Updated Progress Report Year 2013

1. DOE Award Number and Name of Recipient

Award #: DE-FC26-08NT01581

Recipients: Nelson Tansu (Lehigh University) and Volkmar Dierolf (Lehigh University)

2. Project Title:

Enhancement of Radiative Efficiency with Staggered InGaN Quantum Well Light Emitting Diodes

3. Performer:

Lehigh University

4. Principal Investigator:

Enter PI Name Here

Dr. Nelson Tansu

New Century Endowed Chair Professor in Engineering and Applied Science

Department of Electrical and Computer Engineering

Lehigh University

7 Asa Drive, Bethlehem, PA 18015

Phone: (610) 758-2678, Fax: (610) 758-2605

Email: Tansu@Lehigh.Edu

Recent Updates on the Technology:

- ✓ The technology on the large overlap InGaN QWs developed in this program is currently implemented in commercial technology in enhancing the internal quantum efficiency in major LED industry in US and Asia. The scientific finding from this work supported by the DOE enabled the implementation of this step-like staggered quantum well in the commercial LEDs.
- ✓ The US patent associated to staggered InGaN QW technology has recently been approved by the US Patent and Trademark Office [October 2013], and the patent will be issued on January 2014.
- ✓ The DOE program has enabled the training of several PhD graduates in the fields of solid state lighting, who have made contributions in industries (Philips Lumileds, Cree, Veeco) and academia (as professor at Case Western Reserve University).

PROJECT PROGRESS REPORT
2nd Year Review (Year 1 and Year 2)

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Dr. Nelson Tansu

Class of 1961 Associate Professor

Department of Electrical and Computer Engineering

Lehigh University

7 Asa Drive, Bethlehem, PA 18015

Phone: (610) 758-2678, Fax: (610) 758-2605

Email: Tansu@Lehigh.Edu

5. Other Team Members:

- Dr. Nelson Tansu (PI), Bethlehem, PA, USA
- Dr. Volkmar Dierolf (Co-PI), Bethlehem, PA, USA
- Dr. Gensheng Huang (MOCVD), Bethlehem, PA, USA
- Dr. Samson Tafon Penn (CL), Bethlehem, PA, USA
- Ms. Hongping Zhao (MOCVD, Devices), Bethlehem, PA, USA
- Ms. Guangyu Liu (Time-Resolved PL), Bethlehem, PA, USA
- Mr. Xiaohang Li (Low Temperature PL), Bethlehem, PA, USA
- Mr. Jonathan Poplawsky (CL), Bethlehem, PA, USA

6. Date of Report and Period Covered by Report

Date of Report: July 2010

Period Covered by Report: August 15th 2008-July 15th 2010

7. Technology Focus:

Core Technology Research (1.1.2)

8. Relevant Subtask Priority Area:

1.1.2: High-efficiency semiconductor materials

→ Improve IQE across the visible spectrum and in the near UV (down to 360 nm) at high current densities

9. Schedule/Budget Overview:**Actual Cost Charge in DOE Award #: DE-FC26-08NT01581**

	Start Date	End Date	Government Share	Performer Share	Total
Year 1	(7/15/08)	(8/14/09)	\$193,686.00	\$78,141	\$271,827.00
Year 2	(8/15/09)	(6/15/10)	\$135,574.00	\$43,860	\$179,434.00
Year 1 + Year 2	(7/15/08)	(6/15/10)	\$329,260.00	\$122,001	\$451,261.00
Allocated Budget from DOE Award	(7/15/08)	(8/14/10)	\$393,107.00	\$113,911	\$507,018.00

Budget Allocated in DOE Award #: DE-FC26-08NT01581

	Start Date	End Date	Government Share	Performer Share	Total
Year 1	(7/15/08)	(8/14/09)	\$193,686	\$78,141	\$271,827
Year 2	(8/15/09)	(8/14/10)	\$199,421	\$35,770	\$241,908
Year 3	(8/15/10)	(8/14/11)	\$205,338	\$36,570	\$241,908
Total	(7/15/08)	(8/14/11)	\$598,445	\$150,481	\$748,926

10. Schedule Status**Milestones/Deliverables for Year 1:**

- Phase I (0-12 months) – Month 12th
 - 1) Optimized 450-nm emitting MOCVD-grown staggered InGa_N QW LEDs (**accomplished**)
 - 2) Working 500-nm emitting MOCVD-grown staggered InGa_N QW LEDs (**accomplished**)
 - 3) Operational NSOM capabilities for InGa_N QW LEDs (**accomplished**)

Milestones/Deliverables for Year 2 and 3:

- Phase II (12-24 months) – Month 24th
 - 1) Optimized staggered InGa_N QW LEDs emitting at 550-nm with radiative efficiency > 20%.
 - 2) Achieve multi dimensional spectroscopy (spectral, spatial, and temporal) capabilities for

InGaN QW LEDs

- 3) Complete the z-parameter analysis on the staggered InGaN QW LEDsth
 - Phase III (24-36 months) – Month 36
- 1) Achieve optimized 550-nm emitting staggered InGaN QW LEDs with radiative efficiency > 40%
- 2) Complete the studies of multi-dimensional spectroscopy and z-parameter -recombination analysis on 550-nm emitting staggered InGaN QW LEDs.

11. Project Objective:

The objective of the proposed research is to improve the intrinsic quantum efficiency of InGaN-based LEDs for the green spectral region. For this goal, the Recipient shall investigate the use of staggered InGaN quantum wells (QW) as an improved active region. In this research, the Recipient shall address the serious performance-limiting issue presented by the existence of polarization fields in III-Nitride active regions, namely the low electron-hole wave function overlap that becomes a severe problem for structures with higher In-content. To circumvent this problem the Recipient shall use staggered InGaN which will improve the overlap and will lead to increased radiative recombination rate and higher radiative efficiency. The Recipient shall address this challenge in three phases:

- 1) Phase I: proof-of-concept of polarization engineering via staggered InGaN QW for enhanced radiative efficiency
- 2) Phase II: comprehensive recombination analysis and optical characterizations (confocal, near-field scanning optical microscopy - NSOM, and time-resolved Photoluminescence - PL) for understanding the recombination mechanisms in InGaN QW
- 3) Phase III: MOCVD and device optimization of staggered InGaN QW for achieving high radiative efficiency LEDs emitting at 550-nm with radiative efficiency > 40%.

12. Technical Approach and Work Plan:

The research program focused on novel quantum well (QW) design based on staggered InGaN QW active region for enhancing the radiative recombination rate and radiative efficiency of nitride light-emitting diodes (LEDs) in the green spectral regime. One of the most important limitations for achieving high-efficiency InGaN QW LEDs emitting in green spectral regime is the existence of electrostatic fields inside the QW from the spontaneous and piezoelectric polarization fields. The existence of these polarization fields inside the QW leads to charge separation effect, which in turn leads to significantly reduced electron-hole wavefunction overlap (Γ_{e_hh}). The spontaneous radiative recombination rate is proportionally to the square of the electron-hole wavefunction overlap ($\sim |\Gamma_{e_hh}|^2$). The enhancement in radiative recombination rate leads to enhancement of radiative efficiency of the InGaN QW.

As the emission wavelength in InGaN QW is extended to green spectral regime and beyond, the issues mentioned above become more challenging. The charge separation becomes more severe, in particular for two schemes to extend the emission wavelengths into green regime ($\lambda \sim 525$ nm) or beyond as follow: 1) by increasing the In-content in InGaN QW, or 2) by increasing the thickness of InGaN QW. Both approaches lead to severe reduction in the electron-hole wavefunction overlap Γ_{e_hh} in particular for InGaN QW emitting in the green spectral regime.

The tasks will be divided into three phases as follow:

1) Phase I (0-12 months) – Proof of Concept

- MOCVD epitaxy optimization of staggered InGaN QW active regions emitting at 450-500 nm
- Photoluminescence and cathodoluminescence studies will be conducted on the MOCVD-grown staggered InGaN QW
- Implementation into device fabrication for staggered InGaN QW LEDs
- Numerical simulation for optimizing the design for staggered InGaN QW active regions emitting at 450-500 nm. The optimization parameter spaces will include the grading profile of the QW, In-contents, and thicknesses.

2) Phase II (12-24 months) – Recombination and Quantitative Understanding

- Based on the numerical studies in Phase I, optimization of MOCVD epitaxy for staggered InGaN QW LEDs emitting at 500-550 nm will be conducted. Structures grown under different conditions and parameters will be compared.
- Confocal, NSOM, and time-resolved PL will be conducted for understanding the recombination mechanism in staggered InGaN QW.
- The z-parameter recombination analysis will be performed to identify the recombination processes in staggered InGaN QW LEDs.
- Optimization of device fabrication for staggered InGaN QW LEDs.

3) Phase III (24-36 months) – Device Optimization Stage

- Optimization of nanostructure design, MOCVD epitaxy, device fabrication of staggered InGaN QW LEDs with high radiative efficiency ($>90\%$ for $\lambda \sim 450\text{nm}$, and $>40\%$ for $\lambda \sim 550\text{nm}$).
- True multi-dimensional spectroscopy on staggered InGaN QW active regions will be conducted, for improved understanding of the recombination processes in the QW.
- Optimization for high ‘wall plug’ efficiency devices will be emphasized for III-Nitride LEDs emitting at 500-550nm.

13. Progress-to-Date:

Year 1

In this 1st year project report, the works accomplished as part of the DOE program for the first year include the following:

- The growth optimization for achieving 525-nm InGaN QW LEDs based on conventional QW design.
- Comprehensive simulation design for achieving optimized design for 525-nm emitting staggered InGaN QW active region for green LEDs.
- Growth optimization and device fabrication for realizing staggered InGaN QW LEDs emitting in 525-nm regimes.
- Cathodoluminescence characterization of staggered InGaN QW and conventional InGaN QW LEDs for emission in green regime.
- Time-resolved photoluminescence measurements to compare the radiative recombination rate for staggered InGaN QW LEDs and conventional InGaN QW LEDs.

- Completed the set up for the nano-scale microscopy photoluminescence (NSOM-PL) set up for visible InGaN QW LEDs.

Year 2

In the 2nd year project report, the works accomplished as part of the DOE program for the second year include the following:

- The growth optimization for achieving 540-nm InGaN QW LEDs with conventional QW.
- Completed the comprehensive simulation investigation of staggered InGaN QW for achieving optimized design at 540-nm emitting staggered InGaN QW LEDs, as well as extension to longer wavelengths.
- Growth optimization and device fabrication for realizing linearly-shaped staggered InGaN QW LEDs emitting in 540-nm regimes. We found that the use of linearly-shaped staggered InGaN QW by employing current control results in much easier growth process.
- Cathodoluminescence characterization of staggered InGaN QW and conventional InGaN QW LEDs for emission in green regime. Specifically, the comparison of the low-temperature and room-temperature CL intensity are performed to obtain IQE of the LEDs.
- Time-resolved photoluminescence measurements to compare the radiative recombination rate for staggered InGaN QW LEDs and conventional InGaN QW LEDs.
- Perform the simulation and growths of AlInN barriers to achieve reduction in efficiency droop in nitride LEDs, in order to achieve high IQE at high current density.

Refereed Publications for DOE Project (Year 1 and Year 2):

1. **(Invited Conference Paper) N. Tansu**, R. A. Arif, H. P. Zhao, G. S. Huang, and Y. K. Ee, "Polarization Engineering of III-Nitride Nanostructures for High-Efficiency Light Emitting Diodes," in Proc. of the *SPIE Optics + Photonics 2008, The 8th International Conference on Solid State Lighting*, vol. 7058, paper 7058-45, San Diego, CA, August 2008.
2. **(Invited Conference Paper) N. Tansu**, H. P. Zhao, R. A. Arif, Y. K. Ee, G. Y. Liu, X. H. Li, and G. S. Huang, "Polarization Engineering of InGaN-Based Nanostructures for Low-Threshold Diode Lasers and High-Efficiency Light Emitting Diodes," in Proc. of the *IEEE Photonics Global 2008, Nanophotonics Symposium*, Singapore, Republic of Singapore, December 2008.
3. H. P. Zhao, M. Jamil, G. S. Huang, H. Tong, A. M. Driscoll, and **N. Tansu**, "Characteristics of InN Semiconductors Grown on Ga-Polar and N-Polar GaN Templates by Pulsed Metalorganic Vapor Phase Epitaxy," in Proc. of the *SPIE Photonics West 2009, Gallium Nitride Materials and Devices IV*, San Jose, CA, Jan 2009.
4. H. P. Zhao, R. A. Arif, G. S. Huang, Y. K. Ee, and **N. Tansu**, "Growths of Staggered InGaN Quantum Wells Light Emitting Diodes at 470-480 nm Employing Graded Temperature Profile," in Proc. of the *SPIE Photonics West 2009, LEDs: Materials, Devices, and Applications for Solid State Lighting XIII*, San Jose, CA, Jan 2009.
5. H. P. Zhao, R. A. Arif, and **N. Tansu**, "Design of Staggered InGaN Quantum Wells for Green Diode Lasers," in Proc. of the *SPIE Photonics West 2009, Novel In-Plane Semiconductor Lasers VIII*, San Jose, CA, Jan 2009.
6. H. P. Zhao, R. A. Arif, and **N. Tansu**, "Analysis of Current Injection Efficiency and Efficiency Droop of InGaN Quantum-Wells Light-Emitting Diodes," in Proc. of the *SPIE Photonics West 2009, Physics and Simulation of Optoelectronics Devices XVII*, San Jose, CA, Jan 2009.
7. H. P. Zhao, R. A. Arif, Y. K. Ee, and **N. Tansu**, "Self-Consistent Analysis of Strain-Compensated InGaN-AlGaIn Quantum Wells for Lasers and Light Emitting Diodes," *IEEE J. Quantum Electron.*, vol. 45(1-2), pp. 66-78, January- February 2009.
8. H. P. Zhao, M. Jamil, G. Y. Liu, G. S. Huang, H. Tong, G. Xu, Y. J. Ding, and **N. Tansu**, "Pulsed Metalorganic Vapor Phase Epitaxy of In-Polar and N-Polar InN Semiconductors on GaN / Sapphire Templates for Terahertz Emitters," in Proc. of the *IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2009*, Baltimore, MD, May 2009.

9. H. P. Zhao, G. Y. Liu, X. H. Li, G. S. Huang, S. Tafon Penn, V. Dierolf, and **N. Tansu**, "Staggered InGaN Quantum Wells Light-Emitting Diodes at 520-nm Employing Graded Temperature Growths," in *Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2009*, Baltimore, MD, May 2009.
10. H. P. Zhao, G. S. Huang, G. Y. Liu, X. H. Li, J. D. Poplawsky, S. Tafon Penn, V. Dierolf, and **N. Tansu**, "Characteristics of Staggered InGaN Quantum Wells Light-Emitting Diodes Emitting at 480-525 nm," in *Proc. of the 67th IEEE Device Research Conference (DRC) 2009*, University Park, PA, June 2009.
11. H. P. Zhao, R. A. Arif, and **N. Tansu**, "Design Analysis of Staggered InGaN Quantum Wells Light-Emitting Diodes at 500-540 nm," *IEEE J. Sel. Top. Quantum Electron.*, vol. 15 (4), pp. 1104-1114, July-August 2009.
12. H. P. Zhao, G. S. Huang, G. Y. Liu, X. H. Li, J. D. Poplawsky, S. Tafon Penn, V. Dierolf, and **N. Tansu**, "Growths of Staggered InGaN Quantum Wells Light-Emitting Diodes Emitting at 520-525 nm Employing Graded Growth-Temperature Profile," *Appl. Phys. Lett.*, vol. 95(6), Art. 061104, August 2009. [Also listed in Top 20 Most Downloaded Articles in Applied Physics Letters, August 2009]
13. H. P. Zhao, G. Y. Liu, R. A. Arif, and **N. Tansu**, "Effect of Current Injection Efficiency on Efficiency-Droop in InGaN Quantum Well Light-Emitting Diodes," in *Proc. of the IEEE International Semiconductor Device Research Symposium (ISDRS) 2009*, College Park, MD, Nov 2009.
14. **(Invited Journal Paper)** H. P. Zhao, G. Y. Liu, X. H. Li, R. A. Arif, G. S. Huang, J. D. Poplawsky, S. Tafon Penn, V. Dierolf, and **N. Tansu**, "Design and Characteristics of Staggered InGaN Quantum Well Light-Emitting Diodes in the Green Spectral Regimes," *IET Optoelectronics*, vol. 3(6), pp. 283-295, December 2009.
15. **(Invited Conference Paper)** H. P. Zhao, G. Y. Liu, R. A. Arif, Y. K. Ee, X. H. Li, J. Zhang, H. Tong, G. S. Huang, and **N. Tansu**, "Novel Approaches for Efficiency Enhancement in InGaN-Based Light-Emitting Diodes," in *Proc. of the 2nd International Conference on White LEDs and Solid State Lighting 2009*, Taipei, Taiwan, December 2009.
16. **(Invited Conference Paper)** **N. Tansu**, H. P. Zhao, Y. K. Ee, G. Y. Liu, X. H. Li, and G. S. Huang, "Novel Device Concept for High-Efficiency InGaN Quantum Wells Light-Emitting Diodes," in *Proc. of the SPIE Photonics West 2010, Gallium Nitride Materials and Devices V*, San Francisco, CA, Jan 2010.
17. G. Y. Liu, H. P. Zhao, J. Zhang, G. S. Huang, and **N. Tansu**, "Growths of Lattice-Matched AlInN Alloys on GaN," in *Proc. of the American Physical Society (APS) Annual March Meeting 2010*, Portland, Oregon, March 2010.
18. **(Invited Review Article)** **N. Tansu**, H. P. Zhao, G. Y. Liu, X. H. Li, J. Zhang, H. Tong, and Y. K. Ee, "Breakthrough in Photonics 2009: III-Photonics", *IEEE Photonics Journal*, vol. 2 (2), pp. 236-243, April 2010.
19. **(Invited Conference Paper)** H. P. Zhao, G. Y. Liu, X. H. Li, Y. K. Ee, H. Tong, J. Zhang, G. S. Huang, and **N. Tansu**, "Novel Growth and Device Concepts for High-Efficiency InGaN Quantum Wells Light-Emitting Diodes," in *Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2010*, San Jose, CA, May 2010.
20. **(Invited Conference Paper)** H. P. Zhao, J. Zhang, G. Y. Liu, X. H. Li, Y. K. Ee, H. Tong, T. Toma, G. S. Huang, and **N. Tansu**, "Approaches for High-Efficiency InGaN Quantum Wells Light-Emitting Diodes – Device Physics and Epitaxy Engineering," in *Proc. of the American Vacuum Society (AVS) Meeting 2010*, Ann-Arbor, MI, May 2010.
21. H. P. Zhao, and **N. Tansu**, "Optical Gain Characteristics of Staggered InGaN Quantum Well Lasers," *J. Appl. Phys.*, vol. 107, Art. 113110, June 2010.
22. **(Invited Conference Paper)** **N. Tansu**, H. P. Zhao, J. Zhang, G. Y. Liu, X. H. Li, H. Tong, T. Toma, G. S. Huang, and Y. K. Ee, "Device Physics and Epitaxy Engineering for High-Efficiency III-Nitride Light-Emitting Diodes," in *Proc. of the International Union of Materials Research Societies - International Conference on Electronic Materials (IUMRS-ICEM) 2010*, Seoul, Korea, August 2010.

23. H. P. Zhao, G. Y. Liu, R. A. Arif, and **N. Tansu**, "Current Injection Efficiency Quenching Leading to Efficiency Droop in InGaN Quantum Well Light-Emitting Diodes," *Solid-State Electronics*, vol. 54(10), pp. 1119–1124, October 2010.
24. **(Invited Conference Paper) N. Tansu**, H. P. Zhao, J. Zhang, G. Y. Liu, X. H. Li, T. Toma, and G. S. Huang, "Novel Approaches for High-Efficiency InGaN Quantum Wells Light-Emitting Diodes – Device Physics and Epitaxy Engineering," in *Proc. of the SPIE Photonics West 2011, LEDs: Materials, Devices, and Applications for Solid State Lighting XV*, San Francisco, CA, Jan 2011.

Submitted Journal and Conference Publications

25. H. P. Zhao, G. Y. Liu, and **N. Tansu**, "InGaN Quantum Wells with Delta-InN Layer for Light-Emitting Diodes," *Appl. Phys. Lett.* (submitted).
 26. H. P. Zhao, J. Zhang, T. Toma, G. Y. Liu, J. D. Poplawsky, V. Dierolf, and **N. Tansu**, "Cathodoluminescence Characteristics of Linearly-Shaped Staggered InGaN Quantum Wells Light-Emitting Diodes," in *Proc. of the 23rd Annual Meeting of the IEEE Photonics Society*, Denver, CO, November 2010. (submitted)
 27. G. Y. Liu, H. P. Zhao, J. Zhang, H. Tong, G. S. Huang, and **N. Tansu**, "Growths of Lattice-Matched AlInN / GaN for Optoelectronics Applications," in *Proc. of the 23rd Annual Meeting of the IEEE Photonics Society*, Denver, CO, November 2010. (submitted)
 28. H. P. Zhao, J. Zhang, T. Toma, G. Y. Liu, J. D. Poplawsky, V. Dierolf, and **N. Tansu**, "MOCVD Growths of Linearly-Shaped Staggered InGaN Quantum Wells Light-Emitting Diodes at Green Spectral Regime," in *Proc. of the SPIE Photonics West 2011, Gallium Nitride Materials and Devices VI*, San Francisco, CA, Jan 2011. (submitted)
- Patent Application for DOE Project:
 1. Nelson Tansu, Ronald A. Arif, and Yik Khoon Ee, "Gallium Nitride-Based Device and Method". *Novel techniques to achieve high performance visible LEDs and lasers*, **US Patent No. 7,518,139**; approved on April 14th 2009.
 2. Nelson Tansu, Ronald A. Arif, Yik Khoon Ee, and Hongping Zhao, "Staggered InGaN Quantum Well Lasers and Light Emitting Diodes", PCT/US2007/088778, published on February 2009. *Novel approach using polarization engineering for achieving nitride-based gain media with significant enhancement in radiative recombination rate and optical gain for high efficiency LEDs and lasers.* (PCT Application and US Patent Pending).
 3. Nelson Tansu, Ronald A. Arif, Yik Khoon Ee, and Hongping Zhao, *Novel approach using polarization engineering for achieving nitride-based gain media with significant enhancement in radiative recombination rate and optical gain for high efficiency LEDs and lasers.* (PCT Application and US Patent Pending).
 4. Nelson Tansu, Ronald A. Arif, and Yik Khoon Ee, *Novel methods for achieving nitride-based gain media with significant enhancement in radiative recombination rate and optical gain for high efficiency LEDs and lasers.* (PCT Application and US Patent Pending).
 5. Nelson Tansu, Hongping Zhao, and Guangyu Liu, *Novel Staggered InGaN Quantum Well Light-Emitting Diodes.* (Provisional Patent, and US Patent Pending).
 6. Nelson Tansu, Hongping Zhao, Guangyu Liu, and Ronald Arif, *Methods to Suppress Efficiency Droop for High Power Nitride Light-Emitting Diodes.* (Provisional Patent, and US Patent Pending).

• **Brief Narrative Summary of Results:**

Year 1

In this 1st year project report, we present the results from the growths of three-layer staggered InGaN QW LEDs emitting in the 520-525 nm spectral regime employing graded temperature profile, with the QW structure designed specifically for improved electron-hole wavefunction overlap to enhance the radiative recombination rate and radiative efficiency of LED device. Previously, the two-layer staggered InGaN quantum well with step-function like In-content was used to enhance the electron-hole

wavefunction overlap leading to improved radiative efficiency and output power of LED devices emitting in blue spectral regime (460-nm), and the compositional engineering of the In-contents was accomplished by modifying the In-precursor (TMIn) flow rate into the chamber during the InGaN QW growth. As part of the program, the three-layer staggered InGaN QW was grown by metalorganic chemical vapor deposition (MOCVD) with graded temperature profile. The use of graded temperature profile during the growth leads to more practical and repeatable approach to grow staggered InGaN QW.

From our simulation studies (published in IEEE JSTQE July/Aug 2009), we found that the optimized active region design for green-emitting LEDs should employ 3-layer staggered InGaN QWs. For the optimized 3-layer staggered InGaN QW ($\Gamma_{e_{hh}} = 29.9\%$) emitting at 525-nm, the overlap $\Gamma_{e_{hh}}$ is improved by 15% in comparison to that of the optimized 2-layer staggered InGaN QW ($\Gamma_{e_{hh}} = 26.3\%$). The conventional InGaN QW emitting at 525-nm has relatively low overlap ($\Gamma_{e_{hh}} = 14.5\%$). The radiative recombination rate of optimized 3-layer staggered InGaN QW (2-layer staggered InGaN) is calculated as ~ 3.5 -times (or 2.4-times) higher than that of conventional InGaN QW. The ratio of the enhancement for the spontaneous emission radiative recombination rate (R_{sp}) for the 540-nm emitting QWs were shown in figure 1. Thus, the use of 3-layer staggered InGaN QW over 2-layer staggered InGaN QW is important, in particular for extending the emission wavelength into green spectral regime and beyond. Our growth experiments also indicated that the use of 3-layer staggered InGaN QW for achieving peak emission wavelength up to 525-550 nm as more practical.

Recently, we have successfully demonstrated the growth of 3-layer staggered InGaN QW LEDs by employing MOCVD with graded growth-temperature profile. The use of graded growth-temperature profiling allows the growth of 3-layer staggered InGaN QW LEDs emitting in 525-nm. Comprehensive cathodoluminescence characterization were

Fig.1. Radiative recombination rate (R_{sp}) as a function of carrier density for conventional 35-Å $\text{In}_{0.27}\text{Ga}_{0.73}\text{N}$ QW, two-layer staggered 21-Å $\text{In}_{0.32}\text{Ga}_{0.68}\text{N}/14\text{-Å } \text{In}_{0.16}\text{Ga}_{0.84}\text{N}$ QW and three-layer staggered 7-Å $\text{In}_{0.16}\text{Ga}_{0.84}\text{N}/21\text{-Å } \text{In}_{0.32}\text{Ga}_{0.68}\text{N}/7\text{-Å } \text{In}_{0.16}\text{Ga}_{0.84}\text{N}$ QW at room temperature.

Fig.2. Integrated CL of conventional and 3-layer staggered InGaN QWs emitting at 520nm with various CL excitation current at $T=300\text{K}$.

carried out on the 3-layer staggered InGaN QW and conventional InGaN QW, and the CL results indicated 1.8-2.8 times improvement for staggered QW [figure 2].

LED device structures were fabricated as bottom-emitting devices by employing 3-layer staggered InGaN QW as active region. The electrical-injected 3-layer staggered InGaN QW LED devices with emission wavelength in 525-nm regime were demonstrated. The electrical luminescence (EL) for the conventional InGaN QWs and 3-layer staggered InGaN QWs LEDs (area = $510\mu\text{m} \times 510\mu\text{m}$) shows emission at 520-525 nm, measured

under continuous wave (CW) operation. The peak EL for the 3-layer staggered InGaN LED shows enhancement by 1.8 times (1.3 times) at $I=100\text{ mA}$ ($I=200\text{ mA}$), in comparison to that of conventional InGaN QW LED. Figure 3 shows the output power versus the injected current density for conventional and 3-layer staggered InGaN LEDs. The enhancement in both radiative efficiency and output power of the 3-layer staggered InGaN QW LEDs indicated that the increase in radiative recombination rate from the improved electron-hole wavefunction as a dominant contributing factor to the improved device characteristics. The output power of the 3-layer staggered InGaN QW LED was measured as 2.0-3.5 times higher in comparison to that of conventional InGaN QW LED [figure 3].

In addition to the results presented from the cathodoluminescence and electroluminescence device measurements, we have also performed time-resolved measurements on the staggered InGaN QW for comparison purpose. The time-resolved PL set up has been qualified for visible LED samples. The time resolved photoluminescence (TR-PL) measurements were performed for both conventional and three-layer staggered InGaN QW LED samples emitting at 520-525 nm, as shown in figure 4. The TR-PL measurements were carried out by employing excitation lasers emitting at 430-nm with pulse duration of 25 ps. The frequency of the TR-PL measurement

Fig.3. Light output power versus current density for conventional InGaN QW and 3-layer staggered InGaN QW LEDs emitting with peak wavelengths at 520-525 nm. The inset shows the schematic of band lineup for 3-layer staggered InGaN QW.

Fig.4. Time resolved measurements on both 3-layer staggered InGaN QW and conventional InGaN QW LED samples, with peak emission wavelength at 520-525 nm. The measurements were carried out by employing 430-nm excitation lasers with pulse duration of 25 ps.

employed in the measurement is 10 Hz. From the TR-PL measurements on LED device sample (shown in figure 4), the three-layer staggered InGaN QW exhibited 35% reduction of carrier lifetime ($\tau_{\text{staggered}} = 12.3$ ns), in comparison to that ($\tau_{\text{conventional}} = 18.9$ ns) of conventional InGaN QW. The TR-PL measurements were also conducted on PL samples (with no p-GaN cap layer), and the measurements also indicated 35-40% reduction of the carrier lifetime observed for 3-layer staggered InGaN QW in comparison to those measured of conventional InGaN QW PL samples. The enhancement in both radiative efficiency and output power of the 3-layer staggered InGaN QW LEDs, accompanied by a reduction in carrier lifetime, indicated that the increase in radiative recombination rate from the improved electron-hole wavefunction as a dominant contributing factor to the improved device characteristics. The results from the experiments are in agreement with theory.

The nanoscale optical microscopy PL (NSOM-PL) has been developed in-house. In order to characterize the localization effects on the sub-micron scale and nanoscale, we further developed and optimized our NSOM facility to allow the near-field detection of the green emission while exposing the active region with band-to-band (364nm) and or direct quantum-well (442nm) excitation. The instrument allows now the detection of the complete emission spectrum as a function of space with a resolution of 70nm or less. Both the collection mode (in which the collection of the light is localized) and the illumination mode (in which the excitation is localized, shown in figure 5) can be used. Thus, the NSOM-PL set up for visible LED samples are currently completed, and further studies will focus on the comparison measurements on both staggered and conventional InGaN QW to provide the improved understanding of the recombination mechanisms in these QWs.

Fig. 5: left: schematics of our instrument in illumination modes. Right: Intensity distribution of green emission in one of our samples

Year 2

In the 2nd year project report, we presented the results from the growths of various three-layer staggered InGaN QW LEDs emitting in the 520-540 nm spectral regime employing graded temperature profile. The QW structures were designed such that the electron-hole wavefunction overlap is enhanced to increase the radiative recombination rate and radiative efficiency of LED device. In the 2nd year project report, the works accomplished as part of the DOE program for the second year include the following:

1. MOCVD Growths of Linearly-Shaped Staggered InGaN QW LEDs

The concepts of the 2-layer staggered and 3-layer staggered InGaN QWs with enhanced optical matrix element have led to ~2.5-3.5 times increase in radiative recombination rate and radiative efficiency for 520-525 nm emitting nitride LEDs. The

use of 3-layer staggered InGaN QW has shown that the introduction of potential minima in the center of the QW leads to significant enhancement in the spontaneous emission rate. Similarly, the modification of 3-layer staggered QW concept can also be modified into other QW structure with local minima.

In this work, we develop the growths of linearly-shaped (LS) staggered InGaN QWs LEDs by employing graded growth temperature profiles, with the QW structure designed for improved overlap $\Gamma_{e_{hh}}$ to enhance the radiative recombination rate and radiative efficiency of LEDs. Here, the InGaN QWs with LS staggered In-content profile were grown by metalorganic chemical vapor deposition (MOCVD). The linearly-shaped staggered In-content profile is accomplished by employing the triangular growth temperature profile during the MOCVD growth of InGaN QW.

Figure 6 shows the schematics of three different designs of linearly-shaped staggered InGaN QWs (LS-1 staggered InGaN QW, LS-2 staggered InGaN QW and LS-3 staggered InGaN QW). The top three figures [figures 6(a), 6(b) and 6(c)] correspond to the schematics of the growth temperature profiles and the In-content profiles. Note that the TMIn flow was kept constant for all the experiments. The bottom three figures [figures 6(d), 6(e) and 6(f)] show the real growth temperature profiles by MOCVD. By comparing figures 6(a), 6(b), 6(c) with figures 6(d), 6(e) and 6(f), the real growth temperature profiles match very well with the schematics. In contrast to the linearly-shaped staggered InGaN QW, the conventional InGaN QWs contain the constant In-content for the InGaN QW, where the growth temperature for the conventional InGaN QW is constant.

Fig 6: Schematics of the growth temperature, TMIn-flow rate, and In-content for the triangular-1 InGaN QW, triangular-2 InGaN QW, triangular-3 InGaN QW [figure 1(a), (b) and (c)]. Real growth temperature profiles corresponding to figure 1(a), (b), and (c) [figure 1(d), (e) and (f)].

Both conventional and linearly-shaped staggered InGaN QW LEDs emitting at 460-480 nm were grown on 2.5 μm thick n-doped GaN ($n = 4 \times 10^{18} \text{ cm}^{-3}$) on c-plane double-side polished sapphire substrate, employing a low temperature 30-nm GaN buffer layer. Both conventional and linearly-shaped staggered InGaN QW structures consist of 4-period of InGaN QWs with 10 nm undoped GaN barriers. The thickness of the linearly-shaped staggered InGaN QW is calibrated as 3 nm, which is similar to that of conventional InGaN QW. On top of the InGaN QWs, 200 nm p-GaN ($p = 3 \times 10^{17} \text{ cm}^{-3}$) were employed as p-type layer.

The luminescence characteristics of both conventional and linearly-shaped staggered InGaN QWs samples were studied by power-density-dependent cathodoluminescence (CL) measurements performed at $T = 300\text{K}$. We utilized a 10 keV electron beam in spot mode (area = $2.0 \times 10^{-9} \text{ cm}^2$) to excite the InGaN QWs active region. To study the effect of the pumping power on the CL intensity for both conventional and linearly-shaped staggered InGaN QW LEDs, different excitation power density levels were applied on both conventional and linearly-shaped staggered InGaN QW LED samples. The various excitation power densities were obtained by varying the electron beam current (with constant accelerating voltage of 10 keV) from 20 nA up to 800 nA. The linearly-shaped staggered InGaN QW samples exhibit improved peak luminescence by 2.8-5.1 times of that of the conventional InGaN QW. Note that the linearly-shaped staggered InGaN QWs show slight blue shift as compared to the conventional InGaN QW due to the ramping up of the growth temperature during the growths of QWs, which requires further optimization of the growth temperature profile to match the emission wavelength to that of the conventional InGaN QWs.

Integrated CL intensities for both conventional and linearly-shaped staggered InGaN QWs LEDs were obtained by integration of the CL spectra data over the photon energy as shown in figure 7. The LS-1 (LS-2, and LS-3) staggered InGaN QW exhibited improvement by 1.35-3.2 (1.8-2.7, and 2.1-2.6) times of the integrated CL intensity as compared to that of the conventional InGaN QW. Both conventional and linearly-shaped staggered InGaN QWs LEDs show blue-shift in emission wavelengths as the pumping current increases due to the carrier screening effect.

The use of linearly-shaped staggered InGaN QWs in 460-480 nm emitting LEDs leads to significant enhancement of integrated CL intensities. This enhancement of the CL intensity is attributed to the improved optical matrix element by employing the InGaN QW with linearly-shaped staggered In-content profile.

Fig 7: Integrated CL intensity of conventional, triangular-1 InGaN QW, triangular-2 InGaN QW, and triangular-3 InGaN QW versus CL excitation current upto 800 nA at $T = 300\text{K}$.

2. Effect of Interface Abruptness / Grading on LED Performance

The effect of interface abruptness is investigated in staggered InGaN QW. The use of staggered InGaN QW was found to be less dependent on the abruptness of the layers in the QW, rather it is important to introduce local minima in the QW. The introduction of linearly-graded QW structure from the graded growth temperature was shown to affect the spontaneous emission rate relatively minimal.

3. IQE Measurements of Green-Emitting InGaN QW LEDs

Standard IQE measurements were carried out to obtain the IQE of the LED devices grown in our laboratory. The quantification of the IQE is important aspect in particular to compare the results with those published in literature. The standard approach of obtaining IQE is to measure the integrated CL intensity at room temperature with that of low temperature, and this ratio corresponds to IQE of the QW LEDs. The set up has been completed, and the measurements have been completed for various InGaN QW LEDs. The following results were obtained as follow:

- 1) Baseline - Conventional InGaN QWs LEDs
 - ✓ IQE (480 nm) ~ 18.1%
 - ✓ IQE (500 nm) ~ 14.1%
 - ✓ IQE (530 nm) ~ 5.7%
 - ✓ IQE (540 nm) ~ 8.9% (different QW design)
- 2) Findings for Staggered InGaN QW LEDs
 - ✓ LED devices show 2-3 times output power and efficiency enhancement ($\lambda \sim 525$ nm)
 - ✓ CL intensities for LS Staggered InGaN QW show 2.8-5 times enhancement ($\lambda \sim 480$ nm)
 - ✓ IQE for Staggered InGaN QW LEDs is expected to be in the range of ~ 15-20% ($\lambda \sim 520$ -540 nm). However, further direct measurements in the future will be performed to obtain the IQE of staggered InGaN QW LEDs in particular in green spectral regime.
 - ✓ Further optimization of staggered InGaN QW LEDs can lead to IQE (Staggered LEDs) ~ 40%.

4. Efficiency-Droop in Nitride LEDs – Achieving High IQE at High Current Density

To suppress the efficiency-droop observed in InGaN QW LEDs, novel QW-barrier designs with significant suppression of thermionic carrier escape at high current density are required. In nitride based material systems, the choice of appropriate materials is relatively limited for large bandgap materials applicable for InGaN QW growths. The first choice of material is thin layer of tensile AlGaIn material, and the alternative large bandgap material is thin layer of lattice-matched AlInN alloy. In our studies, we will focus on both alloys, however AlInN appears to provide much better potential with regards to the growth compatibility and device performance.

By surrounding the InGaN QW with thin (15-Å) larger-bandgap barrier materials such as $\text{Al}_x\text{Ga}_{1-x}\text{N}$ or $\text{Al}_x\text{In}_{1-x}\text{N}$, significant reduction in thermionic carrier escape rate at high current density can be achieved. Figure 8 shows the comparison of the $\eta_{\text{Injection}}$ as a function of the current density for 24-Å $\text{In}_{0.28}\text{Ga}_{0.72}\text{N}$ QW employing the 15-Å $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ barriers or 15-Å $\text{Al}_{0.83}\text{In}_{0.17}\text{N}$ barriers surrounding the QW. The u-GaN will serve as the barriers surrounding the InGaN / AlGaIn or InGaN / AlInN QW structures. The comparison indicates that the quenching of the current injection efficiency for the InGaN / AlGaIn QW structure is reduced at high current density. The InGaN / AlInN QW structure shows almost no droop up to current density of $J_{\text{tot}} \sim 500 \text{ A/cm}^2$ due to the use of thin lattice-matched $\text{Al}_{0.83}\text{In}_{0.17}\text{N}$ ($E_g \sim 4.5\text{eV}$) barriers.

The comparison of the η_{IQE} for three LED structures (conventional InGaN / GaN QW, InGaN / AlGaIn QW, and InGaN / AlInN QW) is shown in figure 9. It is very clear that the use of AlInN thin barriers leads to significant enhancement in η_{IQE} throughout the entire current density. The use of AlInN barrier will lead to relatively constant η_{IQE} up to current density of 500 A/cm^2 and beyond. The enhancement of η_{IQE} at high current density ($J \sim 800 \text{ A/cm}^2$) for InGaN / AlInN LEDs is ~ 2.14 times (or 1.75 times) over that of InGaN / GaN LEDs (or InGaN / AlGaIn LEDs).

Fig 8: The $\eta_{\text{Injection}}$ as a function of current density for 24-Å $\text{In}_{0.28}\text{Ga}_{0.72}\text{N}$ / GaN QW, 24-Å $\text{In}_{0.28}\text{Ga}_{0.72}\text{N}$ / 15-Å $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ QW and 24-Å $\text{In}_{0.28}\text{Ga}_{0.72}\text{N}$ / 15-Å $\text{Al}_{0.83}\text{In}_{0.17}\text{N}$ QW.

Fig 9: The η_{IQE} of 24-Å $\text{In}_{0.28}\text{Ga}_{0.72}\text{N}$ / GaN QW, 24-Å $\text{In}_{0.28}\text{Ga}_{0.72}\text{N}$ / 15-Å $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ QW and 24-Å $\text{In}_{0.28}\text{Ga}_{0.72}\text{N}$ / 15-Å $\text{Al}_{0.83}\text{In}_{0.17}\text{N}$ QW at 300 K.

5. Future Works (Year 3)

- 1) MOCVD epitaxy optimization of 3-layer staggered InGaN QW LEDs for emission wavelength at 540-nm.
 - ✓ Electron-hole wavefunction overlap for conventional InGaN QW is $\sim 15\text{-}17\%$.
 - ✓ Focus on 3-layer staggered InGaN QW with InGaN / InN delta-layer / InGaN QW with overlap enhancement of almost 4-times
 - ✓ Achieve IQE for green-emitting LEDs of 40%

- 2) Integrate the optimized 3-layer staggered InGaN QW which leads to the best radiative efficiency with novel barrier structures (ie. AlInN) for achieving high IQE at high current density.

✓ To achieve IQE of 40% for staggered InGaN QW LEDs at 540-nm

14. Technical Barriers/Problems:

Several technical barriers are faced by the team members for the 1st year program:

- The H₂ generator failed on February 2009, and the process to fix the generator took approximately 4-5 weeks. We had to re-qualify the MOCVD reactor after the failure in H₂ generator, and the process of re-qualification took another 3 weeks. As a result of this failure, we requested a no-cost time extension for additional 2 months.
- As of April 2009, the reactor is back up and operational. We have re-qualified the reactor, and the new results were grown by using the current reactor. The optimization of the growth conditions for three-layer staggered InGaN QW LEDs had been carried out for emission wavelength at 525-nm.

Several technical barriers are faced by the team members for the 2nd year program:

- The filter and dryer of the H₂ generator was broken on March 2010. The repair process took about ~ 1.5 months, and we need to qualify the reactor after bringing up the generator. This led to a delay of 2 months. Currently, the H₂ generator is operational , and reactor has been qualified

15. Project Team/Capabilities:

Principle Investigator and Co-Principle Investigator:

A. Dr. Nelson Tansu (PI) received his B.S. degree (Applied Mathematics, Electrical Engineering, and Physics; with Highest Distinction) and his Ph.D. degree (Electrical Engineering, with specialization in Applied Physics) from the University of Wisconsin-Madison in May 1998 and May 2003, respectively. He was a recipient of the Bohn Scholarship, the WARF Graduate University Fellowship, the Vilas Graduate University Fellowship, and the Graduate Dissertator Travel Funding Award, the 2003 Harold A. Peterson ECE Best Research Award (1st Prize) at the University of Wisconsin-Madison. From July 2003 till April 2009, he was an Assistant Professor and Peter C. Rossin Assistant Professor (Term Chair 2007-2009) in the Department of Electrical and Computer Engineering (ECE) and the Center for Optical Technologies (COT) at Lehigh University. Since May 2009 till April 2010, he is Associate Professor (with tenure) in the Department of Electrical and Computer Engineering (ECE) and Center for Optical Technologies (COT) at Lehigh University. Since May 2010 till present, Dr. Tansu is Class of 1961 Associate Professor (with Tenure) in ECE department and COT at Lehigh University. Dr. Tansu is also a recipient of the 2008 Libsch Early Career Research Award at Lehigh University.

His research works cover the theoretical and experimental aspects of the physics of semiconductor optoelectronics materials and devices, the physics of low-dimensional semiconductor (nanostructure), and MOCVD and device fabrications of III-Nitride and III-V-Nitride semiconductor optoelectronics devices on GaAs, InP, and GaN substrates. In particular related to this project, recent works in PI's group have focused on high-efficiency III-Nitride light emitting diodes for solid state lighting, as follow: 1) the use of polarization band engineering via staggered InGaN quantum wells for enhanced radiative efficiency, 2) nano-heteroepitaxy of GaN materials on nano-patterened AGOG sapphire substrate, and 3) the use of SiO₂ / PS microlens arrays for enhancing the light extraction efficiency in III-

Nitride LEDs. In this project, the PI's group is responsible for development of the numerical simulation and device physics, MOCVD epitaxy, material characterizations, device fabrications, and z-parameter recombination analysis of staggered InGaN QW LEDs. Dr. Tansu has published widely in numerous refereed international journal and conference publications (total > 200), and he also currently holds several US patents. Dr. Tansu has also given numerous lectures, seminars, and invited talks (total > 42) in universities, research institutions, and conferences in USA, Canada, Europe, and Asia. Dr. Tansu serves as the Primary Guest Editor of the IEEE Journal of Selected Topics in Quantum Electronics Special Issue on Solid State Lighting in 2008-2009, and he also serves as an Associate Editor for IEEE Photonics Journal (2009-present) and as Assistant / Associate Editor for Nanoscale Research Letters (2007-present). Dr. Tansu was also an invited General Participant at the 2008 National Academy of Engineering (NAE)'s U.S. Frontiers of Engineering (FOE) Symposium, and he also serves as the Organizing Committee for the 2009 NAE's U.S. Frontiers of Engineering Symposium. Dr. Tansu is also a recipient of the 2010 Wisconsin Forward Under 40 Award given for Outstanding Alumni (under age 40) of the University of Wisconsin-Madison.

- B. Dr. Volkmar Dierolf (Co-PI)** is a Professor of Physics and Materials Science and Engineering at Lehigh University in Bethlehem, PA, USA where he started in 2000 as an Associate Professor. He is also currently the Chair of the Physics Department. He has a Master of Physics (Stuttgart, Germany 1987) and a Ph. D (Utah, 1992) both in Physics and he obtained a Habilitation in 2000 at the University of Paderborn, Germany. In 2009, he was awarded a Mercator Visiting Professorship at the University of Bonn by the Germany Research Foundation (DFG). He also holds a honorary private lectureship at the University of Paderborn since 2000.

Dr. Dierolf has more than 10 years experience in spectroscopy and microscopy in materials ranging from ferroelectrics to optical fiber to semiconductors. His research is focused on optical spectroscopy and microscopy of defects and localization effects in insulating materials as well as wide-band gap semiconductors. His specialty is combined optical spectroscopy in which correlated spectral, spatial and temporal information is extracted. He has published several books and book chapters along with 100+ reviewed articles including several invited review articles.

As part of the DOE program, he is leading the studies of the staggered QW structures using a variety of unique optical characterization tools that combine spatial, spectral and temporal resolution. He has developed his specialty in novel and improved characterization techniques such as combined excitation emission spectroscopy, UV near-field optical spectroscopy, and combined CL/PL studies. His group is in charge for the nanoscale microscopy photoluminescence, time-resolved photoluminescence, and low-temperature photoluminescence of the staggered InGaN QW LEDs. Dr. Dierolf has more than 70 publications in refereed journal and conferences.

PostDoctoral Research Fellows and PhD Students

- **Dr. Gensheng Huang (MOCVD), Postdoc**
 - ➔ Dr. Huang is in charge of MOCVD epitaxy of InGaN QW LEDs and related process. Dr. Huang also performed the training for MOCVD equipment for PhD students. Dr. Huang is involved in the training of graduate students involved in this program, however he is not funded from the DOE project.
- **Dr. Samson Tafon Penn (CL), Postdoc**
 - ➔ Dr. Tafon Penn is in charge of cathodoluminescence operation and training at Lehigh University. Dr. Tafon Penn is involved in training graduate students involved in this program, in particular for performing cathodoluminescence measurements.

- **Ms. Hongping Zhao (MOCVD, Devices), PhD student**
 - ➔ Ms. Zhao is in charge of the design simulation and MOCVD epitaxy optimization, and device fabrication of staggered InGaN QW LEDs.
- **Ms. Guangyu Liu (Time-Resolved PL), PhD student**
 - ➔ Ms. Liu is in charge of the time-resolved photoluminescence set up and measurements performed on staggered InGaN QW LEDs. Ms. Liu is also involved in the growth optimization of staggered InGaN QW LEDs.
- **Mr. Xiaohang Li (Low Temperature PL, SEM), PhD student**
 - ➔ Mr. Li is in charge of low-temperature photoluminescence measurement set up and scanning electron microscopy measurements performed on the sample.
- **Mr. Jonathan Poplawsky (CL), PhD student**
 - ➔ Mr. Poplawsky is in charge of the cathodoluminescence measurements of staggered InGaN QW LEDs.

C. Commercialization Plan (Relative to Product Focus Area Only):

Currently, we have not worked with industry. However, there have been several LEDs industries that have contacted us about working with us, as well as implementing the intellectual properties from our works in their next generation LEDs (ie. Epistar, which is one of the leading LED manufacturers).

16. Deliverables and Milestones

Phase I – Year 1

- 1) Optimized 450-nm staggered InGaN QW LEDs (*Accomplished*)
- 2) Working 500-nm staggered InGaN QW LEDs (*Accomplished*)
- 3) Operational NSOM capabilities for InGaN QW LEDs (*Accomplished*)

Phase II - Year 2

- 1) Optimized staggered InGaN QW LEDs emitting at 540-nm with $IQE > 20\%$.
 - ✓ *Obtain IQE of 14% for green emitting QW*
- 2) Develop method to *characterize the internal quantum efficiency of electrically-injected LEDs*, which will provide good quantitative IQE for comparison of staggered InGaN QW LEDs.
 - ✓ *Complete measurements and provide quantitative IQE for devices*
- 3) Develop *novel device structure based on staggered InGaN QW LEDs to achieve reduction in efficiency-droop for enabling high IQE at higher current density*. Note that the optimization of the IQE will require the optimization of radiative efficiency and current injection efficiency.
 - ✓ *Complete the simulation of InGaN-AlInN QW LEDs*
 - ✓ *Complete growth optimizations for AlInN barriers*
 - ✓ *Preliminary InGaN – AlInN QW LEDs were grown and demonstrated*

Phase III – Year 3

- 1) Achieve optimized 540-nm emitting staggered InGaN QW LEDs with *internal quantum efficiency > 40%*
- 2) *Demonstrate and optimize novel structure based on staggered InGaN QW LEDs with reduction in efficiency-droop to achieve high IQE at high current density.*