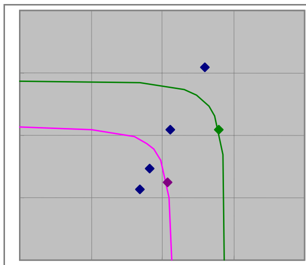
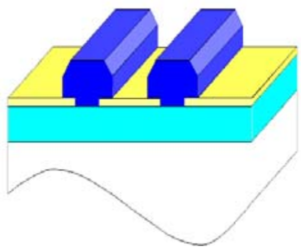
Light Emitting Diodes (LEDs) for General Illumination

AN OIDA TECHNOLOGY ROADMAP UPDATE 2002

TUTORIAL SOURCE MATERIAL

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TABLE OF CONTENTS

PREFACE

This volume supplements the August 2002 update of the OIDA technology roadmap on Light Emitting Diodes (LEDs) for General Illumination, originally prepared in March 2001. The original roadmap produced in collaboration with the Department of Energy (DOE-BTS) responded to a major opportunity to accelerate the development and commercialization of solid state light sources for general illumination. The new light sources offer savings in energy consumption, reduce pollution, offer substantial savings to the consumers and generate a new lighting industry.

The main purpose of the roadmap and subsequent update is to provide recommendations to industry and government on meeting the R&D challenges that must be overcome to reach the desired performance and cost requirements. To enumerate the challenges and highlight the alternate approaches, and hence the decision points, in the course of conducting R&D one must have a thorough knowledge of the technical issues and a clear understanding of the assumptions leading to the recommendations.

Jeff Tsao of Sandia National Laboratories, who assembled the recommendations, has been a major contributor to this field for many years. He not only provided a well-organized and logical set of challenges but thoroughly described the technical issues and the assumption leading to the recommendations. This volume therefore serves as tutorial source material for those who are not familiar with the details of this technical field.

We are indebted to Sandia National Laboratories who provided support in assembling the roadmapping material and, in particular, to Jeff Tsao, for this exceptionally comprehensive and well-written report.

In assembling this report, we had the benefit of contributions from many resources in solid-state lighting: industry, academia and national laboratories. We especially acknowledge contributions to the various chapters of this roadmap from:

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EXECUTIVE SUMMARY

SSL-LEDs and their Benefits

Solid-State Lighting through Light-Emitting Diodes (SSL-LEDs) is the use of solid-state, inorganic semiconductor light-emitting diodes to produce white light for illumination. Like inorganic semiconductor transistors, which displaced vacuum tubes for computation, SSL-LED is a disruptive technology that has the potential to displace vacuum or gas tubes (like those used in traditional incandescent or fluorescent lamps) for lighting.

The enhanced efficiency and versatility associated with SSL-LEDs over traditional vacuum or gas tubes will enable:

- Substantial reductions in electrical energy consumption
- Substantial reductions in carbon-related pollution
- Substantial improvement in the overall human visual experience
- Creation of new semiconductor technologies with spin-off benefit for national security and economic competitiveness
- Creation of a new optoelectronics-based lighting industry, with many new, high-quality jobs
- Substantial savings for the consumer

The Opportunity for the Nation

The science and technology base underlying semiconductor optoelectronics has advanced rapidly over the past decade, and SSL-LEDs have already begun to penetrate color, and some specialty white, lighting markets.

Nevertheless, tremendous challenges must be met for SSL-LEDs to achieve its potential for general white lighting. The opportunity for the United States is to create and execute a Government-sponsored Industry-driven initiative that harnesses our National Laboratories and Universities, and that accelerates the development of the science and technology base of SSL-LEDs. In doing so, penetration of SSL-LEDs into general white lighting will also be accelerated, along with its tremendous benefits.

SSL-LED Roadmaps

The first SSL-LED I Roadmap,[1] completed in March 2001, had as its objective the development of an industry-national-laboratory-university consensus on:

- The major commercial and military applications of SSL-LEDs, and their long-term benefits
- The technology performance targets needed to support these applications
- Some of the research challenges that would need to be met to achieve those target performances

This updated SSL-LED Roadmap, completed in August 2002, has as its objectives:

- An overall updating of the first roadmap
- A more quantitative enumeration of key SSL-LED technology attributes and targets
- A more detailed enumeration and prioritization of the research challenges that will be faced in meeting these technology targets, possible approaches to surmounting them, and some of the key decisions that must be made between competing approaches
- A first look at the lighting systems issues necessary to achieve mass penetration of SSL-LEDs into the marketplace

We note that this Roadmap focuses on general white lighting. Along the way, many niche intermediate lighting applications are already being, and will surely continue to be, developed. These "practice" applications are crucial for improving the performance and reducing the cost of solid-state lighting. However, because these applications are believed to be economically self-sustaining and do not involve the high simultaneous risk and reward associated with general white lighting, we do not include them in this Roadmap.

Technology Targets

The technology performance targets of SSL-LED II, assuming a major government-sponsored industry-driven

[1] Eric D. Jones, "Light Emitting Diodes (LEDs) for General Illumination: An OIDA Technology Roadmap" (Optoelectronics Industry Development Association, Mar, 2001).

initiative with full participation from Industry, National Laboratories and Universities, are:

Year	2002	2007	2012	2020
Luminous Efficacy (lm/W)	25	75	150	200
Lifetime (khr)	20	>20	>100	>100
Flux (lm/lamp)	25	200	1,000	1,500
Lumens Cost ($/klm)	200	20	<5	<2
Color Rendering Index (CRI)	75	80	>80	>80
Lighting Markets Penetrated	Low-flux	Incande-scent	Fluore-scent	All

Meeting these technology performance targets would enable penetration of incandescent lighting by 2007 and of fluorescent lighting by 2012, with massive displacement of incandescent lighting by 2012 and of fluorescent lighting by 2020. In addition, not listed in the table but equally important will be the development of new science and technology with significant spin-off national security and economic benefits, and of a new lighting culture that takes advantage of unique attributes of SSL-LEDs such as energy-efficiency, compactness, reliability and digital controllability ("smart" lights).

The Research Areas and Challenges

The technology targets listed above are believed achievable. The efficiency targets, even the year 2020 target of 200lm/W, are consistent with fundamental physics; and the equivalent electrical-to-optical power-conversion efficiency of 50% has already been achieved in similar technologies at non-visible wavelengths. The cost targets, even the year 2020 target of <2$/klm, are consistent with comparisons to more-mature high-volume semiconductor technologies.

Nevertheless, the targets are challenging: we are currently 6x away from the year 2012 efficiency target and >40x away from the year 2012 cost target. In order to achieve these targets, significant challenges must be overcome in three building-block technologies:

1. Substrates, Buffers and Epitaxy
2. Physics, Processing and Devices
3. Lamps, Luminaires and Systems

These building-block technologies range from fabrication of high-efficiency, low-cost semiconductor materials and epistructures; to the physics, design and processing of high-efficiency optoelectronic devices; to the packaging, white-light conversion, fixturing, and system issues associated with lighting for the 21st century and beyond.

We note that of these areas, lighting systems is the least mature. Lighting systems follow (and are pushed by) the development of the underlying technology; but also they must respond to (and are pulled by) market needs that can be difficult to anticipate. Nevertheless, lighting systems are the ultimate vehicle for implementing solid-state lighting, so we include a first look, however imprecise and incomplete, at their issues here.

Organization of Roadmap Tutorial

The remainder of this Roadmap Tutorial is organized as follows.

Chapter 0, "Technology and Roadmap Overview," contains a discussion of our overall SSL-LED lighting technology targets, as well as our lamp (chip and phosphor) technology sub targets. This Chapter also summarizes the key technology building blocks.

The next three Chapters 1-3 contain a tutorial on the building block technologies, or Challenge Areas, that underlie SSL-LEDs.

The last Chapter is an Appendix containing the processes and resources used in putting together the Roadmap Update.

0 TECHNOLOGY AND ROADMAP OVERVIEW

In this Chapter, we give an overview of SSL-LED technology and the Roadmap.

First, to put this technology in perspective, we briefly review the history of lighting technologies. The major technologies are: Fire, Incandescence, Fluorescence, and, most recently, Solid-State.

Second, we describe SSL-LED technology from the point of view of the birth-death lifecycle of photons, along with the three major design approaches to white-light production: wavelength conversion, color mixing, and hybrid approaches.

Third, we discuss the key attributes (luminous efficacy, lifetime, flux/package, purchase and ownership cost, color temperature and rendering) that are common to all lighting technologies, and discuss targets for the evolution of these attributes for SSL-LED technology over the next 18 years.

Fourth, we break these key attributes apart into "derivative" attributes (chip input power density and cost per unit area, and chip and phosphor wavelengths and efficiencies) for the semiconductor chips, phosphors, and packaging that SSL-LED technology will be based on, and discuss targets for the evolution of these attributes over the next 18 years.

Fifth, we discuss the energy, environment, quality of lighting and human productivity, national-security, and economic benefits of SSL-LED technology, assuming our targets are met.

Sixth, we summarize the building blocks associated with to SSL-LED technology.

0.1 History

Lighting technologies are substitutes for sunlight in the 425-675 nm spectral region where sunlight is most concentrated and to which the human eye has evolved to be most sensitive. The history of lighting[2] can be viewed as the development of increasingly efficient technologies for creating visible light inside, but not wasted light outside, of that spectral region.

The three traditional technologies are Fire, Incandescence, Fluorescence; the technology discussed in this Roadmap constitutes a new, fourth technology, Solid-State Lighting. These four technologies can be differentiated by the type of material (gas or solid) that emits the light, by the spectral bandwidth (broadband blackbody or narrowband) of the light emission, and by the fuel (chemical or electrical) used to create the light. These differences, in turn, have consequences on the fundamental costs and performance of the technologies.

0.1.1 Fire: chemically fueled blackbody emission

The first lighting technology is Fire. This technology involves the burning of a chemical fuel (usually a combination of gases, solids or liquids) to heat a gas or solid that emits broadband blackbody light. Because the light is broadband blackbody, most of which lies outside of the visible spectrum, fire is inherently inefficient.

Moreover, because the fuel is chemical and must be transported into the reaction zone, the transport mechanism itself (typically convective flow) can make it difficult to achieve high temperatures. Hence, most of the emitted light lies outside the visible spectrum, with the peak of that blackbody spectrum in the invisible infrared.

The history of Fire can be viewed as attempts to control the mechanism for fuel transport and burning, to increase the temperature of the emitting gas, and to enhance the amount of visible light emission. Hence, the evolution from: open fires (1.42 million years ago), to torches, to wax candles, to oil and kerosene lamps. The culmination of fire can be thought of as gas-fired lamps, first introduced by William Murdock in 1792, in which the fuel is converted into a continuous incoming stream of gas before being burned.

0.1.2 Incandescence: electrically fueled blackbody emission

The second lighting technology is Incandescence. This technology involves the use of electricity as the fuel to heat a gas or solid that emits broadband blackbody light. Because, as with Fire, the light is broadband blackbody, most of which lies outside the visible spectrum, Incandescence is also inherently inefficient.

However, because the fuel is electrical, and can be transported more easily into a small emitting zone than can chemical fuels, the emitting zone can be very hot. Hence, the peak of the blackbody spectrum can be arranged to be

[2] Brian Bowers, Lengthening the Day: A History of Lighting Technology (Oxford University Press, Oxford, 1998).

near the visible portion of the spectrum, and the efficiency of Incandescence can be much higher than that of Fire.

The history of Incandescence can be viewed as an attempt to increase the temperature of the emitting filament while maintaining an acceptable lifetime. Hence, the evolution from: electric arc, to carbon-filament, to metal-filament lamps. The culmination of Incandescence can be thought of as the tungsten-filament lamp with a trace amount of lifetime-enhancing halogen gases.

0.1.3 Discharge/Fluorescence: electrically fueled narrowband emission from gases

The third lighting technology is Discharge/Fluorescence. This technology involves the use of electricity as a fuel to excite (but not heat) a low-pressure gas that emits narrowband atomic line emission. This primary narrowband light can be used as is, or it can be absorbed and re-emitted as secondary light at different (longer) wavelengths through use of fluorescent or luminescent materials.

Because the light is narrowband, and can be concentrated in the visible portion of the spectrum, the efficiency of Discharge/Fluorescence is much higher than Incandescence. Indeed, the highest-efficiency lamp of any type is the sodium lamp, at 200 lm/W, which emits narrowband yellow light at 589 nm.

However, because the primary light is narrowband, it does not fill the visible spectrum, and appears colored. For general lighting, it is necessary to convert this narrowband emission into semi-broadband emission that optimally fills the visible spectrum and gives the appearance of white light. The history of Discharge/Fluorescence for general lighting has been driven by development of luminescent materials that can perform this conversion while surviving direct exposure to reactive gas plasma discharges. Hence, the evolution from early fluorescent lamps, which had a greenish, low-quality color, to modern fluorescent lamps with phosphor blends and relatively good-quality color.

0.1.4 Solid-State Lighting: electrically fueled narrowband emission from solids

The fourth and most recent lighting technology is Solid-State Lighting. This technology involves the use of electricity as a fuel to inject electrons and holes into a solid-state semiconductor material. When the electrons and holes recombine, light is emitted in a narrow spectrum around the energy bandgap of the material. Because the light is narrowband, and can be concentrated in the visible portion of the spectrum, it has, like Fluorescence, a much higher light-emission efficiency than Incandescence.

However, as with Fluorescence, because the light is narrowband, it does not fill the visible spectrum with light, and appears colored. Hence, the evolution of Solid-State Lighting must eventually include overcoming similar challenges associated with converting the narrowband emission into semi-broadband emission that fills the visible spectrum to give the appearance of white light.

Unlike in Fluorescence technology, the wavelength of the narrowband emission can be tailored relatively easily, hence can be adjusted either to increase the quantum efficiency, or to minimize the quantum energy (or Stokes-shift) inefficiency associated with its conversion to semi-broadband emission. Hence, this technology is potentially even more efficient than Fluorescence.

Both inorganic and organic semiconductors are being considered for this new generation of lighting technology.[3] Inorganic semiconductors (SSL-LEDs), which are much further developed, are the focus of this Roadmap; organic semiconductors (SSL-OLEDs) are the focus of a parallel and separate Roadmap.

The technology of inorganic-semiconductor-based solid-state lighting has been reviewed recently.[4] Light emission from inorganic semiconductors was first observed[5] by H.J. Round in 1907. The first device in which such light emission was controlled was the light-emitting diode (LED), demonstrated by Nick Holonyak and co-workers at the General Electric Corporation in 1962. The first commercial LED products were introduced in 1968: indicator lamps by Monsanto and electronic displays by Hewlett-Packard.

The initial performance of LEDs was poor, with maximum output fluxes of around one thousandth of a lumen, and only one color, deep red, available. However, steady progress has been made: at this point efficiencies and brightness are comparable to those of Incandescence, and the color range has been extended to the entire visible spectrum.

This progress has enabled significant penetration of monochrome applications such as traffic and automotive

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[3] A Bergh, M. G. Craford, A. Duggal, and R. Haitz, "The promise and challenge of solid-state lighting," Physics Today 54 (2001) 42-47.

[4] G. B. Stringfellow and M. G. Craford, High Brightness Light Emitting Diodes (Academic Press, San Diego, 1997).

[5] H. J. Round, "A Note on Carborundum," Electrical World 49 (1907) 309.

signaling, and limited penetration of specialty white lighting such as flashlights, walkway lights and LCD display backlighting. By analogy with the history of other disruptive technologies,[6] we expect these applications to provide crucial vehicles for evolutionary improvements in SSL-LED cost and performance. In addition, if accompanied by the revolutionary improvements anticipated in this Roadmap, it is likely that massive penetration of white lighting will occur, with the huge benefits discussed below in Section 0.5.

0.2 Birth-Death Life Cycle of Photons

SSL-LED technology can be viewed from two perspectives: how it is fabricated (form), and how it performs (function). Form and function are inter-related, of course: how any technology performs depends on what can be fabricated, and what needs to be fabricated is driven by desired performance. In this Section, we introduce SSL-LED technology from the point of view of function. In the next Section, we introduce SSL-LED technology from the point of view of fabrication.

SSL-LED technology can be thought of as a birth-death lifecycle of photons. At the heart of the technology is an LED. Electricity is supplied to the LED by an external power grid. The electricity is applied as a forward current to the p-n junction of the semiconductor that forms the LED, and negatively charged electrons and positively charged holes are injected into the semiconductor. The electrons and holes are trapped in special "active" layers where they recombine, producing monochromatic photons at energies near the bandgap of the semiconductor. These photons are extracted from the semiconductor, and converted into white light. Finally, they are delivered to the environment and eventually to the human visual system.

The overall efficiency, η, of that lifecycle can be thought of as the product of six individual (and interconnected) efficiencies:

$$\eta = \eta_{del} \cdot \eta_{inj} \cdot \eta_{\text{int}} \cdot \eta_{tra} \cdot \eta_{ext} \cdot \eta_{conv} \cdot \eta_{illum} \quad \text{Eq 1}$$

- η_{del} -- the efficiency with which electrons and holes are delivered to the semiconductor
- η_{inj} -- the efficiency with which electrons and holes are injected into the semiconductor
- η_{tra} -- the efficiency with which electrons and holes are transported through, and trapped in, the semiconductor
- η_{int} -- the efficiency with which electrons and holes recombine radiatively to create monochromatic photons
- η_{ext} -- the efficiency with which the monochromatic photons are extracted from the semiconductor chip
- η_{conv} -- the efficiency with which the monochromatic photons are converted (or mixed) to produce broadband white light
- η_{illum} -- the efficiency with which the light illuminates the environment and, ultimately, the human eye

In principle, these efficiencies, and that of the overall life cycle, may be nearly perfect. In practice, there are numerous opportunities for inefficiencies, and numerous challenges associated with reducing these inefficiencies.

0.2.1 Delivering electrons from the power grid

The first step is delivering electrical current to the SSL-LED light fixture.

Because the forward bias on a semiconductor LED is typically a few volts, the electrons must be delivered in the 2-5V range. Because a useful output optical power for illumination is of the order 10W per fixture, and electrical-to-optical conversion efficiencies will be of the order 10-50%, the delivered currents must be of the order (10W/4V)/0.25, or 10A. And, because the semiconductor is an asymmetric p-n junction, the voltage must be DC rather than AC. These voltages and currents are very different from those associated with traditional 110V and 220V AC power systems.

Hence, a general challenge will be the development of efficient power distribution or transformation systems for high (>10A) DC currents and low (<5V) DC voltages.

0.2.2 Injecting electrons and holes into the semiconductor

The second step is injecting electrons and holes from metal contacts into the n- and p-sides of the semiconductor.

Because of the high currents and low voltages associated with SSL-LEDs, the metal-semiconductor contact must have a very low resistance. However, low-resistance contacts usually require high doping densities in the

[6] C. M. Christensen, The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail (Harvard Business School Press, Boston, 1997).

semiconductor, and the wider the bandgap of the semiconductor, typically the more difficult to dope. For semiconductors with bandgaps corresponding to visible and UV light, this is a serious issue.

Hence, a general challenge will be the development of low resistance metal-semiconductor contacts with virtually no parasitic ohmic losses during electron or hole injection.

In addition, it is likely to be necessary to inject high densities of electrons and holes, to produce the highest number of lumens per unit chip area, and hence to reduce the lumens cost per unit chip area. However, a balance will need to be struck between higher injection densities, which will enable lower cost but at the expense of high operating temperatures and possibly lower performance; and lower injection densities, which will enable lower operating temperatures and possibly higher performance at the expense of higher cost.

0.2.3 Transporting and trapping the electrons and holes

The third step is transporting electrons and holes through the body of the semiconductor material, and then trapping them in regions where they can recombine and emit light.

Because transport and trapping require very different kinds of semiconductor materials properties, devices are generally constructed from sequences of epitaxial layers, each of which performs different functions. And, because radiative recombination is faster the more the electrons and holes overlap in space, the epitaxial layers used for trapping will often be bandgap nanostructures of low dimensionality (quantum wells, wires and dots).

Hence, a general challenge will be the development of uniform, precise epitaxial bandgap nanoengineering that enables efficient vertical and lateral electron and hole transport without ohmic loss, as well as efficient trapping of those electrons and holes.

0.2.4 Creating photons

The fourth step is recombining of the electrons and holes to produce photons.

However, electrons and holes may also recombine in ways that do not lead to photons, particularly in materials with structural defects, such as impurities, dislocations, or grain boundaries. Some defects (e.g., dopant impurities), are deliberately introduced to enhance other properties; others are caused by imperfections in the starting substrates, in the epilayers, or in mismatches between the substrate and the epilayers.

Hence, a general challenge will be the development of near-perfect semiconductor substrates, buffers and epi-materials, or imperfect epi-materials with artificial nanostructures, for which radiative recombination dominates nonradiative recombination (by at least 10x).

0.2.5 Extracting photons from the chip

The fifth step is extracting photons from the semiconductor material.

In an LED with a planar, unstructured top surface, much of the light that is emitted randomly in all directions from inside the semiconductor is totally internally reflected and never escapes. Practical high-brightness LEDs are therefore either non-planar, where the chip and its surfaces have been shaped or textured, or engineered so that light is not emitted randomly from inside the semiconductor.

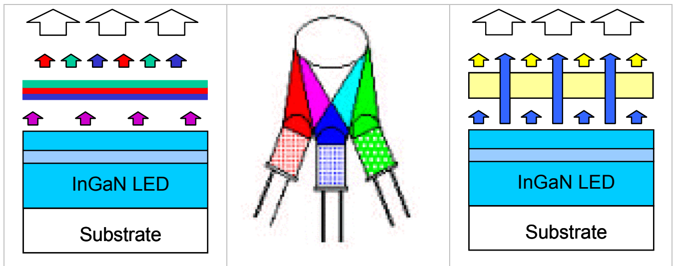
Even then, it is difficult to extract all of the light. Indeed, for one material (AlGaInP) in the deep red, even though the process of creating photons is essentially 100% efficient, the overall power conversion efficiency from the best chip-shaped devices is still only 50%, due primarily to the remaining inefficiency in the process of extracting the light.

Hence, a general challenge will be the development of optimized light emission pattern and overall chip shape for high (>95%) efficiency photon extraction from the chip.

0.2.6 Transforming monochromatic into white light

The sixth step is transforming the narrowband emission that results from radiative recombination in the semiconductor into broadband white light.

Such white light can be generated by three general approaches, illustrated in Figure 1. The first is the wavelength-conversion approach; the second is the color-mixing approach; and the third is a hybrid between the two. It is yet to be determined which approach will ultimately provide the best cost/performance tradeoff – at present, they each have strengths and weaknesses, and they each face different challenges.



A. The wavelength conversion approach, in which white light is created by using a single UV LED to excite a tri-color phosphor.	B. The color mixing approach, in which white light is created by mixing primary light from three LEDs (red, green, blue).	C. A hybrid approach, in which white light is created by mixing primary light from a blue and/or red LED with light created by using the blue LED to excite a mono- or duo-color phosphor.

Figure 1. The three possible approaches to white-light production. Courtesy of S. Nakamura (UCSB) and Paul Martin (LumiLeds).

Because the choice of approach is so fundamental, we will refer to them throughout this Roadmap. We attach to every Challenge discussed the abbreviation "WC" if it pertains to the wavelength-conversion approach, "CM" if it pertains to the color-mixing approach, or "Hy" if it pertains to the Hybrid approach. As technology progresses, one approach may "win," and the Challenges associated with the other approaches will disappear. However, it is also possible that different approaches will be preferred for different applications, and that all the Challenges will persist.

Related to the question of which approach to white light production is the question of how many colors, and in what wavelength ranges, are best suited to SSL-LED technology. This is a complex issue, determined by a balance between three constraints: creating pure white (with a wide latitude for color temperature tuning), a high color rendering ability, and a high luminous efficacy.

6A Wavelength Conversion Approach. The first approach for transforming narrowband emission into broadband white light involves using UV LEDs to excite phosphors that emit light at down-converted wavelengths.[7] In general, this approach is likely to be the lowest cost, because of its low system complexity (only a single LED chip, and since the colors are created already blended, lamp-level optical and color engineering is minimized). It is also likely to be the least efficient, because of the power-conversion loss associated with the wavelength down-conversion; and the least flexible, since the colors are "preset" at the factory.

Hence, a general challenge will be the development of UV (340-380nm) LEDs with high (>70%) external power-conversion efficiency and input power density, and multicolor phosphor blends with high (>85%) quantum efficiency.

6B Color Mixing Approach. The second approach for transforming narrowband emission into broadband white light is to combine light from multiple LEDs of different colors.[8] In general, this approach is likely to be the most efficient, as there are no power-conversion losses associated with wavelength down-conversion. It is also likely to be the most flexible, since the hue of the light can be controlled by varying the mix of primary colors, either in the lamp, or in the luminaire. However, it is also likely to be the most expensive, because of its high system complexity (multiple LED chips, mixing of light from separate sources, and drive electronics that must accommodate differences in voltage, luminous output, element life and thermal characteristics among the individual LEDs).

Hence, a general challenge will be the development of red, green and blue LEDs with high (>50%) external power-conversion efficiencies and input power density, and low-cost optics and control strategies for spatially uniform, programmable color-mixing either in the lamp or in the luminaire.

6C Hybrid Approach. The third approach for transforming narrowband emission into broadband white light is a hybrid approach. The present generation of white LEDs, with luminous efficacies of 25 lm/W, is based on this approach. Primary light from a blue (460nm) InGaN-based LED is mixed with blue-LED-excited secondary light from a pale-yellow YAG:Ce^{3+}-based inorganic phosphor. The secondary light is centered at about 580 nm with a full-width-at-half-maximum line width of 160 nm. The combination of partially transmitted blue and re-emitted yellow light gives the appearance of white light at a color temperature of 8,000 K and a luminous efficacy of about 25 lm/W. This combination of colors is similar to that used in black-and-white television screens – for which

[7] Thomas Justel, Hans Nikol, and Cees Ronda, U.S. Philips Corporation, "White light emitting diode," Patent Number US 6084250 (Jul 4, 2000).

[8] M. Koike, N. Shibata, H. Kato, and Y. Takahashi, "Development of High Efficiency Gan-Based Multiquantum-Well Light-Emitting Diodes and Their Applications," IEEE Journal of Selected Topics in Quantum Electronics 8 (2002) 271-277.

a low-quality white intended for "direct" rather than "indirect" viewing – is acceptable.

Other variations of this approach are possible. The simplest extension would be to mix blue LED light with light from a blue-LED excited green and red duo-color phosphor blend[9] – this variation is likely to be give the best balance between efficiency, color quality, cost and system complexity. A more complex but perhaps more efficient extension of this approach would be to mix blue and red LED light with light from a blue-LED excited green phosphor.[10]

In general, this approach is intermediate amongst the three approaches in efficiency, complexity and cost. It is likely to be intermediate in efficiency, as power-conversion losses from wavelength down-conversion are less from the blue than from the UV, but still greater than no power-conversion losses. It is likely to be intermediate in cost and system complexity, as only one (or at most two) LEDs is used, but light from the LED must still be color-mixed with light from the phosphor.

Hence, a general challenge will be the development of blue LEDs with high (>60%) external power-conversion efficiencies and input power density, blue-excitable duo-color phosphor blends with high (>80%) quantum efficiency, and low-cost optics for spatially uniform color-mixing in the lamp.

0.2.7 Delivering light to the viewer

The seventh and final step is delivery of the white light that has been generated, first to that part of the environment that is to be illuminated, and then to the viewer.

SSL-LEDs have many advantages in this regard. Because they are point sources, they can deliver directed light more efficiently to small areas. Their compactness enables more flexibility in the design of unobtrusive and architecturally blended luminaires. Their ruggedness enables them to be mounted in high-stress positions. And, it may be possible to program their color and direction for optimal interaction with the human visual system. However, we are at a very early stage in understanding how to make use of these advantages.

Hence, a general challenge will be the development of luminaires and lighting systems that convert intense point sources to diffuse light suitable for large-area illumination, which blend into the human workplace, and which enhance human productivity and comfort.

0.3 Lamp Targets

Because solid-state lighting is a new technology, it will bring with it a number of new system-level attributes. These include programmability, small volume, ruggedness and immunity to vibration, compatibility with environmental extremes (cold and heat), and an enhanced efficiency in directed illumination. Ultimately, these system-level attributes are expected to enhance considerably the competitiveness of solid-state lighting relative to traditional incandescent and fluorescent lighting technology.[11]

At this stage, however, it is difficult to assess quantitatively the impact of these system-level attributes, and it is difficult to quantify targets for their evolution. Hence, in this Roadmap we focus on lamp-level attributes that are universal to all lighting technologies: luminous efficacy, lifetime, flux/lamp, purchase cost and color-rendering index. A summary of targets for these attributes is shown in Table 1. The targets for 2007 are intended to enable SSL-LED technology to compete with incandescent lamps; the targets for 2012 are intended to enable SSL-LED technology to compete with fluorescent lamps.

The general intent is that these targets would be met simultaneously, in a single SSL-LED lamp. However, the targets are quite aggressive, and the end-use markets in their infancy, so we leave open at this point the question of whether only subsets of the targets will be met in any single SSL-LED lamp, depending on its intended white lighting application.

In this Section, we discuss each of these target attributes, in the order listed. We also discuss two additional "derived" attributes. The first is ownership cost, which depends on efficiency, lifetime and purchase cost. The second is the correlated color temperature (CCT), which, together with the color-rendering index (CRI), defines the

[9] Christopher H. Lowery, Gerd O. Mueller, and Regina B. Mueller-Mach, Lumileds Lighting U.S., LLC, "Phosphor and White Light LED Lamp Using the Phosphor," Patent Number EP1145282A2 (Oct 17, 2001).

[10] Tetsushi Tamura, Hideo Nagai, Masanori Shimizu, Yoko Shimomura, and Nobuyuki Matsui, Matsushita Electric Industrial Co., Ltd., "LED Lamp," Patent Number EP1160883A2 (Dec 5, 2001).

[11] For example, although the luminous efficacy of a 15W fluorescent lamp may nominally be 60 lm/W, after fixturing it may only be 35 lm/W, and after accounting for wasted undirected illumination, may only be 30 lm/W. A solid-state lamp is likely to suffer fewer of these system-level inefficiencies. Chips Chipalkatti, "LED Systems for Lighting: Where the Rubber Hits the Road," OIDA Solid-State Lighting Workshop (Albuquerque, 30 May 2002).

TECHNOLOGY	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incandescent	Fluorescent
Luminous Efficacy (lm/W)	25	75	150	200	16	85
Lifetime (khr)	20	>20	>100	>100	1	10
Flux (lm/lamp)	25	200	1,000	1,500	1,200	3,400
Input Power (W/lamp)	1	2.7	6.7	7.5	75	40
Lumens Cost ($/klm)	200	20	<5	<2	0.4	1.5
Lamp Cost ($/lamp)	5	4	<5	<3	0.5	5
Color Rendering Index (CRI)	75	80	>80	>80	95	75
Lighting Markets Penetrated	Low-flux	Incandescent	Fluorescent	All		

Table 1. SSL-LED Lamp Targets. Note that metrics for color quality appropriate for SSL-LEDs have not yet been developed; hence the CRI values should be thought of as interim targets. The lumens and lamp costs are "street" costs, roughly 2x higher than OEM costs.

overall color quality of the light.[12] Ownership cost and overall color quality are arguably the most important attributes of lighting technologies.

0.3.1 Luminous Efficacy

A primary attribute of a lighting source is its luminous efficacy (lm/W): the efficiency of the conversion from electrical power (W) to optical power (W), combined with the efficiency of the conversion from optical power (W) to the luminous flux (lumen = lm) sensed by the human eye within its spectral responsivity range.

The luminous efficacy of monochromatic radiation K(λ) at wavelength λ is shown in Figure 2, and is defined by $K(\lambda) = K_m \times V(\lambda)$, where $K_m = 683$ lm/W, and V(λ) is the CIE-defined wavelength-dependent spectral luminous efficiency of photopic vision. K(λ) represents the theoretical maximum light source efficacy at a given wavelength. Monochromatic light at 555 nm, at which the human photopic vision sensitivity peaks, has a maximum luminous efficacy of 683 lm/W; monochromatic light at 450 nm has a maximum luminous efficacy of only 26 lm/W.

The luminous efficacy of polychromatic radiation is a convolution of its spectral power distribution S(λ) with the luminous efficacy of radiation K(λ):

$$K[lm/W] = \frac{K_m \int S(\lambda)V(\lambda)d\lambda}{\int S(\lambda)d\lambda} \quad \text{Eq 2}$$

[12] A general reference on color technology is: Roy S. Berns, Billmeyer and Saltzman's Principles of Color Technology, Third Edition (John Wiley and Sons, Inc., New York, 2000).

Hence, in order to produce a high luminous efficacy, the spectral power distribution S(λ) of the light source should overlap as best as possible the luminous efficiency of photopic vision V(λ).

Indeed, the difference between the luminous efficacies of broadband and narrowband emitters is described by Eq 2. The huge disadvantage of a broadband blackbody light emitter is that it emits light at wavelengths where the luminous efficiency of photopic vision is near zero. The huge advantage of a narrowband light emitter is that it can be tailored to emit light at wavelengths where the luminous efficiency of photopic vision is high.

The past-four-decade evolution of total luminous efficacy

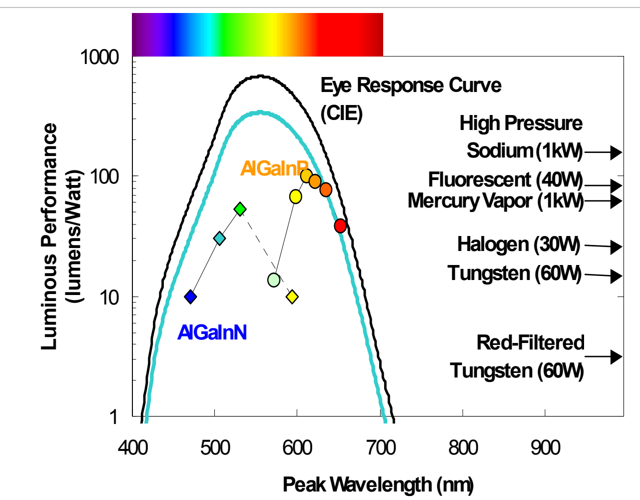


Figure 2. The luminous efficacy, K(λ), of monochromatic radiation at wavelength λ. Also shown are the state-of-the-art luminous efficacies of monochromatic LEDs (data points), and of various white light technologies (arrows at the right). Courtesy of M.G. Craford, LumiLeds.

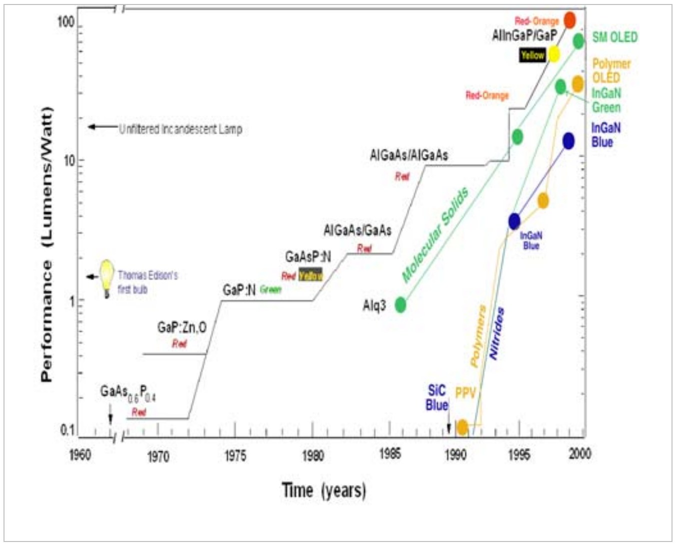


Figure 3. The evolution of total efficacy of solid-state lighting technologies. Also shown are typical efficacies for traditional incandescent and fluorescent technologies. [Courtesy of George Craford, LumiLeds Lighting.]

of various monochromatic solid-state lighting sources is illustrated in Figure 3. Progress has been nothing short of spectacular. Recently, LumiLeds and Philips announced a 610 nm (orange/red) LED with a luminous efficacy of 100lm/W; and LumiLeds has reported green InGaN-based LEDs having luminous efficacies in the range 50 lm/W.

Progress of this sort cannot continue indefinitely, since luminous efficacies are limited by $K(\lambda)$ for monochromatic light and by Eq 2 for white light. Nevertheless, we anticipate significant continued progress. Currently, luminous efficacies for white light LEDs are of the order 25 lm/W. Our technology targets are to achieve 75 lm/W by 2007, 150 lm/W by 2012, and 200 lm/W by 2020. For comparison, the luminous efficacies of incandescent and fluorescent lights are 16 lm/W and 85 lm/W, respectively, which are roughly 10x and 2x lower than our 2012 targets for SSL-LEDs.

0.3.2 Lifetime

A second primary attribute of a lighting source is lamp lifetime.

This can be (and has been) defined in different ways, depending on the light source. In the Incandescent age of Edison, lifetime was defined as the point at which 50% of the bulbs fail. For SSL-LEDs, lifetime is sometimes a similar mean-time-before-failure (MTBF) number, but now is more commonly taken to be the 50% lumen depreciation level.

No matter how it is measured, lifetimes for SSL-LEDs are generally long – a significant factor in the penetration of LEDs into signaling applications (traffic lights, displays, automotive) with high labor costs for replacement and high safety-consequence costs for failure.

Of course, the replacement and safety costs vary greatly with application, and we expect there to be a spectrum of needs for various lifetimes. For the dominant use of white light, industrial and office lighting, a lifetime of 20,000 hrs can already be considered very long. In a typical office, where a lamp might be on 60 hours per week, 50 weeks per year, 20,000 hrs would correspond to a lifetime of about 7 years. However, in a heavy-use factory running "24x7," 20,000 hrs would correspond to a lifetime of only about 2.3 years.

Our technology targets are to achieve lifetimes of >20,000 hrs by 2007, and >100,000 hrs by 2012 and beyond. We target >100,000 hrs so that solid-state lighting will satisfy even the most demanding applications; as discussed above >20,000 should be more than sufficient for mainstream applications.

0.3.3 Flux/Lamp

A third attribute of a lighting source is the total light output produced per bulb, or lumens per lamp.

Figure 4 shows the substantial progress that has been made in the past three decades in increasing the luminous flux obtained from monochromatic red LED lamps.

Typical conventional LED indicator lamps are $(0.25mm)^2$

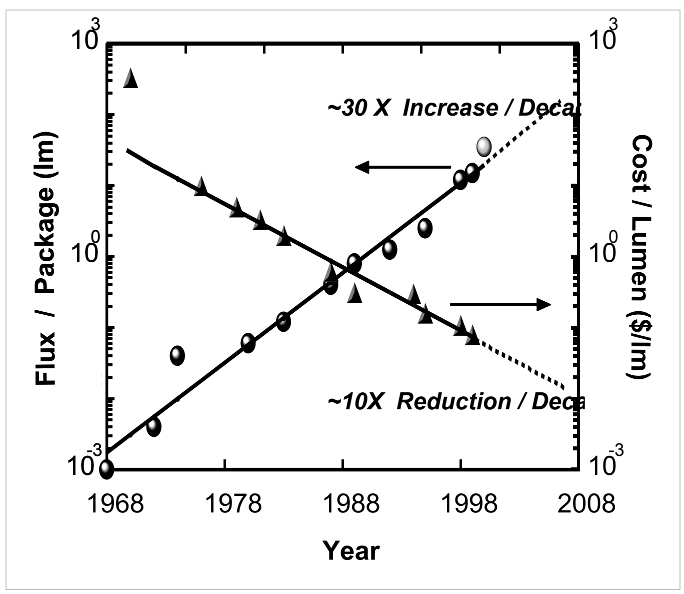


Figure 4. The evolution of lm/package and cost/lm for red LEDs. [Courtesy of Roland Haitz, Agilent Technologies.]

square, are mounted in packages that can handle about 0.1 W of input power, and emit about 1-2 lumens. Larger chips, up to about 1 mm^2 in size, packaged to handle several watts, are now available with outputs of tens of lumens and hundreds of milliwatts of optical power. Such packages are increasingly used for red, amber, and green traffic signaling lights.

Even larger chips, emitting hundreds or even thousands of lumens at tens of watts input power, will be required to compete with traditional incandescent and fluorescent technologies. A traditional 75 W incandescent bulb, with a luminous efficacy of 16 lm/W, puts out approximately 1.2 klm; a traditional tube-type 40 W fluorescent bulb, with a luminous efficacy of 85 lm/W, puts out approximately 3.4 klm. These outputs are yet another two orders beyond those of currently available single-chip SSL-LEDs.

Our technology targets are to achieve fluxes/package of 200 lm/lamp by 2007, 1,000 lm/lamp by 2012, and 1,500 lm/lamp by 2020.

Note that the input power to the lamp is the flux/lamp divided by the luminous efficacy, so these targets can be deduced to be 2.7 W/lamp by 2007, 6.7 W/lamp by 2012, and 7.5 W/lamp by 2020.

0.3.4 Purchase Cost

A fourth attribute of a lighting source is OEM manufacturing cost (for the supplier), or, with suitable mark-up, street purchase cost (for the consumer), in units of $/klm.

The current street price of white LEDs is approximately $200/klm. As discussed in the next Subsection 0.3.5, in order for the ownership cost of solid-state lighting to become competitive with that of traditional fluorescent lighting, the purchase cost must be roughly $5/klm. Hence, our technology targets are to achieve costs per lumen of $20/klm by 2007, <$5/klm by 2012, and <$2/klm by 2020.

Note that the cost of lighting per lamp is the cost per lumen times the lumens per lamp. Hence, the target street purchase cost per lamp can be deduced to be <$5/lamp by 2012. The OEM manufacturing cost of a lamp will be less than this, by roughly 2x.

Note also that the cost per klm must decrease by a factor 40x from the current cost per klm. Clearly, this decrease represents a tremendous challenge. We know some of the ways costs can decrease over time. One way might be through increases in power-conversion efficiency (perhaps 6x). We note that it is mainly through such increases in power-conversion efficiency that the cost of red LEDs, illustrated in Figure 4, has fallen so fast over the years -- about 10x per decade. Another way might be through increases in input power density to, and improved thermal management of, the chip (perhaps another 5x); and yet another way might be through decreases in the manufacturing cost of the chip itself (perhaps another 1.5x). The product of these factors is approximately 40x.

0.3.5 Ownership Cost

A fifth attribute of any lighting source, one that represents a combination of the previously discussed attributes, is "ownership" cost.

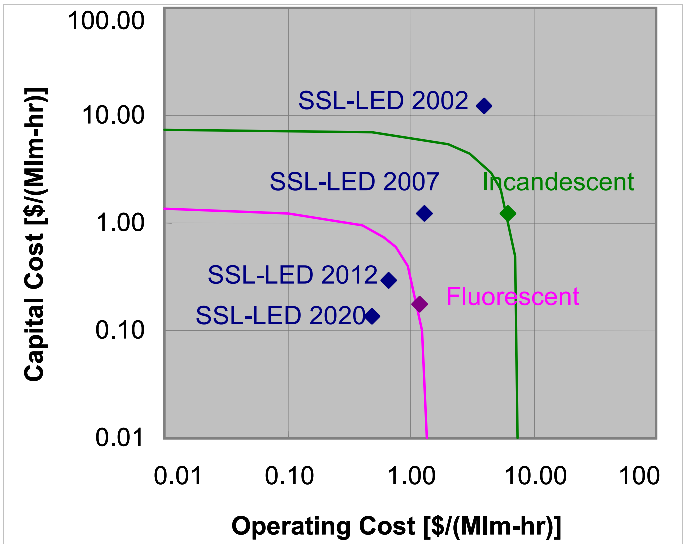
Ownership cost can be viewed as a single figure-of-merit for the economic case for SSL-LEDs. It is the sum of two costs: operating and capital:[13]

$$Cost_{Ownership} = Cost_{Operating} + Cost_{Capital} \qquad \text{Eq 3}$$

The operating cost is the ratio between the cost of the fuel and the luminous efficacy (the efficiency with which the fuel is burned to create usable light). This cost is straightforward to calculate, given an end-user price of electricity, and the luminous efficacies discussed previously. Here, we assume an end-user electricity cost of 10¢/(kW-hr).

$$Cost_{Operating} = \frac{ElectricityCost\,(¢/[kW \cdot hr])}{LuminousEfficacy\,(lm/W)} \qquad \text{Eq 4}$$

[13] This Equation is similar to that given in Equation 25-1 of M. S. Rea, Editor, The IESNA Lighting Handbook, 9th Edition (Illumination Engineering Society of North America, New York, 2000).



COST OF LIGHT	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incan-descent	Fluo-rescent
Capital Cost [$/(Mlm-hr)]	12.00	1.25	0.30	0.13	1.25	0.18
Operating Cost [$/(Mlm-hr)]	4.00	1.33	0.67	0.50	6.25	1.18
Ownership Cost [$/(Mlm-hr)]	16.00	2.58	0.97	0.63	7.50	1.35

Figure 5. Purchase and Operating Costs associated with traditional lamps and SSL-LED target lamps. The sum of the two costs is the Ownership cost. The green curve is an iso-ownership cost curve for incandescent lighting, the purple curve is an iso-ownership cost curve for fluorescent lighting.

The capital cost is the cost to purchase the bulb or lamp, plus the labor cost to replace the bulb or lamp when it burns out, both amortized over its lifetime.[14] For purchase cost, we use the costs discussed above. However, for lifetime, we assume a cut-off at 20,000 hrs – in other words, once a lamp has a lifetime greater than 20,000 hrs, it may, for most applications, be considered infinite – the fixture itself, or some other aspect of the lighting system or infrastructure, will need replacing before the lamp will. For the labor cost to replace the lamp, we use $1 per replacement, divided by the flux/lamp (lm/lamp) numbers also given above. This labor cost assumes a labor rate of $15/hr and 4 minutes per lamp change.

$$Cost_{Capital} = \frac{Cost_{Pur}(¢/klm) + Cost_{Lab}(¢/klm)}{Lifetime(hr)} \quad \text{Eq 5}$$

The operating and purchase costs associated with traditional lighting technologies, as well as the targets for SSL-LEDs discussed above, are illustrated graphically and tabularly in Figure 5.

For incandescent and fluorescent lamps, ownership costs are determined mainly by operating costs and, for a common price of electricity, by luminous efficacies. Since fluorescent lamps are roughly 5x more efficient than incandescent lamps, their ownership cost, and "iso-ownership-cost" contour, is also roughly 5x less.

For solid-state lighting, the opposite is true: ownership costs are currently determined mainly by capital cost. Hence, a major challenge for SSL-LEDs will be to reduce this capital cost.

If the SSL-LED targets on both purchase and operating costs are met, however, one can see from Figure 5 that the ownership cost will decrease dramatically. Currently, SSL-LED ownership cost is 2x that of incandescent and 10x that of fluorescent life-ownership costs. By 2007, the ownership cost will be lower than incandescent, but still higher than fluorescent, ownership costs. By 2012, the ownership cost will be comparable to, and somewhat lower than, fluorescent ownership costs. And, by 2020, the life-ownership cost will be about half of that of fluorescent lamps.

To put these targets in a larger historical perspective, Figure 6 shows estimated ownership costs of light for the past 200 years. This trend represents a tenfold decrease in cost every 50-60 years. Also shown on the plot are the SSL-LED II targets, illustrating that our year 2007, 2012 and 2020 targets are consistent with this trend.

[14] In principle, this cost also includes the disposal cost of the bulb or lamp. This cost can be substantial for fluorescent lamps containing toxic elements such as mercury. Here, we neglect such costs, though it should be included in future Roadmaps.

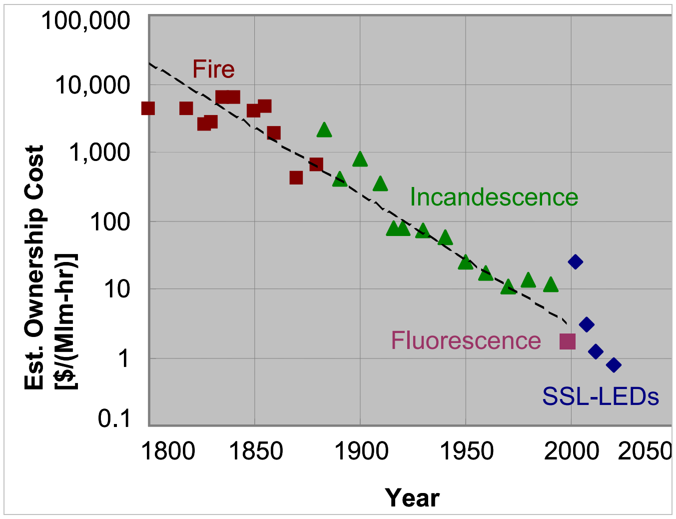


Figure 6. Estimated ownership costs of light, in 1992 dollars. Data for Fire and Incandescence for operating cost are from the work of W. Nordhaus,[15] to which estimates of capital cost have been added. Data for Fluorescence are from our estimates. Data for SSL-LEDs are the targets of this Roadmap.

Note, though, that this trend must eventually run its course. When the capital cost of SSL-LEDs becomes so low that ownership costs are dominated by operating costs, and once luminous efficacies approach 100%, there is little room left for improvement. Further decreases in ownership cost will need to come from decreases in the cost of electricity, or in the efficiency with which light is utilized.

0.3.6 Color Rendering

The sixth attribute of a lighting source is its ability to faithfully render the colors of non-white objects that it illuminates. One quantitative measure of the faithfulness of color rendering is the color-rendering index (CRI).

This measure is based on comparing the colors rendered by a given light source to the colors rendered by a "perfect" reference light source with the same CCT – daylight illumination for CCTs > 5,000 K and Planckian blackbody radiation for CCTs < 5,000 K. The comparison is made for a set of sample colors; the weighted average of the color rendering for each of these sample colors gives the General Color Rendering Index R_a for the light source.

With a maximum value of 100, R_a gives a scale that matches reasonably well with the visual impression of color rendering of illuminated scenes. For example, lamps having R_a greater than 80 are considered high quality and suitable for interior lighting, while lamps having R_a greater than 95 are suitable for visual inspection applications.

However, R_a is not a perfect measure of color rendering quality. It is based on the assumption that a continuous blackbody spectrum will render colors best. Because of the complexity of the human visual system, this may not always be true: removing certain wavelength regions (e.g., the 590 nm wavelength region in GE's recently developed "Reveal" incandescent lamps) may sometimes enhance the human visual system's perception of color.[16] Hence, it will be important to develop new measures for color quality, particularly for SSL-LEDs, which have the capability for tailored, selective filling of the wavelength spectrum.

In the meantime, as the CRI is the best currently accepted measure for color rendering, we use it as an "interim" metric for SSL-LEDs. Our technology targets are to achieve CRIs of 80, appropriate for medium-quality lighting, by 2007, and CRIs of >80, appropriate for high-quality lighting, by 2012 and beyond.

Note that there are strong trade-offs between good color rendering and luminous efficacy. The best color rendering is achieved by light of many wavelengths, while the highest luminous efficacy is achieved by light concentrated at the yellowish-green wavelength (555 nm) to which the human eye is most sensitive. At one extreme, a low pressure sodium lamp (having a light orange color, used in some highways and parking lots) has a luminous efficacy of about 200 lm/W, the highest among available discharge lamps, but colors are not very distinguishable: a red car would appear to be gray. At the other extreme, a xenon arc lamp, with a spectrum very similar to that of daylight and exhibiting excellent color rendering, has a luminous efficacy of only 30 lm/W.

To illustrate the trade-off between CRI and luminous efficacy, Figure 7 shows results of simulations in which, for a fixed color temperature and fixed line widths, the wavelengths and power densities of 2-, 3-, 4- and 5-color white light sources were varied to deduce the envelope of maximum CRI and luminous efficacy. As the maximum luminous efficacy decreases, the maximum CRI increases, as the wavelengths "fill" and move farther to the extremes of the visible spectrum. Moreover, the envelope of maximum CRI and luminous efficacy depends strongly on

[15] William D. Nordhaus, "Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not," in Timothy F. Breshnahan and Robert J. Gordon, The Economics of New Goods (The University of Chicago Press, Chicago, 1997).

[16] N. Narendran, "Solid-State Lighting Systems / Applications Issues," OIDA Solid-State Lighting Workshop (Albuquerque, May 30, 2002).

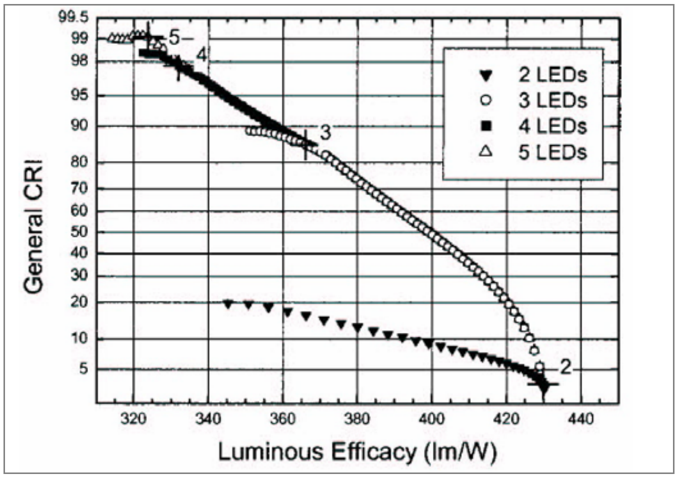


Figure 7. The envelope of maximum CRI and luminous efficacy for multi-LED white light sources with 30nm FWHM line widths and a 4870K color temperature. After A. Zukauskas, R. Vaicekauskas, F. Ivanauskas, R. Gaska, and M. S. Shur, "Optimization of white polychromatic semiconductor lamps," Applied Physics Letters 80 (2002) 234-6.

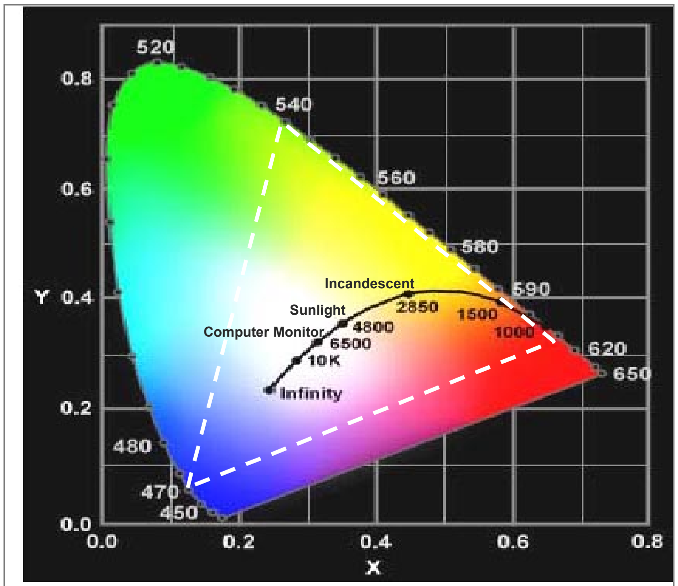


Figure 8. The CIE 1931 chromaticity diagram. The horseshoe boundary, called the spectrum locus, represents monochromatic light. The curve in the center, called the Planckian locus, represents white light. This curve traces the chromaticity coordinates of blackbodies at temperatures between 1,000 and 20,000K, which are perceived by the human visual system to be white. The vertices of the white triangle, at 460, 540 and 610nm, are the centers of the target wavelength ranges for tri-color solid-state white lighting. The interior of the triangle is the "gamut" of colors that would be available to such a light source.

the number of wavelengths. The maximum CRI begins to saturate at 3 for a 2-color source, at 85 for a 3-color source, at 95 for a 4-color source, and at 98 for a 5-color source.

Of course, the more colors, the more complex the lamp must be. Hence, it is likely that a tri-color source, which can achieve our target CRIs of 80 or greater, will provide the best balance between CRI, luminous efficacy, and lamp complexity.

Indeed, the situation for tri-color white light sources composed of broadband phosphors, or of a combination of narrowband LEDs and broadband phosphors, is even more favorable, and CRIs greater than 85 should be possible. Here, SSL-LED technology has advantages and disadvantages relative to fluorescence technology. On the one hand, their initial narrowband light is available in a much greater range of wavelengths, including the visible and the near UV, rather than limited to the available emissions from a gas. On the other hand, phosphors that can simultaneously be excited by these wavelengths while emitting at wavelengths optimal for good CRI have thus far been limited.

0.3.7 Color Temperature

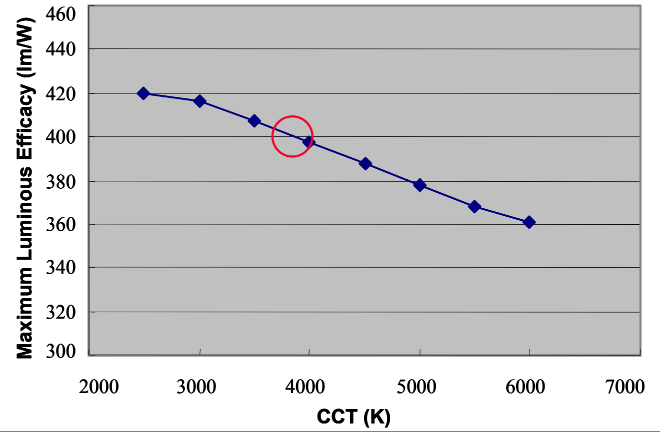
A seventh attribute of a lighting source is its apparent color when viewed directly, or when illuminating a perfectly white object.

This attribute can be quantified through use of chromaticity coordinates (x,y) on the CIE 1931 chromaticity diagram shown in Figure 8. These chromaticity coordinates apply both to monochromatic as well as white light.

The chromaticity coordinates of monochromatic light are represented by the boundary of the horseshoe (the "spectrum locus"). The chromaticity coordinates of mixtures of monochromatic light are intensity-weighted linear combinations of the chromaticity coordinates of the individual monochromatic lights. In other words, a mixture of two colors will produce a chromaticity coordinate falling on the line between their respective chromaticity coordinates.

The chromaticity coordinates of white light lie along the curved "Planckian" locus in the center of the diagram. The type of white on the Planckian locus is specified by the blackbody temperature in Kelvin and is called the color temperature. For example, mixing two equal-intensity LEDS with wavelengths at 485 nm (blue) and 583 nm (orange) will produce white color with a color temperature of about 4,000 K.

Strictly speaking, color temperature cannot be used for color coordinates (x,y) off the Planckian locus. In these



			Wavelengths (nm)		
CCT (K)	CRI	Maximum luminous efficacy (lm/W)	B	G	R
2500	80	419	463	547	610
3000	80	416	462	544	608
3500	80	408	462	543	607
4000	80	397	461	542	606
4500	80	387	460	540	605
5000	80	378	459	539	604
5500	80	368	459	539	604
6000	80	361	459	539	604

Figure 9. Maximum luminous efficacy as a function of color temperature for a tricolor white light source with a CRI of 80 and FWHM line widths of 20nm. The table below lists the wavelengths of the three colors. Results were obtained using a spreadsheet-based simulator/solver: Yoshi Ohno, "White LED Simulator II" (NIST, Jul 11, 2002)..

cases, 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. In principle, the CCT can be deduced by constructing "iso-CCT" lines, which intersect the Planckian locus. In practice, white light sources must lie very close to the Planckian locus, as the human eye is extremely sensitive to even small deviations.

Note that the CCT, though important, is not difficult to engineer. For a tri-color SSL-LED lighting source, the gamut of colors available, as indicated by the white triangle in Figure 8, is more than enough to specify virtually any desired CCT.

However, as with the CRI, there is a strong trade-off between CCT and luminous efficacy. This trade-off is illustrated in Figure 9 for a tri-color white light source. As CCT decreases, the proportion of red to blue light increases. Since, in order to achieve reasonable color rendering, the blue wavelength is so short that the eye is actually more sensitive to the red than to the blue, the overall luminous efficacy increases. At a color temperature of about 3900K, in between those for typical incandescent lamps and daylight, the maximum luminous efficacy is 400lm/W. This is the number we use throughout this Roadmap to represent the luminous efficacy of a 100%-efficient tricolor solid-state lighting source.

Also listed in Figure 9 are the wavelengths of the tri-color white light source that maximizes luminous efficacy at fixed CRI=80 as a function of CCT, where the chromaticity coordinates are exactly on the Planckian locus. The wavelengths are similar to those of the tri-phosphor blends used in fluorescent lamps, and are of course near the "three-peaked" spectral response of the human visual system.

Hence, in this Roadmap, we assume target ranges of wavelengths centered at those colors: red (590-630 nm), green (520-560 nm), and blue (440-480 nm).

0.4 Chip and Phosphor Sub targets

Note that the attributes and targets discussed in Section 0.3 apply to SSL-LED lamps as a whole. These lamps will be composed of pieces, each of which will have derivative attributes and targets that must be met in order for the lamp targets to be met. In the three approaches to producing white light, the two major pieces will be: the semiconductor chip, which is the primary light "engine"; and the phosphor, which is the secondary light producer.

In this Section, we discuss the derivative attributes and targets of these chips and phosphors. Two of these, chip input power density and chip cost per unit area, are related and are discussed in Subsection 0.4.1. Another two, chip and phosphor wavelengths and efficiencies, are also related and are discussed in Subsection 0.4.2.

0.4.1 Chip Input Power Density and Cost per Unit Area

In Subsection 0.3.4 we discussed the targets for the retail cost, in $, to purchase, after suitable mark-up, a packaged lamp which produces a certain number of lumens. This cost folds into it three costs: lamp "mark-up" from OEM to the street, packaging, and the semiconductor chip itself. Here, we assume the following approximate breakout of these costs: 50% for the mark-up, 25% for the packaging, and 25% for the chip.

Because of the importance of the semiconductor chip in the lamp, we focus special attention on its OEM cost.

POWER AND COST TARGET RANGES	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	AlGaInP/ GaAs HB-LEDs	GaInPAs/Ge PV	Si CMOS	HP 810nm Lasers
Chip Temperature (C)	75	125-175	175-225	200-250				
Phosphor Temperature (C)	75	100-150	150-200	175-225				
Input Power Density (W/cm^2)	100	300-600	500-750	600-1000				1,000
OEM Chip Cost ($\$/cm^2$)	125	110-70	90-50	60-30	30	10	5	300
OEM Packaging Cost ($\$/cm^2$)	125	110-70	90-50	60-30				

Table 2. Chip and phosphor power and cost target ranges.

Typically, though, chip cost is in units of $ per unit area or per cm^2, rather than in $ per klm. Hence, we need to derive $\$/cm^2$ chip targets from $/klm lighting targets. This we can do, provided we know the chip percentage of the lamp cost discussed above, the target lamp luminous efficacies, in lm/W, and the input power density to the chip, in W/cm^2. Then, OEM cost per cm^2 can be calculated from $\$/cm^2 = 25\% \times \$/lm \times lm/W \times W/cm^2$.

Luminous efficacy has already been discussed; but input power density has not. The higher the input power density the more lumens can be created per cm^2 of semiconductor chip, and the more expensive per cm^2 the chip can be. The limits on input power density will depend on the ability to extract heat from the chip and phosphor, and on the ability of the chip and phosphor to maintain their conversion efficiencies at high operating temperatures.[17]

Two extreme scenarios can be imagined.

At one extreme, semiconductor material quality remains relatively low, causing internal radiative quantum efficiencies to roll over with increasing junction temperature. Then, allowable junction temperatures are low, and input power densities are limited. For example, the input current densities for GaN-based white LEDs on the market now are limited to roughly 33 A/cm^2 which, with a voltage drop of about 3 V, gives an input power density of 100 W/cm^2. If semiconductor material quality remains this low, and input power densities remain limited to this value, then the chips themselves must become very inexpensive.

At the other extreme, semiconductor material quality improves, enabling high internal radiative quantum efficiency to persist to junction temperatures as high as 200-300C. Combined with improved thermal management technology, this would enable much higher input power densities. For example, the input current densities (averaged over chip, not device, area) for GaAs-based high-power infrared lasers are of the order 0.5 kA/cm^2; for a voltage drop of roughly 3V, the input power density can be inferred to be roughly 1.5 kW/cm^2. Note that this comparison to GaN-based LEDs is somewhat tricky: GaN-based lasers in principle could operate at even higher junction temperatures than GaAs-based lasers, but the quality of GaN material is unlikely to be as high as that of GaAs. Nevertheless, it gives a reasonable estimate to an upper bound on allowable input power densities.

In this Roadmap, we assume a scenario intermediate between these two extremes, but biased towards improved semiconductor material quality, higher junction temperatures, higher input power densities, and higher chip costs. The reason is that improved semiconductor material quality is likely to be necessary to enable high luminous efficacy not just at higher temperatures, but also at any temperature.

Our target ranges for chip and phosphor temperature, and for chip input power densities and costs, are listed in Table 2. They are listed as ranges. The first number in the range is the minimum necessary to meet the lighting targets listed in Table 1. The second number in the range is an aggressive target that would enable the lighting targets to be exceeded, or would enable one of the other sub targets to be "missed," while still meeting the overall lighting targets.

For allowable chip temperatures, we assume steady increases from 75C in 2002, to 125-175C in 2007, to 175-225C in 2012, and finally to 200-250C in 2020. For allowable phosphor temperatures, we assume steady increases from 75C in 2002, to 100-150C in 2007, to 150-200C in 2012, and finally to 175-225C in 2020.[18]

[17] Paul S. Martin, "Performance, Thermal, Cost and Reliability Challenges for Solid State Lighting," OIDA Solid-State Lighting Workshop (Albuquerque, May 30, 2002).

[18] Note that the targets for phosphor temperature are 25C lower than the targets for chip temperature. On the one hand, if the phosphor is applied directly to the chip, and is not separately heat sunk, then the phosphor temperature will be very close to that of the chip. On the other hand, if the phosphor is partially thermally isolated from the chip, and is separately heat sunk, than its temperature can be significantly lower. Because finding phosphors with high quantum efficiencies and long lives at high temperatures is believed to

CHIP AND PHOSPHOR λ AND EFFICIENCY TARGETS	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020
Wavelength Conversion Approach				
LED λs (nm)		UV(370-410)	UV(370-410)	UV(370-410)
Phosphor λs (nm)		R(590-630) G(520-560) B(440-480)	R(590-630) G(520-560) B(440-480)	R(590-630) G(520-560) B(440-480)
Stokes Efficiency		0.73	0.73	0.73
Phosphor Quantum Efficiency		0.75	0.85	0.95
Package Efficiency		0.75	0.90	0.95
Chip Efficiency		0.46	0.67	0.76
Color Mixing Approach				
LED λs (nm)		R(590-630) G(520-560) B(440-480)	R(590-630) G(520-560) B(440-480)	R(590-630) G(520-560) B(440-480)
Phosphor λs (nm)				
Stokes Efficiency				
Phosphor Quantum Efficiency				
Package Efficiency		0.75	0.90	0.95
Chip Efficiency		0.25	0.42	0.53
Hybrid Approach				
LED λs (nm)	B(460)	B(440-480)	B(440-480)	B(440-480)
Phosphor λs (nm)	Y(580)	R(590-630) G(520-560)	R(590-630) G(520-560)	R(590-630) G(520-560)
Stokes Efficiency	0.88	0.86	0.86	0.86
Phosphor Quantum Efficiency	0.60	0.70	0.80	0.90
Package Efficiency	0.50	0.75	0.90	0.95
Chip Efficiency	0.24	0.42	0.61	0.68

Table 3. Chip and phosphor wavelength and efficiency targets.

For allowable chip input power density, we assume that the combination of improvements in chip and phosphor temperatures and in thermal management technology will enable a steady increase in input power density from 100 W/cm^2 in 2002, to 300-600 W/cm^2 in 2007, to 500-750 W/cm^2 in 2012, and finally to 600-1000 W/cm^2 in 2020.

We note that whether these increases in chip input power densities are achieved mostly through increases in chip and phosphor temperatures or through improvements in thermal-management technology is not clear. On the one hand, if allowable chip and phosphor operating temperatures remain low, then thermal management technology will need to improve dramatically. On the other hand, if thermal management technology proves too costly, than the burden will be on increasing the allowable chip and phosphor operating temperatures.

Finally, using these targets for allowable input power density, we can deduce targets for OEM chip cost per cm^2: from \$125 \$/cm^2 in 2002 to 110-70 \$/cm^2 by 2007, to 90-50 \$/cm^2 by 2012, and to 60-30 \$/cm^2 by 2020. Note that from these chip cost targets one can estimate (very) approximate allowable costs for the various "wafer level" fabrication steps: 20% for substrates, 40% for epi and 40% for wafer processing.

We also list in Table 2 some representative OEM costs for similar but more mature technologies. The cost of AlGaInP/GaAs high-brightness LEDs chips is roughly \$30/cm^2. The cost of triple-junction GaInPAs/Ge space solar cells is roughly \$10/cm^2.[19] The cost of Si CMOS is roughly \$5/cm^2.[20] Hence, for these three relatively mature semiconductor technologies, purchase costs are much

be extremely difficult, we assume here that some degree of thermal management will be required to keep the phosphor somewhat cooler than the chip.

[19] James Gee, "SSL 2020 Cost Targets" (Sandia National Labs, 2001, unpublished).

[20] Jason Blackwell, "Foundry wafer prices: Still hanging tough, but for how long?," Semiconductor Business News (Nov 6, 2001) .

lower than our targets for SSL-LEDs. This indicates that our targets are reasonable, and that indeed there may be "headroom" for improvement beyond our targets.

Moreover, even a relatively complex technology, high-power 810 nm GaAs-based lasers, has costs that are in the $200/cm² range. It is not clear how these costs might translate to high-power visible/UV GaN-based lasers. However, the costs are already within 3-5x of our targets, even without the high manufacturing volumes and associated cost reductions that penetration into the general lighting markets would enable. And, costs continue to decline[21] in response to demand for high-power diode lasers for materials processing.

0.4.2 Chip and Phosphor Wavelengths and Efficiencies

In Section 0.3, we discussed the targets for luminous efficacy of the fixtured lamp. This luminous efficacy folds into it five separate efficiencies:

1. The efficiency of the semiconductor chip itself in converting electrical power into primary optical power.
2. The sensitivity of the human visual system to the color(s) of the primary light generated by the semiconductor chip, or to the color(s) of the secondary light generated by the phosphor, or both.
3. The energy lost in converting a blue or UV photon to a longer wavelength photon (the Stokes shift).
4. The Stokes conversion efficiency due to the different energies of the photons absorbed and emitted by the phosphor.
5. The overall package efficiency, currently between 40-60% due to light absorption by internal package components such as the chip, lead frame or sub mount.

If the last four efficiency targets are known (or estimated), and if the overall lamp luminous efficacy target is known, then one can deduce what the first efficiency target, the power conversion efficiency of the semiconductor chip, needs to be.

For the fifth efficiency, we assume that it will be approximately the same for the three approaches -- for the color-mixing approach, difficulties in combining separate sources of light are offset, for the wavelength conversion and hybrid approaches, by difficulties in reducing phosphor scatter. Our target efficiencies are 0.75 by 2007, 0.9 by 2012, and 0.95 by 2020.

For the middle three efficiencies, we need to make assumptions about wavelengths and numbers of wavelengths. Assuming a tri-color source with the target wavelengths discussed in the previous Section, we can deduce derivative targets for phosphor quantum efficiency, Stokes conversion efficiency, and for the optical-engineering efficiency associated with the lamp packaging. These three efficiencies will depend on the approach to white lighting that is taken – wavelength conversion, color mixing, or a hybrid approach.

The phosphor quantum efficiency is likely to be somewhat better for the wavelength conversion approach, since there is a wider range of available phosphors that absorb in the UV. Hence, for the wavelength conversion approach, we assume that phosphor quantum efficiencies will steadily increase from 0.75 in 2007 to 0.85 in 2012 to 0.95 in 2020. For the hybrid approach, which down-converts blue rather than UV light, we assume that phosphor quantum efficiencies will increase more slowly, from 0.7 in 2007 to 0.8 in 2012 to 0.9 in 2020. For the color-mixing approach, of course, there is no phosphor and hence no phosphor-related losses.

The phosphor Stokes conversion efficiency, in contrast, will be lowest for the wavelength-conversion approach, since there is a larger energy difference between the UV and red/green/blue light than between blue and red/green light. Here, we calculate a Stokes conversion efficiency averaged over the down-converted wavelengths using the formula $3\lambda^{in} / \left(\lambda_1^{out} + \lambda_2^{out} + \lambda_3^{out}\right)$.

A last and more difficult assumption to make is wavelength for the UV LED in the wavelength-conversion approach. This wavelength is likely to be determined by balancing: the efficiency of the LED (so far, the shorter the wavelength the less efficient); the quantum efficiency of the phosphors (so far, the shorter the wavelength the more efficient); and the phosphor Stokes conversion efficiency (the shorter the wavelength the less efficient). Based on current knowledge, we assume in this Roadmap that a reasonable target wavelength will be in the range of 370-410 nm.

[21] Roy Szweda, "NOVALAS (Innovative Laser Systems based on High-Power Diode Lasers) in its final round," III-Vs Review 15 (2002) 36-39.

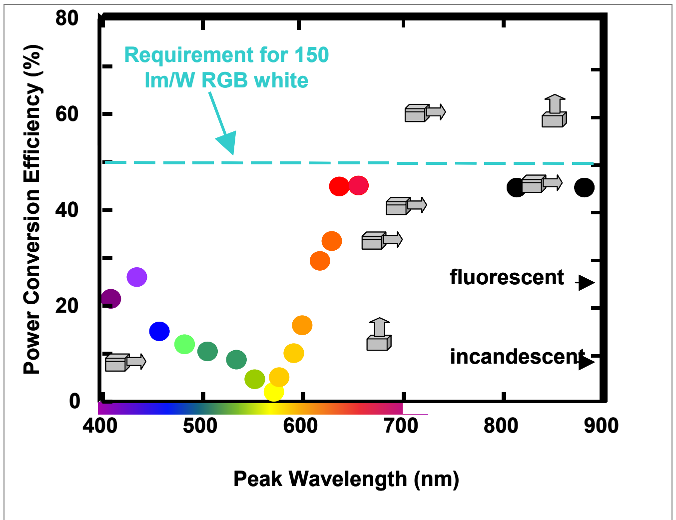
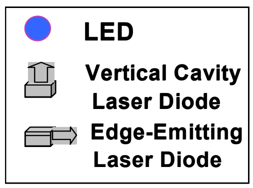


Figure 10. Power efficiency of light sources at various wavelengths. [Courtesy of M.G. Craford, LumiLeds.]



These derivative assumptions and targets are summarized in Table 3 for the three different approaches to white-light production. As can be seen, the wavelength conversion approach imposes the highest requirements on chip power-conversion efficiencies – they must approach 0.7 to meet our 2012 SSL-LED lamp targets. In contrast, the color-mixing approach "only" requires chip power-conversion efficiencies of roughly 0.4 to meet our 2012 SSL-LED lamp targets. The hybrid approach, as expected, is in between, and requires chip power-conversion efficiencies of 0.6 to meet our 2012 SSL-LED lamp targets.

We note that these efficiencies are high, and it is not yet clear whether they can be achieved. However, as illustrated in Figure 10, the power conversion efficiencies of infrared (710-850 nm) lasers and red (650 nm) LEDs are in the 40-60% range. Both of these are relatively mature semiconductor technologies, and serve as existence proofs that comparable efficiencies might be achievable in the visible spectrum.

0.5 Benefits

A vital and growing use of energy is the generation of electricity. In the US alone, producing electricity costs about $50 billion a year. In addition, the cost of electrical energy is not measured in dollars alone -- there is also the environmental cost of smog and carbon dioxide pollution associated with electricity production.

Just as fluorescent and HID sources have provided tremendous energy savings over the last few decades, SSL-LEDs, with their potential for significant improvements in energy efficiency, offer significant potential for energy savings over the next few decades. In this Section, we discuss these and other potential benefits.

0.5.1 Energy and Environment

The most significant benefit of massive replacement of traditional with SSL-LED lighting technology will be on the energy and environment. In the U. S., about 20% of all generated electricity is used for lighting; worldwide usage patterns are similar. Consequently, significant improvements in lighting efficiency would have a major impact on worldwide energy consumption.

In addition, electricity generation from burning of coal and petroleum is a major source of environmental pollution – there is an increasingly strong link between carbon emissions, the greenhouse effect, and global warming. Hence, SSL-LEDs, through their higher efficiency, could reduce significantly environmental pollution. In addition, a side benefit is that SSL-LEDs are mercury-free, and easier to dispose of than fluorescent lamps.

If SSL-LED's ultimate target of 50% efficiency (200lm/W) is realized, along with complete market penetration, the benefits to the U.S. would be spectacular:

- A 50% decrease in the 600 TW-hr/yr of electricity used for lighting, or a savings of 300 TW-hr/yr, or $25B/yr.
- A freeing-up of over 30 GW of electric generating capacity for other uses, or, alternately, elimination of the need for 30 power generating plants.
- A 50% decrease in the 50 Mtons/yr of carbon emissions created during generation of electricity for lighting, or 25 Mtons/yr.

Of course, the actual realized benefits will depend on a complex interplay between how quickly the market is penetrated and how quickly the technology is advanced. This interplay can be thought of as a "virtuous cycle": as technology advances (increased performance and decreased cost), market penetration increases, spurring increased investment in further technology advances.

Several scenarios have been proposed for the evolution of market penetration and technology advance, and have been discussed in the white paper by Haitz, et al,[22] and a more recent market penetration study by Arthur D. Little.[23]

[22]Roland Haitz, Fred Kish, Jeff Tsao, and Jeff Nelson, "The Case for a National Research Program on Semiconductor

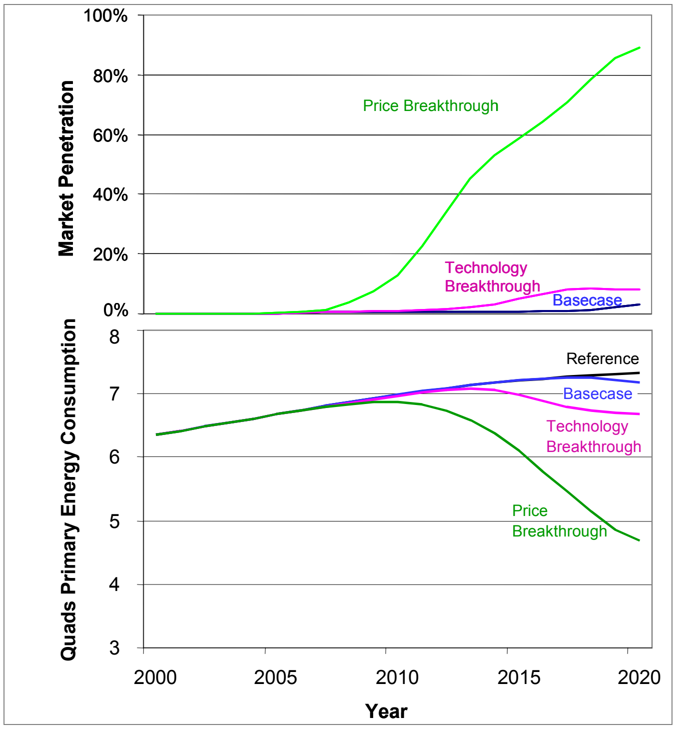


Figure 11. Market penetration and energy savings in both quads of primary energy and terawatt-hours of on-site electricity use. Note that these energy savings and market penetration estimates were based on a draft inventory of US lighting technologies. Estimates based on a revised lighting inventory are expected to be available in early 2003. Mark Kendall and Michael Scholand, "Energy Savings Potential of Solid State Lighting in General Lighting Applications" (U.S. Department of Energy, Office of Building Technology, State and Community Programs, Apr, 2001).

In Japan's "Light for the 21st Century" national project,[24] a market penetration of 13% with an efficiency of 120 lm/W by 2010 was targeted. Our targets are similarly aggressive, and are comparable to those envisioned in the "price breakthrough" scenario discussed in the Arthur D. Little report. In that scenario, for medium (70-79) CRI applications, efficiency and purchase cost reach 110 lm/W and 7 $/klm by 2010, and 120 lm/W and 0.5 $/klm by 2020.

Lighting" (Optoelectronics Industry Development Association, Oct, 1999).

[23] Mark Kendall and Michael Scholand, "Energy Savings Potential of Solid State Lighting in General Lighting Applications" (U.S. Department of Energy, Office of Building Technology, State and Community Programs, Apr, 2001).

[24] T. Taguchi, "Light for the 21st Century Year 2000 Report of Results" (The Japan Research and Development Center of Metals, 2001).

We note that this scenario is so aggressive that it was not even considered in the original April, 2000 white paper by Haitz, et al, and was even viewed as "radical" in the Arthur D. Little report itself. Such is the pace of innovation over the past 2-3 years, however, that, by August 2002, this scenario is now viewed essentially as this Roadmap's targets.

The general conclusions from the Arthur D. Little report for this "price-breakthrough" scenario are shown in Figure 11. SSL achieves nearly 50% market penetration by 2012, and nearly 90% market penetration by 2020. About 0.3 quads/yr of primary energy (27 TW-hr/yr of end-use electricity) is saved by 2012, and about 2.7 quads/yr of primary energy (246 TW-hr/yr of end-use electricity) is saved by 2020. This represents over 35 percent of the projected energy consumption per year for lighting in 2020.

The carbon savings associated with these energy savings forecasts are also substantial. About 3 Mtons/yr of Carbon equivalent is saved by 2012, and about 42 Mtons/yr by 2020.

0.5.2 Quality of Lighting and Human Productivity

Perhaps the second most significant, though less easily quantified, benefit will accrue as entirely new technology-driven lighting applications and a new lighting culture are created. These new applications and culture will change the way we use and interact with light.

Among the unique features that will enable these new uses are:

- Steady output color at all levels of illumination
- Ability to continuously vary output color
- Simplified and flexible design for mounting and fixtures
- Ease of integration into advanced building controls
- Low voltage and safe power distribution
- Ease of miniaturization due to the small size of the light source -- the lighting equipment would be smaller, thinner and lighter
- Simple structure -- no special devices would be needed to control the lighting equipment, and the number of components in the equipment would be reduced.
- High reliability due to the use of all-solid-state devices without any gases or filaments -- very reliable against mechanical shock.

- Flexible and efficient distribution of light -- SSL devices can be manufactured as flat packages of any shape that can be placed on floors, walls, ceilings, or even furniture, and coupled to light pipes and other distribution systems.

0.5.3 National Security and other Spin-Offs

Much of the technology being developed for solid-state lighting (SSL) is based on AlGaInN materials. These materials are complex, but are the basis for many other technologies vital to national security.[25] These include:

- High-power electronics for wireless communications and radars. For example, synthetic aperture radars (SARs) currently rely on heavy and bulky traveling wave tubes and gimbaled antennas. These could be replaced with compact AlGaInN-based electronics and arrayed antennas, resulting in dramatic reductions in weight and opportunities for placement on smaller unmanned aerial vehicles (UAVs) that can fly longer and farther and present a smaller target to any enemy.
- Solar-blind detectors for detecting characteristic spectral signatures associated with missile launches, crucial for early-warning and treaty-verification purposes. AlGaInN materials are ideally suited for these applications, since their bandgaps may be tuned across the visible and UV spectrum where the crossover between sunlight and missile-launch signatures occurs.
- UV light sources for chemical and biological warfare agent detection. This application is perhaps the most closely related to solid-state lighting. When illuminated with deep ultraviolet (UV) light, bacteria, including anthrax, will fluoresce (re-emit light at a slightly longer wavelength) and can be detected. However, at present the sources of UV-light are heavy table-top-sized instruments. SSL-LED technology could be used to develop much more compact deep UV LEDs and laser diodes. Indeed, the Defense Advanced Research Projects Agency (DARPA) recently announced a major initiative to develop just such UV LEDs and lasers, and to demonstrate their use in a compact prototype anthrax detector.[26]
- Visible and UV light sources for medical applications, spectroscopy, and photosynthesis. LEDs have been shown to emit a radiant flux high enough for photo therapy of neonatal jaundice, photodynamic therapy, and dental composite curing. And, owing to their high output power, low noise, ability to generate sub nanosecond pulses, and their simple means of high-frequency modulation, blue and UV LEDs can replace costly lasers in some applications of fluorescence excitation, including time-resolved measurements. And, finally, plant growth under completely solid-state lighting using red AlGaAs and blue InGaN chips has been demonstrated.
- Severe-environment lighting for military use. SSL-LED technology is inherently resistant to impact and vibration, to high and low ambient temperatures. Combined with its energy efficiency and compatibility with battery operation, SSL-LEDs will be the ideal lighting source for military use.

Fundamental understanding of GaN materials physics and growth chemistry underlies not only SSL-LEDs, but also these (and others not yet discovered) technologies vital to national security interests. Hence, a deeper understanding plus manufacturing volumes associated with SSL-LEDs will enable spin-off benefit to these national security applications.

0.6 Building Blocks

We argued, in Sections 0.3 and 0.4, that our SSL-LED targets are physically reasonable and consistent with our knowledge of fundamental physics and with other, more mature, semiconductor manufacturing technologies. Nevertheless, solid-state lighting is in its infancy, just as silicon integrated circuits were in their infancy two decades ago.

Hence, in order to meet the lighting targets and lamp sub targets discussed in Sections 0.3 and 0.4, significant work must be done in a number of areas. We organize these areas into three overall building blocks:

1. Substrates, Buffers and Epitaxy
2. Physics, Processing and Devices
3. Lamps, Luminaires and Systems

[25] Don Cook, "National Security Applications of Solid State Lighting Technology," OIDA Solid-State Lighting Workshop (Albuquerque, May 30, 2002),

[26] John Carrano, "Semiconductor Ultraviolet Optical Sources (SUVOS)," http://www.darpa.mil/mto/suvos/ (2002).

The remainder of this Tutorial is organized around these building blocks.

1 Substrates, Buffers and Epitaxy

Two semiconductor materials systems are the focus of most attention for solid-state lighting: AlGaInN (the column-III nitrides), and AlGaInP (the column-III phosphides). These are the only known semiconductor materials with the following combination of properties required for solid-state lighting:

- Their band-gaps span the range appropriate for visible and near-UV light emission, and perhaps most importantly are direct rather than indirect, and hence emit light efficiently. The AlGaInP materials span the range from the deep red to the yellow-green; the AlGaInN materials span the range from the yellow-green (and potentially the red) to the UV.
- They represent families of materials that can be composition tailored into nanostructures optimized for electron and hole injection, transport, and radiative recombination.
- They are robust enough to withstand semiconductor fabrication processes as well as operation under high-current-density high-stress conditions.

Both of these materials systems are examples of so-called III-V compound semiconductors: combinations of elements from columns III and V in the periodic table. The phosphides are a relatively mature material, while the nitrides are a relatively immature material. Hence, particularly for the nitrides, there are many fundamental physics issues related to materials and nanostructures that are poorly understood.

The two semiconductor families enter into SSL-LED technology in different ways. The brightest and most-efficient light emitters in the red are fabricated from AlGaInP, while those in the green, blue and UV are fabricated from AlGaInN. It is possible that bright, efficient light emitters in the red will someday be fabricated from AlGaInN. If so, having a common materials platform for all three colors could greatly simplify the color-mixing approach to white-light production considerably.

In the absence of such a breakthrough, though, AlGaInP is important mainly for providing red in the color-mixing approach to white-light production, while AlGaInN is important in all approaches to white-light production. Hence, if the color-mixing approach to white-light production emerges as the winner, then AlGaInP is likely to remain, along with AlGaInN, a critical semiconductor. If the wavelength-conversion approach to white-light production emerges as the winner, then only AlGaInN will remain a critical semiconductor.

In this Chapter, we discuss the challenges associated with the "front-end" fabrication of these semiconductor materials: substrates, buffers and epitaxy.

For AlGaInP materials, this front-end fabrication is now reasonably mature. There exists a high-quality, relatively low cost ($\$5/cm^2$), commercially available substrate, GaAs, to which they are well matched chemically, crystallographically and structurally. And, there exist production OMVPE tools for high-volume, high-precision, high-uniformity AlGaInP epitaxy at relatively low cost ($\$15/cm^2$).

These front-end costs are low enough that there is no pressing need for further development of substrates and epitaxy. Even if substrate cost were to become an issue, even-lower-cost Ge substrates (roughly $\$3/cm^2$) should be possible to use. And, the OMVPE tools are very similar to those used for mainstream GaAs and InP compound semiconductor epitaxy, hence epitaxy costs will continue to be driven down in response to demand for GaAs-based epitaxy.

For AlGaInN materials, this front-end fabrication is in its infancy. There does not yet exist a commercial technology for low-defect-density single-crystal substrates of GaN. If such a technology were to be developed, there is no doubt that it would provide the best substrate for subsequent AlGaInN device epitaxy.

In the absence of this technology, however, virtually all AlGaInN SSL-LEDs are currently grown on relatively poorly matched sapphire (Al2O3), silicon carbide (SiC) or silicon (Si) substrates. The extents of the mismatches are listed in Table 4. As a consequence, it has been necessary, in the interim, to develop "buffers." These buffers bridge the mismatches, with the final product being a surface whose crystallography and lattice constant match that of the device that will be grown on top, and which is as structurally perfect (and low cost) as possible.

Substrate	Lattice Mismatch	Thermal Expansion Mismatch
Sapphire	+16%	+39%
SiC	-3.5%	-3.2%
Si	+17%	-56%

Table 4. Lattice and thermal expansion mismatches between GaN and the most commonly used substrates.

Current buffers are relatively thin (1-5 μms) and, though still highly defective (1e6-1e7 defects/cm²), have been adequate for moderate-efficiency light-emitting devices driven at moderate (<100W/cm²) input power densities. However, for high-efficiency light-emitting devices driven at high input power densities, it is believed that defect densities must be decreased by roughly two more orders of magnitude.

This may be possible with evolutionary advances in thin-buffer technology. However, it is more likely to require revolutionary advances in buffer technology – e.g., thick (20-200 μms) buffers subsequently removed from their original substrate.

There has been speculation in the past that with suitable engineering and nanostructuring of the device epitaxy (e.g., using quantum dots), this low structural quality could be "worked around." Indeed, there is some justification to this view, since the current generation of quantum-dot-based AlGaInN devices perform well despite being highly defective compared to common experience with AlGaInP or AlGaInAs devices.

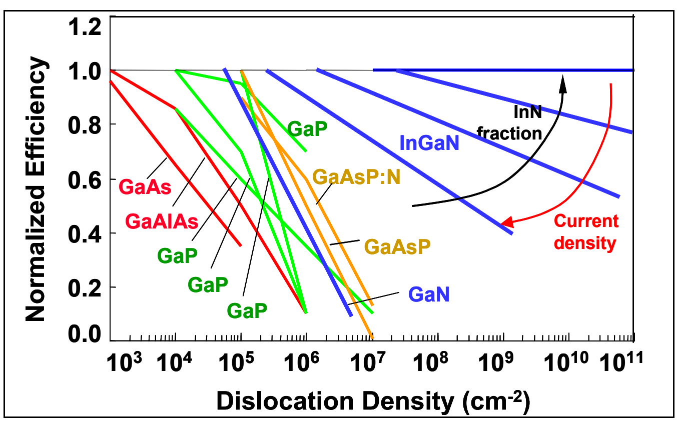


Figure 12. Schematic of dependence of luminescence efficiency of various compound semiconductor materials on dislocation density. After Shuji Nakamura, "Status of GaN LEDs and Lasers for Solid-State Lighting and Displays," OIDA Solid-State Lighting Workshop (Albuquerque, May 30, 2002), modified and augmented from S. D. Lester, F. A. Ponce, M. G. Craford, and D. A. Steigerwald, "High dislocation densities in high-efficiency GaN-based light-emitting diodes," Appl. Phys. Lett. 66 (1955) 1249.

Nevertheless, as illustrated in Figure 12, a growing body of work indicates that dislocations, nanopipes, and other mismatch-related structural defects do have ill consequences. Among these consequences: metal migration along the defects possibly leading to long term degradation; defect-mediated non-radiative recombination of electron-hole pairs; enhanced Coulomb scattering (and reduced mobility) of carriers due to charged dislocations. Hence, structural quality and low-defect-density buffer layers are now widely viewed as extremely important.

Moreover, if defects could be eliminated, it might not be necessary to rely on quantum-dot-like composition nonuniformities that in current devices localize electrons and holes away from the defects. Then, compositionally uniform structures could be used, with potential advantages such as enhanced carrier transport, narrower line widths and higher gain for stimulated emission devices.[27]

Hence, the common goal of the Challenges associated with Section 1.1 (Substrates) and 1.2 (Buffers) is to create a low-defect-density substrate or substrate+buffer combination that is lattice and thermal-expansion matched to AlGaInN epimaterials.

Once a starting substrate or substrate+buffer combination has been created, the next step in the front-end fabrication sequence is epitaxy. All modern, high-performance light-emitting optoelectronic devices rely on bandgap-engineered epitaxially layered materials to control electrons, and holes, and photons. Indeed, the history of semiconductor optoelectronics can be viewed as the development of an understanding of how layered materials can be used to control electrons, holes and photons, and how epitaxy can be harnessed to create those layers.

Again, epitaxy of AlGaInP materials is relatively mature, while epitaxy of AlGaInN materials is relatively immature. In Section 1.3 we discuss epitaxy tools and processes, with a focus on AlGaInN materials.

[27] S. Srinivasan, F. Bertram, A. Bell, F. A. Ponce, S. Tanaka, H. Omiya, and Y. Nakagawa, "Low Stokes shift in thick and homogeneous InGaN epilayers," Applied Physics Letters 80 (2002) 550-2.

1.1 Substrates

In this Section we discuss the starting substrates. As discussed above, substrates for the AlGaInP materials system are relatively well-established. GaAs substrates are approximately $5/cm^2, only 5% of our target chip cost, and Ge substrates are even less expensive. Hence, we focus our attention on substrates for the AlGaInN materials system.

At this stage, there are three substrates being considered.

Challenge 1.1.1 discusses bulk GaN and AlN, which would be a perfect or nearly-perfect chemical, crystallographic, lattice-constant, and thermal-expansion match to AlGaInN.

Challenge 1.1.2 discusses sapphire, which is a substrate relatively "unmatched" to AlGaInN, but on which there has been considerable success at growing buffer layers on which epitaxial devices may be subsequently grown. This substrate is also relatively inexpensive, approximately $10/cm^2, or 10% of our target chip cost.

Challenge 1.1.3 discusses silicon carbide, which is a substrate better matched to AlGaInN than sapphire, but, at $40/cm^2, is relatively expensive.

A final interesting substrate is silicon. This substrate is a much poorer match to AlGaInN materials than either sapphire or silicon carbide, by a substantial amount, so high-performance devices have not yet been demonstrated from material grown on Si. Nevertheless, as discussed in Section 1.2, many groups are pursuing this possibility, and there have been some successful demonstrations of GaN films and device structures on Si wafers having diameters as large as four inches. If successful, an AlGaInN on silicon substrate technology would be extremely exciting. It would take advantage of the maturity and low-cost of silicon substrate technology, as well as the possibility of integration with other advanced Si-based device technologies, such as MEMs and CMOS.

1.1.1 GaN and AlN

As noted above, perhaps the most defining feature of the AlGaInN materials system is the lack of commercially available GaN or AlN substrates that are chemically, crystallographically, lattice-constant, and thermal-expansion matched to the desired device materials. Indeed, it is surprising that AlGaInN materials have come so far so fast without such a matching substrate.

If such a substrate were available, spectacular results are likely. Defect densities in the range of 10^3/cm^2 would be expected, compared with typical defect densities in the range of 10^9 to 10^{10}/cm^2 for AlGaInN materials grown on sapphire. Moreover, bulk GaN and AlN have higher thermal conductivities than sapphire substrates, and could improve thermal management of chips driven at high input power densities.

Unfortunately, the growth of bulk GaN or AlN substrates is in its infancy, with only preliminary results and limited success. It is impossible to employ well-known methods such as Bridgman or Czochralski for GaN bulk crystal growth on account of the extremely high melting temperatures (2800K) and nitrogen vapor pressures (over 45kbar) required. Hence, other approaches are, and will need to be, explored.

1.1.2 Sapphire

Since the demonstration of reasonably-high-quality GaN and AlN buffer layers on sapphire, sapphire has become the dominant substrate for AlGaInN devices. Although similar buffer layers can now be grown on a few other substrates (e.g., SiC, as discussed in Challenge 1.1.3), these other substrates are quite expensive compared to sapphire.

Because of its many other uses, including "transparent armor," optical windows, and silicon-on-sapphire, the technology for manufacturing sapphire substrates is relatively mature. The current commercial process are the Czochralski (Union Carbide) and edge-defined film-fed (EFG) growth processes (Kyocera). Wafers are available at roughly $5-10/cm^2, which is already within the range required for our chip cost targets.

The major challenges are a desire to scale to somewhat larger wafer sizes (4" to 6"), to reduce impurities (e.g., Ti), and to improve the quality of the surface finish and polish.

1.1.3 SiC

Just as with sapphire, it is possible to grow reasonably-high-quality buffer layers of GaN or AlN on SiC substrates. These buffers are slightly better in quality than those on sapphire, because of the smaller lattice mismatch. And, because SiC substrates may be electrically conducting, they enable bottom-of-substrate electrical contact, which simplifies device design and is consistent with the industry standard vertical chip single wire bond structure, quicker LED assembly, reduced manufacturing costs and improved reliability. Also, SiC has somewhat better thermal conductivity than GaN or AlN (350W/m-K for typical conducting SiC vs. 230 W/m-K for GaN and 320 W/m-K for AlN), so this substrate is even better for sinking heat. But, SiC is also absorbing at wavelengths shorter than 380nm in the UV, so for the wavelength conversion approach something would need to be done to avoid this absorption.

The current state-of-the-art manufacturing technology involves physical vapor transport (PVT) via seeded sublimation.[28] At growth temperatures of 2200–2500°C a temperature gradient is established across the growth cell, which is in an inert gas ambient (e.g. Ar, He or N2). The gradient acts as a driving force for the sublimation of the SiC source material, the transport of the SiC species through the vapor phase and the crystallization on a SiC seed.

Continuous improvements of this technique have led to the industrial production of 50–75-mm diameter 6H and 4H wafers and the demonstration of high quality 100-mm wafers.

The main limitations are:

- Cost. Sublimation-grown substrates are currently quite expensive ($2000 for a 2" diameter wafer, or 100$/cm^2). Costs need to come down by nearly an order of magnitude, to $10-20/cm^2!)
- Defects. Defects are perhaps the most significant issue, and among these defects, so-called micro pipes are the most harmful. These micro pipes are associated with dislocations, hence depend strongly on temperature gradients and thermal stresses during growth. The density of these micro pipes has steadily decreased over the past several years, down to densities as low as 1.1/cm^2 for an entire 50-mm wafer, and it may be possible to totally eliminate micro pipes in the next few years. However, eliminating dislocations will be much more challenging – these are still at the 1e3/cm^2 level.

1.2 Buffers

In this Section we discuss the second stage in the substrate engineering process: growth of a buffer layer on an imperfectly-matched starting substrate. For the dominant current AlGaInN device technology, which relies on growth of GaN layers grown on c-plane sapphire, this buffer may well be the most important step in the realization of device quality GaN material.

The purpose of this buffer layer is to transition from the lattice constant or crystallography of the starting substrate so that it is compatible with the AlGaInN wurtzite alloys used for device epitaxy.

The primary issue is misfit dislocations, which must be present to accommodate the lattice mismatch between substrate and layer. These misfit dislocations, when extending into the layers above, form threading dislocations that affect electronic and optical properties. A secondary issue is micro cracking, which results from high residual strains upon cooling to room temperature due to a difference in thermal expansion coefficients between substrate and over layer.

There are a number of competing technologies for growing buffers, and each faces different Challenges.

Challenge 1.2.1 discusses technologies for growth of simple thin buffers, for which no wafer patterning or special processing are performed prior to buffer growth. These are the least expensive buffers, but the dislocation density remains substantial.

Challenge 1.2.2 discusses growth of "complex" buffers, for which patterning or special processing is performed prior to buffer growth. These buffers employ a combination of vertical and lateral growth of GaN-based films through and over patterned oxide or nitride films deposited on a GaN film previously grown on sapphire, SiC or Si.. These techniques are variously referred to as epitaxial lateral overgrowth (ELO or ELOG) or lateral epitaxial overgrowth (LEO). These complex buffers result in a substantial reduction in the density of dislocations; however, they require one or two insertions into the thin film growth sequence that increases the cost.

Challenge 1.2.3 discusses technologies for growth of thick buffers, followed by special processing performed afterwards to transfer the buffer to another substrate, or to create a free-standing buffer through substrate removal.

1.2.1 Thin GaN Buffers

AlGaInN device technology is currently based on GaN or AlN buffers first grown by OMVPE on sapphire or silicon carbide, followed by epitaxy of AlGaInN device layers. Indeed, the demonstration by Amano and Akasaki in the late 1980's that reasonably high quality buffer layers were possible on sapphire is arguably one of the two pivotal breakthroughs (in addition to p-type doping) that triggered subsequent progress in device and SSL-LED technologies.

Both GaN and AlN buffers have been demonstrated, although GaN buffer layers appear to be somewhat

[28] St. G. Muller, R. C. Glass, H. M. Hobgood, V. F. Tsvetkov, M. Brady, D. Henshall, D. Malta, R. Singh, J. Palmour, and C. H. Jr. Carter, "Progress in the industrial production of SiC substrates for semiconductor devices," Materials Science and Engineering B80 (2001) 327-331.

superior, at the expense of somewhat greater process sensitivity related to the lower temperature (450–600C) necessary for the GaN buffer growth, and its tendency to partially desorb as the temperature is raised to the final growth temperature.

Buffers have been demonstrated on sapphire, silicon carbide and silicon.

The current state-of-the-art in buffer layer formation on sapphire consists of a so-called two-step epitaxy.[29] A low-temperature GaN nucleation layer (NL) is deposited first, followed by a high temperature (HT) GaN overgrowth. The NL consists of faceted crystalline islands that exhibit a spread in rotation about the (0001) axis. The lateral growth during HT deposition of GaN occurs preferentially in certain "growth patches", which grow vertically and laterally over the underlying sub grains. The coalescence of these patches produces a continuous GaN layer. The best threading dislocation densities are still rather high (1e9/cm^2), though this is surprisingly low given the significant mismatch between GaN and sapphire.

The scenario for silicon carbide is thought to be similar. The main difference is that the lattice mismatch is significantly less. Hence, coalescence of GaN islands (followed by layer-by-layer growth) occurs within the first several hundred angstroms of growth, as opposed to the first several thousand angstroms of deposition in the case of sapphire. And, buffer layers on SiC substrates also have somewhat lower defect densities than those on sapphire, and this result combined with the added benefit of an electrically conducting substrate has led to a significant use of this buffer layer technology for commercial devices on SiC. Unlike in the case of sapphire, though, the buffer layers on SiC must be electrically conducting, in order to take best advantage of the conductivity of the SiC itself. This typically requires high-temperature rather than low-temperature buffers.

The scenario for silicon is much less favorable. This is not just because the lattice-constant mismatch is greater than it is for sapphire. It is also because the thermal expansion coefficient mismatch is significant, and in such a direction that tensile strain, which promotes cracking, is produced.

The limitations for thin-film buffers on all substrates are the high residual defect density, which compromises device performance significantly.

[29] V. Narayanan, K. Lorenz, Wook Kim, and S. Mahajan, "Gallium nitride epitaxy on (0001) sapphire," Philosophical Magazine A 82 (2002) 885-912.

1.2.2 ELO GaN Buffers

In the previous Challenge, we discussed the technologies for growth of "simple" buffers. These are buffers where no patterning or special processing is performed prior to buffer growth. The best that these buffers have been able to achieve, on any substrate (including sapphire and SiC) has been dislocation densities in the range 1e8-1e9/cm^2. This is a very high number by semiconductor device standards, and it is now clear that device performance is degraded as a consequence. In addition, stress and wafer bowing are issues with simple buffers.

Hence, there has been great interest in developing buffers that, though involving more complex processing, can decrease the dislocation density further, to the range of 1e6-1e7/cm^2. In this Section, we discuss the technologies for growth of "complex" buffers. These are buffers where patterning or special processing is performed prior to buffer growth.

There are three overall approaches to complex buffers. These are, in order of increasing conceptual complexity: epitaxial lateral overgrowth (ELO), pendeo epitaxial lateral overgrowth (pendeo-ELO), and cantilever epitaxial lateral overgrowth (cantilever ELO).

<u>ELO.</u> Epitaxial lateral overgrowth is the epitaxial growth of thin films on substrates that have been masked and patterned in such a way that growth occurs selectively in only certain areas of the substrate. Under the proper conditions, GaN will grow selectively on the GaN buffer, but not on the inert mask. Initially, the growth is upward, but later the growth becomes both upward and laterally outward. Eventually, neighboring growths coalesce over the stripe, creating a continuous film of GaN. Because dislocation replication depends both on the dislocation direction and crystallography, as well as on the direction of (and facet associated with) growth, it is possible to engineer a significant reduction in dislocation density in various regions of the GaN overgrown film. ELO is now routinely used for devices, such as lasers, that are especially sensitive to defects. The operating life and output power of GaN based lasers has now been extended to 10,000 hours, and dislocation densities have been decreased to the range 1e6/cm^2, an approximate 250x reduction from those of simple buffers.

<u>Pendeo-ELO.</u> In order to gain the fullest advantage of ELO, it is possible to perform multiple ELOs, with a reduction in dislocation density each cycle. However, this requires costly multiple process and regrowth steps, along with lithographic alignment across steps. A possible approach that effectively enables a double-ELO in a single

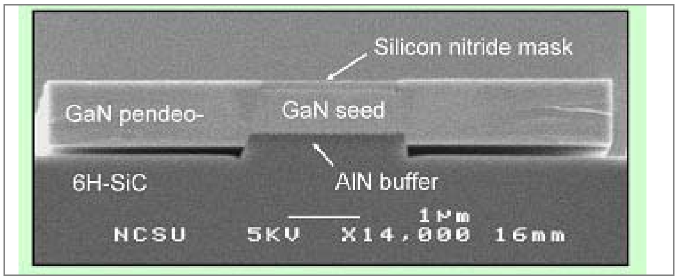


Figure 13. Pendeo-epitaxially grown GaN on a SiC substrate. After Robert F. Davis, "Alternative Substrates for III-Nitride LED Structures," OIDA Solid-State Lighting Workshop (Albuquerque, May 30, 2002).

step is called pendeo-ELO.[30] In this method, growth does not initiate through open windows but begins on sidewalls etched into a GaN seed layer, as shown in Figure 13. As the lateral growth from the sidewalls continues, vertical GaN growth begins from the newly forming (0001) face of the continually extending lateral growth front. Subsequently, once the vertical growth reaches the top of the seed mask, lateral growth over the masked top of the seed begins. The final result is coalescence over and between each seed form, producing a continuous layer of GaN. This is all accomplished in one regrowth step and eliminates the need to align devices or masks for a second LEO layer over particular areas of the GaN surface.

Cantilever ELO. In pendeo-ELO, it is still necessary to grow an initial GaN seed layer, before carrying out the operations of mask-forming and ELO growth. Therefore, growth has to be carried out twice, which is expensive. To avoid this cost, a variant of pendeo-ELO, called cantilever ELO[31] in the U.S. and LEPS (lateral epitaxy on patterned substrates) in Japan, has been developed. In this technique, ELO is performed on a substrate that has been processed to impart it with a groove-and-ridge topography and to create preferential conditions for lateral growth from the ridges. In this way, the technique becomes a single mask one-step growth directly on the starting substrate, rather than a two-step growth that relies first on growth of a buffer layer. Promising results have been reported,[32] including external quantum efficiency of LEPS-grown UV LEDs at 20 mA of 24% and dislocation densities of 1.5 × 10^8/cm^2.

There are several issues that prevent ELO and its variants from being used in LEDs.

- The first is cost and area. Since ELO requires a simple buffer, followed by a process patterning step, followed by an ELO buffer, it roughly doubles the cost of the epitaxy. This is exacerbated because only narrow strips of ELO material are high quality, separated by coalescence boundaries with much higher dislocation densities. Hence, increasing the available area associated with the low defect regions will be important.
- The second is the residual dislocation density even in the "good" areas; these should be decreased still further, to the 1e5-1e6/cm^2 range.
- The third is strain and tilting of the ELO material, which causes wafer bowing, wing tilt accompanied by extended defects at coalescence boundaries, and device performance modifications through strain-induced piezoelectric fields.
- ELO does not work (is not selective) for AlGaN, making it difficult to create variable-composition and variable-lattice-constant buffer layers.

1.2.3 Thick, Removable GaN Buffers

It is possible that thin planar or ELO-based buffer layer technologies will be successful in reducing dislocation densities. However, these technologies generally lead to a bi-material substrate+buffer structure with mismatched thermal expansion coefficients, and difficult-to-control post-buffer and post-epi room-temperature strain states.

If the buffers are thick enough, however, it is possible to remove the original substrate, leaving a free-standing buffer that essentially becomes a new single-material substrate. An example is shown in Figure 14. Very thick buffers also have the advantage that dislocation densities tend to decrease with increasing thickness.

[30] R. F. Davis, T. Gehrke, K. J. Linthicum, P. Rajagopal, A. M. Roskowski, T. Zheleva, E. A. Preble, C. A. Zorman, M. Mehregany, U. Schwarz, J. Schuck, and R. Grober, "Review of pendeo-epitaxial growth and characterization of thin films of GaN and AlGaN alloys on 6H-SiC(0001) and Si(111) substrates," MRS Internet Journal of Nitride Semiconductor Research 6 (2001) 1-16.

[31] C. I. H. Ashby, C. C. Mitchell, J. Han, N. A. Missert, P. P. Provencio, D. M. Follstaedt, G. M. Peake, and L. Griego, "Low-Dislocation-Density GaN From a Single Growth on a Textured Substrate," Applied Physics Letters 77 (2000) 3233-3235.

[32] K. Tadatomo, H. Okagawa, Y. Ohuchi, T. Tsunekawa, T. Jyouichi, Y. Imada, M. Kato, H. Kudo, and T. Taguchi, "High output power InGaN ultraviolet light-emitting diodes fabricated on patterned substrates using metalorganic vapor phase epitaxy.," Physica Status Solidi A 188 (2001) 121-5.

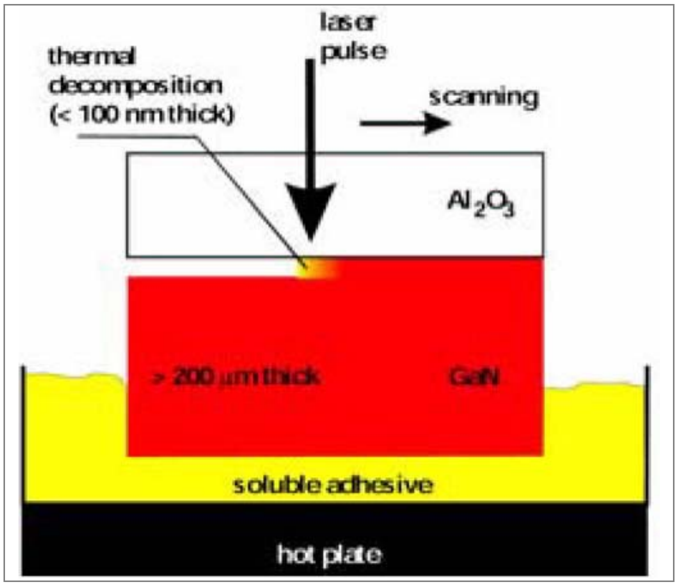


Figure 14. Schematic of laser removal of GaN thick film from substrate. After Robert F. Davis, "Alternative Substrates for III-Nitride LED Structures," OIDA Solid-State Lighting Workshop (Albuquerque, May 30, 2002).

Freestanding GaN buffers have already been demonstrated on a variety of removable substrates, including sapphire, silicon carbide, gallium arsenide, and lithium gallate.

- Sapphire: The current largest freestanding GaN buffer was obtained by growing a thick GaN layer on a sapphire substrate using HVPE and separating the grown layer from the sapphire substrate. However, it is not very easy to separate the GaN layer from the sapphire substrate because sapphire is very hard and is not etched by any etchant.
- SiC: Freestanding GaN buffers have also been demonstrated on SiC, again using HVPE of thick GaN (at growth rates of 1 μm/min) followed by silicon carbide substrate removal (by RIE in a SF_6 containing gas mixture).
- GaAs: Freestanding GaN buffers are also possible on GaAs,[33] since GaAs substrates can easily be removed by aqua regia, and relatively large substrates of high quality are readily available.
- LGO: Freestanding GaN buffers have demonstrated on Lithium Gallate (LGO), which has the advantage of having the best known lattice match to GaN, 0.19% in the a-axis, of any heteroepitaxial bulk substrate. And, entire LGO wafers can be easily removed from the III-nitride films in a matter of minutes through selective etching.

We note that even if thick, removable GaN buffers end up not being economical, if they are high enough quality, they will enable fundamental materials physics properties to be less ambiguously measured (science), so that an assessment can be made of the importance of eliminating defects, and eventually of going to GaN bulk substrates (technology).

1.3 Epitaxy Tools

Epitaxy is a key and demanding “front-end” step in fabrication of the light-emitting device engine. It’s science and technology has advanced considerably this past decade.

For AlGaInP materials, in particular, epitaxy tools are highly advanced, with organometallic vapor-phase epitaxy (OMVPE) emerging as the most important of these tools. Production OMVPE tools with automated cassette wafer loading are now capable of growing five 6” or thirty-five 2” wafers at a time. These tools have driven the cost of AlGaInP LEDs down considerably over the last ten years.

For AlGaInN materials, however, epitaxy tools are still relatively immature. AlGaInN materials, though still compound semiconductors, behave quite differently from conventional AlGaInP and AlGaInAs materials. Indeed, epitaxy tools used to grow more mature compound semiconductor materials such as AlGaInAs cannot be used to grow AlGaInN because of the unusual growth conditions required for the nitride systems. Commercial manufactures of nitride devices currently use a combination of commercial and customized reactor designs, and there is no clear consensus on how to design nitride CVD reactors either for optimal single-wafer results or for multi-wafer high-volume production.

In this Section, we discuss the advanced tools necessary for high reproducibility, uniformity and control of epitaxy, as well as fundamental understanding of mechanisms that can enable improved tools and processes. There are two dominant kinds of tools that are used for device epitaxy.

Challenge 1.3.1 discusses the first: Molecular Beam Epitaxy (MBE). MBE is a simpler technique (evaporation of atoms in ultra-high vacuum), and the engineering technology, though sophisticated, is reasonably well

[33] K. Motoki, T. Okahisa, N. Matsumoto, M. Matsushima, H. Kimura, H. Kasai, K. Takemoto, K. Uematsu, T. Hirano, M. Nakayama, S. Nakahata, M. Ueno, D. Hara, Y. Kumagai, A. Koukitu, and H. Seki, "Preparation of large freestanding GaN substrates by Hydride Vapor Phase Epitaxy using GaAs as a starting substrate," Jpn. J. Appl. Phys. 40 (2001) L140-L143.

understood. However, this approach has not been as heavily emphasized in the past. MBE has not yet demonstrated high quality in situ buffers, and hence its use is limited to device epitaxy, and, even then, only in conjunction with a substrate whose buffer has been created by another method (e.g., OMVPE or HVPE). Nevertheless, for many device structures, MBE has advantages, and further development of MBE tools and processes could be important.

Challenges 1.3.2-1.3.4 discuss the second: organometallic vapor-phase epitaxy (OMVPE), which involves chemically reacting fluid flows. This approach is both currently dominant, and is likely to be dominant in the future. Because of its complexity, we divide the Challenges into three. Challenge 1.3.2 involves unraveling the chemistry underlying OMVPE. Challenge 1.3.3 involves reactive fluid flow models, and the design of OMVPE tools that optimize this reactive fluid flow. Challenge 1.3.4 involves in situ diagnostics, both for understanding OMVPE processes in greater detail, as well as for controlling these processes during epi manufacturing.

1.3.1 MBE Tools and Mechanisms

OMVPE is the dominant current epitaxial technique for epitaxial growth of both AlGaInP and AlGaInN alloys. MBE is an alternative technique.

For AlGaInN materials, however, it is necessary to augment the usual solid sources – Al, Ga, In, Mg, Si – with gas sources, as there is no solid source available for providing the N beam, and with activating the N, since molecular nitrogen is almost totally inert. The three broad approaches for doing so are: RF plasma activation of N_2; microwave cyclotron resonance excitation of N_2 (the so-called ECR source); and thermal cracking of ammonia directly on the substrate.

For AlGaInN devices, MBE has not yet demonstrated very high quality buffers or very high quality optoelectronic devices.[34] However, when used to grow devices on top of buffers grown by other methods (OMVPE or HVPE), the quality of the devices has been gradually improving. For example, photoluminescence from GaInN/GaN multi-quantum-well structures grown by MBE have spectral half-widths of the order of 20nm, centered at 420 nm, indicating reasonably high quality, although light emission intensity is still lower by 1 to 2 orders of magnitude than that of layers grown by OMVPE.

There is no reason to believe that, as with other compound semiconductor devices, MBE will not eventually be able to match OMVPE in terms of device quality and performance. In fact, the MBE technique enables some features that are not yet possible with OMVPE, and that may enable it to surpass OMVPE in some ways. If it does so, it is possible that MBE could be scaled to the high-volume production necessary for solid-state lighting. If it does not do so, MBE still represents an important alternative technology for helping unravel the science of AlGaInN materials and heterostructures.

1.3.2 OMVPE Chemistry

The OMVPE process is fundamentally a chemical one, in which gaseous precursors are injected from a precision gas-mixing manifold into a cold-wall reactor, where they react on, or enroute to, the substrate.

The two key aspects of OMVPE are the chemistry, and the fluid flow. These two aspects are linked, but each is a complex and challenging area of its own. This is particularly the case for AlGaInN, which is much less mature than AlGaInP, and which involves more extreme growth conditions (temperature, pressure), and more unwanted side-reactions. In this Challenge we discuss chemistry and precursors; in the next Challenge we discuss fluid flow (including some aspects of chemistry), and the ramifications on tool design.

The most common precursors for the growth of AlGaInN are the simple Column III metal alkyls (TMAl, TMGa, TMIn) and the Column V hydride (NH3). From these precursors, reasonably high quality AlGaInN materials may be grown. However, despite considerable empirical knowledge accumulated by many research groups, clear understanding of the relative role of different physical mechanisms governing the chemistry is not yet been reached. This may be related to both complex gas-phase as well as complex surface-phase chemistry:

- NH3 decomposition. Even something as basic as ammonia decomposition appears to be relatively poorly understood. Thermodynamic analysis of various nitrogen precursors show that ammonia should almost completely dissociate into inactive N2 and H2 at temperatures as low as ~400° C. If this were the case, growth of GaN would not occur at all, due to the lack of a reactive nitrogen precursor. This means that the pure thermodynamic consideration is not applicable to analysis of the real growth situation. The N-H bond strength is 4.5 eV, similar to O-H and H-H. NH3 cracking may depend on catalytic

[34] G. Pozina, J. P. Bergman, B. Monemar, B. Heying, and J. S. Speck, "Radiative and nonradiative exciton lifetimes in GaN grown by molecular beam epitaxy.," Physica Status Solidi B 228 (2001) 485-8.

dissociation, since the N-H bond breaking energy is so high.

- Precursor interactions. One area of concern in the MOCVD growth of III-N materials is the interaction of the organometallic sources with the high concentrations of NH3 used in this process. The organometallics are strong Lewis acids and will react in the gas phase with ammonia, a strong Lewis base, potentially leading to the production of stable adducts. The degree to which this is a problem is a function of nearly all aspects of the growth environment – pressure, temperature, flow rates, residence times in heated zones, etc.
- Purity. An extremely important consideration in the growth of high-quality epitaxial device structures is the purity of the sources. This is especially true for MOCVD growth of nitrides since the incorporation of Si and O are both of great concern for these materials, particularly for growing heavily p-type AlGaInN alloys. Recently, special high-purity sources of TEGa, TMGa, TMIn, and TMAl, have become available from several vendors, for which oxygen-containing precursors, such as residual alkoxide compounds, have been reduced.
- Particle formation. Recent work indicates that nanoparticle formation in the boundary layer can be a significant parasitic reaction path, both for GaN and AlN OMVPE.[35]

1.3.3 OMVPE Reactive Flow and Tools

The OMVPE process is basically a chemically reacting fluid flow processes. These problems are complex, because they are sensitive to both the chemistry and the fluid flow. In the previous Challenge we discussed chemistry and precursors; in this Challenge we discuss overall chemically reacting fluid flow issues, and especially their ramifications on tool design.

Current OMVPE tools for the more-mature AlGaInAs and AlGaInP materials systems are very well developed. Current OMVPE tools for AlGaInN are much less mature, and there is no consensus on which, if any, is best. The tools take various forms (flows which are oriented horizontally or vertically), and the process conditions also vary (from atmospheric pressure to moderately low few-Torr pressures). And, both commercial and home-built reactors are used.

Simply borrowing from the experience of tools used for OMVPE of GaAs based devices is not sufficient, since much of that experience is contrary to the more complex growth mechanisms associated with AlGaInN.[36] The reasons are those listed above: more extreme growth conditions (high and low temperatures, pressure) and parasitic gas-phase pre-reactions.

The current generation of AlGaInN reactors suffer from: unacceptable composition nonuniformity (which leads to wavelength nonuniformity); inadequate throughput (larger reactors need to be developed in the near future in order to speed up the cost reduction cycle); and inadequate process reliability and reproducibility. This is a special issue for solid-state lighting, because the human eye is so sensitive to slight variations in color. The uniformity and reproducibility of wavelengths, e.g., needs to be within +/- 1% in the green, +/- 0.8% in the blue. Currently, uniformity and reproducibility are about 10x worse for AlGaInN than for AlGaInP.

Fundamentally new reactor designs may be needed. Ideally, these new designs will be based on new knowledge of the chemistry developed in Challenge 1.3.2, and the unique requirements of AlGaInN epitaxy. Some of these requirements will be driven by the novel processes discussed in Challenge 1.4.2, such as those requiring rapid temperature, and gas-flow and pressure cycling.

1.3.4 OMVPE In Situ Diagnostics

For OMVPE growth of traditional AlGaInAs and AlGaInP based compound semiconductors, in situ diagnostics, particularly those based on optical reflectance and optical pyrometry, have made a significant impact on the accuracy and reproducibility of growth. For example, VCSELs, which are among the most demanding device structures, can be grown with less than 0.5% wavelength variation from run to run.

For OMVPE growth of the more complex AlGaInN based compound semiconductors, in situ diagnostics have also shown themselves to be valuable, particularly during growth of buffers, whose microstructure evolves in a complex and sometimes-difficult-to-reproduce manner during growth. They could also be of great value during growth of device epilayers, where compositions and growth

[35] J. R. Creighton, W. G. Breiland, M. E. Coltrin, and R. P. Pawlowski, "Gas-phase nanoparticle formation during AlGaN metalorganic vapor phase epitaxy," Applied Physics Letters 2002) .

[36] T. F. Kuech, "Issues in GaN Growth Chemistry and Reactor Design," OIDA Solid-State Lighting Workshop (Albuquerque, May 30, 2002).

rates must be precisely controlled, but also vary nonlinearly with growth conditions (flows, temperatures, pressures).

However, in situ diagnostics for AlGaInN are relatively immature. Because device epitaxy is often grown on buffers which have undergone considerable microstructural evolution, and whose surfaces are not perfectly smooth, optical reflectance can be somewhat difficult to interpret.

Even the most basic quantity, temperature, which is usually measured through optical pyrometry, is difficult to measure due to blackbody radiation from the susceptor that is nearly completely transmitted through the sapphire substrates. Because of the nonlinear and steep dependences of both buffer layer evolution and device epitaxy growth rates and compositions on temperature, this is a major deficiency.

1.4 Epitaxy Processes

In the previous Section, we discussed the development of new epitaxy tools based on an understanding of epitaxy mechanisms. In parallel with that, discussed in this Section, is the development of epitaxy processes based on existing tools. These processes will be different depending on the material to be grown.

AlGaInP, as discussed before, is the most mature, and is discussed in Challenge 1.4.1 AlGaInN is much less understood, and is discussed in Challenge 1.4.2. For both of these materials systems there are three common themes.

- The first common theme is strain. In some cases it will be desirable to have layers with large strains. In other cases it will be desirable to have layers with no strain. This can be done through use of quaternary AlGaInP and AlGaInN alloys, but it requires a very high degree of compositional control and is extremely demanding of the epitaxial growth tool and process.
- The second common theme is control of compositional modulation or nonuniformity, such as self-assembled quantum dots, which are nearly-universal phenomena in strained materials.
- The third common theme is that all these materials must be able to be tailored in two different ways. On the one hand, when used in active (radiating) parts of a device their radiative efficiency must be very high. This usually means undoped material that is grown as pure as possible. On the other hand, when used in the current transport part of a device their electron or hole conductivity must be very high. This usually means material grown as heavily doped as possible.

Because doping of AlGaInN materials is especially difficult, due to chemical passivation during growth, we discuss this issue in Challenge 1.4.3.

Finally, Challenge 1.4.4 discusses novel materials systems not included in either the AlGaInP or AlGaInN materials family.

1.4.1 Quaternary AlGaInP

Quaternary AlGaInP is the materials system that currently produces the brightest red luminescence, and hence is most likely to be used for the red LEDs in the color-mixed and hybrid approaches to white lighting.

This materials system can be considered mature. Devices made from the Ga-rich end of this materials system (deep red wavelengths of 650nm) have nearly 100% internal quantum efficiency, so the bulk material quality is very high. However, devices made from the Al-rich end of this materials system (mid-red wavelengths of 610nm) have much lower internal quantum efficiencies. Partly, this is due to fundamental materials physics -- the direct/indirect crossover occurs at roughly ¼:¼:½ Al:Ga:In content.

However, the mid-red wavelengths are those that are best-suited for tri-color white light, hence it would be highly desirable to push the AlGaInP materials system further into the mid-red.

1.4.2 Quaternary AlGaInN

Quaternary AlGaInN, typically grown by OMVPE,[37] is the dominant materials system used for the current generation of blue and green LEDs. Hence, it could be used for the blue and green components of a color-mixed approach to white lighting, or for a blue plus phosphor-down-converted yellow or green/red approach to white lighting.

There are three "corners" to the "pseudo-ternary" triangle of this materials system.

- The Ga-rich corner is the most mature. This materials system is mostly GaN, with a small amount of InN for the light-emitting layers, and either pure GaN or GaN with a small amount of AlN for the confining layers. This corner of the triangle emits light in the blue and green.
- The Al-rich corner is less mature. This materials system contains significant amounts of Al. It is

[37] S. P. Denbaars and S. Keller, "Metalorganic Chemical Vapor Deposition (MOCVD) of Group III Nitrides," Semiconductors and Semimetals 50 (1998) 11-37.

generally much lower in quality, and is much less used in devices. Significant opportunities would be opened up to the device designer if these alloys were opened up – particularly UV-emitting devices.

- The In-rich corner is the least mature. This corner would enable amber and red emitting devices, which would open up the possibility of integrating blue, green and red emitters on a single GaN-based substrate. However, when the In content becomes too high, radiative efficiency decreases strongly, and it has been difficult to achieve strong photoluminescence or cathodoluminescence much beyond 580nm.

For all three of these corners, and for quaternary AlGaInN materials generally, there are several common themes.

- Composition modulation. InGaN material tends to phase separate into a compositionally inhomogeneous "quantum-dot-like" microstructure. This tends to confine carriers to regions of lower bandgap, thereby avoiding nonradiative recombination at extended defects in the matrix. Indeed, some In content appears to be essential to the current generation of blue, green and white LEDs. These materials are now reasonably efficient, with internal radiative quantum efficiencies on the order of 50-75%. However, the inhomogeneity broadens spectral line widths, which may be disadvantageous for stimulated emission devices.
- Defects. Until higher-quality substrates and buffers are developed, extended defects such as dislocations will continue to be a significant problem. These defects may make necessary the composition modulation described above.
- Doping. n-type doping is relatively straightforward, as Si works quite well across the composition ranges – Si has a moderate activation energy, and electrons have a relatively high mobility. p-type doping is not so straightforward. Mg is a tricky dopant to use, with a high activation energy, and with a strong propensity to be passivated with hydrogen. In addition, holes have a relatively low mobility.
- In segregation.
- Growth temperature incompatibilities. The ideal growth temperatures of the binary constituents are quite different – AlN requires high temperatures (1200-1300C), GaN medium temperatures (1000-1100C), and InN relatively low temperatures (700-800C). Hence, at growth temperatures optimal for InN, the material quality of AlN is poor, perhaps due to insufficient mobility of Al adatoms strongly bound to the AlN surface. At growth temperatures optimal for AlN or GaN, InN tends to desorb, due to the weak In-N bond.
- Interfaces. Segregation and growth temperature incompatibilities also lead to difficulties in creating sharp and well-defined interfaces in heterostructures. Each of these heterointerfaces represents an opportunity for roughness and interface non-abruptness, all of which can lead to non-radiative recombination, carrier scattering, etc.
- Strain. AlN, GaN and InN have very different lattice constants. Hence, the ternary and quaternary compositions are characterized by large microscopic bond strains, leading to microscopic composition modulation and phase separation. And, they are characterized by large macroscopic strains, due to mismatch of the overall alloy with the substrate. These macroscopic strains can lead to surface morphology issues (via growth mode) and cracking.

1.4.3 Doping and Passivation

OMVPE is characterized by having a large amount of hydrogen present, both from the H2 carrier gas as well as from the ammonia precursor that is present in great quantities. This hydrogen incorporates into the p-type GaN during MOCVD growth, producing highly stable passivation of the Mg acceptors. Hence, this hydrogen must first be released before the Mg-doped material can actually become p-type. The original observation that this could be accomplished through e-beam irradiation, and the later observation that this could be accomplished through thermal annealing, is perhaps one of the most significant advances that enabled high-brightness AlGaInN-based LEDs.

However, much is not understood about this passivation process – how it depends on both the Mg present as well as on other point and extended defects – and about the release process. In fact, there is evidence that complete acceptor activation by thermal H release requires temperatures that threaten material integrity, and may rarely occur in actual devices.

Note that even without passivation, doping of AlGaInN is difficult. In part, this is because it is a wide-gap semiconductor. The ionization energies of dopants goes as m^*/ε^2, where m* is the effective mass and ε is the dielectric constant. In wide-gap semiconductors the effective mass tends to be large (especially for holes) and the dielectric constant tends to be low, so ionization energies tend to be large, and doping becomes relatively difficult. E.g., the depth of the Mg acceptor level is 250 meV, which leads to poor doping efficiency (typically no more than about 1% at room temperature). If shallower acceptors can be found, they would have considerable impact on device design.

A common theme in this Challenge is the importance of linking experiment with theory – both in studying the energetics, as well as the kinetics, of doping and passivation.

1.4.4 Novel Epimaterials

AlGaInP and AlGaInN are the current dominant materials systems. However, similar kinds of bandgap engineering can be done in principle with other materials.

One of the prime candidates is ZnO, in which p-type doping has recently been demonstrated. Note, though, that these results have not yet been widely reproduced, and they may have stability issues because of poor thermodynamic miscibility.

Two additional possibilities are GaNP and GaNAs.[38] These materials are expected to span a very wide band gap range, and may possibly emit red, green, and blue light by changing the ratio of mixed crystals. Thus far, however, there has been a strong tendency towards phase separation in these materials -- regions of hexagonal [0001] oriented GaN, cubic [111] oriented GaAs and hexagonal [0001] oriented GaN{sub 1-x}As{sub x}. Also, the growth mode and optimum V/III ratio is affected dramatically by the addition of As flux, suggesting that arsenic is acting as an isoelectronic surfactant during the growth of GaN films.

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[38] S. V. Novikov, T. Li, A. J. Winser, C. T. Foxon, R. P. Campion, C. R. Staddon, C. S. Davis, I. Harrison, A. P. Kovarsky, and B. J. Ber, "The influence of arsenic incorporation on the optical properties of As-doped GaN films grown by molecular beam epitaxy using arsenic tetramers.," Physica Status Solidi B 228 (2001) 227-9.

2 Physics, Processing and Devices

At the heart of SSL-LED technology is the light "engine" chip. The "front-end" fabrication of this chip involves the substrate, buffer, and epitaxy technologies discussed in Chapter 1. The "back-end" fabrication of this chip involves the processing or shaping of the epiwafers into light-emitting devices, and is discussed in this Chapter.

As was the case for the front-end fabrication, the back-end fabrication of the AlGaInP devices used for red light emitters is more mature than that of the AlGaInN devices used for green, blue and UV light emitters, though perhaps not by as much.

For AlGaInP devices, 50% chip power conversion efficiencies have already been demonstrated. However, these efficiencies are for deep red (650 nm) wavelengths, rather than for the mid-red (610 nm) wavelengths best suited for a tricolor white. And, these efficiencies decrease significantly at the high input-power densities necessary to meet our chip cost targets. Hence, there are still challenges associated with designing and fabricating band-gap-engineered AlGaInP devices.

For AlGaInN devices, 20% chip power conversion efficiencies have been demonstrated. These efficiencies are still quite far from our targets; are at wavelengths that do not yet include the green and red ranges desired for the color-mixing approaches to white-light production; and also decrease significantly at the high input-power densities necessary to meet our chip cost targets. Hence, there are major challenges associated with designing and fabricating band-gap-engineered AlGaInN devices. Also, for AlGaInN, this band-gap engineering is complicated by unique electronic properties, such as strong piezoelectricity, as well as by the general immaturity of the materials.

In Section 2.1, we discuss the basic properties of AlGaInN materials and nanostructures, and the properties of electrons, holes and photons in these materials and nanostructures:

- How electrons and holes are created, how they move, and how they annihilate, either non-radiatively or radiatively.
- How photons are created from radiative recombination of electrons and holes, and how they can be manipulated to maximize escape from, rather than re-absorption by, the semiconductor.

In Section 2.2, we discuss post-epi device-level wafer processing. This Section is diverse, ranging from wafer bonding and film transfer, to metallization, to etching, chip shaping and texturing for enhanced light extraction. Many of these processes are similar to, and borrow from, equivalent technologies for silicon integrated circuits. However, some, such as chip-shaping for efficient external light extraction, are unique to SSL-LEDs, and require overcoming special challenges. These are the processes that we focus attention on.

In Section 2.3, we discuss "simple" light-emitting diodes in which light is emitted spontaneously (and omni-directionally) by the device. In Section 2.4, we discuss lasers or other devices in which light is emitted directionally. Both are possibilities for solid-state lighting, and both have advantages and disadvantages. Spontaneous emission devices are likely to be the least costly to fabricate, will be more linear with drive intensity and hence somewhat easier to control, and perhaps more sensitive to defects, but with less efficient extraction and directability of the light. Stimulated emission devices are likely to be more expensive to fabricate, will be less linear with drive intensity and hence somewhat more difficult to control, perhaps less sensitive to defects, but with more efficient extraction and directability of the light.

For both spontaneous and stimulated emission devices, an additional issue is the level of functionality will be integrated into the semiconductor chip. At one extreme, a single semiconductor chip provides only a single function: emission of monochromatic light at a particular wavelength. At the other extreme, a single semiconductor chip emits light at all the colors necessary for white light, and includes the electronics required to drive and control intensity, color, directionality and focus.

2.1 Semiconductor Physics

In this Section we discuss the basic materials properties of AlGaInP and AlGaInN semiconductors. Particularly for the AlGaInN semiconductors, fundamental knowledge of these properties is substantially less well developed compared to conventional AlGaInAs- and GaInPAs-based compound semiconductor materials, and compared to silicon. The difficulties stem, in part, because the AlGaInN materials system itself comes in four "flavors":

- Crystallographically perfect bulk materials
- Crystallographically perfect materials fabricated into nanostructures for bandgap engineering

purposes

- Crystallographically imperfect bulk materials
- Crystallographically imperfect materials fabricated into nanostructures for bandgap engineering purposes

The last two flavors are perhaps the most common, because of the lack of suitable substrates for epitaxial growth, which leads to epitaxial films with high defect densities. These defects produce electronic states in the band gap that can both modify the overall properties of the material, as well as cause difficulties in measuring those properties.

Also, 2D, 1D and 0D nanostructures fabricated from these materials have properties very different from those of bulk materials, and can be exploited for bandgap engineering purposes. In particular, semiconductor nanostructures will manifest three phenomena: modification and concentration of the electronic density of states; the possibility of materials with higher strain and a wider accessible range of materials compositions and bandgaps; and enhanced carrier confinement and trapping.

It is necessary to improve our understanding of, and ability to manipulate, the physical properties of materials with all four "flavors." Only then can we take full advantage of these materials for scientific design of efficient optoelectronics.

In Challenge 2.1.1, we discuss the basic properties of AlGaInN materials. In Challenge 2.1.2, we discuss high-efficiency recombination of electrons and holes to create photons. In Challenge 2.1.3, we discuss the manipulation of photons through nanostructures engineering to control the directionality and extraction of photons from the device.

2.1.1 AlGaInN Material Properties

Most of the properties of AlGaInP semiconductors are well established. However, the properties of AlGaInN semiconductors are not yet well established. These properties range from even basic ones such as electronic band gap to more subtle ones such as polarization field constants. Some of these properties are listed here.

- AlGaInN Structure. For the common semiconductors (Si, GaAs, InP), one crystallographic structure (diamond cubic) is overwhelmingly favored. For AlGaInN semiconductors, this is not the case. Both hexagonal and cubic phases can be grown. Most devices are currently fabricated from the hexagonal phase; however, devices can also be fabricated from the cubic phase, and there is now a growing literature on the synthesis and properties of this material, particularly by MBE. Moreover, cubic AlGaInN has several properties that make it interesting for devices: it is easier to dope, cleave (especially useful for laser facets) and contact; and it may have higher electron and hole mobilities. Hence, it is of interest to understand the forces that control growth of one or the other of these phases.
- AlGaInN Microstructure. For the common semiconductors (Si, GaAs, InP), microstructure is usually featureless (very few extended defects or compositional nonuniformities). For AlGaInN, however, phase separation into compositionally modulated "quantum-dot-like" material is not only common, but perhaps essential to performance. The quantum-dot-like regions trap free carriers and prevent them from recombining non-radiatively at extended defects. Hence, it is of interest to understand the forces that drive microstructure development, and especially phase separation.
- AlGaInN Electronic Band Structure. The basic electronic band structure of a semiconductor determines how electrons and holes move and recombine in bulk materials and in heterostructures. Of primary importance are the main features of the band structure: band-gaps, band-offsets, and effective carrier (electron and hole) masses. Of secondary importance are the derived properties of the band structure, such as dielectric properties.

To maximize the device designer's ability to take advantage of the full range of AlGaInN alloys, it is important to establish these properties for all the quaternary compositions. In addition, since strain (both intentional and unintentional) and high-temperature operation are universal features of AlGaInN devices for solid-state lighting, these properties need to be established for a range of strains (+/- 5%) and temperatures (0-200C). Also, although almost all current devices are fabricated from hexagonal AlGaInN, there may be some benefit to the use of cubic AlGaInN, hence it will be helpful to establish these properties for both hexagonal and cubic[39] AlGaInN.

[39] S. F. Chichibu, M. Sugiyama, T. Kuroda, A. Tackeuchi, T. Kitamura, H. Nakanishi, T. Sota, S. P. DenBaars, S. Nakamura, Y. Ishida, and H. Okumura, "Band gap bowing

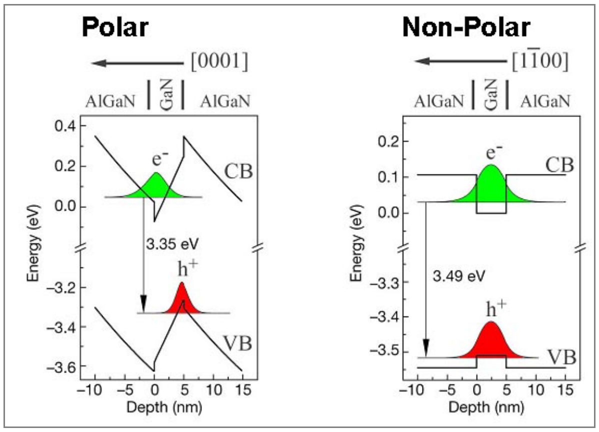

Figure 15. Electron and hole wave-functions in quantum wells are spatially separated when oriented along polar vs. when oriented along non-polar directions. After P. Waltereit, O. Brandt, A. Trampert, H. T. Grahn, J. Menniger, M. Ramsteiner, M. Reiche, and K. H. Ploog, "Nitirde semiconductors free of electrostatic fields for efficient white light-emitting diodes," Nature 406 (2000) 865-868.

- Polarization Fields. A unique feature of AlGaInN materials is polarization fields, due to their non-cubic symmetry. These fields are of two kinds: spontaneous polarization (SP) and piezoelectric polarization (PZ). Both fields are significant and are about an order of magnitude higher than those observed in the common narrower-bandgap zincblende III-V semiconductors.

  The consequence of these polarization fields is significant. For example, in the presence of an interface the difference in the SP or PZ coefficients in the two materials gives rise to a net charge at the interface. In the common case of a quantum well (QW), i.e. a lower bandgap thin semiconductor layer sandwiched between two higher bandgap cladding layers, the two interfaces will have opposite charges, and a strong electric field will be produced across the QW. These fields modify the energy band levels as well as give rise to charge separation and Stark effects which, as illustrated in Figure 15, modify carrier recombination rates and energies. The equivalent sheet charge densities are on the order of 1e13/cm^2, and the resulting electrostatic barriers for charge confinement are comparable in magnitude to those created by band offsets at typical heterojunctions.

  Hence, a quantitative understanding of these polarization fields is necessary in order to understand how to best engineer device heterostructures for carrier transport, trapping and radiative recombination.

- Phonons. At finite temperatures, and especially at the higher temperatures of operation afforded by AlGaInN materials, phonons will be present. Phonons are the dominant mechanism for carrier scattering through deformation potentials and piezoelectric fields at typical operating (0-200C) temperatures of SSL-LED devices. And, phonons may couple with photons to create polaritons with mixed optical properties, and may couple with electrons to create polarons with mixed electronic properties.

  Phonon effects are especially strong in AlGaInN materials. Because nitrogen is more electronegative than the group V atoms in the narrower-bandgap III-V materials, the ionic component of the chemical bond in AlGaInN materials is also much stronger. This, in turn, results in higher optical phonon energies and greater polaron effects. Such fundamental quantities as the Frohlich coupling constant for electron/LO-phonon interactions need to be measured.

  A central related question is whether, in p-doped high-Al-content AlGaN, polarons will form (i.e., self-trapping of holes by coupling to phonons – this is the DX-center analogy).

  Moreover, because the bond strengths and elastic constants for AlN, GaN and InN are so different, the phonon frequencies and dispersion curves are very different in each these materials. Hence, not only are bulk phonons important, but phonons confined to heterointerfaces are also important,[40] as well as phonons confined in 0D structures such as quantum dots.

- Electron and hole transport. Transport of electrons and holes from the contacts to the active regions is an essential step enroute to radiative recombination within the active regions. The transport may be a complex convolution of perpendicular and parallel paths, particularly if significant lateral current spreading is required, as

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and exciton localization in strained cubic InxGa1-xN films grown on 3C-SiC (001) by rf molecular-beam epitaxy," Applied Physics Letters 79 (2001) 3600-3602.

[40] E. F. Bezerra, A. G. Souza, V. N. Freire, J. Mendes, and V. Lemos, "Strong interface localization of phonons in nonabrupt InN/GaN superlattices," Physical Review B 6420 (2001) 1306.

it is with the current generation of devices.

Hence, it is essential to understand the transport dynamics of electrons and holes, in order to understand how they can best be manipulated through alloy and heterostructure composition and design.

- Defects. Defects of many kinds are present in device heterostructures.

  Of primary importance are point defects – including impurities useful for doping. These and other point defects determine the achievable doping levels and conductivities, and the ability to optimize vertical and lateral current transport in devices. If they lead to deep levels, they can also lead to nonradiative recombination that competes with the radiative recombination.

  Of secondary importance are extended defects – including dislocations. These defects are a universal presence in AlGaInN materials, as they are the vehicles for strain relaxation in buffer layers used for virtually all current AlGaInN-based devices. They are of secondary importance because it is now well-established that they are all (edge, screw and mixed, e.g.) detrimental to device performance – they are responsible for deep level traps, for nonradiative recombination paths, as well as for alternate, multi-stage and red-shifted radiative recombination paths. Hence, it is of the greatest importance to understand how to eliminate these defects. It is of lesser importance to understand their energetics and thermodynamics, except as this may assist in understanding how to eliminate or passivate them.

2.1.2 High-Radiative-Efficiency Electron-Hole Recombination

One of the most central Challenges is the recombination of electrons and holes to create photons. In principle, this process can be very efficient, and in many materials and heterostructures does indeed approach 100%. It is in large part because of the high potential efficiency of this process, that Solid-State Lighting is viewed as ultimately more efficient than any of the traditional technologies.

In practice, however, electrons and holes may recombine in many ways that do not lead to photons. They may interact with defects and recombine non-radiatively. They may be injected into heterostructures, but then, particularly at higher injected currents or temperatures, may escape before recombining. Understanding the physics of how electrons and holes interact with each other, and with the heterostructures they are injected into, is essential to the engineering of ultra-high-efficiency electron-hole radiative recombination.[41] Among the issues are the following.

Heterostructures. Because of their charge, electrons and holes interact strongly with each other, and with the electric fields and potential barriers associated with heterostructures.[42] These interactions modify electron and hole energy levels, thereby modifying recombination energies and wavelength. They also modify the spatial overlap of the electron and hole wave functions, thereby modifying recombination rates. Hence, an understanding of these effects is necessary for tailoring the light emission wavelengths of devices, and for optimizing the efficiency of radiative recombination.

Microstructure. In microstructurally perfect material (in the absence of defects), radiative recombination is generally an extremely efficient process in III-V semiconductors. In the presence of defects as numerous as those found in AlGaInN material, however, non-radiative recombination typically becomes a very efficient competing channel.[43] Surprisingly, AlGaInN emits very efficiently (though with much room for improvement). There is a belief that localization effects are important, either through In-rich composition heterogeneities, or through polaron effects, but there are as yet no definite conclusions regarding the origin of the process. Indeed, figuring out ways to maintain high radiative recombination rates without localization would be significant, since localization may impede electron and hole transport. Comparative investigation of quantum well vs. quantum wire, vs. quantum dot active regions should be employed.

Excitons. The most basic electron-hole interaction is the formation of excitons, or electron-hole pairs bound together by Coulomb attraction. In most III-V semiconductors the binding energy is relatively weak, and excitons are observed mainly at lower temperatures.

[41] Weng W. Chow, "Physics of Optical Response in Group-III Nitride Active Structures," OIDA Solid-State Lighting Workshop (Albuquerque, May 30, 2002).

[42] B. Monemar and G. Pozina, "Group III-nitride based hetero and quantum structures," Progress in Quantum Electronics 24 (2000) 239-290.

[43] A. Hierro, M. Hansen, J. J. Boeckl, L. Zhao, J. S. Speck, U. K. Mishra, S. P. DenBaars, and S. A. Ringel, "Carrier trapping and recombination at point defects and dislocations in MOCVD n-GaN.," Physica Status Solidi B 228 (2001) 937-46; T. Miyajima, T. Hino, S. Tomiya, K. Yanashima, H. Nakajima, T. Araki, Y. Nanishi, A. Satake, Y. Masumoto, K. Akimoto, T. Kobayashi, and M. Ikeda, "Threading dislocations and optical properties of GaN and GaInN.," Physica Status Solidi B 228 (2001) 395-402.

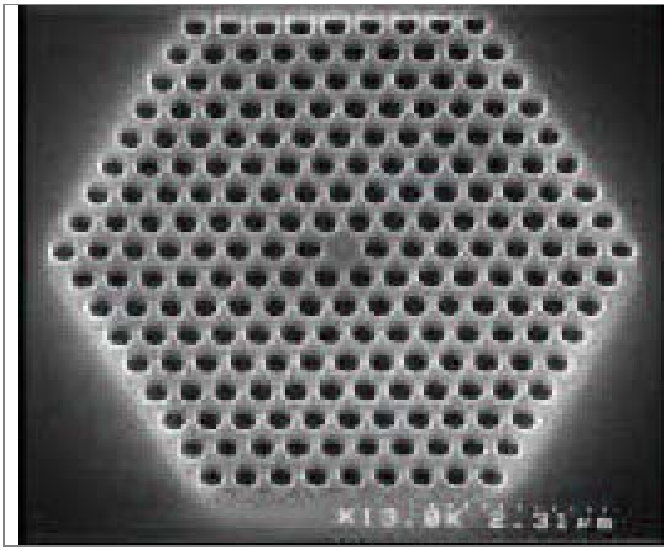

Figure 16. A 2D photonic crystal that surrounds a "defect" cavity from which a light emitter may be constructed. After A. Scherer, J. Vuckovic, and M. Loncar, "Efficient Light Emitter Geometries," OIDA Solid-State Lighting Workshop (Albuquerque, May 30, 2002).

However, in AlGaInN semiconductors, the binding energy is much larger. The reason is their strong ionicity, which leads to less covalent electron density between the ion cores, and less screening of the Coulomb attraction between electron and hole. This is similar to the II-VI materials (e.g., CdS, CdSe, ZnO), for which excitonic effects have been unambiguously shown to enhance radiative recombination in II-VI semiconductor quantum wells.

Electric Fields. An additional important interaction is with electric fields in heterostructures. In an electric field, electrons and holes become spatially separated. In quantum wells with a non-zero polarization field, this leads to what is called the Quantum-Confined Stark Effect (QCSE). In the QCSE, the field within the quantum well separates the electron and hole wave functions, decreasing their radiative recombination rate, and red-shifting their recombination transition energies. For AlGaInN materials, characterized by significant spontaneous and piezoelectric polarization fields, the effect on radiative recombination rate and transition energies can be quite large.

Other potential effects are strong modifications of: the bandstructure; modification of exciton binding to defects; modification of interactions with phonons to form polarons.

2.1.3 Photon Manipulation

Once photons have been created in the semiconductor material, they must be extracted. The development of an understanding of how to guide, reflect, and manipulate the flow of photons will be critical to this.

One recent and particularly intriguing development is photonic band gap materials. These materials are the optical analog of semiconductors with an electronic band gap. Periodic variations in dielectric constant forbid certain photon energies within the photonic lattice. These kinds of structures have the potential to guide and reflect light in a spectrally controlled manner, and to create cavities in which optical modes and spontaneous emission patterns may be modified.

For example, preliminary theoretical and experimental results indicate that they may be used to enhance light output levels of LEDs through both inhibition of, and extraction of light from, in-plane guided modes.[44] An example of such a structure is illustrated in Figure 16.

The physics of these structures, their fabrication methods, and their insertion into devices are all in their infancy. Much more basic and fundamental work is necessary in order to understand how these structures may be used to manipulate light and enhance radiative efficiencies and especially extraction efficiencies.

2.2 Device Processing

Assuming a device has been designed, using the physics-based understanding discussed above, and assuming the appropriate epilayers have been grown, the next step in fabrication of the light-emitting chip engine is device processing. These are the final processes that are done to the substrate and the epilayer, just before the wafer gets diced into chips and packaged.

Epitaxy and device processing are the wafer-level fabrication steps whose manufacturing economics scale with wafer size. It is to the advantage of any semiconductor technology to move as much processing to the wafer level as possible, to take advantage of these economics.

In this Section, we discuss this wafer-level processing -- methods by which the epilayers are laterally patterned into chips with a complex arrangement of etched and deposited

[44] H. Y. Ryu, J. K. Hwang, Y. J. Lee, and Y. H. Lee, "Enhancement of Light Extraction From Two-Dimensional Photonic Crystal Slab Structures," IEEE Journal of Selected Topics in Quantum Electronics 8 (2002) 231-237.

thin films and chip shapes. We discuss them roughly in the order of the flow from the "front-end" to the "back-end.

In Challenge 2.2.1 we discuss processes by which epilayers are bonded and transferred to other substrates. These epilayer transfer processes give device designers greater flexibility in mixing and matching materials that normally incompatible.

In Challenge 2.2.2 we discuss metallization – particularly the ohmic contacts through which high input current densities must flow into the device, and which must have very low resistances and be very robust.

In Challenge 2.2.3 we discuss etching, chip-shaping and texturing. These are the processes that are used to carve 3D shapes into the 2D epilayers, to engineer the transport of electrons, holes photons.

Note that processes that are in common use across the silicon and compound semiconductor industry we don't discuss, since they use tools and technologies that are already well-developed from these other technologies. Instead, we focus on those processes which are unique to SSL-LEDs, and which require overcoming special challenges.

2.2.1 Wafer Bonding and Film Transfer

It is often the case that one family of epitaxial semiconductor materials cannot satisfy all the materials properties necessary for the functionality of a particularly device. This is especially the case with multi-functional devices, such as MEMS (microelectromechanical systems), in which electronic and mechanical functions are combined, or optoelectronics, in which electronic and optical functions are combined. For these kinds of devices, methods are been developed for monolithically integrating materials to provide enhanced functionality. Wafer bonding and film transfer are two promising examples of such methods.

For example, AlGaInP LEDs are normally grown on GaAs substrates. However, the smaller band-gap GaAs substrate absorbs the light produced by the higher-energy AlGaInP active region, thereby limiting the brightness of the LEDs. One approach to circumventing this problem is to use 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.

These transparent substrate AlGaInP LEDs are at least a factor of two more efficient than conventional absorbing substrate AlGaInP LEDs. 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 50% have been determined for conventional-geometry devices in the red wavelength regime. At this point, transparent substrate AlGaInP materials have provided the platform for the world's most efficient visible-spectrum LEDs to date.

Wafer bonding and thin film transfer processes are not yet used in commercial AlGaInN devices, though they are beginning to be explored. Since sapphire is a transparent substrate, its removal is not as important as it is for GaAs in the AlGaInP/GaAs case.

However, substrate removal would enable additional flexibility in device design. For example, it would enable two-sided integration with optical elements, such as DBRs. Indeed, the first VCSEL (optically pumped) in AlGaInN was fabricated using laser lift-off and bonding.

And, if a sequential layer-transfer technique such as Smart-Cut could be developed for GaN, a reusable substrate technology could be very exciting. E.g., Thick GaN HVPE grown on lithium gallate followed by multiple smart-cut onto cheaper substrates (as discussed in the Buffers on Reusable Substrates Section).

Some of the issues in this area are:

- Scale-up of bonding and/or film transfer to 2" (Year 1), 3" (Year 3) and, ultimately, to 4" (Year 5) wafers. Related to this is the ability to do wafer bonding and film transfer without loss of operating or active semiconductor volume.
- Resistance of bonded interfaces, in cases where electrical current must pass through the interface. This may require better understanding and control of contamination (e.g., carbon) at the bonding interface, as well as of the in-plane rotational alignment between the two wafers.[45]

A particularly interesting avenue may be the monolithic integration of AlGaInP and AlGaInN through wafer bonding and film transfer. This would enable the integration of the brightest red-emitting material with the brightest blue- and green-emitting material.

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[45] J. J. O'Shea, M. D. Camras, D. Wynne, and G. E. Hofler, "Evidence for voltage drops at misaligned wafer-bonded interfaces of AlGaInP light-emitting diodes by electrostatic force microscopy," Journal of Applied Physics 90 (2001) 4791-4795.

2.2.2 Metallization and Thin Films

High-quality ohmic contacts are essential to high-power devices. If they do not have a low resistance they will dissipate some electrically injected power, leading to parasitic ohmic losses and excess device heating.

Typical ohmic contact technologies used in GaN-based devices are:

- n-type: Ti/Al with 600C annealing.
- p-type: Ni/Au with 400C annealing.

The limitations, however, which are much more severe for AlGaInN materials than they are for AlGaInP or AlGaInAs materials. Most of the limitations are on the p-type contact side, and stem from the inability to create heavily p-doped GaN material. And, if the Mg doping does become very heavy, it can diffuse into the active region during subsequent processing, quenching luminescence

In addition, since the metallization generally covers at least one side of the LED (unless good current spreading layers can be developed), metallizations that have secondary properties (in addition to high electrical conductivity) such as high optical reflectance or transmission, have also become important.

Finally, the metallizations must be reliable to 100,000 hrs, and must withstand high operating (150C) and soldering (>300C) temperatures associated with die-attach or flip-chip bonding of the LED chip to the lamp package.

2.2.3 Etching, Chip-Shaping, Texturing

In many of device configurations, there is a common need for fabricating optically engineered structures for reflecting or refracting light. These structures require processes that etch or shape the material. This is the case for both AlGaInP and AlGaInN materials, though AlGaInN, being refractory and relatively chemically inert, has special challenges.

For example, edge-emitting laser devices require facets. These facets can be created by cleaving in the AlGaInP/GaAs system, but not easily in the AlGaInN/sapphire system, because of the symmetry of the sapphire substrate. Hence, it would be helpful to develop etched, rather than cleaved facets. In fact, even for AlGaInP/GaAs lasers, it may be helpful to develop etched facet technology, in order to facilitate on-wafer test, maximize usable substrate area, and lower cost.

Chip shaping and texturing are perhaps even more critical. Light extraction depends strongly on the shape of the chip that surrounds the active light-emitting area, and on the texture of the surfaces through which light is being emitted.

Photons may escape only at incident angles smaller than the critical angle of the total internal reflection, as illustrated in Figure 17. The solution widely used at present is to clad the light emitting layer with thick, transparent window layers.

Hence, the difference between a conventional and a high-brightness LED. In a conventional LED, light generated at a certain point in the active layer may only escape upward through a narrow cone. Almost all of the light emitted in other directions is totally reflected and absorbed in the substrate and/or in the active layer. Ideally, the best performance would be achieved in a spherical LED. In practical planar high-brightness LEDs, thick window layers allow the light to escape through six cones. The thick window layers allow the light generated at the center of the chip to escape through the lateral conical paths. Most commercial high-brightness LEDs exhibit light-extraction efficiencies somewhat below 30%.

In order to improve the light-extraction efficiency further, the LED design can employ nonrectangular geometries, textured surfaces,[46] and encapsulants with a higher refractive index (at present, epoxy resins with n_e_1.6 are used).

[46] R. Windisch, C. Rooman, B. Dutta, A. Knobloch, G. Borghs, G. H. Dohler, and P. Heremans, "Light-Extraction Mechanisms in High-Efficiency Surface-Textured Light-Emitting Diodes," IEEE Journal of Selected Topics in Quantum Electronics 8 (2002) 248-255.

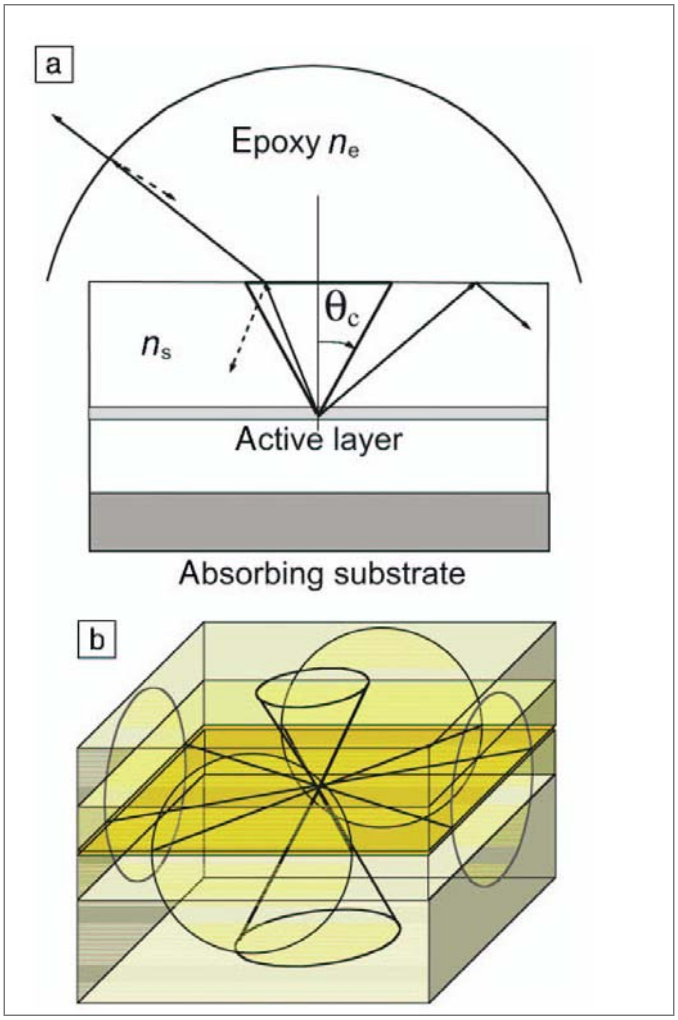

Figure 17. Schematic of light transmitted through, or total internal reflected from, a planar semiconductor surface; and the resulting angular escape cone. After Arturas Zukauskas, Michael S. Shur, and Remis Caska, Introduction to Solid-State Lighting (John Wiley and Sons, Inc., New York, 2002).

The highest performances of AlGaInP/ GaP LEDs are achieved using chips that deviate from a conventional rectangular shape.[47] A truncated inverted pyramid (TIP) shape, which is achieved by dicing a chip with a beveled blade to yield side-wall angles of 35° with respect to the vertical,[7] greatly improves light-extraction. Such a shape totally redirects internally the reflected photons at small incidence angles that fit the escape cones. As of this writing, the AlGaInP TIP LED holds the performance record for an electroluminescent visible-light source. In the orange region (610 nm), it exhibits the highest reported luminous efficiency, exceeding 100 lm/W (close to that of sodium lamps) with a peak luminous flux of 60 lm. In the red region (650 nm), external quantum efficiencies of as high as 55% have been achieved.

Although it may be difficult to separately target internal conversion efficiency and external extraction efficiency, if our chip conversion efficiency goals are 30% in Year 1, 40% in Year 3 and 60% in Year 5, it is expected that external extraction efficiencies will ultimately need to target 90%.

2.3 LEDs and Integrated LEDs

The simplest light-emitting device is the light-emitting diode. These are basically p-n junctions within which electrons and holes are injected into an active region, recombine and emit light. There are two overall LED configurations:

- Vertical-Injection LED. The simplest configuration is the vertical-injection configuration. In this configuration, holes are provided from a ring contact into a p-type semiconductor layer. The holes spread radially inwards within the highly conducting p-type layer, and then inject into the active layer(s). At the same time, electrons are provided from a contact on an n-type substrate, transport through the substrate, and are then injected into the same active layer(s). The electrons and holes are trapped within the active layer(s), and eventually recombine to emit light.
- Lateral-Injection LED. If the substrate (e.g., sapphire) is not conductive, then, in the lateral-injection configuration scheme, the electrons are also injected from a ring contact. They are injected into a highly n-doped layer through which they spread laterally inward, before eventually moving upwards into the active layer(s) to recombine.

All LED structures are variants of these two basic LED configurations. The major functions that the structure must perform are: Ohmic contact; current spreading and transport to the active region; injection of carriers in the active region; spontaneous recombination of carriers; and, finally, light extraction.

The epilayer and wafer processing building blocks that are used to perform these major functions depend on the alloy compositions available at the wavelength of interest. At any particular wavelength, the available alloy

[47] Tun S Tan, Michael R Krames, and Fred A Jr. Kish, Lumileds Lighting U.S., LLC, "Forming LED Having Angled Sides for Increased Side Light Extraction," Patent Number US6323063 (Nov 27, 2001).

compositions may allow some properties but not others, and compromises must be made. The art of device design is to take advantage of the properties that are available at the wavelength of interest, while compensating for the properties that are unavailable.

At all wavelengths (red, green/blue and UV), the common goal is to achieve very high power conversion efficiencies at high input current densities and high operating temperatures.

In Challenge 2.3.1 we discuss red LEDs fabricated from AlGaInP materials. In Challenge 2.3.2 we discuss green, blue and UV LEDs fabricated from AlGaInN materials. In Challenge 2.3.3 we discuss monolithically integrated LEDs in which multiple colors are emitted to create white directly at the chip level.

2.3.1 Red LEDs

Red LEDs would be used in a white lighting system as one of several colors mixed together to create the appearance of white light. Thus far, however, only the AlGaInP materials system has demonstrated efficient red luminescence, hence we focus our attention on AlGaInP-based red LEDs.[48]

The current state-of-the-art in AlGaInP red LEDs is represented by multiple-well, substrate-removed and bonded, chip-shaped structures emitting at 650nm. The structural quality of the active layers, the achievable doping levels, and the active layer design are such that carrier injection, trapping and radiative recombination are all nearly 100% efficient. And, the transparency of the substrate combined with truncated-inverted-pyramid chip shape enables a 60% external extraction efficiency. All together, this LED has an external quantum efficiency approaching 60% at room-temperature, the highest external quantum efficiency of all visible-spectrum LEDs. Taking the electrical series resistance into account, the power conversion ("wall-plug") efficiency of this device approaches 50%.

The major limitations are:

- Cost. This is a relatively expensive device, as it involves removal (and disposal) of a GaAs substrate, combined with thick GaP epitaxy, and chip shaping.
- Wavelength. As the wavelength shortens from 650nm, the internal quantum efficiency for radiative recombination decreases rapidly. This is a significant limitation for red LEDs that are to be color-mixed with other LEDs to create white light. The optimum wavelength for such a red LED is actually closer to 610 nm, as eye sensitivity drops off rapidly towards the red. This is known to be because, 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. Also, non-radiative centers associated with Al are believed to play a role in decreasing the internal quantum efficiency of shorter-wavelength AlGaInP devices.
- High Power. For the same reasons as those given above, at high input power densities, and at high temperatures, carrier leakage over relatively low confining barriers compromises device efficiency.

[48] K. Streubel, N. Linder, R. Wirth, and A. Jaeger, "High Brightness Algainp Light-Emitting Diodes," IEEE Journal of Selected Topics in Quantum Electronics 8 (2002) 321-332.

2.3.2 Green, Blue and UV LEDs

Green and blue LEDs could be used in a color-mixing approach to white lighting as two of several colors mixed together to create the appearance of white light. Blue LEDs could also be used in the hybrid approach to white lighting in conjunction with wavelength conversion materials. UV LEDs could be used in the wavelength-conversion approach to white lighting.

All current (and likely future) high-performance green, blue and UV[49] LEDs are fabricated from the AlGaInN materials system. The state-of-the-art in these LEDs is represented by multiple-quantum-well structures grown on sapphire. Because these LEDs are grown on buffers on sapphire, the structural quality of the active layers is not very high. But, due to clustering into In-rich InGaN "quantum-dot" like regions, which trap most of the carriers, the radiative recombination efficiency can still be relatively high (nearly 30-40%). Also, the transparency of the sapphire substrate enables a 30% external extraction efficiency. All together, these LEDs have power conversion efficiency of about 20-30%.[50]

The major limitations are:

- Cost. These are relatively expensive devices (150 $\$/cm^2$), mostly because of low yield for the

[49] J. Han and A. V. Nurmikko, "Advances in Algainn Blue and Ultraviolet Light Emitters," IEEE Journal of Selected Topics in Quantum Electronics 8 (2002) 289-297.
[50] A. Y. Kim, W. Gotz, D. A. Steigerwald, J. J. Wierer, N. F. Gardner, J. Sun, S. A. Stockman, P. S. Martin, M. R. Krames, R. S. Kern, and F. M. Steranka, "Performance of High-Power Alingan Light Emitting Diodes," Physica Status Solidi a-Applied Research 188 (2001) 15-21.

process of buffer layer growth on sapphire.

- Wavelength. Although their wavelength in the blue is relatively optimal for either color-mixed or blue+yellow phosphor approaches to white lighting, their wavelength in the green is not. The optimum wavelength for such a green LED is 540 nm, which matches the peak of the eye sensitivity. However, as the wavelength lengthens from 520nm, the internal quantum efficiency for radiative recombination decreases rapidly.
- Power Conversion Efficiency. Both their internal radiative efficiency and their external extraction efficiencies are low, hence their overall power conversion efficiencies are low.
- Power Density. Current injection uniformity is poor, due to difficulties in lateral current spreading. As a consequence, the input power density can be limited by "hot" spots at the points of carrier injection.

2.3.3 Monolithic White LEDs

All current commercial devices are "discrete" devices emitting monochromatic light in a narrow band around one wavelength. For signaling applications, which dominate current markets for visible light emitters, this focus on discrete devices is reasonable.

However, there are strong cost motivations for integrating LEDs with one another, or with electronic devices, together onto one chip. First, there are significant costs associated with the white light production process at the package level. This is especially true for the color mixing approach, but also for the wavelength conversion approach. Second, there are significant costs associated with white lighting fixtures, including electronic control circuitry and optical elements for focusing and directing light.

Both of these costs are incurred during chip packaging and fixturing, rather than during chip fabrication. However, chip fabrication is done at the wafer-level, which experience from other semiconductor technologies has shown is always much less expensive than packaging, since it is done in parallel over the entire wafer at once, rather than in series, die by die (or package by package). Hence, shifting functionality from the die or package to the wafer or chip can be an important means for reducing overall system cost.

In addition, monolithic integration at the wafer level would enable the fabrication of compact microsystems with higher functionality as well as enhanced yield and reliability.

2.4 Directional Emitters

The light-emitting diode discussed in Section 2.3 is the simplest light emitter. It requires only that electrons and holes recombine radiatively. However, without any special attention paid to the optics of the LED, the light emission is random and omnidirectional.

As a consequence, in a planar chip, as discussed in Section 2.2, most of the light is totally internally reflected and never escapes from the semiconductor. Then, the chip must be shaped in special ways to maximize the amount of light that escapes.

An alternative to chip shaping is to alter the way in which the light is emitted, so that it isn't random, but directional. Then, light extraction can be much more efficient, without going to the trouble of shaping the chip. These kinds of devices are more complex and perhaps more costly, but are potentially more efficient. In this Section, we discuss these kinds of directional light emitting devices. In Challenge 2.4.1, we discuss resonant-cavity and super-luminescent LEDs. In Challenge 2.4.2 we discuss edge-emitting lasers. In Challenge 2.4.3 we discuss vertical-cavity surface-emitting lasers.

Because stimulated emission enhances radiative recombination, but doesn't affect non-radiative recombination, stimulated emission devices, if driven sufficiently hard, can be less sensitive to defects than spontaneous emission devices. However, stimulated emission devices are more sensitive to material heterogeneities, since these tend to inhomogeneously broadened the gain spectrum, so that much of the material cannot contribute emission into the narrow lasing line.

A common theme to all of these devices is the importance of optoelectronic device simulation tools that can be used to optimize device design and performance.

2.4.1 Resonant-Cavity and Super-Luminescent LEDs

Resonant-cavity[51] and super-luminescent LEDs differ from ordinary LEDs in that light is not emitted equally into all optical modes.

[51] D. Delbeke, R. Bockstaele, P. Bienstman, R. Baets, and H. Benisty, "High-Efficiency Semiconductor Resonant-Cavity Light-Emitting Diodes: a Review," IEEE Journal of Selected Topics in Quantum Electronics 8 (2002) 189-206.

In the case of resonant-cavity LEDs the active region has been placed inside an optical cavity, or resonator. The resonator modifies the spectral density of optical modes in the direction parallel to the cavity axis -- enhancing it at wavelengths corresponding to cavity resonances, and suppressing it at wavelengths away from the resonances. Hence, the spontaneous emission rate, which is proportional both to the square of the carrier density, and to the optical mode density at the carrier recombination wavelength, is enhanced.

In the case of super-luminescent LEDs the active region is placed inside a guided-wave structure. The guided waves cause stimulated emission into, and enhanced intensity in, the guided wave modes.

These enhancements have two beneficial consequences. First, they enable radiative carrier recombination to compete better against non-radiative carrier recombination, thereby increasing the internal radiative efficiency. Second, since the enhancement is only in those optical modes whose light propagation direction is along a particular axis, the overall light emission pattern is no longer omni-directional, but enhanced along that axis. This both enables more compact subsequent collection and focusing optics, and enhances the light extraction efficiency. Typically, the enhancement factor can be as large as 4x, and for a planar transparent-substrate device, extraction efficiencies can be improved from 2.5% to 10%.

In addition, the cost of resonant-cavity and super-luminescent LEDs is not expected to be much greater than that of ordinary LEDs, since they are only "modestly" engineered structures. Hence, the incremental benefit per incremental cost may be quite high.

2.4.2 Edge-Emitting Lasers

Semiconductor lasers go one step further than resonant cavity devices. In simple resonant cavity devices, the optical mode density is modified, but the cavity is relatively leaky (low Q), the optical field strength of the modes is relatively low, and spontaneous emission still dominates.

In lasers, the cavity is not leaky (high Q), the optical field strength of the modes becomes very high, and stimulated emission dominates. In this situation, the same two beneficial effects as for RCLEDs occur, except much more so. First, this enhancement enables radiative carrier recombination to compete much better against non-radiative carrier recombination, thereby increasing the internal radiative efficiency. Second, since the stimulated emission is only in those optical modes whose light propagation direction is parallel to the cavity axis, the overall light emission pattern is completely unidirectional along that axis. The light extraction efficiency becomes 100%.

In addition, lasers are essentially exact point sources of light, rather than approximate point sources of light as are LEDs. Hence, the package- and fixture-level optical engineering associated with color mixing, wavelength conversion, light directing and focusing would be potentially easier with lasers than with LEDs. It is even possible to imagine white lighting systems where the laser is located remotely from phosphors that it excites: phosphors could be painted on a wall and activated by a remote UV laser to produce unusual lighting effects without any power connections in the wall. Unlike an LED, a laser beam could be easily directed with near 100% efficiency to such a remote phosphor.

The current state-of-the-art in high-power semiconductor lasers is edge emitters in the AlGaInAs materials system. The main application of these lasers is optical pumping of solid-state lasers such as Nd:YAG. In that sense, these lasers are used in a similar way to the way lasers might be used in white lighting: as a source of cheap, directable, monochromatic light for input into an optical wavelength and mode converter.

These lasers are moderately mature. In array form, as illustrated in Figure 18, output powers can be as high as 2-3kW. Typically, output powers at 810nm are in the 100W per package range, with retail prices of approximately $40/Watt and wholesale prices of approximately $4/Watt, with power conversion efficiencies in the 50-60% range.

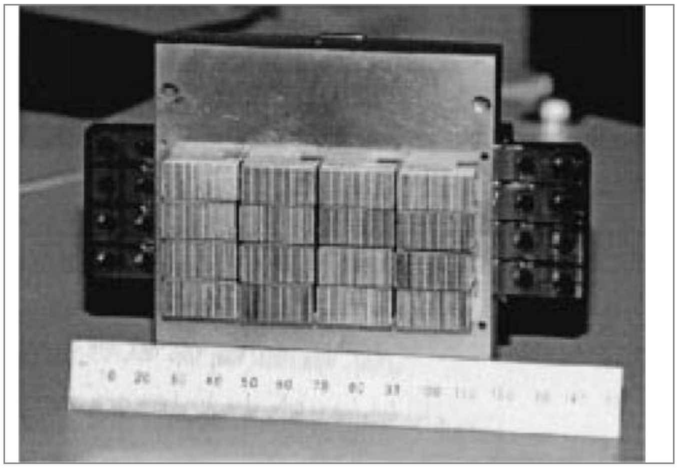

Figure 18. A 2D array of laser diode bars capable of 2.56kW average optical output power. If such powers were available in the three primary colors, the result would be roughly 1Mlm of white light. After D. F. Welch, "A Brief History of High-Power Semiconductor Lasers," IEEE Journal of Selected Topics in Quantum Electronics 6 (2000) 1470-1477.

Indeed, if equivalent optical powers could be created at visible wavelengths, then, using an "average" human eye sensitivity of 400 lm/W, these performance figures would correspond to:

- A luminous efficacy of roughly 200 lm/W, which is exactly the year 2020 target
- A luminous flux per package of 40 klm, which is 25x higher than the year 2020 target
- A purchase cost of 10 $/klm, which is higher (but only by about 5x) than the Year 2020 target.

And, it should be noted, that these lasers are currently manufactured in modest volumes compared to the potential volumes for white lighting, so presumably there is significant room for additional performance improvement and cost reduction.

The major (and huge) limitation, however, is that these kinds of efficiencies and powers have yet to be demonstrated at the visible and near-UV wavelengths that would be interesting for white lighting.

- State-of-the-art red edge emitting lasers in the AlGaInP materials system now have efficiencies in the 40% range, and power outputs in the 1-3W range, at wavelengths in the 630-670nm wavelength range.[52]
- State-of-the-art violet edge emitting lasers in the AlGaInN materials system, now have power outputs of 5mW and lifetimes of 10,000 hrs at wavelengths in the 405nm range. The most intense current interest is for applications in optical data storage (digital versatile disks), so less attention has been paid to raw power. However, much higher powers should be possible. For example, lasers transferred using laser lift-off to copper substrates for improved thermal management have recently demonstrated cw powers as high as 100W.[53]

2.4.3 VCSELs

Vertical-cavity surface-emitting lasers (VCSELs) are a second kind of laser. They differ from edge emitters in that the output direction of the light is out of the plane, rather than in the plane, of the substrate material. This is potentially a more convenient output direction, enabling packaging and optical engineering approaches that borrow heavily from those of conventional LEDs. And they are potentially less expensive than edge-emitting lasers, since they can be processed and tested in wafer form.

Moreover, they have most of the same potential for power conversion efficiencies as edge emitting lasers. Their directionality makes extraction of light near-100% efficient. And their even higher optical circulating power density enables stimulated emission and radiative recombination to compete even more favorably against non-radiative recombination. Indeed, like edge emitters, AlGaInAs-based VCSELs at 850nm with power conversion efficiencies of over 50% have also been demonstrated.

For solid-state lighting, it will be necessary to develop VCSELs that are just as efficient in the UV or visible. AlGaInP-based red VCSELs have been demonstrated. Their power-conversion efficiency (now at 14%) and temperature performance continues to improve,[54] but are still far from our targets.

AlGaInN-based VCSELs in the UV, blue and green are even less mature, but perhaps even more important to emphasize. Recently, an optically pumped InGaN/GaN VCSEL operating at the near-UV wavelength of 384 nm

[52] Wu LZ and Zhang YS, "Selenium doping effects and low-threshold high-power GaInP-AlGaInP single-quantum-well lasers grown by MOVPE," IEEE Photonics Technology Letters 12 (2000) 248-250 .

[53] M. Kneissl, W. S. Wong, D. W. Treat, M. Teepe, N. Miyashita, and N. M. Johnson, "CW InGaN multiple-quantum-well laser diodes on copper substrates.," Physica Status Solidi A 188 (2001) 23-9.

[54] Knigge A, Zorn M, Wenzel H, Weyers M, and Trankle G, "High efficiency AlGaInP-based 650 nm vertical-cavity surface-emitting lasers," Electronics Letters 37 (2001) 1222-1223.

has been demonstrated. This VCSEL made use of distributed Bragg reflectors (DBRs) made of MOCVD-grown GaN/AlGaN and dielectric multilayers. Nevertheless, this kind of device is extremely challenging to fabricate – the vertical electrical resistance of the DBRs is high, and may require horizontal current injection approaches.

And perhaps the biggest challenge will be high power. In the infrared, where there is now a lot of experience with both edge emitters and VCSELs, VCSELs have only been able to compete in low-power, high-modulation-speed applications, such as in data communications. In high-power applications, edge emitting lasers are dominant.

2.4.4 Optoelectronic Simulation Tools

The application of numerical simulations to the design of photonic devices can have a dramatic affect on performance optimization, limiting iteration cycles, reducing development costs and accelerating time to market. Simulation areas of maximum impact include, but are not limited to, the design of LEDs with enhanced light extraction efficiency, resonant cavity LEDs (RCLED) and VCSELs design, optimum phosphor composition, semiconductor bandgap engineering and material gain optimization. In addition, material growth stands to benefit from simulations of epitaxial deposition and defect propagation.

Numerical simulation of RCLEDs and VCSELs must cope with the multilayer structural complexity of the cavities with etched features and open boundaries, and the richness of physical interactions between carriers and photons, including nonlinear effects and multiple spatial/temporal scales. Direct integration of the full set of Maxwell-Bloch equations using finite difference time domain (FDTD) codes resorts to a full resolution of the finer space and time scales involved, using a finite mesh of points in space and time. While in principle the most accurate approach, FDTD and its variants using the paraxial wave equation, the beam propagation method (BPM), lead to complex, time-consuming numerical simulations. It is perhaps no accident that only one such code is commercially available, while a number of similar numerical tools have been developed and used independently by research groups and universities.

Numerical studies for the optimum placement of the oxide aperture in VCSELs offer one indication of the numerical challenge: detailed simulations so far tend to yield opposite conclusions from experiments regarding the node vs. antinode placement of the aperture, due to an underestimating of the scattering losses. An "infinite" number of the unguided continuum part of the waveguide spectrum must be included to capture diffraction and scattering losses.

Regarding the simulation of light extraction, the majority of simulation tools involve "ray tracing" codes. The accuracy of this approach is limited when the typical device size is comparable to the radiation wavelength. Time consuming full wave simulations must be used to address the coherent wave interference in photonic band-gap structures. Although codes for infinite 3-D structures are publicly available, additional complexities due to symmetry breaking must be addressed for 2-D photonic membranes, and thin epi-layers used for enhanced extraction. Finally, no simulation tools are currently available for optimization of light extraction from randomly textured surfaces, an easy and inexpensive-to-apply manufacturing method that has yielded record extraction efficiencies.

Simulation tools for bandgap engineering are in a more mature stage, due to work at Sandia and elsewhere. Still, more work is required to address the challenges of strain-induced piezo-electric fields and composition non-uniformity ("dopant islands") occurring in GaN alloys.

Last, but not least, to our knowledge the simulation of epitaxial growth, defect percolation and defect propagation is still in its infancy. Further development of such tools will have a considerable impact in the areas of substrate growth and material doping, which are high priority areas.

3 LAMPS, LUMINAIRES AND SYSTEMS

In Chapters 1 and 2 we discussed the light-engine chip that is at the heart of solid-state lighting. This chip must ultimately be packaged into a lamp, along with phosphors or chips of other wavelengths. The lamp, in turn, must ultimately be inserted into a luminaire, or fixture, which directs the light from the lamp onto a workspace.

The overall combination of lamp, luminaire, workspace and human viewer, can be thought of as a lighting environment with a wide range of permutations and design possibilities. The importance of this entire lighting environment is clear from the economics of traditional lighting. Of this $40B market, about 1/3 is the lamp, while the remaining 2/3 is the luminaires, the drive electronics, and lighting-specific architectural features.

In Section 3.1, we discuss the most critical materials used in chip packaging: the phosphors which down-convert either UV or blue primary light, and the encapsulants which protect the entire LED and phosphor combination from the external environment.

In Sections 3.2 and 3.3, we discuss the lamp package itself, and the luminaires and fixtures into which the lamp will be inserted. Lamps and luminaires will have an enormous impact on the efficiency, life and cost of SSL-LED technology through their thermal management of high input power density to the light-engine chip, and through their optical engineering for efficient white light production and directing.

It is likely that, particularly in the early years of SSL-LED technology, there will be a diversity of approaches to lamps and luminaires. These approaches will reflect the different approaches to white light production itself – whether by color mixing, by wavelength conversion, or by a hybrid combination. For example, a lamp based on color mixing will likely need to accommodate multi-chip mounting, and perhaps more sophisticated optics. A lamp based on wavelength conversion from the UV will need to accommodate UV-resistant materials and perhaps more heat-generation for the same lumen production because of lower luminous efficacies.

It is also likely that, in the early years of SSL-LED technology, there will be some overlap in the functions performed by the lamp and the luminaire. One expects in the early years for the luminaire, which is easier to customize, to provide more of the functionality, but in the later years for the lamp, which is easier to make complex at low cost, to provide more of the functionality.

One example is color mixing. There already exist commercial luminaires in which multiple lamps of different colors are mixed into programmable shades of colored and white light. And, for the highest-performance lighting, e.g., for theatres and stages, color-mixing at the luminaire level may forever be the best approach. However, for mainstream white lighting, for which cost is expected to a major factor, we expect white light production, whether through color mixing, wavelength conversion, or a hybrid approach, to occur at the lamp level. Hence, for the purpose of this Roadmap, we assume that white-light production and color-mixing are lamp, rather than luminaire, functions.

Finally, in Section 3.4, we discuss the challenges associated with solid-state lighting systems. Just as the emergence of incandescent lighting technology created radically new ways of thinking, this new era of SSL-LED technology will create a new lighting culture through new applications and new ways of lighting. The result will be an exciting new interplay between the lamp, the luminaire, lighting and interior design, and the human visual system

3.1 Phosphors and Encapsulants

In this Section, we discuss challenges associated with two of the fundamental materials used in lamp packaging: the luminescent materials used in the wavelength conversion and hybrid approaches to white light production; and the encapsulant materials used to protect the chip and phosphor from the external environment.

Throughout these challenges, there are three common themes.

The first is high efficiency. For the phosphor this means strong absorption in the blue or near-UV and high quantum efficiency for re-emission in the red, green or blue. For the phosphor+host+encapsulant materials combination this means low parasitic absorption and optical scatter of the down-converted secondary light.

The second is high-temperature operation. Phosphor quantum efficiencies and encapsulant integrity must be sustained even at the high input power densities and temperatures associated with the light-engine chip. The resulting phosphor temperatures may be somewhat lower than the junction temperature in the chip itself, but are nevertheless expected to be in the 150C range.

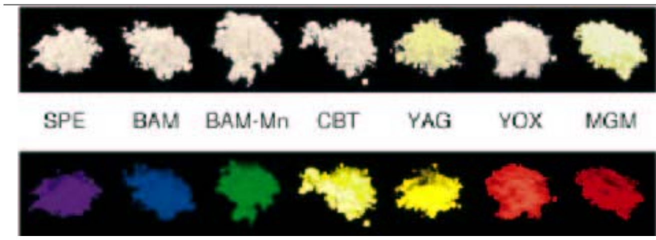

Figure 19. Examples of commercial phosphor powders used in fluorescent lamps and displays, under white light illumination (top) and under UV (254nm) illumination (bottom). The abbreviations are:

SPE	$Sr_2P_2O_7:Eu^{2+}$
BAM	$BaMgAl_{10}O_{17}:Eu^{2+}$
BAM-Mn	$BaMgAl_{10}O_{17}:Eu^{2+}, Mn^{2+}$
CBT	$(Ce^{3+}, Gd^{3+}, Tb^{3+})MgB_5O_{10}$
YAG	$Y_3Al_5O_{12}:Ce^{3+}$
YOX	$Y_2O_3:Eu^{3+}$
MGM	$Mg_4GeO_{5.5}F:Mn^{2+}$

After T. Justel, H. Nikol, and C. Ronda, "Developments in the field of luminescent materials for Lighting and Displays," Angew. Chem. Int. Ed. 37 (1998) 3084-3103.

The third is lumens maintenance. The high quantum efficiency and low parasitic absorption of the phosphor+host+encapsulant materials combination must be maintained over our target operating lifetimes of >100,000 hours.

3.1.1 Phosphor Materials

The function of the luminescent, or phosphor, materials is to absorb the primary near-UV or blue light emitted by the LED chip, and then to re-emit at longer wavelengths such as blue, green or red.

In principle, this wavelength conversion can occur in thin-film materials deposited during chip fabrication. As discussed in Section 2.3, though, efficient luminescent materials with high enough optical absorption to be compatible with (<5-μm-thick) thin-film technologies have not yet been found. Additionally if luminescent thin films were developed, ways must be found to extract the light from the film and avoid light piping. Hence, the current generation of luminescent materials are integrated at the package, or lamp, level, after the LED chip has been fabricated.

In the early stages of solid-state lighting, it is likely that these luminescent materials will borrow from technologies developed for other applications, such as fluorescent lamps, cathode-ray-tube displays, and scintillators.[55] There is a huge variety of such phosphors – a few examples are shown in Figure 19.

Similar to fluorescent lamp phosphors, the phosphors for SSL-LED are required to have high photoluminescent efficiency with desired chromaticity. These can be achieved by inorganic phosphors doped with rare earth, divalent or trivalent, and transition metal ions. Due to their feature of narrow band (a few nm) emission, trivalent rare-earth activated phosphors are widely used in current lighting and display technology, giving both high conversion efficiency and color flexibility. The current generation of commercial white LEDs, based on the approach first used by Nichia) is based on such a phosphor: YAG activated with trivalent cerium ($YAG:Ce^{3+}$), which converts the blue LED radiation into a very broad band yellow emission.

In the middle-to-later stages of solid-state lighting, luminescent materials for solid-state lighting will probably diverge considerably from those used for fluorescent lamps, due to their different requirements.

On the one hand, some of the different requirements will make finding SSL-LED phosphors easier:

- Fluorescent lamp phosphors must be in contact (typically) with a mercury-containing gas discharge, hence must be compatible both with a reactive plasma environment, as well as reactive mercury itself. Hence, sulfide-based phosphors, which react strongly with mercury (as well as under exposure to UV light and moisture), cannot be used.
- Fluorescent lamp phosphors must absorb well both at 254 nm, where 85% of the primary excitation is, and at 185 nm, where an additional 12% of the primary excitation is. The situation is even worse for high-pressure discharge fluorescent lamps, which have much broader primary excitation wavelengths. LED phosphors only need to absorb well at one primary excitation wavelength.
- The high-energy excitation by the primary light (wavelength: 254 and 185 nm) in fluorescent lamps leads to band-to-band electron transitions of the host materials, causing them to be reactive to the mercury plasma and to degrade. LED phosphors, in contrast, are excited with relatively low energy (380 to 470 nm). This excitation usually results in intra-band transitions, and would

[55] G. Blasse and B. C. Grabmaier, Luminescent Materials (Springer-Verlag, Berlin, 1994).

not result in materials degradation.

- The high-energy excitation by the primary light in fluorescent lamps also leads to a larger Stokes shift, hence a lower wall-plug efficiency. In principle, an LED phosphor does not then need to be as quantum efficient as a fluorescent lamp phosphor, in order to achieve the same overall luminous efficacy. In practice, if it is as quantum efficient, then the reduced Stokes shift will lead to a higher wall-plug efficiency.

On the other hand, some of the different requirements will make finding SSL-LED phosphors more difficult.

- Generally speaking, the further into the UV one goes, the better most materials absorb. Since for SSL-LED technology we are looking for high absorption in the blue or near-UV, there will be fewer materials to choose from. This is especially an issue for phosphors that must absorb blue light. If rare earth phosphors, which absorb blue only weakly, are used, then they must be very thick. Increased thickness translates to increased cost, as well as higher optical scattering which, as discussed below, can trap light and reduce light extraction from the LED package
- Low optical scattering of phosphor-converted secondary light by the phosphors themselves is not a consideration for fluorescent lamps, since absorption by other components of the lamp is small, and scattered light will still eventually escape. However, for solid-state lamps phosphor transparency is important, since there are likely to be many packaging materials (e.g., die attach solders) that will absorb scattered light.
- Phosphor performance must be sustained even at temperatures of 150C. This is somewhat higher than the temperatures that need to be sustained by typical fluorescent lamp phosphors (though high-pressure mercury lamp phosphors can experience temperatures as high as 300C).
- Because SSL-LED lamp life is expected to be much longer than fluorescent lamp life (100,000 hours rather than 10,000 hours), SSL-LED phosphors must also be much longer lived than fluorescent-lamp phosphors. The so-called "lumens maintenance" issue is a major one for SSL-LED phosphors, whose emission bands shift and whose quantum efficiency decreases with age. Coloration can result, in the case of inorganic phosphors (e.g., CdZnS), from precipitation of the metal elements and, in the case of organic materials, from breakage of bonds in the molecule.
- SSL-LEDs may encounter more severe environments (moisture, light and heat) than fluorescent lamps, leading to accelerated phosphor degradation. Some environmental factors may be unique to SSL-LEDs, such as electric fields in the vicinity of the chip, leading to electrophoresis-induced emission-wavelength shifts.

The phosphors that need to be developed can be divided into the three principle emission wavelength ranges: red (590-630nm), green (520-560nm) and blue (440-480nm).

Red-emitting phosphors are the most challenging. The main reason is that the red emitter must not only be centered near 610nm, but, because of the sharp decrease in human eye sensitivity at longer wavelengths, it must have a narrow line width. The combination of high absorption in the blue or near-UV, and narrow emission line width, is difficult to achieve.

For example, SrS:Eu2+ absorbs strongly in the blue and near-UV and emits in the red, but with a broadband emission. Or, for example, $Y_2O_3:Eu^{3+}$ has a narrowband red emission and a quantum efficiency for 254 nm excitation close to 100% (the highest of all known lighting phosphors), but absorbs poorly at wavelengths longer than 380nm, even with sensitization.

The situation for green emitting phosphors is slightly more relaxed -- since the human eye is sensitive to a broad range of green light, narrowness of spectral emission is not a dominant concern. The relaxation of this selection criteria allows for a wider range of possible candidates. For example, 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 and for some materials into the blue. For example, SrGa2S4:Eu2+ absorbs strongly in the blue wavelength range 450-475nm and emits in the green.

Nevertheless, optimizing these and other phosphors for quantum efficiencies of >80-85% at >150C temperatures over 100,000hr lifetimes will be a significant challenge. Avenues for the optimization include, but are not limited to, development of non-stoichiometric formulations, protective coatings, optimal doping level, fluxing, and new combinations of activator and sensitizers.

The situation for blue-emitting phosphors is in between that of red and green. Human eye sensitivity cuts off on the purple, but not on the green, side of blue. Hence, there can be an emission tail in the green without a significant decrease in either overall luminous efficacy or color quality.

While many Eu^{2+}-activated phosphors are green emitters, several of them have been identified to be good blue emitters. For example, $(Sr,Ba,Ca)_5(PO_4)_3Cl:Eu^{2+}$ and $BaMg_2Al_{16}O_{27}:Eu^{2+}$ show strong absorption throughout the UV and almost into the visible, and emit blue light. They were developed originally as fluorescent lamp phosphors and recently have been adopted as SSL-LED phosphors. Since these phosphors were designed and optimized for 254nm and 185nm absorption, their efficacy with LED excitation (370-410 nm) is still mediocre. To improve the efficacy, the absorption in the 370-410 nm region needs to be increased. However, these oxide-based phosphors generally offer good chemical stability under exposure to near-UV light and moisture.

Again, optimizing these and other phosphors for quantum efficiencies of >85% (for near-UV-absorbing phosphors) at >155C operating temperatures will be a significant challenge.

3.1.2 Phosphor Synthesis and Application

Assuming that a set of phosphor materials have the necessary optical properties, the materials must still be synthesized into powders and then applied to the SSL-LED chip or lamp.

Traditionally, the synthesis of an inorganic phosphor follows the following procedure:[56]

1. grinding and mixing of the ingredient solid materials
2. firing in a furnace to induce high temperature solid-state reactions that result in a sintered, microcrystalline "cake"
3. mechanical milling of the as-fired product into particles whose sizes are approximately those of the microcrystals in the cake itself
4. washing to remove the unreacted ingredients
5. sieving the product to narrow the typically broad grain size distribution

Recent development on the preparation techniques include: the use of wet chemistry treatments before the high temperature reaction; the use of fluxing materials for better crystal growth; and the use of reducing atmospheres, such as hydrogen, for phosphors whose oxidation state must be carefully controlled, such as those based on Eu^{2+}.

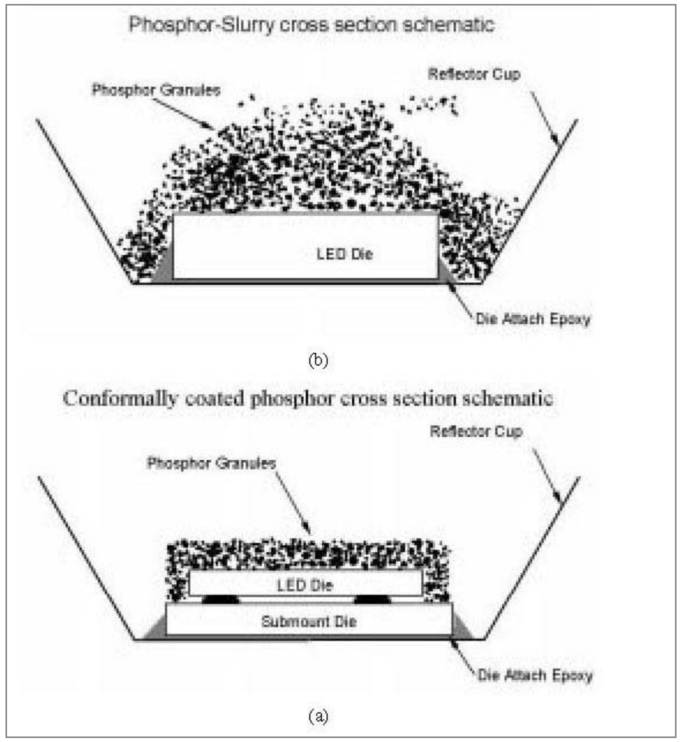

Figure 20. Schematic cross-section of phosphors slurry-deposited on a conventionally-attached LED die and conformally-deposited on a flipped-and-submount-attached LED die. Courtesy of D.A. Steigerwald (LumiLeds).

The resulting phosphor powder can then be mixed with other phosphor powders of different colors, and dispersed in a slurry containing an organic or water-based solvent into which low concentrations of a binding agent and an adhesive have been added. The choice of the solvent depends on the properties of the binders, the adhesive and the phosphors. The viscosity required for the slurry also determines the choice of the solvent. Typical solvents used for lamp phosphor slurry are butyl acetate and xylol. Film-forming binder and adhesive are added to the slurry, the former links the phosphor grains to the film whereas the latter functions as film body. Nitrocellulose and ethylcellulose had been used as the binders, and several phthalates as the adhesives.

Finally, as illustrated in Figure 20, the slurry is applied to the LED chip which has presumably already been mounted in the lamp package.

3.1.3 Encapsulants

The encapsulant is the clear material that lies between the light emitting die/phosphor and the external environment. Typical encapsulants include acrylics, epoxies and silicones. The encapsulant serves both as a key component in the

[56] Shigeo Shionoya and William M. Yen, Editors, Phosphor Handbook, CRC Press, Boca Raton, 1999).

optical design of the LED and as the final seal between the die/phosphor and the external environment. As an optical element of the LED the encapsulant should have high index of refraction and good stability in presence of high intensity light, humidity and high temperature. As a final "seal" between the chip+phosphor combination, and the external environment the encapsulant must protect the chip and phosphor from the mechanical handling and possibly other environmental conditions. Diffusion of water is a particular issue unless higher-cost hermetic packages are used.

The wall-plug efficiency for the LED is very sensitive to the index of refraction of the encapsulant. The nearer the index of refraction of the encapsulant is to that of the LED substrate material the higher the WPE for the LED. This can be best understood by noting that the LED die by necessity has some self-absorption. The largest contributors to this absorption are absorption in the doped semiconductor, absorption of the metal contacts and absorption in the active region. For LEDs grown on sapphire the encapsulant should be as near to the ~1.7 index of sapphire as possible. For LEDs grown on SiC encapsulant index must be even higher to match the ~2.2 index of SiC.

For LEDs that use near UV (~370nm) light to pump phosphors this light can be damaging to the human eye. For this reason then, the encapsulant may have the additional optical requirement that the near UV light be absorbed in the encapsulant and not escape into environment. If the phosphor is integrated with the encapsulant, then there will be the opposite optical requirement that near UV light not be absorbed in the encapsulant.

Clarity of the encapsulant is critical and should be maintained at >80% through a ~5mm thick section under the extremes of operating temperature, humidity and blue/near-UV light intensity.

The whole area of encapsulants is complicated because of the extreme range of wavelengths that may or may not be present in single and multi- chip LEDs. These wavelengths can range from the UV (370 nm) to the red (630 nm). The encapsulant of choice has to survive the effects of wavelength as well as high temperature without degradation.

Current LED encapsulants show degradation due to exposure by both UV and blue light, particularly at high intensities, high humidity and at high temperatures. Epoxy and other thermosetting materials are the most common encapsulants used in LEDs today. These materials degrade rapidly under blue light, high humidity and high temperature and limit the useful life of common indicator LEDs to less than a few thousand hours at maximum rated current.

3.2 Lamps and Electronics

In this Section, we discuss challenges associated with lamp packaging itself. These lamp packages will have an enormous impact on the efficiency, life and cost of solid-state lighting. They will be more diverse than the chips on which they are based, as they must span the various approaches to white light production, and the various permutations in the chips that are used. Lamps that involve wavelength conversion of light from a single chip may look very different from those that involve color mixing of light from multiple chips.

All lamps, though, must share five common characteristics.

The first is cost. The lamp packaging, normalized to the amount of chip area that is used, must be less than roughly $75-50/cm^2.

The second is efficient thermal management, due to the need to drive the light-engine chip at high input power densities (400 W/cm^2 by Year 2012). Thermal management will be especially important for multiple color LED illumination strategies as the temperature sensitivities of GaN-based and AlInGaP-based LEDs are significantly different. This may require electronics inside the package to dynamically adjust the ratio of Blue, Red and Green to maintain a constant white point.

The third is efficient optical engineering for wavelength conversion and color mixing that results in: low package re-absorption losses; and uniform color in the angular cone of directed light, independent of chip operating temperature up to 175C.

The fourth is electronic compensation for color drift with time, input power, and ambient temperature.

The fifth is reliability and disposability. The lamp must last 100,000 hours. And, it must be constructed of non-toxic materials that can be disposed of without harming the environment.

3.2.1 Power Lamps

The initial step in lamp packaging is to mount the LED light chip "engine" in the package. There are five key issues associated with this mounting.

The first issue is cost. If our Year 2012 target on chip cost is $75-50/cm^2, then package cost must be comparable.

The second issue is good electrical and heat conduction into and out of the chip. Our Year 2012 targets for lumens per lamp are 1klm/lamp, and for luminous efficacy are 150lm/W. Hence, it will be necessary to develop lamps that support drive powers of (1klm/lamp)/(150lm/W), or about 7W/lamp. If there is some inefficiency in the lamp driver, and if the driver is integrated into the lamp, then the input power to the lamp could be 30% higher still – 10W/lamp. At the same time, the amount of waste heat that will be generated will be (1klm)/(400lm/W - 150lm/W), or about 4W/lamp. Although this is not a lot of heat, it must be dissipated in the lamp over a small chip area of 1klm / (400W/cm^2 x 150lm/W), or 0.017 cm^2.

We can use the Year 2012 targets to calculate roughly the thermal resistance that the lamp must provide to the chip. As discussed in Sections 2.3 and 3.1, it will be important to increase the operating temperatures of chips and phosphors as much as possible. However, it is likely that the efficiency of the chip will drop significantly at temperatures much above 200C. Also, we can assume that the ambient temperature that the lamp presents to the chip will be less than roughly 75C, due to thermal and thermal stress limitations on the materials from which the lamp is constructed, particularly where it mates to the luminaire. Hence, the die-to-luminaire thermal resistance must be less than (200C-75C)/4W, or about 30C/W. This thermal resistance is comparable to that of current high-power LED packaging, and there is probably room for decreases to the 10-20C/W range, albeit likely at greater cost.

The third issue is thermal stresses, and reliability. The lamp must last 100,000 hours of continuous operation, as well as many tens of thousands of control (turn-on, turn-off, dimming) cycles. Minimizing thermal stress will require improved thermal management, so that temperature gradients within the lamp, and particularly at the interface between the lamp and the chip, are minimized. It will also require development and implementation of lamp materials whose thermal expansion coefficients are well-matched to those of GaAs or Ge (for red LEDs) or of GaN, sapphire or SiC (for green, blue and UV LEDs).

The fourth issue is that the packaging must accommodate both conducting substrate as well as non-conducting substrate light-engine chips.

The fifth issue is that the packaging must be compatible with UV and visible light. It must not degrade under this exposure, and, in order to maintain high efficiency, must absorb very little of the light that it is exposed to.

3.2.2 Color-Mixing and Wavelength Conversion

The packaged lamp must provide the optics associated with color mixing, wavelength conversion, and general high-efficiency extraction of light from the lamp. There are four issues.

The first issue is cost. Normalized per cm^2 of chip area used in the package, it must be less than \$90/cm^2. Normalized per lumen of light output, it must be less than \$0.40/klm.

The second issue is efficiency. In all three approaches to white-light production, we are targeting >90% efficiencies associated with the package – including the optics as well as parasitic package losses. The package efficiency of the current generation of white (blue + phosphor-converted yellow) LEDs has been estimated to be only 50% or less, so there is considerable room for improvement.

The third issue is constancy of the mixing with respect to angle and temperature. This is less of an issue with the wavelength-conversion approach, but is a major issue with the color mixing and hybrid approaches. In the hybrid approach, for example, color non-uniformity occurs because the light from the blue LED is directional while the light from the phosphor radiates over a 2π solid angle. Also, since chip and phosphor efficiency may change with temperature, the ratio of the colors that are being blended will also change with temperature.

The fourth issue is performance over time and long-term reliability. The optics used must not themselves degrade under the expected operating temperatures (150C) and optical fluxes.

3.2.3 Drive Electronics

Drive electronics supply the lamp with the electrical power required to power the light-engine chips. In principle, these electronics can either be integrated into the luminaire along with the lamp, or they can be separate from the luminaire.

In the early stages of solid-state lighting, both approaches are likely to be explored. However, in the later stages, it is more likely that the electronics, as it has with fluorescent lighting, will, to maximize placement flexibility and to minimize cost, be integrated into the luminaire. It could even, at some point, be integrated into the lamp along with the light-engine chip, but as this involves a fairly complex integration of high-temperature electronics with optoelectronics, we don't consider it here.

There are four main issues associated with the drive electronics.

The first issue is voltage transformation. Semiconductor technologies are low-DC-voltage technologies. Hence, just as Si-based computer chips, they are inherently incompatible with traditional high-AC-voltage (110V and 220V) power systems.

It is possible that, at some point, the ubiquitousness of semiconductor technologies, including electronics and lighting will drive the development of new low-voltage electrical distribution standards for buildings. And, it is possible to design lighting systems that use the low-voltage real-time or time-delayed output of solar cells. However, neither of these is considered likely to be adopted on a massive scale in the next 10-20 years, hence we assume here that it is necessary to transform traditional high-AC voltages into low-DC voltages.

This transformation is somewhat easier than that necessary for fluorescent lamps (viz., from high-AC voltages into very-high-AC voltages). And, the electronics can be somewhat similar to those developed for other semiconductor technologies, such as computers.

Related to this voltage transformation is the possibility of a "back reaction" of large concentrations of nonlinear devices on the quality and safety of electric power in the utility infrastructure (including harmonic content, excessive neutral current, transformer and conductor heating, voltage stressing, etc.).

The second issue is lifetime and cost. Drive circuits for consumer electronics do not need to be in the 100,000 hour range, because the lifetime of the application itself is normally not that long. Hence it will be necessary to develop drive circuits with lifetimes and reliabilities more in the range of those used for high-end high-performance 24/7 electronics applications (e.g., servers and communications systems). A target lifetime 50% longer than that of the lamp would guarantee that the drive electronics are not a factor in system lifetime, so here we target a value of 150,000 hours.

At the same time, the costs must be compatible with those for consumer lighting systems. If our Year 2012 lighting targets are 150 lm/W for luminous efficacy and \$5/klm, then the target lighting cost per delivered Watt to must be \$0.75/W = (\$0.005/lm)x(150lm/W). Assuming the power supply can at most be 30% of this cost, we end up with a Year 2012 target for the drive electronics of \$0.25/W.

The third issue is programmability. Because solid-state lighting has the unique ability to maintain its luminous efficacy even at very low lumens out, it is likely that

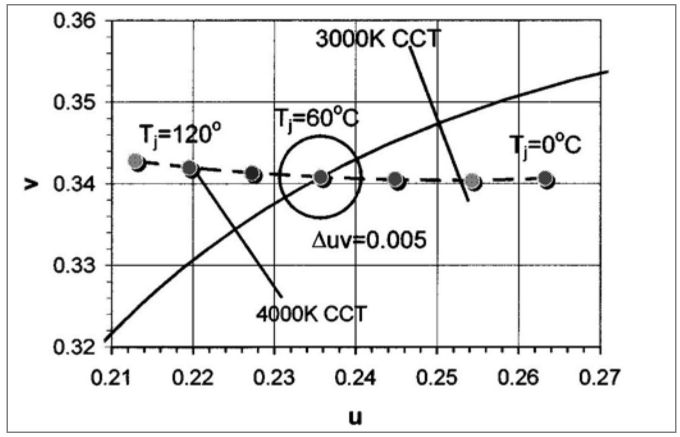

Figure 21. The calculated shift in (u,v) chromaticity coordinates of a color-mixed tri-color LED as the temperature is changed in increments of 20C. The RGB-LED has a color temperature of 3500K at a junction temperature of 60C, but color temperatures of 3000K and 4000K at junction temperatures of 0C and 120C. After S. Muthu, F. J. P. Schuurmans, and M. D. Pashley, "Red, Green, and Blue Leds for White Light Illumination," IEEE Journal of Selected Topics in Quantum Electronics 8 (2002) 333-338.

dimmability will be an important feature to exploit. Moreover, in the color-mixing and hybrid approaches to white-light production, it may be possible to alter the color type and quality of the lamp by tailoring the currents that drive various chips mounted in the lamp.

We note that on the one hand this programmability is a new feature associated with solid-state lighting. On the other hand, for the color-mixing approach to white light production, it may be a necessary feature, if the intensity and color of lamps drift over time and need to be compensated for, as illustrated in Figure 21. It may also be necessary in order to compensate for spread in lumen output and wavelength of manufactured LEDs. Because the consistency and reproducibility of traditional lighting is so high, it is likely to be similarly demanded of solid-state lighting. Manufacturing tolerances may become much tighter for LEDs, but, if not, programmable drive electronics will be necessary.

We also note that this programmability will require drive electronics with multiple outputs, where the average voltage or current at each output can be varied in response to system-level needs.

The fourth issue is efficiency. Because wall-plug efficiency is one of the primary motivations for solid-state lighting, it will be necessary to develop drive electronics that are themselves very efficient. Our target is 95% efficiency (85% is already commercially available). This high efficiency will be challenging, particularly as it must be

	Incandescent	Fluorescent	SSL-LED
Visible Light	0.10	0.19	0.4
IR Light	0.72	0.31	0.3
Conduction/ Convection	0.18	0.36	0.3

Table 5. Approximate fractional energy dissipated into various channels for traditional and solid-state lighting technologies. Values for incandescent and fluorescent lighting are from the 1987 IESNA Handbook (courtesy of N. Narendran); values for solid-state lighting are estimated assuming Year 2012 target for efficiency, and assuming a 70C heat sink, 25C ambient, a 5W device in 25cm3 volume (calculation courtesy of P. Martin).

achieved while maintaining high "quality" (e.g., small reactive impedances, and low RF generation), and in a compact form factor consistent with the compactness of the lamp itself. One vision is for the drive electronics to be miniaturized to the point of enabling the power converter to be an integral part of the fixture or ultimately of the chip itself.

3.3 Luminaires

In this Section, we discuss challenges associated with the luminaire. This is the fixture that houses the lamp, that ultimately directs light from the lamp onto the work-space, and that the end-user primarily sees and interacts with.

Just as lamp packages are likely to be more diverse than the light-engine chips at their heart, so luminaires are likely to be more diverse even than lamp packages. Not only must they span the various permutations in the lamps; they must also span the various end-uses of white light, all the way from direct task lighting to indirect diffuse lighting.

All luminaires, though, must share five common features.

The first is efficient thermal management. Unlike fluorescent lamps, solid-state lamps will be small and, even though efficient, concentrated sources of waste heat. And, unlike incandescent lamps, solid-state lamps will not dissipate their heat primarily through IR radiation, but, as indicated in Table 5, through a combination of IR radiation and conduction/convection.

The second is efficient optical engineering for directing and focusing light from the lamp. This is an area in which there is much to be gained. In contrast to fluorescent and incandescent lamps, solid-state lamps are directional, nearly-point sources. Hence, for directed-light uses, it should be possible to make more-efficient use of light. Instead, the challenge will be, for indirect-light uses, to disperse the light uniformly.

The third is reliability. If chip and lamp lifetimes are 100,000 hours, luminaire lifetimes must also be equally long.

The fourth is cost. The luminaire fixturing, normalized to the amount of chip area that is used, must not be more than roughly \$180/cm². If we use as a rough guide a 30%:30%:40% break-out across chip:packaging:fixturing, then normalized to the lumens that are output, it must not be more than roughly 40% of \$5/klm, or \$2/klm. For our Year 2012 target lamp, which puts out 1 klm, this means the luminaire must be no more than roughly \$2. However, it should be emphasized that the break-out for solid-state lighting may be very different from 30%:30%:40%.

The final issue is safety. The heat sinks will be at high enough temperatures (>75C) that they should not be easily contacted by people.

3.3.1 Power Luminaires

Although solid-state lighting is expected to be very efficient, it will not be 100% efficient, and waste heat will be generated.

Unlike in fluorescent lamps, where the waste heat is distributed over very large surface-area glass envelopes, in solid-state lighting the waste heat is concentrated in very small lamp volumes. And, unlike in incandescent lamps, where much of the waste heat is infrared light which radiates out into the environment, in solid-state lighting the waste heat must at least partially, and perhaps largely, be conducted from the lamp into the luminaire and finally into the environment.

As a consequence, getting rid of waste heat may be more difficult in luminaires designed for solid-state lighting than those designed for traditional incandescent and fluorescent lighting.

Using our Year 2012 targets, we can calculate the amount of waste heat that must be dissipated per lamp to be (1klm) / (400lm/W - 150lm/W), or 4W. Although this is not a lot of heat, it must be dissipated in the lamp over a small chip area of 1klm / (400W/cm² x 150lm/W), or 0.017 cm², and ultimately in the luminaire over a lamp surface areas larger by perhaps 1 order of magnitude, or 0.17 cm².

We can also use our Year 2012 targets to calculate roughly the thermal resistance that the luminaire must provide the lamp. Assuming that the luminaire is much larger than the lamp, and assembled from much less expensive materials, it is not likely to be able to withstand temperatures much above 75C. Then, assuming that the lamp temperature is limited to our target of 175C, the thermal resistance must be less than (175C-75C)/4W, or about 25C/W.

Note that it is critical to meet this thermal resistance target. The power-conversion efficiencies of both the light-engine chip and the wavelength-conversion phosphors decrease with temperature. Developing chips and phosphors that are efficient up to 150-175C will already be very challenging; developing chips and phosphors that are efficient to much higher temperatures would be nearly impossible.

Indeed, if the luminaire can present an even lower thermal resistance to the lamp, it may be possible to relax the chip and phosphor operating temperature targets of 150-175C.

3.3.2 Optics for Directing and Diffusing

Perhaps the most critical aspect of the luminaire is how it distributes light from the lamp into the workspace, according to the application. It is this aspect that will most distinguish luminaires for solid-state lighting from those used in traditional lighting.

Because solid-state lighting lamps are essentially point sources of light, the optics required to collimate, focus and direct are relatively straightforward, and are ideally suited to directed "task-lighting" applications. Indeed, for such applications, solid-state lighting is expected to have a roughly 2x advantage over traditional lighting in the efficiency with which the task area is selectively illuminated [Note from JYT to Chips: reference for this?]

However, because solid-state lighting lamps are point sources of light, it is also necessary to use optics to create the uniform and homogeneous light output necessary for indirect large-area lighting applications. Note, though that these optics can be simpler than those used to convert intermediate-size sources of light.[57] In addition, there are safety considerations, as the lumen output of single lamps is so bright that it could be harmful for humans to look directly at the lamp.

In the early stages of solid-state lighting, luminaire optics will be even more complex, as much of the color-mixing may be done at the luminaire level, and the lack of single lamps with the necessary lumens out will require working with multiple lamps. In the later stages, however, the optics are expected to simplify, as color-mixing and white light production moves to the lamp level, and as single lamps achieve the lumens necessary for single luminaires.

It is likely that there will be a range of luminaire types tailored for the range of end-use applications. However, it is also expected that every human-oriented illumination need will eventually be servable by some solid-state-lighting-based luminaire.

3.3.3 Luminaire Reliability and Disposal

The materials from which luminaires are constructed are a final critical area. There are two key issues:

The first is related to luminaire reliability. Our Year 2012 target for lamp lifetime is 100,000 hours. The luminaire should last at least that long. A 50% margin would guarantee that luminaire lifetime is not an issue. That means all luminaire materials, mechanical, optical and electrical, and their interconnections, must have 150,000-hour lifetimes.

The materials that are of special concern are: polymers and plastics, which can discolor with age and with exposure to intense light; solder materials and joints, which can crack over time; and connector systems, which can corrode, particularly in severe-use environments.

The second is related to the life cycle of the luminaire, especially its end-of-life disposal. For traditional mercury-containing fluorescent lamps, disposal costs are significant. We did not account for these disposal costs in the cost-of-ownership analysis in Section 0.3; doing so would only make fluorescent lamp technology less attractive.

For solid-state lighting, one important challenge will be to ensure that there are no similar end-of-life disposal costs. This means the use of non-toxic materials (e.g., lead-free solders) throughout the chip, lamp and luminaire. It also means assessing disposal issues related to materials that are mildly toxic, such as the GaAs substrates currently used in AlGaInP-based red LEDs. We note that in this example, it would not be difficult to switch to non-toxic Ge substrates, if necessary.

3.4 Lighting Systems

In this Section, we discuss challenges associated with lighting systems. The light-engine chip, the lamp, and the luminaire, are clearly the technology enablers of the lighting system. However, the other pieces of the lighting system are also critically important, with their own unique challenges:

- Delivering low-voltage high-current electricity in a world dominated by high-voltage low-current

[57] P. Kan, L. Whitehead, S. J. Pojar, and K. G. Kneipp, "Structure for Efficiently Coupling Large Light Sources Into Prism Light Guides," Journal of the Illuminating Engineering Society 29 (2000) 78.

sockets.

- Integrating solid-state lighting into building architectures, and the complex and delicate interplay between function and form.
- Understanding the ways in which solid-state lighting interacts with the human visual system to increase comfort and human productivity.
- Adding intelligence to continuously alter the lighting to optimize the balance between energy conservation and human factors.

Throughout these challenges, a common theme is to imagine and implement new (and sometimes radically new) ways of lighting, rather than to simply build in "backward compatibility" with traditional lighting.

It is new features, not just energy efficiency, that are likely to spur: first, adoption of solid-state lighting into new buildings; and second, conversion of traditional lighting in existing buildings. It is even possible, as has occurred in the past with other semiconductor-based technologies, that new features drive an accelerated turnover in lighting systems even before the actual lamps or luminaires burn out. If so, the lighting market could grow at a rate significantly faster than the historical 3%/year associated with traditional lighting.

Also, it is new features that may enable perhaps the most important spin-off benefit of solid-state lighting: enhanced human productivity. We note that even a 0.1% improvement in human productivity would, in a U.S. economy with a gross domestic product of about $1T/year?, would represent a benefit of $10B/year!

And, finally, it is new features and their acceptance by consumers, that will provide necessary guidance to the evolution of the core light-engine chip, lamp and luminaire technologies.

We emphasize that lighting systems is a huge area encompassing a wide variety of disciplines, and encompassing everything beyond the photon creation device, including photon placement, integration into the environment, and interaction with humans. Hence, our thinking about lighting systems is relatively immature. Basic concepts often taken for granted, such as the color rendering index (CRI) or even the definition of the lumen[58] may need to be rethought with respect to solid-state lighting. Nevertheless, lighting systems are the ultimate vehicle for implementing solid-state lighting, so we have tried to take a first look, however imprecise and incomplete, at their issues here.

3.4.1 Human Factors and Productivity

The connection between lighting, the human visual system and, ultimately, human comfort and productivity, has long been complex and controversial.[59] As noted in Section 0.3, even the most basic concept of color rendering quality is not yet well defined.

The connection is all the more critical for solid-state lighting, with its ability to selectively and perhaps programmably fill the visible spectrum through primary light from chips and secondary light from phosphors.

3.4.2 Aesthetic, Intelligent Buildings

One of the most fascinating aspects of solid-state lighting technology is sure to be the development of building and lighting architectures that, 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 Research Center, Lawrence Berkeley National Laboratory's Lighting Systems Research Group, and other efforts connected to the U.S. Department of Energy's Office of Building Technology, State and Community Programs).

Some of these unique features are related to the physical form factors (compactness) and environmental compatibility (rugged and vibration resistant) of SSL-LEDs. These physical characteristics will enable SSL-LEDs to be integrated more readily with building architectures and architectural materials.

Some of these unique features are related to the programmability of SSL-LEDs – including dimmability while maintaining high luminous efficacy, and color tailoring.

Especially in buildings in which lighting is a mix between artificial and natural (daylight) sources, programmable (dimmable) lighting can save significant amounts of energy.[60] Note that the most obvious means of programmability – to turn lights off automatically when a room is vacant, are not unique to solid-state lighting. However, solid-state lighting adds a new dimension to

[58] Particularly for night-time tasks such as driving. See, e.g., http://www.iaeel.org/IAEEL/NEWL/1995/tval1995/HumFa_2_95.html.

[59] S. L. Mccoll and J. A. Veitch, "Full-Spectrum Fluorescent Lighting: a Review of Its Effects on Physiology and Health," Psychological Medicine 31 (2001) 949-964.

[60] D. H. W. Li and J. C. Lam, "Evaluation of Lighting Performance in Office Buildings With Daylighting Controls," Energy and Buildings 33 (2001) 793-803.

programmability – modifying lights according to the use of a room.

Indeed, for traditional lighting, there is a trade-off between programmability and energy efficiency. For an incandescent lamp, e.g., dimming the bulb lowers the filament temperature, which means more of the blackbody spectrum occurs in the invisible infrared. Hence, changing intensity or color quality often results in a decrease in energy efficiency, and compromises must be made. High-efficiency, high-intensity discharge lamps are even more difficult to dim, due to their need for carefully stabilized discharge currents, prompting the development of external and cumbersome large-area modulators.[61]

For solid-state lighting, these compromises may not need to be made – human comfort and productivity through programmable lighting can be optimized more independently of energy efficiency.

The common theme is to make use of both the "hardware" and "software" aspects of SSL-LEDs to create a new generation of more aesthetic and more energy-efficient buildings and homes.

[61] H. Fujikake, Y. Tanaka, S. Kimura, H. Asakawa, T. Tamura, H. Kita, K. Takeuchi, H. Ogawa, A. Nagashima, Y. Utsumi, and K. Takizawa, "Heat-Resistant Liquid Crystal Light Modulator Containing Polymer Network for High-Power Luminaires," Japanese Journal of Applied Physics Part 1 39 (2000) 5870-5874.

A APPENDIX: ROADMAPPING PROCESS AND RESOURCES

This Roadmap was put together in several stages.

2002 Feb. To initiate the Roadmap, OIDA (Arpad Bergh), in consultation with DOE (Jim Brodrick) and NEMA (Kyle Pitsor) identified a facilitator (Jeff Tsao, Sandia) and a technical steering committee (George Craford, LumiLeds, Michael Coltrin, Sandia, Steve DenBaars, UC Santa Barbara, and Jim George, Permalight. Then, OIDA, the facilitator and the steering committee identified the scope of the Roadmap update and the invited speakers for the workshop.

2002 Mar-May. Based on a number of primary references identified by OIDA, the facilitator, the steering committee and the invited speakers, the facilitator created a first-draft Roadmap, including introductory material and a comprehensive set of technical targets, challenges and possible approaches. These primary references are listed in Section 0.

2002 May 30. A technical workshop was held in Albuquerque, NM. The workshop brought together experts from Universities, National Laboratories and Industry. These experts heard invited talks in various technical challenge areas; and in breakout sessions debated and fleshed out the targets, challenges, and possible approaches outlined in the first-draft Roadmap. They also binned the individual challenges by risk and reward, and identified reviewers for them.

2002 Jun-Jul. Based on comments from the May 30 workshop, the facilitator created a more-comprehensive second-draft Roadmap, including a revised set of technical targets, challenges and possible approaches. Explanatory background text was also added. This second-draft Roadmap was sent (in stages) to the steering committee and to the reviewers identified at the workshop.

2002 Jul-Aug. Based on final comments from the steering committee and from the individual challenge reviewers, the facilitator created a third-and-final-draft Roadmap. Figures and references were also added.

2002 Aug. Finally, the Roadmap was separated into two parts: a Roadmap Update 2002, which summarizes the Targets, Decision Points, Challenges and Possible Approaches; and a Roadmap Tutorial, which provides more detail on the Targets, as well as introductory material to the various Challenge Areas.

A-1 Primary References

The primary references used in constructing the first-draft Roadmap are listed here. We do not include secondary references to specific technical research, as these are listed in footnotes to the text of the Roadmap.

1. A survey of the solid-state-lighting journal and patent literature over the period 2001 mid-Oct through 2002 early-Feb. The survey was done by Perspectives, a firm that specializes in technical and market intelligence, on behalf of Sandia National Laboratories. The survey can be viewed at http://lighting.sandia.gov under Issue 11 of the Science, Technology, Business and Headline News section.
2. The Year 2000 Review of Japan's "Light for the 21st Century" Project, translated by K.V. Sereda and J.Y. Tsao, 2002 Mar 29, available from the Optoelectronics Industry Development Association (www.oida.org).
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8. A viewgraph tutorial put together in 2000 by E.F. Schubert on "Light Emitting Diodes," available at www.lightemittingdiodes.org.
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A-2 Workshop Agenda

LED Workshop

Wyndham Albuquerque Hotel • Albuquerque, NM
May 30, 2002

7:30 ***Registration & Continental breakfast***

8:00 Welcome and Introductions – *Arpad Bergh, OIDA*

8:10 National Security Implications of SSL – *Al Romig, Sandia National Laboratory*

8:30 **Materials and Device Research:** *Steve DenBaars, UCSB*

8:40 Make the Photon - Then Get It Out: Strategies for Efficient Semiconductor Light Emitters – *Arto Nurmikko, Brown University*

9:00 Efficient Light Emitters Based on Photonic Crystals and Metallic Extraction Gratings – *Axel Scherer, CALTECH*

9:20 Alternative Substrates for Growth of III-Nitride-based Light-emitting Device Structures with Reduced Densities of Defects and/or Cost – *Robert Davis, NC State University*

9:40 Physics of Optical Response in Group-III Nitride Active Structures – *Weng Chow, Sandia National Laboratory*

10:00 Issues in GaN Growth Chemistry and Reactor Design – *Thomas Kuech, University of Wisconsin*

10:20 Status of GaN LEDs and Lasers for Solid-State Lighting & Displays – *Shuji Nakamura, UCSB*

10:40 ***Break***

11:00 **Lighting Systems**: *James F. George, Permalight Products*

11:10 *Chips Chipalkatti, OSRAM*

11:30 Solid State Lighting: Systems/ Applications Issues – *Nadarajah Narendran, Rensselaer Polytechnic Institute*

11:50 *Kevin Dowling, Color Kinetics*

12:10 ***Lunch*** – *Speaker: Jonathan Epstein, Legislative Fellow, US Senate*

1:10 Wavelength Conversion Materials – *Alok Srivastava, GELcore*

1:30 *Paul Martin, LumiLeds Lighting*

1:50 **Program Priorities & Breakout Objectives:** *George Craford, LumiLeds*

2:00 Break out sessions & Break

- Substrates, Buffers & Epitaxy – *Bob Davis / Tom Kuech*
- Physics, Processing & Devices – *Steve DenBaar / Bernd Keller*
- Packaging & White Light Production – *George Craford / Paul Martin*
- Lighting Fixtures & Systems – *Jim George / Chips Chipalkatti*

5:00 ***Break***

5:30 Breakout reports, Conclusions and Recommendations (15 min. per group)

6:30 ***Reception***

A-3 Bibliography

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