III-Nitride Optoelectronic Devices: *From ultraviolet detectors and visible emitters towards terahertz intersubband devices*

C. Bayram (*Link Foundation Energy Fellow*) and M. Razeghi, (*Faculty Advisor*)

Center for Quantum Devices, Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, Illinois 60208, USA

Corresponding Fellow: cbayram@northwestern.edu; Corresponding Advisor: razeghi@eecs.northwestern.edu

SUMMARY: We review III-Nitride optoelectronic device technologies with an emphasis on recent breakthroughs achieved with the co-support of Link Foundation Energy Fellowship. We start with a brief summary of historical accomplishments and then report the state-of-the-art contributions in three key spectral regimes: (1) Ultraviolet (AlGaN-based avalanche photodiodes and single photon detectors), (2) Visible (InGaN-based solid state lighting), and (3) Near-, mid-infrared, and terahertz (AlGaN/GaN-based gap-engineered intersubband devices). We also describe future trends and possible prospects in III-Nitride optoelectronic devices made possible with the fellow's work.

SECTION I – NARRATIVE SUMMARY

III-Nitride material system (AlGaInN) possesses unique optical, electrical, and structural properties such as a wide tunable direct bandgap, large longitudinal optical phonon energy, inherit fast carrier dynamics; good carrier transport properties, high breakdown fields; and high robustness and chemical stability. Thanks to these inherit advantages, they are investigated for everyday to military and scientific applications such as illumination sources; bio-agent detection, concealed weapons/drugs detection; and space exploration.

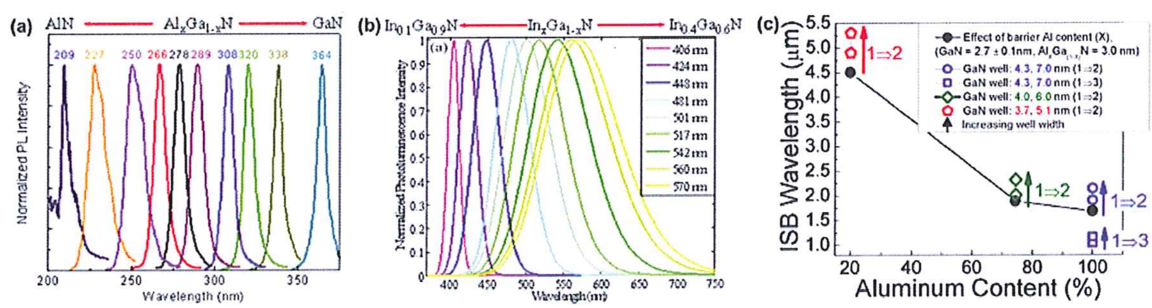

Figure 1: Tunibility of III-nitride material system from ultraviolet to visible towards terahertz spectra. (a) Complete tunibility in the ultraviolet range by $Al_XGa_{(1-X)}N$. (b) Tunibility in the visible regime by $In_XGa_{(1-X)}N$. (c) Tunibility of intersubband transitions in $Al_XGa_{(1-X)}N/GaN$ superlattices from near- to mid-infarred (limited by the substrate – sapphire – absorption).

The first spectrum of interest has been the ultraviolet (UV) spectrum. Ultraviolet region is very important as many biological agents (such as smallpox and anthrax) are luminescent in UV. Scattering of short-wavelengths in atmosphere enables non-line-of-sight secure communications in rugged terrains whereas strong reflection/absorption of UV at ionosphere promises secure space-to-space communications. Where photomultiplier tubes are found to be bulky and fragile, and Si(C)-based photodiodes require external filter elements, compact high performance UV

(Al)GaN avalanche photodiodes (APDs) can be employed. Via Geiger-mode operation of these APDs, single UV photons can be counted that could enable quantum computing and data encryption in near future. As a fellow, Mr. Bayram increased the sensitivity of these detectors by more than three orders of magnitude (gains of 53000) and demonstrated first single photon detection with recent efficiencies as high as 32%.

The second spectrum of interest is the visible spectrum. The total annual energy consumption in the United States for lighting is approximately 800 Terawatt-hours and costs $80 billion to the public. The energy consumed for lighting throughout the world entails to greenhouse gas emission equivalent to 70% of the emissions from all the cars in the world. During his fellowship, Mr Bayram continued developing InGaN-based novel light emitting diodes and proved them as the key components of an affordable, durable and environmentally benign lighting solution that can achieve unique spectral quality and promise superior energy conversion efficiency than current lighting sources.

The third spectrum of interest is the terahertz spectrum. Terahertz spectral range offers promising applications for science (such as cancer detection), industry (such as product defect detection), and military (such as drug, concealed weapon or explosives detection), and III-Nitrides are the integral part of unique quantum cascade laser designs that are theoretically capable of THz lasing at room temperature (RT). As a fellow, most recently, Mr. Bayram engineered AlN/GaN and AlGaN/GaN superlattices to show intersubband energy level controls in near- and mid-infrared spectra, respectively. Moreover, he has shown $Al_XGa_{(1-X)}N$/GaN resonant tunneling diodes to possess negative differential resistance at RT proving electronic quantum transport in this material system. His recent demonstrations motivate RT THz emitters based on GaN.

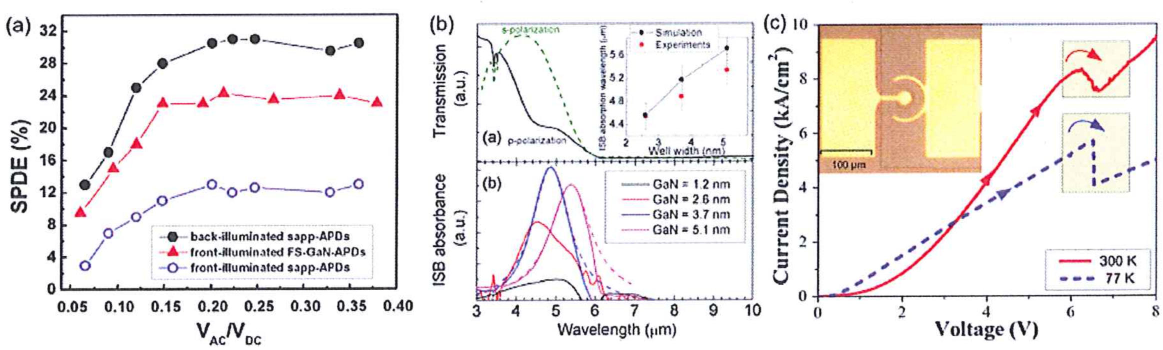

Figure 2: Inter- and intersubband III-nitride devices: Ultraviolet single photon detectors, Mid-IR intersubband absorption devices, and GaN-based quantum tunneling devices. (a) Dependence of single photon detection efficiency (SPDE) on substrate (sapphire or freestanding GaN) and on illumination configuration (back- or front-illuminated). (b) Demonstration of intersubband absorption and its dependence on GaN well width in mid-infrared. Inset compares the theoretical calculations with experimental results. (c) Demonstration of first resonant tunneling quantum device with reliable negative differential resistance in GaN material system at RT and 77 K. Inset shows optical micrograph of a resonant tunneling diode.

Mr. Bayram investigated the growths of III-nitride optoelectronic devices on polar and non-polar substrates. He identified the effects of lattice-mismatched (sapphire) versus latticematched (GaN) substrates and polar (c-plane) versus non-polar (m-plane) substrates on detectors and intersubband devices. The emerging low-dislocation free standing substrates have shown promise from single photon detection to resonant tunneling diodes (RTDs).

In conclusion, with continuous developments in material growth/characterization and device processing/measurement technologies, Mr. Bayram has gap-engineered III-Nitride materials and during the fellowship has extended the unique solutions from ultraviolet and visible wavelengths towards THz spectra. Demonstration of single photon detection efficiencies of 33% in the ultraviolet regime, intersubband energy levels as low as in the mid-infrared regime, and GaN-based resonant tunneling diodes with negative resistance of 67 Ω are demonstrated. His results suggest that with proper device design and gap-engineering, the (sub)bands of AlGaInN can be engineered for a wide optical range from ultraviolet towards terahertz enabling more energy-efficient and environmentally-friendly alternatives to existing technologies.

SECTION II – SCHOLAR CONTRIBUTIONS

Mr. Bayram has made 13 total scientific contributions as a Link Foundation Energy Fellow. The distribution of these contributions are as follows: 3 journal papers, 1 conference paper, and 5 invited talks. In all these contributions, the fellowship is acknowledged where possible.

JOURNAL PAPERS:

1. **C. Bayram**, Z. Vashaei, and M. Razeghi, "*Reliability in room-temperature negative differential resistance characteristics of low-aluminium-content AlGaN/GaN double-barrier resonant tunneling diodes*," Applied Physics Letters 97, 181109 (2010).
2. Z. Vashaei, **C. Bayram**, P. Lavenus, and M. Razeghi. "*Photoluminescence characteristics of polar and nonpolar AlGaN/GaN superlattices*," Applied Physics Letters 97, 121918 (2010).
3. **C. Bayram**, Z. Vashaei, and M. Razeghi, "*Room temperature negative differential resistance characteristics of polar III-nitride resonant tunneling diodes*," Applied Physics Letters 97, 092104 (2010). (Due to strict three-page limitation, acknowledgement was eliminated during APL editing process.)

CONFERENCE PAPERS:

4. Z. Vashaei, **C. Bayram**, R. McClintock, and M. Razeghi, "*Effects of substrate quality and orientation on the characteristics of III-nitride resonant tunneling diodes*", Proc. SPIE 7945, 79451A (2011).

INVITED TALKS AND PRESENTATIONS:

5. **C. Bayram** and M. Razeghi, "*AlGaInN gap engineering from ultraviolet an visible wavelengths towards terahertz regime*," ICDD Spring Meeting Pennsylvania, USA, March 17 (2011).

6. **C. Bayram** and M. Razeghi, "*III-Nitride Optoelectronic Devices*," ICDD Spring Meetings, Pennsylvania, USA, March 15 (2011).
7. Z. Vashaei, **C. Bayram**, R. McClintock, and M. Razeghi, "*Effects of substrate quality and orientation on the characteristics of III-nitride resonant tunneling diodes*", SPIE Photonics West, San Francisco, California, USA, January 22-27 (2011).
8. R. McClintock, E. Cicek, Z. Vashaei, **C. Bayram**, M. Razeghi, and Melville P. Ulmer, "*III-Nitride Based Avalanche Photo Detectors*," SPIE Optics + Photonics, San Diego, USA, August 1-5 (2010).
9. M. Razeghi, **C. Bayram**, R. McClintock, F.H. Teherani, D.J. Rogers, and V.E. Sandana, "*Novel Green Light Emitting Diodes: Exploring Droop-free Lighting Solutions for a Sustainable Earth*", LED 2010: The 4th International Conference on LED and Solid State Lighting, COEX (Seoul), Korea, Feb. 3-5 (2010).

SECTION III – FINANCIAL STATEMENT

Mr. Bayram has used the discretionary funds for research related expenses and attendance to technical meetings. The Fellow bought related books on the field, (re)new related professional society subscriptions, and finite-element-modeling tools for device simulations. The Fellow attended multiple technical meetings where he presented his results. All these enabled him to continue his high impact work and generate continuous ideas for experimentation.

SECTION IV –IMPACT OF FELLOWSHIP

The Link Foundation Energy Fellowship support enabled Mr. Bayram to stay up-to-date, lead in the field, and broaden his work. He has sustained to be a member of academical societies and received daily updates on science and technology enabling him to learn and generate ideas. The academical books bought with the fellowship support have widened his chemistry, physics, and materials science knowledge enabling improved engineering devices ranging from ultraviolet detectors, visible emitters, and intersubband devices. With this kind of continuous multidisciplinary approach, he has been able to undertake the most difficult new challenge: realization of reliable GaN-based resonant tunneling diodes suitable for terahertz emission. He has experimentally demonstrated that tunneling process can be stabilized in III-Nitride materials system and showed promising emission powers of 0.52 mW from these RTDs. Furthermore, fellowship support enabled attendance to many invited talks and distribution of scientific knowledge to a broader audience enabling wide impact.