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Advantages of III-nitride laser diodes in solid-state lighting

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III-nitride laser diodes (LDs) are an interesting light source for solid-state lighting (SSL). Modelling of LDs is performed to reveal the potential advantages over traditionally used light-emitting diodes (LEDs). The first, and most notable, advantage is LDs have higher efficiency at higher currents when compared to LEDs. This is because Auger recombination that causes efficiency droop can no longer grow after laser threshold. Second, the same phosphor-converted methods used with LEDs can also be used with LDs to produce white light with similar color rendering and color temperature. Third, producing white light from direct emitters is equally challenging for both LEDs and LDs, with neither source having a direct advantage. Lastly, the LD emission is directional and can be more readily captured and focused, leading to the possibility of novel and more compact luminaires. These advantages make LDs a compelling source for future SSL.

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1 Introduction III-nitride laser diodes (LDs) are an interesting light source for solid-state lighting (SSL), because of the advantages they could provide over light-emitting diodes (LEDs). Foremost, blue III-nitride LDs have higher power conversion efficiency (or wall-plug efficiency) at high current densities compared to blue III-nitride LEDs. This is because Auger recombination that causes the drop in efficiency (efficiency droop)[1-5] at high currents in III-nitride LEDs cannot grow (is clamped) in LDs after threshold. [6-8]. Therefore, substituting LDs for LEDs as a SSL source is method to circumvent efficiency droop. This could enable high flux emitters with high efficiencies at higher current densities.

III-nitride LDs advantages are not limited to efficiency. Other LD advantages include — the ability to create white light using phosphor conversion,[7,9-11] exploitation of the LD's directional beam enabling new functionality in luminaires and applications,[12] narrow linewidths that provide higher achievable luminous efficacies,[8,13] and fast switching for control in space and time for high light usage efficiencies. [12] Although the advantages of LDs are compelling, there are some disadvantages that need to be addressed before LDs can become truly competitive with LEDs for SSL. These disadvantages include improvements in efficiency and reduction in cost, which are also the same challenges LEDs faced in the early days of SSL.[14]

In this article, several of the LDs advantages are discussed. First, the efficiencies of blue LEDs and LDs are compared. A simple recombination rate analysis is presented that highlights how stimulated emission in the LD clamps Auger recombination. This provides a method for circumventing the efficiency droop to achieve higher efficiencies at higher currents. Then methods to produce white light are discussed. Phosphor conversion techniques to produce white light with LDs are shown, and the importance and limitations of white light formed from direct emitters are discussed. Finally, the advantages of the LD's directional emission are introduced. The directional emission of the LD can be more easily captured and focused onto phosphors to create higher luminance white sources. Such high-brightness sources could enable novel and more compact luminaires.

2 Discussion

2.1 LED and LD efficiency and circumventing efficiency droop In this section, state-of-the-art and future blue LDs and LEDs efficiencies are compared using a simple rate equation analysis. A more detailed examination of III-nitride LD and LED efficiencies can be found in

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Ref. [6], and is suggested reading for a deeper analysis. The more concise discussion below is intended to highlight differences in device operation and the resulting impact on efficiency.

The most compelling reason to consider LDs for SSL is because state-of-the-art blue LDs have higher efficiencies than state-of-the-art blue LEDs at high current densities.[6] Fig. 1(a) shows this advantage where power conversion efficiency (PCE) versus current density is plotted for a state-of-the-art (SOTA) blue thin-film LED [15] and blue edge-emitting LD [16] (solid lines). The blue LED has high peak PCE, but this occurs at very low current densities (~5 A/cm^2), and the PCE drops as the current density increases. The LD, on the other hand, has a peak PCE at ~5 kA/cm^2, which is much higher than the LED's PCE at those current densities. The PCE of the LD does eventually drop at higher current densities, but this decrease is caused by resistive losses, while the LEDs drop in PCE is caused by both Auger recombination (efficiency droop) and resistive losses.

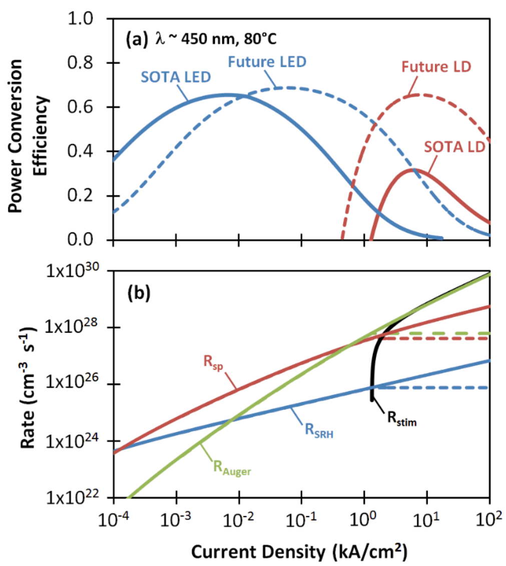

Figure 1 (a) Power conversion efficiency versus current density of state-of-the-art (SOTA) and future blue LEDs and LDs. (b) Recombination rates versus current density for SOTA LEDs and LDs. The dashed lines are for LD rates after threshold that can no longer grow.

The reason why LDs are not subject to Auger induced efficiency droop can be understood by considering the recombination processes within the quantum wells of the LD. The total rate of recombination of carriers (R_{total}) can be written as:

$$R_{total} = R_{SHR} + R_{sp} + R_{Auger} + R_{stim}, \quad (1)$$

where R_{SRH} is the non-radiative Shockley–Read–Hall recombination rate, R_{sp} is the spontaneous recombination rate, R_{Auger} is the non-radiative Auger recombination rate, and R_{stim} is the stimulated recombination rate. The recombination rates versus current density for the state-of-the-art blue LED and LD are plotted in Fig. 1(b). At low current densities the recombination of carriers is caused by Shockley–Read–Hall, spontaneous, and Auger recombination for both the LED and LD. This analysis assumes that the quantum well active regions are the same for the LED and LD, resulting in the same rates.[6] The LED produces light at low current densities, because the LED is designed for high light extraction. The LD, the other hand, does not produce light at low current densities, because it is designed to contain and create a large photon density that leads to stimulated emission. Auger recombination is low at low current densities, but grows rapidly as the current increases and eventually dominates the total recombination rate. This causes a lowering in the radiative efficiency (η_{rad}) that can be written as:

$$\eta_{rad} = \frac{R_{sp}}{R_{SRH}+R_{sp}+R_{Auger}}. \quad (2)$$

The higher the current density the greater the Auger recombination rate, leading to a decrease in η_{rad}. Auger recombination not only affects the efficiency of light produced within the LED, but also affects the efficiency of light produced within the LD impacting threshold currents. [6]

The cavity and the large photon density that builds within the LD with increased current density provide a method to circumvent the efficiency droop. When the optical gain in the LD overcomes the losses, laser threshold is obtained (~1.2 kA/cm^2) and the LD finally emits appreciable light. The non-stimulated recombination processes (R_{SRH}, R_{sp}, and R_{Auger}) can no longer grow (are clamped). This is shown in Fig. 1(b) where those recombination rates no longer increase (dashed lines). After threshold, the LD's steady-state optical gain cannot increase because the internal field would also grow without bound. Clamping of the optical gain implies clamping of the carrier density.[17] This clamped carrier density prevents the further growth of R_{SRH}, R_{sp}, and R_{Auger} after threshold. The result is a rapid increase in R_{stim} which dominates the recombination and emission process (black line in Fig. 1(b)). Therefore, after threshold the LD is not subject to increasing Auger recombination losses (and R_{SRH}, R_{sp}), and results in a much higher PCE than the LED. [6]

Although the state-of-the-art LD has a peak PCE that is lower than the peak PCE of the LED, projections of future improvements suggests the LD efficiency may be able to rival the efficiency of the LED as shown in Fig. 1(a). [6] Ref. [6] identified various methods to improve the efficiency of both blue LEDs and LDs. The result is a peak

PCE of the future LD that is close to the peak PCE of the future LED (dashed lines). No definitive way to eliminate Auger recombination was determined by this analysis, partly because Auger recombination is a fundamental physical property of III-nitride semiconductors. So, blue III-nitride LEDs will always have efficiency droop. This will ultimately limit the operating current densities and power per device of the LED while still retaining reasonable efficiency. If operated at peak PCE, the future LD would produce more photons per area than the future LED, resulting in a higher lumens per device, which is key for the LD to compete economically with LED. [6] The conclusion is that LDs will always be more efficient than LEDs at high current densities, and should be considered (even at today's efficiencies) in applications where high flux from a single emitter is desired.

A plausible solution is to restrict operation of the LED at peak efficiency to avoid the efficiency droop. The disadvantage with this approach is it forces one to increase the LED area (larger chips) to achieve the same output power. The result is an increase in the LED's areal costs, or a lower lumens per dollar, that is uneconomical for SSL. [6]

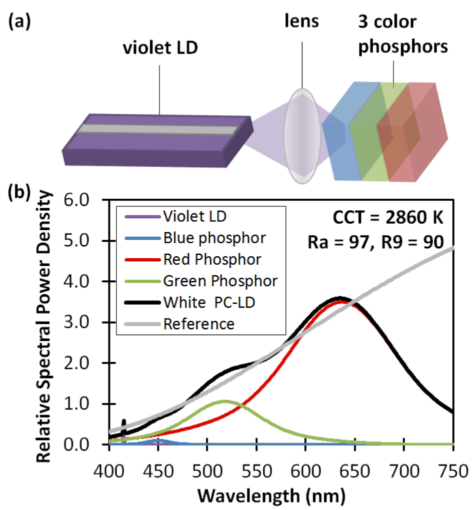

Figure 2 (a) Schematic of a violet laser diode emitting onto three different phosphors via a lens to focus the light to form a full white spectrum PC-LD. (b) Relative spectral power density versus wavelength of the three phosphors, the violet LD, the resulting full spectrum white light, and a tungsten-filament source spectrum as a reference.

2.2 Phosphor converted white light from LDs

Another requirement of LDs for SSL is the ability to create white light. Fortunately, the same phosphor conversion schemes and materials used in white phosphor-converted LEDs (PC-LEDs) can also be used with LDs. In fact, there are many previous reports of white phosphor-converted LD (PC-LDs). [7,9-11] Ref. [7] demonstrates that a PC-LED and PC-LD using the same phosphor plate produces white light with the same color rendering and color temperature. The narrow linewidth of the LD does produce a spectral gap (no light) between the blue LD spectra and the phosphor's longer wavelength spectra (see Fig. 2 in Ref. [7]). Methods to determine color rendering such as the Color Rendering Index (CRI) and the Color Quality Scale (CQS) suggest white light produced with narrow linewidth spectra is sufficient for good color rendering.[8] Contrarily, more stringent methods suggest spectral gaps could pose a problem for color rendering some objects with narrow band or sharp reflectance spectra.[18] Therefore, LD white sources with spectral gaps could possibly be relegated to special applications where spectral gaps are not of importance.

Another method to produce white light is to use multiple phosphors to fill the visible spectrum. This solution avoids the narrow spectra of the LDs and spectral gaps. Such a configuration is shown in Fig. 2(a) where a light from a violet LD is focused into three different phosphors. Simulation of a violet LD (415 nm and 1 nm spectral width) pumping three phosphors emitting red (637 nm), green (518 nm) and blue (450 nm) light with spectral widths of 30 nm, 100 nm and 150 nm, respectively is shown in Fig. 2(b). The color and linewidths of the phosphor are chosen to approximately match those of commercial LED white solutions.[18] The color temperature, general color rendering index (R_a), and saturated red index (R_9) are 2860 K, 97, and 90, respectively. These values are similar to a violet LED pumping similar phosphors.[18] This is not surprising because the spectra of the three phosphors determine the color rendering and color temperature, while the LDs' pump wavelength has little impact. This simple simulation shows that LDs can also produce full spectrum white light with excellent color rendering.

Of course, future work is necessary to see if a PC-LD configuration is realistic. One possible concern is phosphor heating and a decrease in conversion efficiency that may need be addressed in this design. Early commercial products of PC-LDs [19] suggest that heat is not a detrimental limitation though.

2.3 White light from direct emitters Although PC-LEDs and PC-LDs can create white spectra with excellent color rendering, they are limited in other areas. Converting blue light to longer wavelengths results in a Stokes efficiency loss, and limits the luminous efficacy of PC-LEDs and -LDs. White light produced from direct sources (such as red, green, and blue LEDs) do not have this efficiency limitation. In fact, white light produced from the narrow linewidths of LDs with red, yellow, green, and blue wavelengths have luminous efficacies higher than white direct LEDS.[13] This laser white source was found to provide good color rendering under human testing. [8] As discussed above, such spikey spectra can have color rendering problems with certain objects, but in applications where efficiency is more valued than color rendering, or if

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more laser lines were used to fill the spectrum, such a source could be useful.

Another, and maybe more important, advantage of using direct emitters to produce white light is the ability to chromaticity tune. It is now known that human circadian rhythms are affected by light, and blue light suppresses the sleep inducing melatonin release from intrinsically photoreceptive retinal ganglion cells. [20,21] Exposure, even at low light levels to blue light prior to sleeping (such as by exposure to LED-backlit computer screens [22]), can disturb sleep cycles which, in turn, can lead to poorer health. Many other studies show that human performance is also affected by light. For example, students perform better in the classroom when the color temperature of the classroom's light is much higher. [23] Therefore, producing chromaticity tuneable white sources is very important for human health, and should remain a goal for future solid-state-lighting sources.

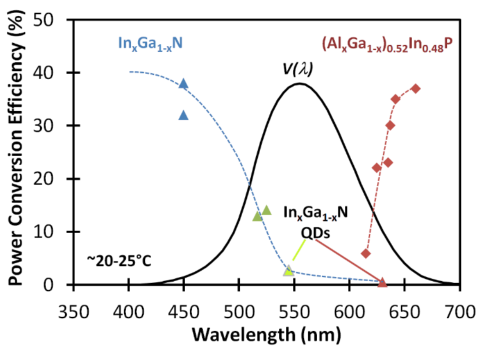

Figure 3 Power conversion efficiency versus wavelength for state-of-the-art InGaN and AlInGaP LDs. The two data points in the green-red use quantum-dot (QD) active regions.

Although there are some commercial products with white light produced from multiple color LEDs, their widespread adoption and dominance over phosphor-converted white sources is lagging because of a lack of efficient emitters in the green-orange spectral range. This deficiency is called the "green-gap". It is a result of a decrease in efficiency of InGaN emitters at wavelengths longer than blue, and of AlInGaP emitters at wavelengths shorter than deep red wavelengths (see Fig. 2 in Ref. [24]).

The green-gap is not only a problem for LEDs, but also for LDs. Fig. 3 shows the power conversion efficiency versus wavelength for the best reported InGaN [25,26] and AlInGaP LDs [27-31] that shows an absence of efficient emitters at green-gap wavelengths. The congruent green-gap problem in LDs and LEDs is of no surprise, because the spontaneous emission rate which limits LEDs is related to optical gain which limits LDs. Since the LED's and LD's green-gap problems are related, any improvements made in the LED's spontaneous emission efficiency should translate to the LD's optical gain and efficiency. It should be noted that InGaN quantum dot (QD) active regions have been able to achieve lasing at green-gap wavelengths.[32,33] The higher optical gain provided by the higher density of states in QDs may be a method to improve LDs at green-gap wavelengths.

2.4 LD's directional emission and luminaire benefits LDs could also have advantages for luminaires, enabling sizes that cannot be achieved with LEDs because of the LD's directional emission. The beam of light emitted from the LD can be more easily collected and focused, compared to the LED's lambertian emission.

Table 1 shows the values to calculate radiance for a SOTA blue LED and LD. Both sources emit 1 Watt of power. The area of the LED is much larger than the area of the LD, which assumes a 15 µm x 1 µm aperture. This small emitting area coupled with the smaller collection angle results in a much higher radiance for the LD compared to the LED.

Table 1 Radiance of blue LED and LD

Parameter	Blue LED	Blue LD
Power (W)	1	1
Emitting area (cm^2)	0.01	1.5×10^{-7}
Half angle (°)	45	15
Radiance ($W/str/cm^2$)	54	3×10^{7}

The LD's higher radiance translates into the possibility of using smaller phosphors. The insets for Fig. 4 show cross-section schematics for a white PC-LED and a PC-LD. In the PC-LED the phosphor plate (ceramic)[34,35] is the same area as the LED, or larger if used in a remote configuration so that all pump light is incident on the phosphor. Therefore, the area of the phosphor is dependent on the area of the LED as shown in the plot of phosphor area versus device area (Fig. 4). Attempts to create a higher luminance source with the PC-LED by reducing the LED area will not work. This is because the LED will need to be driven at higher current densities to compensate for the smaller area, and hence operate at lower PCE (Fig. 1). The LD, on the other hand, has a phosphor area that is much smaller than the LED, because the light can be focused. The phosphor area is not coupled with the LD's aperture area, and remains constant for reasonably sized phosphors.

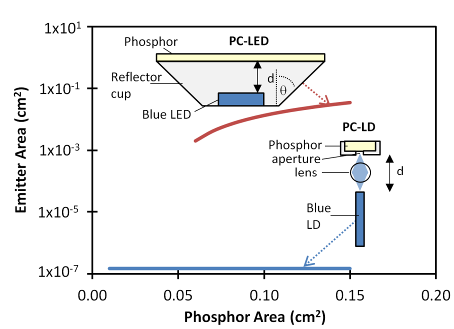

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Figure 4 Emitter area versus phosphor area for the PC-LED and PC-LD. Insets are cross-sectional schematics for the PC-LED (upper right) and PC-LD (lower left). The reflector cup angle is θ and the distance from the emitter to phosphor is d.

Results of phosphor-converted luminance calculations are shown in Table 2 using the blue LED and LD radiance from Table 1. The white light from the phosphor is collected with the same half angle for both cases, but because the phosphor area can be smaller for the PC-LD it's luminance is higher. The phosphor areas are somewhat arbitrary, but are reasonable and are used to highlight the possible luminance benefit. Of course, the power density of the light from the blue LD cannot be so high that it damages the phosphor or leads to heating that can reduce phosphor conversion efficiency. Phosphor plates (or ceramics) have been shown to be superior to typically used phosphor loaded organics at high power densities. [36] Further work needs to be done to determine the power density limits of PC-LDs, and if heating and a reduction of phosphor conversion efficiency is a problem.

Table 2 Luminance of a phosphor-converted LED and LD

Parameter	PC-LED	PC-LD
Power (lm)	250*	250*
Emitting area (cm^2)	0.09**	0.01
Half angle (°)	45	45
Luminance ($lm/str/cm^2$)	1.5×10^3	1.4×10^4

* Assumes 250lm/W from the phosphor.

** Assumes a square geometry, and a remote phosphor that is d=1 mm from the LED within a θ=45° reflector cup.

The PC-LDs smaller phosphor areas should enable lighting solutions that are not possible with LEDs. For example lens size is determined by the size of the source (phosphor area) in order to avoid internal total reflection of any incident light rays (Weierstrass condition). The smaller phosphor areas in the PC-LD allow for a smaller lens. Using the values in Table 2, the lens area could be a factor of 10 smaller than the PC-LEDs. Therefore, PC-LDs could enable micro-luminaires, possibly useful in new lighting applications where the luminaire can be less conspicuous or more efficiently coupled to small optical elements.

3 Conclusion III-nitride LDs have several advantages over LEDs in solid-state lighting. This includes higher efficiency at higher currents, the similar ability to create white light sources, and the ability to create higher luminance sources that could lead to smaller luminaires. These advantages make LDs a compelling source for future SSL.

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