LIGHT EMITTING DIODES (LEDS) FOR GENERAL ILLUMINATION

AN OIDA TECHNOLOGY ROADMAP

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Executive Summary

The objectives of the technology roadmap on inorganic solid state light emitting diodes (SSL-LED) are:

- Reach an industry consensus on the major commercial and military applications of SSL-LED,
- To enumerate the technologies that need to be developed to support these applications, and
- To identify those research and development issues that need to be solved.

The roadmapping process assumes that the technical challenges and opportunities in SSL- LED are:

- Improve efficacy at all visible wavelengths to obtain 200 lumen/Watt white-light sources.
- Reduce cost of solid state light sources so as to be competitive with traditional light sources.
- Explore the opportunities to develop new technologies and products leading to a new lighting industry enabled by the attributes of SSL-LED, such as surface mounted "smart" light sources.

Light emitting diodes, LEDs, are thought to be direct replacements for point sources such as incandescent lamps while organic LEDs (OLEDs) might eventually replace area sources such as fluorescent lamps. Both LEDs and OLEDs are currently under development for special segments of the illumination and display markets.

These technologies have developed rapidly over the last decade as shown by the efficiency curves below:

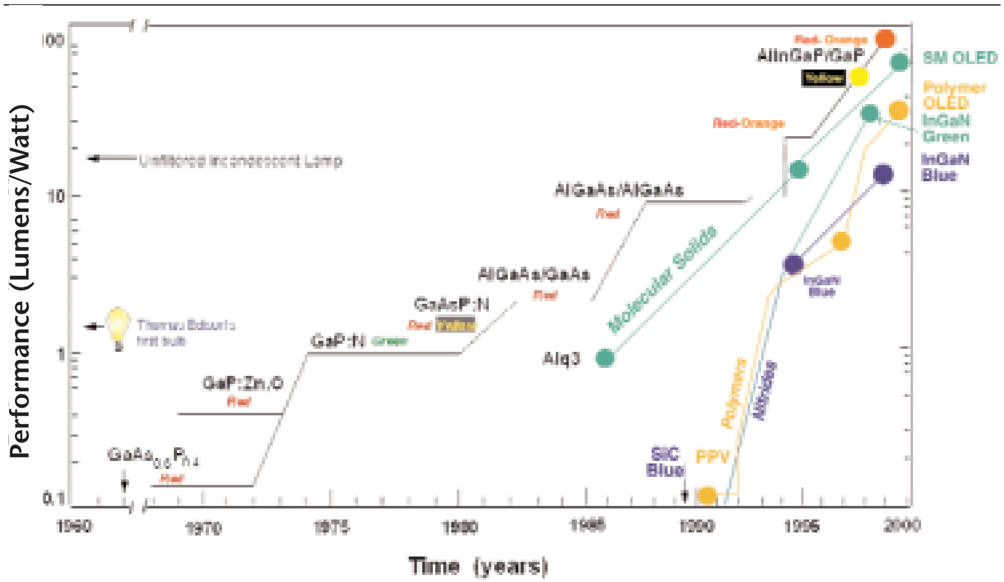

FIGURE 1
Progress in Improving Device Efficiencies of Light Emitting Diodes (*4*)

These impressive scientific achievements are recognized worldwide by the industrial and the scientific community. Major government sponsored industry consortia already exist in Japan, Europe, and Korea while another is in a formative stage in Taiwan.

In terms of scientific recognition it is worth noting that a co-recipient of the 2000 Nobel Prize in Physics was Herbert Kroemer for his contributions to the understanding of heterostructure semiconductor interfaces, a forerunner of today's high performance LEDs. Simultaneously, the 2000 Nobel Prize in Chemistry went to three scientists *"For the discovery and development of electrically conductive polymers"*. One of them, Alan J Heeger, is well known for his pioneering work on OLEDs.

Both LEDs and OLEDs have commercial entry points in special niche applications. Neither technology is aimed, however, at general illumination where the major impact will be eventually realized. It will take a major government sponsored industry driven initiative involving Academia and National laboratories to accelerate the penetration of SSL into general illumination arena as depicted in the table below. Without such an initiative, this technology (and market) will be developed in other countries, where cooperative programs between industry and government already exist.

The evolution of SSL markets assuming a major government sponsored initiative.

Year	LED Applications	OLED Applications
1	Monochrome signaling, traffic lights, automobile tail lights, large outdoor displays, decorative lighting	Small displays, decorative lighting
3	Low flux white light applications, shelf lighting, stair/exit ramp lighting	Low flux white light applications, accent lights
5	High demand general illumination, e.g. mechanical stress, high replacement cost, etc. Low level outdoor illumination (parking lots, bike paths, etc.).	Decorative illumination, glowing wall paper, ceiling lights, etc.
10	Significant penetration into general indoor/outdoor illumination	

The United States has strong industrial R&D, major expertise at National Laboratories (Sandia, LBNL) and relevant fundamental research at over twenty universities. A dedicated Government – industry program that maintains the focus on general lighting could result in:

- Substantial savings in electrical energy consumption,
- Reduction in carbon dioxide pollution, and
- The creation of a new lighting industry, with many new, high quality jobs.

1 Introduction

Solid state lighting (SSL) based on inorganic semiconductor light emitting diodes (LEDs) has the potential to fundamentally change the nature of lighting that people have experienced over the last 100 years. It is estimated that SSL-LEDs lighting can result in cumulative potential savings to ratepayers by the year 2020 of $112 Billion and associated reductions in environmental impacts just in the building sector alone.

To date, the LED core technologies have been developed for use in special niche applications (e.g. traffic signals, auto taillights, displays, etc.) This roadmap focuses on an aggressive industry-driven R&D effort targeting high efficiency, low-cost technology solutions that can successfully provide an energy saving alternative to general lighting.

Background

Since the development of the incandescent lamp in 1879, there has been a drive for brighter, cheaper, smaller, and more reliable sources of light. In the U. S., about 30% of all generated electricity is used for lighting alone. Worldwide usage patterns are similar. Consequently, significant improvements in lighting efficiency would have a major impact on worldwide energy consumption. Unfortunately, none of the conventional light sources (incandescent, halogen and fluorescent) have improved significantly in the past thirty years or so. Since an average of about 70% of the energy consumed by these conventional light sources is wasted as heat, there is clearly room for improvement.

The relatively recent development of light emitting diodes is proving to have significant impact in lighting technology. The General Electric Corporation first demonstrated an LED in 1962 and in 1968 Monsanto introduced LED-based indicator lamps. The initial performance of these devices was poor, with maximum output fluxes of around one thousandth of a lumen. Furthermore, the only color available was a deep red. Steady progress in efficiency made LEDs viewable in bright ambient light, even in sunlight, and the color range was also extended from red to orange, yellow and yellow-green.

These applications include traffic signals, automotive signalling, interior display, and illumination lights, large area displays for outdoor environments, and architectural/directed-area lighting. With the recent development of GaN-based LEDs, solid state sources in the blue and green portion of the spectrum are realized, thereby permitting the development of a white-light source based on color mixing different wavelength LEDs.

Because the design and operation of semiconductor lasers are intimately related to LEDs, an examination of the progress and performance of these devices is not only useful but also have a potential in lighting. Attributes of lasers that make them worthwhile to discuss are directionality and ease of the extraction of light. Initially, these lasers were fabricated as edge-emitters, i.e., the output direction of the laser is in the plane of the substrate material. The development of vertical cavity surface emitting lasers (VCSELs) not only changed the output beam direction to a more convenient geometry, i.e., normal to the surface of the substrate, but also, for 850 nm operation, led to wall-plug (electrical-to-optical) efficiencies of over 50%! [1.2] Furthermore, the VCSEL geometry allows better design for integration into optoelectronic circuits. Semiconductor diode lasers, with active layers based on GaAs and InGaP, cover the orange-red and yellow part of the visible spectrum, while lasers based on GaN emit in the green and blue. Within the past year (2000), an optically pumped InGaN/GaN VCSEL operating at the near-UV wavelength of 384 nm has been demonstrated. [1.3] This result opens up exciting possibilities where the combination of the energy source, i.e., the laser, and illumination source can be physically separated.

The Promise and Potential of Solid State Lighting

Energy Savings

With all of the advances in the LED and semiconductor laser technologies, solid state illumination using LEDs and semiconductor lasers provide an exciting and unprecedented opportunity for revolutionary improvements in the energy efficiency of white lighting technologies. This new lighting technology is growing out of the same exponential growth in knowledge of semiconductor physics that enabled the current microelectronic revolution, and has the potential [1.4] of the following cumulative efforts by the year 2020:

- Decreasing by 50% the amount of electricity used for lighting.
- Decreasing by 11% the total consumption of electricity.
- Producing a reduction of 133 GW of electricity or a savings of about $112 Billion.
- Freeing over 133 GW of electric generating capacity for other uses, alternately, the need for 133 power generating plants..
- Decreasing by 50% the amount of electricity used for lighting.
- Over the same time period, reducing carbon emissions by 259M tons due to lower demands on electricity.

These spectacular benefits constitute the promise of semiconductor lighting envisioned for the year 2025 and beyond and are documented in a recent Sandia/Hewlett-Packard (now Agilent Technologies) white paper. This paper, entitled *The Case for a National Research program on Semiconductor Lighting* by Haitz, et al.,[1.1] proposes a federally-funded industry driven R&D effort involving national laboratories and universities to accelerate the development of the "semiconductor lighting revolution."

Improvements to the Quality of White Lighting

With the realization of SSL, some anticipated improvements to the quality of white lighting for general illumination are:

- Steady output color at all levels of illumination
- Ability to continuously vary output color.
- Simplified and flexible design for mounting fixtures.
- Ease of integration advanced building controls including day lighting.
- Low voltage and *safe* power distribution.

Material Systems and Corresponding Wavelengths

The majority of LEDs are manufactured using III-V compound semiconductors, meaning that they consist of combinations of elements from groups III and V in the periodic table of elements.

Examples of group III elements are aluminum (Al), gallium (Ga) and indium (In). Examples of group-V elements are phosphorus (P), arsenic (As) and nitrogen (N). As such, the semiconductor materials on which commercial LEDs are commonly based are GaAsP, AlGaAs, AlGaInP, GaP, InGaN, and GaN. In general, the arsenide and phosphide-based- alloy LEDs are written as $AlyGa_{1-x-y}In_xAs$ and $AlyGa_{1-x-y}In_xP$, where y and x are respectively the aluminum and indium atomic concentrations with x, y between 0 and 1.

Other semiconductor LEDs based on group-IV elements such as silicon (Si) and carbon (C) combined to form SiC or the II-IV elements cadmium (Cd), zinc (Zn), selenium (Se) and sulfur (S) forming semiconductor materials such as ZnSe to generate the blue end of the visible spectrum, LEDs based on these materials, however, suffer from short operational lifetimes due to the relative ease of defect formation. On the other hand, devices made from Al_yGa_{l-x-y} In_xN alloys combine direct band-gaps and high mechanical stability. The Al_yGa_{l-x-y} In_xN-based LED emission wavelength covers the whole visible spectrum and beyond, ranging from yellow - red (InN) through green - blue (GaN) - to the ultraviolet (AlN) region of the spectrum. InGaN-based LEDs are rapidly replacing SiC and GaP-based systems in applications where high intensity blue or green light is desired.

These recent developments of efficient and reliable blue and green LEDs using AlGaInN- based alloys are significant for the realization of efficient white-light LEDs with excellent quality (high Color Rendering Index.) Because of the problems of short device lifetimes, etc., as found for II-VI material systems, this SSL roadmap concentrates only on the III-V compound semiconductor-based LEDs and III-V laser materials. Organic-based LEDs (OLEDs) are not considered here because this subject is treated in a similar, but separate, DOE sponsored roadmapping program.

Some characteristics of different types of LEDs are compiled in Appendix A. Henceforth, this roadmap will use AlGaInAs, AlGaInP, and AlGaInN respectively as shorthand to denote $Al_yGa_{1-x-y}In_xAs$, AlyGa In_xP, and $Al_yGa_{1-x-y}In_xN$.

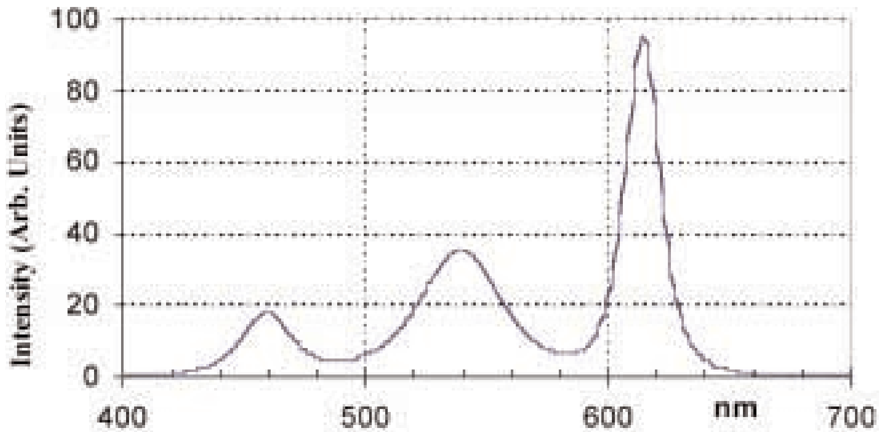

FIGURE 1.1
White-light output emission spectrum from a 3-color multi-chip LED

Strategies and Approaches to White-Light Generation

White light producing LEDs are routinely produced for displays where a LED is used for each color pixel. White light SSL-LEDs suitable for high quality general illumination can be generated in a variety of ways with some examples presented here:

(1) White light from multiple-chip LEDs: As is well known, the three standard colors, red, green, and blue, can be mixed together to generate white light. With currently available LEDs, the generation of white-light can have luminous efficacies of around 30 lm/W (lumens/Watt.) An example of a white-light spectrum produced by combining the outputs from a three color multi-chip LED is shown in Fig. 1.1. Note, that because the human eye response to the red is weak, the intensity of the red color LED is higher to generate white light. These issues along with a discussion of the eye response are treated further in Section 3.

White-light sources are in commercial production and consist of collectively housed LED chips, or arrays of different colored LED lamps, i.e., multiple-chip LEDs.

Potential problems with multi-chip LEDs include:

- Due to the discrete wavelengths of light being used, the color of the light source may change considerably with viewing angle.
- These white-light sources are also relatively expensive since multiple LED chips are required to produce a single source of white light.
- Obtaining a consistent color across an array of such white pixels may also pose a problem because the light intensity of LEDs and driving voltages tend to vary

from diode to diode, and the task of color-tuning individual diodes is likely to be difficult.

- In addition, the multiple-chip LED is subject to significant changes in color and intensity with variations in temperature.
- Another consideration is the variation in operating life of different color LEDs. For example, the light output level of AlGaAs-based LEDs is found to decrease by about 50% after 15,000 to 40,000 hours of operation. This effect represents a serious challenge for multiple-chip LEDs where the white-light color rendering is critically dependent on the relative intensities of the separate red, green, and blue colors.

However, multi-chip SSL-LEDs offer the greatest versatility, the largest efficacies, of all the strategies presented here. When perfected, these devices will be able to produce any color and any color temperature with high color rendering.

(*2) Combining blue LED and phosphor(s):* An alternative (and currently favored) method for white-light generation involves the use of a single LED one or more phosphors.

Commercially available white LEDs are constructed from a blue InGaN LED overcoated with a cerium (Ce) doped yttrium aluminum garnet (YAG) inorganic phosphor. The InGaN LED generates blue light at a peak wavelength of about 460 nm, which excites the Ce^{3+}:YAG phosphor to emit pale-yellow light. The combination of the blue light from the LED and the pale-yellow light from the Ce^{3+}:YAG results in white light. The emission spectrum of the YAG phosphor can be modified (tuned) by substituting some or all the yttrium sites with other rare earth (RE) elements such as gadolinium (Gd), terbium (Tb), etc. The RE^{3+}:YAG emission and absorption spectrum can be further engineered by replacing some or all of the aluminum sites by gallium.

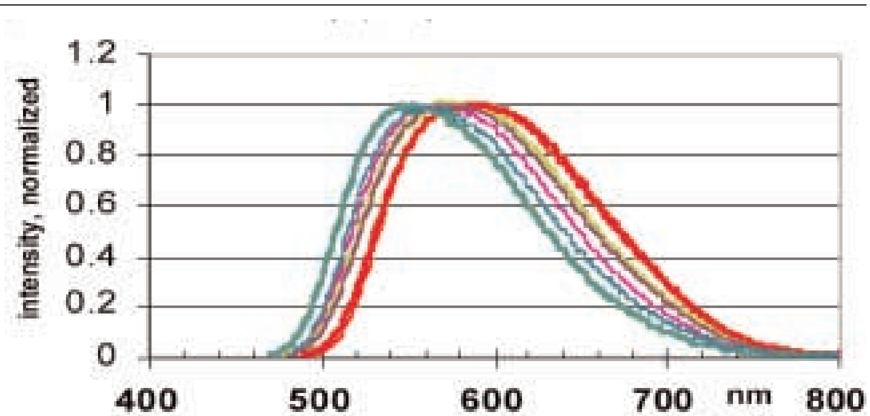

FIGURE 1.2
White-light output emission spectrum from a blue light LED pumped (Ce, Gd)^{3}+:YAG phosphor. The spectral variation, left to right, shows the effect of adding Gd.

An example, from LumiLeds, for the luminescence spectrum of a blue-LED pumped (Ce, Gd)$^{3+}$:YAG as a function of Gd concentration is shown in Fig. 1.2. Instead of illuminating inorganic phosphors such as RE^{3+}:YAG, the blue light emission from the InGaN LED can also be used to generate luminescence from organic polymers which are coated on the domed epoxy encapsulate of an InGaN LED lamp.

Currently, the efficacy of the phosphor-white LEDs can be as high as 15 lm/W with half- lifetimes of 40,000 hours. When compared to multiple-chip LEDs for red, green, and blue color output, an advantage of phosphor-white or hybrid-white LED devices is that it only requires one blue or ultraviolet (UV) LED. A rough estimate for absolute conversion efficiencies for both organic and inorganic phosphors for one-photon processes is perhaps as high as 50%. In addition, white-light LEDs based on phosphors have been shown to have relatively stable color with variations in temperature.

Other Photon Conversion Schemes

Examples for white-light generators based on other photon conversion schemes are:

1 Photon energy conversion techniques based on aggregates of small-sized (nanometer scale) semiconductor materials recently reported, [1.4]

2 Photon-recycling semiconductor LEDs (PRS-LED) discussed by researchers at Boston University, [1.6] where a blue InGaN LED is wafer bonded or otherwise joined to an AlGaInP top layer generating two complimentary colors and hence, white light, and

3 Exploitation of the high power-narrow-bandwidth light output produced by UV lasers. [1.7]

A brief discussion for each of these items follows:

(1) White light from UV-LED pumped nano-sized aggregates: Synthesizing nanometer-size semiconductor structures (whose band-gap energy depends on the size of the nanoparticle due to the effect of quantum confinement of the electron-hole pair) is of particular interest because high quantum yields of visible light may be possible. For example, light emission intensities from 3.0-nm-diameter nanoparticles of CdS are similar in photoluminescence intensity and position to that obtained from laser dyes such as Coumarin 500. Furthermore, the peak of the light emission can be shifted from about 430 to 700 nm by variation of both the size and the surface characteristics of the nanoparticles. The effect of the latter is demonstrated in Fig. 1.3, where the absorbance and fluorescence from CdS nanoparticles coated with a layer of ZnS is shown. By itself, ZnS has emission at about 420 nm.

(2) Photon Recycling Semiconductor LEDs (PRS-LEDs): The maximum theoretical white-light efficacies for PRS-LEDs using a blue InGaAsN LED wafer bonded to a sapphire substrate and a photon recycling wafer (AlGaInP) is estimated [1.5] to be about 300 lm/W. To date, researchers have demonstrated PRS-LEDs that produce about 10 lm/W of white light. [1.5] The emission spectrum from such a PRS-LED is shown in Fig. 1.4.

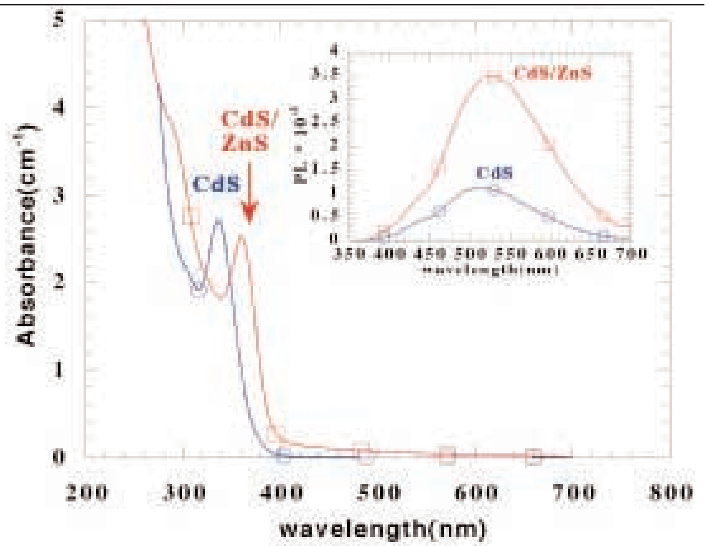

FIGURE 1.3

Plot of the UV absorbance and green photoluminescence spectra, inset, of nano-sized CdS with and without a ZnS coating.

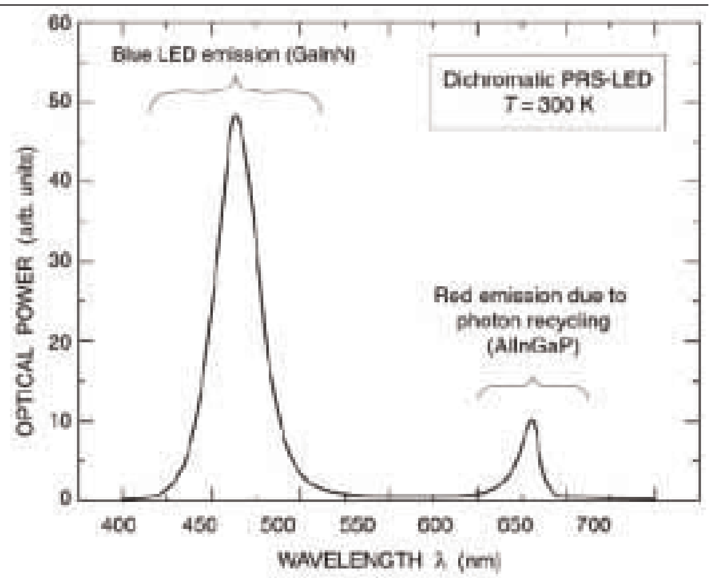

FIGURE 1.4

Emission spectrum of a photon-recycling semiconductor PRS-LED. The emission spectrum consists of a primary peak at 470 nm (blue) and a red secondary emission peak at 625 nm.

(3) Lasers as phosphor exciters: Light generation using semiconductor lasers rather than LEDs may offer significant advantages. For example, UV lasers may allow the phosphor materials to be located remotely, e.g., the phosphors may be painted on a wall and activated by a remote UV laser to produce unusual lighting effects without any power connections in the wall. The utility of using a 380 nm UV laser beam to pump energy conversion devices, such as shown in Fig 1.3 is, unlike an LED, that all of the 380 nm pump beam is easily directed to the phosphor for photon conversion. Recently, researchers at The Institute of Physical and Chemical Research (RIKEN) Japan, observed 230 to 250 nm photoluminescence at 77-K from $AlN/Al_{0.18}Ga_{0.82}N$ and $Al_{0.8}Ga_{0.2}N/Al_{0.18}Ga_{0.82}$ multi-quantum-wells fabricated by metal-organic vapor-phase-epitaxy. [1.8] The emission from the AlGaN MQWs were several ten times stronger than that of bulk AlGaN. The realization of laser action in these sys-

tems is still a long time off, but it is from these kinds of observations that progress is made. Furthermore, this wavelength region is perfect for exciting existing fluorescent lamp phosphors. In another paper, [1.9] these researchers also reported room-temperature LED operation at 333 nm in a $Al_{0.03}Ga_{0.97}N/Al_{0.25}Ga_{0.75}N$ quantum-well with a Mg-doped superlattice. While these authors do not report the luminescence efficiency or output power, they do state that up to 0.33 kA/cm^2, there is no evidence of saturation for the output intensity.

> Fundamental to either white-light generating scheme, e.g., combining red, green, and blue light from multiple-chip LEDs or from energy conversion processes such as inorganic and organic phosphors, etc., is that a considerable amount of research, device development, etc., will be needed to improve LED output levels.

The success of the SSL initiative to produce white-light sources suitable for general illumination critically depends on improving LED efficacies at all wavelengths to obtain 200 lm/W of white light. Recently, LumiLeds and Philips announced a 610 nm (orange/red) LED producing 100 lm/W outputs. [1.9] Furthermore, green and blue InGaN-based LEDs having efficacies in the range of 50 lm/W are being reported by LumiLeds. Current estimates for successfully demonstrating 200 lm/W white-light levels range from three to six years. A second goal is taking laboratory produced LEDs (producing 200 lm/W white light) and commercializing at competitive costs.

Improvements needed for white light SSL-LEDs:

- The lumens/watt output from LEDs across the visible spectrum has to be greatly improved over today's efficacies of 30 - 50 lm/W if the desired 200-lm/W white- light level is to be realized.
- For phosphors and other energy conversion methods, research and development is required in order to understand and improve photon conversion efficiencies and output wave lengths.
- Packaging strategies have to be developed for any of the aforementioned proposed white light strategies.
- Finally, applications exploiting the unique properties of lasers have to be explored.

Technology Roadmap

This technology roadmap describes the major tasks of an initiative for solid state lighting to affect the efficiencies of light generation for general illumination, both in business and home environments. The objectives are:

1. Reach an industry consensus on the major commercial and military applications of SSL,

2. Enumerate the technologies that need to be developed to support these applications, and

3. Identify the R&D issues that need to be solved.

Before discussing the core technologies necessary for achieving the goals of this roadmap, a brief introduction and discussion for the issues of color and the generation of high quality white light is presented in Section 2.

There are three main parts to the roadmap:

1. Section 3 concerns the generation of blue to green to red portion of the visible spectrum and here LEDs, based on the III-V AlGaInN (nitrides) alloy system, have been identified as the principal light emitters. Because these LEDs are only a recent development, there are many issues that are suitable for University/National Laboratory research programs.

2. Section 4, discusses phosphides, AlGaInP, based LEDs, a relatively mature technology for the generation of the yellow to red portion of the visible spectrum

3. Section 5 discusses the important role that phosphors and other energy conversion techniques may play in SSL.

Each section has a background history, an evaluation for the current state of the art, critical challenges for success, and a list of some research issues that are germane to the subject.

Section 6 contains a description of the technology roadmap envisioned for successful implementation of SSL. Finally, the Workshop Agenda and list of attendees is given in Appendices B and C.

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2 Color Issues of White-Light LEDs

Introduction

For LEDs to be used for general lighting, they must have appropriate white color with good color rendering performance for illuminated objects. Color rendering, as well as efficacy, have been the two most important criteria for traditional light sources for general lighting. The U.S. Energy Policy Act (EPACT 1992 [2.1]) specifies the minimum color rendering indices (explained later) as well as the minimum efficacy of common lamps. Color rendering is determined solely from the spectrum of the source. Thus, the white-light spectrum generated from LEDs needs to be designed to meet requirements in both aspects, i.e., efficacy and color rendering.

Color rendering is best achieved by broadband spectra distributed throughout the visible region, while the efficacy is best achieved by a monochromatic radiation at 555 nm (green) the wavelength where the human eye response reaches its maximum.Thus there is a trade- off between the two important criteria for white light; high quality color rendering and high efficacy. For example, a low pressure sodium lamp (having a light orange color, used in some highways and parking lots) has an efficacy of about 200 lm/W, the highest among available discharge lamps, but colors of objects are not distinguishable. A red car (and other colors) in a parking lot appears to be gray. On the other hand, a xenon arc lamp, having a very similar spectrum as day light and exhibiting excellent color rendering, has an efficacy of only 30 lm/W.

An advantage of LEDs is that they are available in most wavelengths in the visible region, and the output spectrum may be more flexible than for traditional discharge lamps, where the output spectrum depends on available phosphors and emissions from gas. In the case of multiple-chip LEDs, white light can be achieved by a mixture of two or more LEDs of different peak wavelengths,

> However, because of the relatively narrow linewidth (~ 2kT) of LEDs, two-chip LEDs can never achieve acceptable color rendering properties.

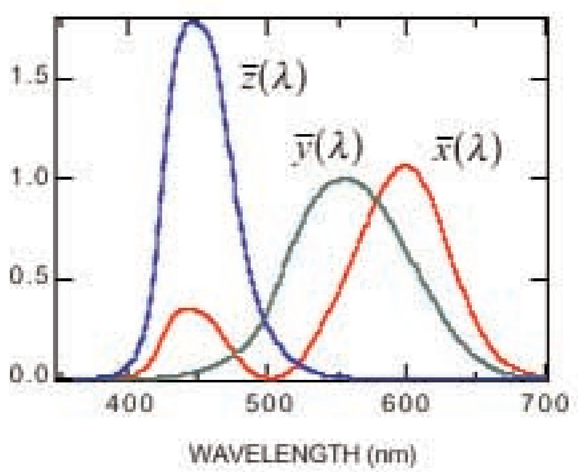
Combining the spectra from three LED chips (or more) is expected to provide good color rendering that can be used for general lighting. White light generated by phosphor-based LEDs can also have good color rendering because the phosphors generally produce broadband radiation. A drawback is the limitation of available phosphors, which pose difficulty to control the color and color rendering characteristics.

The evaluation method for color rendering of light sources is well-established by CIE (Commission Internationale de l'Éclairage = International Commission on Illumination), and since 1965, the color rendering index [2.2] has been widely used in the lighting industry. An outline of the fundamentals of the CIE colorimetry system [2.3] including the color rendering index are discussed below. Applications to the design of white-light LEDs are also presented. The definitions of the terms in photometry and colorimetry used in this section follow that found in Ref. 2.4. For further details of colorimetry, an overview of the CIE system of colorimetry is available in an article by Y. Ohno. [2.5]

Chromaticity Coordinates and Color Temperature

White-light produced by LEDs, or any other light sources for general lighting, should have an acceptable white color in order to show all the colors of illuminated objects appropriately. As mentioned previously, the color of light is expressed by the CIE colorimetry system. [2.3] The spectrum of a given light is weighted by the *XYZ color matching functions* [2.6] as shown in Fig. 2.1. From the resultant three weighted integral values (called *tristimulus values* X, Y, Z) the *chromaticity coordinate x, y* is calculated by x = X/ (X+Y+Z), y = Y / (X+Y+Z). Any color of light can be expressed by the chromaticity coordinate (x, y) on the CIE 1931 *(x, y) chromaticity diagram*, as shown in Fig. 2.2. The boundaries of this horseshoe-shaped diagram are the plots of monochromatic light, called the *spectrum locus*. Also plotted near the center of the diagram is the so-called *Planckian locus*, which is the trace of the chromaticity coordinate of a blackbody at its temperature from 1,000 to 20,000K.

FIGURE 2.1
CIE 1931 XYZ color matching functions



The colors on the Planckian locus can be specified by the blackbody temperature in Kelvin and is called *color temperature*. The colors around the Planckian locus from about 2,500 to 20,000K can be regarded as *white*, 2,500K being reddish white and 20,000K being bluish white. The point labeled "*Illuminant A*" is the typical color of an incandescent lamp, and "*Illuminant D65*" the typical color of day light, as standardized by the CIE. [2.7] The colors of most of traditional lamps for general lighting fall in the region between these two points, i.e., 2,850 to 6,500K. The color shift along the Planckian locus (warm to cool) is generously accepted or purposely varied for general lighting for desired mood, while color shift away from the Planckian locus (greenish or purplish) is hardly acceptable. As an example, Fig. 2.3 shows the chromaticity coordinates of twenty-three common fluorescent lamps. [2.8]

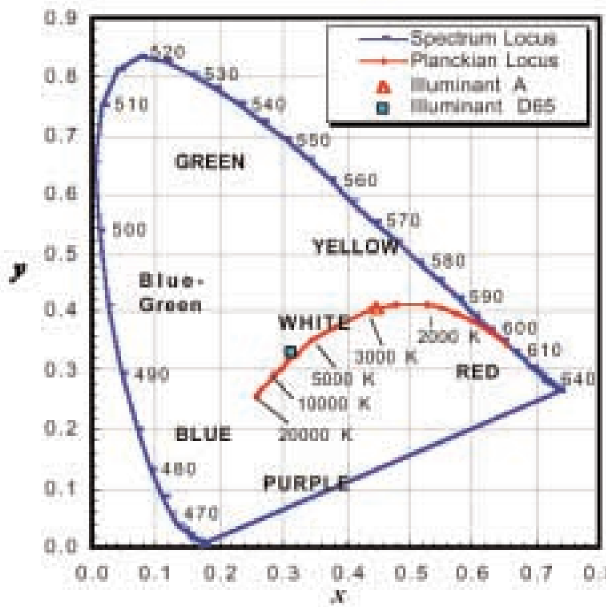


FIGURE 2.2
CIE 1931 (x,y) chromaticity diagram

Strictly speaking, color temperature cannot be used for color coordinates (x, y) off the Planckian locus, in which case the *correlated color temperature* (CCT) is used. CCT is the temperature of the blackbody whose perceived color most resembles that of the light source in question. Due to the nonuniformity of the (x, y) diagram, the iso-CCT lines are not perpendicular to the Planckian locus on the (x, y) diagram as shown in Fig. 2.3. To calculate CCT, therefore, another improved chromaticity diagram (CIE 1960 (eV) diagram - now superseded by 1976 (u',v') diagram [2.3]) is used, where, by definition, the iso-CCT lines are perpendicular to the Planckian locus.

An important characteristic of the chromaticity diagram is that light stimuli on the diagram are additive. A mixture of two colors will produce a chromaticity coordinate falling on the line between their respective chromaticity coordinates. Figure 2.4 shows an example of mixing two LEDS with wavelengths at 485 nm (blue) and 583 nm (orange) each with a half-bandwidth of 20 nm. The mixture of these two colors having the same optical power will produce white color with a color temperature of about 4,000 K (shown as a solid diamond).

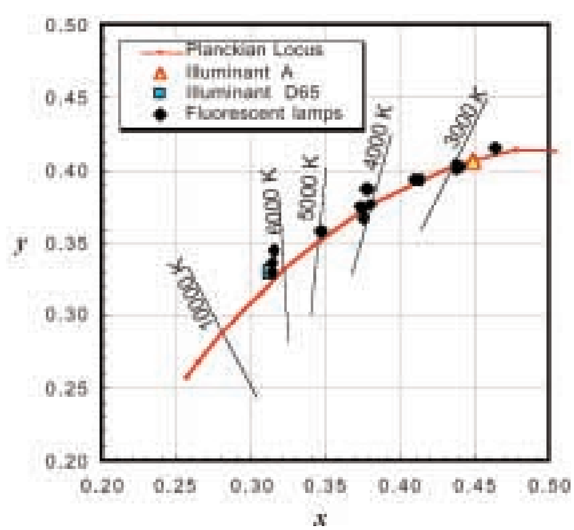


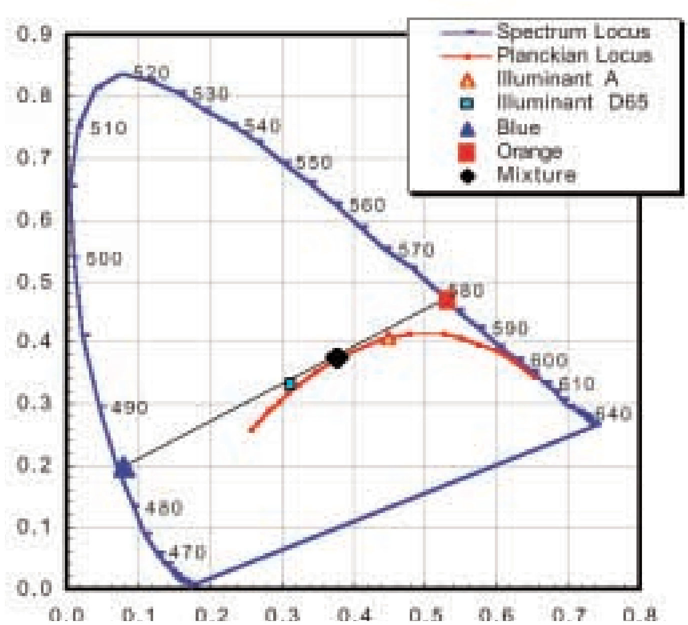
FIGURE 2.3
Chromaticity coordinates of twenty-three common flourescent lamps.

Even though the color of mixed light from two LEDs appears white on white paper, the color rendering index ~ 4 (see section on Application to White LED Design) is unacceptable and is not usable as a light source for general lighting, e.g., green and purple colors would appear gray!

Color Rendering Index

Color rendering of a light source is evaluated by comparing the appearance of various object colors under illumination by the given light source with that under reference illumination, day light for CCT > 5,000 K and Planckian radiation for CCT < 5,000 K. The smaller the color differences of the object colors are the better the color rendering is. The standardized method, the *color rendering index* (CRI), is defined by the CIE [2.2] and has been in wide use in the lighting industry for many years. In this method, fourteen Munsell [2.9] samples of various different colors, including several very saturated colors, were carefully selected. The color differences, denoted as ΔE_i, of these color samples under the test illumination and under the reference illumination are calculated on the 1964 W*U*V* uniform color space. [2.2] The process incorporates corrections for chromatic adaptation. Then the *Special Color Rendering Index* R_i for each color sample is calculated using $R_i = 100\text{-}4.6\Delta Ei$. The R_i value is an indication of color rendering for each particular color. The *General Color Rendering Index* R_a, is given as the average of R_i for the first eight color samples that have medium color saturation. With the maximum value of 100, R_a gives a scale that matches well with the visual impression of color rendering of illuminated scenes. For example,[2.5] lamps having R_a values greater than 80 may be considered to be high quality and suitable for interior lighting, and R_a greater than 95 may be suitable for visual inspection purposes. Thus, the spectral distribution of white-light generating LEDs should be designed to achieve the R_a value required for the application in mind. For compari-

FIGURE 2.4
Mixture of two LEDs at 485 and 580 nm each with a half-maximum width of 20 nm. The (x,y) chromaticity coordinates of the resulting white-light is shown as a solid diamond



son with conventional light sources, the CRI (R_a values) of several common types of fluorescent lamps and HID (High Intensity Discharge) lamps are tabulated in Table 2-1. [2.8]

Table 2.1 General CRI of Common Lamps

	CCT	R_a
Daylight	6430	76
Cool White	4230	64
White	3450	57
Warm White	2940	51
Cool White Deluxe	4080	89
Warm White Deluxe	2940	73
Metal Halide	4220	67
Metal Halide, Coated	3800	70
Mercury, Clear	6410	18
Mercury, Coated	3600	49
High Pressure Sodium	2100	24
Xenon	5920	94

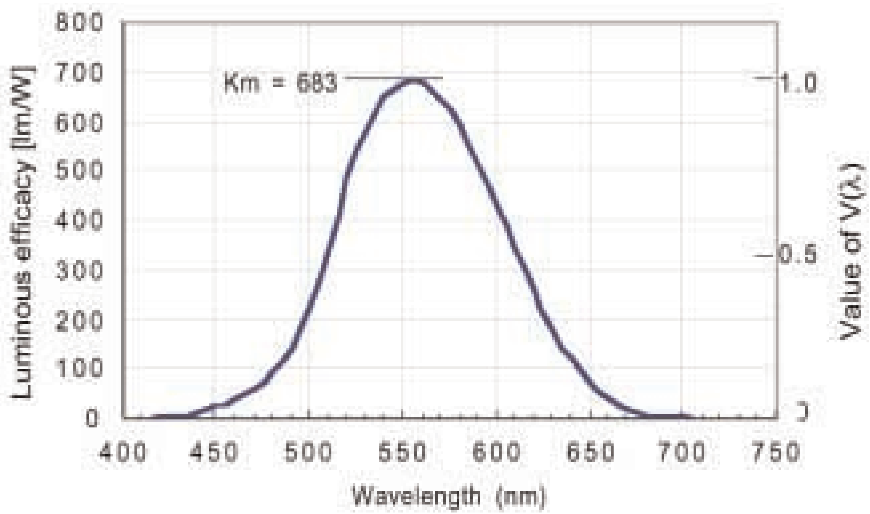
Luminous Efficacy

The luminous efficiency of light sources involves the efficiency of energy conversion from electrical power (W) to optical power (radiant flux in watts), and also the conversion from radiant flux (W) to luminous flux (lumen = lm), which is determined by the eye sensitivity over the spectral distribution of light, and is called *luminous efficacy of radiation* having units of lm/W. The luminous efficacy of monochromatic radiation K(λ) at wavelength l, is shown in Fig. 2.5, and is defined by $K(\lambda) = K_m \times V(\lambda)$, where $K_m = 683$ *lm/W,* $V(\lambda)$ is the spectral luminous efficiency (of photopic vision) defined by CIE [2.10] and is the basis of photometric units. The value for *Km* is a constant given in the definition of the candela, and is referred to as the *maximum luminous efficacy of radiation.* No light source can exceed this efficacy value, as shown in Fig. 2.5. Note that the $K(\lambda)$ peaks at 555 nm, and falls off at both ends of the visible region. The values of $K(\lambda)$ are the theoretical limits of light source efficacy at each wavelength. For example, monochromatic light at 450 nm has luminous efficacy of only 26 lm/W (theoretical limit). For real light sources, including LEDs, the luminous efficacy of radiation, K, is calculated from its spectral power distribution $S(\lambda)$ by

$$K\,[\mathrm{lm/W}] = \frac{K_m \int_0^\infty S_t(\lambda)\, V(\lambda)\, d\lambda}{\int_0^\infty S_t(\lambda)\, d\lambda} \qquad \text{where } K_m = 683\ [\mathrm{lm/W}]$$

The spectral power distribution of white-light producing LEDs should be designed to have high luminous efficacy. For comparison, the total efficacy (lumens per electrical power, including ballast losses) of traditional light sources is summarized in Fig. 2.6 (taken from Ref. 2.11). Within a lamp type, the higher-wattage sources are generally more efficient than the lower-wattage sources. High-pressure sodium, metal halide, and fluorescent lamps are the most efficient white light sources.

FIGURE 2.5
Luminous efficacy of monochromatic radiation, K(l).



Application to White LED Design

When the spectral power distribution of a light source is given, one can calculate the chromaticity coordinates, CCT, CRI, and the luminous efficacy of radiation. The CRI *(R_a)* of the white light produced by mixing the outputs from two 20 nm half-bandwidth LEDs shown in Fig. 2.4 is calculated to be only about *4!* Standard two-chip LEDs in any wavelength combinations can never produce white light with an R_a value acceptable for general lighting. Three-chip LEDs can produce much better color rendering for white light, but the choice of the peak wavelengths is critical. Figure 2.7 shows the results of a simulation of three LEDs having peak wavelengths of 450, 550, and 650 nm, with their relative power adjusted to create white light with a color temperature of 4,000K. Each LED is a model using a Gaussian line shape function, [2.12] with half-bandwidth of 20 nm. In this case, CRI *(R_a)* is only 37 with luminous efficacy of 228 lm/W (theoretical maximum). An R_a = 37 is not acceptable for use in general lighting, except for limited outdoor use. Figure 2.8 shows the result of simulation of another combination, with peak wavelengths of 459.7, 542.4, and 607.3 nm. With this combination, R_a = 80 a luminous efficacy of 400 lm/W (theoretical maximum) is achieved. If the efficiency of the LED chips is 20%, the total efficacy would be 80 lm/W, comparable to typical fluorescent lamps. The value of *Ra* = 80 is acceptable for general lighting including indoor applications. This example is only a demonstration, and is not necessarily the best result. There may be other combinations with even better results. As demonstrated here, the selection of wavelengths makes determines the performance of white-light LEDs. In real cases, the efficiency of LEDs differ at different wavelengths and also the selection of wavelengths is restricted. Using more sophisticated simulation analyses with restrictions applied, optimum designs of white-light LEDs using available color LEDs for any desired CCTs can be made. Using four LED chips should give even better color rendering than that obtained from three chips.

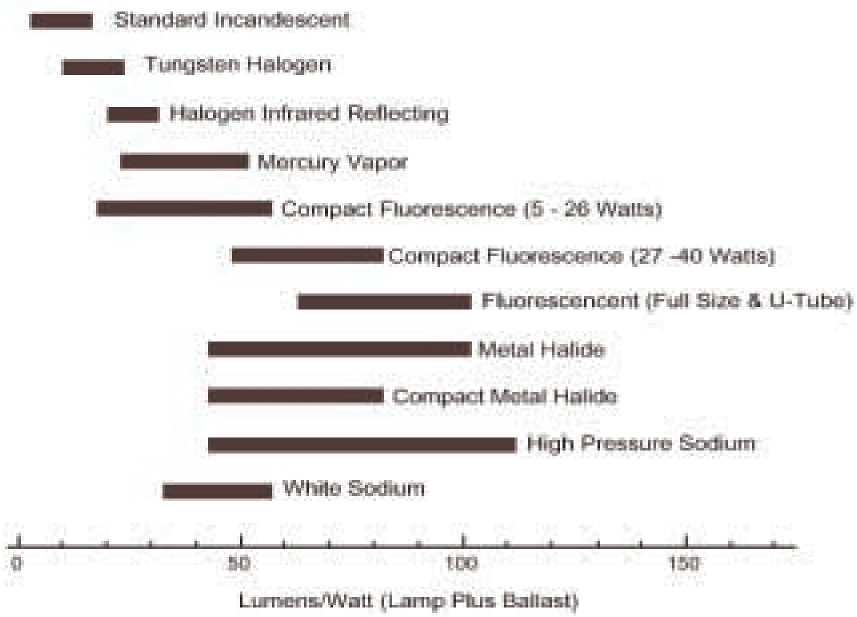
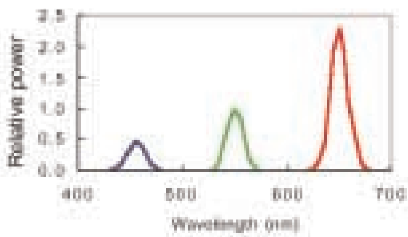
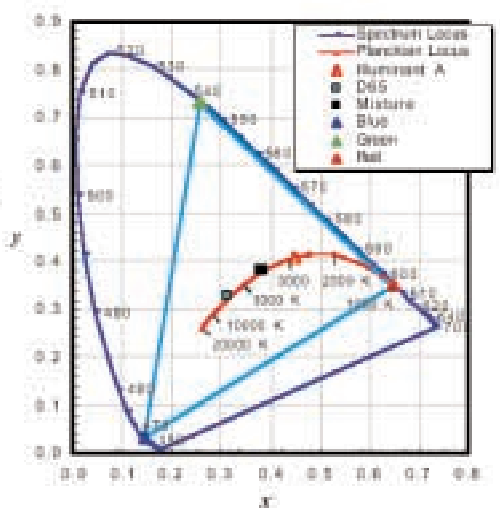


FIGURE 2.6
Efficacy of traditional light sources.



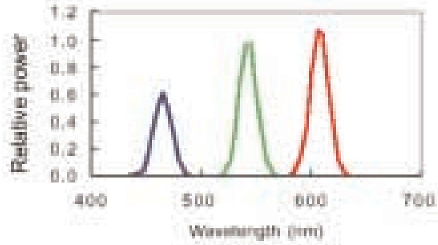


x	0.3792
y	0.3736
CCT (K)	4011
Δuv	0.001
R_a	37
Efficacy (lm/W)	228

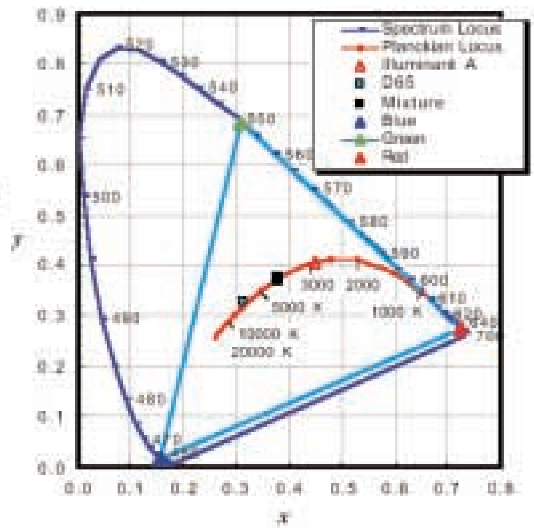
FIGURE 2.7
Simulation of a three-chip white-light LED. The resulting chromaticity coordinates (x, y) for the white light is shown as the solid square near 4,000 K. Because of the low CRI, R_a ~ 37, this is an example of example of white light with poor color rendering even though the efficacy of 228 lm/W is quite large!

As a reminder, the CRI *(R_a)* of the two-chip LED shown in Fig. 2.4 is only about 4. In general, white light produced by the relatively narrow-bandwidth two-chip LEDs, in any wavelength combinations can never produce R_a value acceptable for general lighting. For white light generated from a LED plus phosphor, the situation is more favorable for producing white light with R_a greater than 80. Section 5 discusses this situation involving phosphors and LED pumped phosphors.

FIGURE 2.8
The effect of optimizing the wavelengths of a three-chip white-light LED. The chromaticity coordinates (x, y) for the white light is shown as the solid square near 4,000 K. Because of the CRI, R_a ~ 80, this is an example of example of white light with good color rendering.



x	0.3812
y	0.3795
CCT (K)	4011
Δuv	0.001
R_a	80
Efficacy (lm/W)	399



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3 AlGaInN-Based LEDs for SSL Lighting

Background

The Group-III nitride based semiconductors have recently emerged as the leading material for white-light solid state lighting sources. The AlGaInN alloy system forms a continuous and direct bandgap semiconductor alloy spanning ultraviolet to blue/green/yellow wavelengths. The efficiency of AlGaInN-based LEDs increased rapidly after the first reports by Akasaki in 1989.[3.1] These bright blue and green LEDs complete the primary color spectrum and are so bright that they have enabled the fabrication of large full color LED displays. Currently, the best external quantum efficiencies, achieved for the blue and green AlGaInN-based LEDs is 15 and 12%, respectively.[3.2] The efficiencies of white-light LEDs are approximately 8% and have a luminous efficacy of about 20 lm/W, which is becoming competitive with existing incandescent sources. Recently, 28%-efficient near-UV (405 nm) GaN LEDs have been developed by CREE Lighting.[3.3] These UV LEDs are expected to find new applications in SSL.

Despite their critical importance in future lighting applications, fundamental knowledge of the nitride materials systems and methods for thin film growth are substantially less well developed compared to conventional III-V compound semiconductor materials. This deficiency is due to a combination of the relatively recent development of AlGaInN devices coupled with the unique growth chemistry and lack of suitable substrates for epitaxial growth.

Conventional chemical vapor deposition (CVD) reactors used to grow compound semiconductor materials such as AlGaAs cannot be used because of the unusual growth conditions required for the nitride systems. Even present-day commercial manufactures of nitride devices use customized reactor designs, and there is no clear consensus on how to design nitride CVD reactors for large-scale production nor how to most efficiently make use of the gases used for deposition. No single-crystal substrates of GaN are available in commercial quantities, which has forced researchers to use substitutes such as sapphire or SiC. This leads to epitaxial films with high defect densities. Many electrical properties such as recombination mechanisms and dopant passivation are not well understood, limiting the design of optimized devices.

Current State of the Art

Two types of blue AlGaInN-based LEDs are commercially available: Laterally contacted devices with InGaN quantum well (QW) active region on sapphire substrates from Nichia Chemical Industries, Ltd., and vertically contacted GaN devices on conducting SiC substrates from CREE Research Inc. The second type of LED structure (made by CREE Research Inc.) is grown on SiC substrates and is the only high volume U.S. based commercial provider of blue LEDs. These devices feature a smaller chip size and a smaller lattice mismatch to GaN, owing to the use of SiC substrates.

Several other US-based companies, including Uniroyal Optoelectronics and American Xtal Technology, are offering nitride based LEDs over a broad wavelength range (450-525nm). These companies are actively ramping their manufacturing facilities to high volume.

Technical Challenges

The six critical challenges to penetrate the illumination market have been identified that require R&D support are:

1 Color mixing for achieving high quality white light.

2 Reduce defect densities using, among other things, lateral epitaxy overgrowth (LEO) on SiC or bulk GaN substrates, etc.

3 Improve the understanding of nitride epitaxial growth for applications to optimized CVD reactors and scale up to manufacturing levels.

4 Improve the understanding of nitride materials properties to establish boundaries for efficient optoelectronic design and to suggest novel ways to exploit nitride properties.

5 Develop robust UV/blue resistant high power packages.

6 Develop optimal down conversion inorganic and organic phosphors.

A detailed description for each of these issues is presented here.

1) Quality of SSL white-light/color mixing issues: White light can be generated in a number of ways using AlGaInN-based LEDs. Several scenarios need further investigation in order to determine the most economic and best quality solid state white-light solutions. First, a combination of red, green, and blue LEDs can be mixed to fabricate white-light LEDs; this requires at least three LEDs, one of each primary color, in which current must be individually adjusted to control light intensity. Therefore, the cost of this white-light LED might be higher than that of a single-color LED and in addition, off-angle viewing also might be compromised.

Another scenario is to create white-light within a single LED by exciting phosphors using blue light. This blue wavelength light contains enough energy to excite some phosphors which then convert part of the incident blue light to yellow/orange (amber) light, and the combination of the blue LED light and amber emission of the phosphor yields white light. We should note here that color tuning in these white-light LED systems is very important in optimizing and increasing overall efficiency. By varying the composition of $(Gd, Ce)^{3+}$:YAG, the broad-band peak emission wavelength can be tuned between 510 and 580 nm and combined with the blue LED wavelength, control of the color rendering index of the white light can be achieved. This design structure is cheaper than the former proposed method, but at the expense of low efficiency and poor color rendering index.

A third option is the application of AlGaInN-based UV emitters with several phosphors to achieve high quality white light. Here all incident light emitted by the UV LED is absorbed by a triphosphor blend of red, green, and blue phosphors, whose compositions can be accurately adjusted. The quality of light generated by a triphosphor blend is potentially better than that available from the single phosphor/blue LED combination where the resulting color coordinates are more difficult to control because white light emission is dependent upon incident blue to amber conversion.

However, both scenarios involving phosphor conversion of either a blue or UV LED suffer from ~40 - 50% conversion efficiencies.

2) Reduce defect densities LEO, bulk GaN: Improving defect densities on SiC and development of bulk GaN would greatly improve the lifetime and output power of GaN LEDs, lasers and VCSELs. Besides sapphire and SiC, several other substrate materials are undergoing investigation by many researchers in order to determine if the properties of the GaN thin films can be enhanced by improved structural matching. The identification of a suitable substrate material that is lattice matched and thermally compatible with GaN wurtzite structure (a = 3.19 Å, c = 5.185 Å) will alleviate many of the difficulties associated with the deposition of device quality material. From Figure 4.1 we can see that in addition to sapphire, several other substrates offer potentially better lattice and thermal matching conditions. To this end, 6H-SiC, ZnO, and 3C-SiC, MgO are being explored as alternative substrate materials.

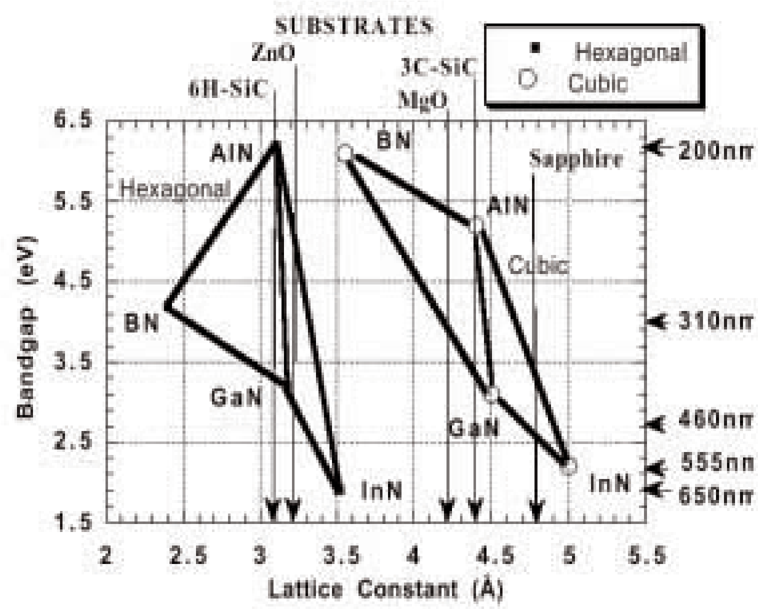

FIGURE 3.1
Energy band daigram for AlGaInN and lattice constant of alternative substrate materials.

Both SiC (lattice mismatch 0.5%) and ZnO (lattice mismatch 0.2%) have a closer lattice constant to GaN than sapphire which has a lattice mismatch of 16%. Recently, lower dislocation densities have been reported for GaN grown on SiC.[4.4] The II-VI material ZnO has a wurtzite structure with lattice constants of (a = 3.32 Å, c = 5.213 Å) and thus offers a better structural match to the equilibrium wurtzite nitride. Also, 3C-SiC and MgO are both cubic zinc-blende structures having better structural and thermal match to the nitrides than sapphire. The cubic lattice constants of 3C-SiC and MgO are respectively a = 4.36 Å and a = 4.22 Å.

The growth parameters and development of large of bulk native substrates of are just now being reported by Samsung and others for GaN [3.5, 3.6] and researchers at RPI for AlN.[4.7] Because of lattice matching conditions offered by using native substrates, defect densities in the range of 10^2 are to be compared with typical defect densities in the range of 10^{10} to 10^{12} for LEDs grown on sapphire. It is anticipated that spectacular results for all GaN-based devices will be demonstrated when native substrates become commercially available.

Recently, lateral epitaxially overgrowth (LEO), cantilever epitaxy, and pendeo-epitaxy have been shown to extend the operating life and output power of GaN based lasers to 10,000 hours.[3.8] The further development of novel epitaxial growth methods such as LEO and pendeo-epitaxy will play a key role in improving efficiency and reliability of the nitrides.

3) Epitaxial growth fundamentals: Even if proof-of-principle devices can be demonstrated, AlGaInN-based devices will not impact the marketplace if they cannot be manufactured in large quantities and at an acceptable cost. Epitaxial growth of these materials is especially demanding, requiring deposition at low (500°C) and high (1150°C) temperatures. The precursor gases react before reaching the substrate, causing severe difficulties in controlling growth rates and composition. Control of doping is also unusually difficult compared to conventional compound semiconductor systems.

Several research groups have reported improved material quality of GaN-based thin film growth by depositing at atmospheric pressures and higher. This places additional strains on the development of a scalable GaN reactor design. At these high pressures, buoyancy- driven convective instabilities become severe and difficult to control. These instabilities become more dominant as the reactor is scaled to larger dimensions. Growth issues are paramount to a successful to LED SSL and thus epitaxy growth issues have to be studied further.

4) Better understanding of nitride materials: Nitride materials are unlike any other conventional compound semiconductor. The lack of suitable substrates for epitaxial growth and unusual chemistry leads to unique challenges in tailoring the material for device applications. Defects play a central role in AlN, GaN, InN, and their ternary mixtures. Dopant passivation from hydrogen is much more important for nitride systems because of the large N – H bond strength. These large values make it difficult to dope nitrides with precision and to achieve high carrier concentrations.

The realization of high efficiency blue and UV LEDs for solid state lighting requires a detailed understanding of carrier recombination mechanisms. Understanding these mechanisms in the III-nitrides has been hampered by high defect densities and the unintentional n-type doping of as-grown GaN. The unusual properties and unique problems of the nitrides must be addressed with fundamental studies to enable optimal device design.

All the above issues (1 - 4) must be resolved before efficient production of commercial nitride CVD reactors can be implemented. Such efforts would benefit from fundamental knowledge of the nitride gas-phase and surface chemistry mechanisms as well as rules of thumb for efficient fluid mechanics design.

The two remaining areas of investigation of equal importance are:

5) Develop robust UV/blue resistant high power packages: Increasing the luminous flux, the reliability, and low cost white-light LED-based emitters is heavily dependent on the packaging technology. Current LED encapsulants show degradation (epoxy yellowing) to exposure by both UV and blue GaN/SiC chips. This problem is further exacerbated with increasing luminous flux and current density. Developing UV-resistant plastics and materials suitable for encapsulation is a high priority. Additionally, die-attach epoxies that are UV/blue degradation resistant will improve SSL lifetime. In order to reduce the cost, the chip size must be smaller, and the current density must be increased. This will involve developing high thermal conductivity component materials.

6) Develop optimal down conversion phosphors/media: The current chemistry and preparation of white-light LEDs rely on a single GaN chip (460 nm) and a Ce^{3+}:YAG amber phosphor to generate a white light. In such a device, a GaN blue LED serves as the primary light source, acting as a pump for the inorganic luminescent materials in which subsequent photon emission occurs at lower energies.

Currently, there are phosphors being used to covert UV to visible light in standard fluorescent tubes. However, the excitation wavelength (~250 nm) is substantially shorter than the needed 380 - 410 nm. These fluorescent tube phosphors do not readily absorb in the blue and therefore new phosphors will have to be identified. There is very little data and phosphor material that effectively can down convert the near-UV and blue wavelengths into red, and green wavelengths. Therefore, there exists a strong need to develop additional phosphors having high conversion efficiencies when irradiated (pumped) by GaN sources.

Novel down converters such as organic dyes [3.9] and conjugated polymers, [3.10] have also shown promising conversion efficiencies and white light demonstrations. A basic scientific study of degradation mechanisms and reliability of all down conversion media should be a strong portion of the SSL roadmap.

Research Issues

Because the development of nitride materials systems is relatively immature and also because nitride systems present unique challenges, a focused basic research effort for nitrides will greatly accelerate commercialization possibilities. Companies attempting to commercialize nitride devices typically have limited resources to perform such research and rely on new developments from University and National Laboratory efforts. The following outlines a few research themes that are appropriate for

University/National Laboratory research programs closely related to nitride lighting applications.

- **Material properties:** Understanding of basic materials properties of the nitrides will help to set bounds on device designs and assist in optimizing performance by allowing one to take full advantage of known physical and electronic behavior. Achieving these goals will involve not only a comprehensive experimental investigation, but also, a theoretical understanding of the material fundamentals.

- **Bulk GaN substrates:** The growth of native (bulk) GaN substrates would remove or alleviate the many issues facing the use of artificial substrates. While preliminary results show some success in producing bulk GaN [3.5, 3.6] and AlN substrates, [3.7] much work is still required. A knowledge of the high-temperature chemistry required for GaN coupled together with high-pressure environments poses serious difficulties for success. However, the successful realization and commercial production of bulk GaN substrates will require a major research effort and will mark a major accomplishment in the field of materials research.

- **Artificial substrates:** A substantial effort must be made to determine whether it is possible to provide a substrate material that allows epitaxial growth of AlGaInN materials without significant lattice mismatch. Such a development would greatly accelerate the development of manufacturable nitride devices. However, given that many efforts are currently underway to solve this problem, fundamental research in alternative approaches such as layered epitaxy overgrowth, pendeo-epitaxy, and strain compensation must be pursued.

- **CVD reactor design:** Although empirical “cut-and-try” methods for designing CVD reactors has been a successful way to develop a commercial product, such approaches have not been as fruitful for nitride reactors. Fundamental research on nitride chemistry, convective instabilities, and in situ monitors would greatly accelerate the empirical development by providing a sound understanding of chemical mechanisms and physical limitations inherent in nitride epitaxy.

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4 AlGaInP-Based LEDs for SSL Lighting

Background

The $(Al_xGa_{1-x})_{0.50}In_{0.50}P$ material system is nearly lattice matched to GaAs and provides direct-band-gap recombination of the carriers for aluminum compositions ranging from from x = 0 to x ~ 53%, corresponding to peak wavelength emission from about 650 nm (deep red) to nearly 555 nm (yellow-green). [4.1] This material system has dominated applications requiring high-brightness red, orange, and/or amber LEDs.

The LED wafers are grown using organometallic vapor-phase epitaxy (OMVPE) in multiple-wafer reactors. These reactors have driven the cost of AlGaInP LEDs down considerably over the last ten years. They are capable of producing several wafers per run with very good yields, coupled with the availability of increasingly larger diameter GaAs substrates.

One drawback of the smaller band-gap energy GaAs substrate is that it absorbs light produced by the higher-energy AlGaInP active region, thereby limiting the brightness of the LEDs. Two approaches exist in commercial LEDs that are designed to alleviate this problem.

One is the use of distributed Bragg reflector (DBR) mirrors between the active region and the substrate, to reflect downward-emitted light away from the substrate and towards the top of the device. This approach improves on-axis brightness considerably, and provides for a measurable increase in total flux.

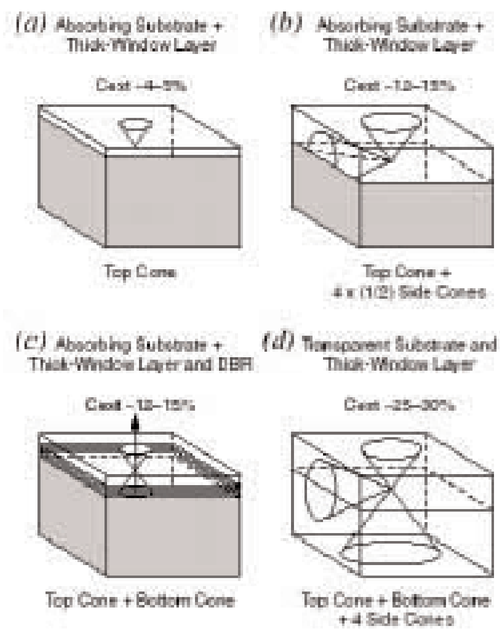
The second approach uses wafer bonding to provide a transparent GaP substrate in place of the original GaAs growth substrate. In this technique, the GaAs substrate is selectively removed after growth, and the GaP substrate is fused to the AlGaInP layers by elevated heat and pressure. The resulting bond is conductive and provides for a vertical-conduction transparent substrate AlGaInP LED.

Although not providing a strong advantage in on-axis intensity compared to the DBR approach, the transparent substrate provides a significant increase in total flux (more than a factor of two). Indeed, transparent substrate AlGaInP materials have provided the platform for the world's most efficient visible-spectrum LEDs to date. [4.2] Estimated extraction efficiencies from various AlGaInP LED geometries are given in Fig. 4.1. [4.3]

For AlGaInP the internal quantum efficiency for small aluminum compositions (< ~10%) is very high (estimated to be near 100%) for room-temperature junction temperatures (Tj ~25°C). For larger aluminum compositions, carrier leakage due to smaller band offsets and increased population of indirect L and X minima reduce internal quantum efficiency considerably. This problem may be overcome by considering novel applications of band gap engineering techniques. For the same reasons, the temperature dependence of the device efficiency is compromised.

The extraction efficiency of AlGaInP LEDs depends strongly on device geometry. For devices employing GaAs (absorbing) substrates, a maximum extraction efficiency of about 15% is achieved using thick transparent windows on top of the active region. For transparent substrate devices, extraction efficiencies as high as 40% have been determined for conventional-geometry devices in the red wavelength regime. In the same wavelength regime, external quantum efficiencies as high as 60% have been measured for shaped transparent substrate AlGaInP LEDs, putting a lower bound for the extraction efficiency of these devices. Extraction efficiencies for shorter-wavelength devices will be lower, due to re-absorption by the active region with quantum efficiency less than 100%, e.g., reduced photon re-cycling.

FIGURE 4.1
Typical LED geometries along with estimated extraction efficiencies [after H. Chui et. al., "High-efficiency AlGaInP light-emitting diodes," in Electroluminescence I, Semiconductors and Smeimetals Vol. 64, p. 69 (2001)]



Current State of the Art

Figure 4.2 shows the best-measured performance for AlGaInP LEDs based on luminous efficacy (lm/W) as a function of peak emission wavelength. These data are for packaged (i.e., epoxy-encapsulated) LED chips and includes the measurement of total flux from the LED lamp into an integrating sphere.

Data in Fig. 4.2 are provided by LumiLeds Lighting. All data points shown are for current densities of about 40 A/cm^2, a typical operating regime (e.g., about 20 mA in most typical LEDs). Data on absorbing substrate AlGaInP LEDs are not shown. The efficiencies are broken down according to two different device types:

- Standard transparent substrate AlGaInP, and
- Shaped-geometry transparent substrate AlGaInP LEDs.

It should be noted that absorbing substrate AIGaInP LEDs are at least a factor of two less efficient than transparent substrate AIGaInP LEDs in terms of total flux and thus are poor candidates for competition in solid-state lighting applications.

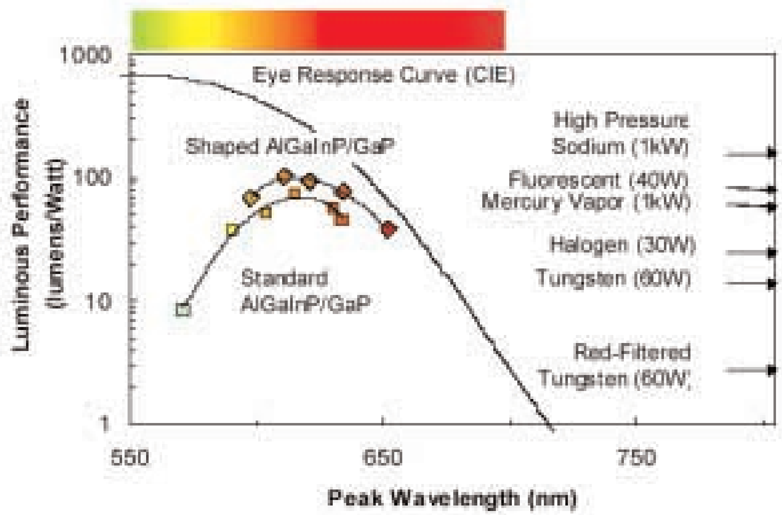


FIGURE 4.2
Best-measured luminous efficiencies (lm/w) for transparent substrate AlGaInP light-emitting diodes as a function of peak emission wavelength (J_f~40 A/cm^2.)

Figure 4.3 shows best-measured external quantum efficiency versus peak emission wavelength for conventional-geometry transparent substrate AlGaInP LEDs. The shape of the curve indicates the strong wavelength-dependence of internal quantum efficiency for this material system. For the red wavelength regime ($\lambda > 630$ nm), the internal quantum efficiencies estimated to be close to 100%.

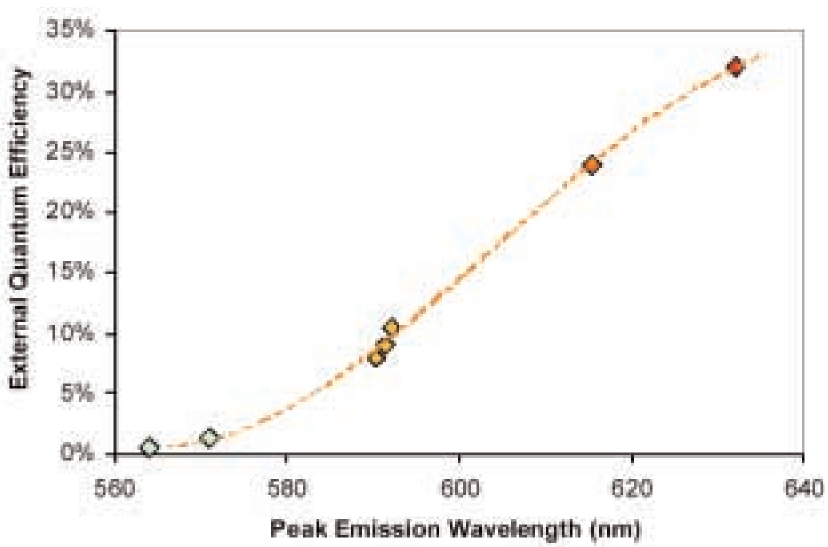


FIGURE 4.3
Best-measured external quantum efficiencies for conventional-geometry transparent substrate AlGaInP light-emitting diodes as a function of peak emission wavelength (J_f~40 A/cm^2.)

Figure 4.4 shows the typical performance for commercially available AlGaInP LEDs where the test conditions are the same as for Fig. 4.2. The efficiencies are for conventional-geometry devices: Absorbing-substrate (e.g., GaAs) and transparent substrate AlGaInP LEDs using GaP.

All AIGaInP LEDs are sensitive to temperature, with the shorter-wavelength (e.g., yellow) devices showing a considerably increased sensitivity compared to longer-wavelength (e.g., red) devices.

The human eye response function tends to exacerbate the problem because of the red shift of emission wavelength with increased junction temperature. The red shift of emission wavelength with temperature is typically ~ 0.1 nm/K for AlGaInP.

FIGURE 4.4
Luminous efficacies (lm/W) for commercially available AlGaInP light-emitting diodes as a function of peak emission wavelength.

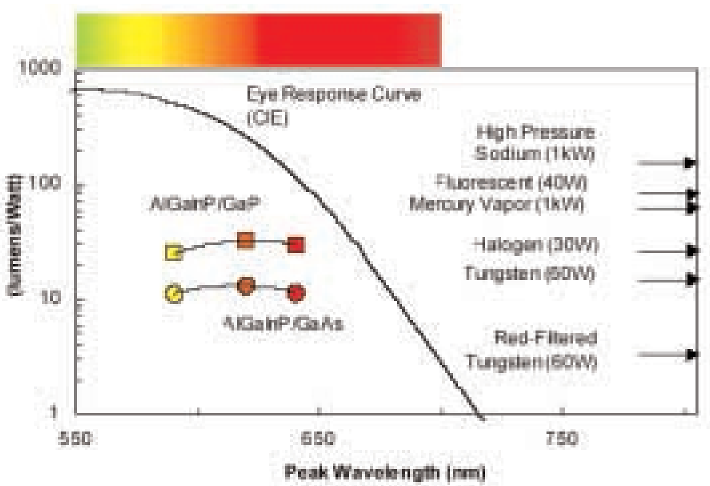


Figure 4.5 illustrates the effect of the human eye response curve combined with the red-shifted spectrum for AlGaInP LEDs. The increasing wavelength with temperature reduces the luminous efficacy of the spectrum, combining with reduced internal quantum efficiency to result in severe temperature dependence for luminous efficiency for AlGaInP. In Fig. 4.5, this is contrasted to the case for AlGaInN LEDs, which are actually assisted by the human response curve to somewhat stabilize flux dependence on temperature.

Figure 4.6 quantifies the typical temperature-dependence of AlGaInP LED luminous efficiency for different peak emission wavelengths, taking into account the CIE eye response effect. The effect is a significant reduction (to less than 50%) for luminous flux at T_j = 100°C compared to room-temperature values.

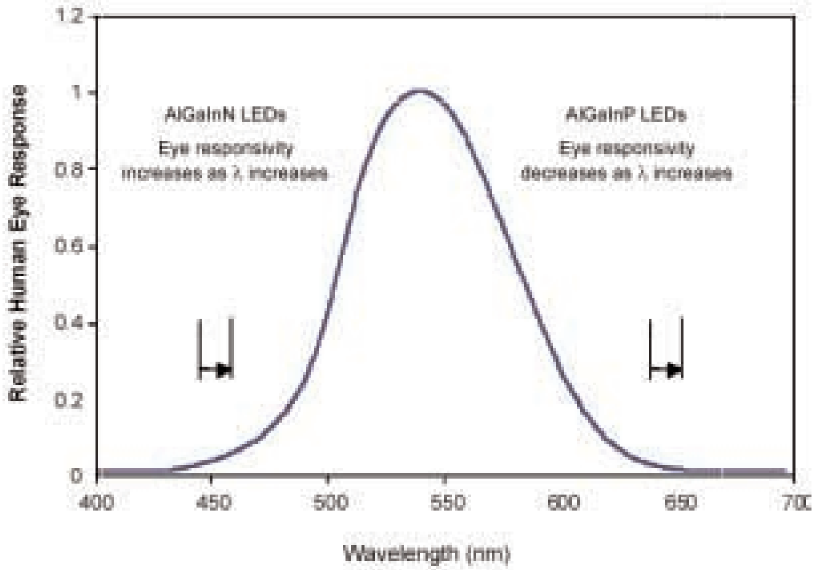


FIGURE 4.5
Effect of human eye response curve on perceived (luminous-based) temperature dependence of AlGaInP LEDs.

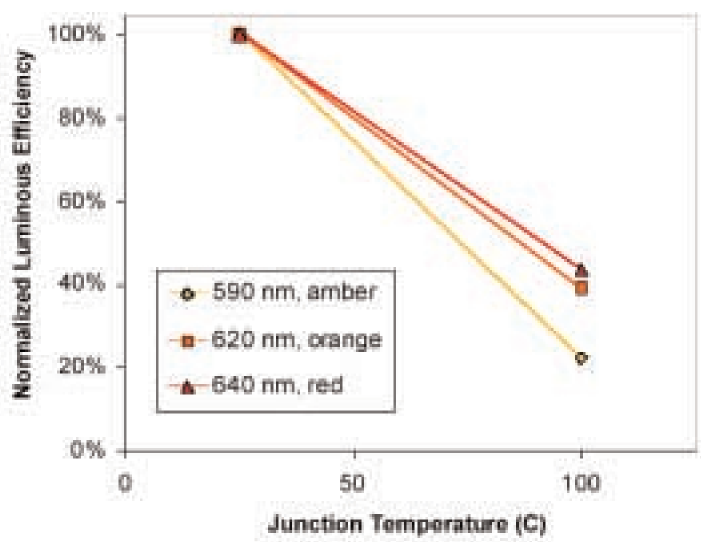


FIGURE 4.6
Normalized luminous efficiencies for AlGaInP LEDs of different emission wavelengths (amber to red) as a function of junction temperature.

Critical Challenges

The AlGaInP material system is now a fairly well understood. The reduction of internal quantum efficiency with increased Al composition has been studied and the dominant mechanisms identified through measurements of carrier leakage and of locations of indirect minima. The extraction efficiencies of the available geometries have been well mapped out. Challenges facing for AlGaInP devices with respect to solid-state lighting include:

(1) Band-gap engineering for improved carrier confinement.

(2) Inexpensive methods for high-extraction efficiency.

(3) Control of degradation mechanisms under high-current, high-temperature operation.

A short description for each item is discussed here:

1) Band-gap engineering for improved carrier confinement: Clearly the most critical challenge for the AlGaInP material system with regards to solid-state lighting is the development of LED structures with drastically reduced carrier leakage due of the indirect L and X minima present in the AlGaInP barrier materials.

While the presence of indirect minima provide a fundamental limit to temperature-insensitivity and performance at shorter wavelengths, evidence suggests that poor carrier confinement due to small band offsets constitute the major cause of these problems. This issue is the reason for the poor performance of laser diodes based on AlGaInP at wavelengths less than ~ 630 nm, and is one of the major reasons why development of yellow AlGaInP optoelectronic devices has been difficult. Finally, it is also the main reason for the reduced quantum efficiency in the short (yellow) wavelength regimes, and for poor temperature dependence of the efficiency.

2) Inexpensive methods for high-extraction efficiency: High-extraction efficiency is currently achieved in AlGaInP LEDs through fairly costly methods, e.g., transparent substrate wafer bonding and chip shaping. Methods are required which enable high extraction efficiencies (> 50%) through simple geometries and inexpensive processes. Possibilities include epi-ready transparent substrates, and photonic band-gap structures.

3) Control of degradation mechanisms: For high brightness solid-state lighting high operating current densities (and thus high junction temperatures) are required. Reliability of AlGaInP LEDs to date shows a dependence on both current density and junction temperature, with more light-output degradation observed as either of these parameters is increased. Typical degradation curves for AlGaInP LEDs in 5-mm lamp packages are shown in Fig. 4.7. These degradation mechanisms must be studied in detail to understand their root nature and cause to discover methods to eliminate them or render them harmless.

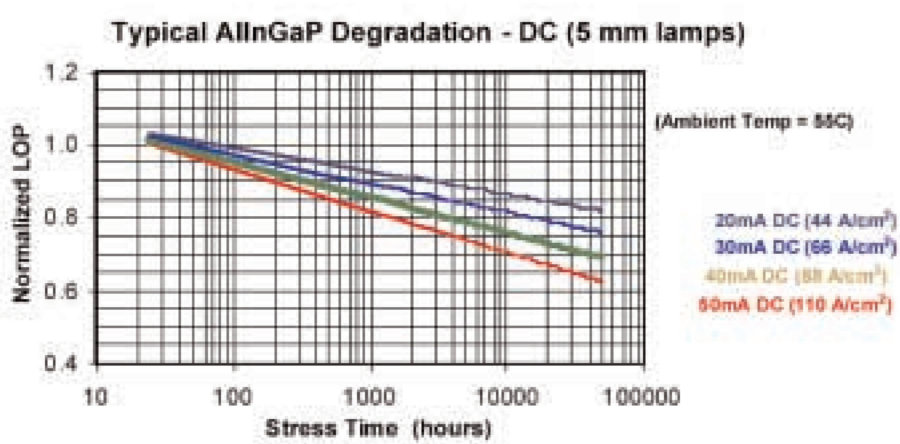


FIGURE 4.7
Typical degradation curves for AlGaInP LEDs at different operating currents (ambient temperature, T_a=55°C).

Additional Research Opportunities

Green light from phosphide emitters: One of the areas of research to be addressed is the production of a highly efficient green light source based *entirely* on the AlGaInP alloys system. Currently both nitrogen and phosphorus-based green LEDs have fairly low efficiencies. The AlGaInN-based green emitters were addressed in Sec. 3 and will not be discussed further here. Although materials made from AlGaInP have band-gap energies that correspond to green wavelengths, the existence of the nearby indirect gap (the energy difference between the direct and indirect energy gaps is about 100 meV and is characteristic of these alloys systems) drastically decreases the emission efficiency of any green light sources based on AlGaInP-based alloy materials.

Reasonable efforts have been taken to achieve green emitters in the AlGaInP-based system utilizing superlattices. However, there is very little published in the open literature. One obvious approach is to use strain to attempt to modify the band-gap energy in these materials to drive the direct to indirect energy-band cross-over far enough away that the emission efficiency would improve dramatically.

Green-emitting quantum dots: The study of strained structures such as superlattices, quantum wires, and quantum dots, for use in green emitters could prove to be a fruitful area of research for producing wavelengths $\lambda < 650$ nm. Because of the large band-gap energy modifications resulting from enhanced quantum confinement and strain, self- assembled quantum dots can be used to obtain light emission at wavelengths unattainable even using highly strained quantum wells, as evidenced by InGaAs/GaAs based quantum dot lasers emitting at 1.3 µm which is an increase in the band-gap energy by almost a factor of four!

These structures would most likely be grown on GaAs or GaP using AlGaInP materials. Substrates based on GaAs would also allow the use of AlGaAs DBR structures. Both molecular beam epitaxy and metal-organic chemical vapor deposition are capable of producing semiconductor nanostructures with dimensions on the order of 10 to 100 nm in all three directions (quantum dots).

Semiconductor structures with these small dimensions will manifest three phenomena:

- An atomic like density of states production giving materials with greatly altered and enhanced optoelectronic properties,
- Access to materials with greater strain and thus semiconductor compositions to achieve optical emission not possible using quantum wells, and
- Additional electrical carrier confinement to overcome lateral diffusion over and within a quantum well producing lower leakage currents.

Photonic lattices: A photonic band gap is the optical analog of an electronic band gap in semiconductors. A periodic variation in the dielectric constant forbids certain photon energies within the photonic lattice.There are several research programs in the U.S which are examining the feasibility of utilizing the unique optical properties of the photonic band gap device to enhance light output levels of AlGaInP-based LEDs.

For example, researchers at the NanoStructures laboratory at MIT have performed computer simulations for the effect of placing a two-dimensional photonic lattice on top of a multiple quantum well LED (InGaP/GaAs) and their results suggest that for their design, a five-fold increase in extraction efficiency may be possible.

References

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5 Phosphors for LED-Based White-Light Illumination

Introduction

This section discusses the development of white-light sources suitable for illumination, based upon a near UV emitting chip (380 to 410 nm peak wavelength) and a blend of down-conversion phosphors. The quality of the white light should closely approximate that of current fluorescent lamps, which utilize a triphosphor (red, green and blue) blend. Since there is a dearth of phosphor materials which are efficiently excited in the 380 to 410 nm range, particularly red and green emitting phosphors, it will be necessary to develop these materials.

Background

While a variety of spectral lights are distinguishable by the normal human visual system there are three independent (although overlapping) spectral responses (the tristimulus curves) that feed the human visual system with maximum efficiency was previously shown in Fig. 2.1, but for convenience is displayed here as Fig. 5.1. Each of the spectral responses sample a different region of the visible spectrum (red, green and blue) and is characterized by a singular wavelength that defines the peak sensitivity.

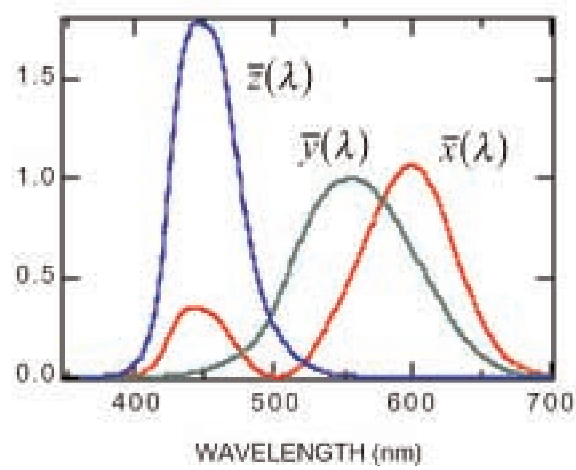

FIGURE 5.1
The tristimulus functions x(λ) (red), y(λ) (green, and z (λ) (blue)

Phosphors for UV LEDs

This understanding of the human eye response suggests a lamp design departure from the traditional methodology of commercial incandescent lamps, which imitate daylight as a continuum. Strong visual effects such as higher perceived brightness per watt and better color rendering results when white light more closely resembles the three pure spectral colors and the rest of the visible spectrum is left as nearly empty as possible (as in fluorescent lamps).

Phosphors for UV LEDs

Commercial fluorescent lamps utilize phosphors as converters of UV emission of rare gas/mercury discharge plasma into visible (white) light. The basic mechanism of white light generation is therefore the same in white light UV-LEDs and in commercial fluorescent lamp (conversion of UV radiation to visible light). In the 1970's a revolutionary blend of three phosphors (called triphosphor or tricolor blend) emitting in the blue, green and red spectral region led to the development of a new generation of white light fluorescent lamps which simultaneously combined markedly high color rendering with high efficacy.

The role of the phosphors in the triphosphor blend of the fluorescent lamp is to generate photons with high efficiency at wavelengths near the "three-peaked" spectral response of the human visual system. The three narrow emission bands centered near 450 nm (blue component), 550 nm (green component) and 610 nm (red component) are the ideal "prime-colors" for the human visual system. The resulting white light has high efficacy and excellent color rendering.

The individual phosphors currently used in the tricolor blend of a typical fluorescent lamp are listed in Table 5-1 and the respective emission spectrum is shown in Fig. 5.2. Note that the color temperature can be varied by changing the ratio of the power in the three components while restricting any changes in the peak wavelength emission of the three components (Fig. 5.2 inset).

With a corresponding triphosphor blend excitable at 380 to 410 nm, we hope to realize our goal of developing a phosphor assisted white light LED with high efficacy and good color rendering. Moreover, once such a blend is available it will be possible to design white- light LEDs with a variety of color temperatures (e.g. cool and warm white), and also very high color rendering index.

Table 6.1.

Phosphors currently used in the triphosphor blend of typical fluorescent lamps (activator or emitting ions are indicated in bold; phosphors excited by 254 nm wavelength radiation)

PHOSPHOR	COLOR	EMISSION WIDTH	EMISSION PEAK (nm)
Eu^{2+}:(Sr, Ba, Ca)$_5$(PO$_4$)$_3$Cl	Blue	Broad	450
Eu^{2+}:BaMg2Al16O27	Blue	Broad	450
(Ce, Tb)$^{3+}$:LaPO4	Green	Narrow	543
Eu^{3+}:Y2O3	Red	Narrow	611

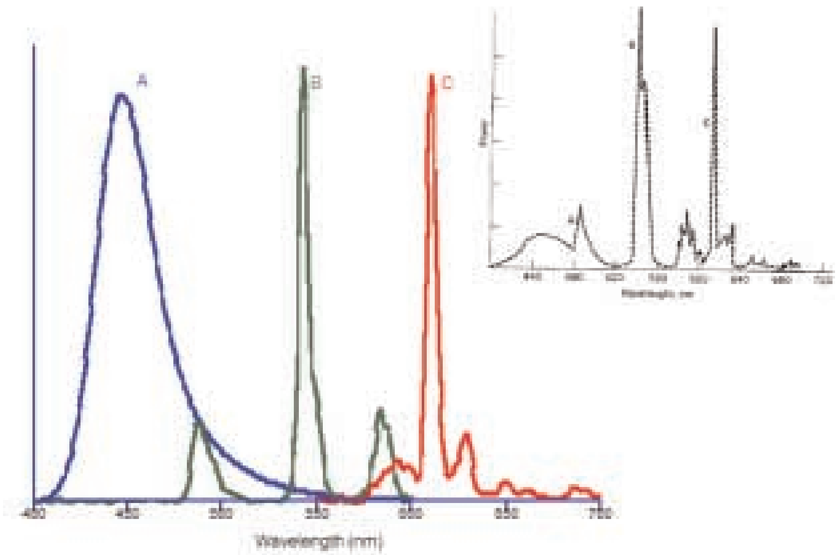

FIGURE 5.2

Emission spectra of phosphors of the triphosphor blend: A is Eu^{3+}: $(Sr,Ba,Ca)_5(PO_4)_3Cl$ (blue), B is (Ce^{3+}, Tb^{3+}): $LaPO_4$ (green), and C is Eu^{3+}: Y_2O_3 (red). The inset shows the emission spectrum of a triphosphor blend with a color temperature of 4,000 K.

Phosphors for Blue LEDs

The recent development of white-light LEDs is based on the phosphor assisted conversion of blue radiation (wavelength of 450 - 470 nm) from the LED into yellow light. The phosphor, YAG activated with trivalent cerium (Ce^{3+}:YAG), converts the blue LED radiation into a very broad band yellow emission. The emission is centered at about 580 nm with a full-width-at-half-maximum linewidth of 160 nm. The emission of Ce^{3+}:YAG contains enough orange emission to produce 'white' light at a color temperature of 8,000 K and an efficacy of about 15 lm/w. The color temperature can be lowered by using more phosphor, however, the system efficacy is also decreased. There is a need for phosphor coated LED having higher efficacy and a lower color temperature.

There are several technological problems with producing pseudo-white light via a blue LED and a yellow phosphor, which makes this technology suitable for displays and low color rendering index (CRI) illumination. They are:

1) Halo effect of blue/yellow color separation due to the different emission characteristics of the LED (directional) and the phosphor (isotropic).

2) Low color rendering index (~65 - 75).

3) Broad color 'bins' are necessary to ensure reasonable product yield.

4) Most lamps have color points that do not lie on the black body curve.

5) The color shifts (from blue to yellow) with aging and variation in drive current.

Challenges

The phosphor requirements for LED-based white-light illumination assume that the new phosphors would operate in the same manner as they do in conventional fluorescent lamps:

- Phosphors must strongly absorb at the wavelength of the LED radiation (absorption should exceed 90%.)
- The intrinsic phosphor efficiency defined by the ratio of the emitted photons to absorbed photons must be high (quantum efficiency 85% or higher.)
- The phosphors should be compatible with operation in the LED device.
- The phosphors should display excellent lumen maintenance (defined as the change in lumens/brightness with time).
- The phosphors should be easily manufactured.

Phosphor Requirements

If the UV LED is selected as the primary device then the phosphors must be capable of absorbing incident UV light at 380 to 410 nm. The red, green and blue emitting fluorescent lamps phosphors (see Table 5.1) are tuned to absorb the 254 nm radiation of the mercury discharge. This limitation precludes the exploitation of these highly efficient phosphors for developing a practical white-light LED device. The exceptions are the blue emitting phosphors [Eu^{2+} activated $(Sr,Ba,Ca)_5(PO_4)_3Cl$ and $BaMg_2Al_{16}O_{27}$] which show strong absorption throughout the UV and almost into the visible. However, there still is a need for efficient green and red emitting phosphors that will satisfactorily absorb the incident UV LED radiation.

Red phosphors: It is crucial that the red emitter displays an emission spectrum that has s narrow linewidth (essentially a line emission) and centered at 611 nm. The emission of trivalent europium (Eu^{3+}) is ideally suited for the practical realization of this principle. The red emitter Eu^{3+}:Y_2O_3 displays an emission spectrum that is ideal for red color generation (Fig. 5.2c). The quantum efficiency of the Eu^{3+}:Y_2O_3 phosphor under 254 nm excitation is close to 100% and is the highest of all known lighting phosphors. However, photons with wavelength of 380 to 410 nm are very poorly absorbed by this phosphor. Therefore in the current form the phosphor is unusable as a red color generator in the UV LED device.

The discovery of red emitters based on the Eu^{3+} luminescence for UV LED application will invariably require sensitization for the following reason. The UV absorption of the Eu^{3+} ion is due to a charge transfer transition involving the Eu^{3+} ion and the surrounding anions. It is known that the quantum efficiency of Eu^{3+} activated phosphors is low when the charge transfer transition is centered at wavelengths longer than about 300 nm. Hence, for UV LED application, where the phosphor is expected to absorb 380 to 410 nm radiation, sensitization of the Eu^{3+} luminescence is imperative.

As we learn more about the sensitization mechanism we have devised a set of rules to identify potential red emitting candidates and to optimize the sensitization efficiency. These rules are based on our knowledge of crystal chemistry, energy level structure, and optical selection rules for the sensitizer and the activator (Eu^{3+}) ions.

Green phosphors: The situation for green emitting phosphors is different from that for red-emitting phosphors. Since green light intrinsically has higher luminosity (the green response and the luminosity curve coincide) narrowness of spectral emission in the green has some importance but it is not the dominant concern that it is in the red spectral region. The relaxation of this selection criteria allows for the identification of a good number of candidates for green emitting phosphors. The broad-band emission of divalent europium ion (Eu^{2+}) which is due to $4f^6$ 5d -> $4f^7$ optical transitions is extensively tunable with emission wavelengths extending from the UV to red wavelength spectral regions. Moreover, the absorption by $4f^7$ -> $4f^6$ 5d optical transitions usually extend throughout the ultraviolet.

Blue phosphors: The Eu^{2+} based blue-emitting fluorescent lamp phosphors will absorb the UV LED radiation and emit at the required wavelength of 450 nm. However, the absorption for 380 to 410 nm radiation can be further improved by increasing the europium content in the phosphor formulation (recall that the phosphor composition has been optimized for absorption of the 254 nm radiation.) The increase in europium concentration is limited by the efficiency loss arising from concentration quenching and by the high cost of europium. Nevertheless, for the specific application in UV LEDs, there are numerous subtle trade-off possibilities that require re-optimization of the phosphor composition.

Improved Phosphor Conversion Through Packaging:

For direct application of the phosphor layer to the LED, a coating technology similar to the coating of phosphor on the interior of the fluorescent lamp glass tube can be used. The individual phosphors may be dry blended and then added to a liquid suspension medium or the individual phosphors may be added to a liquid suspension, such as nitrocellulose/butylacetate binder and solvent solution used in commercial lacquers. Many other liquids including water with a suitable dispersant and thickener or binder such as polyethylene oxide, can be used. The phosphor containing suspension is then painted, or coated, or otherwise applied to the LED and dried.

Alternatively, the phosphors can be combined in suitable liquid polymer systems, such as polypropylene, polycarbonate, or polytetrafluoroethylene, or, more commonly, epoxy resin or silicone, which is then coated or applied to the LED and dried, solidified, hardened, or cured.

For optimum brightness, it is imperative to develop high quality coatings with minimum defects, and to arrange the phosphor blend about the chip in such a fashion as to convert as much of the chip radiation into visible light as possible. Also, the absorption, reflection, etc., of the binder materials and the overall conversion efficiency has to be taken into account. Thus, methods to minimize intrinsic efficiency loss are important.

Phosphor sensitizers: Unlike the triphosphor blend used in fluorescent lamps, one of the issues with existing phosphors, excited by Blue LEDs, is that the absorption in the blue by the rare earth ion, say Ce^{3+}, is low. This situation is reminiscent of the early days solid state laser research using Nd^{3+}:YAG where Nd^{3+}:YAG has a similar absorption problem when pumped by flash lamps, i.e., not much absorption in the blue. With the discovery that adding Cr to YAG increased the blue light absorption and thus, through excited state energy transfer processes, energy is transferred from the Cr3 ion to the Nd^{3+} ion, thereby increasing the overall efficiency. Similar ideas for increasing the blue absorption process for the triphosphor blend and/or other phosphors should be explored.

Energy conversion devices - nanoparticles: Inorganic semiconductors have some advantages compared to traditional organic phosphors for lighting applications. For example they are less likely to suffer photochemical degradation during electron or hole injection in electroluminescent displays. However, the peak in their emission energy occurs near the band-gap of the particular material chosen, requiring several types of materials to span the visible light regime (400 to 700 nm). Also, it is not always possible to find acceptable semiconductors with band-gaps in this energy range. However, these kinds of applications are just now being examined and questions regarding efficiencies, etc., are still yet to be determined.

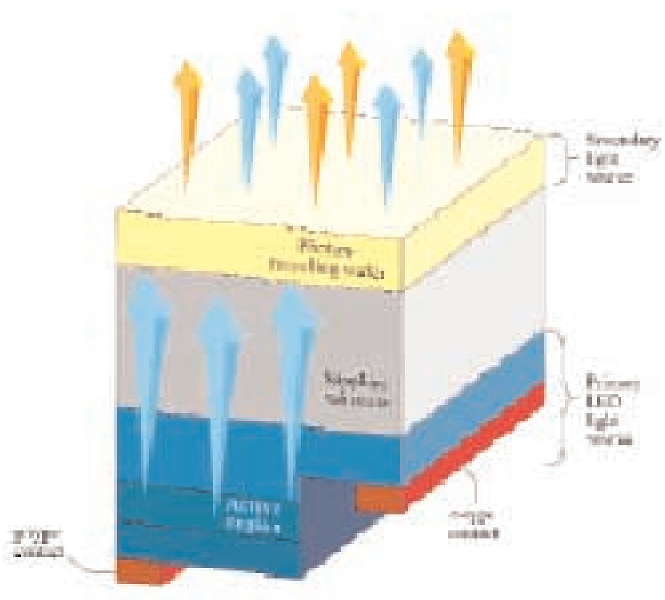

FIGURE 5.3
Structure of a photon-recycling semiconductor LED. The LED consists of a primary LED emitting in the blue wavelength range and the photon recycling wafer emitting the complementary color.

Methods of chemically synthesizing nanosize semiconductors whose band-gap depends on the size of the nanoparticle due to the effect of quantum confinement of the electron-hole pair.[5.1] The II-VI semiconductors, like CdS, which are direct band- gap materials in bulk form are of particular interest since high quantum yields of visible light are possible. For example, light emission intensities have been demonstrated from 3.0 nm CdS nanoparticles similar in photoluminescence intensity and position to that obtained from laser dyes like Coumarin 500. Furthermore, the peak of the light emission can be shifted from about 430 nm to nearly 700 nm by variation of both the size and the interface characteristics. The effect of the latter is demonstrated in Figure 1.3 where a co-plot of the absorbance and fluorescence from a solution of CdS nanoparticles coated with a layer of ZnS (ZnS by itself has emission at ~420 nm) was shown. A red-shift and enhancement of over a factor of three in the light emitted occurs due to the coating. There is also a shift in the peak absorbance exciton, but no increase in the absorbance intensity.

It is also possible to alter the peak energy and quantum efficiency by varying the excess ions at the nanoparticle interface. For example, intense blue-green emission at ~488 nm occurs with an excess of Cd at the interface, while weaker red emission at 590 nm is observed with excess S at the nanoparticle surface. Thus, by variation of both size and interface chemistry it is possible to obtain a wide range of output colors even with only a single semiconductor material.

A critical challenge with these kinds of nanoparticles for LEDs is to improve the quantum efficiency. To date, an absolute determination of the energy conversion efficiency has not been made, but studying this phenomenon is attractive and may have a long term pay off.

Photon semiconductor LEDs: A brief description for PRS-LEDs was given in Section 1. The PRS-LED is a semiconductor light source emitting two or more discrete colors that are perceived as white light by the human observer. A two color device structure, shown in Fig. 5.3, consists of an electrically driven primary and an optically pumped secondary light source. The secondary light emitter is bonded to the primary light source LED and as a result, part of the emitted blue light is absorbed is by the secondary light source and re-emitted (or recycled) as yellow light. Because the two colors are complementary, the human observer perceives the light emitted by the PRSD-LED as white light. The emission spectrum with AlGaInP as the secondary source, is shown in Fig. 1.4. Because of the narrow bandwidth, the two color mixing scheme, primary and complementary, may prove to be difficult in achieving a high color rendering index.

The maximum theoretical white-light efficacies for PRS-LEDs using a blue InGaAsN LED wafer bonded to a sapphire substrate and a photon recycling wafer (AlGaInP) is about 300 lm/W.[5.2] However, to date, PRS-LEDs have produced about 10 lm/W white light.[5.2] Because a theoretical maximum efficacy of 300 lm/W greatly exceeds current values of today's commercial LEDs. Further research into these kinds of devices is highly recommended.

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6 Technology Roadmaps

Roadmaps

One of the key deliverables from the workshop is a set of "consensus" roadmaps for the three emerging application areas of interest; nitrides, phosphides, and phosphors. For the workshop, there were four basic questions posed to the participants:

1. How to achieve higher efficiency?
2. How to reduce cost?
3. What major R&D activities must be funded in Industry?
4. What research should be in Academia? in National Laboratories?

A series of breakout sessions were held to develop an industry consensus on the issues and challenges for the successful realization of LED based SSL

Breakout Sessions: An integral and important part of the workshop were the breakout sessions. This is the place where consensus was reached on major issues which are to be included in the recommendations. A recognized expert chaired each breakout session. Three breakout sessions in lamp technologies; namely nitrides, phosphides, and phosphors, supplemented by three additional breakout groups dealing with technology issues applicable to all three lamp technologies.

The following Sections describe illumination strategies and core technologies followed by roadmaps for the three lamp technologies incorporating the appropriate core technologies.

Strategies for Solid State Lighting for General Illumination

There were three viable options identified for achieving LED-based SSL white lighting.

I. Blue LED with phosphor(s)

II. UV LED with several phosphors

III. Three or more different LEDs.

The ultimate requirement of 200 lm/W will be most readily reached by option III. This option, however, poses many challenges and will be probably the last to reach commercial applications. Various issues of lifetime, stability, photon extraction, etc., are common to all SSL white light strategies and will require cooperative research programs between Industry, Universities and or National laboratories to solve these problems. Another issue involves increasing the wall-plug-efficiencies for all LEDs. The following sections outlines the pros and cons of each of the above three options.

I. Blue Led With Phosphor(s): At the present time, the blue LED plus phosphor strategy has the shortest time line for completion. Companies such as Nichia, CREE, and others, already have demonstrated "white-light" generation by using a blue LED and a single phosphor (Ce^{3+}:YAG). Part of the blue light emitted by the LED is transmitted through the phosphor while the rest is converted by the phosphor to an amber color. The amber colored light is the complimentary color of the blue light emitted by the LED, thereby producing white light. There are two principal problems with this approach,

- Poor color uniformity and
- The low level of absorption of blue light by existing phosphor.

Color uniformity: The color non-uniformity occurs because the light from the blue LED is directional while the amber light from the phosphor radiates over a 2p solid angle. Thus, the color uniformity of a white surface illuminated by these LEDs tends to be poor. Improved designs for packaging the LED with the phosphor will need to be developed to eliminate this problem.

Low light absorption by phosphor: The second problem is the limited absorption of the blue light by the phosphor. For rare earth phosphors, the absorption in the blue is weak, requiring thick phosphors. Long term research is necessary to identify new phosphors with strong absorption in the blue wavelength region (450 to 480 nm) emitted by the LED.

The blue LED approach is not limited to only one phosphor, it may be used with a two- component phosphor system (e.g. green and red) to generate high-quality white light and this also has been demonstrated experimentally. Improving existing red and green phosphors or identifying new ones will be important to optimize quantum efficiency and stability with temperature.

As mentioned in Sections 2 and 6 of this report, Professor Fred Schubert at Boston University used the semiconductor alloy AlInGaP as a phosphor. A similar approach might be employed using quantum-dot nanoclusters or organics. Much work is required before high-efficiency, high color-rendering white light will be achieved with this approach.

A conclusion voiced at the workshop is that the blue LED plus single phosphor strategy is a good place to start public demonstrations showing the utility of solid state white lighting. At a later date, other strategies might replace or surpass this technique because of the limitations of achieving a good color rendering index from using only two colors. Furthermore, when today's phosphor conversion efficiencies are taken into account, in order to demonstrate 200 lm/W of white light, the blue LED has to generate light with power conversion efficiency in excess of 60%. This target of external quantum efficiency exceeds the highest efficiency of visible LEDs reported to date (45% at 610 nm).

II. UV LED Plus Three Or More Phosphors: This option uses output from a UV LED to pump several phosphors to simultaneously generate multiple colors. High color rendering indices, similar to standard fluorescent lamps, can be realized. Also, the fact that the UV light is not used directly (as the blue light used is in the previous approach) will further demand that the UV-emitter efficiency be higher to account for conversion losses. In order to achieve 200 lm/W white light, a power conversion efficiency of over 70% might be required for the UV LED.

Currently, efficient emitters have been demonstrated in the 400 nm regime. In fact the highest-reported efficiency in an InGaN-based emitter is a power conversion efficiency of 21% and was reported at the SSL-LED Workshop by CREE for a ~400 nm LED. But clearly, the challenge to increase this to the 60-70% level is a formidable one. Also, the same issues regarding absorption efficiencies by the three phosphors that were raised above for the single blue LED plus phosphor strategy also apply here. All components of the UV-pumped phosphor system must have high UV absorption, high quantum efficiency, and also, good photo- and temperature-stability. New phosphors must be identified in the red, green and especially in the blue wavelength regimes which satisfy these requirements. In spite of these challenges, the current Lm/W performance of UV/phosphor based white LEDs is already comparable to blue/Ce:YAG white LEDs available today.

III. Three or More LEDs of Different Colors: In the long term, this option may be the preferred method for producing high quality white light for general illumination. First, the more colors one has to mix, the more control one has in producing white light with a high color rendering index. Secondly, photons from each LED contribute directly to the white light intensity, i.e. no photon conversion efficiencies have to be considered. Thirdly, by changing the relative intensity of the different color LEDs it is relatively easy to change the color and hue of this light source for different applications.

However, the separate colors from the individual components must be mixed appropriately to achieve uniform white light. Considerable further effort is required for the multi-chip solution to achieve 200 lm/W white light. While phosphor conversion is not required, the combined multi-chip emitter must still operate at a power conversion efficiency of approximately 50%. This level is a minimum requirement when taking into account color mixing losses.

Furthermore, because the three or more different color components have different voltage requirements, different degradation characteristics and different temperature dependencies, a sophisticated control system might be required. The first step, however, is to achieve 50% conversion efficiency at red, green, yellow and blue colors. This is a formidable task and hence it is difficult to tell when the multi-chip white light sources will reach commercial implementation.

Despite these challenges multicolor sources may offer the greatest brightness, the most versatile color control and the greatest ease of integration with control electronics to produce versatile, smart lights. Hence the exploration of such light sources should be part of the long term research program on LED based solid-state lighting.

Summary of Recommendations from LED Solid State Lighting Workshop

Long Term Research Issues

This section presents the consensus opinion for long-term research, packaging and scale- up issues. Because time lines are difficult to establish for exploratory research a brief description is provided for each subject.

(1) Materials Research and the Physics of Light Generation

A major goal for long term solid state lighting research is to gain a better fundamental understanding of light generation mechanisms. It was felt that a better understanding of the mechanisms for light generation, carrier recombination, and material/device degradation is required in the existing materials and devices.

Long term research should focus on the development of new experimental techniques, complete characterization of materials and devices, detailed first principles modeling, and the development of new semiconductor materials and device structures. This research should include the investigation of improved electrical confinement structures such as quantum dots and bandgap engineered structures. It should cover work on understanding the problems with defects, p-type doping, contacts, and high indium and aluminum incorporation in InGaN and AlGaInN to make more efficient green LEDs and carrier confinement in phosphide-based LEDs to improve the efficiency of red LEDs.

During the first year an extensive analysis of existing materials should be carried out to catalogue the fundamental properties of current LED material systems. This work is required to generate data needed for optical and electrical modeling of device performance and will serve to provide benchmarks by which new materials and/or device designs may be evaluated. On the three year time frame the optimized materials as well as new materials should be incorporated into optimized structures as determined by experiments coupled to advanced modeling. The fifth year should culminate with the introduction of devices with improved efficiencies.

(2) Substrate materials

Currently there are at least three different substrate materials used to produce GaN-based LEDs, sapphire and SiC. Each material system has its pros and cons but neither system provides a large area defect free substrate with good lattice match at a reasonable cost. Another possible contender, a bulk GaN substrate, is currently under development. If produced with low defect density and reasonable diameter (>50 mm), such a substrate could offer a major improvement in the performance of GaN based LEDs. For AlInGaP based LEDs, the development of transparent substrates suitable for epitaxy growth (epi-ready substrates) will have a significant impact on LED reliability and cost. A major effort is required to develop such ideal substrates.

(3) Reactor Design

The next area centers on epitaxial reactor development (these reactor systems deposit thin semiconductor films on the substrate and the resulting wafers are processed into LED chips). For GaN materials, the current reactors are not very efficient, reliable and the results are not always reproducible. We need to gain a better understanding of the fundamental chemical reactions particularly for the growth of nitride materials to enable the design of better growth systems or new reactors. It is important to keep in mind that the largest fraction of the GaN LED cost (>80%) is determined by the wafer cost, so efficient, high throughput reactor systems will be required for hitting LED performance targets at a reasonable cost per lumen.

Current reactors are primarily variants of the existing equipment used for the production of GaAs based devices. It was felt that the design of highly efficient, reliable, and robust reactors for the commercial production of GaN based devices can only be achieved after more is understood about the complex gas phase chemical reactions which complicate the growth of GaN. A more complete description of the chemistry during the growth of GaN coupled to a complete fluid dynamics simulation should enable the design of more efficient and robust reactors.

For the nitride systems, it is imperative that fundamental chemical and fluid flow studies be funded over a five-year period. This time frame is necessary in order to develop a sufficient understanding of the chemistry of gas-phase precursors, the role of impurities, the chemistry of dopant precursors, and the effect of pressure on fluid dynamics. The chemical reactions and fluid dynamics will also need to be coupled to gain a more complete understanding of the proposed reactor designs. This knowledge will provide a sound basis for rational design and scale up of nitride CVD reactors that are efficient, reliable, and reproducible.

(4) Light Extraction

The group felt a need to focus on light extraction. Due to the high refractive index of the LED material a large fraction of the generated light is trapped inside the LED structure. Research to overcome this might include developing transparent substrates, reflective contacts, photonic bandgap structures, shaped die or other novel concepts such as new substrates and novel device architectures. It was felt that the development of first principles modeling for light extraction as well as complete lighting systems should also be investigated. Advanced fabrication technology for the economical creation of novel LED die shapes will also need to be developed.

The development of modeling capabilities and the identification of new methods for light extraction should be explored in the first year. Extensive computer modeling as well as experimentation should be carried out in the first three years to identify efficient means of light extraction from existing devices as well as novel device ideas. Use of these new or existing techniques/device structures in system demonstrations should be achieved in the five year time frame.

(5) **Photon Conversion Materials**

Another category discussed at the workshop dealt with the development of photon conversion materials and structures. This included the development of phosphors that would convert radiation in the 370 - 470 nm range to visible light. Investigations of the compatibility of the phosphors with LED operating conditions should also be explored. Novel semiconductors and other new wavelength conversion materials such as nanoclusters and organic materials should also be investigated. The development of encapsulants that are insensitive to radiation in this region is also necessary for the production of long lived LEDs.

The first year should be spent evaluating the conversion efficiencies and stability of existing phosphors and other photon converting materials such as nanoclusters at certain wavelengths. The demonstration of highly efficient photon conversion schemes using either new or existing materials/novel concepts should be achieved in the three to five year time frame.

(6) **Novel Concepts of Solid State Light Emission**

This area of investigation centers on the development of solid state light emission to expand devices beyond light emitting diodes. This might include areas such as novel device structures, VCSELs, super luminescent diodes, edge emitters, and other novel concepts such as quantum dots, photonic lattices, etc.

New concepts of light emission should be identified in the first year. The next two years should focus on demonstrating these concepts and picking the best ones to proceed with in the next two years. Highly efficient devices should be fabricated in the five-year time frame.

(7) **Packaging**

Packaging has an enormous impact on the efficiency, life and cost of LED devices. New packaging concepts must be explored to significantly improve thermal management, increase light extraction from the LED to the illuminated surface to provide color mixing, to incorporate control circuits and to assure long operating life. In addition to lm/W targets, total lumens from LED illumination sources will be important so packages handling large or multiple dies at high drive current with good thermal management will be critical. Thermal management is especially important for multiple color LED illumination strategies as the temperature sensitivities of GaN based and AlInGaP based LEDs are significantly different.

An additional role of the package will be to provide advanced optical design for good color mixing and efficient light extraction. This will include optimizing the optical design for efficient light distribution. Ideally, advanced packaging designs for LEDs will be integrated to innovative illumination technologies tailored for LED lighting-based characteristics and advantages of reliability and energy efficiency.

The breakout group also iterated the importance following topics:

Multiple or Single Devices: Depending on the scheme for white light generation, i.e., single LED (blue or UV) plus phosphor(s) or multi-chip LEDs, the packaging issues must address:

- The size and geometry of the Dies,
- Single or multiple lenses,
- Mounting of substrates if differing materials are employed, etc.

Die Issues: The Die issues concern the area of chip processing. Also, die characterization and testing remain to be a challenge. For example, what is the definition of a "good" die in order for comparisons to be made.

Encapsulates: The whole area of encapsulates must be studied in detail because of the extreme range of LED wavelengths that may or may not be present in single and multi- chip LEDs. These wavelengths can range from the UV (~400 nm) to red (~610 nm). The encapsulant of choice has to survive the effects of wavelength as well as high output power induced temperature effects and possible encapsulant degradation. The bonding of the various LED chips to the common Die also have to survive the same environment that the encapsulating materials used to form the lens, etc., of the LED. In multi-chip LED geometries, individual LED lamps may be envisioned as one solution to the wide wavelength range of the output spectrum, but in itself, this concept introduces a different set of problems such as the "halo" effect or the differing beam divergences of the blue, green, and red LEDs which can effect the viewing or illumination angle from these devices.

Module Packaging: Discrete versus integrated circuits, axial versus surface mounted leads have to be considered before the final design of the LED package can be formulated.

Circuitry and Electronics: There are many issues regarding the LED drive electronics, LED addressing, and also issues about the use of "On board" controllers for multi-chip LED systems. Before any commercial production of white-light generating LEDs can be implemented, circuit and electronic designs must be stable and be able to be produced at low costs.

Thus if a low cost replacement for present day fluorescent or incandescent lights is to be realized, the packaging issues, of which a few were outlined above, represent barriers.

(8) Lighting Infrastructure:

It should be noted that light bulbs represent only one third of the $40 Billion lighting market. A larger segment of the market involves powering, fixtures, light distribution, etc. A separate efforts is needed at developing building and lighting architectures that could, at a system level, exploit the unique characteristics of solid state lighting while still appealing at a consumer level to human ergonomics. Many of these efforts are already ongoing (e.g., the RPI lighting institute, Lawrence

Berkeley's Lighting Research Center, and other efforts connected to the U.S. Department of Energy's Office of Building Technology, State and Community Programs), and should be expanded to include broader industry participation in a forward-looking R&D on solid state lighting.

Roadmap for Nitrides, Phosphides, and Phosphors

A summary is presented in table format for the three important SSL-LED lamp technologies: Nitrides, Phosphides, and Phosphors. For each topic, specific tasks are broken out along with their potential advantages in each of the tables.

Nitride-based LEDs: Progress in the growth for the AlGaInN semiconductor material has made rapid gains in the last decade. The substrate issue still proves to be the major stumbling block for the growth of defect free materials. In spite of the large lattice mismatch between sapphire and GaN, remarkable results have been reported. The critical challenges to face for AlGaInN with respect to solid-state lighting are in several main areas:

- Defect free substrates suitable for producing large areas GaN-based LEDs
- Inexpensive methods for high-extraction efficiency
- Control of degradation mechanisms under high-current, high-temperature operation.
- Increased quantum efficiency at longer wavelengths, especially red.
- Cost effective color mixing and packaging technology.

NITRIDE MAJOR GOALS & MILESTONES

TOPIC	FOCUS/IMPACT	1 YR	3 YR	5 YR
Substrates	Cost, Manufacturability	2″ GaN	3″- 4″ SiC and sapphire	6″ SiC and sapphire, 4″ GaN
LEO Substrates	Alternative approach to defect reduction	LEO substrates, silicon stress control, lift-off technologies	Commercial source of alternative substrate	6″ Commercial sources
Large Area Bulk Substrates	Defect Free LEDs with improved performance and long term reliability.	2″ Homoepitaxial substrates @ twice the price performance of standard SiC/Sapphire	3″ Homoepitaxial substrates @ twice the price performance of standard SiC/Sapphire	4″ Homoepitaxial substrates @ twice the price performance of standard SiC/Sapphire
Low costs methods for improved light extraction efficiency.	Improved $/lm of white LEDs.	$100/klm	$50/klm	$20/klm
Increased external quantum efficiency	Fundamental under standings of GaN device and materials physics.	30lm/watt	60lm/watt	120lm/watt
Lifetime and lumen maintenance.	GaN material defects and device degrada tion mechanism.	10k hours	50k hours	100k hours
Color Mixing and High Power Packaging.	UV, Near UV and low wavelength phosphor down con version media & novel packaging techniques.	CRI 60 100 lumens	CRI 80 300 lumens	CRI 90 1000 lumens
Reactor Issues	Understand fundamentals of fluid sta bility, pressure and precursor chemistry	Establish research programs aimed at novel design of nitride CVD reactors	Develop system-level design tools for opti mal nitride reactor design and active control	Commercial nitride reactors adapted to unique chemistry of nitride systems
In Situ Monitors	Process control and yield	Establish programs for in situ measure ment of growth rate, wafer temperature, and doping	Pyrometer system adapted to 500-1200 C on transparent sub strates.	Growth rate control to < 1%, temperature to 1x, doping to x2
Yellow LED's	Alternative to phosphides	Investigate injection dependent wave length shifts. Examine blue/UV to yellow conversion schemes	Demonstrate stable LED operation	Stable, yellow AlGaInN LED
Light extraction	Maximize wall-plug efficiency	Establish research programs in novel extraction methods such as flip-chip bot tom emitting or novel microstructures	> 20% efficient nitride LED	> 50% efficient nitride LED

Phosphide-based LEDs: The AlGaInP material system is now relatively well understood. The reduction of internal quantum efficiency with increased aluminum composition has been studied and the dominant mechanisms identified through measurements of carrier leakage and of locations of indirect minima. The significant gains were made through improved extraction efficiency. The critical challenges for AlGaInP with respect to solid-state lighting are in four main areas:

- Band structure re-engineering for improved carrier confinement and radiative efficiency (minima) to improve internal quantum efficiency and temperature-dependence
- Inexpensive methods for high-extraction efficiency.
- Control of degradation mechanisms under high-current, high-temperature operation.
- Development of a bright yellow light source.

PHOSPHIDE MAJOR GOALS & MILESTONES

TOPIC	FOCUS /IMPACT	1 YR	3 YR	5 YR
Substrates	New lattice constant and strain engineering for band structure with higher η_{int} and improved temperature dependence	- Identify suitable new substrates - Model new band structures (including strain)	- Focus on select few substrates - Demonstrate 600nm LED with improved temperature dependence	- Demonstrate 600 nm LED with improved hint (>90%) and T-dependence (ΔEL < 20% at 100⁄C)
	Inexpensive, epi-ready transparent substrates (TS) for high extraction efficiency	- Identify suitable substrates	- Focus on select few substrates - Demonstrate first TS LEDs	Demonstrate TS LEDs without penalty to ηint - Demonstrate TS LEDs on 4" substrates
Degradation	Understand fundamental causes of light out put degradation vs. current density and junction temperature	- Survey and list poten tial causes of degrada tion	- Degradation experiments and materials characterization to rank dominant causes of failure	- Implement solutions to dominant problems - Demonstrate LED with less than 5% deg- radation at 10,000 hrs (200 A/cm2 and Tj = 130⁄C)
Active Region Design	Improve ηint and T- dependence by providing new active region material	- InGaP quantum (QD) dot active regions - III-N, P, As mixed alloys for red emission - wafer-bonded (or mixed epi) heterostructures for improved carrier confinement	- Fabricate and characterize LEDs with QD active regions - Fabricate and characterize LEDs with mixed-alloy active regions - Fabricate and characterize LEDs with hetero epi (e.g. II-VI) or bonded layers	Demonstrate QD LEDs with improved η_{int} and T-dependence Demonstrate mixed alloy LEDs with improved η_{int} and T- dependence - Demonstrate hetero epi/bonded LEDs with improved η_{int} and T- dependence GOAL: η_{int} > 90% and T-dependence DEL < 20% at 100⁄C
Photonic Bandgap (PB) Structures	Improved radiative emission rate for improved η_{int} and T- dependence; also improved extraction	- Modeling to determine practical structure - Identify manufacturable process and fabricate first PB structures	- Demonstrate LED with improved quantum efficiency - Quantify effects on radiative emission rate and extraction efficiency	- Optimize PB structure and demonstrate LEDs with η_{int} > 90% and extraction efficiency > 60%
Reactor Issues	Reduced LED cost through improved yields	- Identify necessary set of In Situ monitor tools	- Demonstrate processes for improved uniformity in thickness, doping, and wavelength	- Scale to larger substrate diameters (4" and above)
Chip Shaping	High extraction efficiency	- Modeling & design for extraction efficiencies > 60%	- Demonstrate > 50% extraction with minimal die cost increase	- Demonstrate > 60% extraction with minimal die cost increase

Phosphors and Wavelength Converters: Wavelength converters include traditional powder phosphors, semiconductor crystals and organic semiconductors. They are an integral and important component for SSL lighting. Because so much work has taken place in developing phosphors suitable for flourescent lighting over many years, the natural starting point is to adapt existing phosphors to be pumped by solid state sources such as LEDs. The next step is to identify new phosphors optimized for LED wavelengths and other luminescent materials. The critical challenges to faced for wavelength converters with respect to solid-state lighting are in three main areas:

1. Improving the absorption of the LED light (blue or UV) by the various phosphors.

2. Achieve > 90% internal quantum efficiency in blue, green, and red phosphors (or other luminescent materials)

3. Control of degradation mechanisms under high-current, high-temperature operation.

PHOSPHOR MAJOR GOALS & MILESTONES

TOPIC	FOCUS / IMPACT	1 YR	3 YR	5 YR
New inorganic phosphors for near UV (360-410nm) and blue (>410nm)	UV flux and temperature. Potentially includes existing phosphors with new sensitizers	- Survey/search for RGB materials. - Define candidates.	- Screen candidates - Optimize RGB phosphors.	- QE (90%+) absorption (95%+). - White blends of these materials for various illumination markets.
Quantum dots & nanoclusters	Materials must be robust, of high QE and tunable with size.	- Determine feasibility	- Screen candidates. - Optimize RGB phosphors. - Demonstrate first TS LEDs	- As above. - Resolve deposition technique.
New organic phosphors: near UV (360-410nm) and blue (>410nm	Materials must be robust; no decomposition under UV, moderate tempera ture (150C)	- Survey and list potential causes of degradation	- Screen candidates. - Optimize RGB phosphors.	- RGB materials available with high QE (90%+), absorption (95%+). - White blends of these materials.
Integrated approaches (e.g. doped GaN)	Conversion close to source. New GaN activators	- Determine feasibility - Exploratory research for concept.	- Demonstrate proof of concept	- Demonstrate 120 lm/W white light chip
Phosphor application techniques	High conversion and extraction efficiency. Manufacturable technique. Inexpensive, amenable to multichips.	- Develop optical and thermal models. 50% extraction	- 70%	- 90%

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Appendix A: Characteristics and Performance of III-V & Other LEDs

Material System	Color of Emission	Peak l (nm)	Band Gap Type	Structure[a]	External Quantum Efficiency (%)	Luminous Efficacy (lm/W)
$GaAs_{0.6}P_{0.4}$	Deep Red	650	Direct	HJ	0.2	0.15
$N{:}GaAs_{0.35}P_{0.65}$	Red	630	Indirect	HJ	0.7	1
$N{:}GaAs_{0.14}P_{0.86}$	Yellow	585	Indirect	HJ	0.2	1
GaP	Green	555	Indirect	HJ	0.1	0.6
N:GaP	Yellow-Green	565	Indirect	HJ	0.4	2.5
Zn,O:GaP	Deep Red	700	Indirect	HJ	2	0.4
AlGaAs	Red	650	Direct	SH	4	2
	″″		″	DH	8	4
	″″		″	DH-TS	16	8
AlGaInP	Red	636	Direct	DH-TS	24	35.5
	Red	632	″	MQW-TS	32	73.7
	Orange-Red	620	″	DH	6	20
	Orange	610	″	TIP-MQW-TS	~30	102.0 (100mA)
	Orange	607	″	DH-TS	-	50.3
	Orange	598	″	TIP-MQW-TS	~35	6 (100mA)
	Amber	590	″	DH-TS	10	40
	Yellow	585	″	DH	5	20
	Yellow-Green	570	″	DH-TS	2	14
	Green	525	″	SQW-TS	6.3	18
	Blue	450	″	SQW-TS	9.1	2
SiC	Blue	470	Indirect	HJ	0.02	0.04
InGaN	Green	570	Direct	DH-TS	2	14
	Green	520	″	SQW-TS	11.6	30
	Blue	450	″	?	11.2	5
	UV	371	″	?	7.5	NA
Zn,Si:InGaN	Green	517	Direct	DH-TS	2.6	6.5
	Blue	450	″	DH-TS	5.5	50
ZnTeSe	Green	512	Direct	SQW	5.3 (10mA)	17 (10mA)
ZnCdSe	Blue	489	Direct	MQW	1.3 (10mA)	1.6(10mA)

Appendix B. LED Solid State Lighting Workshop Agenda

Thursday, October 26

8:00 Continental Breakfast and Registration

8:30 Welcome - Arpad Bergh, OIDA, Al Romig, Sandia National Labs

8:50 Greetings from Alliance to Save Energy Senator Bingaman (NM) or Staffer

9:05 DOE Perspective/Energy Saving Potential - Ed Petrow, U.S. Dept. of Energy

9:25 Logistics of Workshop Fred Welsh, OIDA Applications and Markets

9:40 Conventional Light Sources Lighting Requirements, Steve Johnson, LBNL

10:00 Advantages of SSL; Critical Issues & Time Scale for Success
Roland Haitz, Agilent

10:20 Solid State White Light Architectures : Quality of White Light -
Mike Pashley, Philips

10:40 Break GaInAlP

11:10 EPI Fabrication and Packaging Gloria Hofler, LumiLeds

11:30 Future Challenges / Breakthrough Technologies

An Industry Perspective Frank Sternaka, LumiLeds

11:50 Lunch GaInN

1:00 Growing on Different Substrates (SiC, GaN, Sapphire) Tim Anderson,
Univ. Florida

1:20 EPI and Fabrication Steve DenBaars, CREE

1:40 Device Design and Packaging Bob Karlicek, GELcore

2:00 Future Challenges / Breakthrough Technologies

An Industry Perspective Ian Ferguson, EMCORE

A University Perspective Fred Schubert, Boston University

2:40 Introduction to Breakout Sessions Fred Welsh, OIDA

3:00 Break

3:20 Breakout Session

Group I Phosphides, Mike Krames, LumiLeds

Group II Nitrides, Mike Dunn, CREE

Group III Long Term Research Issues, Bob Biefeld, SNL

4:45 Breakout Group Reports

5:30 Adjourn

6:00 Reception

Friday, October 27

8:00	Continental Breakfast
8:30	Phosphors Wavelength Conversion Technologies Mike Krames, LumiLeds
	Phosphors Technology Dan Doxee, GELcore
9:10	Performance Goals and Recommendations Performance & Cost Goals for
	Solid State Light Sources Mike Dunn, CREE
	SSL Government-Industry Initiatives Outside the US Arpad Bergh, OIDA
9:50	Framework for National
	Industry-Government Initiatives Ed Petrow, DOE
	IP Issues Joseph Paladino, U.S. Dept. of Energy
	Planning Process Doug Brookman, Public Solutions Inc.
10:10	Break
10:30	Breakout Session
	Group I Phosphors,Dan Doxsee, GELcore
	Group II Packaging,Bill Kennedy, Uniroyal
	Group III Scale up and Automation, Bill Breiland, SNL
12:00	Lunch
1:00	Breakout Group Report
1:30	General Discussion and Conclusions
2:00	Tour of Sandia National Laboratories

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