SANDIA REPORT

SAND2006-4360

Unlimited Release

Printed August 2006

SOLID-STATE LIGHTING TECHNOLOGY PERSPECTIVE

Michael E. Coltrin, Jeffrey Y. Tsao

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.osti.gov/bridge>

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>

SAND2006-4360
Unlimited Release
Printed August 2006

Solid-State Lighting Technology Perspective

Michael E. Coltrin
Advanced Materials Sciences Department

Jeffrey Y. Tsao
Energy Sciences Department

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1086

Abstract

Solid-State Lighting (SSL) uses inorganic light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs) to convert electricity into light for illumination. SSL has the potential for enormous energy savings and accompanying environmental benefits if its promise of 50% (or greater) energy efficiencies can be achieved. This report provides a broad summary of the technologies that underlie SSL. The applications for SSL and potential impact on U.S. and world-wide energy consumption, and impact on the human visual experience are discussed. The properties of visible light and different technical metrics to characterize its properties are summarized. The many factors contributing to the capital and operating costs for SSL and traditional lighting sources (incandescent, fluorescent, and high-intensity discharge lamps) are discussed, with extrapolations for future SSL goals. The technologies underlying LEDs and OLEDs are also described, including current and possible alternative future technologies and some of the present limitations.

Contents

Contents	5
Introduction to Solid-State Lighting	7
Applications and Potential Impact	8
Applications	8
Impact on Energy Consumption	9
Impact on Human Visual Experience	10
Technology Characteristics	11
Characteristics of Visible Light	11
Cost of Light: Capital and Operating Cost Breakout	14
Cost of Light: Luminous Efficacy and Power Delivery Breakout	16
Luminous Efficacy	17
Power Delivery Cost	19
Inorganic Light-Emitting Diodes (LEDs)	20
White Light Creation Architectures	21
Wavelength Conversion Materials	21
Light Creation Materials	22
Light Extraction Approaches	25
Thermal Management	26
Organic Light-Emitting Diodes	27
White-Light Creation Architectures	27
Carrier Injection and Transport	30
Exciton Dynamics and Light Creation	31
Encapsulation	32
Light Extraction	33
Acknowledgements	33
References	36
Distribution	38

Introduction to Solid-State Lighting

Solid-state lighting (SSL) may completely change the way we generate and use lighting in all aspects of our lives and, in doing so, enable significant savings in national and worldwide energy consumption. Significant advances in semiconductor science were key to enable the computer revolution in the last half of the twentieth century. Analogous advances are essential for SSL to fulfill its promise of unprecedented luminous efficacy combined with real-time digital control of intensity, chromaticity, and spatial placement.

There are many basic research needs and opportunities underlying SSL technologies, which were the subject of an intensive workshop¹ sponsored by the Department of Energy Office of Basic Energy Science in 2006. A broad view of SSL applications and technology provides a useful context for the identification of fundamental scientific challenges that must be understood and overcome, and potential research approaches to address them. This document provides a high-level overview of SSL technology to put the underlying scientific challenges into their broader technology context.

We set the stage with a brief overview of SSL's potential applications, and SSL's potential impact on national/worldwide energy consumption and the human visual experience. There are a number of characteristics of SSL that will be important if SSL is to achieve its potential impact—these characteristics are illustrated in Figure 1. The quantitative metrics that underlie these features are summarized in the following section. The final two sections review the current state-of-the-art of inorganic light-emitting diodes (LEDs) and organic LEDs (OLEDs), as well as their limitations.

Figure 1. Various characteristics of SSL that will likely play important roles in SSL's ultimate impact on national/worldwide energy consumption and the human visual experience.

¹ The workshop "Basic Research Needs for Solid-State Lighting" was held May 22-24, 2006 in Bethesda, MD. This document was originally prepared as an Appendix for the final workshop report.

Applications and Potential Impact

Applications

SSL uses LEDs and OLEDs to convert electricity into light for illumination.² Whereas more than 90% of the power input into a traditional incandescent light bulb is wasted as heat, SSL has potential energy efficiencies of 50% or greater. In addition, SSL can offer ultra-long lamp lifetimes, rugged tolerance to mechanical stress, compactness, directionality, and tunability in its light characteristics (e.g., spectral power distribution, color temperature, temporal modulation).

Applications for high-brightness LEDs and SSL broadly fall into two categories, lighting for indication and for illumination (Figure 2). Indication is the use of a self-luminous source that is to be viewed directly, such as signage. Illumination is the use of light to make other things visible by reflection from those objects, for example, the traditional incandescent light bulb commonly in residential use and fluorescent lighting most often employed in commercial and industrial settings.

Figure 2. Some current and near-term applications using high-brightness LEDs and Solid-State Lighting.

As indicators, high-brightness LEDs have many benefits. This is particularly so for many monochromatic applications, in which LEDs are replacing extremely inefficient filtered incandescent light sources. Some initial applications of monochromatic LEDs for indicators have been (Haitz et al. 1999) traffic lights, safety/emergency lights, outdoor decorative lighting, automobile tail lights, outdoor displays, and backlighting for wide-color-gamut graphic displays. For example, LEDs have four distinct advantages over filtered incandescent sources for traffic signals: higher brightness and directionality, improved daytime visibility; lower operating costs saving up to \$1,000 per intersection per year (derived from Navigant 2003); and an expected seven-year lifetime versus one year for incandescent lamps. A red LED traffic light quickly pays back the initial higher purchase cost (approximately \$75 versus \$3 for an incandescent source) with lower energy usage; the seven-year cost of ownership of a red LED traffic light is approximately one-third the cost of using an incandescent source (Navigant 2003).

² Although this is the normal usage, SSL could more broadly include generation of light from the conversion of non-electrical energy (e.g., chemiluminescence or bioluminescence from chemical reactions).

As illumination sources, solid-state lights face much greater challenges, with an accompanying larger payoff. Replacement of all incandescent and fluorescent light sources with solid-state white lighting could have revolutionary global impact for energy savings and accompanying environmental benefits, as discussed below. However, current white-light LEDs are not yet up to the task. Today, white solid-state lights are mainly in specialized, low-flux applications, such as shelf lighting, stair/aisle lights, accent lights, landscape path lights, and flashlights.

Impact on Energy Consumption

Because of its long-term goal of increasing the efficiency of energy consumption in the U.S., the Department of Energy (DOE) is especially interested in SSL for general-purpose illumination. The Department of Energy-Energy Efficiency and Renewable Energy-Solid-State-Lighting (DOE-EERE SSL) Roadmap (Navigant 2006) goal for white lighting is 50% electrical-to-visible-optical power-conversion system efficiency by 2025. The present day electrical-consumption mix for U.S. lighting is 42% incandescent, 41% fluorescent, and 17% high-intensity discharges (Navigant 2002). This mix yields an aggregate electrical-to-visible-optical-power-conversion efficiency of less than 15% for lighting.

The total energy consumption in the U.S. is about 10,000 Terawatt hours per year (TWh/y). As illustrated in Figure 3, 38% of that energy is consumed as electricity, and of that, 22% is consumed by lighting. So, around 8% of the energy consumption is from lighting (Navigant 2002). Assuming reasonable growth rates, by the year 2025, the U.S. may be consuming as much as 1,000 TWh/y of electricity for lighting. At a price of \$0.07/kWh, that is about \$70B/y. The worldwide trends are similar, with the consumption amounts increased by factors of three to four.

Figure 3. Historical and projected U.S. energy and electricity consumption for all uses and for lighting, with and without SSL; adapted from M. Kendall and M. Scholand, "Energy Savings Potential of SSL in General Lighting Applications" (U. S. DOE-OBT study by Arthur D. Little, 2001, and EIA Statistics).

If SSL, with a system efficiency of 50%, completely displaced current white-lighting technologies, the impact would be enormous. The electricity used for lighting would then be cut by 70% (or 1–15%/50%), and total electrical energy consumption would decrease by more than 14% (or 22% $\times$ 70%). Savings to the consumer in electricity cost would be around \$50B/y (or 70% $\times$ \$70B/y) in 2025, and there would be a savings in electricity production of around 700 TWh/y (or 70% $\times$ 1,000TWh/y), or 80 GW average power.

The savings in energy production by SSL would also be important for its impact on a cleaner environment. Currently, the U.S. generates approximately 10^6 tons of carbon-equivalent emissions to the atmosphere for every 6 TWh of electrical energy consumed. If the U.S. continues to produce its electricity with roughly the same mix of technologies, the 700 TWh/y savings in energy through SSL would be a reduction of about 115 Megatons of carbon-equivalent emissions per year.

Although the DOE-EERE SSL Roadmap goal of 50% system energy efficiency is aggressive and will be challenging, there is no known fundamental physical (e.g., thermodynamic) constraint to cap the efficiency even at this value. If near 100% power-conversion efficiency could be achieved, the economic and environmental benefits above would be even greater.

Impact on Human Visual Experience

SSL could enhance in many fundamental ways the human visual “experience” with lighting, and thereby enhance human functionality, safety, and comfort. Potential improvements in the quality of white light include steady color output at all levels of illumination, the ability to continuously vary output color temperature, simplified and flexible design for mounting fixtures (including the elimination of lossy luminaires and diffusers), low voltage, and safe power distribution.

A host of novel applications could also be enabled by SSL, for example (Schubert 2005):

- The ability to create large-area, diffuse lighting or, perhaps, weaving strands of light-emitting material into fabrics using OLED technology open up new architectural possibilities for room designs and clothing.
- New interior design concepts are possible, such as integration with distributed color/intensity sensors for optimization of an entire lighting space.
- Lighting could be “personalized” in real time according to the preferences of an individual entering a room; for example, tuning of color preferences might be important for an aging population.
- Lighting could also be tailored to emphasize those features of the environment that are more desirable to notice at a given time.
- Mood enhancement may be possible by programming interior lights to change room color temperature throughout the day, corresponding to outdoor circadian cycles.

- Lighting could also be tailored for photopic versus scotopic (i.e., normal lighting vs. low-lighting) conditions.

Technology Characteristics

Characteristics of Visible Light

The visible light produced from all sources, including solid-state, can be characterized by various quantitative metrics. This section summarizes those most relevant to SSL .

The *Spectral Power Distribution* (SPD), $P(\lambda)$, is the radiant power emitted by a source at each wavelength or band of wavelengths over the entire spectrum (e.g., in units of W/nm). The SPD provides a complete description of the spectral properties of a light source.

The color of a light source can be described by the Commission Internationale de l'Éclairage (CIE) chromaticity coordinates, calculated as follows. Figure 4a displays the three *Color-Matching Functions*, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$, which define the “1931 CIE Standard Observer.” The function $\bar{y}(\lambda)$ was defined to be identical to the photopic luminous efficiency function, V_λ , which describes the brightness perceived by the human eye of light of a particular wavelength under day-brightness conditions (the scotopic luminous efficiency function, which we do not discuss here, is the perceived brightness under night-brightness conditions). The other two Color-Matching Functions, $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$, do not have such simple physical interpretations (Fairman, Brill, and Hemmendinger 1997; Brill 1998), but, together with the first, are necessary to determine the color of light, as described next.

Figure 4a. CIE 1931 Color-Matching Functions.

Figure 4b. CIE 1931 (x,y) Chromaticity Diagram.

The *tristimulus values* X , Y , and Z of a light source are defined as

$$X = k \int P(\lambda) \bar{x}(\lambda) d\lambda; Y = k \int P(\lambda) \bar{y}(\lambda) d\lambda; Z = k \int P(\lambda) \bar{z}(\lambda) d\lambda, \quad (1)$$

where k is a proportionality constant. The Y value will be equal to one of the photometric quantities (such as luminous flux) of the light source if $k=K_m$ ($K_m=683 \text{ lm/W}$) is used. The tristimulus values were derived such that $X=Y=Z$ is equal-energy white.

The *chromaticity coordinates* x, y are calculated as $x=X/(X+Y+Z)$ and $y=Y/(X+Y+Z)$. Any color of light can be represented on the CIE 1931 (x, y) chromaticity diagram, which is shown in Figure 4b. The chromaticity diagram is a guitar-pick-shaped 2-D plot of all possible hue and saturation values of a light source, independent of luminance. The perimeter of the guitar pick is the locus of chromaticity coordinates for the spectral colors (i.e., monochromatic light, wavelengths in nm).

The black arc plotted in the interior of the chromaticity diagram gives the chromaticity coordinates of emission from a blackbody at temperatures between 1000 K and infinity. It is called the Planckian locus and is a convenient way of representing a white light source. Positions along the Planckian locus can be specified by the temperature of the blackbody, called the *color temperature*, thereby reducing the hundreds of numbers in a SPD, or the two numbers of chromaticity coordinate, to a single number.

A non-blackbody source is often described by the *correlated color temperature* (CCT), which is the temperature of a blackbody radiator that most closely resembles the color from a source of equal brightness. Lines of a specified (constant) CCT would cross the Planckian locus at coordinates of that blackbody temperature, as indicated in Figure 4b.

The terms “warm white” and “cool white” are often used in lighting discussions. “Warm white” is similar to light from an incandescent bulb and is somewhat yellow or red in appearance, whereas “cool white” has more of a pure white (or even blue) tone. Interestingly, “warm white” actually has a lower correlated color temperature (in the range of 2,700 K) than does “cool white” (with a CCT in the range of 4,100 K).

A powerful feature of the chromaticity diagram is that light produced by mixing output from two sources having different chromaticity coordinates will fall on the line connecting the coordinates of the sources alone; the position along the line is determined by the weighted average of the brightness of each source. Similarly, the chromaticity coordinate of light produced by mixing three light sources will fall within the triangle formed by the chromaticity coordinates of the three sources as the vertices. It is important to note that any color falling outside this triangle cannot be produced by mixing the three sources. The complete subset of colors that can be produced by mixing n light sources is referred to as the *color gamut*.

The definition of *luminous efficacy* depends upon whether one is referring to properties of (1) *radiation* (in which it is often more precise to use the term “luminous efficacy of radiation,” [LER]) or of (2) a *source* that emits radiation. Both usages are expressed in lm/W. In the first case, Watts refers to the radiant power content of the radiation; in the second case, it refers to the amount of electrical power input to the radiation source. The second usage is directly related to the effectiveness of a device in converting input electrical power into visible light. Unless stated otherwise, the second usage is meant when discussing SSL and efficacy targets.

Luminous Efficacy of Radiation (LER) is a measure of the amount of radiant power (radiant flux in W) that can be observed by the eye as luminance (luminous flux in lm). The LER is determined by the sensitivity of the eye to different wavelengths of light, (i.e., the photopic luminous efficiency function, $V(\lambda)$) and the spectral power distribution (SPD, or $P(\lambda)$) of the radiation. For monochromatic light of wavelength λ , the LER is simply $K_{rad}(\lambda) = K_m \cdot V(\lambda)$, where K_m is a conversion factor relating radiant power (W) to luminous flux (lm) at the single wavelength (555 nm) at which $V(\lambda)=1$; this factor is 683 lm/W. Thus, the maximum possible luminous efficacy of radiation is, for monochromatic light at 555 nm (green), at the peak of the eye’s responsiveness, 683 lm/W. For radiation with a distribution of wavelengths, the LER K_{rad} is found by integrating the product of the radiation’s SPD, $P(\lambda)$, and the photopic luminous efficiency function, $V(\lambda)$, over all wavelengths, and normalizing by the total amount of radiant power:

$$K_{rad} = K_m \frac{\int P(\lambda)V(\lambda)d\lambda}{\int P(\lambda)d\lambda}. \quad (2)$$

The *Luminous Efficacy of a Source* is a measure of the amount of radiant power emitted by a source that can be observed by the eye as luminous flux divided by the electrical power that is input into the source (W_{in}), normalized by the same constant K_m used above. Thus, the luminous efficacy of a source, such as an LED or OLED, is given by

$$K = K_m \frac{\int P(\lambda)V(\lambda)d\lambda}{W_{in}}. \quad (3)$$

Manipulating the two formulas above, it is easy to see that the luminous efficacy of a source K is just the LER multiplied by the “wall-plug efficiency” (WPE), where

$$\text{WPE} = \frac{\int P(\lambda)d\lambda}{W_{in}}. \quad (4)$$

The *Color Rendering Index* (CRI) is a metric for color quality. It takes a subjective measure and attempts to quantify it. The CRI gauges how colors of certain standard reference objects appear when illuminated by a test light source, compared to the colors observed under illumination by a reference light source of the same correlated color temperature; if there were no difference between the colors rendered by the reference and test light sources, the test source would have a CRI of 100. Light from a standard incandescent light bulb has a CRI near 100. CRI is calculated from the SPD of the test light source. To evaluate the CRI of real light sources, the SPD must be measured, although today mathematical models exist to simulate the SPDs of various white LEDs (Ohno 2004).

Recently, there has been some discussion about the adequacy of the current CRI scale. One problem is that it is based on an obsolete color space (the 1964 W*U*V* color space), which is no longer recommended for use. Another problem is that it is based on eight reference samples of low to moderate color saturation. On the one hand, this causes some Red Green Blue (RGB) LEDs to have high CRI scores even though they render some poorly saturated colors. On the other hand, RGB white LEDs tend to enhance color contrast, which is generally preferred and can be an important feature of SSL, but is currently penalized by the present CRI system (Ohno 2004). To solve these problems, new metrics are being proposed (e.g., see Davis and Ohno 2005). Since color quality is very important for acceptance of SSL products in the marketplace, these problems need to be studied further with visual experiments. The CIE Technical Committee 1-62 "Colour Rendering of White LED Light Sources" is investigating problems with the CRI scale, with a plan for developing a new metric.

Cost of Light: Capital and Operating Cost Breakout

The Cost of Light (COL) is the total cost of ownership for an SSL LED, i.e., the sum of the purchase, maintenance, and operating costs over its entire lifetime. The commonly accepted formula for calculating the COL is (IESNA 2000; Navigant 2006):

$$CostofLight = \left(\frac{1}{LampLumens} \right) \left(\frac{LampCost + LaborCost}{Lifetime} + EnergyUse \times EnergyCost \right), (5)$$

where *CostofLight* is the total cost of the light over its operational lifetime (in \$/10⁶ lmh); *LampLumens* is the light output of the lamp (in 1000 lumens); *LampCost* is the initial cost of the lamp (in \$); *LaborCost* is the labor cost to replace the lamp (in \$); *Lifetime* is the useful life of the lamp (in 1000 h); *EnergyUse* is the power consumption of the lamp (in W); and *EnergyCost* is the cost of electricity (in \$/kWh). For SSL, the useful lifetime of the lamp is often measured at 70% lumen maintenance; the labor cost is typically taken to be \$1 for a 1 klm lamp, which is used in our analysis.

In the formula above, the first term in the second set of parentheses determines the Capital Cost, and the second term determines the Operating Cost; the sum of the two determines the Cost of Light.

The COL for different white-lighting technologies is displayed in Figure 5; cost is plotted in units of dollars per million lumen hours. The three solid curves represent contours of constant COL. In Figure 5, the triangle, square, and diamond symbols represent the highest market-value incandescent, fluorescent, and high-intensity discharge (HID) lamps, respectively.³

Figure 5. Factors contributing to SSL total cost of light. The SSL data in this and subsequent figures are gathered in Table 1.

Of the three traditional lighting technologies, incandescent has the highest COL, because of low luminous efficacy (high operating cost). As it develops, if SSL follows trends of traditional lighting, one might expect the COL to fall along, or below, the trend (black line in Figure 5) that capital cost represents about 1/5 of the operating cost. As the cost of energy inevitably increases in the future, the ratio of capital cost to operating cost will decrease for all technologies, including SSL.

The 100% efficient SSL point corresponds to the maximum possible luminous efficacy of 386 lm/W (assuming a red, green, yellow, blue [RGYB] source with a CRI of 85), an operating cost of $\$0.07/\text{kWh}/386 \text{ lm/W} = \$0.18/\text{Mlmh}$, and a capital cost 1/5 this amount.

Three representative SSL white lights are represented in Figure 5. The point labeled “High CRI LED 2006” is a Lumileds LXHL-BW03 “Warm White” emitter. The two points labeled “Low CRI LED 2006” represent Lumileds K2 series emitters driven at 0.35A and 1A (note that, as can be seen in Table 1 at the end of this Appendix, these two LEDs have similar COL—driving the LED “harder” produces more lumens, so the capital

³ Based on published market analysis (Navigant 2002).

cost of the lamp decreases, but the luminous efficacy decreases, so operating cost increases).⁴ The point labeled “WOLED” (for “white OLED”) is taken from the 2002 OLED Roadmap (OIDA 2002), although it should be noted that no WOLEDs are being manufactured for lighting, rendering this point very speculative.

Cost of Light: Luminous Efficacy and Power Delivery Breakout

Another way of characterizing white lighting technologies is displayed in Figure 6, in which the abscissa and ordinate correspond more directly to quantities the technologist can impact.

The first of these quantities is the “power delivery cost.” The power delivery cost is the capital cost to make a lamp that can be driven at a certain power ($\$/kW_{in}$). It reflects the fact that the more power one can supply to a lamp, the greater the light output, but at a higher manufacturing cost (heat sinking the device being one important driver). The second of these quantities is luminous efficacy (lm/W).

Note that these two quantities, together with the lamp lifetime, are sufficient to determine the various components of the COL introduced earlier in Equation 5. $EnergyUse/LampLumens$ is just the reciprocal of luminous efficacy; $LampCost/(LampLumens \times Lifetime)$ is just power delivery cost over luminous efficacy, divided by the lamp lifetime.

Figure 6. Relationship between luminous efficacy and power delivery cost for different lighting technologies.

⁴ All luminous efficacies are “typical” as quoted on the published specification sheets.

The solid curves are contours of fixed COL. The meanings of the symbols are the same as in Figure 5. Although incandescent lights have the lowest power delivery cost, their low luminous efficacy gives them the highest overall COL. Thus, contours passing through the incandescent point represent the highest COL. In proceeding from fluorescent to high-intensity discharges, there is an increase in complexity (and, thus, power-delivery cost). However, their luminous efficacies are greater, decreasing the COL.

A hypothetical “trajectory” for improving SSL is perpendicular to the contours of constant Cost of Light, shown schematically as the dashed white curve. As shown in Figure 5, the 100% efficient SSL point corresponds to the maximum possible luminous efficacy of 386 lm/W for an RYGB source with CRI 85.

Luminous Efficacy

Luminous efficacy and wall-plug efficiency of LEDs are strong functions of emission wavelength, as illustrated in the top and middle portions of Figure 7, respectively. For several of the lamps, the luminous efficacy and the electrical-to-optical power-conversion efficiency are plotted for output at more than one drive current and voltage.⁵

Figure 7. Top – Luminous efficacy of commercially available LEDs as a function of wavelength; Middle – External energy conversion efficiency as a function of wavelength; and Bottom – LED wavelengths that give best luminous efficacy for a specified CRI.

⁵ The blue and beige lines correspond to the Lumileds Low CRI and High CRI white LEDs, respectively. For the nitride-based LEDs (colored symbols in the range 455 to 530 nm), the data correspond to: 0.35 A, 1.2 W (higher luminous efficacy points), and 1.0 A, 3.7 W.

Note that for LED devices, wall-plug efficiency drops significantly as emission approaches the deep green and yellow regions. Efficiency in the nitride materials goes down because of the difficulty of attaining high indium composition (which shifts emission to longer wavelength) while still maintaining good material quality. (Generally, achieving high-In content requires low growth-temperatures, resulting in poor quality material with greatly increased defect densities.) Phosphide LED emission drops sharply as the Al content x increases, where the alloy composition is $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$; increasing Al fraction pushes emission to shorter wavelengths. In this alloy system, the drop in emission with increasing x is because the X-valley drops in energy relative to the Γ -valley, leading to an increasing number of electrons involved in indirect transitions, which are not radiative. The band gap crosses over from direct to indirect near $x=0.5$, leading to a nearly complete suppression of light emission.

Although the wall-plug efficiency of these visible-light LEDs has a minimum in the region near 550 nm, the luminous efficacy of this series of LEDs is highest in this range (upper portion of Figure 7). This is simply because the human eye response to light (also plotted in the top part of Figure 7) is most sensitive at 555 nm.

High CRI is best achieved by a broad spectral distribution of light covering the entire visible range. Mixing a small number of different wavelengths of light (e.g., three or four) to approximate natural white light decreases the CRI (<100), but improves the luminous efficacy by concentrating the light output to subsets of the spectrum. Thus, there is a fundamental trade-off between CRI and luminous efficacy for any light source.

For a given CRI, one can calculate the combination of RGB or RYGB wavelengths that would give the maximum luminous efficacy. These wavelength combinations are given in the bottom portion of Figure 7. This plot was generated using a white LED simulator (Ohno 2004). (The calculations assume that the source full-width at half maximum power is 20 nm for the red, yellow, and blue sources and 30 nm for the green, and CCT=4000 K.) The black dotted line in this plot represents the approximate upper limit of CRI that can be obtained using the three-color (RGB) approach.

The CRI vs. luminous efficacy for current light sources is shown in Figure 8. The two steep, solid (blue and beige) curves near the right of Figure 8 represent the maximum theoretical luminous efficacy that could be obtained from either a RGB or RYGB color combination scheme. For example, for a CRI of 50, the maximum luminous efficacy that can be achieved is 421 lm/W; for a CRI of 85, the maximum luminous efficacy is 386 lm/W (values at CCT=4000 K).

CRI and luminous efficacy are shown for several different incandescent (triangle symbols), fluorescent (squares), and high-intensity discharge (diamonds) lamps; the areas of these symbols are proportional to usage in Tlmh/yr (Teralumen hours per year). Of the three traditional white lighting sources, incandescent lamps have the highest CRI, but the lowest luminous efficacy. Fluorescent lamps and high-intensity discharge lamps provide lower CRI, but much higher luminous efficacy. Also plotted are data from two current commercial LEDs (the high-CRI and low-CRI devices from Lumileds discussed in

previous plots). The dashed white and blue curves in Figure 8 are hypothetical technology evolution curves that would eventually achieve both a high CRI and the maximum possible luminous efficacy.

Figure 8. Map of Color Rendering Index vs. Luminous Efficacy for different white-lighting technologies.

Power Delivery Cost

The power delivery cost can be further broken down into the ratio of the maximum input power density to the device (W_{in}/cm^2) and the capital cost of making the LED normalized to its chip area ($$/cm^2$), illustrated in Figure 9. As the figure illustrates, different approaches can achieve the same ratio.

Figure 9. Trade-off between LED lamp cost and maximum power input.

WOLEDs, for example, have very low lamp cost per chip area, but also very low chip power density. High-power lasers have high lamp cost per chip area, but also high chip power density. Conventional low-power LEDs have medium lamp cost per unit chip area, and medium chip power density.

In 2006, the Luxeon K2 (Lumileds) device lies between the low-power LEDs and the high-power lasers, and one can ask the question whether there is more "room" for the technology to improve by lowering its lamp cost per chip area or by increasing its chip power density. Of course, normally these quantities are strongly coupled (i.e., increasing chip power density usually means increasing lamp cost per chip area). A technology "breakthrough" or "shift" would be needed that allows one either to lower lamp cost per chip area without decreasing chip power density, or to increase chip power density without raising lamp cost per chip area.

Inorganic Light-Emitting Diodes (LEDs)

SSL technologies based on inorganic LEDs start with inorganic direct bandgap semiconductors that emit in the visible spectrum. There are two inorganic LED-based architectures in use for white lighting, as discussed below.

White Light Creation Architectures

The entire spectral range of visible light can be produced by III-V semiconductor LEDs. AlGaInP LEDs can cover the spectral range from red to amber, and their commercial production is relatively mature. AlGaInN LEDs are the prime candidates for producing wavelengths from blue to yellow. Two main approaches for producing white light are being pursued:

Color Mixing. This approach mixes output from three (or possibly four) different colors of LEDs. First, it has the potential for higher luminous efficacy, provided that efficient LEDs of the constituent colors can be developed; there is no Stokes loss from energy down-conversion, as in the blue + phosphor or photon-recycling approaches. Color rendering index will be highest by blending output from at least three different wavelengths. However, substantial problems still exist with this approach. A major limitation is that *efficient green and yellow LEDs are still not currently available*. A second problem is that LEDs of different colors tend to age and degrade at different rates. Over time, the color balance and color rendering quality of a multi-LED white light may decay significantly; electronic solutions exist, but at a cost. Third, uniform color mixing can be a problem; color variation in the far-field pattern depends on architecture. Fourth, even in the blue, overall efficiencies are far from 100%, and they decrease significantly when driven at high currents.

Wavelength Down-Conversion. By using light from a blue LED to excite fluorescence from a yellow phosphor, the combination of blue and yellow produces white light. Because of the early development of blue LEDs and ready availability of yellow phosphors, the first white LED products, for example flashlights, have used this scheme. The current state-of-the-art uses an InGaN LED emitting at about 460 nm to excite a cerium-doped yttrium aluminum garnet (YAG) phosphor, which is ground into a powder and dispersed in an epoxy cap on the device. There is an unavoidable Stokes energy-loss in converting a blue photon to a lower-energy yellow photon. The color quality in this approach can be enhanced, making it closer to that of incandescent lamps, by additionally adding a red phosphor to improve CRI.

Ultraviolet (UV) LED pumping of RGB phosphors is another possible down-conversion approach. This scheme would potentially be simple to manufacture; it is similar to a television or fluorescent lamp, with electron excitation replaced by a UV LED. Excellent color rendering would be possible, but with fundamental limitations on efficiency because of phosphor conversion efficiency and Stokes loss. In addition, LED packaging material would degrade more quickly from exposure to high-energy near-UV photons.

Wavelength Conversion Materials

Rare-Earth Phosphors. Inorganic phosphors doped with rare-earth metals are used for a variety of applications. A wide array of these phosphors has been developed for use with fluorescent lamps. The first SSL white LEDs have used an yttrium aluminum garnet doped with trivalent cerium (YAG:Ce⁺³) to convert output from a blue LED into

very broad-band yellow light. The sum of the two emissions appears white. For efficient white lighting with good color rendering, quantum efficiencies $>85\%$ (for phosphors absorbing in the near-UV) at operating temperatures $>155^{\circ}\text{C}$ (for phosphors in intimate contact with the LED) will be needed.

A red-emitting phosphor centered near 610 nm with narrow band emission (required because of the steep drop-off in human eye sensitivity at longer wavelength) and absorption in the near-UV or blue region has been difficult to achieve. Broader-band emission is acceptable in the green region because of the eye's sensitivity to a wider range of wavelengths in this region. Phosphors based on divalent europium (Eu^{+2}) are available in the green, and even into the blue emission region.

Photon Recycling Semiconductors. This approach is a photon down-conversion scheme similar to using yellow phosphors, in which an AlGaInP photoluminescent quantum well (QW) or active layer is laminated to a GaN LED. Some of the blue emission from the GaN chip is absorbed in the phosphide layer, which emits complementary yellow light. The combined blue and yellow emission produces white light.

Semiconductor Nanoparticles. White light can be produced using semiconductor nanoparticles. For example, the band-gap of CdS nanoparticles can be tuned over the entire visible spectrum by the changing their size (because of quantum confinement effects) and surface characteristics (e.g., coating the nanoparticles with ZnS, or changing the nature of chemical groups bonded to the nanoparticle surface).

Light Creation Materials

Different families of inorganic semiconductor materials can contribute to solid-state white lighting. The primary chemical systems used for LEDs are Group-III Nitrides and Group-III Phosphides. It is, however, possible that breakthroughs in a different material system, for example ZnO, will be important.

AlGaInN Materials. LEDs based on gallium nitride (GaN) and ternary alloys with indium (InGaN) and aluminum (AlGaN), as well as quaternary alloys (AlGaInN) can span the entire visible spectrum. The current applications for SSL utilize InGaN structures to produce high brightness blue and green light; longer wavelength light can be efficiently generated by AlGaInP LEDs. UV light from AlGaN LEDs could also be used to pump RGB phosphors, as mentioned above. A schematic of a current nitride LED is shown in Figure 10.

Figure 10. Schematic of a Nitride LED.

Nitride materials are usually grown by Metal Organic Vapor Phase Epitaxy (MOVPE)—also referred to as Metal Organic Chemical Vapor Deposition (MOCVD)—from organometallic sources (e.g., trimethyl-gallium, -indium, or -aluminum) and an excess of ammonia. A major difficulty is the lack of low-cost, single-crystal GaN to use as a growth substrate. Group-III nitrides are normally grown on poorly matched sapphire (lattice mismatch +16%, thermal expansion mismatch +39%) or more expensive silicon carbide (lattice mismatch -3.5%, thermal expansion mismatch -3.2%) substrates. As a result, the films have a great number ($>10^8/\text{cm}^2$) of dislocations and other structural defects, resulting in defect-mediated nonradiative recombination of electron-hole pairs and reduced mobility because of carrier scattering from charged defect centers. An intermediate buffer (or nucleation) layer is normally grown at reduced temperature between the substrate and the n-GaN layer (a GaN nucleation layer on sapphire substrates, or AlN on SiC). This low temperature buffer reduces defect densities from up to 10^{12} to $10^9/\text{cm}^2$. Further defect reduction (by roughly two orders of magnitude) can be achieved by substrate patterning techniques such as Epitaxial Lateral Overgrowth, Pendeo Epitaxy, or Cantilever Epitaxy; these approaches rely on spatial “filtering,” terminating, and/or turning of threading dislocations, so they do not reach the device active region.

GaN is readily n-doped with Si (usually using a silane source). However, p-type doping with Mg (usually using the metal organic precursor bis-cyclopentadienyl magnesium, Cp_2Mg) is much more difficult, because of passivation by hydrogen during growth, and the magnitude of the hole ionization potential associated with Mg. Depassivation of the Mg acceptors is achieved by thermal annealing or low-energy electron beam irradiation.

Indium incorporation pushes emissions to longer wavelengths; indium fractions greater than 20% are required for green LEDs. This represents a significant challenge in material growth. Low temperatures are required for In incorporation because of lower thermal stability, leading to poorer material. As In composition increases, lattice-mismatch strain also increases, leading to a variety of strain-induced defects (e.g., point-defects, V-defects, and carbon and oxygen impurities) and lower optical efficiencies.

AlGaInP Materials. The $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$ alloys are nearly lattice matched to GaAs, and production of LEDs emitting from 555 nm (yellow-green) to 650 nm (deep red) is a relatively mature technology. The availability of single crystal GaAs substrates enables growth of high-quality phosphide material by MOVPE. But the bandgap of GaAs

Figure 11. Left – AlGaInP LED with DBR mirror for improved light extraction; Right – AlGaInP LED wafer-bonded to transparent GaP substrate.

is 1.42 eV (870 nm) at room temperature, so this substrate absorbs emitted light below this wavelength, greatly lowering the LED efficiency. Two solutions to this problem are illustrated in Figure 11.

One way to prevent absorption of emitted light by the substrate is to insert a reflective structure between the LED active region and substrate, illustrated in the left portion of Figure 11. The mirror structure is a Distributed Bragg Reflector (DBR), consisting of many (e.g., 5 to 50) alternating high-refractive index and lower-refractive index layers. Because of the differences in refractive indices, a portion of the downwardly directed light is reflected upward (and out of the device) at each layer interface. The mirror stack thicknesses are adjusted so that all of the reflected waves are in constructive interference. The DBR is highly effective for light incident normal to the DBR plane; glancing incident light, however, is only partially reflected by the DBR.

Another approach is to remove the GaAs substrate after the epitaxial layers have been grown, and then to bond the remaining structure to a transparent GaP substrate. The resulting structure of a wafer-bonded LED is shown in the right half of Figure 11. Total light extraction from the wafer-bonded AlGaInP LED can be more than a factor of two greater than the LED + DBR design.

For low Al fraction, the internal quantum efficiency approaches 100%. $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$ is a direct bandgap semiconductor for $x < 0.5$; above that composition, it is an indirect-gap material. The crossover occurs at bandgap energy of about 2.23 eV (555 nm). Thus, the AlGaInP LED quantum efficiency drops precipitously (Figure 7) at shorter wavelengths because of the approach of the direct-indirect bandgap crossover. That is, as the indirect-gap X-band becomes more populated, the radiative lifetime increases, allowing other nonradiative processes to become more dominant. Efficiency also drops at higher drive currents and operating temperatures because of poor carrier confinement in heterostructures as the direct-indirect-gap crossover is approached.

ZnO Materials. ZnO-based alloys are another possibility for generation of light from the visible to the near-UV. ZnO has a number of physical properties that make it a good potential candidate for SSL. However, progress toward making it a practical material is still at an early stage.

The material is a wide-bandgap semiconductor (3.4 eV, comparable to the 3.5 eV of GaN) with a wurtzite crystal structure. Single-crystal ZnO can now be produced, and commercial 2 inch wafers are available, offering the possibility of homoepitaxy. The material can be etched by wet chemical means, making it relatively easy to process. Because ZnO has a high exciton binding energy (60 meV, compared to less than 30 meV for GaN), higher operating temperatures are possible.

ZnO has a high intrinsic n-type conductivity, the source of which is not known. It has been difficult to obtain p-doping; although there has been good recent progress, consistency is still hard to achieve. Growth of high-quality ZnO films and hetero-structures is still being developed. It may be possible to tune the bandgap of ZnO by

Figure 12. Some LED light extraction schemes.

alloying with MgO (7.9 eV bandgap) or CdO (2.3 eV). However, these two oxides have cubic crystal structures, so it may be difficult to add large fractions to ZnO without introducing dislocations. Further, the use of the heavy metal Cd in commercial LED structures may not prove acceptable because of long-term safety and environmental issues.

Light Extraction Approaches

In principle, 100% of the light could be extracted from an LED, but the current state-of-the-art light extraction efficiency is about 50%. Limitations in light extraction include internal reflection at interfaces and light absorption within the device or in the packaging. Figure 12 shows some light-extraction methods.

Encapsulation can reduce the index step between the semiconductor and air, creating a favorable geometry. High-index encapsulants are desirable. Limitations of this approach include transparency and degradation of epoxy encapsulants from exposure to high temperatures and intense radiation. For this reason, silicone encapsulants are replacing epoxy.

Chip shaping has been used to increase light extraction from LEDs. Lumileds used an inverted pyramid shape to boost light output from a red (AlGaInP) LED to achieve wall-plug efficiency as high as 50%. Cree has also used chip shaping to increase efficiencies in their commercial blue and green LEDs.

Surface texturing produces random scattering at the surface, increasing the likelihood that light will encounter a surface within its escape cone, thus increasing light extraction.

Photonic crystals can be used in multiple ways to increase light extraction. Two-dimensional photonic crystals can be used to scatter waveguided modes out of the active layer region. Another approach is to use 2D photonic crystals to change the photonic density of states in the active layer so that no in-plane modes are permitted. This would cause all emitted light from the quantum wells to be normal to the LED surface, so that it would lie within the escape cone and not be reflected. A third possibility is to increase the internal quantum efficiency by enhancing the photonic density of states at the LED emission wavelength. Finally, 3D photonic crystals could be utilized as highly reflective mirrors for resonant cavity LEDs and laser diodes, which are described below.

Resonant cavity LEDs or Lasers pumping phosphors have the potential to be efficient white-light sources. Resonant cavity LEDs and lasers have the highest energy conversion efficiency of all optoelectronic devices (80% reported for a laser in the infrared). Despite inherent energy loss because of photon down-conversion from exciting phosphors, the net luminous efficacy of this scheme could be very high. However, capital costs to manufacture these complex devices may make them too expensive to be practical.

Thermal Management

Junction temperature of an LED affects luminous efficacy, color, and reliability. As high brightness LEDs are driven harder, managing the heat from the semiconductor will be increasingly important.

Epoxy encapsulants quickly degrade if the temperature exceeds the epoxy glass transition temperature. This can lead to device failure modes.

An increase of 75°C can reduce luminous flux in AlGaInP LEDs to one-half the room temperature value; however, a similar increase in temperature reduces emission intensity of a 470 nm GaInN/GaN LED by only about 5% (Schubert 2003). The dominant emission wavelength of a phosphide-based LED shifts to longer wavelength with increasing junction temperature, about one nanometer for every 10°C (Lumileds 2002); the shift in emission wavelength of a 400 nm nitride LED is about a factor of 3 smaller (Cho et al. 2005). (To put these wavelength shifts into perspective, the human eye can detect wavelength shifts as small as 2 nm to 4 nm, depending upon the color; this is the wavelength discrimination function.)

Removing excess heat from the lamp consists of two or more components of thermal resistance in a serial configuration. As part of the packaging, the LED die is attached to a metal slug (e.g., aluminum or copper) to conduct heat away from the lamp. Depending on the end-use, the lamp might be connected to a printed circuit board or other electrical mounting system. In any case, thermal management of heat flow from the lamp package through the mounting and then to the surrounding ambient must be an engineering consideration for any application.

Organic Light-Emitting Diodes

Organic light-emitting diodes (OLEDs) are based on small molecules (Tang 1987), dendrimers (Halim 1999), or polymers (Burroughes 1990). OLEDs have significant potential for low-cost manufacturing and enable novel lighting architectures such as curved light emitting surfaces. Issues of particular relevance to OLEDs include carrier injection and transport, exciton formation, utilization, and conversion to light, operating lifetime, encapsulation, and light extraction.

White-Light Creation Architectures

The two dominant material sets for white-light OLEDs are small molecule (discrete molecular units with relatively weak inter-molecular bonding) and polymer (covalently bonded repeat units where addition or subtraction of one repeat unit does not significantly affect the properties of the molecule). While OLEDs typically have broad emission spectra, they are not sufficiently broad for white light (the exception is emission from excimers or exciplexes, which is usually relatively inefficient). General lighting, therefore, requires, as with inorganic LEDs, mixing the light from at least two sources by either pumping a down-conversion phosphor, combining two or three electroluminescent devices on a substrate using lateral patterning, co-doping a single layer with spatially separated multiple chromophores, or stacking multiple devices using transparent intervening electrodes to generate coaxial color mixing. Compared to inorganic LEDs, organic devices offer more potential for stacked geometries since lattice matching and strain are essentially irrelevant. However, patterning is more of a challenge since organic semiconductors are typically damaged by photolithography chemicals such as resists, etchants, and solvents. OLEDs are fundamentally broad-area emitters requiring relatively large-area substrates to generate the lumen output required for general lighting; however the lower operating current density makes heat dissipation less of a limiting issue. The large area, low brightness characteristic also potentially eliminates the need for a luminaire, since there is no dazzle from such a distributed source. This not only saves capital cost, but also increases their *effective* efficiency, since the reflector and diffuser enclosure required for a point source reduces the lighting system efficiency by 30–50%.

Small-Molecule OLEDs (SM-OLEDs). The most efficient OLEDs are currently based on “small molecule” materials (referred to as SM-OLEDs); a schematic of a SM-OLED is shown in Figure 13. SM-OLEDs consist of many layers in a structure such as:

1. Substrate, which is usually transparent. However, it is possible to make either or both electrodes of an OLED transparent (Burrows et al. 2000) so in some cases opaque substrates such as metal foil can be used.

2. A transparent anode through which light is usually emitted; indium tin oxide (ITO) was originally used but more complex compounds such as zinc indium tin oxide with more optimal work function properties are now common in the displays industry.
3. A hole-injection layer (HIL) such as Poly(3,4-ethylenedioxythiophene)–Polystyrene (PEDOT-PSS) or copper phthalocyanine
4. A hole-transport layer (HTL), such as N,N'-bis-(1-naphthyl)-N,N'-biphenyl-4,4'-diamine (NPD)
5. An emissive layer (EML) containing fluorescent and/or phosphorescent dyes usually doped into a host matrix, discussed separately below
6. An electron transport layer (ETL), e.g., tris(8-hydroxyquinolato) aluminum (Alq₃); perhaps with an additional hole-blocking molecule, e.g., bathocuproine (BCP), either added to this layer or as a separate exciton and hole-blocking layer (HBL) between the EML and ETL layers to minimize carrier leakage and exciton quenching at the cathode
7. A cathode consisting of a thin layer of LiF capped with aluminum. In top-emitting architectures, the cathode is transparent, permitting the use of extremely low cost substrate materials, such as metal foil.

Figure 13. Schematic diagram of a Small-Molecule OLED (SM-OLED) and a Polymer OLED (PLED).

SM-OLED organic layers are usually grown by vacuum deposition (also known as vacuum thermal sublimation) in which organic source molecules are heated to sublimation within a vacuum chamber (base pressure around 10^{-6} Torr), for deposition on a substrate that is usually close to room temperature. (Active cooling is typically not required due to the relatively low temperature of the source materials.) The vacuum equipment required represents a high capital cost but is capable of coating large areas and achieving high product throughput, since lattice-matching constraints are absent for this materials system. Another growth technique that has been applied recently is organic vapor phase deposition (OVPD), in which a carrier gas transports organic molecules within a hot-walled, low-pressure (0.1–1 Torr) growth chamber onto a cooled substrate (Baldo et al. 1998). This method yields higher deposition efficiency than vacuum

deposition, since only the substrate is coated while the reactor walls remain clean; this may also reduce downtime for cleaning and allow for an extra degree of control over thin film morphology. However, this, and the related technique (Sun, Shtein, and Forrest 2005) of organic vapor jet printing (OVJP), are very new, and the limits on deposition rate over large areas, throughput, and therefore cost are still unclear.

Solution-based processing for small molecule materials is now also being developed. Branched molecules known as dendrimers have generated particular recent interest for this processing method, and are claimed to combine the best features of small molecule and polymeric materials.

The operating lifetime of OLEDs is inversely proportional to the operating current density, which may be of concern for high brightness lighting applications. Recent results on single-color OLEDs, however, show promise. For example, Universal Display Corporation (UDC) has developed a sky blue (CIE 0.16,0.37) OLED with 100,000 hour lifetime at 200 cd/m² and luminous efficacy of 20 cd/A, and a deeper blue (CIE 0.16,0.29) device with a 17,500 hour lifetime at 200 cd/m² and 21 cd/A luminous efficacy. In early 2006, Thompson (U. So. Cal.), Forrest (U. Michigan), and UDC announced white OLEDs using (a) side-by-side RGB stripes or (b) mixed phosphors within the same EML, each with luminous efficacy of 20 lm/W at 800 cd/m².

Polymer OLEDs (PLEDs). An alternate approach is to use a single polymer-containing emission layer between two electrodes to produce a PLED (polymeric LED), shown schematically in Figure 13. Polymers can be deposited over broad areas with relatively simple solution-based approaches such as spin casting or doctor-blading, which are less capital-intensive than vacuum deposition. The need to pattern more than one color of device on a single substrate has led to the further development of ink-jet printing techniques.

The limits to the manufacturing cost of such techniques over the large areas required for lighting is unknown. A further challenge of the solution process is the difficulty of making multilayer heterostructure devices, which can give higher efficiency but require either polymers with orthogonal solvent systems or polymers which can be cross-linked by thermal treatment. Currently, PLEDs are less power efficient than small-molecule devices. This is primarily because of the lack of very high quantum efficiency electrophosphorescence in polymeric systems, which is not fully offset by the lower operating voltage of PLEDs compared to SM-OLEDs. Conjugated polymers such as poly(phenylene)vinylene and polyfluorene polymers have been used for OLEDs in the past for fluorescent devices. However, these polymer systems appear to quench phosphorescence emission, and nonconjugated polymers are now being used for higher-efficiency phosphorescent devices. Nevertheless, 4 square-foot. lighting panels have been demonstrated by General Electric (Duggal 2005).

White light can be produced by mixing polymer hosts with RGB-emitting chromophores within a single EML, or in a multilayer structure in which different layers emit different colors of light to produce white. In addition, polymers with different

dopants can be applied using commercial inkjet technology to apply RGB patterning (e.g., pixels or stripes of three colors) to produce white light or for pixelation in full-color displays.

Some recent benchmark PLED results indicate the current state of the art in PLED technology. As for single-color devices, in late 2005 Cambridge Display Technology announced a blue PLED with 37,500 hour lifetime at 200 cd/m² and 10 cd/A luminous efficacy, and a red PLED with 125,000 hour lifetime at 200 cd/m² and 7 cd/A luminous efficacy.

Concerning white OLEDs (WOLEDs), at the 2005 Fall MRS Meeting, Yang (UCLA) reported a white PLED with 14 lm/W. In early 2006, Franky So's group (U. Florida) also reported a WOLED with 25 lm/W using a blue organic phosphorescent dye (FIrpic) and wavelength down-conversion employing a nitridosilicate phosphor (Krummacher et al. 2006).

Carrier Injection and Transport

General features of carrier injection and transport are schematically shown in Figure 13; for simplicity, a single organic layer structure is used for illustration, with some details near the interfaces such as band bending and defect states omitted. Many features of injection and transport are common to both PLEDs and SM-OLEDs, although the details differ because of stronger carrier localization in the latter class of materials. Indium tin oxide (ITO) is illustrated here as the hole-injecting anode, and the medium for carrier transport is a conjugated organic material, such as polyphenylene vinylene or tris (8-hydroxyquinoline) aluminum. Delocalized π -bonding orbitals form the equivalent of the valence band, and anti-bonding π^* orbitals form the organic equivalent of the conduction band. The energy of the highest occupied molecular orbital (HOMO) corresponds to the top of the valence band, and the lowest unoccupied molecular orbital (LUMO) energy corresponds to the bottom of the conduction band. (Although the LUMO and HOMO appear similar to conduction and valence bands in semiconductors, charge carriers are much more localized in organics, and they are also more strongly coupled to phonon modes. Where bands exist in any meaningful sense, they are very narrow and background carrier densities are very low relative to conventional semiconductors.)

In the case where the interaction between adjacent materials is weak and the interface dipole is negligible, the difference between the ionization potential of the organic HTL and the work function of the anode (Φ_a) is the barrier for hole injection (ΔE_h). The energy levels of ITO and PPV are well aligned to give a relatively low barrier of 0.2 eV for hole injection (Brown et al. 1992). In many cases, however, interfacial dipoles or surface chemistry act to change these idealized barriers.

The cathode is a metal film deposited on top of the final organic layer via thermal evaporation. The difference in energy between the cathode work function (Φ_m) and the electron affinity of the LUMO (E_A) is the barrier for electron injection (ΔE_e). As drawn in Figure 14, a lower cathode work function gives a lower electron injection barrier. For this reason, low work function metals (e.g., barium or calcium) are typically used as OLED cathodes. Because of the reactivity of these metals, the cathode is capped with a layer of aluminum. Again, however, almost all effective OLED cathodes react with the ETL forming dipoles and defect states which enhance electron injection. In essentially oxygen-free environments, covalent bonds can form between the initially deposited metal atoms and the organic, modifying the electronic structure of the system. The metal-organic interfacial region is on the order of 20–30 Å, comparable to the electron tunneling distance (Salaneck and Bredas 1996). The presence of even low amounts of oxygen can cause formation of an insulating oxide layer which degrades performance. Interface-modification layers such as LiF are often used between the organic layer and the cathode to improve this interface.

When a charged carrier is injected onto a conjugated molecule, it distorts the molecular geometry which relaxes around the extra charge creating a polaron (Holstein 1959) which is often referred to as a self-trapped state. The mechanism of carrier transport through organics is often “polaron hopping” from one molecule to a neighbor. Disorder in the largely amorphous organic films disrupts charge transport and plays a dominant role in determining the charge carrier mobility.

Exciton Dynamics and Light Creation

Electrons and holes within the emission layer combine to form a neutral exciton, which can then diffuse. If normal Langevin statistics prevail, singlet and triplet excitons are formed in a 1:3 ratio. A crucial step towards making very efficient OLEDs is to convert *all* the singlet and triplet excitons into light output. The first generations of OLEDs were based on fluorescent dyes. In fluorescence, quantum mechanical spin is conserved when a singlet excited state (exciton) emits a photon and drops to the singlet ground state. However, because a triplet-to-singlet transition via light emission does not conserve spin, it is a “forbidden transition;” the energy of the triplet excitons is wasted as dissipated heat. Thus, OLEDs utilizing fluorescence alone were fundamentally limited to an internal quantum efficiency of 25%. There is ongoing debate as to the exact singlet-triplet ratio in organics, and there is evidence for a material dependence, with measurements suggesting well over 25% singlets in some PLEDs (Reufer et al. 2005). There is some practical significance to this debate because the ability

Figure 14. OLED energy level diagram of illustrating carrier injection.

to engineer materials for very high singlet exciton generation could potentially recover the exchange energy that is currently lost in phosphorescent devices, yielding even higher efficiencies. Such a device, however, has yet to be demonstrated.

Another approach is a phosphorescent OLED (PhOLED), in which the presence of a heavy metal atom (e.g., Pt, Pd, Ir, Au) within a phosphor provides spin-orbit coupling and mixing of the singlet and triplet states. The goal is conversion of all excitons to the triplet state, followed by rapid phosphorescence; phosphorescent materials can relax from a mixed spin metal ligand charge transfer excited state to the ground state by emission of a photon, and the spin statistics of exciton creation are therefore irrelevant. Examples of such organometallic phosphors are platinum octaethylporphine (PtOEP) and iridium tris(phenylpyridine) (Ir(ppy)₃), with triplet excited state lifetimes of ~100 μs for the former and <1 μs for the latter. There is still an inherent energy loss (known as the exchange energy) when a singlet exciton is converted by this process to a lower-energy triplet exciton. A recent approach is to combine fluorescent and phosphorescent dyes to utilize the singlets for blue light and the triplets for lower-energy green and red light (Sun et al. 2006). The relatively long excited-state lifetime of triplet excitons also creates exciton-exciton and exciton-polaron quenching effects at high drive currents, which result in efficiency loss at high brightness (Baldo, Adachi, and Forrest 2000).

Encapsulation

Low-cost packaging and encapsulation approaches are needed to limit degradation of OLEDs. Low work-function metals such as Ca are used as cathodes in OLEDs and must be protected from reactions with oxygen and water. These ambient vapors will particularly degrade the metal-organic interface, limiting device lifetime. Excited-state organic molecules in the OLED EML are also very susceptible to oxidation (photo-oxidation), and must be protected from contact with air. Ingress of water vapor likely leads to electrochemical reactions near the electrodes and is particularly deleterious.

Currently, OLEDs are encapsulated by attaching a glass or metal lid above the cathode using a bead of epoxy. Desiccant is incorporated in the package to absorb residual moisture released from, and permeating through, the epoxy seal. This approach is limited to rigid and small-area devices. For the envisioned flexible and large-area OLEDs required for lighting, new encapsulation methods will be needed unless air-stable materials can be developed. High-barrier coatings can be used to provide low-cost thin-film encapsulation. These barriers must be pin-hole free, robust, and tolerant to high temperatures that will occur when devices are driven for high brightness. These barriers need to transmit <10⁻⁶ g/m²/day of water and <10⁻⁵ cc/m²/day of oxygen to ensure adequate OLED lifetimes (Burrows et al. 2001). Furthermore, these targets will have to be met at low cost over large areas and in a manufacturing environment. Achieving this may require new breakthroughs in both the science and engineering of encapsulation.

Figure 15. Inefficient light extraction in OLED device.

Light Extraction

As much as 80% of the light produced in an OLED can be lost to internal reflections and waveguiding within the device or substrate layers (Figure 15). A number of different approaches to improving the light extraction coefficient, R_e , have been employed. Because of the difference in refractive indices of air (1.0) and the glass substrate and organic layers (both on the order of 1.5 to 1.8), only light incident on the interface within a certain escape cone will pass through. Techniques for improving light extraction efficiency primarily try to increase the effective light cone. Light extraction is even more of a problem for inorganic LEDs, where the solid indices of refraction are much larger, on the order of 2.5. While the same fundamental physics likely applies to both cases, the economics of light extraction from large area OLEDs, rather than a small inorganic semiconductor die, likely creates new challenges.

Many approaches for improved light extraction are being pursued including: roughening or texturing the outside surface of the glass substrate; corrugating the surface to increase Bragg scattering in the forward direction; using a two-dimensional photonic crystal structure to improve light output coupling; attaching an ordered array of micro lenses to the glass substrate; shaping the device into a mesa structure, and including reflective surfaces within the device.

Improvements in light extraction efficiency by factors of two to three have been reported for most of the techniques listed above. Other issues that must be considered include manufacturing cost and avoiding undesirable changes in the radiation pattern or an angular-dependent emission spectrum. A single standard approach to light extraction for OLEDs has yet to be established, and this is an important area for development.

Acknowledgements

This report was originally prepared as part of the final report for the workshop “Basic Research Needs for Solid-State Lighting,” sponsored by the U. S. Department of Energy (DOE) Office of Basic Energy Sciences (BES). Funding for this report was

provided by the U.S. DOE / BES, and is gratefully acknowledged. Many of the organizers and participants in this workshop provided valuable feedback on the technical content, including: workshop chair Julia Phillips (Sandia National Laboratories), workshop co-chair Paul Burrows (Pacific Northwest National Laboratory), panel chair Jerry Simmons (Sandia National Laboratories), panel chair George Malliaras (Cornell University), panel chair Franky So (University of Florida), Jim Brodrick (DOE Energy Efficiency and Renewable Energy), George Craford (LumiLeds Lighting), Mary Crawford (Sandia National Laboratories), Yoshi Ohno (National Institute of Standards and Technology), Dale Work (Philips Lighting, representing the Next Generation Lighting Industry Alliance), and Kevin Dowling (Color Kinetics). We are grateful to Fred Schubert (Rensselaer Polytechnic Institute) for providing Figure 1 of this document. This work was conducted at Sandia National Laboratories, for the United States Department of Energy under Contract No. DE-AC04-94AL85000.

Table 1 Cost and Performance Characteristics for some Solid-State Lighting Technologies^[1]

	Product or Technology	I (A)	V (V)	Die Size mm ²	Output (lm)	lm/W	W _{out} /W _{in}	Life (khr)	CRI	CCT (K)	\$/lamp	λ/Δλ (nm/nm)
Low CRI Power White Luxeon LEDs	K2 LXX2-PW12-R00	0.35	3.42	1.00	45.00	37.6	0.093	50 ^[2]	70	6500	3.45 ^[3]	440/20 +
	K2 LXX2-PW14-U00	1.00	3.72	1.00	100.00	26.9	0.067	50 ^[2]	70	6500	3.45 ^[3]	560/130
High CRI Power Warm White Luxeon LEDs	LXHL-BW03	0.35	3.42	1.00	26.00	21.7	0.056	50 ^[4]	90	3200	2.99 ^[3]	450/20 + 560/100 + 640/90
Power Color Luxeon LEDs	K2 Royal Blue LXX2-PR12-L00	0.35	3.42	1.00	200 mW ^[5]	n/a	0.167	50 ^[6]	n/a	n/a	2.86 ^[3]	455/20
	K2 Royal Blue LXX2-PR14-Q00	1.00	3.72	1.00	475 mW ^[5]	n/a	0.128	50 ^[6]	n/a	n/a	2.86 ^[3]	455/20
	K2 Blue LXX2-PB12-K00	0.35	3.42	1.00	9.50	7.9	0.128	50 ^[6]	n/a	n/a	2.86 ^[3]	470/25
	K2 Blue LXX2-PB14-N00	1.00	3.72	1.00	25.00	6.7	0.108	50 ^[6]	n/a	n/a	2.86 ^[3]	470/25
	K2 Cyan LXX2-PE12-Q00	0.35	3.42	1.00	35.00	29.2	0.105	50 ^[6]	n/a	n/a	2.86 ^[3]	505/30
	K2 Cyan LXX2-PE14-T00	1.00	3.72	1.00	80.00	21.5	0.077	50 ^[6]	n/a	n/a	2.86 ^[3]	505/30
	K2 Green LXX2-PM12-R00	0.35	3.42	1.00	45.00	37.6	0.064	50 ^[6]	n/a	n/a	2.86 ^[3]	530/35
	K2 Green LXX2-PM14-U00	1.00	3.72	1.00	100.00	26.9	0.046	50 ^[6]	n/a	n/a	2.86 ^[3]	530/35
	K2 Amber LXX2-PL12-Q00	0.35	2.95	0.65	35.00	33.9	0.066	50 ^[7]	n/a	n/a	2.57 ^[3]	590/14
	K2 Red-Orange LXX2-PH12-S00	0.35	2.95	0.65	60.00	58.1	0.207	50 ^[7]	n/a	n/a	2.57 ^[3]	617/20
	K2 Red LXX2-PD12-R00	0.35	2.95	0.65	45.00	43.6	0.218	50 ^[7]	n/a	n/a	2.57 ^[3]	627/20
OLED	SSL 2002 EERE/OIDA Roadmap			11,764.70	10.00	10.0	0.025	0.3			2.00	
High Power IR Laser	Lumics LU0915T040-8605N12A 915nm Laser Module						0.535					915/5
100%-efficient high CRI SSL	100% Efficient RYGB SSL with CRI = 85 and cap/op = 1/3	1.50	3.85	1.00	2,229.15	386.0	1.000	50	85	4000	0.46	

Notes:

1. Data compiled in May 2006.
2. Lifetime for White Luxeon K2 is projected as 70% lumen maintenance at 50,000 hours at 1000 mA operation, T_j maintained at or below 120 °C.
3. Price listed is for volumes up to 10K units. Higher volume pricing is negotiated depending on customer and application specific requirements.
4. Lifetime for White Luxeon is projected as 70% lumen maintenance at 50,000 hours at 350 mA operation, T_j maintained at or below 90 °C.
5. Royal Blue product is tested and binned for radiometric power rather than photometric flux.
6. Lifetime for Royal Blue, Blue, Green and Cyan Luxeon K2 is projected as 70% lumen maintenance at 50,000 hours (1000 mA operation, T_j ≤ 150 °C).
7. Lifetime for Red, Red-Orange, and Amber Luxeon K2 is projected as 70% lumen maintenance at 50,000 hours at 350 mA operation, T_j ≤ 120 °C).

References

- Baldo, M., M. Deutsch, P. E. Burrows, H. Gossenberger, M. Gerstenberg, V. Ban, and S. R. Forrest, "Organic Vapor Phase Deposition," *Advanced Materials* 10, 1505-1514 (1998).
- Baldo, M. A., C. Adachi, and S. R. Forrest, "Transient Analysis of Organic Electrophosphorescence. II. Transient Analysis of Triplet-Triplet Annihilation," *Physical Review B* 62 (16) 10967-10977 (2000).
- Brill, M. H., "How the CIE 1931 Color-Matching Functions Were Derived from Wright-Guild Data (Erratum)," *Color Research & Application* 23, 259 (1998).
- Brown, A. R., D. D. C. Bradley, J. H. Burroughes, R. H. Friend, N. C. Greenham, P. L. Burn, A.B. Holmes, and A. Kraft, "Poly(p-phenylenevinylene) Light-Emitting Diodes: Enhanced Electroluminescent Efficiency Through Charge Carrier Confinement," *Applied Physics Letters* 61, 2793-2795 (1992).
- Burroughes, J. H., D. D. C. Bradley, A. R. Brown, R. N. Marks, K. Mackay, R. H. Friend, P. L. Burns, A. B. Holmes, "Light-Emitting Diodes Based on Conjugated Polymers," *Nature* 347, 539-541 (1990).
- Burrows, P. E., G. Gu, E. P. Vicenzi, and S. R. Forrest, "Semitransparent Cathodes for Organic Light-Emitting Diodes," *Journal of Applied Physics* 87, 3080-3085 (2000).
- Burrows, P. E., G. L. Graff, M. E. Gross, P. M. Martin, M. K. Shi, M. Hall, E. Mast, C. Bonham, W. Bennet, and M. B. Sullivan, "Ultra Barrier Flexible Substrates for Flat Panel Displays," *Displays* 22, 65-69 (2001).
- Cho, J., C. Sone, Y. Park, and E. Yoon, "Measuring the Junction Temperature of III-Nitride Light-Emitting Diodes Using Electro-Luminescence Shift," *Physica Status Solidi (a)*, 9, 1869-1873 (2005).
- Davis W., and Y. Ohno, "Toward an Improved Color Rendering Metric," Proc. Fifth International Conference on Solid-State Lighting, *SPIE* 5941, 59411G (2005).
- Duggal, A. R., J. J. Shiang, D. F. Foust, L. G. Turner, W. F. Nealon, J. C. Bortscheller, "Invited Paper Large Area White OLEDs," *Digest of Technical Papers from the SID International Symposium* 36, 28-31 (2005).
- Fairman, H. S., M. H. Brill, and H. Hemmendinger, "How the CIE Color-Matching Functions Were Derived from Wright-Guild Data," *Color Research and Application* 22, 11-23 (1977).
- Haitz, R., F. Kish, J. Y. Tsao, and J. Nelson, "The Case for a National Research Program on Semiconductor Lighting," Optoelectronics Industry Development Association (1999).
- Halim, M., J. N. G. Pillow, D. W. Samuel, P. L. Burn, "Conjugated Dendrimers for Light-Emitting Diodes: Effect of Generation," *Advanced Materials* 11, 371-374 (1999).
- Holstein, T., "Studies of Polaron Motion: 1. The Molecular-Crystal Model," *Annals of Physics* 8, 325-342 (1959).
- IESNA, *IESNA Lighting Handbook*, Ninth Edition, New York, IESNA Publications (2000).
- Krummacher, B. C., V.-E. Choong, M. K. Mathai, S. A. Choulis, F. So, F. Fiedler, and M. Zachau, "Highly Efficient White Organic Light-Emitting Diode," *Applied Physics Letters* 88, 113506 (2006).
- Lumileds Application Brief, "Thermal Management Considerations for SuperFlux LEDs," Lumileds Application Brief AB20-4 (September 2002).

Navigant Consulting, U.S. Department of Energy, *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (September 2002).

Navigant Consulting, U.S. Department of Energy, *Energy Savings Estimates of Light-Emitting Diodes in Niche Lighting Applications* (November 2003).

Navigant Consulting, U.S. Department of Energy, "Solid-State Lighting Research and Development Portfolio: Multi-Year Program Plan FY'07-FY'12" (March 2006).

Ohno, Y., "Color Rendering and Luminous Efficacy of White LED Spectra," *Proceedings of the SPIE* 5530, 88-98 (2004).

OIDA (Optoelectronics Industry Development Association), U. S. Department of Energy, "Organic Light-Emitting Diodes (OLEDs) for General Illumination Update 2002" (August 2002).

Reufer, M., M. J. Walter, P. G. Lagoudakis, A. B. Hummel, J. S. Kolb, H. G. Roskos, U. Scherf, and J. M. Lupton, "Spin-Conserving Carrier Recombination in Conjugated Polymers," *Nature Materials* 4, 340 (2005).

Salaneck, W. R., and J. L. Bredas, Metal-on-Polymer Interface in Polymer Light Emitting Diodes," *Advanced Materials* 8, 48-52 (1996).

Schubert, E. F., *Light-Emitting Diodes*, Cambridge: Cambridge University Press (2003).

Schubert, E. F., and J. K. Kim, "Solid-State Light Sources Getting Smart," *Science* 308, 1274-1278 (May 27, 2005).

Sun, Y., M. Shtein, and S. R. Forrest, "Direct Patterning of Organic Light-Emitting Devices by Organic-Vapor Jet Printing," *Applied Physics Letters* 86, 113504 (2005).

Sun, Y., N. C. Giebink, H. Kanno, B. Ma, M. E. Thompson, and S. R. Forrest, "Management of Singlet and Triplet Excitons for Efficient White Organic Light-Emitting Diodes," *Nature* 440, 908-912 (2006).

Tang, C.W., and S. A. Van Slyke, "Organic Electroluminescent Diodes," *Applied Physics Letters* 51, 913-915 (1987).

Tsao, J. Y., "Roadmap Projects Significant LED Penetration of Lighting Market by 2010," *Laser Focus World* (May 2003).

Distribution

20	MS 1086	M.E. Coltrin
2	MS 1086	J.R. Creighton
2	MS 1086	D.D. Koleske
1	MS 1086	R.M. Biefeld
1	MS 1086	G.T. Wang
1	MS 1086	A.A. Allerman
1	MS 1086	K. Bogart
1	MS 1086	S.R. Lee
1	MS 1086	D.L. Barton
1	MS 1086	M.H. Crawford
1	MS 1086	A.J. Fischer
10	MS 1421	J.Y. Tsao
1	MS 1421	J. Simmons
1	MS 1427	J.M. Phillips
2	MS 9018	Central Technical Files, 8944
2	MS 0899	Technical Library, 4536