Illumination With Solid State Lighting Technology

Daniel A. Steigerwald, Jerome C. Bhat, Dave Collins, Robert M. Fletcher, Mari Ochiai Holcomb,
Michael J. Ludowise, *Member, IEEE*, Paul S. Martin, and Serge L. Rudaz

Invited Paper

***Abstract*—High-power light-emitting diodes (LEDs) have begun to differentiate themselves from their more common cousins the indicator LED. Today these LEDs are designed to generate 10–100 lm per LED with efficiencies that surpass incandescent and halogen bulbs. After a summary of the motivation for the development of the high-power LED and a look at the future markets, we describe the current state of high-power LED technology and the challenges that lay ahead for development of a true "solid state lamp." We demonstrate record performance and reliability for high-power colored and white LEDs and show results from the worlds first 100-plus lumen white LED lamp, the solid state equivalent of Thomas Edison's 20-W incandescent lightbulb approximately one century later.**

***Index Terms*—Flip chip, gallium nitride, GaN, illumination, solid-state lighting, LEDs, light-emitting diodes, phosphor, white light.**

I. Introduction

LIGHT-EMITTING DIODES (LEDs) have gained broad recognition as the ubiquitous little lights that tell us our monitors are on, the phone is off the hook or the oven is hot. Recent advances in AlInGaP Red and AlInGaN Blue and Green semiconductor growth technology have enabled applications wherein several single to several millions of these indicator style LEDs can be packaged together to be used in full color signs, automotive interior and exterior signaling applications including traffic signals. These more recent applications differ from the "the ubiquitous little lights" of a decade ago in that the viewer is often not tens to hundreds of centimeters from the LED source but may be tens to hundreds of meters away from the LED source. Still the preponderance of applications require that the viewer look directly at the LED. In this sense, even the "high brightness" or "high efficiency" LED applications are dominated by *indicator* LEDs. This is NOT "Solid State Lighting". Artificial "lighting" sources are $4'$ fluorescent tubes, 60-plus Watt incandescent light bulbs, high intensity discharge lamps etc. which all share three key characteristics differentiating them on the evolutionary tree as a species apart from the indicator lamp. First, they are rarely viewed directly. Light from a lighting source is viewed in reflection off of the illuminated object. Second, the unit of measure (flux) is the kilolumen (klm) or higher, not the mlm, lm or worse yet the Cd often used for indicator LED lamps. Finally lighting sources are predominantly white with CIE color coordinates (x, y) very near the Planckian, producing good to excellent color rendering. Today there really is no such thing as a commercial "solid state lamp" for use in illumination. However, a branch in the evolutionary tree is forming and differences are beginning to appear in the technologies used for low power LED indicators and the high power LED light sources that will evolve into lighting sources. In this paper we will trace the common ancestors for indicator and high power LEDs, look at the markets that are driving advancement of high power LEDs, address technical challenges in moving toward true solid state lighting sources, summarize recent advances in power flip chips, including lamp reliability, white LED technology, and conclude with a look at what the future might hold for Illumination with Solid State Lighting Technology.

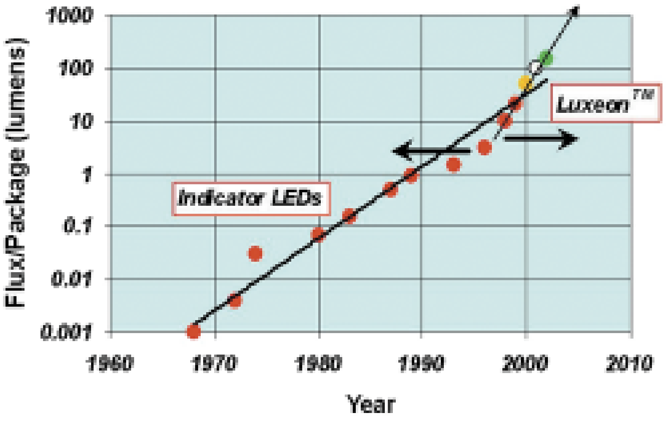


Fig. 1. Haitz's Law for LED flux—LED flux per package has doubled every 18–24 mo for $30+$ years.

II. LED Evolution—Common Ancestor of Indicator and High Power LEDs

The first practical LED was developed in 1962 and was made of a compound semiconductor alloy, gallium arsenide phosphide [1], which emitted red light. From 1962, compound semiconductors would provide the foundation for the commercial expansion of LEDs. Analogous to the famous Moore's Law [2] in silicon which predicts a doubling of the number of transistors in a chip every 18–24 months, LED luminous output (flux, measured in lumens) has been following Haitz's Law (Fig. 1) [3], doubling every 18–24 months for the past 34 years. From 1968 when the first commercial LEDs were introduced

Manuscript received January 9, 2002; revised February 13, 2002.
The authors are with Lumileds Lighting, San Jose, CA 95131 USA.
Publisher Item Identifier S 1077-260X(02)03760-7.

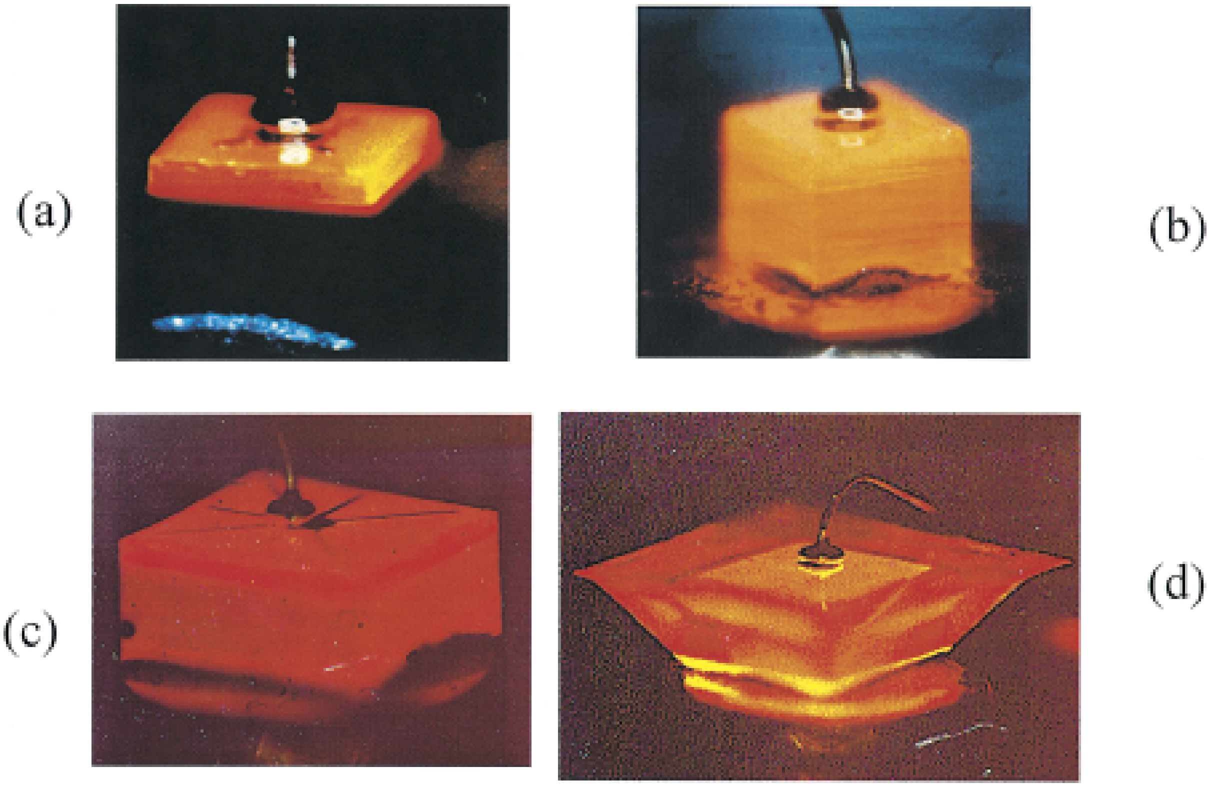


Fig. 2. Four generations of AlInGaP LEDs: (a) Absorbing substrate (AS) LED. (b) Transparent substrate (TS). (c) High-power LED with 5× TS flux. (d) Trunction inverted pyramid (TIP) LED with 1.5× flux of high-power square chip.

at 0.001 lm/LED using GaAsP until the mid-1990s commercial LEDs were used exclusively as indicators. In terms of number of LEDs sold, indicators and other small signal applications in 2002 still consume the largest volume of LEDs, with annual global consumption exceeding several LEDs per person on the planet.

The development of AlGaAs LEDs grown on GaAs substrates and employing fully lattice-matched direct bandgap systems and hetero-structure active regions [4] allowed these early red LEDs to exceed the luminous efficiency of a red-filtered incandescent bulb. Efficiency was further doubled by the use of transparent substrate devices (AlGaAs grown on AlGaAs) [5].

The development of organo–metallic vapor phase epitaxy (OMVPE) crystal growth techniques enabled the introduction of a new material system, AlGaInP on GaAs. AlInGaP resulted in the fabrication of high-brightness materials from yellow to red [6]. In the early 1990s, LumiLeds Lighting (then the Hewlett-Packard Optoelectronics Division [1]) mastered the complex OMVPE growth process of quaternary aluminum indium gallium phosphide (AlInGaP) on GaAs substrates. The AlInGaP material system allows the creation of light in the red and amber regions of the spectrum. Alloy ordering, hydrogen passivation of acceptor atoms [7], p–n junction placement and oxygen incorporation into the aluminum-containing semiconductor layers proved to be substantial challenges that required nearly a decade of work to resolve [8]. The result was AlInGaP LEDs with internal quantum efficiencies approaching 100%; nearly every electron and hole pair injected into the device resulted in the creation of a photon [AS AlInGaP Fig. 2(a)]. The problem was then how to get the photons that had been generated inside the semiconductor LED out into the world outside the semiconductor where they could be used. The first hurdle was to prevent light from being absorbed in the narrow bandgap (1.42 eV = 870 nm) GaAs substrate. Techniques such as incorporation in the epitaxial structure of Bragg mirrors, and direct growth on GaP have been tried, but the most successful technique is removal of the GaAs substrate by etching and replacement with transparent GaP by wafer bonding as developed at Hewlett-Packard in 1994. [TS AlInGaP Fig. 2(b)] At 25 lm/W efficiency, nearly ten times the efficiency of a red filtered light bulb, and several lumens per LED, these LEDs enabled the first LED stop lights on automobiles, LED red traffic signals, and single color outdoor signs. But at 3 lm/LED uses were still limited to those applications where the user was expected to look directly at the LED.

Following closely behind the commercialization of AlInGaP, two groups, Shuji Nakamura at Nichia Chemical [9] and Prof. Akasaki and Prof. Amano [10] at Nagoya University and later Meijo University were mastering the complex OMVPE growth process of aluminum indium gallium nitride on sapphire substrates using atmospheric-pressure OMVPE. The AlInGaN material system has a wider bandgap than AlInGaP and allows access to the higher energy green, blue,

---

[1] Originally the Hewlett-Packard Optoelectronics Division (OED). OED became part of Agilent when Agilent was divided from Hewlett-Packard. In 1999, Lumileds Lighting was formed as an Agilent and Philips joint venture, retaining the high-brightness LED businesses of the old HP OED.

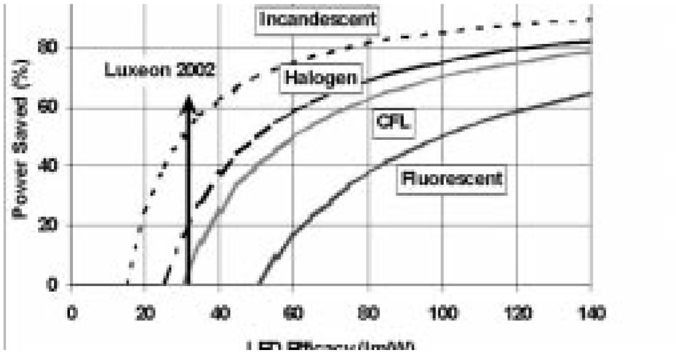


Fig. 3. Potential power savings versus traditional lighting. Today's Luxeon white pc-LEDs are in the 20–30 lm/W range, but flux/LED is still low. Assumed 50% optical flux utilization for CFL and Fluorescent, but 100% for LED.

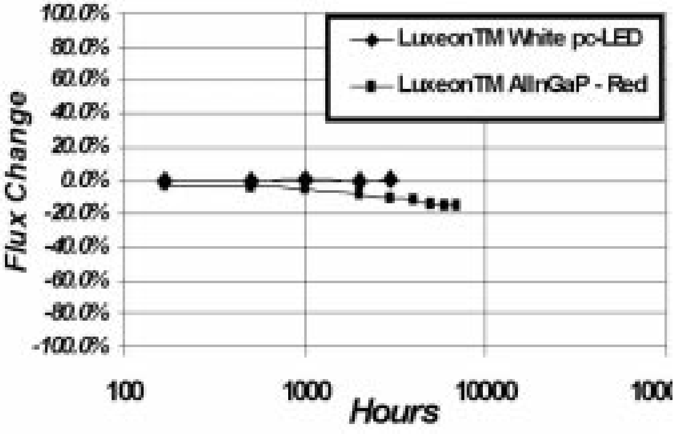


Fig. 4. Luxeon high-power LED reliability for white pc-LED and red AlInGaP LED under room-temperature operating life condition.

and UV parts of the color spectrum. As has been found in AlInGaP, alloy clustering, hydrogen passivation of acceptor atoms [11], p–n junction placement and oxygen incorporation into the aluminum-containing semiconductor layers proved to be substantial challenges. The AlInGaN material system is not as well understood as the AlInGaP material system, and today internal quantum efficiencies at typical operating current densities for AlInGaN green devices hover around 20–40% with blue devices operating in the 40–60% range. Nevertheless, by taking advantage of the transparent sapphire substrate and the human eye's greater sensitivity to green light than to either blue or red, Nichia Chemical, Lumileds and others have been able to introduce multilumen green LEDs that together with multilumen red AlInGaP and ~1 lumen blue LEDs enables large full color signs to be made entirely from solid state light sources. Along with the high brightness blue LEDs, white LEDs that use high energy blue photons from a blue AlInGaN LED, and incorporate a phosphor to convert some of the blue photons into yellow, the complementary color to blue, have emerged. The human eye perceives this combination of blue and yellow light as a white light. Finally, 30 years after the introduction of the first commercial LED in 1968 the stage has been set for some new thinking.

III. THE PROMISE OF SOLID STATE LIGHTING

In 1999, the USA consumed 3 Trillion kWh of energy, 21% of which was used for lighting. Incandescent bulbs consumed 40% of the energy used for lighting (252 Billion kWh) to generate 15% of the total light produced. The more efficient fluorescent and discharge light sources consumed the remaining of the energy (378 Billion kWh) generating ~85% of the light. At nearly \$60 B/year, \$12 B of which is for sources alone, the lighting market dwarfs the \$3 B/year (2000) indicator LED market [12].

With the convergence in the mid 1990s of major advances in AlInGaN and AlInGaP material technologies by the turn of the millennium LEDs were rapidly surpassing the efficiency of color filtered fluorescent light bulbs and white incandescent and halogen light bulbs. Fig. 3 shows the percentage power savings for LEDs versus other conventional illumination sources. LEDs inherit other important advantages including lifetimes measured in tens of thousands of hours, ruggedness, environmental friendliness (no mercury), compact size, low operating voltages, and cool operation. Their small size allows design flexibility in the control and steering of the emitted light by utilizing sophisticated secondary optics. However, today's lighting applications which require a light source to illuminate a desk, a screen, or a room demand not only high efficiency and long life, but also high flux, all at a low unit cost. A single 60-W incandescent bulb emits ~1 klm of white light with a color rendering index near 100; that is 300 times the amount the light emitted by a typical phosphor converted indicator white LED (pc-LED) at a small fraction of the upfront cost. The challenge is designing LED devices and packages that sustain two to three orders of magnitude higher input drive power than traditional ($\leq$60 mW) indicator LEDs whilst retaining the same high efficiency and reliability.

The pioneering work on high-power LEDs began at Lumileds Lighting[1] in 1998 with the introduction of the first commercial high power LED [13]. At 1-W input power, Luxeon devices operate at power levels 20 times that of traditional 5-mm indicator LEDs with efficiencies that can be as much as 50% greater. Lifetimes extrapolate into the tens of thousands of hours (Fig. 4). Commercialization of high-power LEDs in 1998 has impacted the decades-old Haitz's Law (Fig. 1), manifesting as a knee in the lm/LED versus time plot, defining the point in LED evolution when power LEDs diverged from indicator LEDs. Key among Lumileds' achievements is a dramatic reduction in package thermal resistance from the 300 K/W level of indicator LEDs to less than 15 K/W for the Luxeon line of LEDs (Fig. 5). This 20× reduction in thermal resistance enables devices to be pumped to 20× the input power whilst emitting 55-lm red, 30-lm green, 10-lm blue, about 25-lm (pc-LEDs) white light, for ~1 W of input power. At 0.025 klm, the white devices are still 40 times below the 1 klm per unit flux threshold for entry into general illumination as single device sources. Fig. 6, however, shows an overhead table lighting fixture designed by Philips Lighting utilizing a cluster of 12 Luxeon white sources generating ~0.3 klm of white light. Fig. 7 shows a next-generation Luxeon LED, which is the world's brightest white LED at 0.15 klm at 5-W drive, next to a 15-W incandescent bulb. This LED generates nearly 40% more light, occupies <1% of the package volume, and requires only 33% of the power of the in-

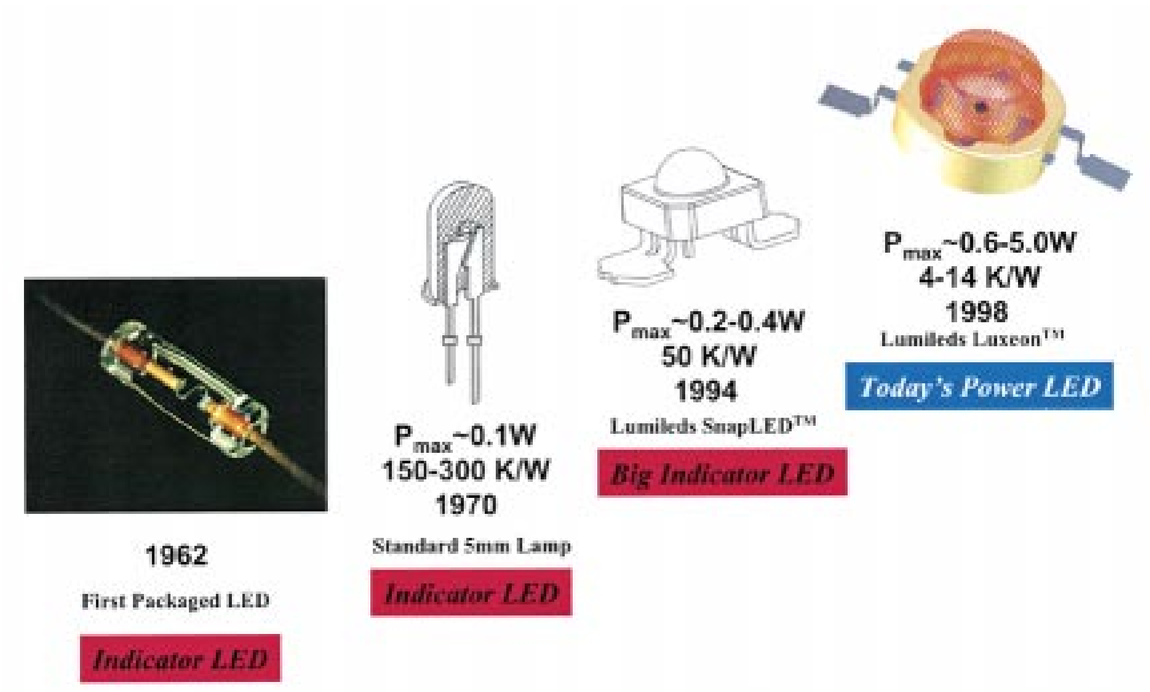


Fig. 5. Evolution of LED package technology: Power LEDs can handle ~50× power of a typical indicator LED.

Fig. 6. Lumileds Luxeon Ring: Fixture design by Philips Lighting and Lumileds. Twelve Luxeon sources, ~0.24-klm total light output.

candescent lightbulb. Twelve of these high-powered 0.15-klm devices are sufficient to make a blue-tinted high-intensity discharge (HID) equivalent 1.8-klm automotive headlamp. Single color green versions of the 5-W Luxeon devices offer luminous fluxes in excess of a 0.13 klm per package. Two of these Luxeon sources can replace the 150-W light bulb in a typical 8″ or 12″ US traffic signal resulting in 90% energy savings. RGB combinations of Luxeon sources have efficiencies that even rival those of cold cathode fluorescent lamps. For example, applications such as backlighting for LCD televisions and monitors take advantage of the compact source size and narrow color bands, while providing extended color range, ruggedness, and eliminating high-voltage power supplies.

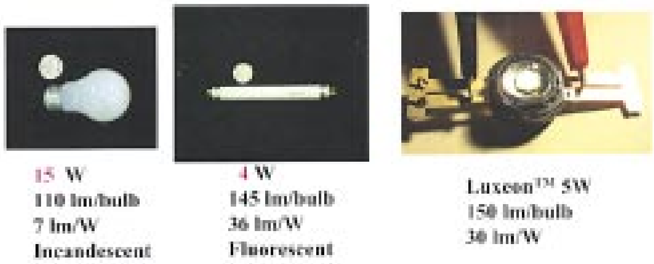


Fig. 7. Comparison of common low wattage incandescent, fluorescent, and high-power LED bulb. The high-power LED solution offers nearly 40% more light than the 15-W incandescent while using $1/3$ of the power!

IV. HIGH POWER LED NITRIDE FLIP-CHIP TECHNOLOGY

A. Conventional Indicator LED Device Structures

The bulk of commercially available GaN-based devices are grown on sapphire substrates. LEDs have a cross section similar to that depicted in Fig. 8. n-type GaN layers are grown on the substrate, an active layer is grown on top of this, and p-GaN layers are then grown over the top of the structure. Part of the p-GaN and active layers are etched away to reveal and allow the formation of an electrical contact to the underlying n-GaN layers. Light is extracted from these devices through the uppermost p-GaN layers. However, the limited conductivity of p-GaN results in the requirement for superficial metallic current-spreading layers to be deposited on the p-GaN surface. These current-spreading layers consist of Ni and Au and are partially optically absorbing, resulting in a lowered extraction efficiency of the devices. In order to minimize absorption of the emitted light, the thickness of the current-spreading layers is

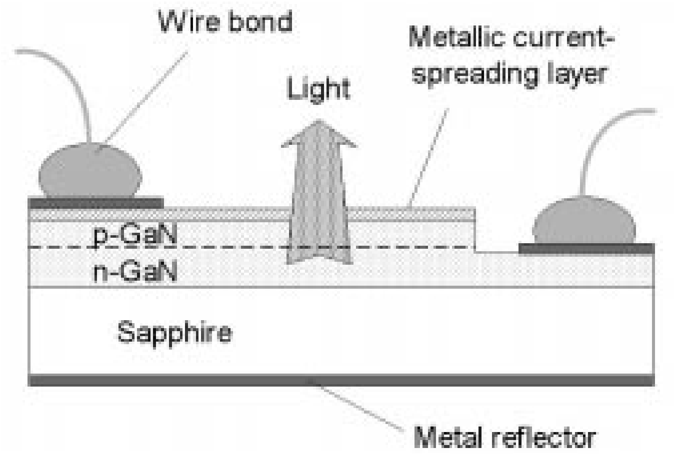


Fig. 8. Diagramatic cross section through a standard, commercially available GaN-based LED. Light is extracted through a partially absorbing Ni–Au-based layer which acts as both hole-spreading layer and a hole injecting contact to the p-GaN.

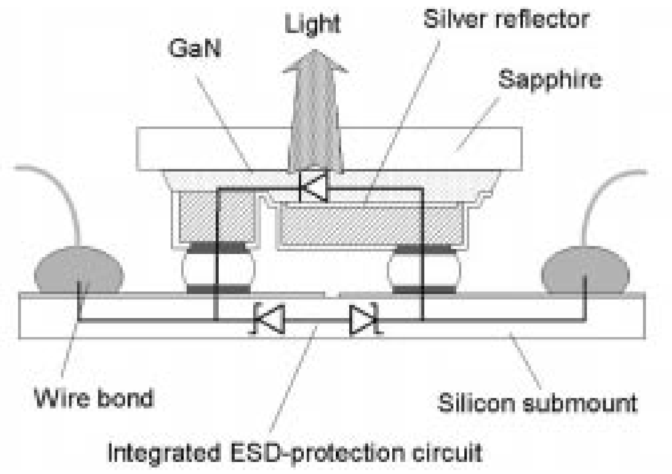


Fig. 9. Diagrammatic cross section through a commercially available GaN-based flip-chip LED. The flip chip is mounted on a Si submount which incorporates ESD-protective circuitry and which lends the LED a resilience to discharges of >16 kV (Human Body Model) and 2 kV (Machine model), and allows electrical connection to the flip chip via standard wire bonds. Conventional GaN-based LED chips can be susceptible to damage during electrostatic discharges of <100 V.

limited to a few tens of Angstroms. This limits the ability of the current spreading layers to uniformly and reliably spread large currents across the surface of the p-GaN. The operating power of the LED is thus limited by the structure of the p-contact.

The device resistance is a critical parameter for high-power solid-state light sources and determines the power density that the source can operate. The resistivity of the underlying n-GaN layers are approximately 3–6 mΩcm and the thickness is limited to $\sim$3 um due to epitaxial growth constraints, resulting in a sheet conductivity in the range of 10–20 $\Omega/\square$. The finite sheet conductivity of the underlying n-GaN layer limits the efficiency of small-size indicator LEDs when run at higher current densities, and limits the arbitrary scaling of the size of the LED since the resistance scales with the linear dimensions. LEDs having the structure depicted in Fig. 8 are heat sunk through their insulating sapphire substrates, further limiting their efficiencies and achievable operating powers, and the bond pads and wire bonds over the top of the die obscure that light which can be extracted from the LED into the package. LEDs having this standard configuration are therefore suboptimal from optical, electrical, and thermal points of view, and will, therefore, be severely limited in their ability to compete with standard light sources in mass illumination markets.

B. LED flip-chip Device Structures

LEDs built in a flip-chip geometry provide an alternative to the standard method of fabricating LEDs. In this configuration, LEDs are fabricated with highly reflecting metallizations to the epitaxial semiconductor, which act as both electrical contacts to the semiconductor, and as optical reflectors. The bulk of the light is extracted through the substrate rather than directly from the epitaxial semiconductor surfaces shown in Fig. 9. Light no longer has to be extracted through a partially absorbing layer, and can, therefore, be extracted from the LED with minimal attenuation. For an ideal device in which there is no optical absorption in the semiconductor layers, the metallizations to the device provide the only source of optical attenuation in a device. Choice of appropriate high-reflectivity metallizations which also make stable, ohmic, low-resistivity contact to GaN is key to maximizing the overall- or wallplug-efficiency of the devices.

Replacement of the thin current-spreading layer in conventional LEDs with the thick, opaque metallic contact of flip-chip LEDs allows the flip-chip LEDs to be operated at increased current densities with high reliability. The device configuration further allows the semiconductor to be directly heat-sunk through the conductive metallizations in contrast to conventional GaN LEDs which are heat sunk through the sapphire substrate. This combination allows GaN flip-chips LEDs to be operated at over twice the current density of conventional LEDs with increased reliability in adverse operating environments. Finally, the displacement of the wirebonds from over the top of the device results in reduced obscuration of light within the package, and hence, to an increase in the overall optical extraction efficiency of the packaged LED.

C. Materials Selection for Flip-Chip LED Design

Aluminum makes a good candidate material for the construction of GaN-based flip-chip LEDs; Al is highly reflective and makes tenacious, stable, ohmic contact to n-GaN. However, Al does not make ohmic contact to p-GaN, and a thin Ni–Au-based ohmic contact layer must be interspersed between the Al reflector and the p-GaN in order to provide efficient hole injection into the device as reported by Wierer *et al.* [14]. Current spreading in these devices occurs readily in the overlying Al reflector, allowing the thickness of this hole-injection layer to be kept to a minimum. The optical absorption of the Ni–Au-based layer is thereby minimized, and the extraction efficiency of the flip chip is increased over that of the standard LED. The wallplug efficiency of the flip-chip LED can be further improved by replacing the Al metallizations with Ag. Silver can form electrically superior contacts to p-GaN than Ni–Au, and has higher reflectivity than Al. Silver deposited directly onto p-GaN, therefore provides the ideal p-type contact to GaN-

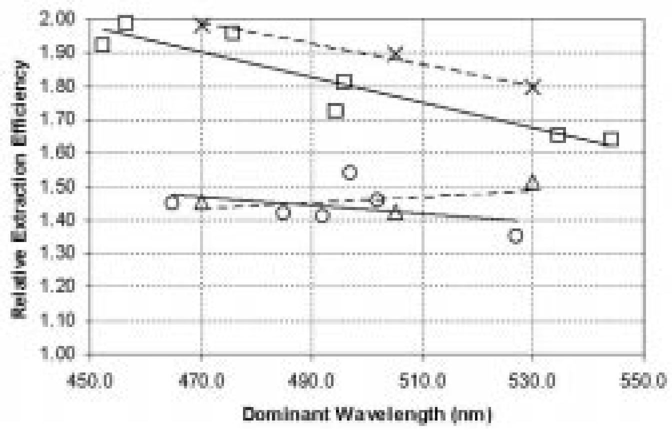


Fig. 10. Measured and modeled extraction efficiencies of 1-mm-square GaN-based flip-chip power LEDs relative to those of 1-mm-square LEDs having conventional, semitransparent Ni–Au-based p-contact through which the light is extracted. “O” (measured), and “Δ” (modeled) relative extraction efficiency of Ni–Au–Al-based flip-chip LEDs. “□” (measured), and “X” (modeled) relative extraction efficiency of Ag-based flip-chip LEDs. Solid and dashed lines represent best fit lines to the measured and modeled data, respectively.

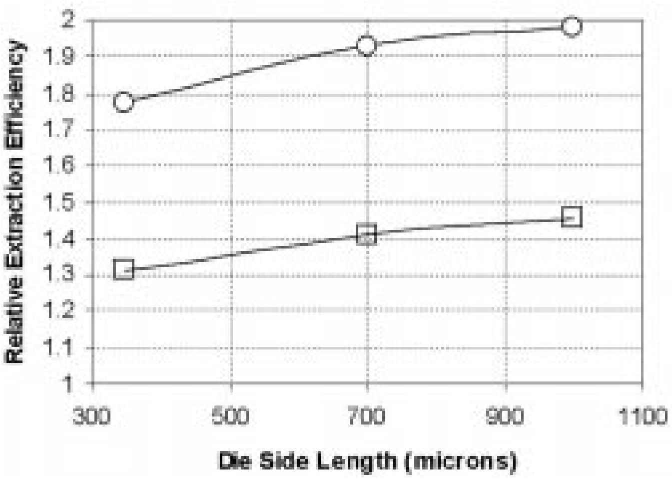


Fig. 11. Relative extraction efficiencies of GaN-based flip-chip LED s to conventional GaN-based LEDs as a function of die size. “□”—Ni–Au–Al-based, and “O”-Ag-based flip-chip LEDs.

based LED flip chips, and provides an increase in extraction efficiency of the device over that of the Al-based flip chip.

The optical extraction efficiencies of InGaN LED dice can be simply and straightforwardly modeled using standard, commercially available optical ray tracing software. The dimensions of the LEDs produce semicoherent microcavity interference effects within the epitaxial semiconductor layer, not accounted for in such models. However, the results obtained are in reasonable quantitative agreement with the experimental results. The modeled and measured extraction efficiencies of GaN-based flip-chip LEDs relative to those of LEDs having the structure of standard commercially available LEDs are compared in Fig. 10. It is seen that in moving from a conventional Ni–Au-based LED to an Al-based flip-chip LED, extraction efficiency of the LED is increased by a factor of approx. 45%. In moving from the conventional Ni–Au-based LED to a Ag-based flip chip, a doubling of the optical extraction efficiency can be obtained.

The sensitivity of the extraction efficiency of LED flip chips to the reflectivity of the metallizations can be understood by considering the ray trace model of the LED. A certain fraction of the light incident on the GaN-sapphire interface undergoes reflection back into the GaN at this interface. Much of the light extracted through the sapphire undergoes multiple reflections within the GaN layer, and therefore, undergoes multiple, compounded reflections against the top metal reflector prior to extraction from the LED chip. Small variations in the optical constants of the metals, therefore, have a relatively large effect on the extraction efficiency of the device, as can be verified by the modeling. The presence of some very small absorption which has not been accounted for in the optical modeling is evident in the modeled relative extraction efficiencies of the Ag-based flip-chip LEDs being some 5% larger than measured.

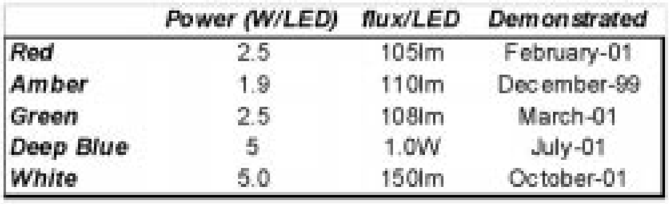
D. LEDs for Power Applications

As the requirement for increased flux per LED grows, LED chip sizes are increasing. 1-mm-square 1-W InGaN LEDs are currently in mass production [15] and industry leaders are already looking to larger-area, 5-W LED [16], [17]. The requirement for increased flux per LED will continue to grow strongly as LED technologies start to penetrate illumination markets. However, the extraction efficiency of LEDs decreases with increasing LED chip size as observed in AlInGaP- and GaN-based LEDs.

The origin of the size dependence of the extraction efficiency of the LEDs is the presence of absorption within the LED chips and their metallizations. In the case of standard GaN-based LEDs grown of sapphire substrates, the main source of absorption is the semitransparent p-contact. In a 350-um-square LED, up to 40% of the light extracted from the LED can be extracted through the sidewalls of the substrate. This sidelight is not extracted through the p-contact, and therefore, undergoes significantly reduced absorption. As the LED dimension is increased to 1-mm-square, the proportion of light extracted from the LED as sidelight decreases to 25% or less. A greater fraction of the extracted light passes through the p-contact, and the overall extraction efficiency of the device is, therefore, reduced. In the case of GaN-based LEDs grown on conducting SiC substrates, the conducting substrate itself forms a significant source of absorption in the structure, and arguments akin to those forwarded for the AlInGaP devices [18] lead to the reduced extraction efficiency of large-area LEDs.

For flip-chip LEDs, light extracted through the top of the substrate undergoes no more absorption than light extracted through the side of the substrate, and little penalty in extraction efficiency is paid in moving to larger-area LEDs. In moving from small-area to large-area devices the extraction efficiencies of GaN flip-chip LEDs relative to those of conventional GaN LEDs therefore increase substantially as demonstrated in Fig. 11.

In moving to larger-size flip-chip LEDs, consideration must still be paid to the finite conductivity of the n-GaN layers in the devices. In order to maintain a low device series resistance, the active region of the LED must be interdigitated with electrical contacts to the underlying n-GaN as discussed by Weirer *et al.* [14]. This style of electrode structure allows the LED size to scale arbitrarily while maintaining a constant device resistivity.



	Power (W/LED)	**flux/LED**	**Demonstrated**
Red	2.5	105lm	February-01
Amber	1.9	110lm	December-99
Green	2.5	108lm	March-01
Deep Blue	5	1.0W	July-01
White	5.0	150lm	October-01

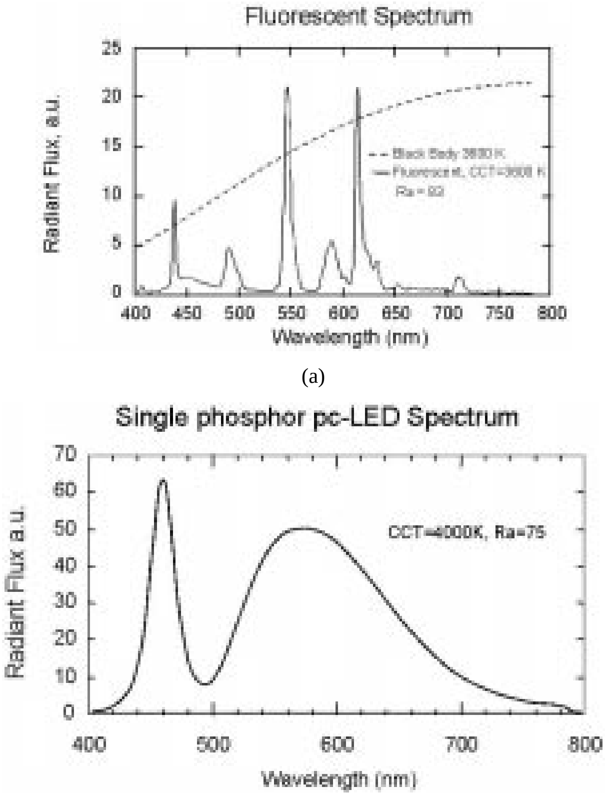
Fig. 12. Lumileds 100 lumen club! These are the only LEDs that within an order of magnitude of the klm scale flux required for "illumination."

For 1 mm square LEDs, the series resistance is typically 1 ohm, versus a resistance of 30 ohms for a 0.35 mm indicator LED.

As a result of the advances in semiconductor quality and of this device technology, the LED efficiency exceeds the best available colored (filtered) incandescent, halogen, and fluorescent lighting in all colors, and the white LED efficiency exceeds the efficiency of both incandescent and halogen sources. The total flux of a single commercial LED package now extends to over a hundred lumens (Fig. 12), from the cyan through the red parts of the spectrum as well as in the white, and deep blue parts (430 nm) offer in excess of 1 Watt per LED at 25% WPE. A single blue-green (505 nm) LED consuming 5 W can emit over 0.17 klm and replace an 80 W 0.7 klm bulb in an 8-in traffic ball while offering a 100-fold increase in lifetime.

V. WHITE LED TECHNOLOGY

Illumination means white light, and a very particular kind of white light at that. Having evolved under a black body emitter, the sun, with a correlated color temperature (CCT) in the 3000 K–6500 K range depending on time of day, weather and season, the human eye is quite sensitive to small changes in spectral content of illumination sources. The Planckian locus on the CIE diagram is scaled in Kelvin, denoting the CCT describing the color of a black body source. Sensitivity to color change is a function of location on the CIE curve. Near 3000 K–4000 K where incandescent bulbs and halogen lamps operate typical humans can detect changes in CCT on the order of $\sim$50 K–100 K. Multiple illumination sources visible at the same time must therefore have CCTs that are the same to within $\sim$50 K–100 K and chromaticity coordinates lying very near the black curve. However, this is still insufficient. Even though a white light source may have color coordinates close to the black body curve, the source may not render true colors when used to illuminate an object. If the wavelengths reflected by a surface are absent in the source, then the surface will appear dark or gray, not colored. Upon reflection or transmission, spectrally incomplete sources will produce less vivid color quality than those with a more complete spectrum. The ability of an illumination source to render true colors is determined by measuring the color rendering index, Ra, scaled 0 to 100 [19]. The noon-day sun, incandescent lamps and other near black body radiators have Ras of near 100. Fluorescent lamps with choppy emission spectra such as that shown in Fig. 13(a) have lower Ras in the 75–90 range which explains why most people would prefer to see their own reflections when illuminated with incandescent rather than fluorescent lights. Before LEDs can be seriously considered to be sources of "illumination", CCT variations within a lamp and from lamp to lamp must be homogeneous to within 50 K–100 K, and Ra > 75.



(a)

(b)

Fig. 13. (a) Comparison of a Fluorescent lamp emission spectra to a black body spectra of the same CCT. The fluorescent lamp has a color rendering index measured at 83. (b) Emission spectrum of a single-phosphor pc-LED showing the blue peak of light leaking through the phosphor and the broader yellow peak from the phosphor.

There are three general approaches to generating white light from LEDs, illustrated in Fig. 14 [20]. The first method directly mixes light from three (or more) monochromatic sources, red, green and blue (RGB), to produce a white source matching with the RGB sensors in the human eye. The second technique uses a blue LED to pump one or more visible light-emitting phosphors integrated into the phosphor-converted LED (pc-LED) package. The pc-LED is designed to leak some of the blue light beyond the phosphor to generate the blue portion of the spectrum, while phosphor converts the remainder of the blue light into the red and green portions of the spectrum. The third technique uses an ultraviolet LED to pump a combination of red, green and blue phosphors in such a way that none of the pump LED light is allowed to escape. Each of these approaches has potential advantages and clear technical challenges.

The most straightforward technique mixes the emission from at least three different colored LEDs. Referring to the C.I.E. chromaticity diagram, Fig. 15, a three-colored (RGB) LED array will be perceived as a color within the triangle depending upon the relative luminance balance of the sources. Properly balanced, the array can produce any particular point within the triangle and in particular along the Planckian black body curve. In more sophisticated versions, onboard electronics adjust the individual drive currents to change the CCT at will

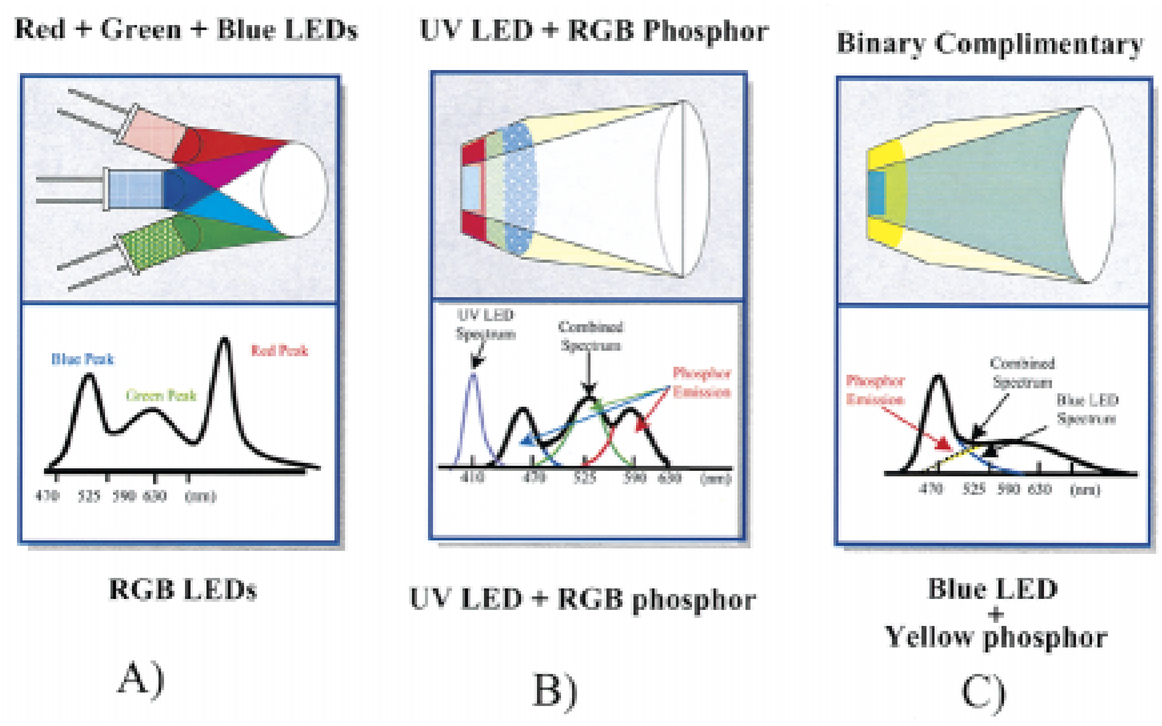


Fig. 14. Three methods of generating white light from LEDs—(a) red+green+blue LEDs. (b) UV LED+RGB phosphor. (c) Pc-LED = blue LED+yellow phosphor.

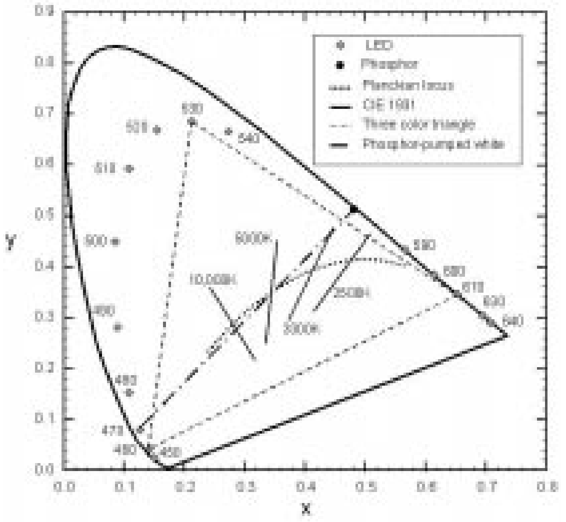
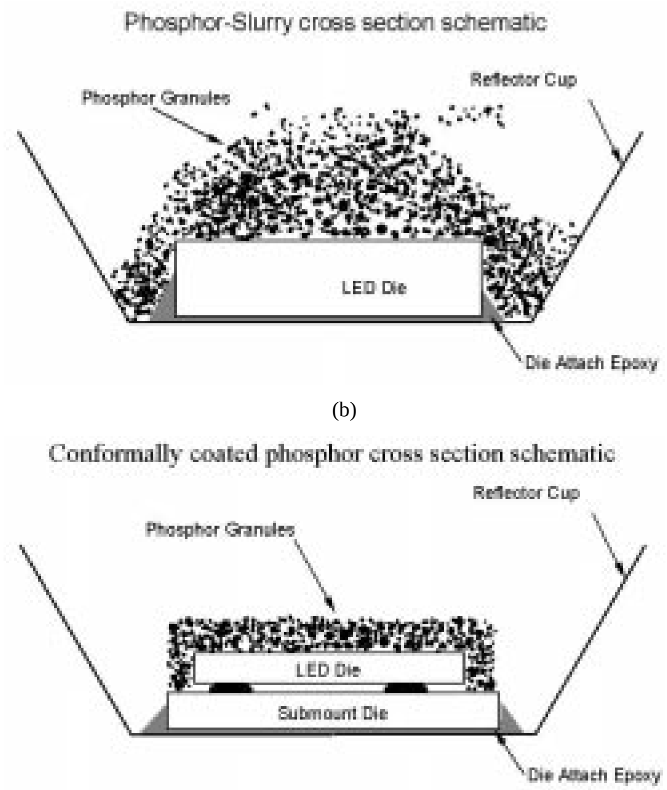


Fig. 15. CIE chromaticity diagram showing typical LED color points, the Planckian black-body locus, the accessible colors with a three color mix (triangle) and the phosphor-pumped tie-line crossing the black-body curve at 5 000 K.

[21], or to maintain the color point as each source ages over the life of the array or changes with the ambient temperature. RGB mixing is the most efficient way to make white light from LEDs since there is no quantum deficit (arising from the Stokes shift characteristic of photonic energy down-conversion of the phosphor [22]), and offers infinitely graduated color and white point control. Efficiencies for state of the art devices are in the 30–40 lm/W. Color rendering can be excellent, >95, but CCT is controlled dynamically by an external detector plus feedback system. For specialized applications such as LCD backlighting or projection images, and applications requiring dynamic color control, RGB mixing is the preferred choice.

By far the most common LED-based white light source is the pc-LED used in a configuration with a blue LED and a complimentary yellow phosphor. The blue LED is used to pump a yellow emitting phosphor integrated into the LED package. Inherently less efficient than an RGB source, simple white sources are made. The phosphor density and thickness are chosen to leak a predetermined fraction of the blue light. Mixed with the resulting yellow phosphor emission, white light results. Striking the correct blue/yellow ratio depends upon having the correct amount, density, and particle size of phosphor, distributed evenly around the blue-emitting chip. Variations in any of these parameters will give rise to color or CCT variations at different viewing angles from a single lamp, or between adjacent LED lamps. First generation white pc-LEDs are made by depositing in measured quantities of a slurry mixture of phosphor and epoxy within a containment cup surrounding the pump die during the encapsulation step [Fig. 16(a)]. Several factors inhibit process uniformity, including the difficulty of measuring precise small quantities of a viscous fluid, slurry settling both before and after dispensing, distribution of the mixture within the cup, and phosphor powder grain size variations (Fig. 17). To illustrate typical variations, the circles in Fig. 18 illustrate typical CCT control within a single LED radiation pattern (viewing angle) using a first generation slurry deposited pc-LED to be very large, ~800 K, or 8–16 times the human detectable difference. The triangles indicate results from a second-generation phosphor deposition process developed by Lumileds in which a conformal layer of phosphor is deposited only around the die, Fig. 16(b). In this case, variation within a single LED radiation pattern drops



(b)

(a)

Fig. 16. (a) Schematic cross section of a pc-LED made with slurry deposited phosphor. (b) Schematic cross section of a pc-LED made by conformally coating the chip with phosphor after the die are flipped and soldered to the submount wafer. Connecting wire-bonds are not shown.

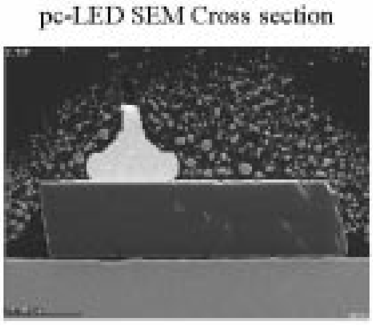


Fig. 17. SEM cross section of a pc-LED made with slurry deposited phosphor, showing variations in grain size, variability of deposition thickness, and nonuniformity at the sides of the chip.

to ∼80 K, fully 10 times better than first generation pc-LED technology. In effect, the flip-chip LED with the conformal layer of phosphor act as a white light-emitting die.

The conformal deposition process also improves LED to LED color variation. To demonstrate, examine the color locus created from combining a 470-nm pump LED and a 575-nm emitting phosphor as show by the dark tie line in Fig. 15. This line crosses the Planckian at a color temperature of 5000 K. Small variations in phosphor thickness, grain size and efficiency create lamps spanning a range large compared to the ∼50–100 K minimum detectable CCT difference.

Fig. 13(a) and (b) compare the spectral outputs of a fluorescent light and a single pc-LED spectrum, which produce respectively, Ra $= 83$ and Ra $= 75$. The Ra for the single phosphor pc-LED is low due to the lack of spectral content in the red. By employing two phosphors, covering a broader emission range, the two-phosphor pc-LED rises to Ra $= 92$, well above acceptable levels for most illumination. The pc-LED technique with state-of-the art material gives luminous efficacy performance in the 25–30 lm/W.

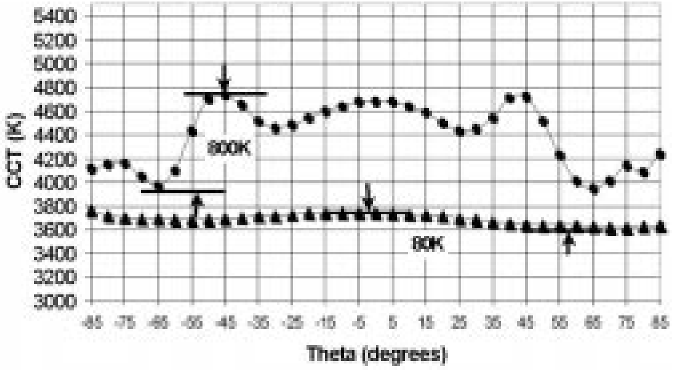


Fig. 18. Color uniformity verses angle can be very good for a pc-LED. Circles represent the first generation of slurry deposited phosphor LED showing CCT variation as a function of angle in the 800-K range which is visible as blue and yellow rings when the LED is shone onto a white screen. Triangles represent the next generation conformally coated Luxeon pc-LED showing CCT variation as a function of angle one order of magnitude better at ∼80 K. 50–100 K is acceptable for illumination.

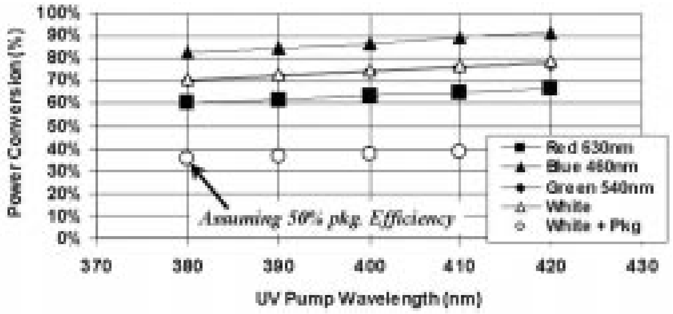


Fig. 19. UV-LED pumped RGB phosphors—UV-LED must have twice the WPE as direct green LED for same lm/W efficacy. Downshift in color causes fundamental energy loss. Scattering in phosphor plus absorption in package reduces extraction efficiency. Today's best package efficiencies are in the ∼50% range for blue pump plus YAG phosphor.

Recently, there has been renewed interest in creating a white source using a UV-emitting LED to pump a trio of RGB-emitting of phosphors, the UV-LED. The UV light is completely adsorbed by the phosphors, and the mixed RGB output appears white much the same as an RGB mixed LED array. The quantum deficit between the UV pump and the phosphors, especially the low-energy red phosphor, dissipates significant energy and makes this approach inherently less efficient than either the RGB or the pc-LED schemes for generating white light. Fig. 19 shows power conversion efficiency verses UV pump wavelength by considering the Stokes' shift in converting UV to red, green, blue. Scattering and absorption losses in the package are also considered. The result indicates that an UV-LED must be more than twice the wall plug efficiency of the green LED in an RBG solution in order to overcome packaging and Stokes' losses. Today, there are no ideal blue phosphors that emit efficiently in the 450–470-nm blue range while absorbing efficiently in the 400–430-nm pump range, so actual efficacy numbers are not yet available. The UV-LED approach has the advantage that color can be controlled by the phosphor mix at least at one point in time and at one temperature, so color rendering should be excellent. On the other hand, the high-energy UV light deteriorates the organic LED package materials, limiting the useful lifetime of the lamp. As of today, no UV-LED based RGB white products are in production.

Though the basic tradeoffs between the three different approaches to making white LEDs are well established, the long-term winner is hard to predict. Today most of the LEDs used to make white light are based on the pc-LED with a blue pump plus a single yellow phosphor. The best of these lamps are at least two orders of magnitude too high in cost per lumen to compete in major illumination markets. The major cost driver stems from low yields into the very narrow bins that are required for CCT and color point control. The winning alternative depends upon which set of problems yields most expediently.

VI. THE FUTURE OF SOLID STATE LIGHTING

There has been dramatic progress in the last few years on high power LEDs and there is now clear difference in appearance and performance for LEDs designed as indicators and LEDs that are the forefathers of solid state lamps. However, today even the most powerful LEDs being made are still an order of magnitude too low in flux per LED, and two orders of magnitude too high in cost per lumen to significantly penetrate the general illumination market. Making the jump in flux/LED will require major improvements in packaging and fixture integration that further reduce thermal resistance from LED junction to ambient into the $<$10-K/W range. Progress in reducing cost per lumen will come from process improvements and the volume increases that result from market penetration of the pure color and high value niche white applications. One hundred years after Edison's discovery of a filament that made incandescent bulbs practical, we cannot yet speak of "Solid State Illumination," but we are near enough to see the outlines of the future of solid state lighting.

ACKNOWLEDGMENT

The authors would like the acknowledge the ceaseless efforts and unstinting support of our colleagues who have contributed so much to this work, including S. Subramanya, G. Mueller, R. Mueller-Mach, A. Kim, J. Wierer, R. Khare, S. Stockman, M. Krames, F. Steranka, and G. Craford, along with the entire technician and support staff at Lumileds.

REFERENCES

[1] N. Holonyak Jr. and S. F. Bevaqua, "Coherent (visible) light emission from $GaAs_{1-x}P_x$ junctions," *Appl. Phys. Lett.*, vol. 1, pp. 82–83, 1962. In 1995, Nick Holonyak received the Japan Prize for his seminal work on LED's and lasers.

[2] G. E. Moore, "Cramming more components onto integrated circuits," *Electron.*, vol. 38, no. 8, Apr. 1965.

[3] R. Haitz, private communication.

[4] H. Rupprecht, J. M. Woodall, and G. D. Petit, "Efficient visible electroluminescence at 300 K from $Ga_{1-x}Al_xAs$ p–n junctions grown by liquid-phase epitaxy," *Appl. Phys. Lett.*, vol. 11, pp. 81–83, 1967.

[5] H. Ishiguro, K. Sawa, S. Nagao, H. Yamanaka, and S. Koike, "High efficency GaAlAs light-emitting diodes of 660 nm with a double heterostructure on a GaAlAs substrate," *Appl. Phys. Lett.*, vol. 43, pp. 1034–1036, 1983.

[6] C. P. Kuo, R. M. Fletcher, T. D. Osentowski, M. C. Lardizabal, M. G. Craford, and V. M. Robbins, "High performance AlInGaP visible light-emitting diodes," *Appl. Phys. Lett.*, vol. 57, pp. 2937–2939, 1990.

[7] S. A. Stockman and G. E. Stillman, "Hydrogen in III-V device structures," *Mater. Sci. Forum*, vol. 148–149, pp. 501–536, 1994.

[8] M. R. Krames *et al.*, "High-power truncated-inverted-pyramid $(Al_xGa_{1-x})_{0.5}In_{0.5}P/GaP$ light-emitting diodes exhibting$>$ 50% external quantum efficiency," *Appl. Phys. Lett.*, vol. 75, pp. 2365–2367, 1999.

[9] S. Nakamura, "GaN Growth using GaN Buffer Layer," *Jpn. J. Appl. Phys.*, pt. 2, p. L1705, 1991.

[10] 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, p. 353, 1986.

[11] W. Goetz *et al.*, "Activation of acceptors in Mg doped GaN grown by metalorganic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 68, no. 5, pp. 667–669, 1996.

[12] R. V. Steele, "High-brightness LED market overview," in *Proc. SPIE*, vol. 4445, 2001, pp. 1–4.

[13] G. E. Höfler, D. A. Vanderwater, D. C. DeFevere, F. A. Kish, M. D. Camras, F. M. Steranka, and I.-H. Tan, "Wafer bonding of 50-mm diameter GaP to AlGaInP–GaP light-emitting diode wafers," *Appl. Phys. Lett.*, vol. 69, p. 803, 1996.

[14] J. J. Wierer, D. A. Steigerwald, and M. R. Krames, "High-power AlGaInN flip-chip light-emitting diodes," *Appl. Phys. Lett.*, vol. 78, p. 3379, 2001.

[15] "LumiLeds lighting launches multi-format luxeon light sources," *Compound Semiconductor Mag.*, vol. 7, no. 6, p. 11, 2001.

[16] W. Goetz, F. Ahmed, J. Bhat, L. Cook, N. F. Gardner, E. Johnson, M. Misra, R. S. Kern, A. Y. Kim, J. Kim, J. Kobayashi, M. R. Krames, M. Ludowise, P. S. Martin, T. Mihopoulos, A. Munkholm, S. Rudaz, S. Salim, Y.-C. Chen, D. A. Steigerwald, S. A. Stockman, J. Sun, J. J. Wierer, D. Vanderwater, F. M. Steranka, and M. G. Craford, "Power III-Nitride LEDs," in *International Conf. Nitride Semiconductors*, Denver, CO, July 2001.

[17] Paul S. Martin, J. Bhat, C.-H. Chen, D. Collins, W. Goetz, R. Khare, A. Kim, M. Krames, C. Lowery, M. Ludowise, G. Mueller–Mach, S. Subramanya, S.-C. Tan, J. Thompson, T. Trottier, S.-C. , and R. Khare, "High Power White LED Technology for Solid State Lighting," in *Proc. SPIE*, San Diego, CA, July 2001.

[18] H. Chui, N. F. Gardner, P. N. Grillot, J. W. Huang, M. R. Krames, and S. A. Maranowski, "High efficiency AlInGaP light-emitting diodes," in *Semiconductors and Semimetals*, G. B. Stringfellow and M. G. Craford, Eds. New York: Academic, 2000, vol. 64, p. 49.

[19] G. Wyszecki and W. S. Stiles, *Color Science: Concepts and Methods, Quantitative Data and Formulae*, 2nd ed. New York: Wiley, 1982.

[20] S. Muthu, F. J. P. Schuurmans, and M. D. Pashley, "Red, Green, and Blue LEDs for white light illumination," *IEEE J. Select. Topics Quantum Electron.*, vol. 8, pp. 333–338, Mar.–Apr. 2002.

[21] Lumileds Corporate Website [Online]. Available: www.lumileds.com/solutions/LCD/ LCDindex.html

[22] 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. Topics Quantum Electron.*, vol. 8, pp. 339–345, Mar.–Apr. 2002.

Daniel A. Steigerwald was born in Pittsburgh, PA in 1960. He received the B.S. and Ph.D. degrees from the Metallurgical Engineering and Materials Science Department of Carnegie-Mellon University, Pittsburgh, PA, in 1982 and 1985, respectively.

From 1985 to 1987, Dr. Steigerwald was a National Research Council post-doctoral fellow at the Surface Science Division of the National Institute of Standards and Technology in Gaithersburg, MD. He is currently a Senior Scientist in the III–V Materials Research and Development Group at Lumileds Lighting, San Jose, CA, after spending 13 years at the Optoelectronics Division of Hewlett-Packard.

Jerome C. Bhat was born in Oxford, U.K. in 1973. He received his M.Eng. in engineering and materials science in 1995, and his Ph.D. in engineering science in 1998, both from the University of Oxford, and held a graduate scholarship during his time there. From 1998 to 2000, he worked as a research and development engineer on high-speed InP-based DFB lasers at Hewlett-Packard in Ipswich, U.K. He is currently working as a research scientist at Lumileds Lighting, San Jose, CA.

Dave Collins was born on March 4, 1950 in San Diego, CA. He received the B.S. degree and the Masters degree in scientic instrumentation in physics from the University of California at Santa Barbara, Santa Barbara, CA, in 1973 and 1975, respectively.

From 1975 to 1983, he was with HP Microwave Semiconductor Division in Marketing and Product Development on a variety of mesa diodes, from high-power impatt diodes to MMWave, PINs, and SRDs. From 1983 to 1999, he was with HP Optoelectronics Division Marketing and Product Development on products and systems ranging from Motion Control ICs to LED Printheads to LED Lamps and the genesis of Power LEDs. From 1999 to 2000, he was with Agilent Technologies in Power light-emitting diode (LED) product development and 2000 to present at Lumileds Lighting on high-power phosphor converted LED devices and packages. He is now a senior scientist in the Research and Development Department at LumiLeds Lighting.

Robert M. Fletcher received the B.S. degree in electrical engineering from Rice University, Houston, TX, in 1978 and the M.S. and Ph.D. degrees in electrical engineering from Cornell University Ithica, NY, in 1981 and 1985, respectively.

In 1985, he joined the research and development group at the Hewlett-Packard Optoelectronics Division, San Jose, CA, where he worked on the development of AlInGaP and InGaN light-emitting diodes (LEDs). At present, he is a senior engineer at Lumileds Lighting, San Jose, CA, and is involved in the development of new manufacturing processes for high-brightness InGaN LEDs.

Mari Ochiai Holcomb received B.S. and Ph.D. degrees from the departments of Electrical Engineering at Rice University, Houston, TX, and Colorado State University, Boulder, CO, in 1990 and 1997, respectively.

She is currently with III–V Materials Research and Development Group at Lumileds Lighting, San Jose,CA.

Michael J. Ludowise (M') received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Illinois, Urbana Champaign, IL, in 1972, 1973 and 1977, respectively.

From 1977 to 1979, he was a member of the technical staff at Rockwell International Science Center, Thousand Oaks, CA, working on long wavelength III–V materials epitaxy. In 1979, he joined the Varian Central Research Laboratory Palo Alto, CA, working on organo–metallic vapor phase epitaxy of III–V materials for monolithic multijunction terrestrial and space solar cells. From 1984 to 1998, he was at Hewlett-Packard Research Laboratories Palo Alto, CA, working on organo–metallic vapor phase epitaxy for laser and LED fiber optic sources, and later for GaN visible light-emitting diodes (LEDs). He is currently a senior scientist at Lumileds working on high-power LEDs. He is a member of the American Physical Society.

Paul S. Martin was born in San Jose, CA in 1963. He received a B.S. degree in physics from Cal Poly San Luis Obispo and the Ph.D. degree in physics from MIT in 1995 and 1996, respectively. In 1989, he was with the KDD Meguro Research Laboratories, Tokyo, Japan, as part of the MIT-Japan internship program. In 1996, he joined Hewlett-Packard's Optoelectronics Division Research and Development Group, San Jose, CA. Since joining HP, Paul has remained in the same building while his company changed around him; from HP to Agilent to Lumileds Lighting. Currently Paul is manager of the device Research and Development Group for Lumileds Lighting.

Serge L. Rudaz was born in Vevey, Switzerland, in 1952. After graduating in physics from the Swiss Institute of Technology (ETHL), he was awarded a research grant from the Swiss National Foundation to pursue studies in the U.S.A. In 1983, he received a Ph.D. in physics from the University of Illinois in Urbana-Champaign. He then spent two years as a post-doctoral fellow at Rice University, at Los Alamos National Laboratories, and at the SIN near Zurich, using accelerators to study material properties of semiconductors. Dr. Rudaz is currently a Senior Scientist in the III-V Materials Research and Development Group at Lumileds Lighting in San Jose, after spending 15 years at the Optoelectronics Division of Hewlett-Packard.