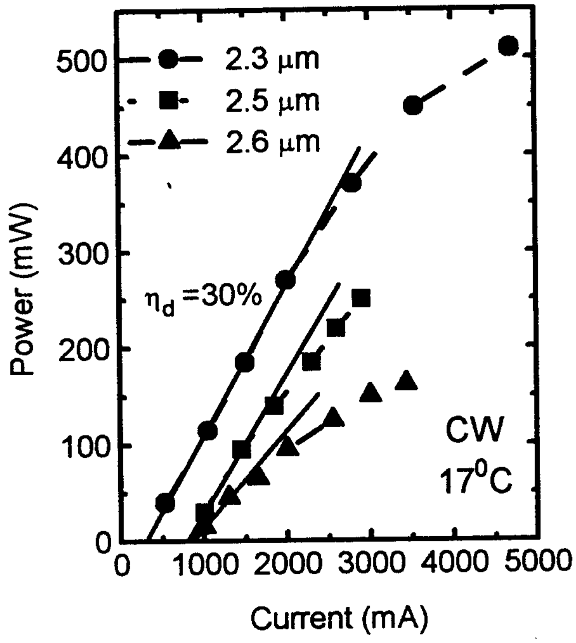

Figure 2. CW output power characteristics for the diode lasers with different wavelengths.

Advanced characterization of broad area lasers was performed. **Temperature dependencies of the optical gain and loss were measured for the first time**. The value of total loss was determined through the TE-TM gain crossing method. The results are shown in **Figure 3** for 2.3 μm broad–area lasers.

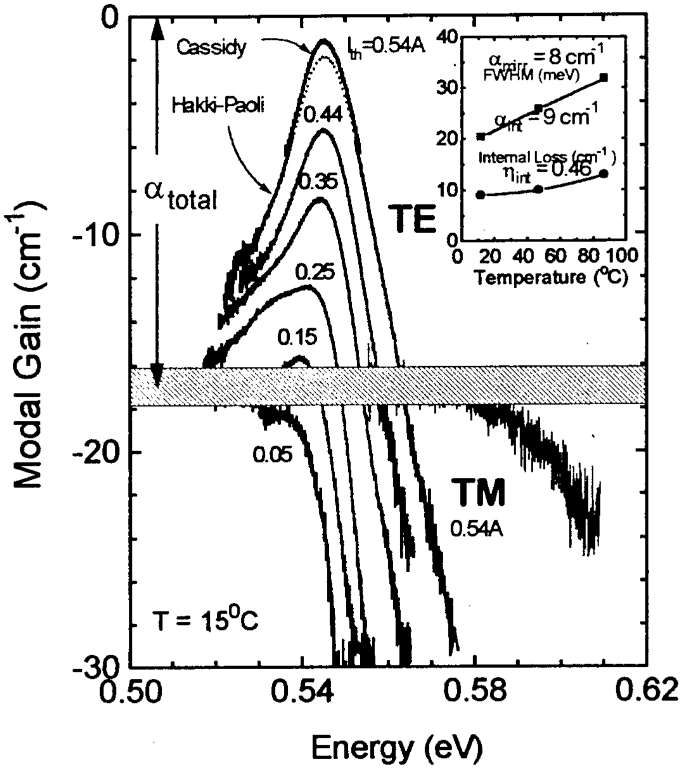

Figure 3. The current dependences of modal gain spectra obtained at room temperature for 2.3 μm InGaAsSb laser with 100 μm aperture. The temperature dependences of internal loss and full-width at half-maximum (FWHM) of the modal gain are shown in the inset.

No essential increase of optical loss was observed, however the typical value of internal loss of 6-8 cm^{-1} is higher than it was suggested before. The optical gain degradation with temperature was investigated. It was discovered that the internal efficiency is of primary importance in determining differential efficiency. One can conclude that low internal efficiency (typical values of 40-50%) rather than optical loss is the cause limiting the differential efficiency of GaSb-based lasers. We observed a noticeable gain broadening with increasing temperature and current (see inset in **Figure**

3). This effect causes gain suppression and significantly contributes to the temperature performance of GaSb-based lasers.

The microscopic calculations of Auger recombination and interband absorption in GaSb-based QW lasers were carrier out. The calculations show that the dominant Auger process in these laser structures is the process with hole excitation from the QW level to the continuous spectrum. The calculations show that the Auger coefficient C weakly varies with temperature and this variation cannot be the sole cause of essential temperature dependence of the threshold current. To obtain the value of n_{th} at given temperatures we fit the calculated gain spectra to the measured gain. Gain temperature broadening and caused by this broadening threshold concentration n increase lead to the rise of Cn^3 contribution to the total current. Thus, **a significant value of the Auger coefficient and the temperature dependence of laser gain are the major factors determining the temperature dependence of the threshold current in 2.3-2.6 μm InGaAsSb/AlGaAsSb QW lasers.**

The lateral far-field pattern confirms single spatial mode operation of our ridge lasers. CW output powers in the range of 3-20 mW were obtained for wavelengths of 2.35-2.55 μm at room temperature. Threshold current for the 0.5 mm long cavity devices was about 50 mA at 15 °C. CW operation was obtained up to 70 °C. No degradation was observed during preliminary lifetime testing. However, the measured differential efficiencies (10.5% at 2.45 μm) for ridge-waveguide lasers were lower than expected compared with our previous results for broad contact devices.

A switch of the laser emission to shorter wavelength at drive currents of about 4-5 times the threshold value was observed. The photon-energy spacing between the original and new peaks was almost the same for both lasers at about 40 meV. This value fits the calculated difference in the energies of 2e-2hh and 1e-1hh transitions in our QWs with accuracy better than 5%. The strong TE-polarization of both peaks confirms the interpretation of the peak nature.

This result indicates that the carrier concentration and energy-distribution continues to change when current exceeds I_{th} for 1e-1hh transitions. One can conclude that twofold difference in the differential efficiency for 1e-1hh and 2e-2hh transitions originates from non-equilibrium carrier distribution rather than from the spectral dependence of optical losses. **A non-equilibrium distribution of carriers above threshold plays the decisive role in limiting the internal efficiency.**

Investigation of single spatial mode laser spectra revealed the current and temperature ranges where one of the longitudinal modes dominates with side mode suppression ratio of 22-25 dB. It was shown that the dominant mode could be tuned in wavelength by varying the current and temperature. The lasers used to record high-resolution CO absorption lineshape (R30 transition, 2ν band) near 2.302 μm fit the theoretical Voigt profile reasonably well confirming the corresponding line strength in the HITRAN database to within 2%. For a minimum detectable absorbance of 0.01% and a 1-meter long path, the CO measurement sensitivity for this line is about 5-10 ppm at 1000K. This value is two orders of magnitude better than the sensitivity reported for CO detection with conventional diode lasers operating near 1.56 μm (3ν band).

VI. Technology transfer

Commercially available external cavity lasers can operate in wavelength range up to 2 μm with typical continuously tuning band of 50 nm. For spectroscopy application it is highly desirable to have a wide tuning band. This band is limited by the width of laser optical gain. A typical laser diode gain bandwidth $\Delta\nu/\nu$ at the level of 1/2 is about 0.04. To extend this band we suggest using laser diode structures with wide quantum wells. It was shown that utilization of 200A quantum well and short laser cavity of 500 μm with high total optical loss increases the gain bandwidth $\Delta\nu/\nu$ up to 0.14. **Ridge-waveguide lasers with broad modal gain spectra covering wavelength range of 2.1 - 2.5 μm at room temperature were demonstrated (Figure 4).**

Result: The technology to extend the bandwidth of the optical gain of room-temperature-operating single-mode 2.3μm - InGaAsSb/AlGaAsSb/GaSb lasers includes:

1. Utilization of high Al-content material (30%) for a separate-confinement layer.
2. Utilization of two quantum wells of 200A width.
3. Utilization of ridge-waveguide lasers with a high controllable value of total loss.

Application: Development of ***widely tunable external-cavity*** semiconductor lasers requires laser diodes with broad gain spectra. The optical gain bandwidth - full-width at half-maximum (FWHM) defines the range of the device tunability. The tuning range of commercially available diode lasers remains below 120 nm. FWHM of a conventional laser is about 30 meV. Proposed technology allows to demonstrate $\lambda = 2.3$-μm laser with a record value of gain FWHM of 70 meV (or 300 nm).

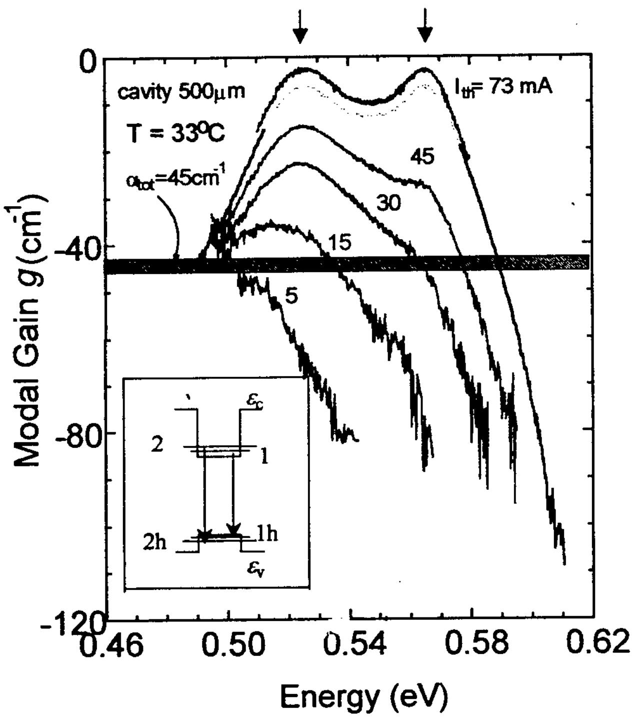

Figure 4. Broad modal gain in wide quantum well ridge-waveguide lasers with high value of total loss. The schematic transitions in a quantum well are shown in the inset.

VII. Supported personnel

G.L.Belenky	- Professor
A.D.Andreev	- Consultant
L.E.Vorobjev	- Consultant
D.V.Donetsky	- Ph.D. Student
L.M.Shterengas	- Ph.D. Student
D.Westerfeld	- Ph.D. Student
A.Gurevich	- Ph.D. Student
S.Anikeev	- Ph.D. Student

VIII. Publications

Papers

1. D.Garbuzov, R.Menna, M.Maiorov, H.Lee, V.Khalfin, L.DiMarco, D.Capewell, R.Martinelli, G.Belenky, and J.Connolly, "2.3-2.7 μm Room Temperature CW-Operation of InGaAsSb/AlGaAsSb Broad-Contact and Single-Mode Ridge-Waveguide SCH-QW Diode Lasers", Part of SPIE Conference on In-Plane Semiconductor Lasers III, *SPIE* Vol.3628, 124-129, 1999.
2. D.V.Donetsky, G.L.Belenky, D.Z.Garbuzov, H.Lee, R.U.Martinelli, G.Taylor, S.Luryi and J.C.Connolly, "Direct measurements of heterobarrier leakage current and modal gain in 2.3 μm double QW p-substrate InGaAsSb/AlGaAsSb broad area lasers", *Electronics Letters*, Vol.35, No4, 298-299, February 1999.
3. A.D.Andreev, D.V.Donetsky, "Analysis of temperature dependence of the threshold current in 2.3 –2.6 μm InGaAsSb/AlGaAsSb quantum-well lasers", *Applied Physis Letters*, Vol.7, No19, 2743-2745, May 1999.
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Waveguide SCH QW Diode Lasers", *IEEE Photonics Technology Letters*, Vol.11, No7, 794-796, July 1999.

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6. D.V.Donetsky, D.Westerfeld, G.L.Belenky, R.U.Martinelli, D.Z.Garbuzov, J.C.Connolly, "Extraordinary wide optical gain spectrum in 2.2-2.5 μm In(Al)GaAsSb/GaSb quantum-well ridge-waveguide lasers", to be published in *J. of Appl.Phys.*, Sept 15, (2001)

Conference Proceedings

1. D. Z. Garbuzov, H. Lee, V. Khalfin, L. A. DiMarco, R. U. Martinelli, R. J. Menna, J. C. Connolly, "2.3-2.7 μm room temperature CW operation of InGaAsSb/AlGaAsSb broaded waveguide SCH QW diode lasers (invited paper), Conference "Photonics West", San Jose, CA, January 27-29, 1999
2. D.V.Donetsky, G.L.Belenky, S.Luryi, D.Z.Garbuzov, H.Lee, R.U.Martinelli, J.C.Connolly, "Current and temperature dependencies of the modal gain in wide aperture 2.3 μm InGaAsSb/AlGaAsSb QW lasers", Conference on Lasers and Electro-Optics, CLEO/QELS'99, Baltimore MA, May 23-28, 1999
3. G.L.Belenky, D.Z.Garbuzov, D.V.Donetsky, H.Lee, R.U.Martinelli, J.C.Connolly, "Gain and optical loss in 2.3-2.5 μm InGaAsSb/AlGaAsSb QW Broad-Area and ridge-waveguide lasers", International Conference on Lasers and Electro-Optics, CLEO/Europe-2000, Nice, France, September 10-15, 2000
4. D.V.Donetsky, D.Westerfeld, G.L.Belenky, R.U.Martinelli, D.Z.Garbuzov, M.Maiorov, J.C.Connolly, "2.2-2.5 μm InGaAsSb/AlGaAsSb QW diode laser with extraordinarily wide ($\Delta\lambda \approx 300$ nm) optical gain spectrum", Conference on Lasers and Electro-Optics CLEO/QELS-2001, Baltimore, May 6-11, 2001

IX. References

1. D.Garbuzov, R.Menna, M.Maiorov, H.Lee, V.Khalfin, L.DiMarco, D.Capewell, R.Martinelli, G.Belenky, and J.Connolly, "2.3-2.7 μm Room Temperature CW-Operation of InGaAsSb/AlGaAsSb Broad-Contact and Single-Mode Ridge-Waveguide SCH-QW Diode Lasers", Part of SPIE Conference on In-Plane Semiconductor Lasers III, *SPIE,* **3628**, 124-129 (1999).
2. G.L.Belenky, R.F.Kazarinov, J.Lopata, S.Luryi, T.Tanbun-Ek, P.A.Garbinski, "Direct measurement of the carrier leakage out of the active region in InGaAsP/InP laser heterostructures" IEEE Trans. on Electron. Dev., **42**, 215 (1995).
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8. H.C.Casey, Jr., M.B.Panish, W.O.Schlosser, T.L.Paoli, "GaAs-$Al_xGa_{1-x}As$ heterostructure laser with separate optical and carrier confinement", *J.Appl.Phys.,* **45** (1), 322-333 (1974).

X. M.S. and Ph.D. thesis preparation and defense

One Ph.D. thesis ("Temperature performance of InP and GaSb based lasers" by D.Donetski, May 2000, available at http://wwwlib.umi.com/cr/sunysb/main) and one M.S. thesis ("Broad optical gain in GaSb-based QW diode lasers" by D.Westerfeld, May 2001) were defended during the Project. Three graduate students (L.Shterengas, S.Anikeev and A.Gurevich) continue to work toward a Ph.D. degree.

XI. Summary

A new approach was employed to the design of mid-infrared lasers based on Type-I In(Al)GaAsSb/GaSb lasers. **GaSb/InGaAsSb/AlGaAsSb diode lasers with room-temperature CW operation covering wavelength range of 2.3-2.7 μm were implemented.** CW output powers of 500, 250 and 160 mW were obtained at room temperature for 100 μm stripe-width lasers emitting at wavelength of 2.3, 2.5 and 2.6 μm respectively (**Figure 5**).

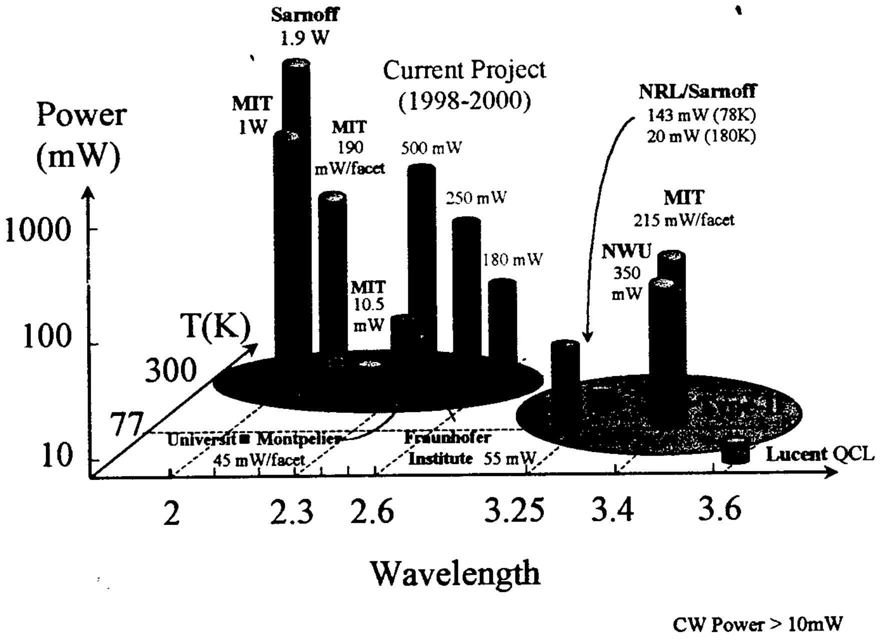

Figure 5. Up-to-date CW performance of mid IR diode lasers with electrical pumping.

Ridge –waveguide lasers were developed and optimized to obtain a single lateral mode CW operation. New experimental methods of device characterization were developed to mid-infrared range devices for the first time.

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13. ABSTRACT *(Maximum 200 words)*

Our project was aimed at finding solutions to one of the urgent problems facing mid-infrared laser development, namely, creating high-efficiency 2.3 um and 3.3 um electrical laser sources operating at room temperature. These lasers are essential for chemical sensing for pollution monitoring, leak detection, chemical process control, countermeasures against heat seeking missiles, IR illumination and can be used to engage terrestrial targets from space.

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