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Development of gallium-nitride-based light-emitting diodes (LEDs) and laser diodes for energy-efficient lighting and displays

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Abstract

Light-emitting diodes (LEDs) fabricated from gallium nitride (GaN) have led to the realization of high-efficiency white solid-state lighting. Currently, GaN white LEDs exhibit luminous efficacy greater than 150 lm W^{-1}, and external quantum efficiencies higher than 60%. This has enabled LEDs to compete with traditional lighting technologies, such as incandescent and compact fluorescent (CFL) lighting. Further improvements in materials quality and cost reduction are necessary for widespread adoption of LEDs for lighting. A review of the unique polarization anisotropy in GaN is included for the different crystal orientations. The emphasis on nonpolar and semipolar LEDs highlights high-power violet and blue emitters, and we consider the effects of indium incorporation and well width. Semipolar GaN materials have enabled the development of high-efficiency LEDs in the blue region and recent achievements of green laser diodes at 520 nm.

Keywords: GaN; LEDs; Laser diodes; Solid-state lighting

1. Introduction

Group-III nitrides composed of GaN and its alloys with InN and AlN have revolutionized the solid-state lighting market due to their ability to emit a wide range of wavelengths in the visible spectrum. GaN-based high-efficiency light-emitting diodes (LEDs) have increasingly become a viable light source for illumination applications, such as automotive headlights, interior/exterior lighting and full color displays. However, current commercial GaN LEDs grown on the *c*-plane of the wurtzite crystal are negatively impacted by the quantum confined Stark effect (QCSE) due to the large polarization-related spontaneous and piezoelectric fields [1]. This effect causes tilted conduction and valence bands in the active region, resulting in the separation of electrons and holes in active regions, thus reducing the overlap of the electron and hole wave functions, resulting in a reduction in internal quantum efficiency (IQE) [2].

The past several years have seen remarkable progress in the GaN material system for visible laser diode (LD) applications as well. Development of GaN LDs on the standard basal plane is also challenged by the polar nature of the GaN wurtzite crystal structure, particularly for emission wavelengths beyond 500 nm. Alternative crystal orientations of GaN with reduced or no polarization are referred to as semipolar and nonpolar planes, respectively, and offer several benefits that make them a superior candidate over the polar basal-plane GaN, especially for high-wavelength applications. These alternative planes are not without their own challenges related to crystal growth and device design. This paper outlines some of the material properties, growth issues and device considerations for GaN-based LEDs and LDs on nonpolar and semipolar planes for visible wavelength applications.

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2. White GaN LEDs

GaN is a direct band gap semiconductor material with a 3.45 eV band gap which corresponds to near ultraviolet (UV) light (364 nm). GaN was first investigated as a potential material for LEDs in the late 1960s by Paul Maruska and Jacques Pankove at the Radio Corporation of America (RCA) and in later years additionally by Isamu Akasaki [3] and co-workers at the Nagoya University in Japan and Shuji Nakamura at the Nichia Corporation [4]. Early attempts to realize blue-emitting semiconductors initially focused on SiC, but these devices proved to be inefficient (0.03% efficiency [5]) due to the material's indirect band gap. The GaN revolution has since provided efficient UV, violet and blue light emitters.

Due largely to these achievements it is now possible to actually generate white light using GaN LEDs. The three most popular and well-established approaches to using LEDs to generate white light are shown in Fig. 1. They are a blue LED with yellow phosphors; a UV LED with blue and yellow phosphors (or red, green and blue phosphors); and a device that combines red, green and blue LEDs. Currently, the blue GaN LED plus yellow phosphor dominates the white LED industry. The advantage to using a blue LED and yellow phosphor is ease of manufacture and its high theoretical efficacy, which is attractive for the creation of a cheap, bright white light source. However, this benefit comes at the expense of a lower color rendering index value, which is typically low, and makes such devices undesirable for indoor use. Typically an additional red or green phosphor is then added to the phosphor mix to get broader spectral emission and hence higher CRI values. Violet and UV LEDs with tri-color phosphor mixtures provide better color rendering index (CRI) values and are suitable for indoor applications but at the expense of poorer efficacy. If one desires to dynamically control white light, the third approach, a combination of three (or more) LEDs of different wavelengths, is attractive, and will enable higher efficacies than the UV phosphor LEDs, but will generally be the most expensive option of the three until further advances are made.

The first two white LED approaches use phosphors for creating broad-band white light by using a material which absorbs light of one wavelength and emits at longer wavelength. Phosphors are commonly used for this task and a selected few have received considerable attention, such as rare-earth doped yttrium aluminum garnets (YAG:RE, $Y_3Al_5O_{12}$(RE)). For example, cerium-doped YAG can absorb blue and UV light and emit yellow light relatively efficiently [6]. Crucial to this process is the fact that higher energy light (e.g. UV or blue) is converted to lower energy (e.g. yellow or red). Therefore, LEDs emitting red light – the lowest energy color in the visible spectrum – are not feasible for white light generation using phosphors; instead, a short-wavelength UV, violet or blue LED is required. In addition, yellow LEDs made from InGaN are still not as efficient as blue InGaN LEDs pumping yellow phosphors [7].

3. LED efficiency

There are several key performance parameters to consider when discussing LEDs. Recent research has focused heavily on improving the external quantum efficiency (EQE) of an LED. The external efficiency is the ratio of photons externally emitted from the device, divided by the electrons injected into the device. Over the past decade most of the improvements in materials and device design have enabled the evolution of EQE from 25% in the early 2000s [8], to over 70% for vertical LEDs (VLEDs) today, as shown in Fig. 2. The device improvements primarily relied on increased light extraction by either patterned sapphire substrates (PSSs) or roughening in VLEDs to achieve efficiencies of over 50%. Other LED parameters of importance included improving the internal quantum efficiency (IQE), that is, the ratio of photons generated to the number

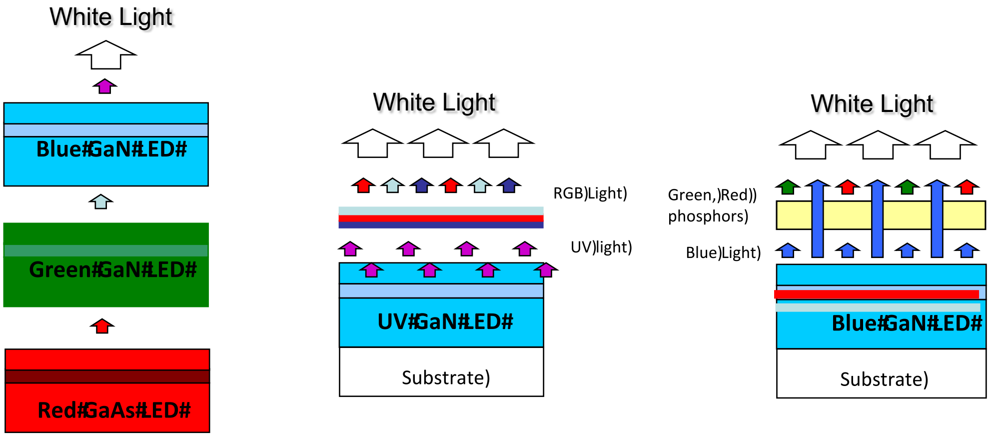

Fig. 1. Three ways of generating white light from GaN LEDs: (a) combination of red, green and blue LEDs, (b) UV GaN LED plus three phosphors, and (c) blue GaN LED plus yellow phosphor. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

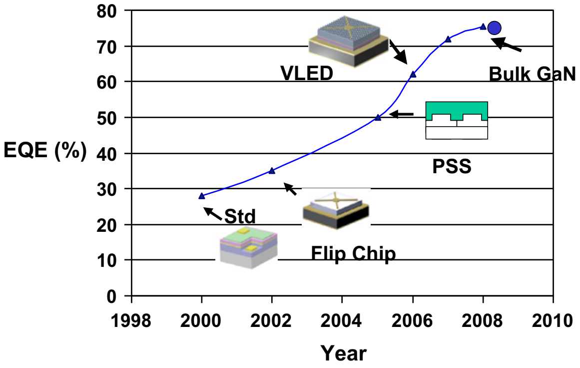

Fig. 2. Evolution of external quantum efficiency over the past decade has been driven by improvements in chip design and material improvements.

of electron–hole recombinations through improvements in the material quality, and reducing the defect density by using bulk GaN substrates. In the case of white light generation, using phosphors with a high conversion efficiency factor enabled a high ratio of emitted longer wavelength photons to shorter wavelength absorbed photons, thus improving the luminous efficiency. Future progress will heavily depend on improvements in all of the following major areas: (1) internal quantum efficiency, (2) light extraction efficiencies, (3) eliminating significant roll-off in EQE when operating LEDs at high currents to push today's peak laboratory EQE values of ~70% to even higher values and (4) phosphor conversion efficiency.

The IQE of today's best LEDs has reached values higher than 80% for blue 450 nm LEDs at low current densities (<30 A cm^{-2}). Further improvements towards 100% IQE will require a reduction of nonradiative pathways such as nonradiation recombination at defects and reduction in nonradiative Auger recombination. Generally speaking, polar devices, which are currently the dominant devices produced in industry, experience "efficiency droop" at higher drive currents. This efficiency droop is thought to be caused in large part by the strong piezoelectric field in the quantum wells (QWs), which in turn requires device designs with very thin quantum well active layers (2.5 nm). Growing the LEDs from polar to nonpolar/semipolar crystallographic directions instead is needed, to eliminate strain-induced electric polarization fields currently seen within the QWs [9]. This topic is currently a major research area as semiconductor growth techniques in nonpolar crystallographic directions are still immature [10]. Growing in nonpolar/semipolar directions allows one to further optimize the devices structure, for example by increasing the thickness of the QWs to greater than 8 nm [11], thereby further increasing the IQE at high current density.

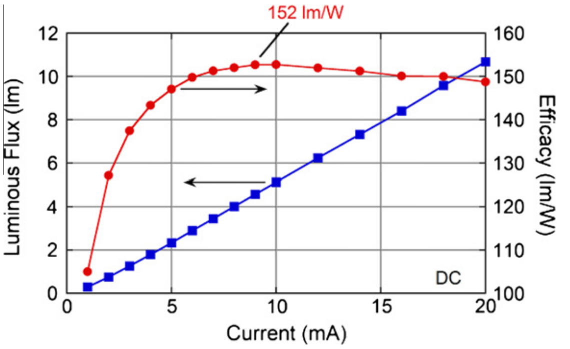

Fig. 3. White LEDs exhibit high luminous efficacies of 150 lm W^{-1} at low drive currents.

As for the light extraction efficiency, due to large differences in the indices of refraction of air and the GaN materials system, a considerable fraction of the generated photons within the LED are trapped by total internal reflection. Methods under investigation include ways to increase the amount of light hitting the LED/air interface at near perpendicular values to reduce the occurrence of total internal reflections (e.g. surface roughening techniques to generate micro-cones on the surface [12], optimizing the exterior shape of the LED chip and patterning the sapphire substrate to reduce light scattering), and methods to eliminate the passage of light through certain layers of material by integrating/embedding photonic crystals into the LED [13].

One of the biggest problems when scaling LEDs to illumination level output powers is the roll-off in EQE seen when operating at higher current densities (>10 A cm^{-2}) when trying to increase the luminous flux (currently ~160 lumens per power LED chip (see Fig. 3), roughly equivalent to a 30 W incandescent bulb). This efficiency droop may be associated with enhanced Auger recombination [14], or possibly carrier overflow from the quantum wells due to the high carrier population [15]. While the exact cause has not been determined yet, it is believed that the use of thicker quantum wells and altering the device structure to lessen carrier overflow will reduce this effect to a point that operating at higher efficacies and currents will be possible. Nonpolar and semipolar materials are one of the most promising means to increase the width of the quantum wells in the active layer, and will be discussed in detail in the next section.

Also, further progress in optimizing the phosphor materials and mixtures to improve the conversion efficiencies [6] and improve the quality of the white light through longer wavelength phosphor emission is being made and must continue [16].

4. Nonpolar and semipolar materials

Hexagonal wurtzite (WZ) GaN is the most thermodynamically stable crystal structure of GaN and the basal *c*-plane (0 0 0 1) is the most commonly used crystal orientation, as shown in Fig. 4. Wurtzite GaN is noncentrosymmetric, which lacks inversion symmetry, yielding large built-in spontaneous polarization P_{sp} in the [0 0 0 1] *c*-direction. The values for spontaneous polarization for (Al,In,Ga)N materials are nearly one-third the

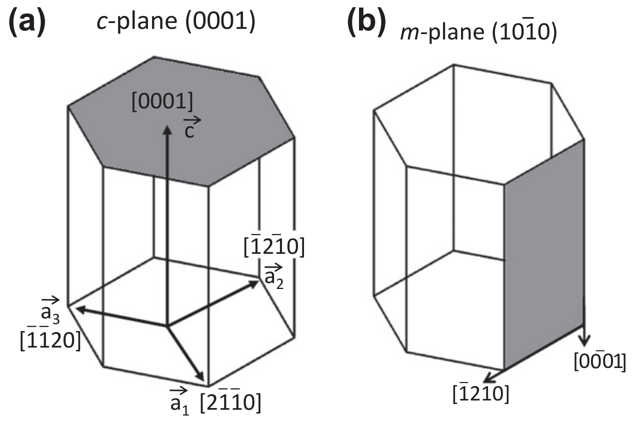

Fig. 4. Crystal planes of GaN: (a) basal polar *c*-plane and (b) nonpolar *m*-plane.

values for typical perovskite ferroelectrics such as $BaTiO_3$ [17].

Stemming from the lattice mismatch of InN and GaN, InGaN QWs grown pseudomorphically on GaN substrates will become elastically strained as long as it is below the critical thickness for plastic relaxation. For *c*-plane GaN, this is a biaxially compressive stress that induces an additional piezoelectric polarization on the order of 1 MV cm^{-1} [1]. For QW structures, the discontinuities in polarization cause a build-up of sheet charges at the interfaces, producing an electric field that bends the energy bands, as illustrated in Fig. 5. This band bending directs the electron and hole wave functions in opposite directions, and the resulting spatial separation of confined carriers can reduce oscillator strength and recombination rates [18]. Additionally, the band bending reduces the transition energy of the bound states which can red-shift the emission wavelength. This effect, the quantum-confined stark effect (QCSE), can have deleterious effects on optoelectronic devices and worsens for QWs with higher indium compositions due to increased lattice mismatch, making it particularly detrimental for higher wavelength applications.

An additional side-effect of the internal fields of *c*-plane GaN light emitters is that the emission peaks will gradually blue-shift with increasing current densities, due to gradual Coulomb screening of the polarization-related internal electric fields. For high current densities required for LDs (above 1 kA cm^{-2} and sometimes as high as 10 kA cm^{-2}) this blue-shift of wavelength can be quite significant, requiring even higher indium compositions to realize the target wavelength. Minimizing the blue-shift with current density can be possible by increasing the number of wells, which should reduce the effective carrier density in each well Additionally, stronger polarization fields in the active region may act as potential barriers for carrier transport, which can result in a high operating voltage. To avoid these problems, QWs grown on polar *c*-plane GaN are generally limited to less than 3 nm in width.

There are several symmetric nonpolar crystal planes that occur several times in the WZ unit cell, orthogonal to the basal plane. Because of their crystal symmetry, the nonpolar *a*-planes $11\bar{2}0$ and *m*-planes $10\bar{1}0$ have zero inherent spontaneous polarization. Further, InGaN QWs grown on nonpolar GaN orientations do not induce any polarization discontinuities or suffer from any strain-induced piezoelectric polarization effects along to the growth direction. For QWs grown on nonpolar crystal orientations, the energy bands remain flat, as shown in Fig. 5. Because there is no spatial separation of electron and hole wave functions, the wave function overlap is essentially unity.

There are a number of additional planes with a nonzero *h*, or *k*, or *i* and nonzero *l* Miller–Bravais indices that can also serve as growth surfaces. Since these mixed index

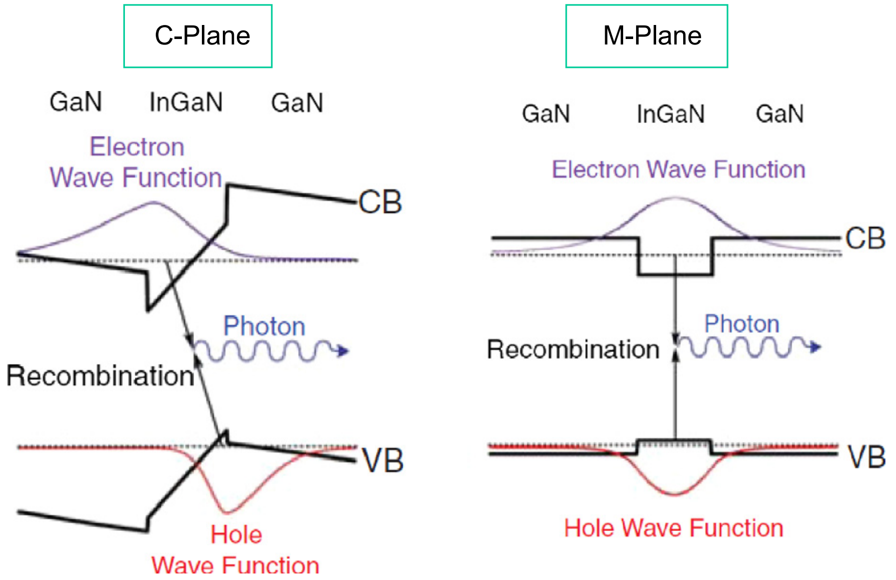

Fig. 5. Band diagram for *c*-plane (polar) and *m*-plane (nonpolar) InGaN/GaN quantum wells. The piezoelectric field in *c*-plane leads to electron and hole separation, whereas the nonpolar wells have minimal fields and good electron–hole pair overlap.

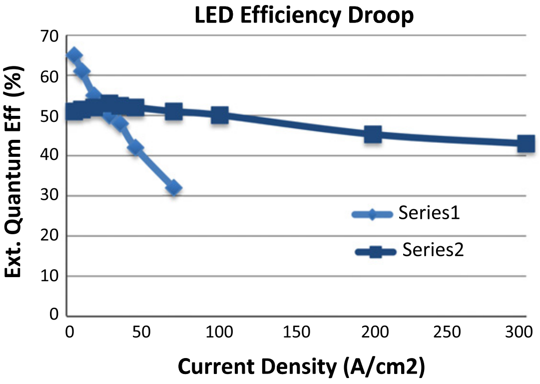

Fig. 6. EQE vs. current density: at higher current densities *c*-plane LEDs on bulk GaN exhibit efficiency droop (series 1), semipolar LEDs on bulk GaN exhibit less droop (series 2).

planes have a *c*-axis component in their normal direction they have some spontaneous polarization, and are collectively referred to as semipolar planes. The strength of the total polarization and the polarization discontinuity between strained InGaN layers and GaN substrate depend on both the angle from the *c*-plane and the composition of the InGaN layer.

Over the past several years, semipolar LEDs and LDs have been explored on a variety of planes, including $(11\bar{2}2)$, $(10\bar{1}1)$ and $(20\bar{2}1)$ (oriented 58°, 62° and 75° from the *c*-plane, respectively. The $(20\bar{2}1)$ semipolar orientation has so far shown the best performance for longer wavelength applications, owing to reduced polarization effects compared to the *c*-plane, as well as other advantageous material qualities such as high compositional homogeneity in the QW and possibly increased indium uptake.

Recently we demonstrated semipolar $(20\bar{2}\bar{1})$ blue[1] LED with high light output power (LOP) and low efficiency droop by utilizing a single 12 nm thick InGaN QW. Both LED structures were grown on bulk GaN with similar defect densities, with the QW thickness and reduced piezoelectric effect in the semipolar plane being the main factor leading to the reduced droop. Fig. 6 shows the EQE of the semipolar $(20\bar{2}\bar{1})$ blue LED vs. current density in comparison to *c*-plane LEDs with six 3 nm QWs. As seen in Fig. 6, semipolar blue LEDs show high EQEs of 50.1%, 45.3%, 43.0% and 41.2% at 100, 200, 300 and 400 A cm^{-2}, respectively, under pulsed conditions. The electroluminescence spectrum of the semipolar $(20\bar{2}\bar{1})$ blue LEDs also shows very little blue shift with increasing injection current and a narrow full-width at half maximum (FWHM). These results indicate that semipolar LEDs are an attractive crystal orientation for reducing efficiency droop in blue LEDs.

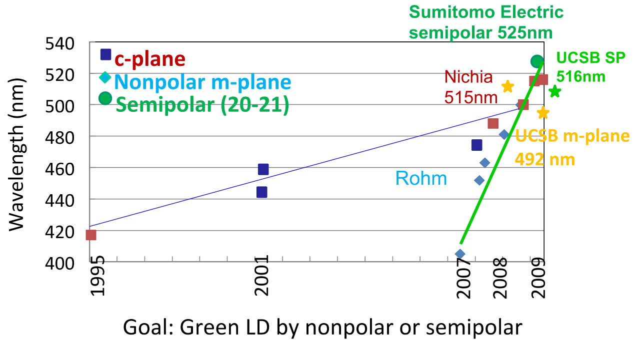

Fig. 7. Evolution of GaN laser diode wavelengths from violet, blue and recent green wavelengths. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.1. Green GaN laser diodes

While GaN is closing in on the green gap and could see immediate implementation in a variety of display applications, there have still been several challenges towards achieving GaN LDs much beyond 450 nm. These longer wavelengths require high indium concentration in InGaN quantum well active regions, which can be difficult from both a growth and materials perspective, particularly on the most commonly used basal *c*-plane GaN, which is limited by built-in polarization. The longest wavelength GaN LDs grown on the basal plane still have lower output powers and wall plug efficiencies (WPEs, a ratio of optical power output over the input current and voltage) compared to LDs in the pure blue spectrum: approximately one-tenth of the output power (80 mW compared to 800 mW) and one-fourth of the WPE (5–6% compared to 20%).

Orientations of GaN other than the standard basal plane have some very desirable properties that may make them a better choice for solving the green-gap problem, the most important of which is the reduction or elimination of the built-in polarization field that plagues polar *c*-plane InGaN devices as well as increased material gain. The first violet LDs on nonbasal orientations of GaN were demonstrated simultaneously by Mathews et al. at UCSB [19] and Okamoto et al. [20] in 2007 on *m*-plane $(10\bar{1}0)$ GaN plane, 11 years after the first *c*-plane LD demonstration. The first semipolar LD was demonstrated by Tyagi et al. [21] on

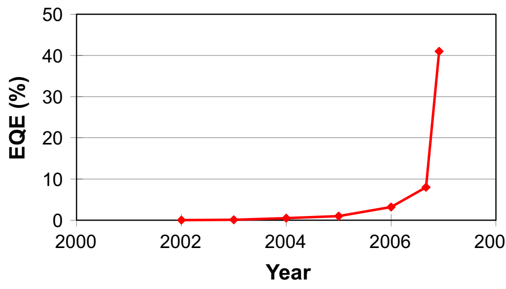

Fig. 8. Evolution of nonpolar LED external quantum efficiency as a function of year. The development of bulk GaN crystals with low defect densities in 2007 was a key breakthrough.

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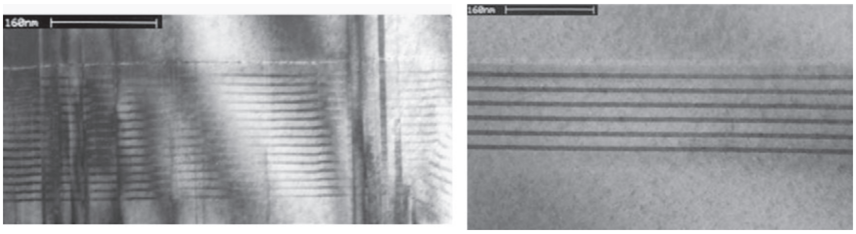

(a) Nonpolar QW on sapphire (b) Nonpolar QW on bulk GaN

Fig. 9. TEM of LEDs grown on nonpolar surface with (a) sapphire substrates and (b) bulk GaN substrates.

free-standing $(10\bar{1}\bar{1})$ later that year. Despite the relatively late start in the race towards achieving lasing in the green wavelengths, LDs on nonpolar and semipolar planes have seen rapid improvements rivaling the best results on the *c*-plane, particularly at wavelengths in the blue and green, as shown in the summary of evolution of wavelength with time in Fig. 7. Raring et al. recently demonstrated state-of-the-art blue and green LDs using unspecified nonbasal planes of GaN, citing some of the highest WPEs reported for single-mode blue LDs at 23% [22]. Sumitomo Electric demonstrated the first purely green (above 520 nm) LDs on a semipolar $(20\bar{2}1)$ plane in 2010, and at the time of writing, currently holds the record for longest wavelength GaN-based LD ever reported, at 533.6 nm [23].

4.2. Role of defects and compositional fluctuations

The role of defects in GaN light emission efficiency is a complex and challenging issue. Early in the development of GaN LEDs researchers were surprised by the large number of defects (10^9 cm^{-2}) that were present in surprisingly bright GaN LEDs [24]. LEDs made from other III-V materials systems would not show any light emission under such large defect densities. The reason *c*-plane InGaN LEDs are thought to be bright in spite of large defects is because of localized states in the InGaN alloys which exist in the active region of InGaN quantum wells [25,26]. The mechanism of InGaN localization is still under research, with phase separation [27] and stress [28] being two of the leading theories on the driving force for localized InGaN states. In the nonpolar orientations the role of defect reduction in bulk GaN is more clear and led to a fivefold increase in the external quantum efficiency [29]. The development of true bulk GaN substrates in 2007 was a key enabler in achieving bright InGaN LEDs on nonpolar surfaces. As shown in Fig. 8, LED quantum wells grown on bulk GaN with a defect density of 10^6 cm^{-2} showed an EQE as high as 45%. Transmission electron micrographs (TEMs) of nonpolar LEDs grown on bulk GaN show significantly lower defect densities than those grown on sapphire (see Fig. 9).

5. Conclusion

In conclusion, white light sources based on III-nitride LEDs have a promising future, and continued advancements in materials science and device engineering are expected to enable luminous efficacies over 200 lm W^{-1}. Nonpolar and semipolar GaN-based LEDs and laser diodes show great promise in achieving lower efficiency droop and longer wavelengths. As the manufacturing costs decrease, becoming similar to other semiconductor products, cost-effective drop-in replacements for incandescent bulbs will be readily available in the next couple of years.

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