Research Works and Projects

Lehigh MOCVD and NanoPhotonics Group

"Advancing the Physics of Nanotechnology for Energy, Communications, and Biotechnology"

Our research areas cover both the theoretical / computational and experimental aspects of the physics of semiconductor optoelectronics materials and devices & the physics of low-dimensional semiconductor (semiconductor nanostructure). Our research field, which is in the Applied Physics area, utilizes knowledge and ideas derived from fundamental physics to advance the science & technology of semiconductor optoelectronics for engineering applications. The fundamental physics cover knowledge of quantum mechanics, quantum electronics, solid state physics, semiconductor physics, statistical mechanics, and electromagnetic, and we utilize these knowledge to solve problems related to the device physics of semiconductor nanostructures and optoelectronics. The experimental aspects include the material epitaxy with metalorganic chemical vapor deposition (MOCVD) & device fabrications of III-V and III-Nitride compound semiconductor nanostructures and optoelectronics devices. In our laboratory (as part of Center for Optical Technologies), we currently have two MOCVD reactors, with one reactor dedicated for the III-Nitride (GaN-based) optoelectronics and nanostructures research (P-75 reactor) and the other for GaAs / InP-based optoelectronics and nanostructures research (D-125 reactor).

Several focus of our research works are listed below. Our research works on semiconductor nanostructure and optoelectronics primarily focus on applications in the fields of energy (wide bandgap semiconductor for high-efficiency solid state lightings, and high-efficiency solar photovoltaic cells), optical communications (dilute-nitride or InGaAsN QW lasers), free space and NLOS communications (mid-IR lasers and UV LEDs), biological and chemical sensors (mid-IR and UV optoelectronics), and recently also on III-Nitride based dilute-magnetic semiconductors.

On-Going and Current Research Projects / Works

1. **"III-Nitride Semiconductor Optoelectronics Materials and Devices"**
   "Physics, Devices, and MOCVD Epitaxy of III-Nitride Semiconductor Nanostructures for High-Efficiency Solid State Lightings and Solar Photovoltaic Cells Applications "

- ***Polarization Engineering with Novel Type-II InGaN-GaNAs Quantum Well Gain Media for Efficient Visible LEDs and Lasers***

  Though blue InGaN-GaN quantum well (QW) light emitting diodes (LEDs) and lasers have been demonstrated with good performance, extending the emission wavelength by solely increasing the In-content in the InGaN QW for green and yellow lasers has been challenging. The longest emission wavelength reported utilizing InGaN QW lasers is at 482-nm (green-blue). As the In-content in the InGaN QW is increased, phase separations and higher defect density lead to reduction in internal radiative efficiency. The polarization field also significantly reduces the electron-hole wavefunctions overlap of InGaN QW to 25-30% for 500-550 nm regime, resulting in low optical gain in this regime.

  In this work, we present and analyze a new nitride-based gain media of InGaN-GaNAs type-II QW on GaN for lasers and LEDs. We found that this new gain media offers wide emission wavelength coverage, from blue (~450 nm) to yellow-green (~550 nm), with low In-content and dilute As-content (<6-8%). The type II alignment and polarization fields in the InGaN-GaNAs-InGaN QW structures allows wavelength extension, while maintaining significantly larger wavefunctions overlap (65-70%) in comparison to that (25-30%) of the conventional InGaN QW. The increase in the wavefunctions overlaps in the type-II InGaN-GaNAs QW results in increased optical gain of up to 8 times for the optimized QW structure emitting at 530-nm, in comparison to that of the conventional InGaN QW approach. Optimization for the type-II approach emitting from 450-550 nm were conducted. This novel type-II InGaN-GaNAs QW should potentially allow the realization of green and yellow lasers on GaN.

  <u>Selected Relevant Publications:</u>

1. R. A. Arif, Y. K. Ee, and **N. Tansu**, "Type-II 450-550 nm InGaN-GaNAs Quantum Well Lasers and Light Emitters Active Region on GaN," in Proc. of the SPIE Photonics West 2006, Physics and Simulation of Optoelectronics Devices XIII, San Jose, CA, Jan 2006.

2. R. A. Arif, Y. K. Ee, and **N. Tansu**, "Polarization Field Engineering with Type-II InGaN-GaNAs Quantum Well for Improved Nitride Gain Media at 420-550 nm," in *Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2006*, Long Beach, CA, May 2006.
3. R. A. Arif, Y. K. Ee, and **N. Tansu**, "Nitride-Based Type-II InGaN-GaNAs 'W' Quantum Well Gain Media at 420-550 nm," in *Proc. of the TMS Electronics Material Conference (EMC) 2006,* State College, PA, June 2006.

- ***Nanostructure Engineering of the InGaN Quantum Wells for Improved Radiative Recombination Rate and Optical Gain for High-Efficiency LEDs and Lasers***

In our research group at Lehigh, we focused on the nanostructure engineering of InGaN QWs active regions for enhancing the radiative recombination rate and optical gain. By using a novel QW design, significant enhancement of the radiative efficiency of the QWs active media and InGaN QW LEDs were observed. Both the theoretical and experimental studies showed excellent agreement, with the leading to significant enhancement of radiative recombination rate (by almost a factor of ~4), as well as significant improvement of luminescence and LEDs output power by > ~4 times (almost up to 10 times). The advantages of the InGaN QW LEDs employing this concept was demonstrated experimentally emitting from 420-500 nm, but the same idea can also be applied for achieving high-efficiency nitride-based LEDs emitting in the yellow and red regimes as well (applicable for high-efficiency solid state lightings).

Selected Relevant Publications:

1. R. A. Arif, Y. K. Ee, and **N. Tansu**, "Enhancement of Radiative Efficiency of Nitride-Based LEDs via Nanostructure Engineering of InGaN Quantum Wells Emitting at 420-500 nm," in Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2007, Baltimore, MD, May 2007 (submitted).

- ***MOCVD Epitaxy and Optical Properties of Self-Assembled InGaN and InN Quantum Dots via Stranski-Kastranow Growth Mode***

In our research group at Lehigh, we investigated the epitaxy and optical properties of self-assembled InGaN quantum dots (with In-content > ~35%) grown by MOCVD via Stranski-Kastranow growth mode, emitting in the 520-nm regime (green emission). The atomic arrangement for the S-K growth mode with lowest surface strain energy results in 1) self-assembled InGaN QDs 3-D nanostructure, and 2) a thin (1-2 MLs) InGaN wetting layer underneath the QDs. MOCVD epitaxy of self-assembled $In_{0.35}Ga_{0.65}N$ QDs (λ~520-nm) on GaN via Stranski-Kastranow growth mode had been realized in our lab at Lehigh. From the AFM studies, the density and dimensions of the S-K $In_{0.35}Ga_{0.65}N$ QDs were measured as ~ 4 x 10^9 cm^{-2} and 40nm x 40nm x 4nm, respectively. PL measurements of $In_{0.35}Ga_{0.65}N$ QDs indicated λ_{peak} of ~520-nm, with inhomogeneously-broadened FWHM of 56.6–69.6 nm. Further optimization to achieve InGaN QDs with higher QD density and higher In-content for device implementation will be conducted. Preliminary results on the InN QDs have also been achieved.

Selected Relevant Publications:

1. Y. K. Ee, R. A. Arif, M. Jamil, and **N. Tansu**, "MOCVD Epitaxy and Optical Properties of Self-Assembled InGaN Quantum Dots via Stranski-Kastranow Growth Mode Emitting at 520-nm," in Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2007, Baltimore, MD, May 2007 (submitted).

- ***Novel Approach for Enhancement of Light Extraction Efficiency of III-Nitride LEDs***

High-efficiency InGaN quantum well (QW) light-emitting diodes (LEDs) play an important role for solid state lightings. The total internal reflection on the GaN / air interface results in narrow escape cone probability of only ~4 % from top surface of the LEDs device. Several approaches had been proposed with their respective advantages and limitations, but primarily the high cost (with e-beam lithography) and low yield are the two main limitations of the existing approaches.

In our research group at Lehigh (collaboration of Tansu's and Gilchrist's groups), we pursue a novel approach to improve the light extraction efficiency of InGaN quantum wells light emitting diodes (LEDs). The novel device implementation has led to significant improvement up to ~232% increase of the LEDs output power. This approach also leads to a low-cost and straight-forward solution to improve the light extraction efficiency of LEDs, without using the costly e-beam lithography process. Improvement in the integrated luminescence of the LEDs with this approach is observed (almost >~330% improvement), and the InGaN QW LEDs devices utilizing this novel approach also exhibited increase in maximum output power (almost > ~ 230 % improvement). The concept was utilized in the InGaN QW LEDs emitting from 420-nm up to 480-nm, but this device design concept is also applicable for nitride-based LEDs emitting in the 500-650 nm (applicable for solid state lightings).

Selected Relevant Publications:

1. Y. K. Ee, P. Kumnorkaew, R. A. Arif, J. F. Gilchrist, and **N. Tansu**, in *Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2007*, Baltimore, MD, May 2007 (submitted).
2. H. Tong, B. R. Davis, S. J. Millman, and **N. Tansu**, in progress.

- ***Nanoheteropitaxy of III-Nitride (AlGaN and GaN) Semiconductors on Nano-Patterned Sapphire Substrate***

High quality AlGaN quantum well are important for gain media of a low-cost and compact UV (λ~280-350 nm) light source (LEDs or lasers), which will lead to a low-cost and compact Anthrax bioagent countermeasure system. Semiconductor-based UV LEDs for biosensors have the advantages of compactness, low cost, high-volume production, and low power consumption. The proposed low-cost and compact sensors can then be effectively integrated for rapid deployment by soldiers in the battlefield, as well as for usage in civilian populations.

In our process, the MOCVD growth of the AlGaN and GaN material systems are conducted on the novel nano-patterned grooves formed on the surface of a sapphire substrate (in collaboration with Prof. H. M. Chan's and Prof. R. P. Vinci's group) via a novel AGOG process. By utilizing the In-containing alloys (InAlGaN) as the quantum well gain media, the threading dislocation is expected to reduce, which in turn should lead to improved efficiency of the UV LEDs/lasers. In addition to pursuing the high-performance AlGaN-based UV LEDs/laser on AGOG substrate, we also will investigate and improve understanding of the physical phenomena responsible for the reduction in the quantum efficiency of the AlGaN UV LEDs (in collaboration with Prof. V. Dierolf, Prof. S. Cargill, and Dr. M. Wrabak).

Selected Relevant Publications:

1. H. Li, J. T. Perkins, H. M. Chan, R. P. Vinci, Y. K. Ee, R. A. Arif, R. S. Tummidi, J. Li, and **N. Tansu**, "Nanopatterning of Sapphire for GaN Heteroepitaxy by Metalorganic Chemical Vapor Deposition," in *Proc. of the MRS Fall Meeting 2006: Symposium I: Advances in III-V Nitride Semiconductor Materials and Devices*, Boston, MA, USA, November-December 2006.

- ***MOCVD-grown of InN Semiconductor for High-Efficiency Solar Photovoltaic Cells on Sapphire and Silicon Substrates***

Recently, it has been discovered that the bandgap of InN was at about ~0.65-0.7 eV. The small bandgap of InN materials corresponds to long absorption cut off wavelength at ~1850 nm, which is applicable for covering the solar spectrum up to ~1850 nm regime. In particular, the availability of high-quality InN materials allows the additional coverage of solar spectrum in the ~1400-1850 nm regimes. Tandem solar cells can be implemented in the III-Nitride semiconductor material systems, to realize nitride-based monolithic high-efficiency solar cells with full spectrum utilization. As GaN has an energy bandgap of 3.4 eV, the solar spectrum from 280-nm up to 360-nm can be covered by the GaN-based solar cell. By engineering the InGaN alloys from low In-content (~33%) InGaN up to InN alloy, the solar spectrum from deep UV regime (~280-nm) up to ~1800-nm can be covered by varying the In-composition in the multiple junction cell. The ability of InGaN alloy in covering almost all the solar spectrum makes this alloy ($In_xGa_{1-x}N$) an excellent material candidate for making full spectrum high-efficiency solar cells.

In our research group at Lehigh, we pursue the MOCVD epitaxy of the InN materials for high-efficiency solar photovoltaic applications. The MOCVD epitaxy of the InN materials was pursued on both sapphire substrates and Silicon substrates. Replacing the conventional multijunction solar cell material by III-nitrides grown on sapphire or Silicon, not only reduces the cost but also make the design and production more flexible because the bandgap can be fine-tuned by merely varying Ga/In ratio. Thus, successful MOCVD epitaxy of high-quality $In_xGa_{1-x}N$ materials with high In-content (>37%

up to 100%) have strong impact for the realization of low-cost high-efficiency solar cells as competitive alternative for electrical energy generation.

Selected Relevant Publications:

1. M. Jamil, Y. K. Ee, R. A. Arif, H. Tong, and **N. Tansu**, "Study of Nucleation and Growth Modes of InN films by MOCVD on Sapphire Substrate for Photovoltaic Applications," in *Proc. of the MRS Spring 2007: Symposium Y: Thin-Film Compound Semiconductor Photovoltaics*, San Francisco, CA, USA, April 2007 (submitted).

- ***MOCVD-grown of Crack-Free GaN Semiconductors on Silicon Substrates***

Silicon-based technology is a mature technology, and the Si substrates are widely available with very low cost. The availability of large area Silicon substrate will also be a suitable for enabling the hetero-epitaxy of III-V or III-Nitride semiconductor on low-cost substrates.

In our research group at Lehigh, we pursue the MOCVD epitaxy of III-Nitride semiconductor (in particular GaN, AlGaN, and InN) on Silicon substrates. The epitaxy of GaN and AlGaN semiconductor on Si is challenging due to the large lattice mismatch and large thermal expansion coefficient of the III-Nitride semiconductor and Si substrates, thus resulting in cracking on the III-Nitride film grown on Silicon substrates. By utilizing novel buffer layer grown in situ in MOCVD reactor, the cracking issue can be suppressed, thus resulting in crack-free GaN film on Si substrates. Our research goal is to pursue the optimization of the buffer layers, as well as the III-Nitride optoelectronics device implementation on Si substrates.

Selected Relevant Publications:

1. M. Jamil, H. Tong, Y. K. Ee, R. A. Arif, and **N. Tansu**, in progress.

- ***MOCVD-grown Ultraviolet AlGaN-Based Photodetectors and LEDs***

Semiconductor LEDs and photodetectors emitting in the UV and deep-UV regimes have tremendous applications for biological sensing, non line of sight (NLOS) communications, and water purification. In our group at Lehigh, we pursue the MOCVD epitaxy ande devices of high-performance AlGaN-based UV and deep-UV LEDs and photodetectors. The emphasis on the UV photodetectors is to realize high responsivity, high speed AlGaN-based photodetectors, applicable for NLOS communications. The UV LEDs are also pursued with the goal of achieving high efficiency and high output power devices.

Selected Relevant Publications:

1. H. Tong, M. Jamil, and **N. Tansu**, in progress.

2. "Computational Physics of Semiconductor Nanostructure Gain Media Optoelectronics"

"Computational Physics of Semiconductor Nanostructure Gain Media for Improved Understanding and Optimizing the Experimental Aspects of Optoelectronics Devices "

- ***Computational Physics of Semiconductor Nanostructure Gain Media***

Computational tools are developed for analyzing complex type-II quantum well structures, polar quantum wells, interdiffused quantum well, and intersubband quantum wells. Computation tools for dilute-nitride and Sb-based semiconductor nanostructures are also developed. These computation tools allow one to improve the physical understanding, to design and predict experiments, and to optimize the gain media structure for realizing high performance optoelectronics devices.

As semiconductor devices become ever smaller, such as quantum dots, there is also a need to have a flexible method to determine the eigenvalues and eigenfunctions of these structures. Solving them analytically is exhaustive and inefficient. To accomplish an efficient method for solving problems related to 3-D semiconductor nanostructure, one can apply various computational approaches. An interesting method to accomplish this is to solve the Schrödinger's wave equation using the finite-difference time-domain (FDTD) method. This method is capable of simulating nearly any structure within the limits of discretization. No approximations are made except for the finite differencing of the derivatives for implementation into computer simulations. As FDTD is a time-domain technique which finds the wave function everywhere in the computational domain, this allow one to track the time evolution of the wave function up to the steady state condition.

Selected Relevant Publications:

1. **N. Tansu**, and L. J. Mawst, "Design Analysis of 1550-nm GaAsSb-(In)GaAsN Type-II Quantum Well Laser Active Regions," IEEE J. Quantum Electron., vol. 39(10), pp. 1205-1210, October 2003.
2. I. Vurgaftman, J. R. Meyer, **N. Tansu** and L. J. Mawst, "(In)GaAsN-GaAsSb Type-II "W" Quantum-Well Lasers for Emission at λ=1.55 μm," in Appl. Phys. Lett., vol. 83(14), pp.2742-2744, October 2003.
3. I. Vurgaftman, J. R. Meyer, **N. Tansu**, and L. J. Mawst, "InP-Based Dilute-Nitride Mid-Infrared Type-II "W" Quantum-Well Lasers," J. Appl. Phys., vol. 96(8), pp. 4653-4655, October 2004.
4. R. A. Arif, and **N. Tansu**, "Interdiffused InGaAsSbN Quantum Wells on GaAs for 1300-1550 nm Lasers," in Proc. of the SPIE Photonics West 2005, Physics and Simulation of Optoelectronics Devices XIII, San Jose, CA, Jan 2005.
5. R. A. Arif, and **N. Tansu**, "Interdiffused SbN-Based Quantum Wells on GaAs for 1300-1550 nm Lasers," in Proc. of the MRS Fall Meeting 2005: Symposium EE: Progress in Semiconductor Materials V—Novel Materials and Electronic and Optoelectronic Applications, Boston, MA, USA, November-December 2005.
6. R. A. Arif, Y. K. Ee, and **N. Tansu**, "Type-II 450-550 nm InGaN-GaNAs Quantum Well Lasers and Light Emitters Active Region on GaN," in Proc. of the SPIE Photonics West 2006, Physics and Simulation of Optoelectronics Devices XIII, San Jose, CA, Jan 2006.
7. R. S. Tummidi, R. A. Arif, Y. K. Ee, and **N. Tansu**, "Design Analysis of Lattice-Matched AlInGaN-GaN Quantum Wells for Optimized Intersubband Absorption in the Mid-IR Regime," in Proc. of the SPIE Photonics West 2007, Physics and Simulation of Optoelectronics Devices XV, San Jose, CA, Jan 2007 (accepted).
8. Y. K. Ee, Y. P. Gupta, R. A. Arif, and **N. Tansu**, "Quantum 3-D Finite-Difference-Time-Domain (FDTD) Analysis of InGaAs-GaAsP and InN-GaN Quantum Dots Nanostructures," in Proc. of the SPIE Photonics West 2007, Physics and Simulation of Optoelectronics Devices XV, San Jose, CA, Jan 2007 (accepted).

3. "Surface Plasmon-Based III-Nitride Optoelectronics" (*New Project*)

- ***Device Physics and Fabrication of Plasmonic III-Nitride LEDs and Detectors***

4. "III-Nitride Dilute Magnetic Semiconductors" (*New Project*)

- ***MOCVD Epitaxy and Devices of III-Nitride Based Dilute Magnetic Semiconductors***

Other Recent / Past Research Projects / Works

5. "Dilute Nitride Semiconductor Lasers"

"Physics, Devices, and MOCVD Epitaxy of Novel Dilute-Nitride Semiconductor Nanostructure Gain Media for High-Performance Near-Infrared and Mid-Infrared Lasers"

- ***Strain-Compensated InGaAsN Quantum Well Lasers Emitting at Near Infrared (1200-nm up to 1400 nm) by Metalorganic Chemical Vapor Deposition***

Our novel approach of strain-compensated InGaAsN QW is by utilizing a compressively-strained InGaAsN QW sandwiched by tensile GaAsP barriers to achieve 1) strain-compensation and 2) strong electron and hole confinements. This approach has resulted in very low (best reported) threshold current density of 1300-nm InGaAsN QW lasers under continuous-wave (CW) operation at room temperature up to elevated temperature of 100 ^{0}C. This approach also resulted in the first InGaAsN QW lasers, grown by MOCVD, with lower (or better) threshold current density than the previous-record devices grown by MBE. Threshold current densities of only 200-210 A/cm^2 were realized for our strain-compensated 1280-1320 nm InGaAsN QW lasers. Threshold current densities of only 65-90 A/cm^2 and 450-540 A/cm^2 were also achieved for 1170-1233 nm InGaAs QW and 1370-nm InGaAsN QW lasers on GaAs, respectively. These record-low threshold MOCVD-grown InGaAsN QW lasers were realized by a combination of both the understanding of the device physics and MOCVD material development of dilute-nitride semiconductor QW in laser devices.

In addition to the pursuit of high-performance MOCVD-grown InGaAsN QW lasers, we have also analyzed the fundamental device physics on the temperature characteristics, high-temperature behaviors, and the current injection efficiency of 1300-nm InGaAsN QW lasers. Our studies indicate heavy hole leakages and temperature sensitivity of material gain for dilute-nitride laser are the dominant factors that limit its high-temperature performance. The heavy hole leakages phenomena in InGaAsN QW lasers are confirmed by their theoretical and experimental works. By suppressing the heavy hole leakage in InGaAsN QW (utilizing higher bandgap GaAsP barriers), significant reduction in threshold current density and increase in the differential efficiency of the InGaAsN QW lasers are achieved at high-temperature operation. As a result of reduced heavy hole escape rate, InGaAsN lasers with higher bandgap barriers also showed reduction in the temperature sensitivities of both the threshold current density and slope efficiencies. Utilizing our strain-compensated InGaAsN QW with larger bandgap barrier of GaAsP, high performance 1300-nm InGaAsN QW lasers were realized with very low threshold current density of only 360-400 A/cm^2 operating at temperatures of 90-100 ^{0}C.

<u>Selected Relevant Publications:</u>

1. (Invited Review Paper) **N. Tansu**, J. Y. Yeh, and L. J. Mawst, "Physics and Characteristics of 1200-nm InGaAs and 1300-1400 nm InGaAsN Quantum-Well Lasers by Metalorganic Chemical Vapor Deposition," IOP Journal of Physics: Condensed Matter Physics, vol. 16 (31), pp. S3277-S3318, August 2004.
2. **N. Tansu**, and L. J. Mawst, "Current Injection Efficiency of 1300-nm InGaAsN Quantum-Well Lasers," J. Appl. Phys., vol. 97(5), Art. No. 054502, March 2005.
3. **N. Tansu**, J. Y. Yeh, and L. J. Mawst, "Experimental Evidence of Carrier Leakage in InGaAsN Quantum Well Lasers," Appl. Phys. Lett., vol. 83(11), pp. 2112-2114, September 2003.
4. **N. Tansu**, J. Y. Yeh, and L. J. Mawst, "Low-Threshold 1317-nm InGaAsN Quantum Well Lasers with GaAsN Barriers," Appl. Phys. Lett., vol. 83(13), pp. 2512-2514, September 2003.
5. **N. Tansu**, N. J. Kirsch, and L. J. Mawst, "Low-Threshold-Current-Density 1300-nm Dilute-Nitride Quantum Well Lasers," Appl. Phys. Lett., Vol.81(14), pp. 2523-2525, September 2002.

<u>Relevant US Patents:</u>

1. Luke J. Mawst, **Nelson Tansu**, and Jeng-Ya Yeh, Novel techniques on dilute-nitride semiconductor for long wavelength lasers on GaAs. (US-Patent pending).

- ***Type-II GaAsSb-(In)GaAsN Quantum Well Lasers on GaAs***

Though high-performance 1300-nm InGaAsN-QW lasers on GaAs have been realized, low-threshold 1550-nm InGaAsN QW lasers have yet to be realized. To extend the emission wavelength of the gain media for lasers on GaAs substrate into 1550-nm wavelength regime, we proposed a novel approach based on GaAsSb-(In)GaAsN type-II quantum well gain media on GaAs. In this structure, the electron-wells consist of (In)GaAsN layers and the hole-well consist of GaAsSb layer. This approach is an <u>*original and novel method*</u> to realize high-performance lasers emitting at wavelength of 1550-nm on a GaAs substrate. Strain-compensated structures with compressively-strained GaAsSb and tensile-strained GaAsN also allow the growth of multiple QW stages to achieve the necessary optical gain for lasers.

Material optical gain as a function of radiative current density at 300 K for optimized 1550-nm lasers based on GaAsSb-(In)GaAsN type-II QWs have been analyzed by us, in collaboration with NRL and UW-Madison. Energy dispersion, wavefunctions, and optical matrix elements were calculated using 10-band ***k·p*** formalism, with band anti-crossing model employed to take into account the N-like band in the dilute-nitride layers. Our recent experimental work has also resulted in the <u>*first experimental realization*</u> of this novel dilute-nitride type-II QW gain media grown on GaAs substrate emitting with peak luminescence wavelength at 1600-nm. The envisioned GaAsSb-(In)GaAsN type-II QW edge-emitters and VCSELs are expected to be a competitive alternative approach to achieve a high-performance GaAs-based 1550-nm diode lasers.

<u>Selected Relevant Publications:</u>

1. **N. Tansu**, and L. J. Mawst, "Design Analysis of 1550-nm GaAsSb-(In)GaAsN Type-II Quantum Well Laser Active Regions," IEEE J. Quantum Electron., vol. 39(10), pp. 1205-1210, October 2003. This paper presents the first and original proposal of novel approach to reach emission wavelength at 1550-nm on a GaAs substrate.

2. I. Vurgaftman, J. R. Meyer, **N. Tansu** and L. J. Mawst, "(In)GaAsN-GaAsSb Type-II "W" Quantum-Well Lasers for Emission at λ=1.55 μm," in Appl. Phys. Lett., vol. 83(14), pp.2742-2744, October 2003.
3. **N. Tansu**, L. J. Mawst, I. Vurgaftman, and J. Meyer, "GaAsSb-(In)GaAsN Type-II Quantum-Wells Lasers," in Proc. of the 16th IEEE Laser and Electro-Optics Society (LEOS) Annual Meeting 2003, Tuczon, AZ, October-November 2003.
4. (Invited Conference Paper) J. R. Meyer, I. Vurgaftman, **N. Tansu**, and L. J. Mawst, "Dilute-Nitride Type-II 'W' Quantum Well Lasers for the Near-IR and Mid-IR," in Proc. of the SPIE Photonics West 2005, Novel In-Plane Semiconductor Lasers 2005, San Jose, CA, Jan 2005.
5. J. Y. Yeh, A. A. Khandekar, B. E. Hawkins, T. F. Kuech, L. J. Mawst, J. R. Meyer, I. Vurgaftman, and **N. Tansu**, "Long Wavelength Emission from InGaAsN/GaAsSb Type-II 'W' Quantum Wells," in Proc. of the 12th Biennial Workshop on Organometallic Vapor Phase Epitaxy (OMVPE) 2003, Big Sky Resort, Montana, July 2005.
6. A. Khandekar, B. E. Hawkins, T. F. Kuech, J. Y. Yeh, L. J. Mawst, J. R. Meyer, and I. Vurgaftman, and **N. Tansu**, "Characteristics of GaAsN/GaAsSb type-II Quantum Wells on GaAs substrates grown by Metalorganic Chemical Vapor Deposition," J. Appl. Phys. , vol. 98(12), Art. No. 123525, December 2005.
7. J. Y. Yeh, L. J. Mawst, A. A. Khandekar, T. F. Kuech, J. R. Meyer, and I. Vurgaftman, and **N. Tansu**, "Long Wavelength Emission of InGaAsN/GaAsSb Type-II "W" Quantum Wells," Appl. Phys. Lett., vol. 88(5), Art. No. 051115, January 2006.

<u>Relevant US Patents:</u>

1. **Nelson Tansu,** and Luke J. Mawst, "Type-II Quantum Well Optoelectronics Devices," *Novel techniques to achieve* 1500-*3000 nm wavelength emission on GaAs*", **US Patent No. 6,791,104**; approved on September 14th 2004 (filed on September 26th 2002).

- ***Dilute-Nitride Type-II "W" Quantum Well Lasers on InP***

In collaboration with NRL and the UW-Madison, we have also proposed to extend the technology of dilute-nitride type-II *"W"* quantum well gain media for 3-5 μm mid-infrared laser application on InP substrate. Previously, the <u>interband</u> lasers to achieve mid-infrared range (3-5 μm) can only be achievable utilizing the quantum well structure grown on GaSb substrate. The <u>*original and novel approach*</u> is to utilize the GaAsSb-InGaAsN type-II quantum well gain media grown on InP, which should allow the realization of mid-infrared (3-5 μm) lasers on the more-conventional InP substrate. This work potentially should allow the realization of mid-infrared <u>interband</u> semiconductor lasers on conventional substrate capable of operating at room-temperature under continuous-wave operation.

<u>Selected Relevant Publications:</u>

1. I. Vurgaftman, J. R. Meyer, L. J. Mawst, and **N. Tansu**, "Dilute-Nitride Mid-Infrared Type-II 'W' Quantum-Well Lasers on InP Substrates", in Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2004, San Francisco, CA, May 2004.
2. I. Vurgaftman, J. R. Meyer, **N. Tansu**, and L. J. Mawst, "InP-Based Dilute-Nitride Mid-Infrared Type-II "W" Quantum-Well Lasers," J. Appl. Phys., vol. 96(8), pp. 4653-4655, October 2004.
3. (Invited Conference Paper) J. R. Meyer, I. Vurgaftman, **N. Tansu**, and L. J. Mawst, "Dilute-Nitride Type-II 'W' Quantum Well Lasers for the Near-IR and Mid-IR," in Proc. of the SPIE Photonics West 2005, Novel In-Plane Semiconductor Lasers 2005, San Jose, CA, Jan 2005.

<u>Relevant US Patents:</u>

1. Luke J. Mawst, **Nelson Tansu**, Igor Vurgaftman, and Jerry R. Meyer, "Type-II Quantum Well Mid-Infrared Optoelectronic Devices" *Novel techniques to achieve 3000-5000 nm wavelength emission. Lasers*, **US Patent Application No. 20050173694** (<u>US Patent Pending</u>).

- ***Interdiffused InGaAsSbN Quantum Well for 1300-1550 nm Lasers***

InGaAsSbN QW grown by molecular beam epitaxy (MBE) is a very promising approach to realize type-I quantum well on GaAs substrate for achieving diode lasers emitting at 1550-nm, with very promising results produced by Prof. Jim Harris' group at Stanford. Nonetheless, the pursuit of

InGaAsSbN material systems growth by MOCVD is still immature, due to the challenges in incorporating both Sb- and dilute-N-species into InGaAs material systems simultaneously under optimum MOCVD growth conditions.

He we proposed a novel approach to realize interdiffused InGaAsSbN QW lasers on GaAs for 1550-nm emission wavelength, utilizing a combination of MOCVD epitaxy and interdiffusion process. In our approach, we propose to combine the already-established MOCVD growth technique of InGaAsN and InGaAsSb QWs, with a post-growth annealing that leads to interdiffusion of Sb and N-species. As the InGaAsN and InGaAsSb are grown in separate layers, optimization of their individual MOCVD growth parameters can be achieved independently. From their studies, this combined MOCVD + interdiffusion method should allow realization of InGaAsSbN QW active region with emission wavelength in the 1300-1550-nm regime without having to grow the quinary compound epitaxially by MOCVD. The Sb-N interdiffusion process is feasible for achieving SbN-based quantum well gain media, due to the large disparity of the Sb-N diffusion constants. Both the numerical and experimental works on the interdiffused InGaAsSbN QW have indicated the feasibility of realizing interdiffused InGaAsSbN QW.

Selected Relevant Publications:

1. R. A. Arif, and **N. Tansu**, “Interdiffused InGaAsSbN Quantum Wells on GaAs for 1300-1550 nm Lasers,” in Proc. of the *SPIE Photonics West 2005*, *Physics and Simulation of Optoelectronics Devices XIII*, San Jose, CA, Jan 2005.
2. R. A. Arif, and **N. Tansu**, “Interdiffused SbN-Based Quantum Wells on GaAs for 1300-1550 nm Lasers: Theory and Experiments,” in *IEEE Semiconductor Lasers Workshop 2005*, Baltimore, MD, May 2005.
3. R. A. Arif, and **N. Tansu**, “Interdiffused SbN-Based Quantum Wells on GaAs for 1300-1550 nm Lasers,” in *Proc. of the MRS Fall Meeting 2005: Symposium EE: Progress in Semiconductor Materials V—Novel Materials and Electronic and Optoelectronic Applications*, Boston, MA, USA, November-December 2005.

6. “Device Physics of Semiconductor Nanostructure Gain Media Optoelectronics”

- ***Temperature Characteristics of Quantum Well Lasers***

In the temperature characteristics studies of quantum well lasers, we develop a new method to analyze and elucidate the understanding of the contributing factors that affects the figures of merits characterizing the temperature sensitivity of the threshold current density (J_{th}) and external differential quantum efficiency (η_d). The T_0 and T_1 can be expressed as functions of the temperature dependence of the physical device parameters, which include transparency current density, current injection efficiency, material gain parameters, and internal loss. The characteristic temperature coefficients for each device parameter are determined from the measured device performance as a function of cavity length and temperature. The expression of T_o and T_1 can be expressed as functions of their physical parameters in a limited temperature regime. By analyzing the measured values of the physical parameters independently, important insights into the mechanisms affecting the temperature behavior of the lasers can be achieved. In our studies, we have applied the detailed theory and analysis on the InGaAsN QW lasers emitting at the 1300-nm and 1360-nm wavelength regime.

Selected Relevant Publications:

1. **N. Tansu**, Y. L. Chang, T. Takeuchi, D. P. Bour, S. W. Corzine, M. R. T. Tan, and L. J. Mawst, “Temperature Analysis and Characteristics of Highly-Strained InGaAs(N)-GaAs-InGaP (λ> 1.17 μm) Quantum Well Lasers,” IEEE J. Quantum Electron., Vol.38(6), pp. 640-651, June 2002.
2. **N. Tansu**, and L. J. Mawst, “Temperature Sensitivity of 1300-nm InGaAsN Quantum-Well Lasers,” IEEE Photon. Technol. Lett., Vol.14(8), pp. 1052-1054, August 2002.
3. J. Y. Yeh, **N. Tansu**, and L. J. Mawst, “Temperature Sensitivity of 1360-nm Dilute-Nitride Quantum Well Lasers,” IEEE Photon. Technol. Lett., vol.16(3), pp. 741-743, March 2004.

- ***Carrier Transport and Current Injection Efficiency of Quantum Well Lasers***

In our studies, we developed a detailed analysis of the below-threshold, at-threshold, and above-threshold current injection efficiency of single quantum well lasers, taking into account the recombination in the QW, recombination in the barriers (SCH), carrier transport and capture effect, and thermionic carrier escape effects. We find that the higher temperature sensitivity of the current injection efficiency for InGaAsN QW lasers can be understood from an increase in heavy-hole-leakage, due to the smaller hole-confinement in the InGaAsN QW lasers. By understanding the performance limitation of the InGaAsN QW lasers at high temperature, we are able to design structures with significantly increased hole confinement by surrounding the quantum well with GaAsP barriers. This improved structure of InGaAsN QW lasers with large bandgap GaAsP barriers allows suppression the thermionic hole leakage, resulting in very low threshold current density at elevated temperature. Utilizing GaAsP barriers in InGaAsN QW lasers also leads to the realization of InGaAsN QW lasers with temperature-insensitive slope efficiency at elevated temperature, confirming the predictions of our model.

Selected Relevant Publications:

1. **N. Tansu**, and L. J. Mawst, "The Role of Hole-Leakage in 1300-nm InGaAsN Quantum Well Lasers," Appl. Phys. Lett., Vol.82(10), pp. 1500-1502, March 2003.
2. **N. Tansu**, J. Y. Yeh, and L. J. Mawst, "Experimental Evidence of Carrier Leakage in InGaAsN Quantum Well Lasers," Appl. Phys. Lett., vol. 83(11), pp. 2112-2114, September 2003.
3. **N. Tansu**, and L. J. Mawst, "Current Injection Efficiency of 1300-nm InGaAsN Quantum-Well Lasers," J. Appl. Phys., vol. 97(5), Art. No. 054502, March 2005. This paper presents the detailed analysis of the current injection efficiency in 1300-nm InGaAsN QW lasers, and its implication to the lasing characteristics. The analysis presented here can be applied in general to any QW lasers.
4. J. Y. Yeh, L. J. Mawst, and **N. Tansu**, "The Role of Carrier Transport on the Current Injection Efficiency of InGaAsN Quantum-Well Lasers," IEEE Photon. Technol. Lett., vol. 17(9), pp. 1779-1881, September 2005.

- ***Physics of Optical Gain, Recombination Mechanisms, and Dynamics of Quantum Well Lasers***

To better understand the physics of the gain media, we have also conducted various measurements to understand the recombination mechanisms in the quantum well. The measurements include the optical gain measurements, true spontaneous emission measurements, and the high-frequency optical / electrical modulation of the QW gain media. These studies are conducted together with UW-Madison, Cardiff University, SUNY-Stony Brook, Colorado State University, and Marburg University. The studies are mainly conducted on the MOCVD-grown InGaAs QW and InGaAsN QW lasers on GaAs, emitting at 1200-nm and 1300-nm, respectively.

Selected Relevant Publications:

1. D. J. Palmer, P. M. Smowton, P. Blood, J. Y. Yeh, L. J. Mawst, and **N. Tansu**, "Effect of Nitrogen on Gain and Efficiency in InGaAsN Quantum Well Lasers", *Appl. Phys. Lett.,* vol. 86 (7), Art. No. 071121, February 2005.
2. Anton, D. Patel, C. S. Menoni, J. Y. Yeh, L. J. Mawst, J. M. Pikal, and **N. Tansu,** "Increased Monomolecular Recombination in MOCVD Grown 1.3-µm InGaAsN–GaAsP–GaAs QW Lasers From Carrier Lifetime Measurements," *IEEE Photon. Technol. Lett.*, Vol 17 (5), pp. 954-955, May 2005.
3. Thranhardt, I. Kuznetsova, C. Schlichenmaier, S. W. Koch, L. Shterengas, G. Belenky, J. Y. Yeh, L. J. Mawst, **N. Tansu**, J. Hader, J. V. Moloney, and W. W. Chow*,* "Nitrogen Incorporation Effects on Gain Properties in GaInNAs Lasers: Experiment and Theory," *Appl. Phys. Lett.* vol. 86, May 2005.
4. L. Shterengas, G. Belenky, J. Y. Yeh, L. J. Mawst, and **N. Tansu***,* "Differential Gain and Linewidth-Enhancement Factor in Dilute-Nitride GaAs-based 1.3µm Diode Lasers," *IEEE J. Select. Topics. in Quantum Electron,* vol. 11(5), pp. 1063-1068, September-October 2005.
5. Anton, D. Patel, C. S. Menoni, J. Y. Yeh, T. T. Van Roy, L. J. Mawst, J. M. Pikal, and **N. Tansu**, "Frequency Response of Strain-Compensated InGaAsN/GaAsP/GaAs SQW Lasers," *IEEE J. Select. Topics. in Quantum Electron,* vol. 11(5), pp. 1079-1088, September-October 2005.

6. L. Xu, D. Patel, C. S. Menoni, J. Y. Yeh, L. J. Mawst, and **N. Tansu**, "Optical Determination of Electron Effective-Mass of Strain Compensated $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ / GaAs Single Quantum Well," *Appl. Phys. Lett.*, vol. 89, Art. 171112, October 2006.

- ***Interdiffused InGaAsP Quantum Dots Lasers on GaAs by Metal Organic Chemical Vapor Deposition***

Self-assembled InGaAs quantum dot (QD) gain media grown by metal organic chemical vapor deposition (MOCVD) technique has a natural peak emission wavelength of around 1100-1200 nm due to its specific composition, shape, and size. In this work, a promising method to push emission wavelength of MOCVD-grown InGaAs QD gain media on GaAs to ~1000 nm by utilizing InGaAsP QD has been demonstrated. Incorporation of phosphorus species in the barrier layer into the QD is achieved by interdiffusion process. Our study consists of two main steps. Rapid thermal annealing (RTA) and low temperature photoluminescence (LT-PL) measurements are performed on MOCVD-grown InGaAs QD samples with GaAsP and GaAs barriers. All the samples are grown on GaAs substrate. In general, one observes an increasingly narrow full width at half max (FWHM) of PL spectrum with annealing time. For instance, after annealing for 300 s at 700ºC, sample with 20% P in the barrier and P-free barrier exhibit reduction in FWHM by 10.48 meV and 15.2 meV, respectively. The PL blueshift of sample annealed at 700ºC for 300 s with 20% P in the barrier is found to be 78 nm, while for P-free sample annealed under the same condition, the blueshift is observed to be only 64 nm. This marked difference in blueshifts is an indication of P-species incorporation into the QD, and this finding agrees well with the fact that P-containing QD possesses a larger energy gap that leads to shorter emission wavelength than P-free structure.

Diode laser devices based on unannealed and annealed QD gain media with 20% and 30% P in the barrier are fabricated. For a 4 mm-long $InGaAs/GaAs_{0.8}P_{0.2}$ laser device (annealed at 700ºC for 200 s), a reasonably low threshold current density of 202 A/cm^2 is measured. The peak lasing wavelength is found to be blueshifted by 23 nm in comparison to that of the device utilizing unannealed sample. Comparable characteristics are exhibited by 4 mm-long $InGaAs/GaAs_{0.7}P_{0.3}$ (also annealed at 700ºC for 200 s) laser device, where threshold current density and lasing wavelength of 288 A/cm^2 and 1040 nm are measured, respectively. The peak wavelength of this device is also found to be 23 nm shorter than that of the unannealed device. Future experiments utilizing InGaAs QD surrounded by InGaP barrier grown on GaAs substrate will also be conducted to further investigate the P-species incorporation into the QD gain media. One major potential application of this study includes EDFA pump lasers for optical telecommunication.

<u>Selected Relevant Publications:</u>

1. R. A. Arif, N. H. Kim, L. J. Mawst, and **N. Tansu**, "Interdiffused InGaAsP Quantum Dots Lasers on GaAs by Metalorganic Chemical Vapor Deposition," in *Proc. of the MRS Fall Meeting 2005: Symposium EE: Progress in Semiconductor Materials V—Novel Materials and Electronic and Optoelectronic Applications*, Boston, MA, USA, November-December 2005.

7. "Physics of Nonlinear Optical Devices"

"Physics of Nonlinear Optics for Compact and Efficient Coherent Sources for Mid-Infrared and Beyond, Capable of Room Temperature Continuous-Wave Operation"

- ***Novel Approach for Efficient Mid-Infrared Coherent Emitters Based on Continuously-Phase-Matched 'W' Optical Waveguide***

Compact mid-infrared (mid-IR) coherent emitters capable of continuous-wave (CW) operation at room temperature have applications in the area of biological- and chemical-sensors, and military applications. The type-II GaSb laser has limitation of the less-mature GaSb technology, and its maximum operation temperature for mid-IR CW lasers is still limited to 220 K. Mid-IR InP-based quantum well (QW) intersubband lasers had been recently demonstrated for CW operation at room temperature. However, QW intersubband laser requires relatively-complex epitaxy and processing steps, and its reliability under CW operation at high temperature is still an issue.

In this work, we present a novel approach for achieving semiconductor-based mid-infrared (MIR) coherent emitters by implementing the continuously phase-matched difference frequency generation (DFG) nonlinear process of two near-IR lasers in our novel "W" optical waveguide, resulting in efficient generation of coherent mid-IR radiation. The DFG frequency conversion utilizes W-waveguide, which is formed by conventional GaAs-AlGaAs semiconductor material system. By maintaining continuous phase matching in our W-waveguide, coherent CW power of 1.9mW at wavelength of 4.77μm is achievable at room temperature based on the DFG process of 0.92μm and 1.14μm incident waves with input power of 0.8W. The multi-layered structure of W-waveguide can readily be grown by metalorganic chemical vapor deposition (MOCVD), and the photonic integration of the near-infrared lasers and the nonlinear device sections is achievable by utilizing the selective-area intermixing and selective-area MOCVD epitaxy. The tunability and optimization of this W-waveguide approach for efficient generation of coherent emitter at 4.77 μm will also be discussed.

Selected Relevant Publications:

1. Z. Jin, and **N. Tansu**, "Novel Approach for Efficient Mid-Infrared Coherent Emitters Based on Continuously-Phase-Matched 'W' Optical Waveguide," in Proc. of the *SPIE Photonics West 2006*, *Physics and Simulation of Optoelectronics Devices XIII*, San Jose, CA, Jan 2006.

8. "Novel Design and Active Region Vertical Cavity Surface Emitting Lasers (VCSELs)"
"Device Physics and Novel Design of Vertical Cavity Surface Emitting Lasers"

- ***Al-free InGaAsP-QW Active Region VCSELs for 850-nm***

The conventional active region for 850-nm laser diodes is based on lattice-matched GaAs quantum-wells (QWs) active region on GaAs substrate. Despite the ease in realizing lattice-matched QW active regions, there exist various disadvantages related to the electronic and optical properties of the lattice-matched QWs. The degeneracy of the light-hole and heavy-hole near the edge of the valence-band for lattice-matched QWs leads to an increase in transparency carrier density. The increase in transparency carrier density (n_{tr}) in lattice-matched QWs is related to its larger density of states (DOS) in the valence bands. This larger density of states in the valence bands leads to an increase in the transparency current density (J_{tr}) and reduction in the differential gain (dg/dn) for lattice-matched QWs, which will in turn lead to a larger threshold current density for lattice-matched QW lasers. Despite their larger threshold current density, 850-nm lattice-matched GaAs QWs lasers still have very good static lasing characteristics. One important issue for 850-nm GaAs QW lasers arises as the lasers are modulated at 10 Gb/s. The low differential gain (dg/dn) of the GaAs QW active region results in the requirement to operate at very high injection current, because the square of the modulation bandwidth for QW lasers is proportional to the differential gain and injection current above threshold. The low dg/dn in the lattice matched QW will require high current operation to achieve modulation bandwidths up to 10 Gb/s. Unfortunately the requirement of operating the 850-nm GaAs-QW VCSELs devices at high current density to achieve 10 Gb/s may lead degradation in the longterm reliability.

Our approach to develop the compressively-strained QW systems for 850-nm VCSELs is by utilizing InGaAsP QW. The use of the compressively-strained InGaAsP QW for λ =850nm, is predicted to lead to a strain-induced reduction in the threshold and transparency current density of the lasers. Our work has also demonstrated a highly-temperature-insensitive compressively-strained InGaAsP QW (at λ=850 nm) diode lasers for the first time. The utilization of the InGaAsP QW is also expected to improve device reliability due to the existence of indium in the QW, which has been shown to inhibit dark-line defect propagation. As part of this work, λ=850 nm emitting VCSELs utilizing the compressively-strained InGaAsP QW have also been demonstrated for the first time.

Selected Relevant Publications:

1. **N. Tansu**, S. Rusli, D. Zhou, and L. J. Mawst, "Compressively Strained InGaAsP-Active (λ=0.78-0.85-μm) regions for VCSELs," in *Proc. of the 12th IEEE Laser and Electro-Optics Society (LEOS) Annual Meeting 1999*, San Francisco, CA, Nov 1999.
2. **N. Tansu**, D. Zhou, and L. J. Mawst, "Low Temperature Sensitive, Compressively-Strained InGaAsP Active (λ=0.78-0.85-μm) Region Diode Lasers," *IEEE Photon. Technol. Lett.*, Vol.12(6), pp.603-605 , June 2000. This represents ***the highest reported T_0 and T_1 values for 850-nm diode lasers.***
3. **N. Tansu**, and L. J. Mawst, "Compressively-Strained InGaAsP-Active (λ=0.78-0.85-μm) regions VCSELs," in *Proc. of the 13th IEEE Laser and Electro-Optics Society (LEOS) Annual Meeting 2000*, Rio Grande, Puerto Rico, pp.724-725, Nov. 2000. This represents ***the first demonstration of the compressively-strained InGaAsP-QW 850-nm VCSELs***.

- ***Narrow Lateral Waveguide Single Mode VCSELs and Computational FDTD VCSELs***

We proposed a novel approach for achieving high power single mode VCSELs, by using the concept of narrow lateral waveguide. The use of this concept allows one to achieve a large near field spot size for VCSELs structure. A narrow-waveguide VCSEL design incorporating a separate current confinement aperture is analyzed. This design then allows one to adjust the optical overlap with the gain region by choosing the current aperture. The device is fabricated by two-step MOCVD growth. The analysis of its modal properties is done by employing a full-wave FDTD simulation, for extracting the optical field profiles and cavity Q. Due to the nature of the narrow waveguide, only a single-spatial single mode is supported.

The novel idea of narrow lateral waveguide is also applied into edge emitting lasers (US Patent No. 6,845,116**)**. This approach is regarding a new method to achieve high power edge-emitting semiconductor lasers by utilizing the novel 'narrow lateral waveguide semiconductor lasers'**.** Often times, the maximum optical lasing power achievable from semiconductor lasers is limited by the high optical power density that damage the facet of the semiconductor lasers (due to the high optical power density at the output facet; typically high optical power density at the facet will melt the semiconductor facet, which would lead to catastrophic optical mirror damage of the diode lasers). The invention shows that by utilizing the 'narrow lateral waveguide' approach, one can spread the optical lasing mode field over a very wide (extremely wide) region thus leading toward lower optical power density at the output facet of the semiconductor lasers, which in turn will lead to higher maximum optical power achievable from the diode lasers (as the power density at the facet is lower, then higher maximum power can then be achievable before the laser facet will melt). The spreading of the optical mode of the diode laser based on this invention is achievable while maintaining the single mode operation throughout the whole lasing operation. The proposed method in this invention can also be grown by standard III-V semiconductor MOCVD / MBE epitaxy, and the device structures can also be fabricated by utilizing the standard semiconductor processing technology.

Selected Relevant Publications:

1. D. Zhou, T. W. Lee, **N. Tansu**, S. C. Hagness, and L. J. Mawst, "Large Spot Size Narrow Waveguide VCSELs," in *Proc. of the 14th IEEE Laser and Electro-Optics Society (LEOS) Annual Meeting 2001*, San Diego, CA, Nov. 2001.

Relevant US Patents:

1. Luke J. Mawst, **Nelson Tansu**, and et.al., "Narrow Lateral Waveguide Lasers," *Novel techniques to achieve high power single mode edge emitting lasers*, **US Patent No. 6,845,116**; approved on January 18th 2005.

- ***Quasi-Guided for Single Mode VCSELs for High Power***

High-power single-lateral-mode VCSELs plays an important role in today's laser industry, in particular as emitter for optical communication. Achieving single-lateral-mode and high-power operation in a VCSELs has always been a challenge. The research toward achieving this goal has been conducted in several areas: adding the external cavity, or using the shallow surface relief which introduces the higher mirror loss for the higher-order lateral modes, or modifying the waveguide design for lateral effective index of refraction. Several alternatives, such as anti-guided, S-ARROW, and ARROW, have been implemented into lateral waveguide design to allow VCSELs operating at high-power and single-mode.

Our approach for achieving high-power single-lateral-mode VCSELs utilizes a novel optical waveguide structure to control the lateral modes of the VCSELs. The proposed structure is called as the quasi-guided optical waveguide (QGOW), where the fundamental mode of the lateral mode is guided, whilst the higher order modes are all antiguided. The proposed QGOW structure allows one to increase the lasing aperture of the VCSELs, while maintaining single mode operation. The QGOW VCSELs structure suppresses the fundamental mode loss and allows a large radiation loss difference between the fundamental mode and the higher-order modes. Owing to the large loss difference of the fundamental and higher order modes, the proposed QGOW VCSELs structure allows a stable single lateral mode operation during above threshold operation.

Selected Relevant Publications:

1. Z. Jin, R. S. Tummidi, Y. P. Gupta, D. M. Schindler, and **N. Tansu**, "Quasi-Guided-Optical-Waveguide VCSELs for Single-Mode High-Power Applications," in *Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2006*, Long Beach, CA, May 2006.

- ***Lateral Mode Control in VCSELs with Photonic Crystals***

Lateral mode control for achieving high-power single-lateral-mode VCSELs can also be achieved photonic lattice approach. The photonic lattice VCSELs structure allows one to engineer single mode VCSELs with low radiation loss for the fundamental mode, while maintaining large radiation loss for the higher order modes. Computational tools to compute the lateral mode profiles and radiation loss of the photonic-lattice/crystal-type VCSELs are also developed.

Selected Relevant Publications:

1. Z. Jin, and **N. Tansu**, "Design Comparison of Photonic Lattice and ARROW-Type Single-Mode Vertical Cavity Surface-Emitting Lasers," Poster in *Lehigh* Center *for Optical Technologies (COT) Open House 2005,* ***Lehigh University***, Bethlehem, PA, USA, May 2005.
2. Z. Jin, R. S. Tummidi, Y. P. Gupta, D. M. Schindler, and **N. Tansu**, "Quasi-Guided-Optical-Waveguide VCSELs for Single-Mode High-Power Applications," in *Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2006*, Long Beach, CA, May 2006.