

Status and Future of High-Power Light-Emitting Diodes for Solid-State Lighting

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(Invited Paper)

Abstract—Status and future outlook of III-V compound semiconductor visible-spectrum light-emitting diodes (LEDs) are presented. Light extraction techniques are reviewed and extraction efficiencies are quantified in the 60%+ (AlGaInP) and ~80% (InGaN) regimes for state-of-the-art devices. The phosphor-based white LED concept is reviewed and recent performance discussed, showing that high-power white LEDs now approach the 100-lm/W regime. Devices employing multiple phosphors for “warm” white color temperatures (~3000–4000 K) and high color rendering (CRI > 80), which provide properties critical for many illumination applications, are discussed. Recent developments in chip design, packaging, and high current performance lead to very high luminance devices (~50 Mcd/m² white at 1 A forward current in 1 × 1 mm² chip) that are suitable for application to automotive forward lighting. A prognosis for future LED performance levels is considered given further improvements in internal quantum efficiency, which to date lag achievements in light extraction efficiency for InGaN LEDs.

Index Terms—Light-emitting diodes (LEDs), light sources, nitrogen compounds, phosphors, phosphorus compounds, semiconductor devices.

I. INTRODUCTION

THE light-emitting diode (LED), unlike conventional light sources, provides a direct transfer of electrical energy into light. The ramifications are significant and indeed the LED has been foreseen as an “ultimate lamp” for the future [1], [2]. In this paper, we review the present state-of-the-art of LEDs for visible-spectrum light emission and compare their performance to conventional light sources. In particular, we review various light extraction schemes which are important for achieving the highest possible light output efficiencies. An emphasis is placed on high power (>~1-W input) LEDs which are most likely to compete with conventional light sources on a system cost basis, rather than small-area low-power LEDs. Recent performance in external quantum efficiency for high power LEDs is reviewed, as well as luminous efficacy of white LEDs based on phosphor down-conversion. The evolution of increasing LED surface brightness, or luminance, by improved packaging technology, power-handling capability, and chip design, is presented. These improvements in LED performance are discussed in the context of selected applications such as illumination and automo-

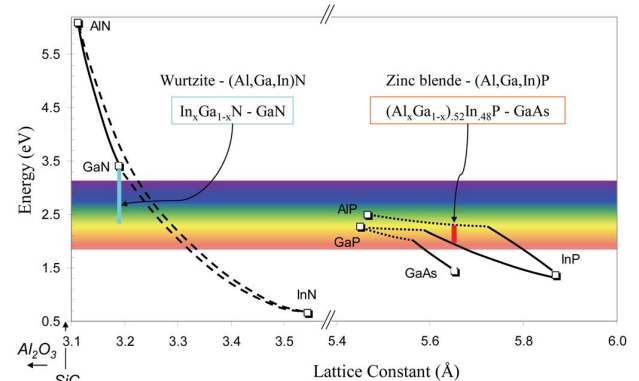


Fig. 1. Energy bandgap versus lattice constant for wurtzite III-nitride and zincblende III-phosphide semiconductor alloy systems employing Al, In, and Ga [3], [4]. Solid lines indicate direct-bandgap alloys, dotted lines indicate indirect-bandgap alloys, and dashed lines are estimates (due to relative uncertainty in bowing parameters for high InN-fraction alloys). The $(\text{Al}_x\text{Ga}_{1-x})_{0.52}\text{In}_{0.48}\text{P}$ system is lattice-matched to GaAs and emission is tuneable from red (~650 nm) to yellow (~580 nm). The InGaN system is grown pseudomorphic to GaN, and strain and alloy miscibility issues have, to date, limited the useful emission wavelength range from UV-A (~365 nm) to deep green (~550 nm).

tive forward lighting. Finally, key challenges remaining in LEDs for solid-state lighting are elucidated and discussed, and future performance levels estimated.

II. MATERIALS FOR SOLID-STATE LIGHTING

The workhorse materials for solid-state lighting are III-V compound semiconductor systems based on phosphorus, and nitrogen, respectively. The electronic energy bandgap versus lattice constant relationships are shown in Fig. 1.

As indicated in the figure, the III-phosphide material system, $(\text{Al}_x\text{Ga}_{1-x})_{1-y}\text{In}_y\text{P}$, is lattice-matched to GaAs for $y = 0.48$. The wide commercial availability of high quality GaAs bulk substrates allows for relatively straightforward epitaxial growth of optoelectronic device layers in this material system, with high quality devices demonstrated by both metal-organic chemical vapor deposition (MOCVD) as well as molecular-beam epitaxy (MBE) methods. The former method has been particularly productive with respect to AlGaInP LEDs, with strong progress in performance over the last 15 years [5]–[10]. The energy bandgap is tuneable on the GaAs lattice constant by varying the AlInP molar fraction x . Direct bandgap emission is available from $x = 0$ (InGaP), at ~1.9 eV (~650 nm, deep red) to $x \sim 0.53$, at ~2.2 eV (~560 nm, yellow-green), beyond which

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the indirect X valley minima provide the lowest bandgap energies. In addition to the proximity of indirect bandgap minima to carriers in the emission layer, carrier confinement to that layer becomes a challenge since the available bandgap offset is spoiled by the relatively low electron confinement potential provided by AlInP [11]. These two effects have consequences for the performance of AlInGaP LEDs, limiting practical emission wavelengths to ~ 580 nm or longer, and causing increased thermal sensitivity to device performance as emission wavelength is reduced shorter than deep red [12].

Fig. 1 also depicts the energy bandaps for the wurtzite III-nitrogen material system. The alloy of interest for visible-spectrum LEDs is $\text{In}_x\text{Ga}_{1-x}\text{N}$, wherein increase of the InN mole fraction decreases the emission bandgap from $x = 0$ (GaN), at ~ 3.4 eV (~ 365 nm, UV-A) to, in principle, $x \sim 1$, at ~ 0.7 eV (~ 1800 nm, infrared), maintaining a direct-bandgap across the entire alloy composition range. Key breakthroughs [13], [14] in the 1980s ushered in the modern era of GaN-based optoelectronic device development and led to the realization of high brightness blue and green LEDs [15], [16] and laser diodes [17] in the subsequent decade. Many years later, there are still several factors which limit the range of useful InGaN alloy compositions. Due to the lack of native bulk substrates, InGaN alloys used in today's LEDs are lattice-matched to c-plane GaN typically grown on the basal plane of either sapphire (sublattice $a \sim 2.75$ Å), or silicon carbide ($a \sim 3.08$ Å), bulk substrates. The lattice mismatch between the underlying GaN and sapphire (or SiC) provides for very high dislocation densities which, although having been reduced by improved epitaxial growth techniques from $\sim 1\text{E}10$ to $\sim 1\text{E}8$ cm^{-2} over the last decade, are known to act as nonradiative recombination centers [18] and are linked to degradation in laser diode structures [19]. Pseudomorphic growth of InGaN on GaN results in compressive strain in the InGaN emission layer which increases as InN mole fraction increases. Furthermore, the wurtzite crystal structure provides for spontaneous and piezoelectric polarization within the InGaN layer that causes large built-in electric fields along the c -axis [20], [21], complicating device operation and characterization of basic optical processes. While epitaxial growth on other planes (a -, m -, or even in between) can be exploited to achieve a zero-field situation, the materials quality rendered by these approaches is to date inferior to the case of c -plane growth, and the (documented) performance of non- c -plane LEDs reflects this [22]–[24]. Regardless of crystal orientation, miscibility issues make it difficult to form high quality InGaN films when high InN incorporation is attempted and, at excessive compositions, lead to alloy non-homogeneity and eventually breakdown of the crystallographic structure [25].

Even so, reasonably high internal quantum efficiencies are obtained with InGaN-GaN structures, especially for relatively low InN mole fractions. High performing LEDs are available from ~ 365 (UV-A) to ~ 550 (deep green) nm, and laser diode wavelengths have expanded from their initial ~ 405 nm regime to between ~ 350 [26] and ~ 470 nm.¹

State-of-the-art performance of high-power LEDs versus emission wavelength, shown in Fig. 2, reflect the characteristics of the III-V material systems as discussed above. Details behind the data points in Fig. 2 are described in the following sections.

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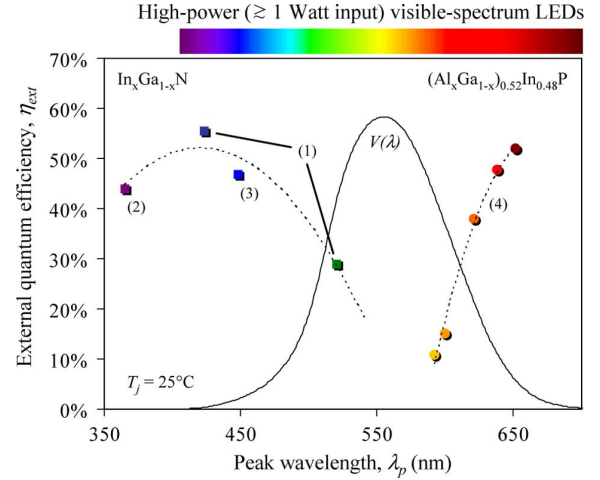


Fig. 2. State-of-art external quantum efficiencies for high-power visible-spectrum LEDs ($T_j = 25^\circ\text{C}$): (1) InGaN TFFC LEDs, 350 mA (this paper); (2) InGaN VTF LED, 1000 mA [42]; (3) InGaN CC LEDs employing patterned substrates [35]; and (4) Production performance, AlGaInP TIP LEDs [9], Philips Lumileds Lighting Co., 350 mA. $V(\lambda)$ is the luminous eye response curve from CIE. Dashed lines are guides to the eye.

III. CHIP DESIGN AND LIGHT EXTRACTION

A. Basic Principles

Light extraction from LED chips has continued to remain a challenge since their inception several decades ago [27]. The basic problem is that photons are generated in III-V crystals with relatively high optical refractive indices— $n \sim 3.5$ for AlGaInP and $n \sim 2.4$ for InGaN. From an imaging optics point of view, brightness conservation alone would demand a $1/n^2$ reduction in optical power transfer to air. Any non-imaging (e.g., texturing for light redirection) approach may attempt to overcome this limitation but must deal with optical loss mechanisms within the LED chip, which include impurity or free-carrier absorption, low-bandgap layers, metal contacts, and even reabsorption in the active layer(s) itself. Another important consideration is the radiation pattern of light from the active layer, which is often neglected in discussions of LED light extraction. For cubic crystals like AlGaInP, light generation is equally probable along all three axis orientations, so random dipole light generation dominates and the radiation pattern within the active layer can be considered isotropic. For wurtzite InGaN-GaN, this is not the case; the dipole transition parallel to the c -axis is not observed [28]. Thus, the emission pattern is “egg-shaped” with preferential emission along the c -axis [see Fig. 5(a)]. This serves to assist in light extraction for c -plane InGaN-based LEDs. All of these considerations must be taken into account if one is to talk quantitatively about C_{ext} from a first principles approach.

External quantum efficiency may be written

$$\eta_{\text{ext}} = \eta_{\text{int}} \cdot C_{\text{ext}} \quad (1)$$

where η_{int} is the internal quantum efficiency (ratio of generated photons to electrons injected into the LED contacts), and C_{ext} is the light extraction efficiency. As written in (1), η_{int} includes both radiative and injection efficiency terms lumped together. Of course, (1) shows that a measure of η_{ext} gives a lower bound to C_{ext} . This can be useful in estimating C_{ext} for LEDs wherein η_{int} can be considered close to 100%. We will attempt

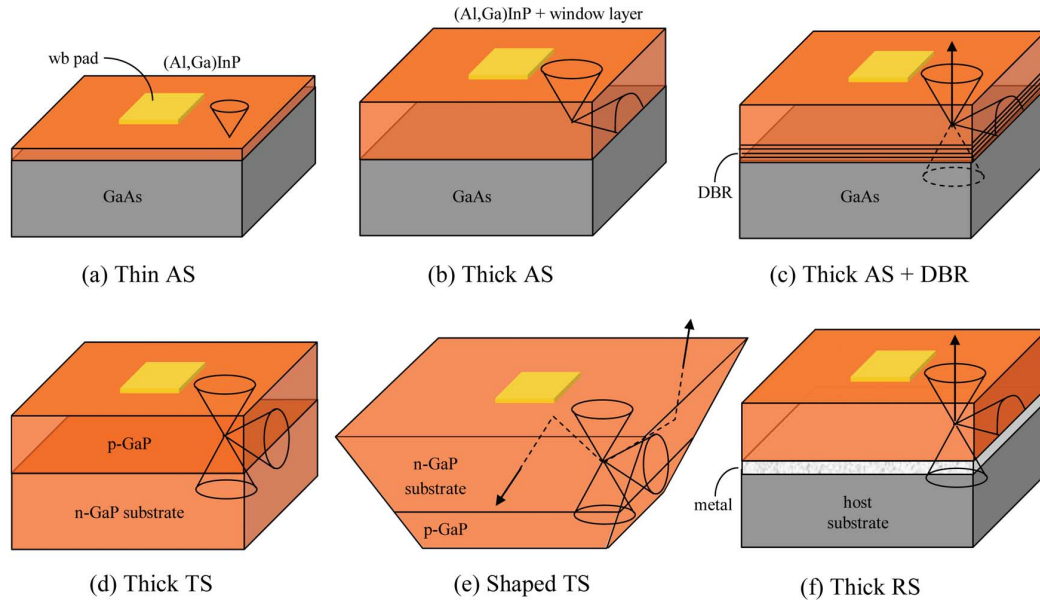


Fig. 3. Common chip designs for AlGaInP LEDs. (a) Thin epilayers on GaAs absorbing substrate (AS). (b) Thick window layer on AS. (c) Thick AS design but including distributed Bragg reflector (DBR) above substrate. (d) Thick window layer on transparent substrate (TS). (e) Shaped TS (truncated-inverted-pyramid, TIP, LED shown). (f) Thick window layer on reflective substrate (RS). Consideration of escape cones (shown) allow estimations of extraction efficiencies.

to quantify C_{ext} for state-of-art AlGaInP and InGaN LEDs in Section III-B and III-C, below.

B. III-Phosphide LEDs

Common to all high-efficiency AlGaInP LED design approaches is the requirement to reduce or (preferably) eliminate the negative effect of the absorbing GaAs epitaxial growth substrate on light extraction. Several approaches are shown in Fig. 3.

1) *Thin AS*: The case of thin ($\ll$ chip width) epilayers on the GaAs absorbing substrate (AS) provides the lowest light extraction. The “escape cone” (a useful concept popularized with the development of AlGaInP LEDs during the 1990s) provided according to Snell’s Law is governed by a critical angle of $\theta_c = \arcsin(n_a/n_s)$, n_a and n_s being the refractive indices of the ambient medium and the LED semiconductor, respectively. Photons impinging the semiconductor/ambient interface at angles beyond θ_c are totally internally reflected back into the chip. In the case of a AS chip, this reflected light is absorbed. Therefore, light extraction is limited to one escape cone out the top surface. For isotropic emission from the active layer, and taking Fresnel reflection into account, one may approximate $C_{\text{ext}} \sim [1 - (n_s - n_a)^2 / (n_s + n_a)^2] (1 - \cos \theta_c) / 2$ (see, for example, [11, p.184]). Since most LED chips are encapsulated with epoxy or silicone to improve light extraction, $n_a \sim 1.5$, and we may calculate $C_{\text{ext}} \sim 4\%$. This is an upper limit, since unless special measures are taken for current spreading, a large fraction of light is generated underneath (and thus occluded by) the Ohmic contact on top of the chip.

2) *Thick AS*: In this design, a thick, conductive, and transparent window layer is provided atop the device epitaxial layers. One choice is AlGaAs, provided the AlAs fraction is high enough for transparency. Since the window layer does not participate in the minority carrier processes, even metamorphic epitaxy is allowed as long as defects do not migrate down

into the active region. GaP has in fact become a common window layer [7]. The window layer serves the dual purpose of spreading current from the top electrode to the full chip active area, and also provides for light extraction from “side” escape cones. In the case of hydride vapor phase epitaxy (HVPE), very fast growth rates allow window layers exceeding $50 \mu\text{m}$ in thickness. For typical small-area chip widths of $\sim 250 \mu\text{m}$, such a window layer thickness provides access to effectively two ($4 \times 1/2$) additional escape cones, as implied in the figure. Thus, we may calculate $C_{\text{ext}} \sim 12\%$.

3) *Thick AS + DBR*: In this design, a thick window layer is accompanied by an epitaxial distributed Bragg reflector (DBR) stack provided between the active layer and absorbing substrate [29]. For most AlGaInP LEDs, the active region is too thick to allow design of resonant structures, so the most one can hope for is the recovery of the “bottom” escape cone, which would give $C_{\text{ext}} \sim 16\%$. In practice, limited angular/spectral bandwidth of DBR designs provided by AlGaAs–AlGaAs or AlInGaP–AlInP, and absorption within the active region, reduce the achievable extraction efficiency to below this upper limit.

4) *Thick TS*: In this design, the GaAs substrate is replaced with a transparent substrate (TS). For example, the GaAs may be removed by selective wet chemical etching, and the remaining epitaxial layers bonded to a GaP “host” substrate at elevated pressure and temperature. Under the correct conditions, an Ohmic interface can be provided between the AlGaInP epitaxial layers and the GaP host substrate [8]. Now all four side cones are available and, depending on the reflectivity of the bottom-side metallization, the bottom cone as well. So, $C_{\text{ext}} \sim 20\%–24\%$ are estimated.

Unlike the previous cases, light within a TS chip which does not extract upon “first or second pass” at the semiconductor/air interface, still has a chance for escape upon further passes provided there is low residual optical loss, and the chip geometry

is ergodic or there are optical scattering mechanisms provided to re-orient the light. Indeed, peak external quantum efficiencies as high as 40% are measured (data not shown) in TS LEDs improved by reduction of internal optical loss mechanisms.

5) *Shaped TS*: In the case of a TS device, the option of shaping the transparent material around the active layer provided a lever arm for increasing light extraction. One example is the case of a hemispherical dome surrounding a smaller active layer area. A suitable design can ensure that most generated light will satisfy criteria for escape, but cost and other practical considerations have limited the impact of such designs. Another shape is the compound parabolic concentrator (CPC) which can be used to collimate all generated light to within an escape cone. Again, practicality prevents implementation of the full structure. However, a related design is the truncated-inverted-pyramid (TIP) structure which has demonstrated peak external quantum efficiencies of $\sim 60\%$ [9]. This chip structure is currently utilized in commercially available high-power LEDs,² and is behind the AlGaInP data points in Fig. 2. Junction area, A_j , is $\sim 0.5 \times 0.5 \text{ mm}^2$. The TIP LED design is shown in Fig. 3(e), where extraction of rays outside the escape cones for rectangular parallelepiped geometries are possible, as illustrated.

6) *Thick RS*: This idea is an alternative to the TS approach, in which semiconductor-semiconductor wafer bonding is replaced with metallized wafer bonding in order to provide a “reflective substrate” (RS). The metal-bonded substrate is typically chosen for thermal expansion coefficient matching and to minimize thermal resistance. GaAs, Ge, and Si are common choices. In order to approach extraction efficiencies as high as for a TS LED, means for light extraction must be incorporated into the lifted-off epitaxial film. One approach is to texture the top surface of the LED for light randomization so that “multiple pass” light may eventually escape the device. In addition, high reflectivity on the LED side of the metallized wafer bond is important. Light extraction from such devices may be modeled by considering a “photon gas” within the semiconductor chip, with parasitic optical loss dominating the light extraction efficiency [30].

The RS structure has also been combined with shaping, by providing very small partitions of active regions which are surrounded by “micro-reflectors” [10]. This combination of micro-shaping and top surface texturing provides reasonably high extraction efficiency, as evidenced by peak external quantum efficiencies reaching 50% [31]. This performance is still below that of the TIP LEDs. However, one advantage of the RS approach is that light emission is predominantly from the top surface, which simplifies package design and reduces optical source size, or étendue.

Evolution of C_{ext} for AlGaInP LEDs, based on the preceding discussion, is shown in Fig. 7. The final limit for C_{ext} in these devices has likely not been reached, but improvement well beyond the current state-of-art will be a challenge due to the very high refractive index and certain inherent optical losses. The relatively thick active regions required for sufficient minority carrier electron confinement cause built-in optical loss [32], and complicate the design of advanced structures such as resonant-

cavity and photonic-crystal LEDs. Furthermore, internal efficiencies well below 100% at operating temperatures limit the positive impact of photon recycling.

C. III-Nitride LEDs

Device design for III-nitride LEDs depends critically on the substrate technology. In the case of SiC, which is both transparent and conductive, the Thick TS and Shaped TS approaches described above are viable, with the latter exhibiting η_{ext} as high as 47% for small-area low-current, $\sim 455\text{-nm}$ LEDs [33]. For the case of sapphire, the electrically insulating substrate requires new designs, with the main approaches summarized in Fig. 4.

1) *Conventional Chip (CC)*: In this “epi up” configuration [15], the cathode must be realized by etching down through the p layers to expose the n-type layers and depositing an Ohmic contact. The fairly resistive GaN:Mg p-type layers ($\sim 1 \Omega \cdot \text{cm}$) do not provide sufficient current spreading outside the anode wirebond pad, so typically a semi-transparent Ohmic metallization (e.g., NiAu or ITO) is applied over the p-layer mesa. Quick calculation of C_{ext} is made more difficult due to the large refractive index step between GaN (~ 2.4) and sapphire (~ 1.8) and the anisotropic InGaN emission ($\sim 1 + \cos^2 \theta$), with the dipole axes parallel to the crystallographic *c*-plane (in-plane dipoles only). However, assuming top and bottom escape cones encounter $\sim 50\%$ loss through the semi-transparent metallization (reasonable for $\sim 100 \text{ \AA}$ NiAu, for example), and that all light coupled into sapphire escapes (e.g., through chip side-walls) into silicone or epoxy ($n \sim 1.5$), we arrive at a best-case $C_{\text{ext}} \sim 30\%$. Reduced loss at the p metallization (e.g., replacing NiAu with ITO) could push C_{ext} to $\sim 40\%$. Critical to remember is that approximately half of the generated light is trapped within the GaN. Further improvements must involve harvesting this trapped light, and various approaches in patterning the sapphire growth substrate have been employed. In one such case, the use of a Ag mesh p electrode achieved a peak η_{ext} of 54% measured for a small-area blue LED [34]. More recently, the use of an indium-tin-oxide (ITO) contact in such a configuration is estimated to achieve $C_{\text{ext}} \sim 77\%$ for a small, low-power chip and $C_{\text{ext}} \sim 62\%$ for a large, high-power chip, respectively [35]. (The latter is behind one of the data points in Fig. 2.)

2) *Flip Chip (FC)*: One inherent problem with the CC design is the trade-off between current spreading and light extraction efficiency as current density increases. That is, at higher currents, the required increase in semi-transparent metallization thickness for adequate spreading results in increased optical loss. Furthermore, the fairly poor thermal conductivity of sapphire inserts a barrier to efficient heat extraction from the LED. These two concerns make a flip-chip design attractive, especially for high-power InGaN LEDs [36], [37].

In the flip-chip design, a highly reflective (typically Ag-based), thick metallization is applied to the p mesa area. The n contact is formed similar to the case for the CC design. Then, interconnect metallization is applied to both cathode and anode for either solder or Au-Au die attach.

Especially in FC LEDs, the combination of localized (quantum-well) light emission and typically thin ($\sim 1000 - 3000 \text{ \AA}$) p layers—which puts the distance between

²[Online.] Available: <http://www.philipslumileds.com>

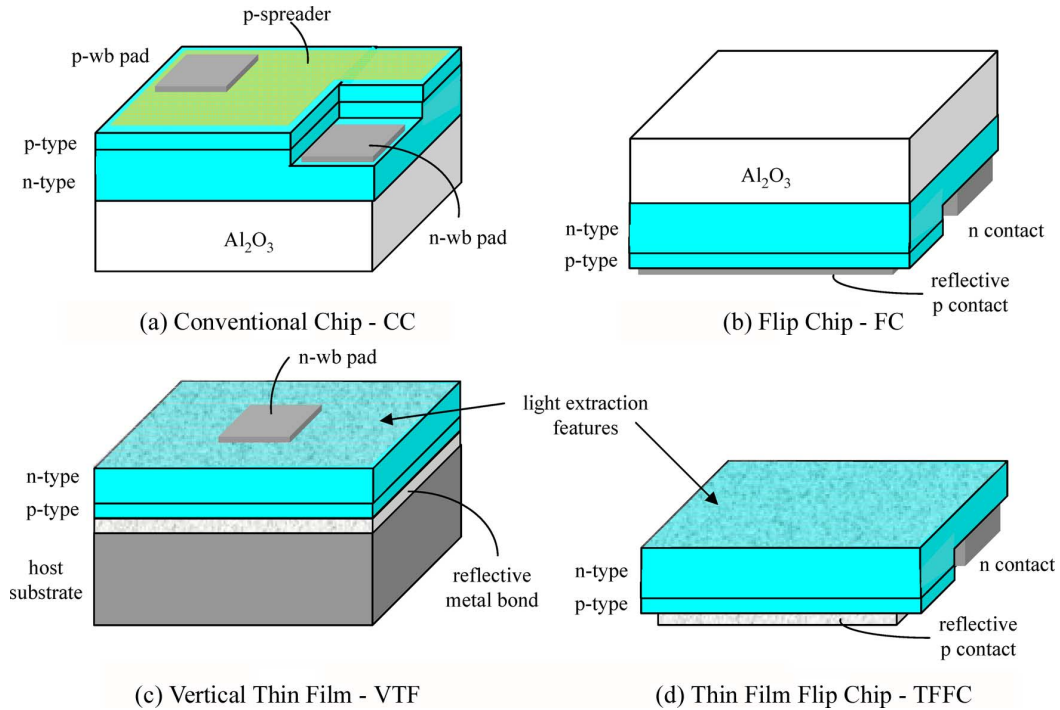


Fig. 4. Common chip designs for sapphire-based InGaN-GaN LEDs: (a) “Epi-up” conventional chip (CC) with semi-transparent top p contact. (b) Flip-chip (FC) with reflective p contact. (c) Vertical-injection thin-film (VTF) bonded to reflective metal on host substrate. (d) Thin-film flip-chip (TFFC). Both thin-film designs provide access to the GaN surface for incorporation of light extraction features such as texturing or micro-optics.

InGaN-GaN quantum-well (QW) heterostructure flip-chip (FC) LED: Internal radiation patterns

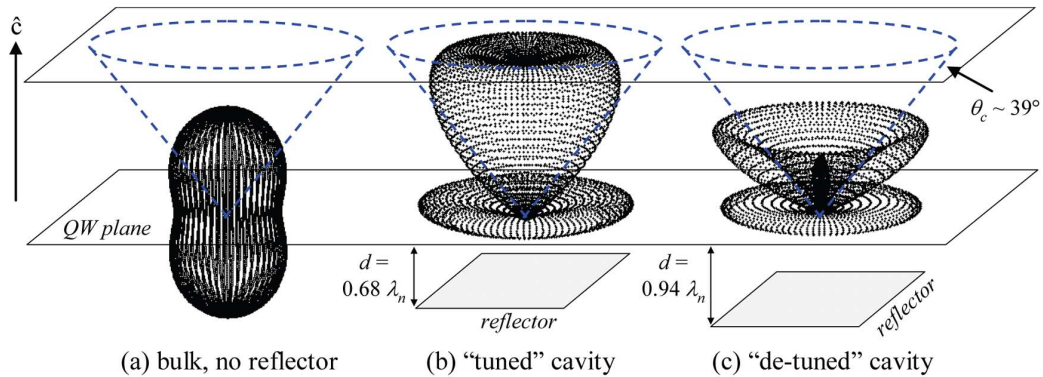


Fig. 5. Calculated internal radiation patterns within GaN for a single InGaN-GaN quantum well heterostructure. (a) Bulk emission is preferentially oriented parallel to crystallographic c-axis due to in-plane-only dipole transitions. (b) Cavity-dependent radiation pattern (emission modified by proximity of close Ag-based reflector with $R \sim 90\%$) using a half-cavity model for a distance $0.68 \lambda_n$ between active region and reflector results in optimal coupling of light into the escape cone from GaN to silicone ($\theta_c \sim 39^\circ$). (c) Cavity-dependent radiation pattern for $d = 0.94 \lambda_n$, for which light coupling to the escape cone is minimized, severely reducing light extraction efficiency.

the highly reflective p contact and the quantum wells, d , on the order of the optical wavelength (λ_n)—results in strong optical cavity effects which dominate C_{ext} . A simplified half-cavity model is sufficient to describe the overall effect, and we may term d the half-cavity length [38]. The radiation pattern from the quantum wells is heavily modified by the presence of the close reflector, as shown in Fig. 5 which displays the internal radiation pattern in GaN for (a) bulk, compared to that for (b) “tuned” ($d = 0.68 \lambda_n$) and (c) “detuned” ($d = 0.94 \lambda_n$) devices

for the case of a Ag-based reflector. We see that for the tuned device, there is strong overlap between the forward lobe of the radiation pattern and the escape cone ($\theta_c \sim 39^\circ$) into silicone.

Using the half-cavity model we may calculate C_{ext} for silicone-encapsulated FC LEDs as a function of d . The internal light generation pattern is first calculated and all flux which couples into the sapphire superstrate is considered to extract into silicone. This is reasonable as light totally-internally-reflected at the sapphire-silicone interface will be extracted

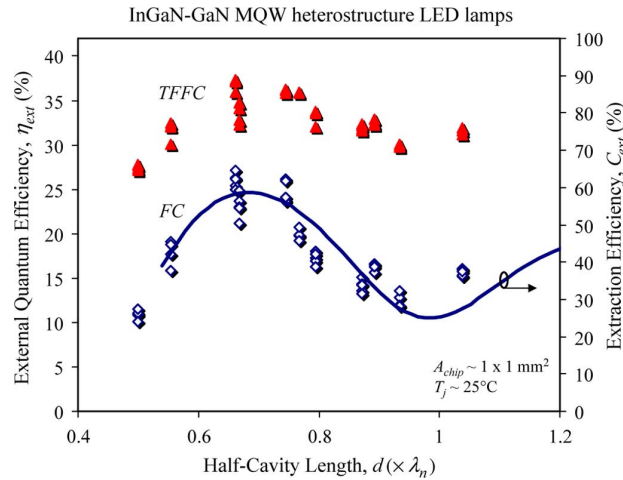


Fig. 6. External quantum and calculated extraction efficiencies versus half-cavity length, d , for FC and TFFC LEDs (silicone encapsulated). The diamonds (FC) and triangles (TFFC) are experimentally measured η_{ext} and correspond to the left-hand ordinate. The curve is the calculated extraction efficiency for Ag-based FC LEDs using the half-cavity model, and corresponds to the right hand ordinate, which is scaled to overlap the experimental data, suggesting $C_{\text{ext}} \sim 60\%$ for a tuned FC LED. The TFFC LEDs are $\sim 1.3\times$ more efficient, corresponding to $C_{\text{ext}} \sim 80\%$.

through the sapphire chip sidewalls since θ_c (sapphire/silicone) $\sim 56^\circ > 45^\circ$. The calculations are compared to a series of InGaN-GaN quantum-well LED runs with varying p layer thicknesses, which were fabricated into Ag-based FC LEDs ($A_j \sim 1 \times 1 \text{ mm}^2$) and measured. The results are shown in Fig. 6. The diamonds are experimentally measured η_{ext} (left-hand ordinate) for FC LEDs, ranging from ~ 10 to $\sim 27\%$ (350 mA). The solid curve represents the half-cavity calculations of C_{ext} plotted against the right-hand ordinate, which is adjusted in order to overlap the experimental FC-LED data. The comparison is justified if we assume similar η_{int} for each of the LED epi runs. The agreement is reasonable and suggests $C_{\text{ext}} \sim 60\%$ for a tuned, versus $< 30\%$ for a de-tuned FC-LED. The strong dependence on d emphasizes the importance of layer thickness control in epitaxial growth for these devices.

Based on this result, we may conclude that for a tuned FC LED essentially all light is extracted into silicone except modes that are totally-internally reflected at the GaN/sapphire interface. While thinner p layers could potentially eliminate the lateral modes ($\sim \lambda_n/4$ case), and provide for even higher light extraction from FC LEDs, such thicknesses may be difficult to realize in practice, and the probability to couple into lossy surface plasmon modes may increase.

In addition to reasonably high C_{ext} , the FC-LED enjoys excellent heat-sinking by close proximity of the active region to the package heat sink. Also, the elimination of wirebonds from the device allows for simplified application of phosphor material to the LED chip, providing superior color control and uniformity versus viewing angle in high volume manufacturing compared to other methods [37].

3) *Vertical Thin Film (VTF)*: This device is very similar to the RS AlGaInP LEDs described earlier, with the main differences being the substrate removal method (typically, excimer

laser-liftoff for sapphire [39], [40]) and the required epitaxial thickness. The resistivity of GaN:Si at $\sim 0.005 \Omega \cdot \text{cm}$ is about $10\times$ lower than that of n-type GaP, allowing a much thinner layer for current spreading from the cathode contact. Since the GaN epitaxy is directly accessible after liftoff, it is possible to texture its surface in order to harvest light that would normally be trapped within. In this case, assuming sufficient light randomization at the textured surface, potentially all light can participate towards light extraction and the process may be described by a photon gas model [30]. C_{ext} as high as 75% has been claimed [41]. In addition to high light extraction, such a design provides the benefit of almost 100% top-surface emission and a near-Lambertian radiation pattern. Ordered texturing has also been applied to VTF LEDs. A $\sim 365\text{-nm}$ high-power InGaN LED using ordered texturing and delivering 44% η_{ext} at 1-A drive current has been reported [42], and is one of the data points of Fig. 2.

Similar to the CC design, the typical VTF design suffers from increased thermal resistance due to insertion of the metal-bonded substrate into the heat extraction path, and from the need for a topside wirebond, the latter of which occludes light, complicates phosphor deposition and secondary optics application, and has been known to cause reliability problems.

4) *Thin-Film Flip Chip (TFFC)*: An alternative design is the TFFC structure [43], which combines the benefits of the VTF chip with the improved robustness, heat removal, and wirebond-free characteristics of FC LEDs.

For the TFFC LED, both contacts are formed opposite the sapphire substrate as for the FC device. After dicing and interconnecting to a submount or package, the sapphire is removed from the LED chip. Then, a photo-electrochemical etch process is used to texture the exposed GaN top-surface, in order to provide means for harvesting light that would normally be trapped within the GaN. In addition to improved light extraction efficiency, the elimination of the wirebond and proximity of active region to the chip top surface allows very close placement of secondary optics and is especially helpful in luminance conservation.

Light extraction in TFFC LEDs can be quantified by nearest-neighbor comparisons to FC LEDs from the same epi wafer. This was performed for the LEDs in Fig. 6, and the results for the TFFC LEDs are indicated by the triangles. The data show a gain of $\sim 1.3\times$ versus “tuned” FC LEDs, corresponding to $C_{\text{ext}} \sim 80\%$ for the TFFC LEDs. As for VTF LEDs, the TFFC LED output is $\sim 100\%$ top-light. Evolution of InGaN LED extraction efficiency with improvements in chip design is shown, alongside AlGaInP LEDs, in Fig. 7.

As an example, recent performance of blue- and green-emitting high-power TFFC LEDs is shown in Fig. 8. The data are acquired under dc drive conditions and no active cooling is employed. For the blue ($\lambda_p \sim 425 \text{ nm}$) device, $\eta_{\text{ext}} \sim 56\%$ at 350 mA and peaks to $\sim 62\%$ at lower currents. This device produces more than 1.3-W optical power at 1 A dc drive. For the green ($\lambda_p \sim 520 \text{ nm}$) device, $\eta_{\text{ext}} \sim 29\%$ at 350 mA and peaks to $\sim 36\%$ at lower currents. In photometric terms, the green TFFC LED peaks at $\sim 162 \text{ lm/W}$ at low currents, decreasing to $\sim 87 \text{ lm/W}$ at 350 mA dc forward current. The decrease in efficiency is slightly due to increased forward voltage and heating,

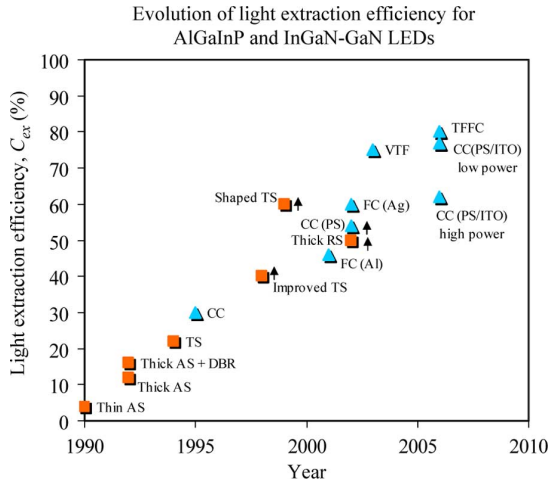


Fig. 7. Evolution of extraction efficiencies for AlGaInP (orange squares) and InGaIn-GaN (blue triangles) LEDs. Upward arrows indicate minimum estimates based on measured η_{ext} . Other points are calculations. “FC(Al)” and “FC(Ag)” refer to Al-based [36] and Ag-based [37] mirror technologies for flip-chip LEDs. “CC(PS)” refers to the case of patterned sapphire substrate [34]. “CC(PS/ITO)” refers to LEDs employing indium-tin-oxide contacts and a patterned sapphire substrate [35].

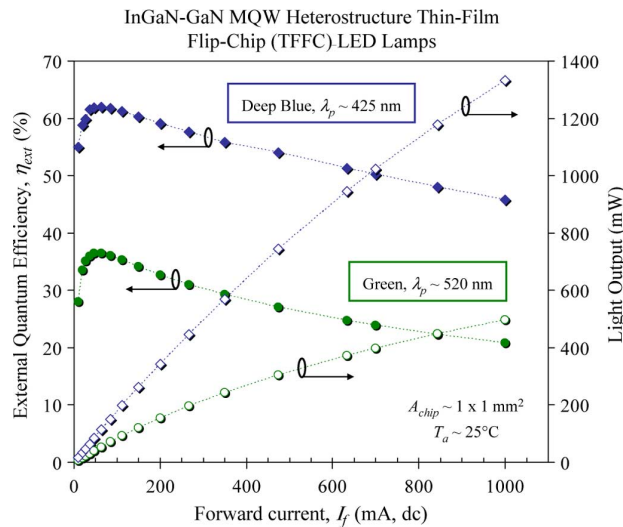


Fig. 8. External quantum efficiency and light output versus dc forward current for both blue and green InGaIn-GaN QW-based TFFC LED lamps. Chip sizes are $1 \times 1 \text{ mm}^2$.

but is in fact dominated by a decreasing internal quantum efficiency as current density is raised, a ubiquitous characteristic that, at the time of this writing, plagues all commercially available InGaIn-GaN visible-spectrum LEDs. Total light output for the green device reaches $\sim 497 \text{ mW}$ ($\sim 222 \text{ lm}$) at a drive current of 1 A. To our knowledge the performance of these devices is the best reported for high-power LEDs in these wavelength regimes. The 350-mA performance has been summarized in Fig. 2.

D. Advanced Designs

Further exploitation of cavity resonance effects beyond the FC LED are the objective of resonant-cavity (RC) and photonic-crystal (PX) LEDs. An RCLED is simply a one-dimen-

sional photonic crystal, typically fabricated by sandwiching the active region between two DBR mirror stacks. As an alternative, some designs employ a reflective metal for one of the mirrors. External quantum efficiencies as high as 27% have been measured in the infrared [44], with somewhat inferior performance observed for visible-spectrum RCLEDs [45]. A problem with the RCLED approach is the tradeoff between a high- Q cavity for enhancement versus the need to deal with the entire full-width of the internally generated emission spectrum. Relatively small refractive index differences available to AlGaInP and (conductive) AlGaInN layers exacerbate the problem. Finally, except for extremely thin cavities which can be difficult to fabricate, a significant portion of light emission is trapped in waveguide modes that can only be extracted through photon recycling.

The PX LED design is more likely to improve overall extraction efficiency, since trapped light can be addressed directly. The PX modifies the modal structure within the semiconductor and can increase coupling into radiated modes. A typical design involves a two-dimensional lattice of holes with center-to-center spacing on the order of the wavelength of light [46]. Indeed, improvements against standard planar LEDs are observed [47]. Three dimensional structures have also been demonstrated. The PX approach is attractive for InGaIn LEDs [48] because of very thin active regions and the relatively low carrier surface recombination velocity of GaN [49]. Finally, tailoring of the far-field radiation pattern is possible [48], suggesting that in the future sophisticated lensing operation may be incorporated directly into the chip, removing the need for a lens encapsulant. Novel techniques for photonic crystal fabrication, such as imprinting, laser interference, and deep UV lithography, are increasing in sophistication and are today supporting the development of PX LEDs towards the commercial realm.

IV. PHOSPHORS AND WHITE LEDs

A. Basic Concepts

The notion of wavelength down-conversion is old, and was applied to III-V semiconductors in the visible-spectrum shortly after their debut [50]. The development of high-efficiency InGaIn-GaN blue LEDs in the early 1990s provided an opportunity for the use of a common down-converting phosphor material used in cathode ray tubes and discharge lamps, $\text{Y}_3\text{Al}_5\text{O}_{12} : \text{Ce}^{3+}$, or “YAG.” The excitation spectrum for YAG at $\sim 440\text{--}460 \text{ nm}$ is well-matched to blue InGaIn-GaN LEDs, and its yellow emission provides an opportunity for obtaining a white point in the 4000–8000-K correlated color temperature (CCT) region by simply mixing in a portion of the blue “pump” light [51], [52]. Also, the dual ground-state YAG emission is broad enough to provide a reasonable color rendering index (CRI) in the $\sim 70\text{--}80$ range.

The approach is illustrated in Fig. 9. The emission spectra and color points for a blue (460 nm) LED pumping a typical YAG phosphor are shown as a function of blue light leakage. For this particular example, the white point crossover occurs at a CCT $\sim 5000 \text{ K}$ for a blue light leakage fraction of 35%. At this condition, the lumen equivalent (LE) of the white emission spectrum is 328 lm/W , but the theoretical efficiency for the LED is lower than this and can be determined as follows.

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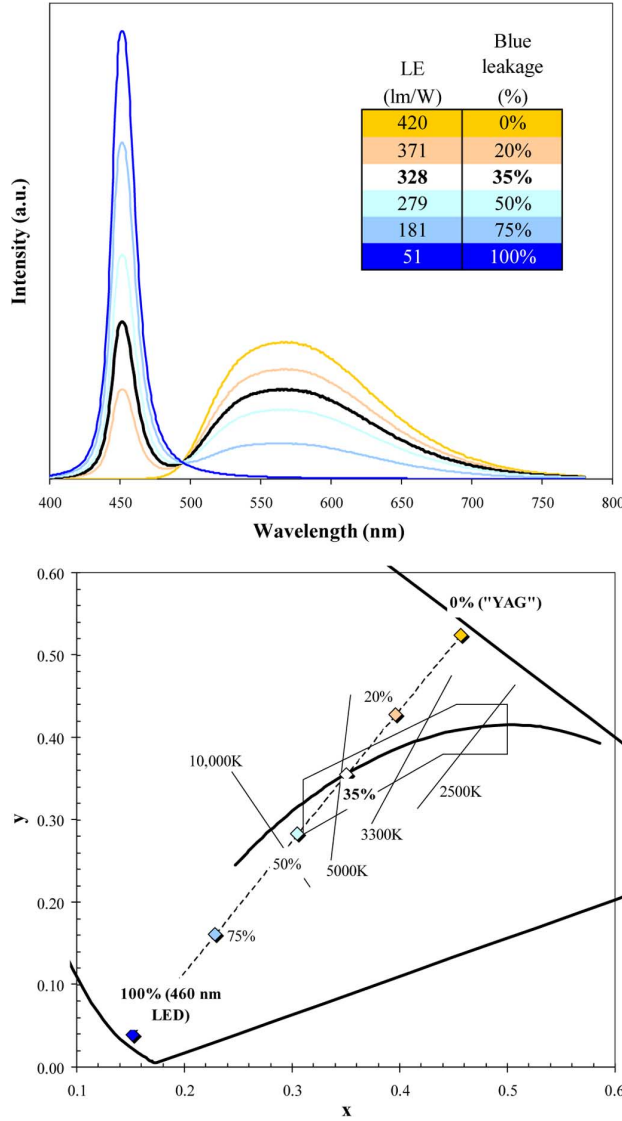


Fig. 9. (Top) Example emission spectra of blue (460 nm) LED-pumped YAG phosphor as a function of blue light leakage. The emission ranges from entirely blue (100% leakage, no conversion) to yellow (0% leakage, full conversion). The inset lists the lumen equivalent for each spectrum. (Bottom) Color points on the CIE x, y chromaticity chart, corresponding to the spectra above, showing a crossover of the blackbody curve at a color temperature of ~ 5000 K.

For an LED producing a total output power of P_{LED} and pumping a single phosphor, the white light exiting the phosphor consists of two parts, residual or “leaked” pump light:

$$l \cdot P_{LED} \cdot \eta_{opt,pump} \quad (2)$$

and down-converted light:

$$(1 - l) \cdot P_{LED} \cdot \eta_{QE,ph} \cdot \frac{\bar{E}_{n_{phosphor}}}{\bar{E}_{n_{pump}}} \cdot \eta_{opt,ph} \quad (3)$$

where l is the pump light leakage fraction, $\eta_{QE,ph}$ is the quantum efficiency of the phosphor, and $\bar{E}_n$ and η_{opt} are the centroid photon energies and optical extraction efficiencies, for

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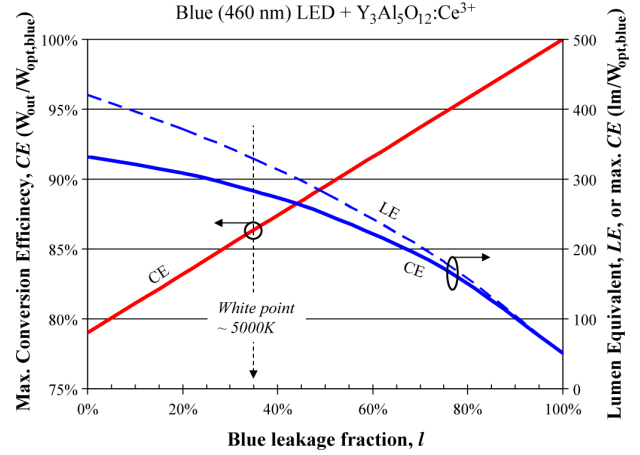


Fig. 10. Maximum achievable conversion efficiencies for a blue (460 nm) LED + YAG phosphor example as a function of the blue light leakage fraction. The red curve is the radiometric conversion efficiency and corresponds to the left-hand ordinate. The blue curves are the photometric conversion efficiency (solid) and spectral lumen equivalent (dashed), which correspond to the right-hand ordinate. A white color point is obtained at 35% blue light leakage which yields a color temperature of 5000 K.

the phosphor and pump emission, respectively. The ratio of photon energies is sometimes termed the “quantum deficit,” and represents the fundamental energy loss in down-conversion, which increases as the Stokes’ shift of the phosphor increases.

The down-conversion efficiency, CE , is simply the sum of (2) and (3) divided by P_{LED}

$$CE = \left[l \cdot \eta_{opt,pump} + (1 - l) \cdot \eta_{QE,ph} \cdot \frac{\bar{E}_{n_{phosphor}}}{\bar{E}_{n_{pump}}} \cdot \eta_{opt,ph} \right] \cdot LE(l) \quad (4)$$

The multiplication by LE (a function of l) is optional depending on whether a radiometric (%), or photometric (lm/W_{opt}), quantity is desired.

The maximum possible conversion efficiency is given when $\eta_{QE,ph}$ and η_{opt} are 100%. This theoretical limit is calculated for an example of a blue (460 nm)-pumped YAG white LED, and plotted as a function of blue light leakage, in Fig. 10. The red curve is the radiometric CE , corresponding to the left-hand ordinate, which ranges from 100% (no conversion) to 79% (full conversion of blue to yellow). The photometric CE and spectral lumen equivalent are given by the blue solid and dashed lines, respectively, and correspond to the right-hand ordinate. The photometric CE ranges from 51 lm/W_{opt} (blue, no conversion) to 332 lm/W_{opt} (yellow, full conversion). At the white point (~ 5000 K for this particular combination of blue LED and YAG phosphor) the theoretically maximum CE is 86% (or 283 lm/W_{opt}).

The use of phosphors suitable for blue pump excitation provides a benefit in white LED efficiency since a significant fraction of the blue light is used directly in the final emission spectrum, with no down-conversion required. This is in contrast to the case of UV-pumped phosphor LEDs, for which leaked pump light only serves to decrease LE , and the higher pump photon energy reduces CE fundamentally.

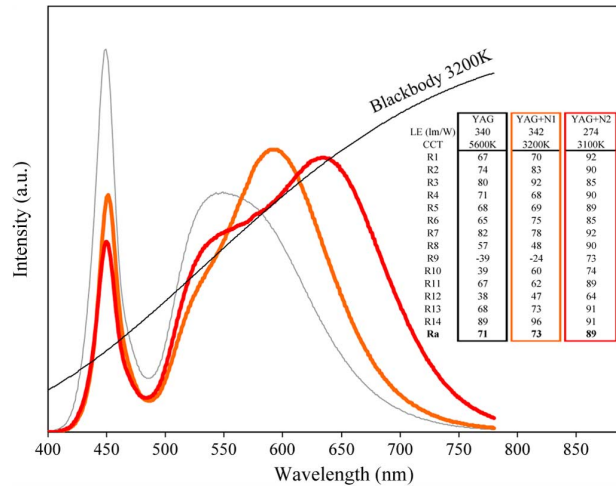


Fig. 11. Luminescence spectra of blue (450 nm)-pumped phosphors for generating white light. Shown are high CCT white from YAG (grey), and low or “warm” CCT white from YAG plus nitride phosphors N1 (orange) and N2 (red). The inset shows all color rendering indices for each spectrum. The deep red phosphor improves color rendering at the expense of spectral lumen equivalent.

B. Multi-Phosphor Approach

The blue LED + YAG approach is a simple one and very efficient, and produces reasonable quality white light for applications such as portable lighting and outdoor use. However, its CRI is typically below 80 and the CCT is limited on the low end to about 4000 K. For indoor illumination, CRI >80 and lower (warmer) color temperatures are required, with the CCT of incandescent tungsten-halogen at 3200 K being a common target. Suitable white light spectra from LEDs are possible using a two-phosphor approach, wherein a yellow or green phosphor is combined with a red one, all pumped by a single blue LED [53].

Such concepts have spurred the development of a wide array of novel host lattices for phosphors. In particular, research in nitride compounds for Eu^{2+} activators has led to the development of a new class of phosphors based on nitridosilicates [54]. These materials exhibit high quantum efficiencies, good thermal quenching behavior, and chemical robustness, and are thus excellent candidates to partner with InGaN LEDs for solid state lighting applications [55].

In Fig. 11 are shown equal-lumen [56] white emission spectra for blue (~ 450 nm)-pumped phosphor LEDs based on YAG only (grey curve), and with the addition of novel nitride-based Eu^{2+} phosphors, denoted N1 (orange curve) and N2 (red curve). N1 is a red-orange emitter, and in combination with YAG allows achieving “warm white” CCTs while maintaining a fairly high LE. N2 is a deeper red emitter which sacrifices LE to achieve higher CRI based on improved color rendering in the red. For reference is also shown an equal-lumen blackbody spectrum for $T = 3200$ K. The CRIs of YAG and YAG+N1 devices are 71 and 73, respectively, while that of YAG+N2 is 89. The inset of Fig. 11 shows the color rendering index values for all fourteen color standards provided by CIE, for each spectrum. CRI is typically given as R_a which, rather arbitrarily, is the average of only the first eight colors standards. R9 in particular is critical for deep red rendering and is important in biomedical applications,

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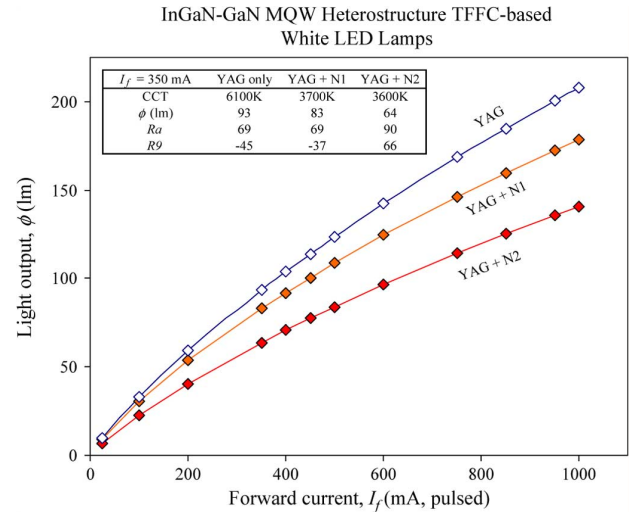


Fig. 12. Light output versus forward current for high-power TFFC white LEDs based on YAG only (black), YAG plus red-orange phosphor N1 (orange), and YAG plus deep red phosphor N2 (red). The inset lists performance characteristics at 350-mA forward current.

especially surgery. (A much needed improvement to color rendering standardization for illumination has been elucidated by the advent of high quality white LEDs and is the topic of recent work in the field of colorimetry [56], [57].) The significantly better color rendering of the YAG+N2 emission comes at the expense of LE, which is only 274 lm/W_{opt} , compared to 340 and 342 lm/W_{opt} for the YAG and YAG+N1 cases, respectively.

Light output versus current (pulsed) characteristics for high-power TFFC LEDs employing YAG, YAG+N1, and YAG+N2 phosphors are shown in Fig. 12. (Note these devices are a different set from those of Fig. 11.) The YAG white LED (~ 6100 K) exhibits up to ~ 208 lm, while the “warm white” YAG+N1 (~ 3700 K) and YAG+N2 (~ 3600 K) LEDs deliver ~ 179 and ~ 141 lm, respectively, at 1 A forward current. The inset of Fig. 12 shows the LED characteristics at a forward current of 350 mA. The CRIs for the YAG and YAG+N1 LEDs are ~ 69 , while that of the YAG+N2 LED is ~ 90 . Deep red color rendering for the YAG+N2 LED is very good, with R9 ~ 66 , compared to large negative R9’s for the other two LEDs. For a typical forward voltage of 3.4 V at 350 mA, the lumen outputs would correspond to luminous efficacies of ~ 80 , ~ 70 , and ~ 55 lm/W for the YAG, YAG+N1, and YAG+N2 devices, respectively. The lower efficiencies for the two-phosphor LEDs are due to increased quantum deficit, increased optical losses due to lower quantum efficiencies (today, compared to YAG), and (in the case of N2) lower LE. Nevertheless, these performance levels far exceed incandescent (~ 17 lm/W) and halogen (~ 25 lm/W) lamps and are comparable to compact fluorescent lamps. Furthermore, a recent announcement of performance in the ~ 115 lm/W regime for a high-power cool-white LED suggests significant improvements for commercially available devices in the near future. Such performance levels surpass that of large-area fluorescent tubes (~ 80 – 100 lm/W), and suggest that warm white LED performance will compete directly with that of large fluorescents relatively soon. Further improvements

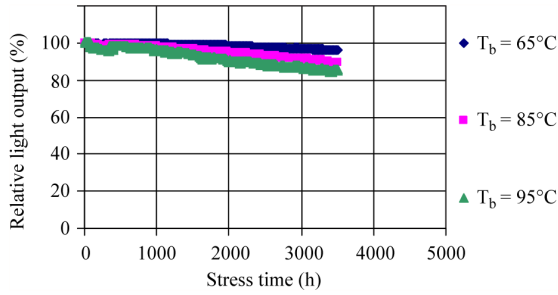


Fig. 13. Lumen maintenance curves for high power white LUXEON LEDs at 450 (blue), 700 (magenta), and 885 (green) mA drive in a 35 °C ambient. Resulting board temperatures are 65 °C, 85 °C, and 95 °C, respectively. (Data from the Lighting Research Center, Rensselaer Polytechnic Institute [60].).

in the quantum efficiencies of red phosphors will accelerate this. In addition, as described later in Section VII, LED performance can be expected to significantly surpass even these levels in the future as internal quantum efficiency is increased.

V. RELIABILITY AND PACKAGING

Penetration of the general lighting market by LEDs is contingent upon reductions in cost (per lm) compared to conventional sources. The implied high lumen density mandates power chips and packages that can handle high power densities ($> 500 \text{ W/cm}^2$). Total cost of ownership of a light source includes maintenance (“re-lamping”) and a significant advantage of LEDs is their inherent robustness and promise of long-life operation [58]. However, reliability of the LED “lamp” is not guaranteed, especially at the high power densities necessary for high lumen output per package (i.e., minimum \$ per lm). To this end, specially designed power LED packages have been developed in recent years. The first one [59]—LUXEON—was introduced in 1998 and has become a benchmark standard in the solid state lighting industry. Recent reliability data from the Lighting Research Center at the Rensselaer Polytechnic Institute, which benchmarks commercial LED performance, are shown in Fig. 13 [60]. The three curves correspond to white LUXEON III LEDs with drive current levels of 450, 700 (rated), and 885 mA which produce board temperatures of 65 °C, 85 °C, and 95 °C, respectively, under 35 °C ambient conditions. At 3500 hrs, the lumen depreciation is 5%, 10%, and 15%, respectively. Typical end-of-life for incandescent and fluorescent lamps are ~ 2000 and $\sim 10\,000$ – $16\,000$ h, respectively. Note that most reliability issues with high power LEDs tend to be package, and not chip, related. In particular, organic components (glues, encapsulants, etc.) have a difficult time under the combination of high heat (> 100 °C) and extreme photo fluence ($> 50 \text{ W/cm}^2$). This is especially true in the case of high photon energy blue light, and poses an even greater challenge for UV LEDs.

Recent improvements in high power packaging for LEDs are highlighted in the LUXEON K2 package released in 2006, which is shown schematically (right) in Fig. 14 alongside its predecessor (left). The improvements in base material and attach technologies provide a package that can allow 150 °C (white) or higher (185 °C, non-white) junction temperature operation with forward currents up to 1.5 A dc, which is 50%

higher than its predecessor. This increase in useful flux from a single device serves as a benchmark for the further push of solid-state lighting into the mainstream.

VI. SELECTED APPLICATIONS

A. Automotive Forward Lighting

Many lighting applications are based on imaging optics and for these applications source brightness is a critical parameter since it determines the size (cost) of the optical system necessary to direct the light for the required application. Source brightness can be described in terms either radiometric,

$$R = \frac{dP}{dE} \quad (\text{radiance}) \quad (5)$$

or photometric,

$$L = \frac{d\phi}{dE} \quad (\text{luminance}) \quad (6)$$

where P is the source output flux in Watts, ϕ is the same in lumens, and E is the source étendue, defined by

$$E = n^2 \iint dA_s \cos \theta d\Omega \quad (7)$$

where n is the refractive index for the source distribution, A_s is the source area, and θ is polar angle with respect to the optical axis. For planar surface emitters, (7) reduces to $E = n^2 A_s \pi \sin^2 \theta$. For a uniform, Lambertian source distribution, flux $\sim \sin^2 \theta$ and luminance (or radiance) is constant regardless of viewing angle. In this case the luminance of an emitting surface is simply

$$L = \frac{\phi}{n^2 \pi A_s} \quad (\text{Lambertian}) \quad (8)$$

To estimate the luminance of an arbitrary LED design, we may use (8) to sum over all emitting surfaces of an LED, which individually are assumed to provide Lambertian light output. Recasting the flux in terms related to LED performance, we have

$$L = \frac{\eta_{\text{ext}} E_{\text{ph}} J_f A_{\text{active}} L E}{n^2 \pi \sum A_s} \quad (\text{LED}) \quad (9)$$

where E_{ph} is the average emitted photon energy [in electron volts (eV)], J_f is the forward current density, A_{active} is the area of the active region, the summation in the denominator represents the total surface area of the LED, and the other terms are as described previously. Equation (9) shows that luminance is increased when η_{ext} and J_f are increased, and when the total surface area of the LED is minimized to match the active region area. Also, it is clearly detrimental to embed the chip in a high-index encapsulant, which magnifies the source size and increases étendue, decreasing luminance.

Equation (9) was used to calculate luminance for LEDs of various III-V materials systems and chip designs over the last few decades and the results are plotted in Fig. 15 along with the effective luminances of conventional light sources: tube fluorescents, automotive halogen, automotive Xe high-intensity discharge (HID), and ultra-high-performance (UHP) discharge lamp used in projection applications. The LED data points are color-coded corresponding to emission wavelength: red,

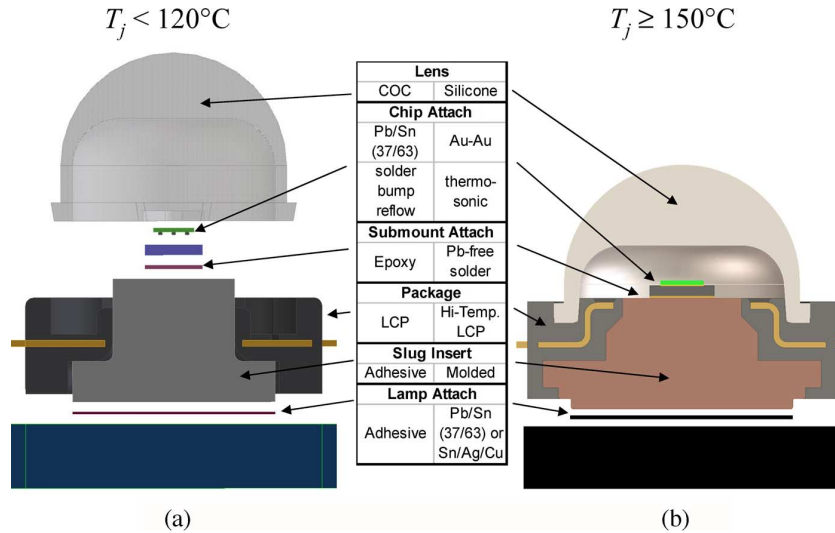


Fig. 14. High power LED "lamp" packages used in solid-state lighting applications. (a) LUXEON circa 1998. (b) LUXEON K2 circa 2006.

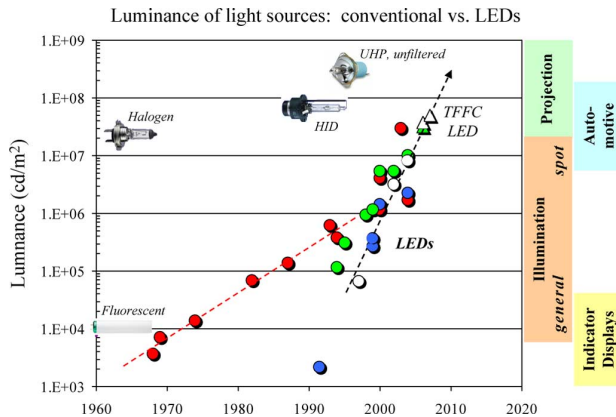


Fig. 15. Luminance evolution of LEDs compared to conventional light sources. LED data points are color coded corresponding to emission wavelength. Ranges required for various applications are shown to the right of the chart. Dashed lines are guides to the eye for luminance evolution of early red, and more recent power LEDs, respectively. TFFC LED performance is indicated by the triangular data point. Luminance of the (120 W) UHP lamp is 300 Mcd/m², corresponding to unfiltered, collected flux of 4500 lm within 15 mm² · sr, an étendue typical for micro-display projection [61].

green, blue, or white. Early LED progress (red dashed line) was largely given by improvements to η_{ext} due to improved material systems and better chip designs for light extraction. The more recent, rapid improvement for power LEDs (black dashed line) comprises increased performance in η_{ext} , but is augmented by increases in J_f (allowed by more sophisticated LED packaging technology) and improved LED chip design for high luminance. For example, the point at 50 Mcd/m² for white is given by an all-top-emitting TFFC blue LED coated with YAG phosphor, but not lens encapsulated. We note that at this performance level, LEDs are suitable for automotive forward lighting and projection display applications, with those required luminance ranges shown at right of the chart in Fig. 15. Moreover, continued progress at this rate would see

LEDs reach $\sim 300 \text{ Mcd/m}^2$, matching the effective luminance of an unfiltered UHP lamp, by 2010.

The availability of very high brightness white LEDs will allow the replacement of conventional automotive "headlamps." A side-by-side comparison of flux and brightness characteristics for a white TFFC LED versus that of conventional "low-beam" automotive halogen and Xe HID lamps is shown in Fig. 16. The useful flux is provided by the average luminance of the source, measured by a radiant imaging system. The particular TFFC LED measured gives 50 Mcd/m² at 1 A drive, compared to 20–30 and 60–80 Mcd/m² for halogen and HID lamps, respectively. The $1 \times 1 \text{ mm}^2$ TFFC LED provides $\sim 120 \text{ lm}$ at an input power of 3.6 W. Early prototyping of automotive forward lighting systems suggest light utilization to reach $\sim 60\%$ – 80% , compared to 25%–40% for the conventional lamps. This suggests that halogen (55 W) and HID (35 W) lamps could be replaced by as few as 3–7 (~ 12 – 28 W), and 6–11 (~ 24 – 44 W), LEDs, respectively. The use of LEDs in forward lighting not only allows a more compact auto headlamp design but offers other benefits such as integrated high-/low-beam functionality. The precisely defined emitting area creates the potential for sharper far-field radiation patterns, which improve visibility while reducing glare for on-coming traffic. Finally, selective use of down-converting phosphors offers flexible tailoring of the spectral content of the LED headlamp beam.

B. Illumination

No doubt the most popular application in discussion of LEDs is that of general illumination. One of the most appealing opportunities is a reduction in worldwide energy consumption by replacing incandescent lamps (now) and fluorescent tubes (future) with LED-based luminaires. Commercially available high power white LEDs, which at the time of this writing operate in the $\sim 70\text{-lm/W}$ regime, require less than 1/4th the energy of incandescent lamps. Furthermore, the small source size and well defined position of LEDs improves the light utilization (as discussed above) in a practical luminaire, putting light only where

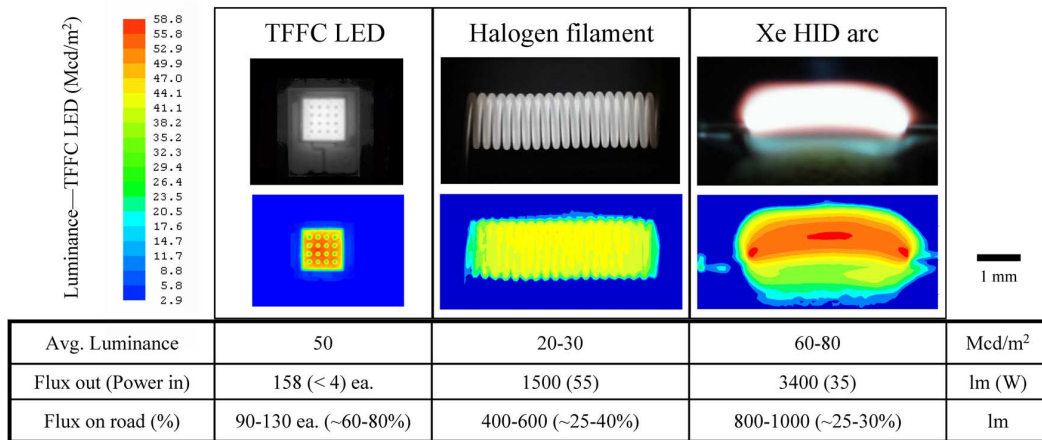


Fig. 16. Comparison of a TFFC white LED against conventional halogen and HID lamps used for “low-beam” automotive forward lighting. Top row is the lit visual image. Underneath is the color-scaled luminance image. The scale for the halogen filament and HID arc are the same. The scale for the LED is different, and is indicated at left. The table lists average luminance, source flux, input power, and useful flux (utilization percentage) in the application.

it is needed and not wasting it. The difference between this utilization efficiency for LEDs versus conventional sources can be a factor of two, or even more in the case of task lighting.

Quality of white light from LEDs—which has been considered an issue mainly due to the ubiquitous status of blue + YAG white LEDs which are limited to high color temperatures and low color rendering—has improved dramatically with the development and commercial release of multi-phosphor LEDs. Warm white LEDs with CRIs up to 90 are now available. The main focus of work in this area should be to have the multi-phosphor LED efficacy come up to approach that of the simple single-phosphor system based on YAG. Several groups worldwide are working on new and improved phosphor systems towards this end.

The U.S. Department of Energy roadmap for solid state lighting anticipates 137-lm/W white power LED performance by 2015 [62]. At such a level, the worldwide opportunity for energy savings—if all conventional light sources were replaced by LEDs—approaches ~1000 TW·h/year. This is a savings of ~\$100 B/year and corresponds to an annual reduction in carbon emissions of about 200M tons [63]. While it is not realistic to expect full replacement of existing lamp technology within a short time horizon, even penetration by a fraction could have a profound impact on reducing the rate of global energy consumption. The progress in white LED efficiency over time, compared to conventional light source development, is shown in Fig. 17.

Additionally, the low power consumption and portability of solid-state light devices make them extremely attractive for implementation in developing countries that do not have a power distribution infrastructure, i.e., in areas that are “off-grid.” Using a simple solar cell and/or battery combination, significant light levels can be brought into homes and schools in the most remote regions on Earth, extending peoples’ “day” and improving conditions for school learning and work.³

Finally, the use of three (or more) primary colors (e.g., red-green-blue or RGB) provides the capability for dynamic color

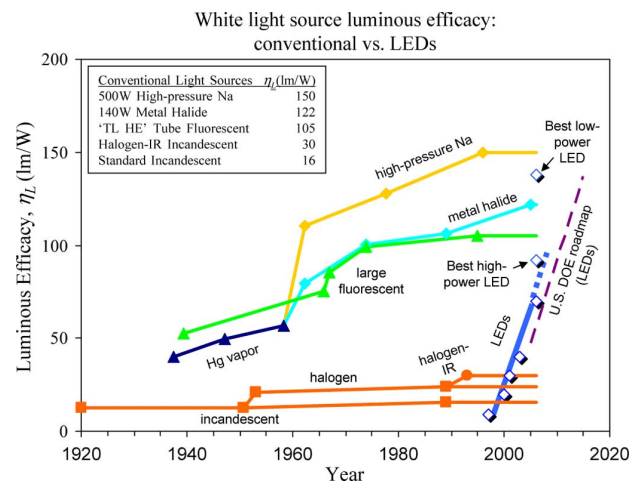


Fig. 17. Evolution of luminous efficacy performance of white light sources. Commercially available high-power LED performance is indicated by the points along the solid blue curve. Best documented high-power LED is ~92 lm/W at 350-mA drive, while best low-current device is 138 lm/W (20 mA) [35]. The U.S. Department of Energy projections for commercially available high-CCT white LED performance is indicated by the dashed purple line. Inset lists description and performance of best conventional light sources available today.

control. The near-instant response of solid-state lighting devices enables real-time spectral tuning to provide light ambience that can suit a particular situation, or adapt to certain human factors, such as Circadian rhythm, etc. This capability has enabled applications for which conventional light sources offered no practical solution, and will continue to expand the use of LEDs in lighting applications.

C. Displays

Displays are of course a major application for LEDs. The low power consumption, saturated colors, and high-speed switching characteristics make them extremely suitable for LCD back-lighting applications. Furthermore, the recent progress in high luminance devices, as indicated in Fig. 15, position LEDs as

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promising light sources for applications in rear-projection television, and front projection for business or personal use. By using in particular red, green, and blue LEDs, the illumination efficiency can be dramatically improved by, for example, removing color wheels or color filters, which typically have efficiencies in the range of only 20%–35%. Indeed, several LED based “personal” projectors are now commercially available. Display applications for LEDs are the topic of one of the other papers in this issue [64].

D. Others

Mainstay applications such as cell-phone backlighting, automotive exterior signaling, traffic signals, and signage continue to grow the worldwide LED market. In addition, other new applications begin to surface as LED performance and cost improves.

Relatively new applications for LEDs include the flash function for cell-phone cameras and replacement of xenon for digital still cameras. These applications have warranted new power LED package designs. The low profile of such LEDs is very attractive to the cell phone market and the “flash” LED can second as a torch light when operated dc.

VII. FUTURE OUTLOOK AND CHALLENGES

A. Internal Quantum Efficiency

The internal quantum efficiency of AlGaInP LEDs is limited due to well known bandstructure constraints (e.g., direct-indirect crossover, small conduction band offsets) as discussed in Section I. Regarding InGaN–GaN, Section II shows that light extraction efficiencies of $\sim 80\%$ are realized for TFCC LEDs. A reconciliation of this fact with the external efficiencies in Fig. 2 confirms that state-of-the-art internal quantum efficiencies of InGaN/GaN quantum-well blue and green LEDs (at ~ 50 A/cm²) are (at most) $\sim 70\%$ and $\sim 36\%$, respectively. Furthermore, η_{int} decreases as current density is further increased and junction temperature is raised. This presents a serious challenge for solid-state lighting since high operating current density is key to reduced cost of ownership.

The overall fairly low internal quantum efficiency for InGaN–GaN is likely due to several culprits in combination, including: 1) high threading dislocation densities on the order $\sim 1\text{E}8$ cm⁻²; 2) high point defect concentrations due to the required low growth temperature for high InN mole fraction alloys in MOCVD; and 3) built-in field effects which separate electrons and holes and increase radiative lifetime. The “droop” in efficiency with current density is often attributed to electron leakage into p-layers, or de-localization of carriers from “quantum-dot-like” low-energy regions provided by InN compositional fluctuation. Obviously, much further work is necessary to improve internal quantum efficiency to achieve performance level of other direct bandgap III-V systems such as (Al)GaAs.

It is instructive to consider the impact that such improvement to η_{int} would provide. Fig. 18 shows energy balance diagrams for blue-pumped single-phosphor high-power white LEDs based on a 350-mA drive (about ~ 1 -W total input power). Fig. 18(a) shows the case for commercially available performance at the time of this writing (~ 70 lm/W) and Fig. 18(b)

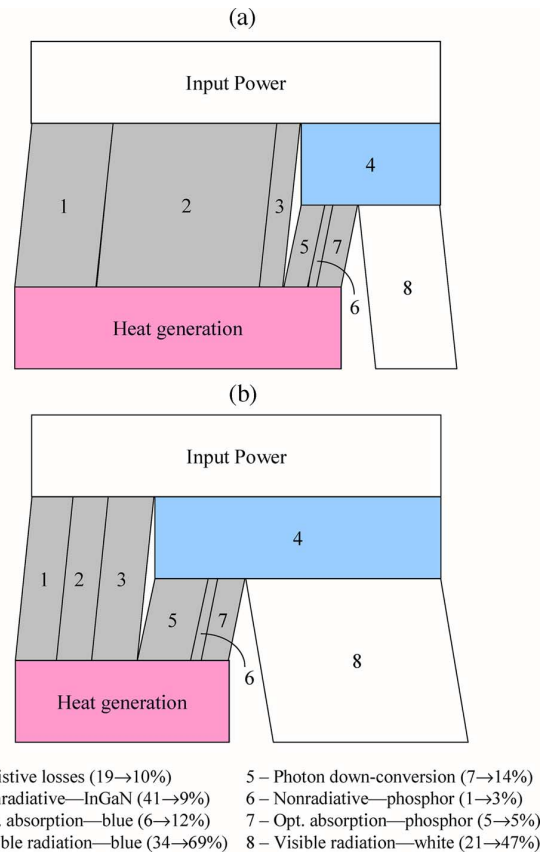


Fig. 18. Energy balance diagrams for blue-pumped single phosphor (YAG) high-power white LEDs (350 mA). (a) Commercially available LEDs at 70 lm/W: $\sim 80\%$ of power is lost to heat, so only 20% goes to useful light output. (b) Potential future performance—assuming internal quantum efficiency for the blue LED reaches 90% and modest reductions to electrical and optical losses—reaches 160 lm/W. In this case, the power split between heat and light is approximately 50/50.

shows the potential future performance under the assumption that η_{int} is increased to 90%, and that modest reductions are made to electrical and optical losses. Under these assumptions, the power conversion efficiency of the white LED increases dramatically from $\sim 20\%$ to almost $\sim 50\%$. For a typical LE in the 330–340 lm/W_{opt} range this yields a luminous efficacy of ~ 160 lm/W, which surpasses the performance of any conventional white light source. Warmer color temperatures will have slightly lower efficiencies ($\sim 10\%$ – 20%) due to larger quantum deficit and lower lumen equivalent.

For white solid-state lighting systems based on the multi-primary (e.g., RGB) approach, efficiencies even higher than 160 lm/W would be achieved if each source reached the performance level of the blue LED indicated in Fig. 18(b). This requires breakthrough in not only blue, but also in InGaN green, and in red.

B. Heat Generation

It is clear from Fig. 18 that the heat removal problem for LEDs becomes vastly simpler as the internal efficiency is improved. In today’s state-of-the-art white power LED, there is about four

times more heat generated than light, whereas for the future case the amount of heat generation reduces to be about the same as the light generation. For the former, a single 1000-lm emitter would have to dissipate roughly 12 W of heat in one package. In the small form factors desired for solid-state lighting, it is difficult to imagine dissipating this much heat without resorting to active cooling, which would serve to increase complexity and cost of the solid-state lighting system. In the future case, only ~ 3 W of heat would need to be removed, which in fact is already well within the scope of today's high power LED packages.

Even so, for applications using the multi-primary (e.g., RGB) approach, provision must be made for colors at wavelengths >550 nm, presumably the domain of AlGaInP LEDs. At junction temperatures above $\sim 100^\circ\text{C}$, the efficiency of these LEDs suffers significantly in comparison to InGaInP LEDs. Breakthroughs in AlGaInP LED temperature dependence, which appears to be fundamentally related to bandstructure, are not readily anticipated. A nitride-based solution for red currently does not exist and, rather curiously, has not been the subject of strong interest in the scientific community until very recently. As InGaInP efficiency, especially in the green, continues to improve, the "red problem" will present a greater and greater challenge (opportunity).

C. Cost Considerations

As for heat generation, cost considerations closely track efficiency. As efficiency and drive current increase, the total lumens per emitter increases, reducing the initial cost of light in addition to providing energy savings. Today's standard household incandescent bulbs generate ~ 1000 lm (60 W) and initial cost is $\sim \$1$ for the end user. The operating cost, assuming $\$0.1$ per kW-h, over the useful life of the bulb (~ 2000 h) is $\sim \$12$, which far outweighs the initial cost of the light source. The operating cost of today's best high-power LEDs is $<\$3$ over the same time period. However, at the current level of ~ 100 lm per LED, the initial cost of a ~ 1000 lm solid-state light source (~ 10 power LEDs $\times \sim \$3 = \sim \$30$) presents a significant barrier to the customer. To compete adequately against initial cost, a single 1000-lm LED is warranted. If internal quantum efficiency for InGaInP can reach its potential (i.e., for phosphor-based down-conversion: $\sim 160+$ lm/W for cool white, and ~ 130 – $150+$ lm/W for warm white), a single power LED at ~ 6 – 8 W input drive should achieve this. In addition, a price scenario of $\sim \$1$ for this single 1000-lm light source is not unreasonable in the foreseeable future. This is in contrast to the case for small, low-current LEDs, which are heavily package- and assembly-cost loaded at such high lumen output levels. At 1000 lm per $\$1$, LEDs become attractive even on initial costs, and significant penetration of the general lighting market is inevitable since maintenance and energy savings significantly reduce the total cost of ownership versus incandescent or fluorescent (esp. compact) solutions.

VIII. CONCLUSION

The status of LEDs for solid-state lighting applications has been presented. The AlGaInP (red to yellow) and InGaInP (blue to green) material systems dominate the field and sophisticated device structures based on these material systems

result in light extraction efficiencies of 60%+ and $\sim 80\%$, for AlGaInP and InGaInP, respectively. At the time of this writing, commercially available high-power white LEDs based on phosphor down-conversion provide luminous efficacies of ~ 70 lm/W. Recent laboratory results suggest devices in the ~ 100 -lm/W regime will be available soon, surpassing both incandescents and compact fluorescent lamps, and competing directly with large fluorescent performance. Moreover, recent improvements in LED luminance place them brighter than halogen filaments, making LEDs attractive for use in automotive headlamps for the first time. The challenge for solid-state lighting now is clearly in internal quantum efficiency, which for the InGaInP and AlGaInP (at operating temperatures) is far below what has been achieved in other III-V systems such as (Al)GaAs. Breakthroughs in internal quantum efficiency would result in high-power phosphor-white LEDs with efficiencies reaching ~ 160 lm/W or more, a performance level surpassing anything known to date for a practical white light source.

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REFERENCES

- [1] N. Holonyak, Jr., "Is the light emitting diode (LED) an ultimate lamp?," *Am. J. Phys.*, vol. 68, pp. 864–866, 2000.
- [2] M. G. Craford, N. Holonyak, Jr., and F. A. Kish, Jr., "In pursuit of the ultimate lamp," *Scientific Amer.*, pp. 83–88, Feb. 2001.
- [3] I. Vurgaftman and J. R. Meyer, "Band parameters for III-V compound semiconductors and their alloys," *J. Appl. Phys.*, vol. 89, pp. 5815–5875, 2001.
- [4] K. M. Yu *et al.*, "On the crystalline structure, stoichiometry and band gap of InN thin films," *Appl. Phys. Lett.*, vol. 86, p. 071910, 2005.
- [5] C. P. Kuo *et al.*, "High performance AlGaInP visible light-emitting diodes," *Appl. Phys. Lett.*, vol. 57, pp. 2937–2939, 1990.
- [6] H. Sugawara, M. Ishikawa, and G. Hatakeoshi, "High-efficiency InGaInP/GaAs visible light-emitting diodes," *Appl. Phys. Lett.*, vol. 58, pp. 1010–1012, 1991.
- [7] K. H. Huang *et al.*, "Twofold efficiency improvement in high performance AlGaInP light-emitting diodes in the 555–620 nm spectral region using a thick GaP window layer," *Appl. Phys. Lett.*, vol. 61, pp. 1045–1047, 1992.
- [8] F. A. Kish *et al.*, "Very high-efficiency semiconductor wafer-bonded transparent-substrate $(\text{Al}_{0.5}\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}/\text{GaP}$ light-emitting diodes," *Appl. Phys. Lett.*, vol. 64, pp. 2839–2841, 1994.
- [9] M. R. Krames *et al.*, "High-power truncated-inverted-pyramid $(\text{Al}_{0.5}\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}/\text{GaP}$ light-emitting diodes exhibiting $>50\%$ external quantum efficiency," *Appl. Phys. Lett.*, vol. 75, pp. 2365–2367, 1999.
- [10] K. Streubel, N. Linder, R. Wirth, and A. Jaeger, "High brightness AlGaInP light-emitting diodes," *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 2, pp. 321–332, Mar. 2002.
- [11] F. A. Kish and R. M. Fletcher, "AlGaInP light-emitting diodes," in *Semiconductors and Semimetals*, G. Stringfellow and M. G. Craford, Eds., San Diego, CA: Academic, 1997, vol. 48, pp. 149–226.
- [12] D. P. Bour, D. W. Treat, R. L. Thornton, R. S. Geels, and D. F. Welch, "Drift leakage current in AlGaInP quantum-well lasers," *IEEE J. Quantum Electron.*, vol. 29, no. 5, pp. 1337–1343, May 1993.

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- [13] H. Amano, N. Sawaki, I. Akasaki, and Y. Toyoda, "Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer," *Appl. Phys. Lett.*, vol. 48, pp. 353–355, 1986.
- [14] H. Amano, M. Kito, K. Hiramatsu, and I. Akasaki, "P-type conduction in Mg-doped GaN treated with low-energy electron beam irradiation (LEEBI)," *Jpn. J. Appl. Phys.*, vol. 28, pp. L2112–L2114, 1989.
- [15] S. Nakamura, M. Senoh, and T. Mukai, "High-power InGaN/GaN double-heterostructure violet light emitting diodes," *Appl. Phys. Lett.*, vol. 62, pp. 2390–2392, 1993.
- [16] S. Nakamura, M. Senoh, N. Iwasa, and S.-I. Nagahama, "High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes," *Appl. Phys. Lett.*, vol. 67, pp. 1868–1870, 1995.
- [17] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, "InGaN-based multi-quantum-well-structure laser diodes," *Jpn. J. Appl. Phys.*, vol. 35, pp. L74–L76, 1996.
- [18] S. J. Rosner, E. C. Carr, M. J. Ludowise, G. Girolami, and H. I. Erikson, "Correlation of cathodoluminescence inhomogeneity with microstructural defects in epitaxial GaN grown by metalorganic chemical-vapor deposition," *Appl. Phys. Lett.*, vol. 70, pp. 420–422, 1997.
- [19] S. Nakamura, "The roles of structural imperfections in InGaN-based blue light-emitting diodes and laser diodes," *Science*, vol. 14, pp. 956–961, 1998.
- [20] F. Bernardini, V. Fiorentini, and D. Vanderbilt, "Spontaneous polarization and piezoelectric constants of III-V nitrides," *Phys. Rev. B*, vol. 56, pp. R10024–R10027, 1997.
- [21] T. Takeuchi *et al.*, "Determination of piezoelectric fields in strained GaInN quantum wells using the quantum-confined Stark effect," *Appl. Phys. Lett.*, vol. 73, pp. 1691–1693, 1998.
- [22] N. F. Gardner, J. C. Kim, J. J. Wierer, Y.-C. Shen, and M. R. Krames, "Polarization anisotropy in the electroluminescence of m-plane InGaN-GaN multiple-quantum-well light-emitting diodes," *Appl. Phys. Lett.*, vol. 86, p. 111101, 2005.
- [23] R. Sharma *et al.*, "Demonstration of a semipolar (10-1-3) InGaN/GaN green light emitting diode," *Appl. Phys. Lett.*, vol. 87, p. 231110, 2005.
- [24] M. Funato *et al.*, "Blue, green, and amber InGaN/GaN light-emitting diodes on semipolar {11–22} GaN bulk substrates," *Jpn. J. Appl. Phys.*, vol. 45, pp. L650–L662, 2006.
- [25] N. A. El-Masry, E. L. Piner, S. X. Liu, and S. M. Bedair, "Phase separation in InGaN grown by metalorganic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 72, pp. 40–42, 1998.
- [26] K. Iida *et al.*, "350.9 nm UV laser diode grown on low-dislocation-density AlGaN," *Jpn. J. Appl. Phys.*, vol. 43, pp. L499–L500, 2004.
- [27] W. B. Joyce, R. Z. Bachrach, R. W. Dixon, and D. A. Sealer, "Geometrical properties of random particles and the extraction of photons from electroluminescent diodes," *J. Appl. Phys.*, vol. 45, pp. 2229–2253, 1974.
- [28] G. O. Mueller, Philips Lumileds Lighting Co., San Jose, CA, data, unpublished.
- [29] H. Sugawara, K. Itaya, H. Nozaki, and G. Hatakoshi, "High-brightness InGaAlP green light-emitting diodes," *Appl. Phys. Lett.*, vol. 61, pp. 1775–1777, 1992.
- [30] I. Schnitzer and E. Yablonovitch, "30% external quantum efficiency from surface textured, thin-film light-emitting diodes," *Appl. Phys. Lett.*, vol. 63, pp. 2174–2176, 1993.
- [31] K. Streubel, Osram Opto Semiconductors, Regensburg, Germany, Jul. 2006, private communication.
- [32] N. F. Gardner, H. C. Chui, E. I. Chen, M. R. Krames, J.-W. Huang, F. A. Kish, S. A. Stockman, C. P. Kocot, T. S. Tan, and N. Moll, "1.4 × efficiency improvement in transparent-substrate $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$ light-emitting diodes with thin ($\leq 2000 \text{ \AA}$) active regions," *Appl. Phys. Lett.*, vol. 74, pp. 2230–2232, 1999.
- [33] J. Edmond *et al.*, "High efficiency GaN-based LEDs and lasers on SiC," *J. Crystal Growth*, vol. 272, pp. 242–250, 2004.
- [34] M. Yamada *et al.*, "InGaN-based near-ultraviolet and blue-light-emitting diodes with high external quantum efficiency using a patterned sapphire substrate and a mesh electrode," *Jpn. J. Appl. Phys.*, vol. 41, pp. L1431–L1433, 2002.
- [35] Y. Narukawa *et al.*, "Ultra-high efficiency white light-emitting diodes," *Jpn. J. Appl. Phys.*, vol. 45, pp. L1084–L1086, 2006.
- [36] J. J. Wierer *et al.*, "High-power AlGaInN flip-chip light-emitting diodes," *Appl. Phys. Lett.*, vol. 78, pp. 3379–3381, 2001.
- [37] D. A. Steigerwald *et al.*, "Illumination with solid state lighting technology," *IEEE J. Sel. Topics Quant. Electron.*, vol. 8, pp. 310–320, 2002.
- [38] Y.-C. Shen *et al.*, "Optical cavity effects in InGaN/GaN quantum-well-heterostructure flip-chip light-emitting diodes," *Appl. Phys. Lett.*, vol. 82, pp. 2221–2223, 2003.
- [39] M. K. Kelly, O. Ambacher, R. Dimitrov, R. Handschuh, and M. Stutzmann, "Optical process for liftoff of group III-nitride films," *Phys. Stat. Sol. (A)*, vol. 159, pp. R3–R4, 1997.
- [40] W. S. Wong, T. Sands, and N. W. Cheung, "Damage-free separation of GaN thin films from sapphire substrates," *Appl. Phys. Lett.*, vol. 72, pp. 599–601, 1998.
- [41] V. Haerle *et al.*, "High brightness LEDs for general lighting applications using the new ThinGaN technology," *Phys. Stat. Sol. (A)*, vol. 201, pp. 2736–2739, 2004.
- [42] D. Morita *et al.*, "Watt-class high-output-power 365 nm ultraviolet light-emitting diodes," *Jpn. J. Appl. Phys.*, vol. 43, pp. 5945–5950, 2004.
- [43] O. B. Shchekin *et al.*, "High performance thin-film flip-chip InGaN-GaN light-emitting diodes," *Appl. Phys. Lett.*, vol. 89, p. 071109, 2006.
- [44] J. J. Wierer, D. A. Kellogg, and N. Holonyak, Jr., "Tunnel contact junction native-oxide aperture and mirror vertical-cavity surface-emitting lasers and resonant-cavity light-emitting diodes," *Appl. Phys. Lett.*, vol. 74, pp. 926–928, 1999.
- [45] R. Joray, R. P. Stanley, and M. Ilegems, "High efficiency planar MCLEDs," *Phys. Stat. Sol. (B)*, vol. 242, pp. 2315–2325, 2005.
- [46] S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and E. F. Schubert, "High extraction efficiency of spontaneous emission from slabs of photonic crystals," *Phys. Rev. Lett.*, vol. 78, pp. 3294–3297, 1997.
- [47] M. Rattier *et al.*, "Toward ultrahigh-efficiency aluminum oxide microcavity light-emitting diodes: Guided mode extraction by photonic crystals," *IEEE J. Select. Top. Quant. Electron.*, vol. 8, pp. 238–247, 2002.
- [48] J. J. Wierer *et al.*, "InGaN/GaN quantum-well-heterostructure light-emitting diodes employing photonic crystal structures," *Appl. Phys. Lett.*, vol. 84, pp. 3885–3887, 2004.
- [49] M. Boroditsky *et al.*, "Surface recombination measurements on III-V candidate materials for nanostructure light-emitting diodes," *J. Appl. Phys.*, vol. 87, pp. 3497–3504, 2000.
- [50] G. E. Stillman, M. D. Sirkis, J. A. Rossi, M. R. Johnson, and N. Holonyak, Jr., "Volume excitation of an ultrathin single-code CdSe laser," *Appl. Phys. Lett.*, vol. 9, pp. 268–269, 1966.
- [51] P. Schlöter, R. Schmidt, and J. Schneider, "Luminescence conversion of blue light emitting diodes," *Appl. Phys. A*, vol. 64, pp. 417–418, 1997.
- [52] S. Nakamura and G. Fasol, *The Blue Laser Diode*. Berlin, Germany: Springer, 1997, pp. 216–219.
- [53] R. Mueller-Mach, G. O. Mueller, M. R. Krames, and T. Trottier, "High-power phosphor-converted light-emitting diodes based on III-nitrides," *IEEE J. Select. Top. Quant. Electron.*, vol. 8, pp. 339–345, 2002.
- [54] H. A. Höpfe, H. Lutz, P. Morys, W. Schick, and A. Seilmeier, "Luminescence in Eu^{2+} -doped $\text{Ba}_2\text{Si}_5\text{N}_8$: Fluorescence, thermoluminescence, and upconversion," *J. Phys. Chem. Solids*, vol. 61, pp. 2001–2006, 2000.
- [55] R. Mueller-Mach *et al.*, "Highly efficient all-nitride phosphor-converted white light emitting diode," *Phys. Stat. Sol. (A)*, vol. 202, pp. 1727–1732, 2005.
- [56] G. O. Mueller, R. Mueller-Mach, and M. R. Krames, "Proposal for a new metric on the illumination quality of light," in *LRO Symp. on Light and Color*, 2005.
- [57] W. Davis and Y. Ohno, "Toward an improved color rendering metric," in *Proc. SPIE*, 2005, vol. 5941, pp. 283–290.
- [58] P. N. Grillo, M. R. Krames, H. Zhao, and S.-H. Teoh, "Sixty thousand hour light output reliability of AlGaInP light emitting diodes," *IEEE Trans. Dev. Mater. Rel.*, submitted for publication.
- [59] G. E. Höfner, C. Carter-Coman, M. R. Krames, N. F. Gardner, F. A. Kish, T. S. Tan, B. Loh, J. Posselt, D. Collins, and G. Sasser, "High-flux, high-efficiency transparent-substrate AlGaInP/GaP light-emitting diodes," *Electron. Lett.*, vol. 34, pp. 1781–1782, 1998.
- [60] N. Narendran, Rensselaer Polytechnic Institute, Troy, NY, Troy, NY, Jul. 2006, private communication.
- [61] G. Derra, "UHP lamp systems for projection applications," *J. Phys. D: Appl. Phys.*, vol. 38, pp. 1995–2000, 2005.
- [62] "Solid-State Lighting Research and Development Portfolio," 2006, p. 48, prepared for U.S. Dep. of Energy.
- [63] R. Haitz, F. Kish, J. Tsao, and J. Nelson, "The case for a national research program on semiconductor lighting," presented at the Optoelectronics Industry Development Association, Washington, D.C., 1999, unpublished.
- [64] G. Harbers, S. Bierhuizen, and M. R. Krames, "Performance of high power light-emitting diodes in display applications," *J. Display Technol.*, no. 2, Jun. 2007.

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