III-Nitride Photonics

Nelson Tansu, Hongping Zhao, Guangyu Liu, Xiao-Hang Li, Jing Zhang, Hua Tong, and Yik-Khoon Ee

(Invited Paper)

Center for Optical Technologies, Department of Electrical and Computer Engineering, Lehigh University, Bethlehem, PA 18015 USA

DOI: 10.1109/JPHOT.2010.2045887

Manuscript received January 27, 2010; revised February 23, 2010. Current version published April 23, 2010. Corresponding author: N. Tansu (e-mail: tansu@lehigh.edu).

Abstract: The progress in III-Nitride photonics research in 2009 is reviewed. The III-Nitride photonics research is a very active field with many important applications in the areas of energy, biosensors, laser devices, and communications. The applications of nitride semiconductors in energy-related technologies include solid-state lighting, solar cells, thermoelectric, and power electronics. Several new research areas in III-Nitride photonics related to terahertz photonics, intersubband quantum wells, nanostructures, and other devices are discussed.

Index Terms: III-Nitride, photonics, light-emitting diodes, lasers, solid state lighting, nanotechnology, energy, thermoelectric, photodetector, terahertz, intersubband quantum well.

The fields of III-Nitride photonics have made significant progress in the Year 2009. The applications of III-Nitride semiconductor photonics cover many different areas including visible diode lasers, solid-state lighting, solar cells, and biosensors. In addition to the progress of nitride semiconductor devices for these applications, new research areas in III-Nitride photonics have arisen such as terahertz generation, intersubband quantum well (QW) devices, nitride-based nanostructures, and other opto-electronics devices.

High-performance III-Nitride light-emitting diodes (LEDs) play significant role for solid-state lighting [1]. Recent significant progress in 2009 has focused on three important aspects limiting the performance applicable for solid-state lighting [2], [3], namely 1) "green gap" issue in nitride LEDs, 2) efficiency-droop in high-power LEDs, and 3) novel approaches for high light extraction efficiency.

To address "green gap" nitride LEDs, there are two important issues, namely 1) charge separation issues in InGaN/GaN QWs and 2) low material quality for high-In-content InGaN QWs required to achieve green emission. The existence of the strong electric field from both spontaneous and piezoelectric polarizations causes the charge separation in the InGaN QWs, which leads to a significant reduction of the electron-hole wavefunction overlap (Γ_{e_hh}). The significant reduction of Γ_{e_hh} in InGaN QW leads to significant reduction in its radiative recombination rate $(\sim|\Gamma_{e\_hh}|^2)$. The charge separation effect has been one of the most challenging factors leading to significant reduction in radiative efficiency in green-emitting nitride LEDs (a key technology for solid-state lighting). In order to address the charge separation issues in nitride QWs, several approaches have been pursued with the goal to achieve high-internal-quantum-efficiency InGaN QW LEDs to address the "green gap" in solid-state lighting devices. The use of nonpolar InGaN QW LEDs has been investigated as a potential approach to address charge separation issue [4]–[6], and significant progress on this

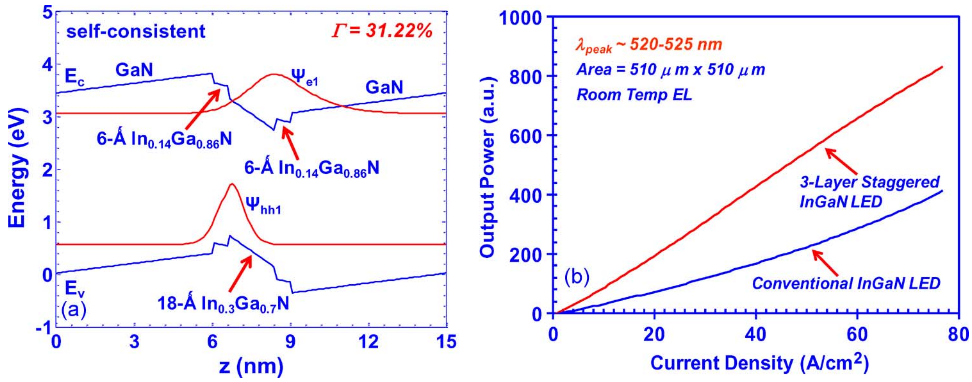

Fig. 1. (a) Schematic of band lineup for three-layer staggered InGaN QW active region with improved overalp emitting at green spectral regime. (b) Comparison of the light output power for green-emitting staggered InGaN QW LEDs and conventional InGaN QW LEDs.

exciting technology has been reported in 2009 [4]–[6]. One of the main issues for nonpolar InGaN QW LEDs is related to less mature material epitaxy and substrate availability; thus, the advances in improved epitaxy and nonpolar GaN substrate developments will have a tremendous impact on the progress of this technology.

In addition to the pursuit of nonpolar nitride QW technologies, there are significant efforts to engineer the polar InGaN QW structures with improved electron-hole wavefunction overlap [9]–[23]. By improving the electron-hole wavefunction overlap $(\Gamma_{\text{e\_hh}})$ in the InGaN-based QW, several successful demonstration have been reported to increase the radiative recombination rate and radiative efficiency (and internal quantum efficiency) of nitride LEDs emitting in blue and green spectral regime. The concept of staggered InGaN QW LEDs was proposed and demonstrated previously [7]–[9], and recent experimental works on the growth of three-layer staggered InGaN QW LEDs have resulted in a 2.5–3 times enhancement in radiative efficiency and output power of the devices [10]–[12] emitting in the green spectral region, as shown in Fig. 1. Time-resolved photoluminescence from the staggered InGaN QW LEDs had also shown that the enhancement in output power can be attributed to the increase in radiative recombination rate [12]. Based on the comprehensive modeling of staggered InGaN QW, it is expected that the use of this active region will potentially result in internal quantum efficiency in the range of 50% for green-emitting devices [10]. In addition to the use of staggered InGaN QW LEDs, several other approaches have been pursued as follow: type-II InGaN-GaNAs QW [17], [18], strain-compensated InGaN-AlGaN QW [19], [20], triangular InGaN QW [21], InGaN QW with delta-AlGaN layer [22], [23], and dip-shape QWs [15]. Another issue on the “green-gap” LEDs is related to the material quality. Wetzel *et al.* identified the importance of improving the epitaxy of high-In-content InGaN QW to reduce the V-defect density [24], which will improve the radiative efficiency of the active region by suppressing the nonradiative process.

One of the major challenges for high-power nitride LEDs is the issue of “efficiency-droop.” The use of c-plane InGaN-based QW LEDs suffers from the reduction in efficiency at high operating current density, which is referred as “efficiency-droop” [25]–[35]. Both the external (EQE) and internal (IQE) quantum efficiencies reach their maximum and start to drop at current densities of 10–60 A/cm^2 [25]–[35]. The efficiency-droop is a very important limitation for achieving high-power LEDs, as these devices are required to operate at relatively high operating current density $(> 200-300\ \text{A/cm}^2)$. The origin and dominant mechanisms leading to efficiency-droop phenomenon in nitride LEDs are very controversial, and the understanding of the factors leading to the droop is lacking. Several factors have been suggested as potential reasons affecting the efficiency-droop in LEDs, however two leading theories have arisen, namely 1) carrier leakage process [27]–[30] or/and 2) Auger process in InGaN active region [34], [35]. Recent theoretical studies predicted Auger recombination coefficient in InGaN/GaN QW system as $C = 3.5 \times 10^{-34}\ \text{cm}^6/\text{s}$ [36]. However, it is important to note that recent experimental studies have indicated the possibility of the Auger recombination coefficient in thick InGaN/GaN double-heterostructure active regions

($d_{Active} = 10-77$ nm) in the range of $C = 1.4 \times 10^{-30}$ cm^6/s up to $C = 2 \times 10^{-30}$ cm^6/s [34], [35]. Recent theoretical works have suggested the possibility of interband Auger recombination as the dominant process in InGaN bulk semiconductor [37]. Further studies are still required to clarify and confirm the Auger coefficients (C) for InGaN/GaN QW system, due to the large discrepancies for the reported Auger coefficients in the literatures [34]–[37]. Another leading theory has attributed the carrier leakage from the polarization field as the main factor in the efficiency-droop in the InGaN QW LEDs. Recently, InGaN QWs employing polarization matched quaternary AlInGaN barriers instead of GaN barriers have been demonstrated as a method to reduce the efficiency droop [29], [30]. Another interesting approach to suppress efficiency-droop is by employing very thin large bandgap barriers (i.e., AlInN or AlInGaN) to surround the InGaN QW active region [38]. The complete description of the current injection efficiency and radiative efficiency in nitride LEDs are important to provide complete understanding and indicate potential solutions to efficiency-droop in nitride LEDs [38]. The use of thin larger bandgap barrier materials in more mature GaAs-based diode lasers had resulted in significant carrier leakage suppression, leading to high-performance laser devices [39]–[44]. The accurate determination of internal quantum efficiency in nitride LEDs is still challenging, and recently, Getty *et al.* presented an approach to determine the IQE by taking into consideration the light extraction efficiency of the LEDs [45].

The coupling of the surface plasmon mode to the InGaN QW active region leads to an increase in density of states and to a Purcell enhancement factor, which in turn leads to significant increase in radiative recombination rate and radiative efficiency of the InGaN QW LEDs [46], [47]. The tuning of the surface plasmon mode by employing metallo-dielectric stacked layers was proposed [48], [49], and recently, the use of double metallic layer was also proposed as an approach to tune the surface plasmon frequency over a wide range of spectrum [50]. The demonstration of the electrical-injected surface plasmon InGaN QW LEDs was recently demonstrated [51]. However, significant works are still required to achieve optimized device structures.

Other important aspect of nitride LEDs focused on the pursuit of novel low-cost colloidal-based microlens arrays as an approach to enhance the light extraction efficiency of nitride LEDs [52]–[55]. The use of convex colloidal microlens arrays based on SiO_2/polystyrene microspheres had resulted in enhancement of more than 2.5 times in light output power, in comparison with that of conventional planar LEDs [52]–[54]. The use of concave microlens arrays have also been demonstrated with enhancement of 1.7 times [55], and the use of this approach have the potential to result in self-focusing in the far-field pattern. Recently, the use of photonic crystal have also resulted in significant enhancement in nitride LEDs [56], [57], with encapsulated light extraction efficiency as high as 73% [56].

In addition to the issues presented above for solid-state lighting, other interesting progress to realize white LEDs have been reported in 2009. The use of a phosphor-free approach to generate white LEDs have focused on the mixing of blue- and yellow-emitting QWs in a device structure [58]. Another approach has focused on the use of 1) patterning and selective area epitaxy or 2) *in situ* roughening to realize GaN with different planes, such that the different polarization fields will lead to emission from two different spectra [59], [60].

The availability of high-quality GaN substrate is important for the progress of GaN-based optoelectronics, and the issues related to research and development of this substrate technology is reviewed by Paskova *et al.* [61]. Another important aspect is the use of novel epitaxy technique to reduce the dislocation density in GaN material grown on sapphire substrate. The use of new "abbreviated growth mode" of GaN on nanopatterned sapphire [62], [63] leads to the growth of GaN material with significant reduction in dislocation density (2-order of magnitude), as well as a reduction in epitaxy time/cost. The experimental works have resulted in improvement in radiative efficiency of InGaN QW LEDs employing this growth technique by approximately 25% [62], [63].

The visible diode lasers have applications as light sources for DVD, medical, industrial, display, and laser mini projectors. The availability of green-emitting nitride diode lasers will be advantageous over current technology based on frequency-doubled sources. In order to overcome the detrimental effect from the polarization fields, nitride heterostructures and QWs grown along nonpolar or semipolar orientations have been attempted. Recently, nonpolar m-plane InGaN/GaN QW laser diodes (LDs) emitting at 404 nm without Al-containing waveguide cladding layers grown on free-standing m-plane

GaN substrates have been demonstrated [64]. The threshold current density and operating voltage of the nonpolar diode lasers are 6.8 kA/cm^2 and 5.6 V, respectively, and the devices operate under continuous-wave (CW) condition at room temperature for more than 15 h. More recently, asymmetric p-GaN/n-AlGaN-cladded InGaN-based pure blue (440–460 nm) LDs were fabricated on the nonpolar m-plane GaN substrate [65]. The lasing wavelengths are 443 nm and 465 nm, with threshold current densities of 14 kA/cm^2 and 19 kA/cm^2, respectively. Despite the theoretical promise of the higher optical gain for nonpolar InGaN QW resulting from the elimination of the polarization field in the active region, the performance of the nonpolar lasers is still limited by the epitaxy and material quality issues. The epitaxy and material quality of current nonpolar and semipolar materials are still less mature than the more established c-plane (0001) GaN, where nonpolar GaN films are found to contain high concentration of stacking faults and threading dislocations. The progress in the nonpolar InGaN–GaN QW active region is very promising, and it is expected that the nonpolar nitride materials and devices would have impacts in the field of diode lasers and solid-state lighting. However, the maturity of this technology is still at early stage, and a significant amount of research and development works are still required to enable this technology to compete with polar c-plane GaN materials.

Recently, InGaN-QW-based LDs grown on c-plane GaN substrate with lasing wavelength of 510–515 nm was demonstrated by Nichia with threshold current density of 4.4 kA/cm^2 at 25 °C and output power of 5 mW (at $I = 88$ mA and $V = 5.5$ V) [66]. Note that the laser structure [66] was fabricated by employing both facets coated with high-reflectivity (HR) dielectric films (HR/HR), which reduces the mirror loss and threshold gain. However, the HR/HR coatings on both facets limit the output power and external differential quantum efficiency of LDs, which leads to limitations of conventional InGaN QW as active regions for high-power LDs or other laser devices requiring high-gain active region (i.e., VCSELs). Recently, OSRAM reported the 500-nm electrically driven InGaN-based LDs grown on c-plane GaN substrate with threshold current density of 8.2 kA/cm^2 and output power of several tens of milliwatts [67], with mirror coatings of 50% and 95%. OSRAM also reported InGaN LDs emitting at 515 nm with threshold current density of $\sim$9 kA/cm^2 [68]. It is very challenging to extend the conventional InGaN-QW-based LDs to the green spectral regime with high output power and low-threshold current density. Further advances are still required to reduce the threshold current density from 4.4–8.2 kA/cm^2 down to more acceptable level. Significant reduction in threshold carrier density and threshold current density in green-emitting diode lasers are important, in particular, for enabling the nitride QW lasers as practical and reliable laser technology in the green spectral regimes. Polar novel InGaN-based QWs with improved overlap design are expected to reduce the threshold carrier density [18], [20], [69], which in turn have the potential to enable the realization of high-performance green-emitting LDs.

Significant progress on the theoretical description of the nitride quantum dots have been reported in 2009. Williams *et al.* [70] and Wu *et al.* [71] reported the simulations of nitride QDs as significantly different than those of GaAs-based QDs, due to the existence of the polarization fields and strong shape-dependent characteristics. One of the important challenges in the growth of self-assembled nitride QDs is the relatively low-density QD density for enabling realization of high-performance photonics devices [72]. The progress in the growths of high-quality and ultrahigh-density nitride QDs are still ongoing.

High-efficiency multijunction tandem solar cells of InGaN/InN material have the potential to compete with the traditional III–V tandem cells [73]–[75]. Recent progress on the InGaN-based single-junction solar cells has been exciting. Dahal *et al.* reported the use of $In_{0.3}Ga_{0.7}N$ multiple QWs resulting in open circuit voltage of about 2 V and fill factor of 60% [74]. Neufeld reported the use of 2.95 eV InGaN junction to achieve solar cells with open circuit voltage of 1.81 V and fill factor of 75% [75]. The pursuit of narrow bandgap junction by employing InN semiconductor with metalorganic chemical vapor deposition is important [76]–[78], and the use of pulsed MOCVD growth method has resulted in narrow-bandgap (0.77 eV) InN with relatively low V/III ratio [77], [78].

The pursuit of near-infrared intersubband QW devices require large conduction band offset, which can be accomplished by GaN/AlN heterostructure. Transition wavelengths in the spectral range of 2 μm had been reported for GaN/AlN QWs measured under optical pumping [79]. Sodabanlu *et al.* have reported the use of AlGaN interlayer to modify the strain in the GaN/AlN QWs and shift the wavelength into the 1.54-μm spectral regime [80]. Significant works are still required to investigate the use of polar GaN/AlN-based QWs to realize intersubband QW lasers. The pursuit of intersubband devices by employing nitride quantum dots and nanowires are important to enable the realization of devices operating at room temperature.

The use of ultrafast laser pulses have led to efficient generation of broad terahertz pulses from InN films [81]–[83]. The average output power reached 0.93 μW based on result for 700-nm-thick InN film [83], and the mechanism can be attributed to the resonance enhanced optical rectification. Recently, a new results based on terahertz generation from pulsed-MOCVD grown have indicated the existence of destructive interference between optical rectification and photocurrent surge [84]. From the studies in reference [84], optical rectification is the primary mechanism for the terahertz generation in the frequencies of 300 GHz–2.5 THz, with ultrafast laser pulses at 782 nm. The highest output power reported is 2.4 μW at an average pump intensity of 176 W/cm^2 from the 220-nm-thick pulsed-MOCVD grown InN film [84].

In summary, significant progress and exciting research advances in III-Nitride photonics have been reported in 2009. The impacts of III-Nitride photonics are wide ranging with applications in solid-state lighting, solar cells, visible lasers, and biosensors, and the progress in these fields are expected to continue. Further growths in new research areas such as intersubband QW devices, surface plasmonic-based devices, novel nanostructures, Terahertz generation, and potential uses for thermoelectric applications are expected in the research areas of III-Nitride photonics and semiconductors. Nitride-based LEDs and lasers have been employed as light sources for probing biological materials in the visible and UV spectral regimes. Recently, AlGaN/GaN high-electron-mobility transistor (HEMT) has been demonstrated for solid-state biosensor application with excellent thermal, chemical, and mechanical stability, which suggests that nitride HEMTs are excellent candidates for pressure sensor and piezoelectric-related applications [85]. The avalanche photo diodes (APDs) based on GaN material have also been developed, and recently, first principle simulations have also provided accurate modeling of the properties of these devices [86].

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